BNL-81685-2008
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 92

PKU-RBRC Workshop on Transverse Spin Physics

June 30th - July 04, 2008
Beijing China

International Organizers: Harut Avakian (Jefferson Lab); Gerry Bunce (Brookhaven National Laboratory); Feng Yuan (Lawrence Berkeley Lab/RIKEN BNL Research Center)

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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Memorandum of Understanding between RIKEN and BNL, initiated in 1997, has been renewed in 2002 and again in 2007. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group and the RBRC Experimental Group consists of a total of 25-30 researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~50 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. In most cases all the talks are made available on the RBRC website. In addition, highlights to each speaker's presentation are collected to form proceedings which can therefore be made available within a short time after the workshop. To date there are ninety proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998.

N. P. Samios, Director
March 2008

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

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Conference Coordinator: *Yu Zhu (Peking University)*

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Introduction

Understanding the structure of the nucleon is a fundamental question in sub-atomic physics, and it has been under intensive investigation for the last several years. Modern research focuses in particular on the spin structure of the nucleon. Experimental and theoretical investigations world-wide over the last few decades have established that, contrary to nave quark model expectations, quarks carry only about 30% of the total spin of the proton. The origin of the remaining spin is the key question in current hadronic physics and also the major driving forces for the current and future experiments, such as RHIC and CEBAF in US, JPARC in Japan, COMPASS at CERN in Europe, FAIR at GSI in Germany. Among these studies, the transverse-spin physics develops actively and rapidly in the last few years. Recent studies reveal that transverse-spin physics is closely related to many fundamental properties of the QCD dynamics such as the factorization, the non-trivial universality of the parton distribution and fragmentation functions. It was very timely to bring together the theorists and experimentalists in this field at this workshop to review and discuss the latest developments and future perspective in hadronic spin physics.

This workshop was very success in many aspects. First of all, it attracted almost every expert working in this field. We had more than eighty participants in total, among them 27 came from the US institutes, 13 from Europe, 3 from Korea, and 2 from Japan. The rest participants came from local institutes in China. Second, we arranged plenty physics presentations, and the program covers all recent progresses made in the last few years. In total, we had 47 physics presentations, and two round table discussions. The discussion sessions were especially very useful and very much appreciated by all participants. In addition, we also scheduled plenty time for discussion in each presentation, and the living discussions impressed and benefited all participants.

As of many outcomes of this workshop, we identified the most important issues that both experiment and theory should address thoroughly in the futures. On the theory side, we had the following wish list,

- Quantitative Connection between SSA and Quark Orbital Angular Momentum
- Energy Evolution of the SSA, next-to-leading perturbative QCD correction
- Soft gluon resummation at small transverse momentum region
- Robust separation of Sivers and Collins contributions in pp collisions
- Underlying Physics of the nontrivial $P_\perp$ dependence observed by STAR at RHIC

- The detailed functional dependence of $(k_\perp, x)$ for the TMD parton distributions, $\cdots$

On the experiment side, we listed:

- Drell-Yan SSA
- Photon-jet SSA in pp collisions
- Quark Transversity and Tensor charge (h_1)
- Test the Large transverse momentum behavior of the SSA $(1/P_\perp)$
- Transverse momentum dependence of the Double Spin Asymmetries
- SSA in vector boson (W and Z) production in pp collision
- Flavor separation of SSA via He3 at JLab and RHIC
- Large-x Sivers/Collins contributions
- Polarized nucleon-nucleus experiments (nuclear effects in B-M function)
- Experimental studies of SSA with kaons and rho, $\cdots$

Many of the above items share concerns from both experiment and theory sides. We hope some of the above issues will have answer at the next transverse spin physics workshop.

Let us summarize by thanking RIKEN/BNL Research Center (RBRC) of Brookhaven National Laboratory for the financial support. We are also grateful to the Center for High Energy Physics, Peking University for the warm host and strong support for this workshop. The financial supports from the Thomas Jefferson National Accelerator Facility, the Institute of Theoretical Physics, Peking University, China Center of Advanced Science and Technology (World Laboratory), Beijing, and Shandong University are also helpful and very much appreciated.

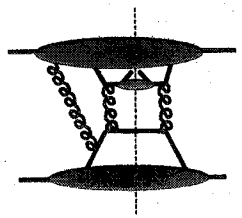
Organizers:
Harut Avakian (Thomas Jefferson National Accelerator Facility)
Gerry Bunce (Brookhaven National Laboratory)
Feng Yuan (Lawrence Berkeley National Laboratory and RIKEN/BNL Research Center, Brookhaven National Laboratory)

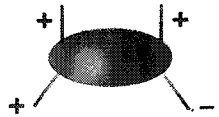
Transverse Spin Phenomena in QCD

Werner Vogelsang

Physics Department, Brookhaven National Laboratory, Upton, New York 11973, U.S.A.

We give an overview of the recent developments in the field of transverse spin physics in QCD, many of which will be discussed in detail in talks at this workshop. Our focus is in particular on the theoretical progress. We discuss connections that have been established between two widely considered mechanisms for single-transverse spin asymmetries, in a physical process. We also mention recent extensions of that work. We also review the question of universality of the Sivers mechanism in general QCD hard scattering, which has received particular attention over the past years. We highlight recent phenomenological studies of single-transverse spin asymmetries and transverse-momentum dependent parton distributions which, among other things, have led to a first extraction of the proton's transversity distributions. Finally, we give an overview of some of the recent theoretical efforts to find connections between transverse-momentum dependent parton distributions and generalized parton distributions.





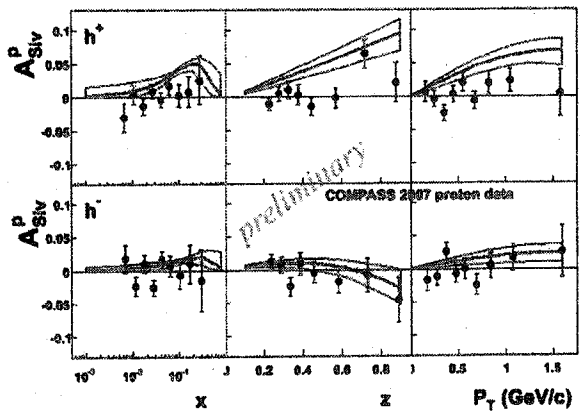
- phase in hard scattering
- hel. flip because of $qg\bar{q}$
- factorization for $pp \to \pi X$ established
- phenomenology

Qiu, Sterman
Kouvaris, Qiu, WV, Yuan

- phase in distribution fct. (but where exactly?)
- hel. flip because of OAM
- factorization for $pp \to \pi X$ *assumed* ($k_\perp \sim p_\perp$?)
- phenomenology

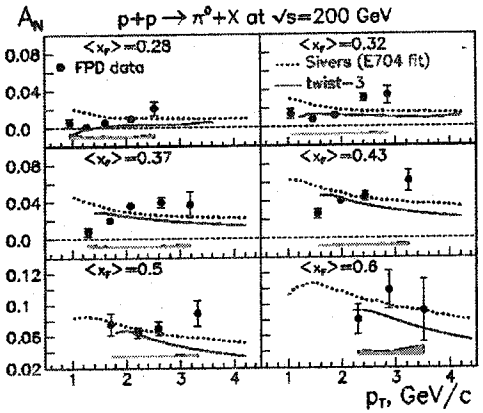
Anselmino, Boglione, D'Alesio, Leader, Melis, Murgia, ...

COMPASS



- New data continue to puzzle us:

STAR

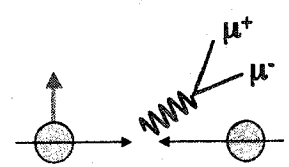


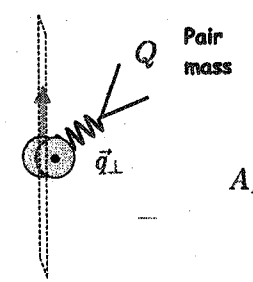
- mechanisms tied to factorization theorem that applies

Q: In what way are mechanisms connected ?

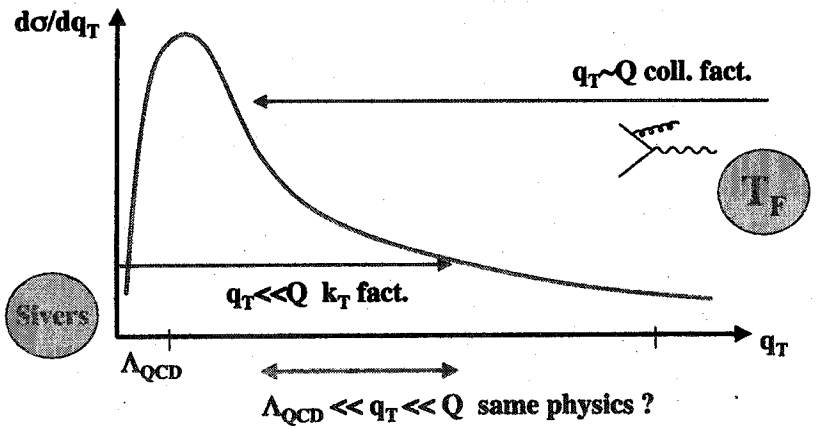
- Boer, Mulders, Pijlman $\quad T_F(x,x) \sim \int d^2k_\perp\, k_\perp^2\, f_{1T}^\perp(x,k_\perp)$
- see interplay of mechanisms in a physical process ?

Example : Drell-Yan





$$A_N = \frac{L-R}{L+R}$$



"Unification" / Consistency of formalisms

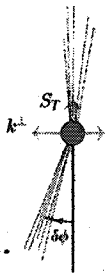
- verified at 1-loop

X. Ji, J.W. Qiu, WV, F. Yuan

- What happens in more general QCD hard scattering? (that is, in processes that are not just color singlet)

Bomhof, Mulders, Pijlman; Qiu, WV, Yuan; Collins, Qiu

Consider pp→jet jet X



$\vec{q}_\perp$ = jet pair transv. mom.

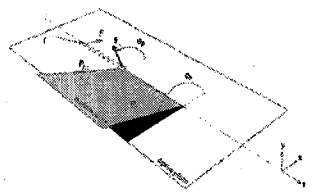
Underlying this: all QCD 2→2 scattering processes

Bacchetta, Boer, Diehl, Mulders

$$\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xQ^2}\frac{y}{2(1-\varepsilon)}$$

$$\varepsilon = \frac{1-y}{1-y+y^2/2}$$

$$\times\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h) F_{UU}^{\cos 2\phi_h}$$
$$+ \lambda_e \sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}$$
$$+ S_\parallel\Big[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h) F_{UL}^{\sin 2\phi_h}\Big]$$
$$+ S_\parallel\lambda_e\Big[\sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\Big]$$
$$+ |S_\perp|\Big[\sin(\phi_h-\phi_S)\big(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\big)$$
$$+ \varepsilon\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}$$
$$+ \sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S) F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$
$$+ |S_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S F_{LT}^{\cos\phi_S}$$
$$+ \sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\}.$$

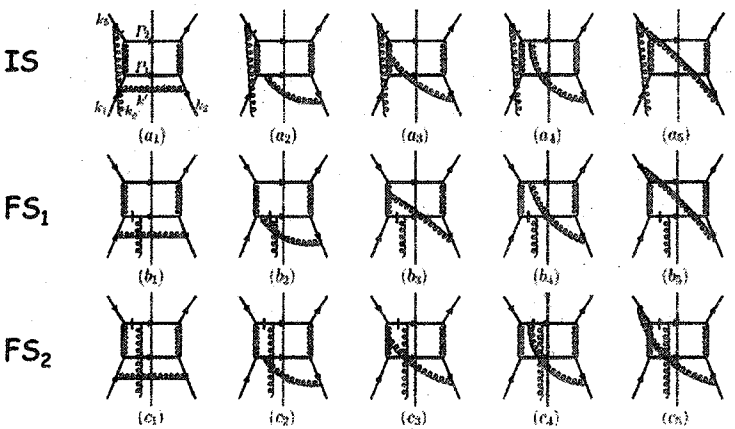


- pQCD tails and TMD expressions do not always match

Example: qq' → qq'

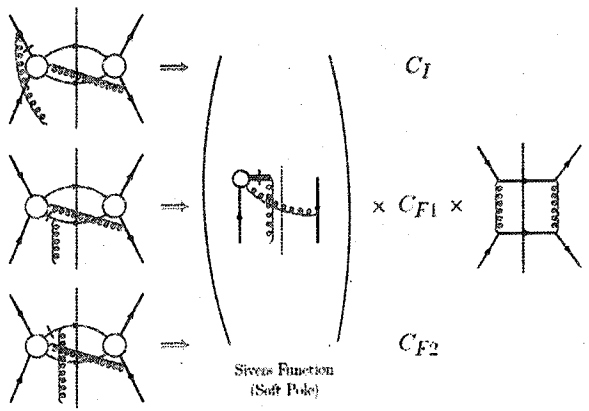
Qiu, WV, Yuan

- for Qiu/Sterman calculation: subset of diagrams



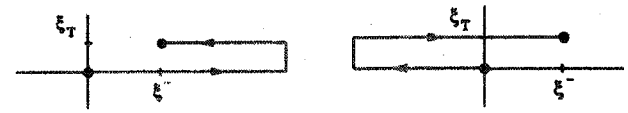
(these are soft-pole)

k' parallel to pol. hadron:



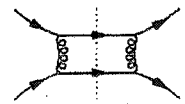
Likewise for hard-pole contributions

However,

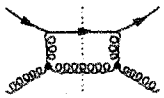


DIS $\quad \Phi_q \propto \langle \overline{\psi}(0)\mathcal{U}^{[+]}\psi(\xi)\rangle \qquad$ DY $\quad \Phi_q \propto \langle \overline{\psi}(0)\mathcal{U}^{[-]}\psi(\xi)\rangle$

Bomhof, Mulders, Pijlman



$$\Phi_q \propto \langle \overline{\psi}(0)\left\{\frac{N_c^2+1}{N_c^2-1}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\mathcal{U}^{[+]} - \frac{2}{N_c^2-1}\mathcal{U}^{[\Box]}\mathcal{U}^{[+]}\right\}\psi(\xi)\rangle$$



$$\Phi_q \propto \langle \overline{\psi}(0)\left\{\frac{1}{2}\frac{N_c^2}{N_c^2-1}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]\dagger}\right]}{N_c}\mathcal{U}^{[+]} + \right.$$
$$\left. + \frac{1}{2}\frac{N_c^2}{N_c^2-1}\frac{\mathrm{Tr}\left[\mathcal{U}^{[\Box]}\right]}{N_c}\mathcal{U}^{[-]} - \frac{1}{N_c^2-1}\mathcal{U}^{[+]}\right\}\psi(\xi)\rangle$$

Non-universality !

What this means:

Structure at this order can be organized as

$$\frac{d\Delta\sigma}{dy_1\,dy_2\,dP_\perp^2\,d^2\vec{q}_\perp} \propto q'(x)\,q_T^{\mathrm{SIDIS}}(x,q_\perp)\,\underbrace{(C_I + C_{F_1} + C_{F_2})\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}}_{\frac{N_c^2-5}{4N_c^2}\,\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}}$$

- happens for all partonic channels:

$$H^{\mathrm{Sivers}}_{ab\to cd} = \frac{\alpha_s^2\pi}{\hat{s}^2}\sum_i (C_I^i + C_{F1}^i + C_{F2}^i)\,h^i_{ab\to cd}$$

individual diagrams

At this order, it appears that there could be a TMD factorization with universal functions !

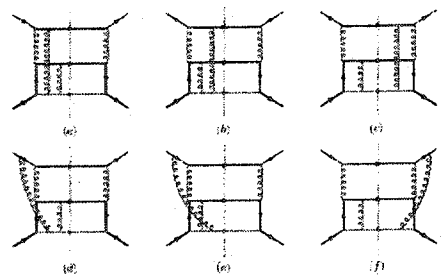
How to reconcile the observations ?

Yuan, WV
Collins

(1) Expand "Amsterdam" gauge links to first order in coupling g

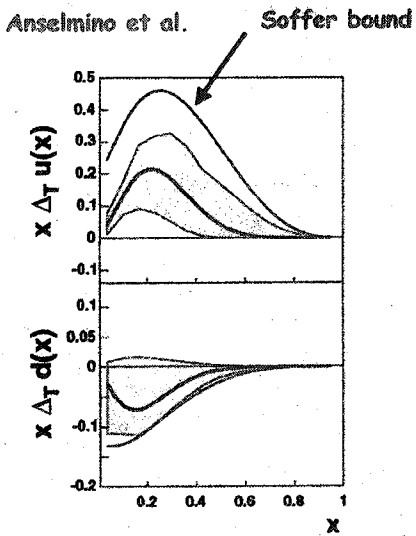
→ this reproduces "universal" first-order result

(2) Examine two-gluon exchange contribution



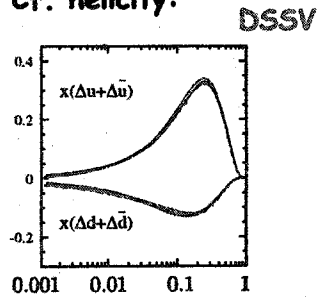
→ this reproduces expectation from gauge link

Anselmino et al.



Absolute sign ?

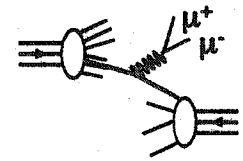
Cf. helicity:



- u transversity appears to be smaller than expected from models and lattice

Wakamatsu

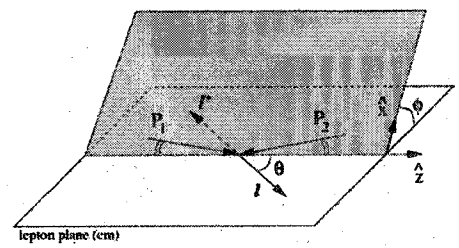
TMDs in unpolarized reactions:



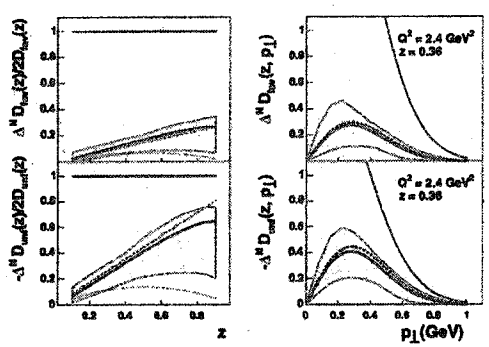
$$\frac{d\sigma}{d\Omega d^4q} = \frac{\alpha^2}{2(2\pi)^4 Q^2 s^2}\{W_T(1+\cos^2\theta) + W_L(1-\cos^2\theta)$$

$$+ W_\Delta \sin 2\theta \cos\phi + W_{\Delta\Delta}\sin^2\theta\cos 2\phi\}$$

Lam, Tung: Collins



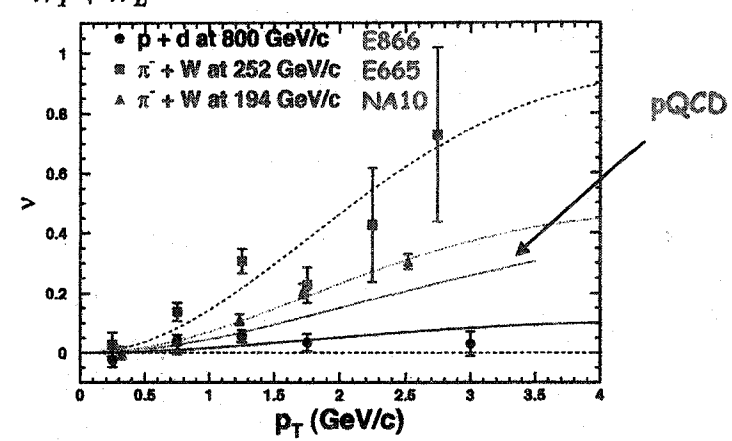
Collins functions:



- Universality of Collins functions is central to this.

  Collins, Metz; Gamberg, Mulders, Mukherjee
- Arguments for pp scattering: Yuan
- Note: Collins not necessarily suppressed in A_N in pp Yuan

$$\nu = \frac{2W_{\Delta\Delta}}{W_T + W_L}$$



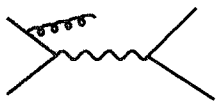
$1 - \lambda - 2\nu = 0$ Lam-Tung relation

- ν is measure of (T-odd) Boer-Mulders function:

$$\nu \propto \frac{\sum_a (\ldots) h_1^{\perp a}\, h_1^{\perp \bar{a}}}{\sum_a (\ldots) f_1^a\, f_1^{\bar{a}}}$$

Boer; Lu, BQ Ma; Gamberg, Goldstein, Oganessyan; Boer, Brodsky, Hwang; Zhang, Lu, BQ Ma, Schmidt; ...

- π+N more sensitive to valence, p+d to sea (small?)
- Zhang, Lu, Ma, Schmidt find $h_1^{\perp u}$, $h_1^{\perp d}$ with same signs
- however: also radiative pQCD contribution:



$$\nu_{\rm CS} \approx \frac{p_T^2}{Q^2 + \frac{3}{2} p_T^2}$$

- in same way,

Burkardt; Meißner, Metz, Goeke

$$-\int d^2\vec{k}_T k_T^i \frac{\epsilon_T^{kj} k_T^k}{M} h_1^{\perp q}(x, \vec{k}_T^2)$$

$$\approx \int d^2\vec{b}\; \mathcal{I}^{q,i}(x, \vec{b}_T) \frac{\epsilon_T^{kj} b_T^k}{M} \left(\mathcal{E}_q^T(x, b_T^2) + 2\tilde{\mathcal{H}}_q^T(x, b^2)\right)$$

magnitude of Boer-Mulders ~ distortion of transv. pol. quarks in unpolarized target

- estimates (using models Pasquini, Pincetti, Boffi; Burkardt, Hannafious or lattice) gives

$h_1^{\perp u}$, $h_1^{\perp d}$ both sizable and negative

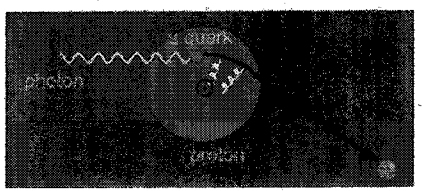
- expected to be "target-independent"

$$-\int d^2\vec{k}_T k_T^i \frac{\epsilon_T^{jk} k_T^j S_T^k}{M} f_{1T}^{\perp q}(x, \vec{k}_T^2) \simeq \int d^2\vec{b}_T \mathcal{I}^{q,i}(x, \vec{b}_T) \frac{\epsilon_T^{jk} b_T^j S_T^k}{M} \frac{\partial}{\partial b_T^2} \mathcal{E}_q(x, b_T^2)$$

- Satisfied in a variety of models (likely not beyond)

Meißner, Metz, Goeke

- Suggests: spatial deformation of pdfs and OAM as origin of single-spin asymmetries



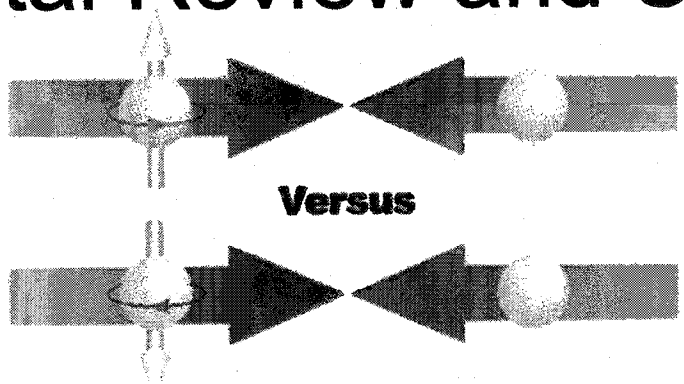
Burkardt; Diehl, Hägler

Qualitatively, expect

$$f_{1T}^{\perp u} < 0 \qquad f_{1T}^{\perp d} > 0 \qquad f_{1T}^{\perp d} \sim -f_{1T}^{\perp u}$$

- This is a golden age for our field: major advances in experiment and theory
- theory: still many issues
  - * factorization
  - * radiative corrections, evolution, higher twist, ...
- Look forward to more data: RHIC, COMPASS, Jlab, EIC, GSI-FAIR, J-PARC

Experimental Review and STAR Results

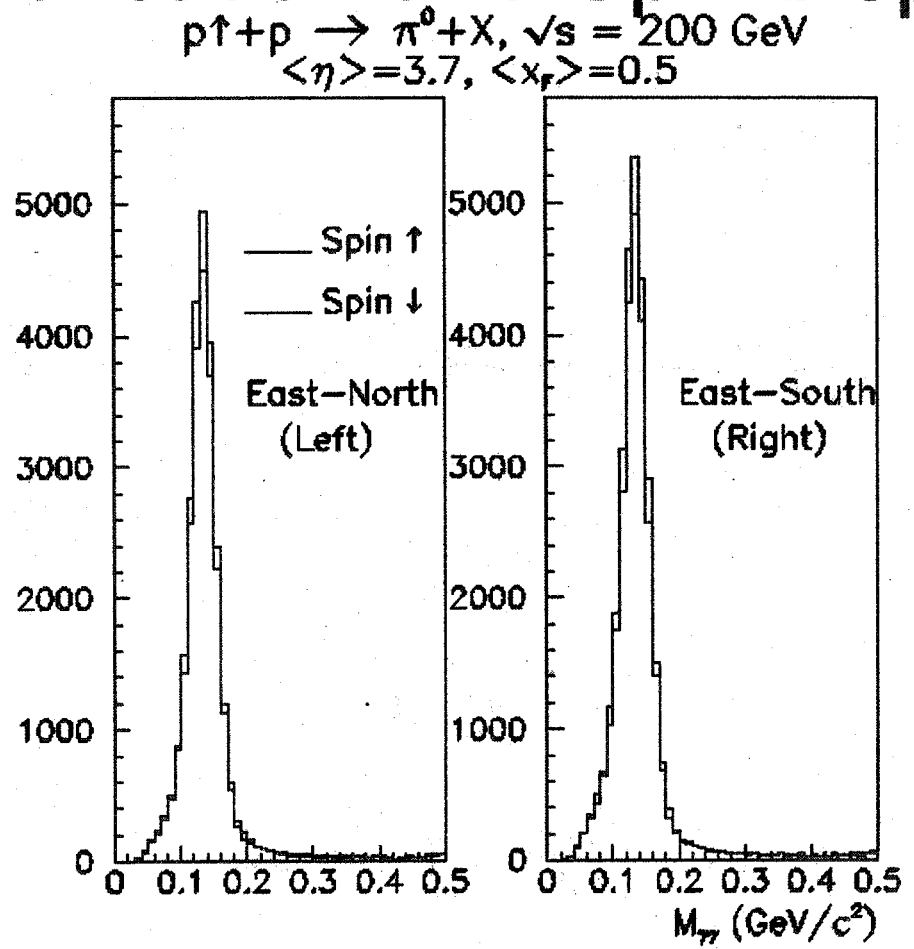


$$A_N = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}$$

Probing for orbital motion within transversely polarized protons

Transverse Spin Workshop, Beijing
L.C. Bland
Brookhaven National Laboratory
30 June 2008

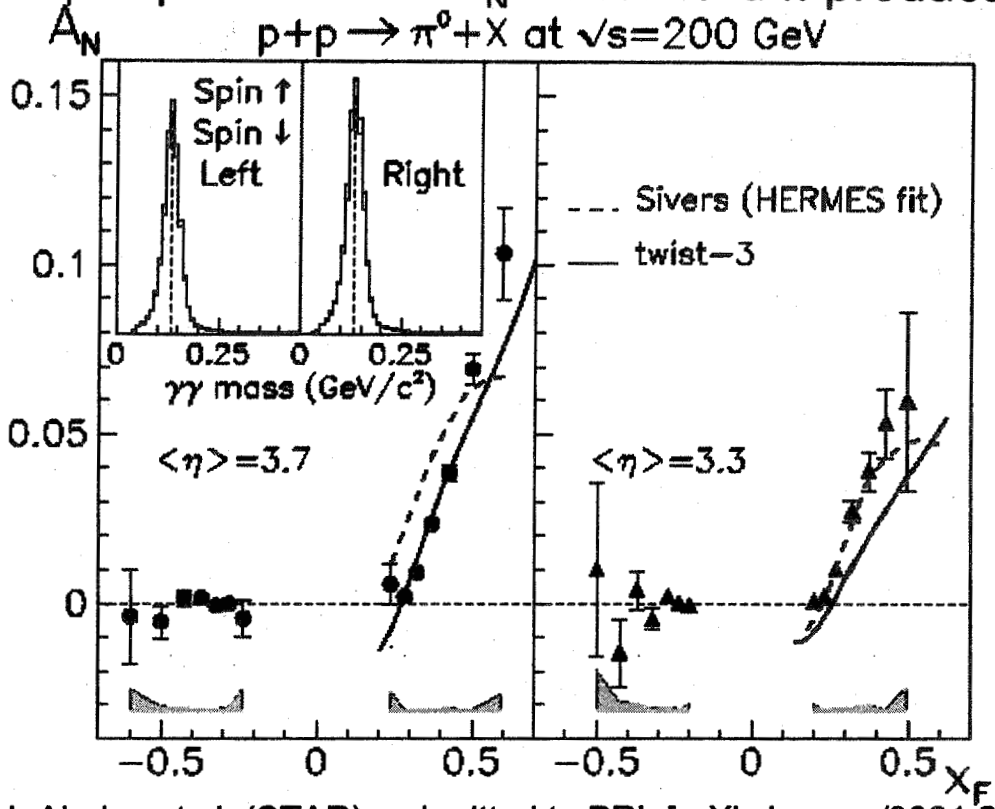
π^0 Identification and Spin Dependence



- Large rapidity measurements require careful calibration
- Left/right symmetric detectors cancels many sources of systematic errors
- Spin effect is clearly visible in the raw spin-sorted yields

Final Results

x_F dependence of A_N for forward π production



Data: B.I. Abelev et al. (STAR), submitted to PRL [arXiv:hep-ex/0801.2990]

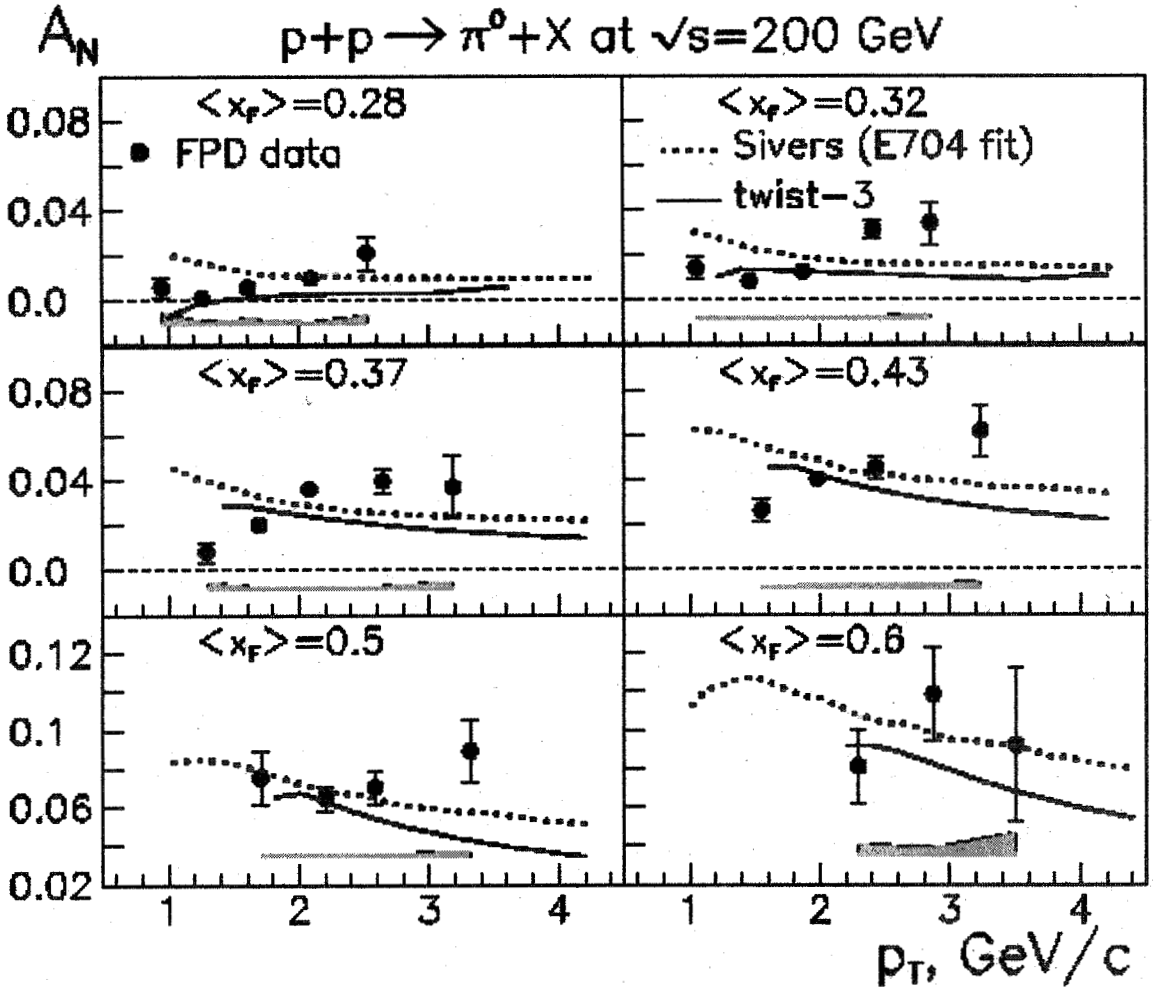
Theory (red): M. Boglione, U. D'Alesio, F. Murgia PRD 77 (2008) 051502.

Theory (blue): C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan, PRD **74** (2006) 114013

Even though the kinematics of the SIDIS measurement and the forward π^0,$\pi^\pm$ data have little overlap, it is possible to account for most of the features of the RHIC data by calculations based on phenomenological fits to the SIDIS data

Final Results

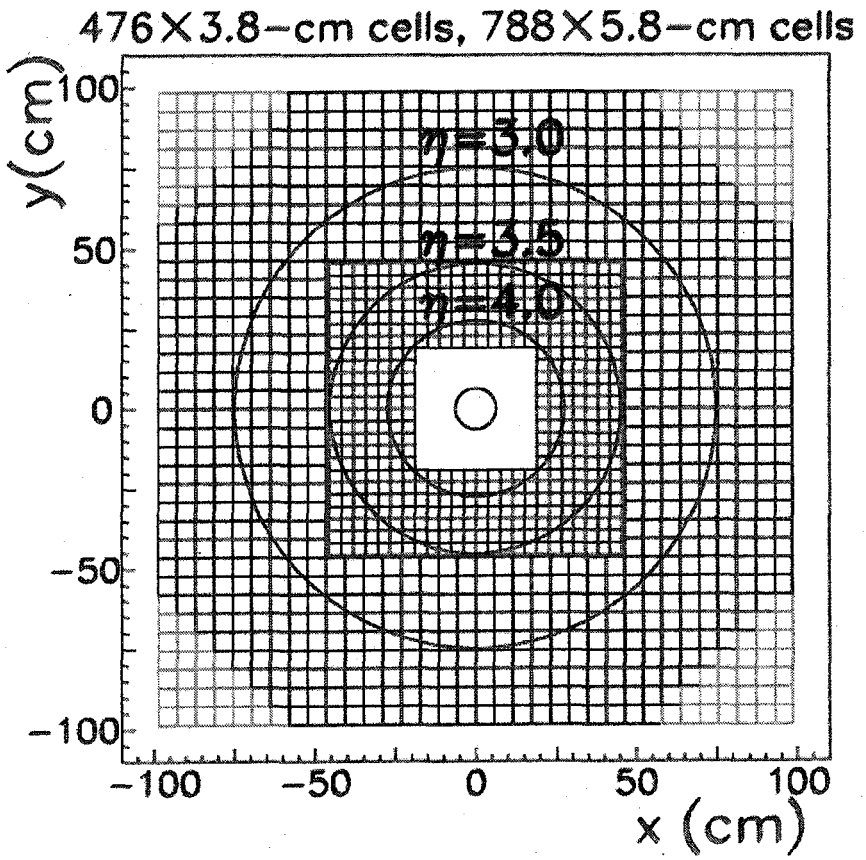
p_T dependence of A_N for forward π production



A key feature of the RHIC data that cannot be explained is the p_T dependence at fixed x_F. Calculations based only on the Sivers mechanism require A_N to decrease with increasing p_T. This trend is not what is observed.

Recent Developments

Increased Acceptance for Forward Calorimetry



Factor of ~20 increase in forward calorimetry acceptance in change from Forward Pion Detector to Forward Meson Spectrometer

Summary

- Firmly established that large transverse single spin asymmetries are observed at $\sqrt{s}$ = 200 GeV, where generally cross sections agree with pQCD calculations.
- Large transverse single spin asymmetries are observed only at large x_F; midrapidity asymmetries are small.
- Large x_F spin asymmetries show the same pattern for $20 \leq \sqrt{s} \leq 200$ GeV
- First observation of p_T dependence at fixed-x_F, enabled by the run-6 luminosity/performance

$\Rightarrow$ Some aspects of the theory are still not understood

- Forward calorimeter with 20x larger acceptance now in place and operational at STAR. Near-term future includes prospects for direct photon transverse spin physics. Longer-term future heading towards transverse spin Drell-Yan.

TRANSVERSE SPIN EFFECTS AT COMPASS
(F. Bradamante)

COMPASS, a fixed target experiment at the CERN SPS, started operation in 2002, using a longitudinally polarised μ^+ beam of 160 GeV/c momentum. Up to 2006 a ^{6}LiD solid polarised target was used, oriented either parallel or perpendicular to the muon beam direction. In 2007, data have been collected on a polarised proton target (solid NH_3). In 2008 we have started a search of glueballs and exotic hadrons scattering 190 GeV/c pions on a LH_2 target.
In this presentation I will only summarize a few results obtained in the muon runs.
A two stage magnetic spectrometer detects the scattered muon and the produced hadrons. Charged particles are identified by a RICH (Ring Imaging CHerenkov) and by hadron calorimeters.
The physics programme is very broad. When the target spin is longitudinal, it spans from the measurement of g_1, to the flavour separated helicity distributions, to Λ-physics and to vector meson - physics. Alternatively, the target spin can be rotated orthogonally to the incoming muons, and transverse spin effects are investigated.
In this report, I will mention only transverse spin and transverse momentum effects, mostly obtained with the deuteron target, and the most recent preliminary results from the proton run of last year.
Among the results obtained with the deuteron target, a preliminary analysis of SIDIS data on an unpolarized target has allowed to extract the $\cos\varphi$, $\sin\varphi$, and $\cos 2\varphi$ azimuthal asymmetries of the produced positive and negative hadrons. For this analysis the data collected with opposite target polarization (both longitudinal and transverse) have been added up.
I will then review all the results for the Collins and Sivers asymmetries on the deuteron (published). The results show small values for the asymmetries (if any), statistically compatible with zero, and have been interpreted as due to cancellation between u- and d-quark PDFs.
I will also show and discuss the new data obtained with the proton target. The Collins asymmetries definitely show a non-zero effect in the valence region, both in the positive and in the negative hadron samples, which is compatible in sign and magnitude with the one measured at smaller energy by the HERMES Collaboration. This result is a nice confirmation of the leading-twits nature of the effects which have been measured, and opens up high-energy SIDIS for precision measurements of transversity.
The Sivers asymmetries we have measured are small, statistically compatible with zero, both for positive and for negative hadrons. The negative hadron result is in line with the observation of HERMES, while the positive hadron hadron asymmetry is definitely smaller. The statistical compatibility of the two results is marginal, at a few percent level.

COMPASS

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

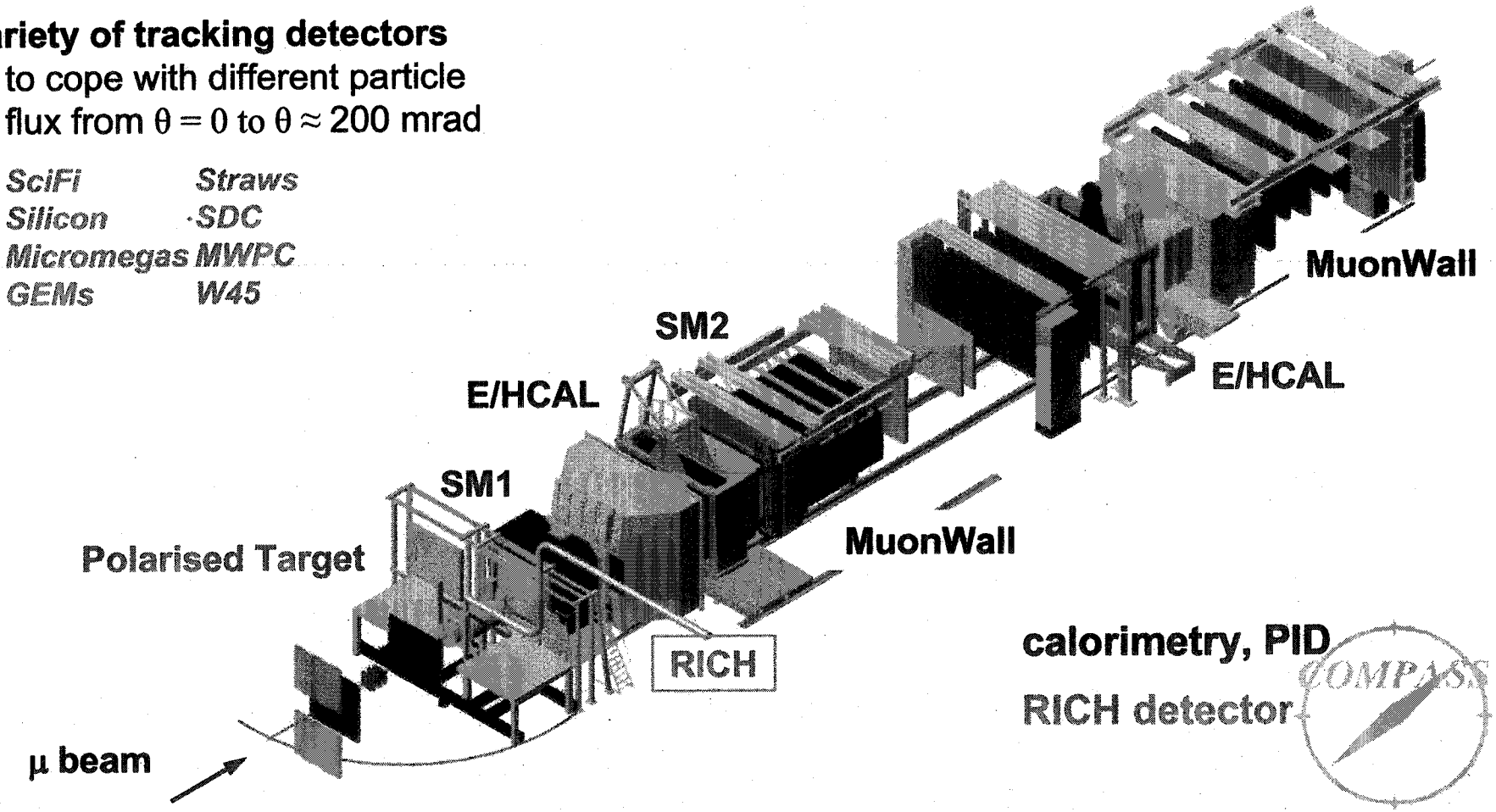
Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad

SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



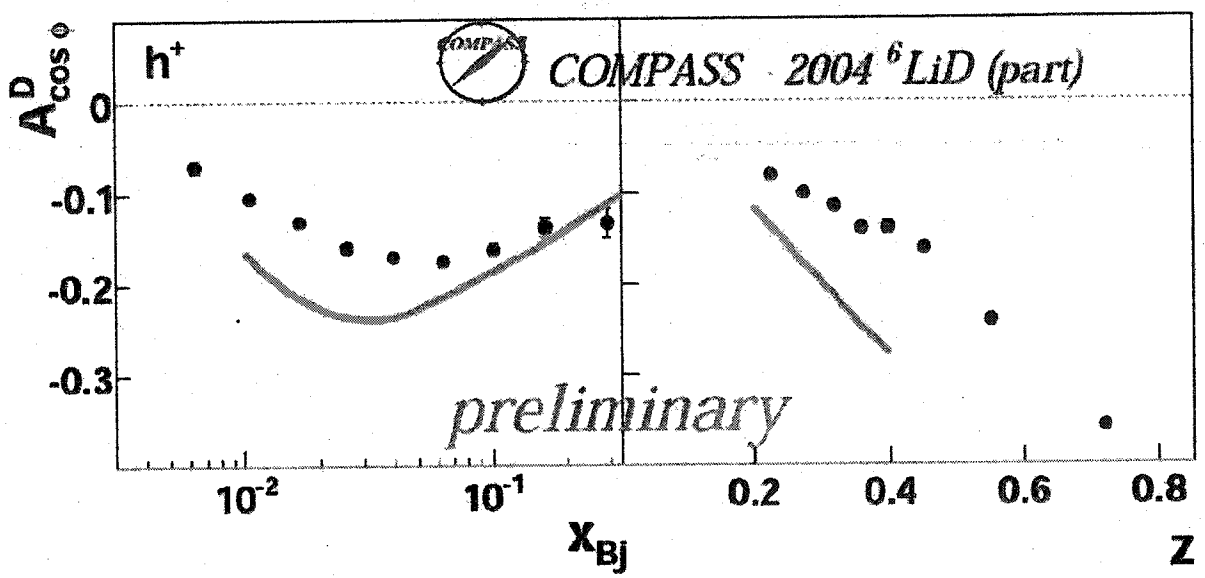
calorimetry, PID

RICH detector

Unpolarised Azimuthal Asymmetries

cosϕ modulation

comparison with theory

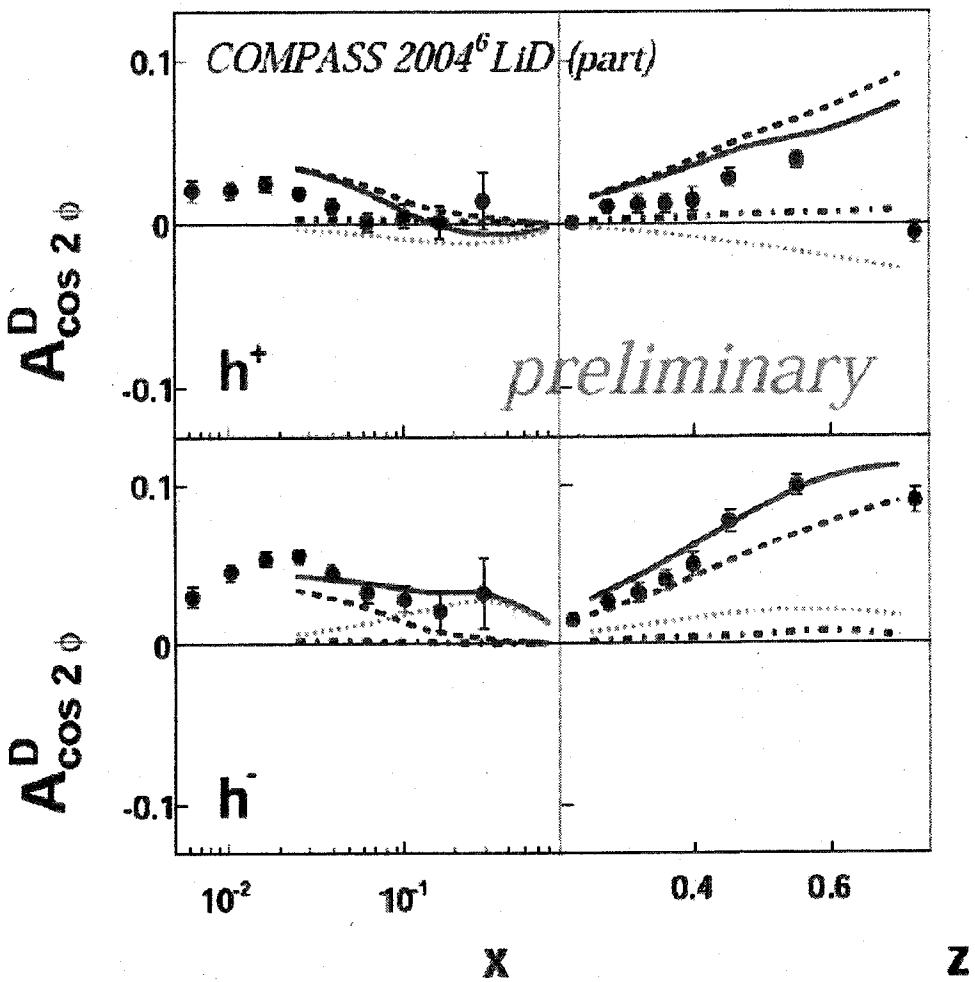


M. Anselmino, M. Boglione, A. Prokudin, C. Türk
Eur. Phys. J. A 31, 373-381 (2007)
does not include Boer – Mulders contribution

Unpolarised Azimuthal Asymmetries

cos2ϕ modulation

comparison with theory



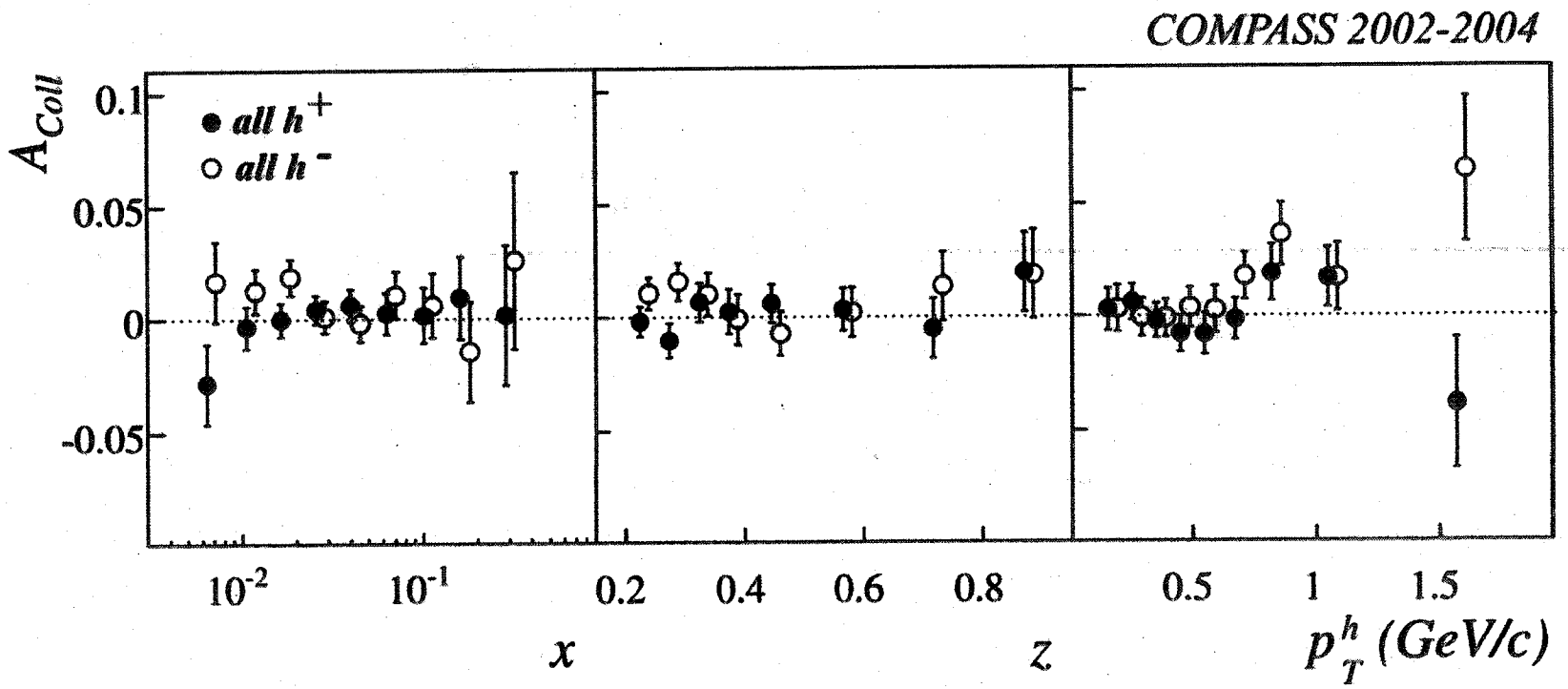
total — Boer Mulders
Cahn — pQCD

V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

Collins Asymmetry - Deuteron data

charged hadrons

- 2004: first results from 2002 data [PRL94 (2005) 202002] confirmed in
- 2006: **final results from 2002-2004 data** [NPB765 (2007)31]



asymmetries compatible with zero within the statistical errors
(syst. errors much smaller)

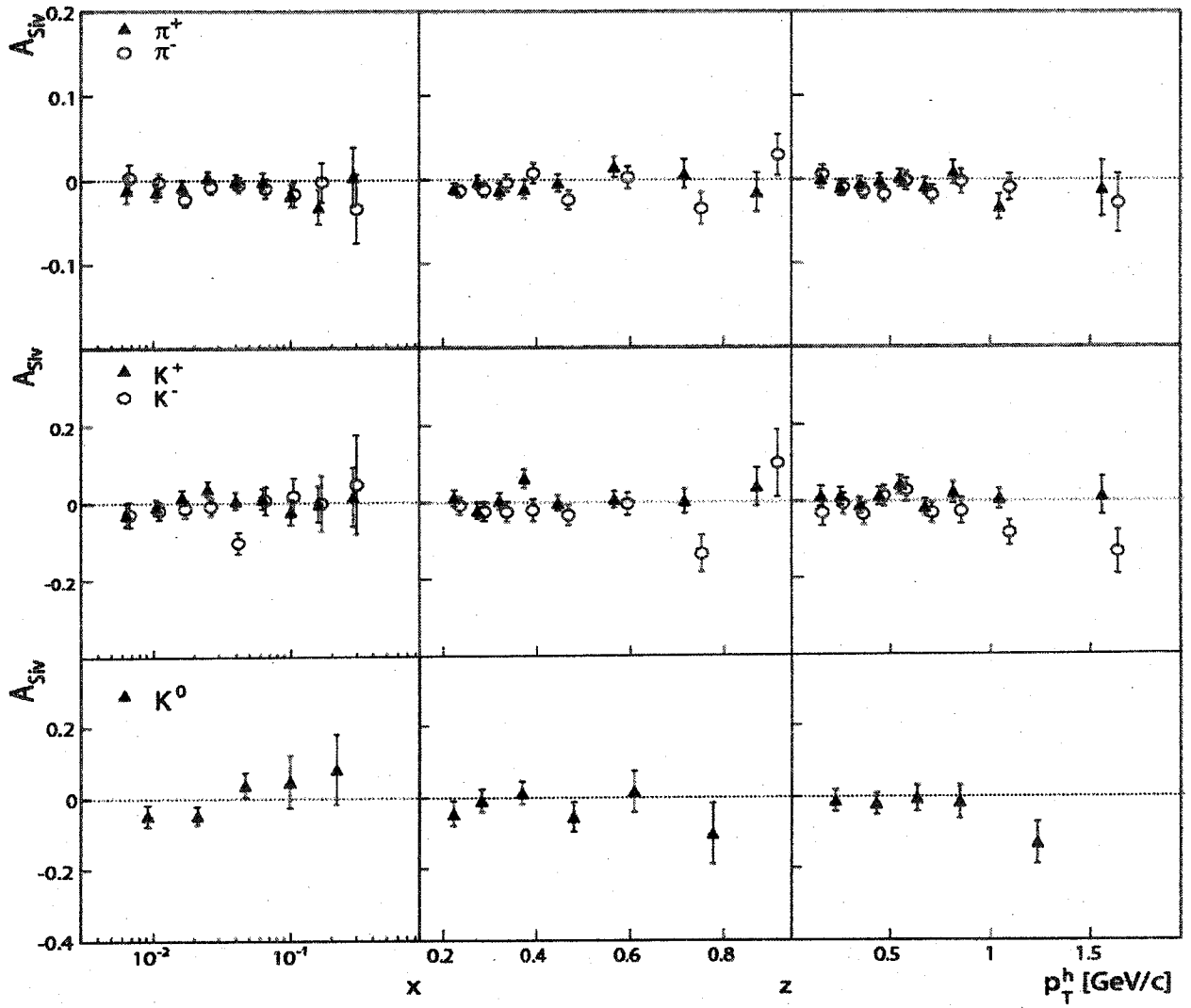
the same with leading h

with HERMES results, cancellation between u and d quark contributions

Sivers Asymmetry - Deuteron data

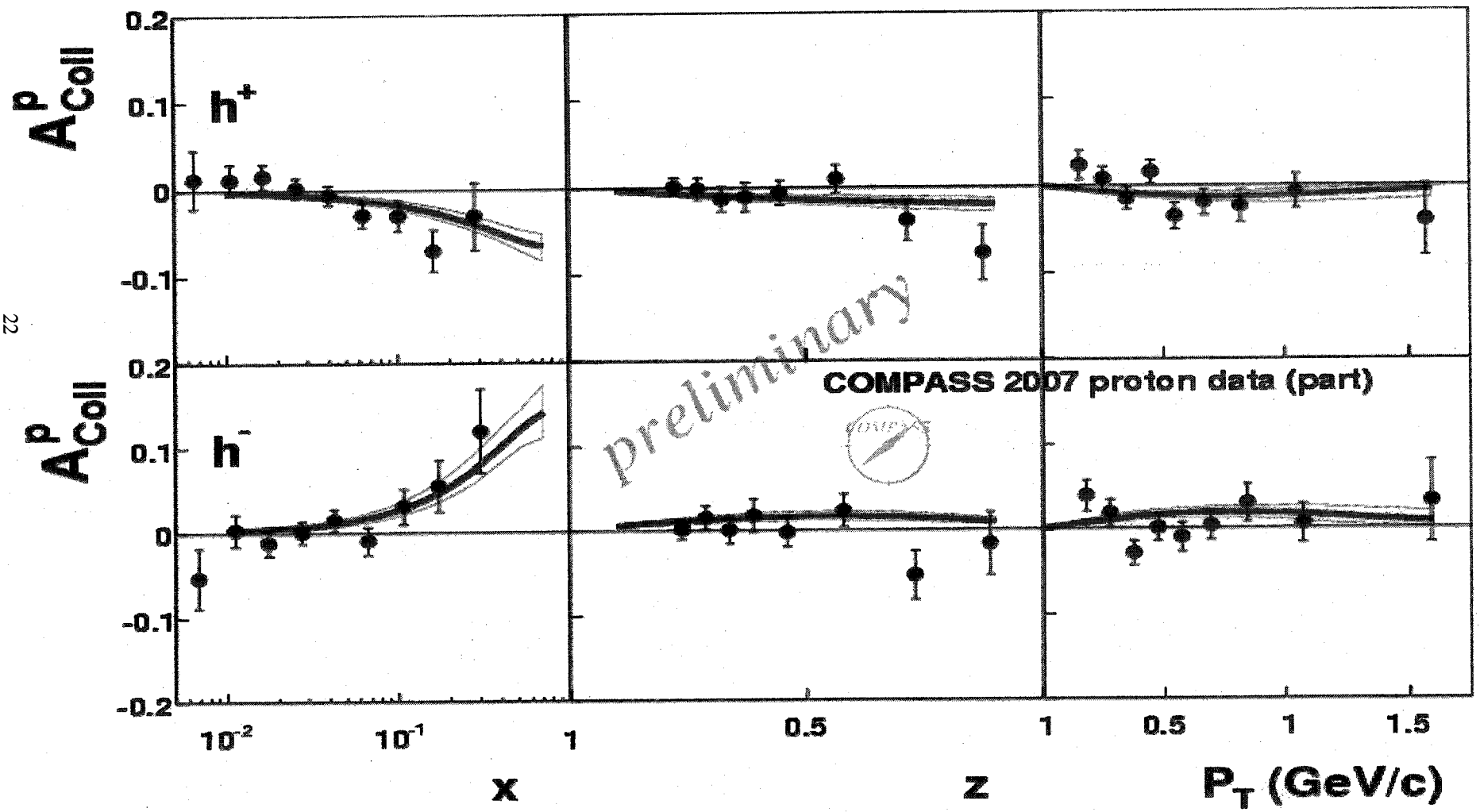
identified hadrons

- 2007: **final results from 2002-2004 data** [arXiv:0802.2160]



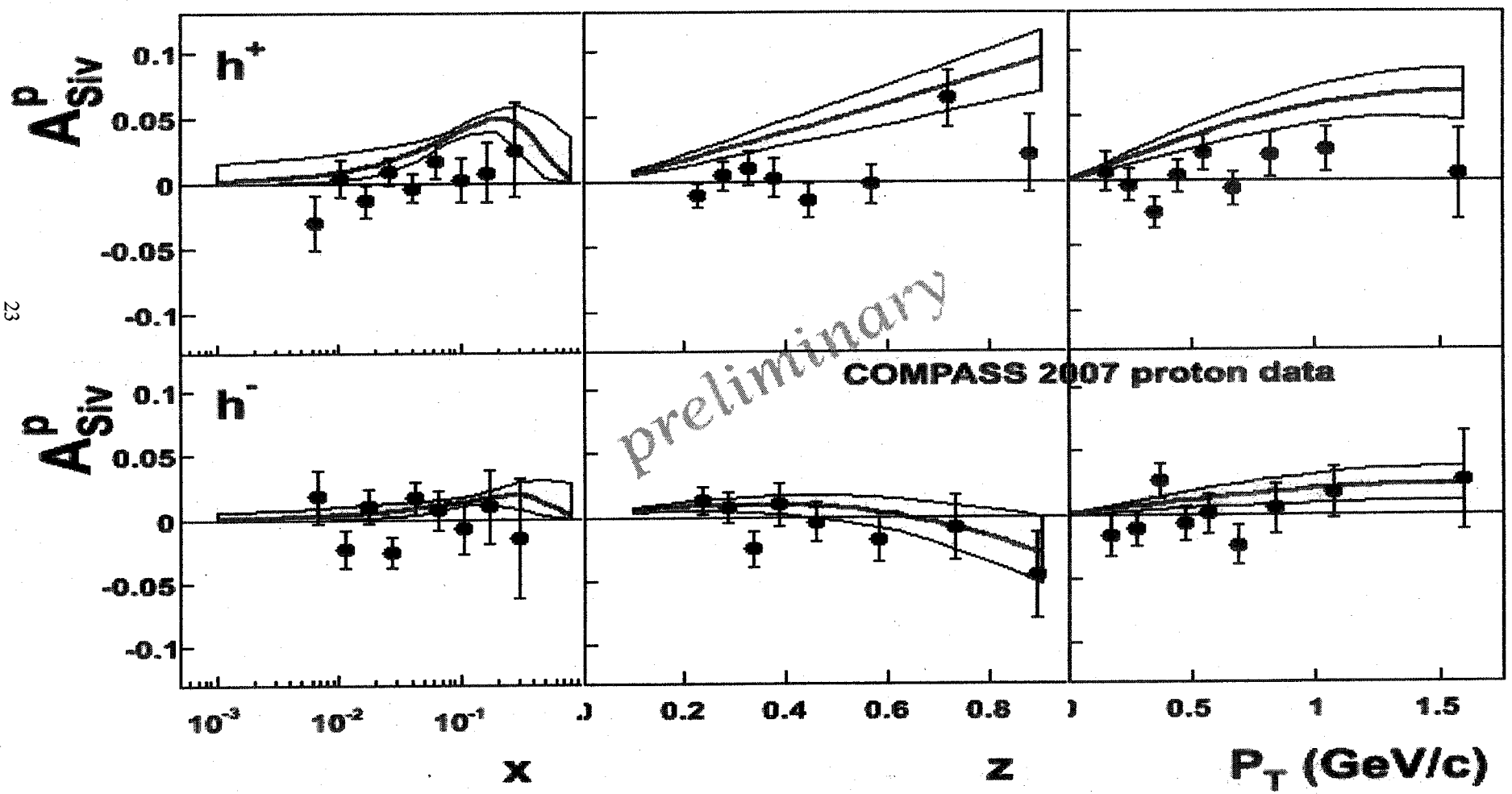
Collins asymmetry – proton data

comparison with M. Anselmino et al. predictions



Sivers asymmetry – proton data

comparison with the most recent predictions from M. Anselmino et al.



CONCLUSIONS

new COMPASS results for

- unpolarised hadron asymmetries on deuteron
  for positive and negative hadrons

- Collins and Sivers asymmetries on protons
  - Collins asymmetry different from zero
    the effect is there at COMPASS energies!
  - Sivers asymmetry: smaller, compatible with zero
    to be understood

near future: analysis of the whole 2007 proton data sample

longer term:
transverse spin physics is one of the items being spelled out for the future COMPASS program

the study of transverse spin effects needs further precise measurements and the COMPASS facility is the only place where SIDIS can be measured at high energy

The HERMES measurement of transverse single-spin asymmetries

Markus Diefenthaler (on behalf of the HERMES collaboration)

Physikalisches Institut II, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erwin-Rommel-Straße 1, 91058 Erlangen, Germany

Keywords: transverse single-spin asymmetries, Collins mechanism, Sivers mechanism, transversity distribution, dihadron fragmentation functions
PACS: 13.60.-r,13.88.+e,14.20.Dh,14.65.-q

In 2005 the HERMES collaboration published first evidence for azimuthal single-spin asymmetries (SSA) in the semi-inclusive production of charged pions on a transversely polarized hydrogen target [1]. Significant signals for both the Collins and Sivers mechanisms were observed in data recorded during the 2002–2003 running period of the HERMES experiment. In the conference contribution a preliminary analysis of these data combined with additional data taken in the years 2003–2005 is presented; i.e. an preliminary analysis of the full data set with transverse target polarization. All data were recorded at a beam energy of 27.6 GeV using a transversely nuclear-polarized hydrogen-target internal to the HERA storage ring at DESY. The HERMES dual-radiator ring-imaging Čerenkov detector allows full $\pi^{\pm}$, $K^{\pm}$, p separation for all particle momenta within the range $2\,\mathrm{GeV} < P_h < 15\,\mathrm{GeV}$. Therefore, a preliminary analysis of SSA in the electroproduction of charged kaons on a transversely polarized target is also presented. In addition the measurement is accompanied by an preliminary analysis of reconstructed neutral-pion events. The results for the full data set with transverse target polarization contribute substantially to the global analysis of the transversity distribution and provide clear evidence for the naive time reversal odd Sivers distribution function.

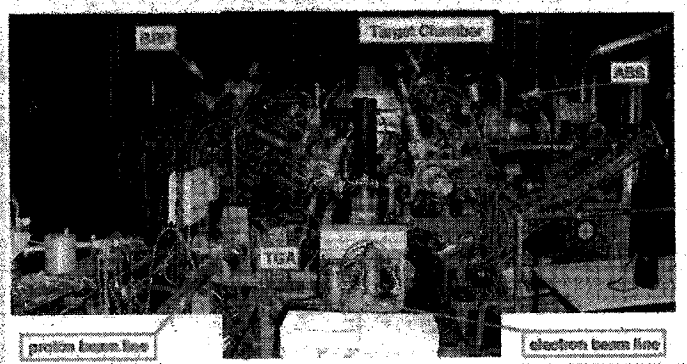
The recently published results on single-spin asymmetries in semi-inclusive dihadron production provide an independent experimental constraint on the transversity distribution [2]. Thereby first evidence is found for a non-zero naive time reversal odd chiral-odd dihadron fragmentation function $H_{1,q}^{\sphericalangle}$.

REFERENCES

1. A. Airapetian *et al.* [HERMES collaboration], Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target. *Physical Review Letters*, 94:012002, 2005.
2. A. Airapetian *et al.* [HERMES collaboration], Evidence for a transverse single-spin asymmetry in leptoproduction of $\pi^+\pi^-$ pairs JHEP **0806** (2008) 017

The transversely polarised target:

- polarised **gas target** internal to the HERA storage ring
- background-free measurements from highly polarised nucleons
- **2002–2005: transversely polarised hydrogen** target

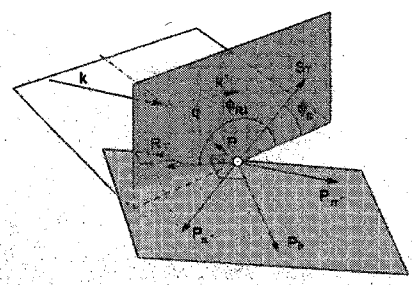


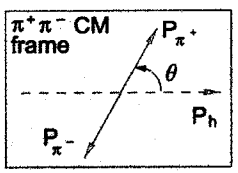
(front view of the HERMES interaction region)

Transverse single-spin asymmetries:

- **naive time reversal odd** (naive-T-odd) **functions**
- involve interference of amplitudes with different helicities
  - ➥ suppressed in perturbative QCD
  - ➥ assigned to distribution and fragmentation functions
- **associated with spin/orbit effects** ($S \cdot (P_1 \times P_2)$)
- observed in semi-inclusive DIS on a transversely polarised target:
  - **single-hadron production** ($ep^{\uparrow} \to e'hX$):
    - $S_q \cdot (p_q \times P_h)$
      - ➥ *Collins mechanism*, sensitive to transversity
    - $S_N \cdot (P \times p_q)$
      - ➥ *Sivers mechanism*, sensitive to L_q
  - **dihadron production** ($ep^{\uparrow} \to e'h_1h_2X$):
    - $S_q \cdot (p_q \times R)$
    - transfer of transverse quark spin to relative orbital angular momentum of hadron pair ($2R = P_{h_1} - P_{h_2}$)
    - sensitive to transversity

The semi-inclusive production of $\pi^+\pi^-$ pairs:





$$P_h \equiv P_{\pi^+} + P_{\pi^-}$$

$$R \equiv \frac{P_{\pi^+} - P_{\pi^-}}{2}$$

$$R_T \equiv R - (R \cdot \hat{P}_h)\hat{P}_h$$

azimuthal angles ϕ_S and ϕ_{R_T}:

$$\phi_S \equiv \frac{(q \times k) \cdot S_T}{|(q \times k) \cdot S_T|} \arccos\left(\frac{(q \times k) \cdot (q \times S_T)}{|(q \times k)|\,|q \times S_T|}\right)$$

$$\phi_{R_\perp} \equiv \frac{(q \times k) \cdot R_T}{|(q \times k) \cdot R_T|} \arccos\left(\frac{(q \times k) \cdot (q \times R_T)}{|(q \times k)|\,|q \times R_T|}\right)$$

SSA in semi-inclusive $\pi^+\pi^-$ production:

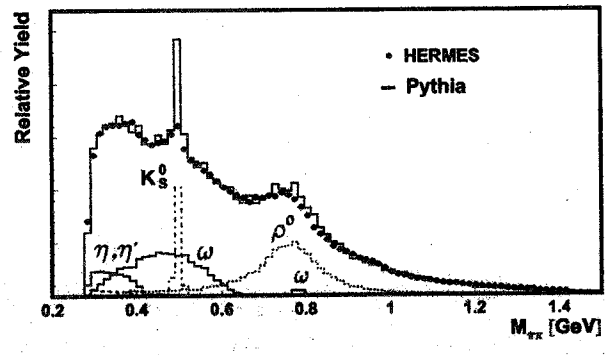
- Fourier/Legendre amplitude $A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ of

$$A_{UT}(x,y,z,\phi_S,\phi_{R\perp},\cos\theta,M_{\pi\pi}) = \frac{1}{|S_T|}\frac{d^7\sigma_{U\uparrow} - d^7\sigma_{U\downarrow}}{d^7\sigma_{U\uparrow} + d^7\sigma_{U\downarrow}}$$

- provides signal for
  - transversity distribution $h_1^q(x)$
  - dihadron fragmentation function $H_{1,q}^{\sphericalangle}(z, M_{\pi\pi}, \cos\theta)$:
    - leading-twist
    - chiral-odd
    - naive-T-odd
- at leading twist, in leading order in α_s, integrated over $P_{h\perp}$:

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} = -\frac{(1-y)}{(1-y+\frac{y^2}{2})}\,\frac{1}{2}\sqrt{1-4\frac{M_\pi^2}{M_{\pi\pi}^2}}\;\frac{\sum_q e_q^2\, h_1^q(x)\, H_{1,q}^{\sphericalangle,sp}(z,M_{\pi\pi})}{\sum_q e_q^2\, f_1^q(x)\, D_{1,q}(z,M_{\pi\pi})}$$

The $M_{\pi\pi}$ spectrum:



- sizable contribution from spin-1 resonances
- dominant **contributions to** $H_{1,q}^{\sphericalangle}(z, M_{\pi\pi}, \cos\theta)$:
  - s-waves components, e.g. $\pi^+\pi^-$ pair in non-resonant state
  - p-waves components, e.g. ρ^0 decay ($\rho^0 \to \pi^+\pi^-$)

Evaluation of the asymmetry:

- all $\pi^+\pi^-$ pairs have been selected from $ep^{\Uparrow} \to e'h_1h_2X$
- kinematic requirements:

$1\,\mathrm{GeV}^2 <$	Q^2	
$(0.1 \leqslant)$	y	< 0.85
$10\,\mathrm{GeV}^2 <$	W^2	
$2\,\mathrm{GeV} <$	M_X	
$1\,\mathrm{GeV} <$	P_h	$< 15\,\mathrm{GeV}$

- for every bin in
  - x, z $(M_{\pi\pi} \in [0.5, 1.0])$
  - $M_{\pi\pi}$ $(M_{\pi\pi} \in [0.5, 1.0])$
- evaluation in $(\phi_{R\perp} + \phi_S) \times \theta$ binning:

$$A_{U\perp}(\phi_{R\perp}, \phi_S, \theta) = \frac{1}{|S_T|} \frac{N^{\Uparrow}(\phi_{R\perp}, \phi_S, \theta) - N^{\Downarrow}(\phi_{R\perp}, \phi_S, \theta)}{N^{\Uparrow}(\phi_{R\perp}, \phi_S, \theta) + N^{\Downarrow}(\phi_{R\perp}, \phi_S, \theta)}$$

The extraction of $A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$:

$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \sim \frac{\sum_q e_q^2 h_1^q(x) H_{1,q}^{\sphericalangle,sp}(z, M_{\pi\pi})}{\sum_q e_q^2 f_1^q(x) D_{1,q}(z, M_{\pi\pi})}$$

- focus on **sp- and pp-interference** ($M_{\pi\pi} < 1.5\,\mathrm{GeV}$):

$$D_{1,q} \simeq D_{1,q} + D_{1,q}^{sp}\cos\theta + D_{1,q}^{pp}\frac{1}{4}(3\cos^2\theta - 1)$$
$$H_{1,q}^{\sphericalangle} \simeq H_{1,q}^{\sphericalangle,sp} + H_{1,q}^{\sphericalangle,pp}\cos\theta,$$

- symmetrisation around $\theta = \pi/2$:

$$\theta \to \theta' \equiv \left|\left|\theta - \frac{\pi}{2}\right| - \frac{\pi}{2}\right|$$

- $D_{1,q}^{sp}$ and $H_{1,q}^{\sphericalangle,pp}$ contributions drop out
- reducing the statistical uncertainty on $A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$

Functional form of the χ^2 fit:

- extraction of $a \equiv A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta}$ in a linear fit

$$A_{U\perp}(\phi_{R\perp} + \phi_S, \theta') = \sin(\phi_{R\perp} + \phi_S)\frac{a\sin\theta'}{1 + b\frac{1}{4}(3\cos^2\theta' - 1)}$$

- while varying b within positivity limits

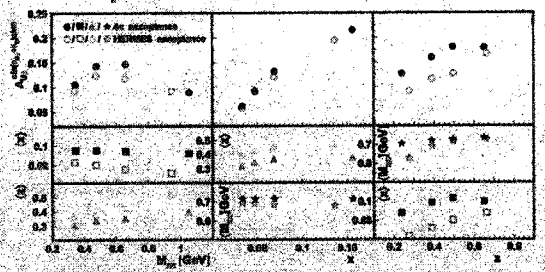
$$-\frac{3D_{1,q}^{p}(z, M_{\pi\pi})}{2D_{1,q}(z, M_{\pi\pi})} \leq b \leq \frac{3D_{1,q}^{p}(z, M_{\pi\pi})}{D_{1,q}(z, M_{\pi\pi})}$$

- limits estimated with PYTHIA6 (tuned for HERMES kinematics)
- systematic uncertainty due to "b-scan":
  - central value in the ranges of a ↪ SSA amplitude
  - standard deviation ↪ systematic uncertainty

Influence of the experimental acceptance:

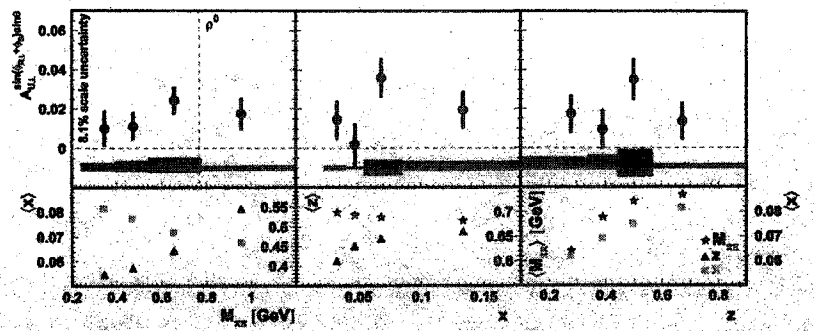
$$N^{\uparrow(\downarrow)}(\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}) \propto \int dx\,dy\,dz\,d^2P_{h\perp}\,\epsilon(x,y,z,P_{h\perp},\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}) \times \sigma_{U\uparrow(\downarrow)}(x,y,z,P_{h\perp},\phi_{R\perp},\phi_S,\theta,M_{\pi\pi}),$$

Estimation of acceptance effects:



models f_1 by Gluck et al. (Eur.Phys.J.C5:461-470,1998),
h_1 by Schweitzer et al. (Phys.Rev.D64:034013,2001),
D_1, $H_1^\sphericalangle$ by Bacchetta and Radici (Phys.Rev.D74:114007,2006)

Published Results (JHEP 0806:017,2008):



- $A_{UL}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} = 0.018 \pm 0.005_{stat} \pm 0.002_{b-scan} + 0.004_{acc}$
- additional 8.1% scale uncertainty (target polarisation)
- first evidence for $H_{1,q}^\sphericalangle$
- transversity can be studied in dihadron production

The Collins and Sivers amplitudes:

- A_{UT}^h for hadron type h:

$$A_{UT}^h = \frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$$

$$\propto -2|S_T|\,\underset{\substack{\uparrow\\ \text{distinguishable}}}{\sin(\phi+\phi_S)}\,\frac{\overbrace{\sum_q e_q^2\,h_1^q(x)\otimes H_1^{\perp q}(z)}^{\text{Collins amplitude}}}{\sum_q e_q^2\,q(x)\,D_1^q(z)}$$

$$-\;2|S_T|\,\underset{\substack{\downarrow\\ \text{Signature}}}{\sin(\phi-\phi_S)}\,\frac{\overbrace{\sum_q e_q^2\,f_{1T}^{\perp q}(x)\otimes D_1^q(z)}^{\text{Sivers amplitude}}}{\sum_q e_q^2\,q(x)\,D_1^q(z)}$$

- convolution over intrinsic transverse momenta

The convolution over intrinsic transverse momenta:

- transverse target cross section contains a convolution integral $\mathcal{I}$ over intrinsic transverse momenta $p_\perp$ and $k_\perp$:

$$\mathcal{I}(\ldots) \equiv \int d^2p_\perp\,d^2k_\perp\,\delta^{(2)}\left(p_\perp - \frac{P_{h\perp}}{z} - k_\perp\right)(\ldots)$$

- e.g. Sivers SSA amplitude:

$$2\langle\sin(\phi-\phi_S)\rangle_{UT}^h = -2\frac{\sum_q e_q^2\,\mathcal{I}\left[\frac{p_\perp \hat{P}_{h\perp}}{M_h} f_{1T}^{\perp,q}(x,p_\perp^2)\,D_1^{q\to h}(z,z^2k_\perp^2)\right]}{\sum_q e_q^2 f_1^q(x)\,D_1^{q\to h}(z)}$$

- **Disentangling the convolution integral**
  - using $P_{h\perp}$-weighted SSA
  - using several model assumptions

Problems using $P_{h\perp}$-weighted SSA:

- **complete integration over $P_{h\perp}$:**
  Can the integration to ∞ be approximated by an integration up to certain cut-off value $P_{h\perp}^2 \ll Q^2$?
- **Possibly large acceptance effects:**
  - **correction with multidimensional UNFOLDING:** appears to work in 5D (e.g. Boer-Mulders function), but not in 6D
  - **multi-parameter fit:**

> - evaluation of the **full kinematic dependence** $(x, Q^2, z, P_{h\perp})$
> - through a **multi-parameter fit** (e.g. 48) to the full set of semi-inclusive events
> - folding with $\sigma_{UU}(x, Q^2, z, P_{h\perp})$ in 4π
> ↪ acceptance-corrected results
> - Monte Carlo tuned to data used for $\sigma_{UU}(x, Q^2, z, P_{h\perp})$
> - method has been studied in Monte Carlo

The Gaussian ansatz:

- ***unweighted SSA amplitudes*:**

$$2\langle \sin(\phi - \phi_S)\rangle_{UT}^h = -2\frac{\sum_q e_q^2\, \mathcal{I}\left[\frac{\mathbf{p}_\perp \cdot \hat{\mathbf{P}}_{h\perp}}{M_N} f_{1T}^{\perp,q}(x, p_\perp^2) D_1^{q\to h}(z, z^2 k_\perp^2)\right]}{\sum_q e_q^2 f_1^q(x) D_1^{q\to h}(z)}$$

- use of model assumptions, e.g. **Gaussian ansatz**

$$\langle \sin(\phi - \phi_S)\rangle_{UT}^h = -\frac{\sqrt{\pi}}{2M_N} R_S \langle p_\perp^2\rangle_s \cdot \frac{\sum_q e_q^2 f_{1T}^{\perp,q}(x) D_1^q(z)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

$$\frac{1}{R_S^2} \equiv \langle k_\perp^2\rangle + \langle p_\perp^2\rangle_s$$

- $x-$ or $z-$dependence and flavour-dependence of R_S and $\langle p_\perp^2\rangle_s$
- problems with flavour decomposition

Selection of semi-inclusive events:

- pions and charged kaons have been selected from $ep^\uparrow \to e'hX$
- kinematic requirements:

$1\,\mathrm{GeV}^2 <$	Q^2	
$(0.1 \leqslant)$	y	< 0.95
$0.023 <$	x	< 0.4
$10\,\mathrm{GeV}^2 <$	W^2	
$2\,\mathrm{GeV} <$	P_h	$< 15\,\mathrm{GeV}$
$0.2 <$	z	< 0.7
$0.02\,\mathrm{rad} <$	$\theta_{\gamma^* h}$	

- **mean kinematics:**
  $\langle Q^2\rangle = 2.4\,\mathrm{GeV}^2$, $\langle x\rangle = 0.094$, $\langle z\rangle = 0.36$, $\langle P_{h\perp}\rangle = 0.41\,\mathrm{GeV}$
- evaluation of **lepton-beam asymmetries**
- due to unknown $R = \sigma_L/\sigma_T$ for semi-inclusive DIS measurements

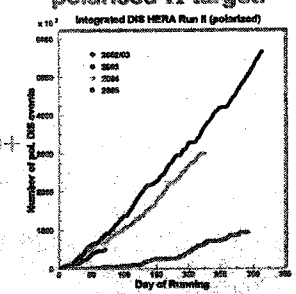
Simultaneous extraction of unweighted amplitudes:

- maximum likelihood fits are used for pions charged kaons:

$$\mathrm{F}\left(2\langle \sin(\phi \pm \phi_S)\rangle_{UT}^h, \ldots, \phi, \phi_S\right) =$$
$$\frac{1}{2}\Big(1 + P_\alpha^z \big(2\langle \sin(\phi + \phi_S)\rangle_{UT}^h \cdot \sin(\phi + \phi_S) +$$
$$2\langle \sin(\phi - \phi_S)\rangle_{UT}^h \cdot \sin(\phi - \phi_S) +$$
$$2\langle \sin(3\phi - \phi_S)\rangle_{UT}^h \cdot \sin(3\phi - \phi_S) +$$
$$2\langle \sin(2\phi - \phi_S)\rangle_{UT}^h \cdot \sin(2\phi - \phi_S) +$$
$$2\langle \sin\phi_S\rangle_{UT}^h \cdot \sin\phi_S\big)\Big)$$

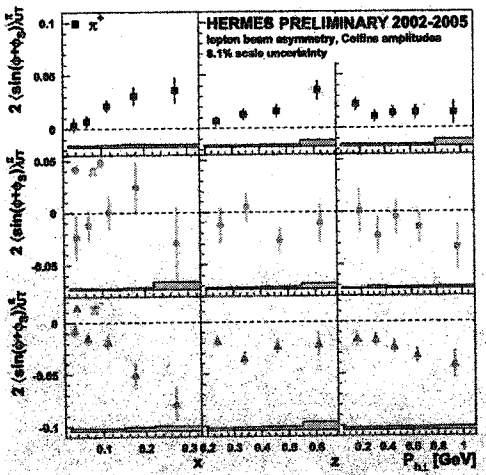
- the logarithm of the likelihood function $\mathcal{L} = \prod (\mathrm{F}_i)^{w_i}$ is maximised with respect to the SSA amplitudes (w_i RICH PID event weights)

polarised H target:



$e^\pm$	$8.4 \cdot 10^6$
π^+	$7.4 \cdot 10^5$
π^0	$2.1 \cdot 10^5$
π^-	$5.1 \cdot 10^5$
K^+	$1.2 \cdot 10^5$
K^-	$2.2 \cdot 10^4$

The Collins amplitudes for pions:



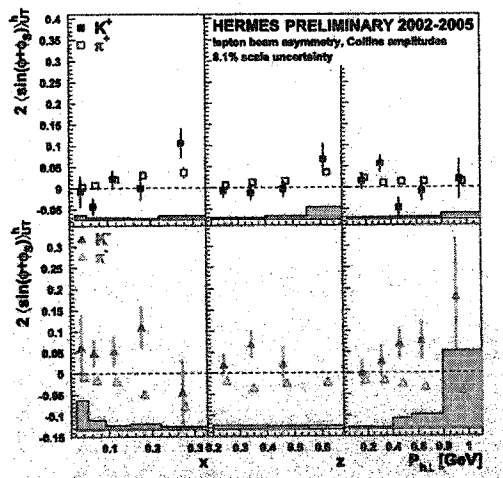
Results of the Collins amplitude:

$$h_1^q(x) \otimes H_1^{\perp q}(z)$$

from 2002–2005 data:

- positive amplitudes for π^+
- large negative π^- amplitudes is unexpected
- $H_1^{\perp,\text{unfav}}(z) \approx -H_1^{\perp,\text{fav}}(z)$
- isospin symmetry of π-mesons is fulfilled
- information from another process on the Collins fragmentation function (BELLE) permits extraction of transversity (e.g. Anselmino et al, Phys.Rev.D75:054032,2007)

The Collins amplitudes for charged kaons:



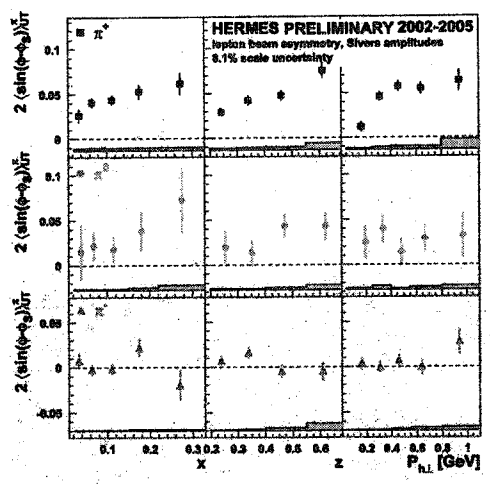
Results of the Collins amplitude:

$$h_1^q(x) \otimes H_1^{\perp q}(z)$$

from 2002–2005 data:

- no significant non-zero Collins amplitudes for both K^+ and K^-
- Collins amplitudes for K^+ are within statistical accuracy consistent with π^+

The Sivers amplitudes for pions:



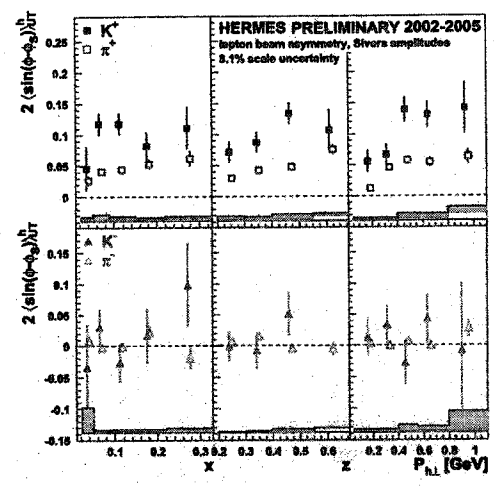
Results of the Sivers amplitude:

$$f_{1T}^{\perp q}(x) \otimes D_1^q(z).$$

from 2002–2005 data:

- significantly positive for π^+
- implies non-zero L_z^q
- π^- amplitude consistent with zero
- isospin symmetry of π-mesons is fulfilled
- **extraction of the Sivers function** is possible as spin-independent fragmentation function $D_1^q(z)$ is known

The Sivers amplitude for charged kaons:



Results of the Sivers amplitude:

$$f_{1T}^{\perp q}(x) \otimes D_1^{\perp q}(z).$$

from 2002–2005 data:

- significantly positive for K^+
- implies non-zero L_z^q
- K^- amplitude consistent with zero
- K^+ amplitude larger than π^+ amplitude
  $\Rightarrow s\bar{s}$ contribution to Sivers mechanism may be important:
  $K^+ = |u\bar{s}\rangle \quad \pi^+ = |u\bar{d}\rangle$

Transverse single-spin asymmetries: Past, Present and Future

Jacques Soffer
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In high energy particle physics, *spin* was considered for a long time as an inessential complication and *transverse spin* as even more inessential. Only very recently, its importance has been recognized and I will try to present this evolution over the last thirty forty years or so, with striking examples, without trying to separate *Past, Present and Future*, because they are strongly entangled.

After reminding the definitions of a transverse single-spin asymmetry (SSA), I will revisit some interesting SSA observed in two-body reactions and very intringing results in inclusive reactions, still unexplained since 1976. The Schwinger effect, first suggested in 1948, from Coulomb-Nuclear interference in pp elastic scattering has been observed recently at RHIC-BNL and it turns out to be very relevant for polarimetry at very high energies.

We will also mention some aspects of the Regge phenomenology which has been used in the seventies to explain these transverse SSA, with only limited success. Over the last 15 years or so, it became clear that these phenomena had to be described in the framework of the QCD parton model. So a new approach emerged slowly in terms of quarks and gluons and it was realized that the orbital motion of these fundamental constituants could be related to transverse SSA. In addition to the usual unpolarized and helicity quark distributions, $q(x, Q^2)$ and $\Delta q(x, Q^2)$, one had to consider a new object, the quark transversity distribution $\delta q(x, Q^2)$, whose experimental determination has just been initiated. Two QCD mechanisms have been proposed, one based on the transverse momentum dependence of distributions functions (Sivers effect) or of the fragmentation functions (Collins effect) and the other one based on higher twist operators. These new ideas have driven a deeper understanding of some gauge-invariance properties and are giving rise to a very active phenomenology. Concerning this last point, before claiming one can explain a transverse SSA, we have emphasized and demonstrated the importance of a good understanding of the corresponding unpolarized cross section, which is known to be generated by the dominant dynamical mechanism.

Transverse single-spin asymmetries A_N

What is a transverse single-spin asymmetry (SSA)?

Consider the $a + b$ collision with one particle of momentum $\vec{p}$, carrying a transverse spin $\vec{s_T}$ and producing an outgoing hadron with momentum $\vec{k}$. The SSA defined as

$$A_N = \frac{d\sigma(\vec{s_T}) - d\sigma(-\vec{s_T})}{d\sigma(\vec{s_T}) + d\sigma(-\vec{s_T})}$$

is zero, unless the cross section contains a term $\vec{s_T} \cdot \vec{n}$, where $\vec{n} = (\vec{p} \times \vec{k})$
It can be shown that this requires the existence of an helicity flip and final state interactions, which generate a phase difference between the flip and the non-flip amplitudes, to avoid violation of time reversal invariance.

Some exemples

1)- Two-body reactions $a + b^{\uparrow} \rightarrow a' + b'$
The scattering amplitude reads $f_+ + f_- \vec{\sigma} \cdot \vec{n}$. Here f_+ and f_- are non-flip and flip helicity amplitudes, respectively. We will consider two relevant observables $d\sigma/dt = |f_+|^2 + |f_-|^2$ and $\mathrm{A}_N = \frac{2Im(f_+ f_-^*)}{|f_+|^2 + |f_-|^2}$

- $A_N \neq 0$ only if $f_- \neq 0$ and has a phase difference with f_+.

- One also has a kinematic constraint, $A_N = 0$ in the forward direction, i.e. for $k_T = 0$.

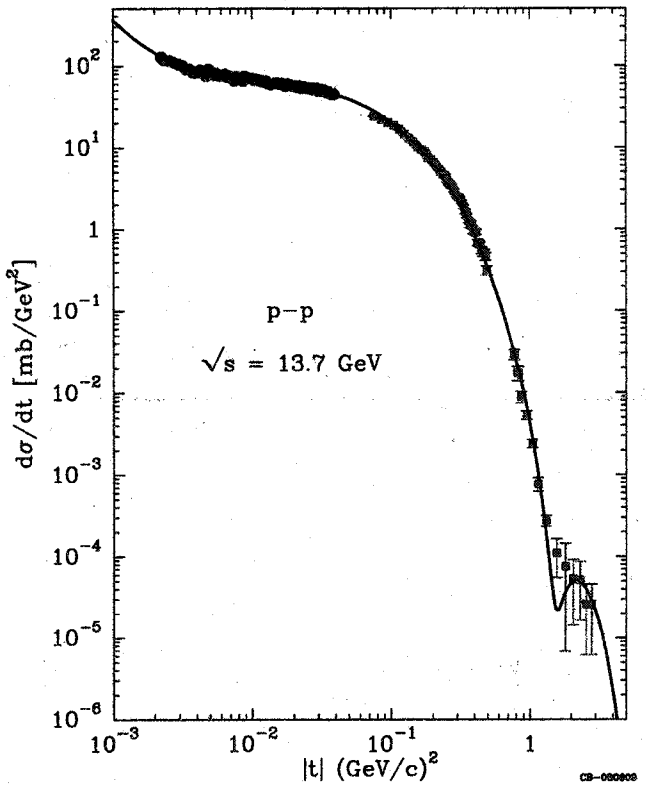
Transverse single-spin asymmetries A_N

2)- One particle inclusive reactions $a + b^{\uparrow} \rightarrow c + X$
It is directly related to M which denotes the absorptive part of the *forward* amplitude for the elastic $3 \rightarrow 3$ reaction $a + b + \bar{c} \rightarrow a + b + \bar{c}$. It has the general expression $M = H_1 + H_2 \vec{\sigma} \cdot \vec{n}$.
Here H_1 and H_2 are non-flip and flip amplitudes, respectively.
We will consider 2 relevant observables:

$$\frac{Ed^3\sigma}{d^3p} = H_1 \qquad and \qquad A_N = \frac{H_2}{H_1}$$

- $A_N \neq 0$ only if $H_2 \neq 0$. According to a NAIVE argument, one should expect $A_N = 0$, since one is summing over many different inelastic channels X, which should have SSA of random magnitudes and signs, such that the sum will average to zero.
- Also a kinematic constraint, $A_N = 0$ in the forward direction, i.e. for $k_T = 0$.

$d\sigma/dt$ at all angles in pp elastic scattering at 100 GeV/c

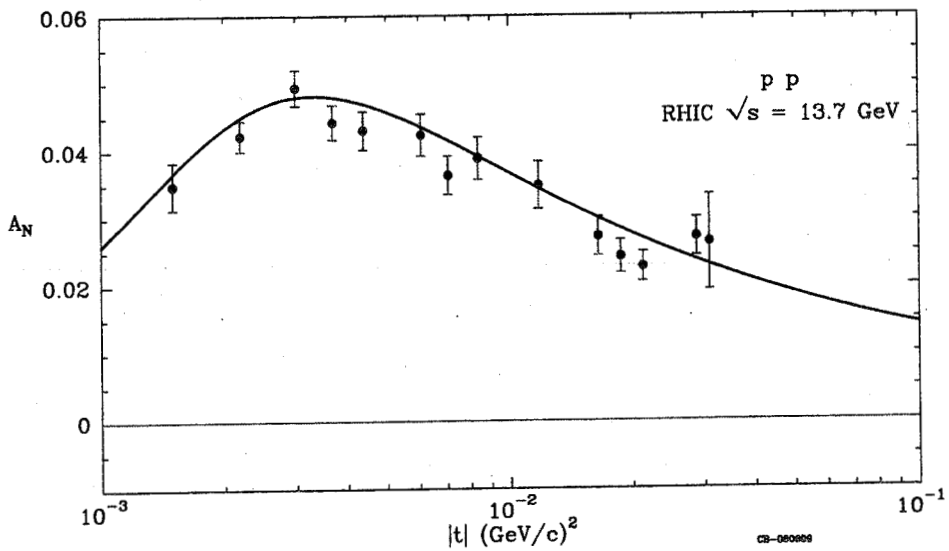


The cross section is very well described by the BSW impact picture and A_N is well predicted with no hadronic spin dependence (C. Bourrely, J. S. and T.T. Wu, Phys. Rev. D76, 053002 (2007))

A_N at very small angles in pp elastic scattering

$|t|$ lies between 10^{-3} and 10^{-1} GeV^2

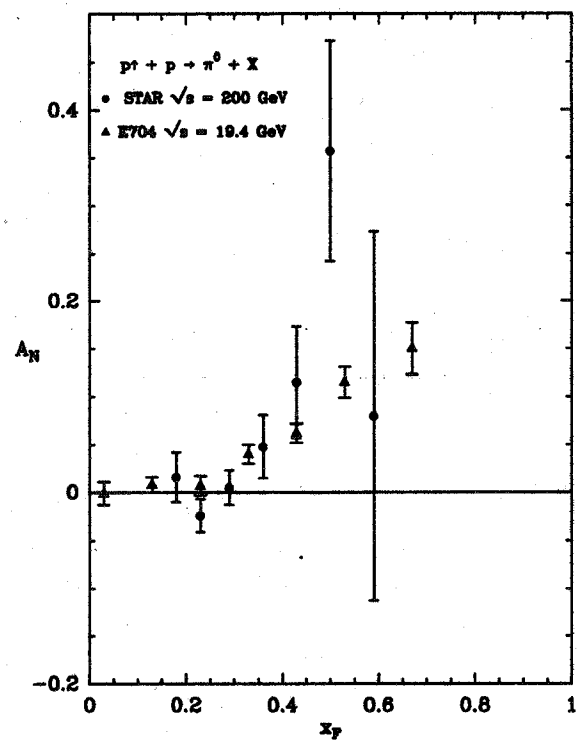
Data from H. Okada et al., Phys. Lett. B 638, 450 (2006)



Brillant confirmation of the Schwinger effect.

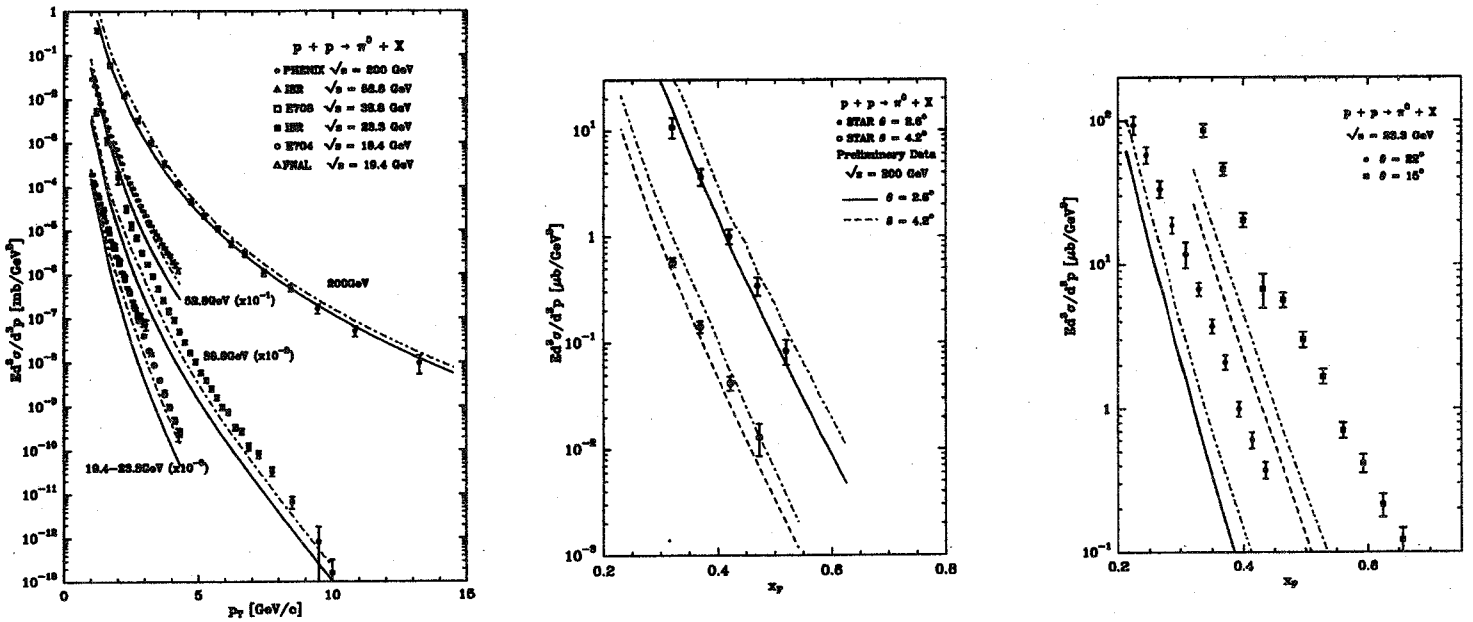
Relevant for polarimetry at RHIC

An interesting case: A_N in π^0 production from E704 and STAR



Do we understand this asymmetry, given the fact that STAR is at very small angle 2.6° and E704 at 9°to 64°?

An interesting case: A_N in π^0 production from E704 and STAR



The pQCD calculation underestimates the cross section at low energies and small angles. This is not the case at 90° and at small angles at high energy, which is the STAR kinematic range.
Don't try to "explain" the asymmetry, ignoring the unpolarized cross section (C. Bourrely and J. S., EPJC 36,371 (2004)) . Need also to consider resummation effects (see W. Vogelsang et al.).

[redacted]

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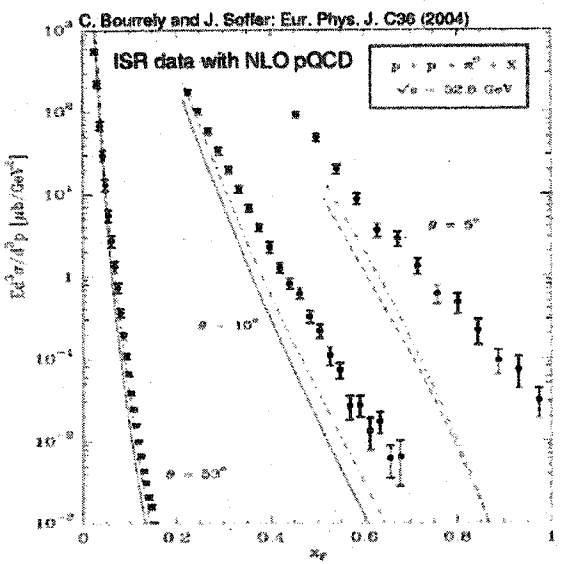
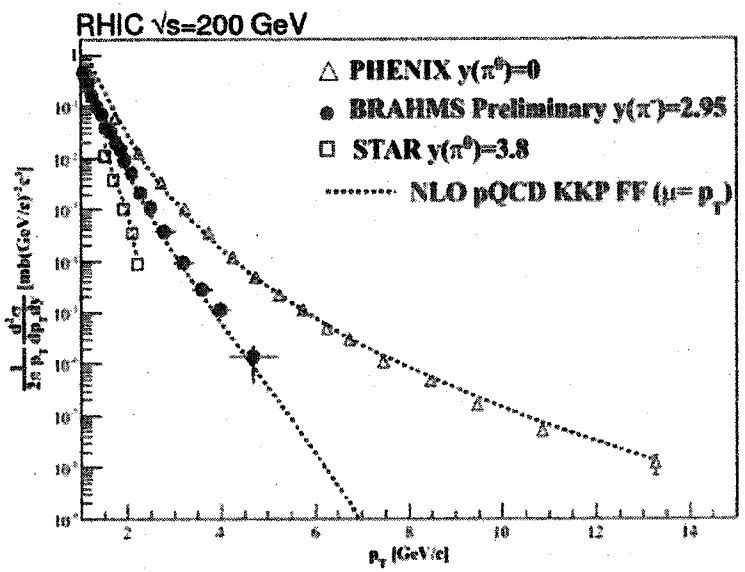
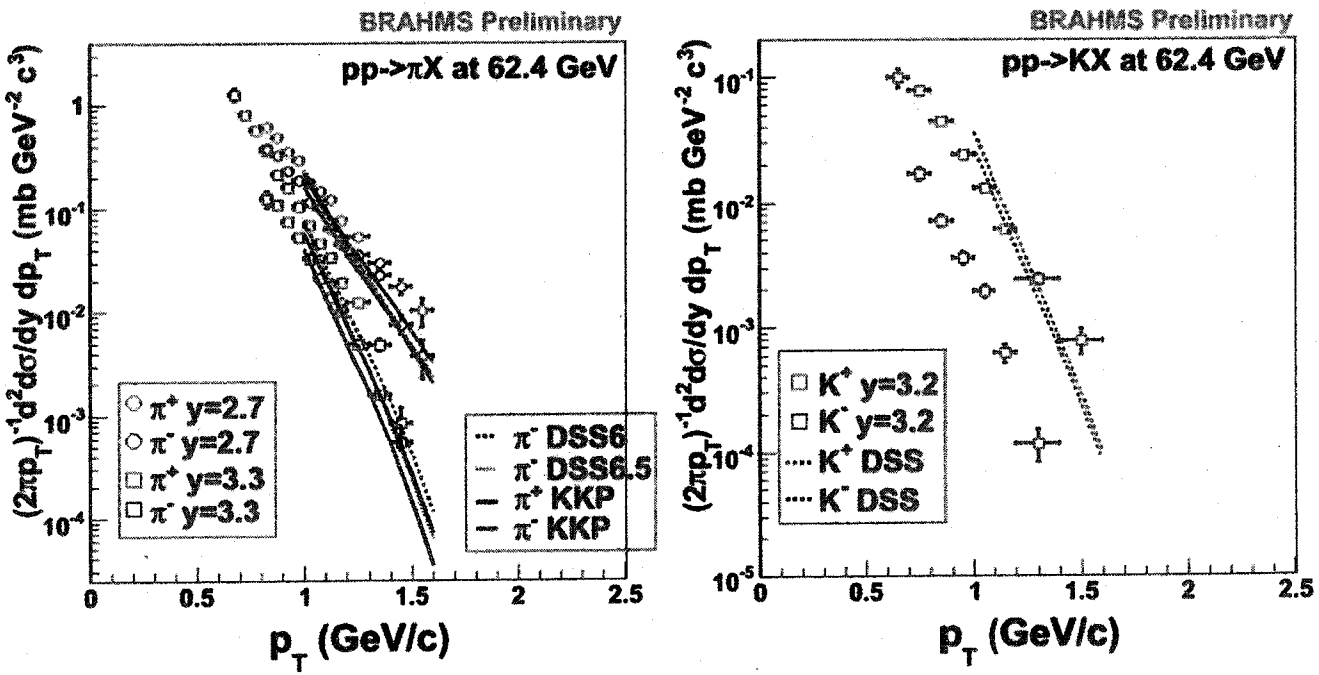
June 30, Transverse Workshop 2008, Beijing

$\sqrt{s} =$



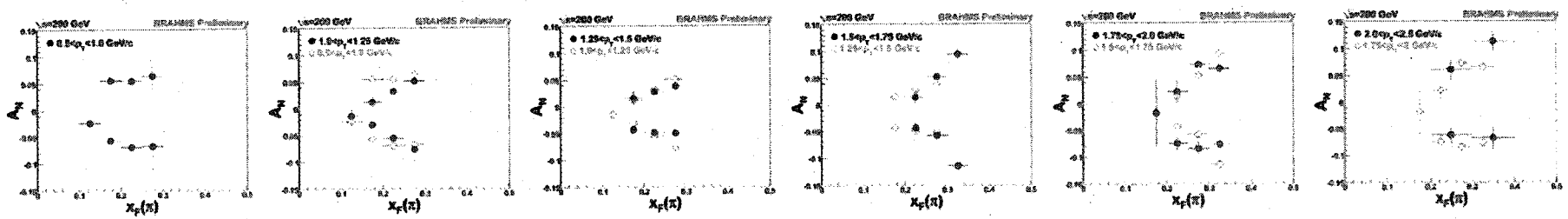


- At $\sqrt{s} = 200$ GeV, NLO pQCD framework is successful for mesons at mid- and forward rapidities
- At $\sqrt{s} = 52$ GeV, NLO pQCD significantly deviates, especially at high-x_F, from the ISR measurements

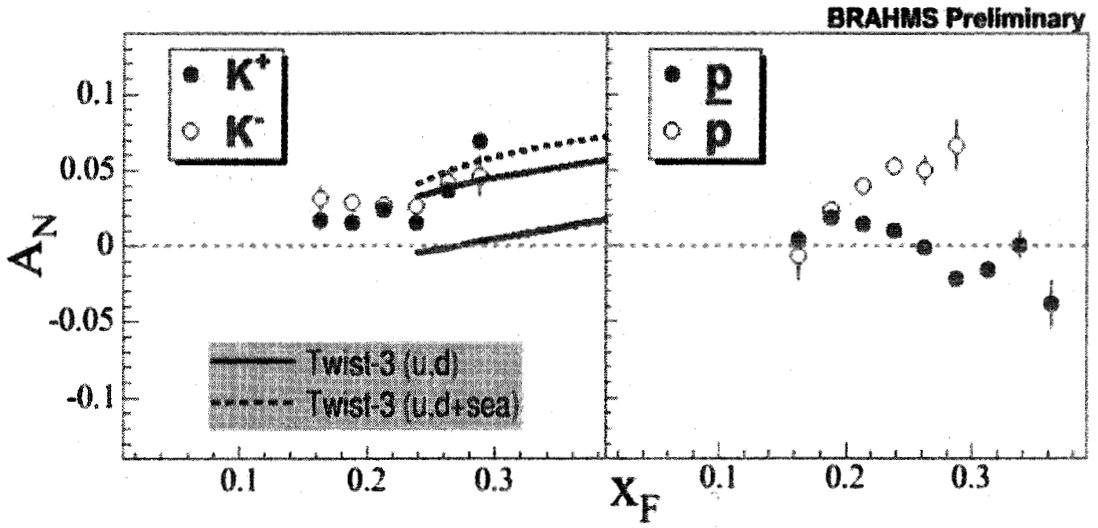


- NLO pQCD calculations in a reasonable agreement/under-predict with π, K^+
- The K^- data are suppressed order of magnitude (valence quark dominance)
- DSS FFs (CTEQ6, CTEQ6.5): $K^+ \sim K^-$. Related to fragmentation or PDFs?

$\pi^{\pm}$ $\sqrt{\ } =$



- $A_N(\pi)$ decreases with p_T at $\sim$1 GeV/c
- Non-"trivial" p_T-x_F dependence complicated by limited kinematic sampling at higher-p_T?



- $A_N(K^+) \sim A_N(K^-)$: positive 2-5% for $0.15 < x_F < 0.3$
- If main contribution to A_N at large x_F is from valence quarks: $A_N(K^+) \sim A_N(\pi^+), A_N(K^-) \sim 0$: disagreement with naïve expectations
- $A_N(\bar{p}) \sim A_N(K^-)$ while $A_N(p) \sim 0$: require better understanding of non-leading, sea-quark, gluon FF?

$\pi^{\pm}$ $\sqrt{\ } =$

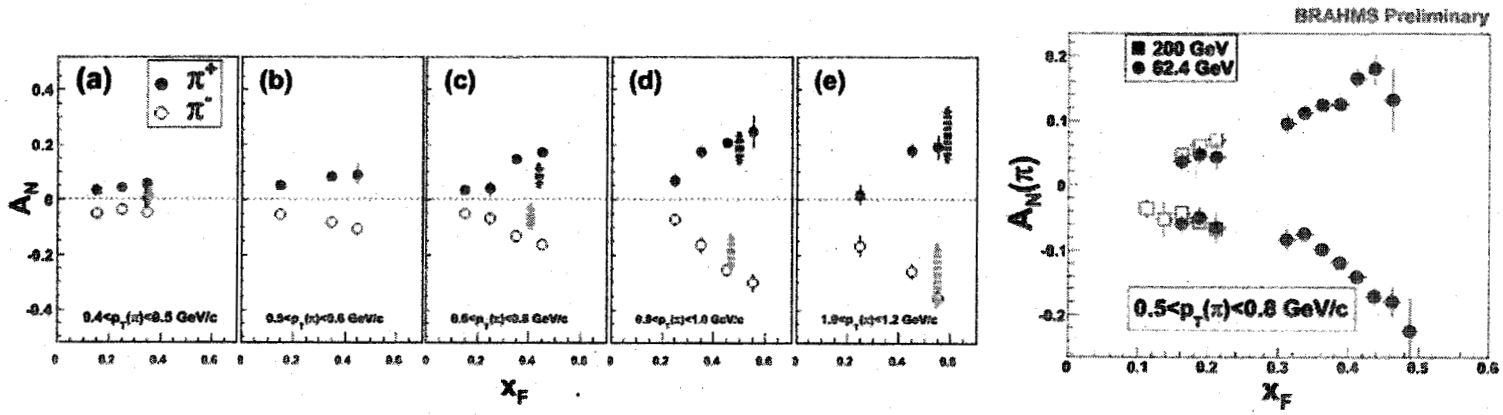
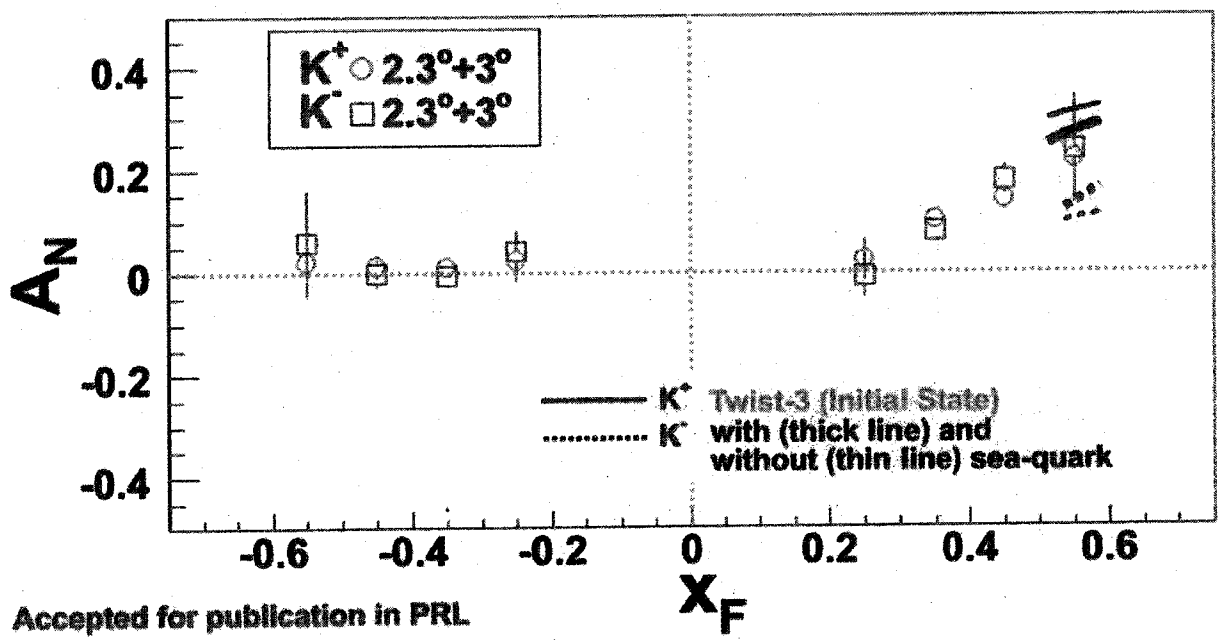


Figure: Left: 62 GeV *vs.* 20 GeV, Right: 200 GeV *vs.* 62 GeV

- At low-p_T ($p_T \sim< 1$GeV/c) $A_N(\pi)$ decreases as p_T decreases: (Constraint: $A_N \to 0$ as $p_T \to 0$). Non-pQCD effect dominant?
- At $p_T \sim> 1$GeV/c, $A_N(\pi)$ increase with $1/p_T$
- Perturbative/Non-perturbative $\sim$ 1 GeV/c?

$\pm \quad \sqrt{\quad} =$



Accepted for publication in PRL

- $A_N(K^+) \sim A_N(K^-)$: positive $\sim$ 20% at $x_F \sim$ 0.5-0.6
- If main contribution to A_N at large x_F is from valence quarks: $A_N(K^+) \sim A_N(\pi^+), A_N(K^-) \sim 0$: disagreement with naïve expectations
- Cross-section: $K^+ \sim K^- \times 10$ and Common production ($\phi \rightarrow K^+K^-$) negligibly small
- Contributions from non-leading FFs ($D_u^{K^-}$) and/or Collins effect?

BRAHMS measurements of cross-sections and SSAs of $\pi^{\pm}$, $K^{\pm}$ at $\sqrt{s}$=62.4 GeV and 200 GeV

- Cross-section and SSAs: In the pQCD context
  - NLO pQCD describe unpolarized cross-section at RHIC in wide kinematic region
  - TMD PDF (Sivers function) alone cannot describe polarized and unpolarized data
  - Gluonic degree of freedom (Twist-3) is significantly responsible for the large A_N
  - Understanding on non-valence, non-leading PDF and FF need to be improved
- SSAs: Interplay with significant non-pQCD effect at large-x_F with intermediate-p_T?
  - Energy (in)dependence
  - Large SSA without valence quark
  - Non-trivial p_T-dependence

Transverse Single Spin Asymmetry in Heavy Flavor Production in Polarized p+p Collisions at RHIC

Han Liu

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Abstract

The measurement of transverse single spin asymmetries (A_N) at high energies gives us an opportunity to probe the quark and gluon structure of transversely polarized nucleons. At RHIC energy, heavy flavor production is dominated by gluon-gluon fusion, so the Collins effect has minimum impact on A_N as the gluon's transversity is zero. The measurement of A_N in heavy flavor production is uniquely sensitive to the gluon Sivers distribution which is related to the orbital angular momentum of gluons inside the polarized protons.

The PHENIX experiment has collected 2.7 pb^{-1} data in transversely polarized p+p collisions at 200GeV in 2006 run. Results for J/ψ and open heavy flavor A_N at forward rapidity will be presented.

Heavy flavor A_N at forward rapidity with muon spectrometers

Why heavy flavor?

- Eliminate Collins' effects
  * heavy flavor production dominated by gluon gluon fusion at RHIC energy

    Pythia 6.1 simulation

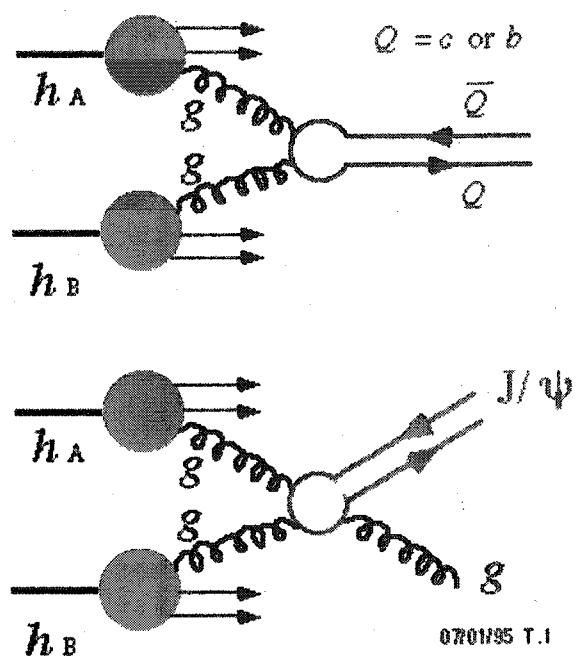
$c\bar{c}: \; gg \rightarrow c\bar{c}$	95%
$b\bar{b}: \; gg \rightarrow b\bar{b}$	85%

  * gluon has zero transversity

- A perfect channel for gluon Sivers function
  * Gluon's orbital angular momentum?

- Important to understand the origin of observed large A_N at large x_F

Gluon Fusion



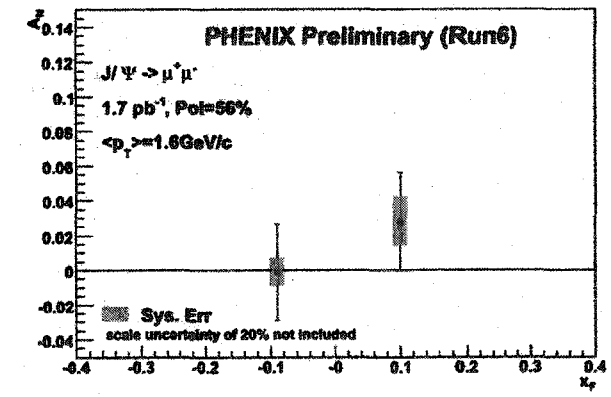
J/Ψ A_N at RHIC

The asymmetry is very sensitive to the J/ Ψ production mechanism

-- For pp scattering (both initial and final state interactions), SSA vanishes if the pair are produced in a color-octet model but survives in the color-singlet model (Feng Yuan, hep-ph:0801.4357)

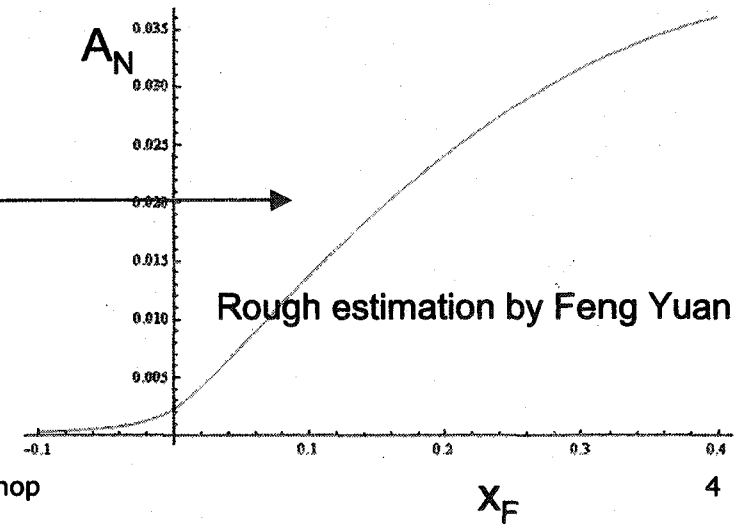
-- At RHIC, color-octet dominate the production cross section

-- 30%-40% J/Ψ comes from Ψ' and χ_c feeddown

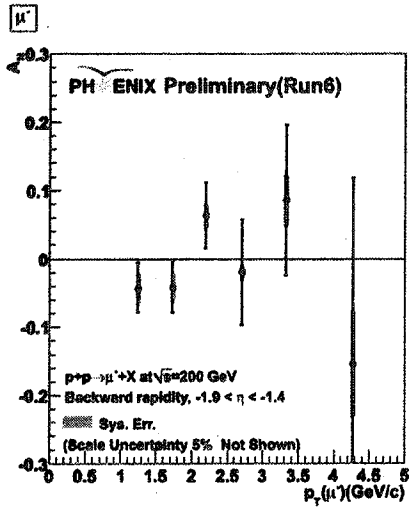


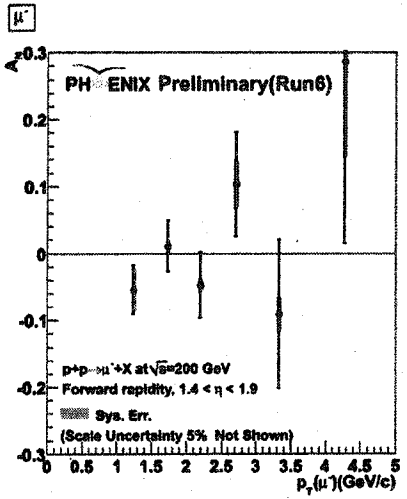
Assume:
--Gluon Sivers function ~ 0.5 x(1-x) times unpolarized gluon distribution (expect large-x and small-x suppression of the Sivers function as compared to the unpolarized one)

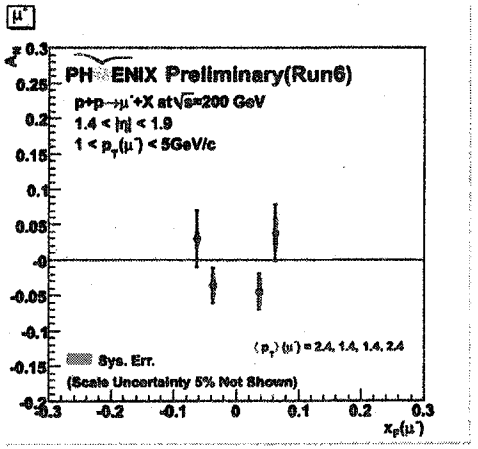
-- 30% J/Ψ comes from χ_c feeddown

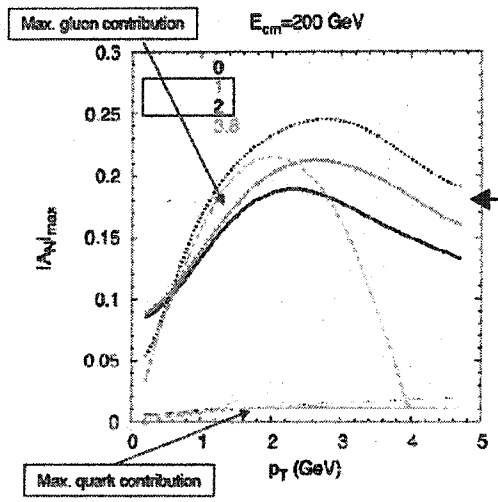


Prompt Muon (from heavy flavor decay) A_N vs. p_T (x_F)

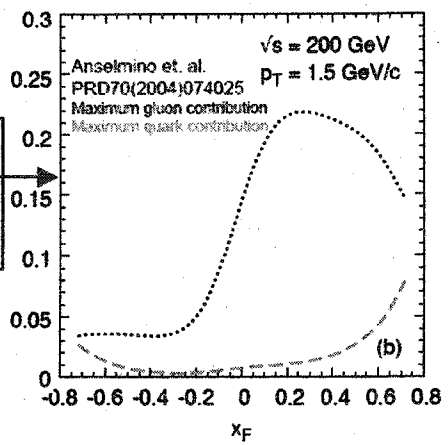








Anselmino's prediction on A_N in inclusive D meson production at 200GeV

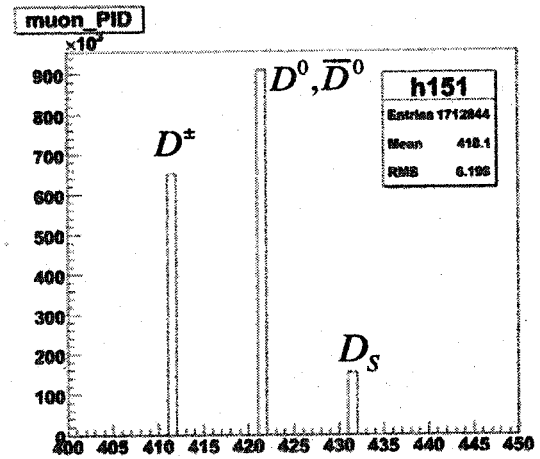


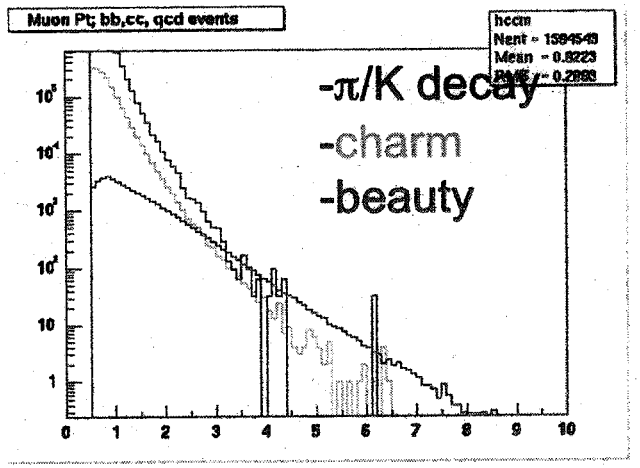
Translation between muon and D and B meson kinematics

- PYTHIA simulation

-- D^0, $D^{+/-}$ hadron relative fraction

-- D/B fractions





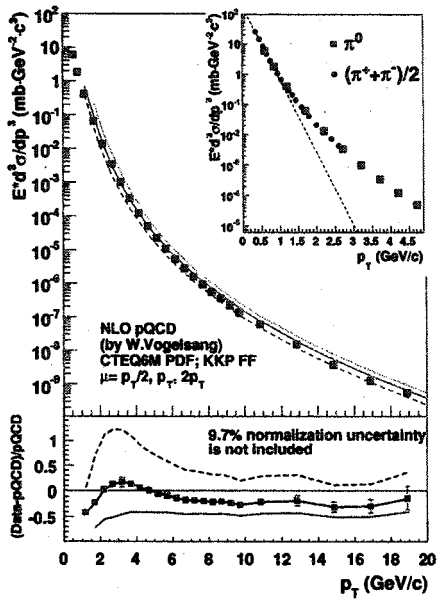
-- Qualitative conclusion: Data constrain the gluon Sivers function to be significantly smaller than the maximal allowed

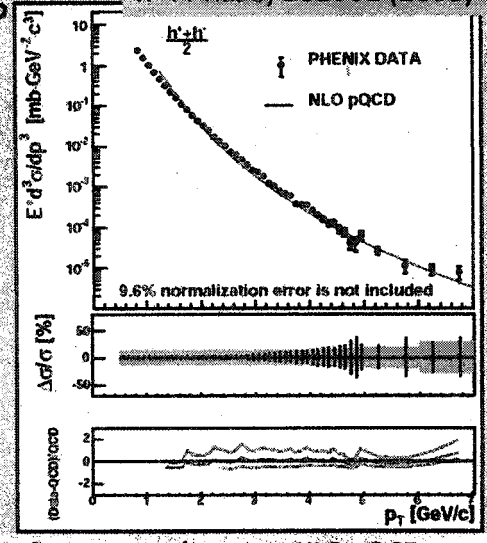
-- Translation between D meson and muon kinematics and estimate of charm vs. bottom components underway

-- More quantitative comparison will come in the future

Unpol. Cross Section in pp: √s=200 GeV

π^0: PRD76, 051106 (2007) $|\eta|<0.35$ $h^{\pm}$: PRL95, 202001 (2005)

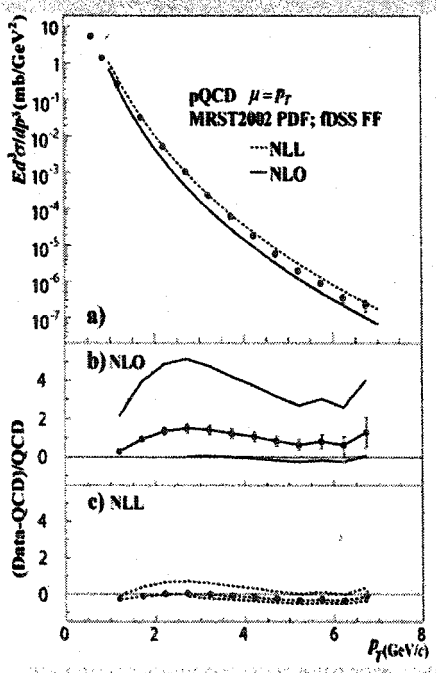




Good agreement between NLO pQCD calculations and data ⇒ confirmation that pQCD can be used to extract spin dependent pdf's from RHIC data.

- Same comparison fails at lower energies

Unpol. Cross Section in pp: √s=62 GeV



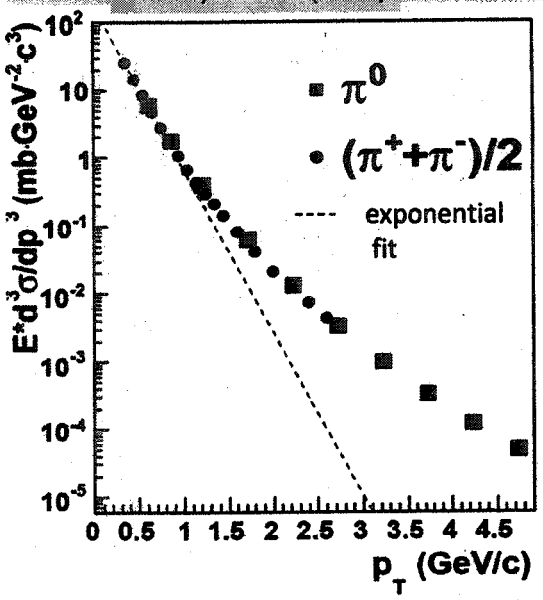
Comparisons to NLO and NLL pQCD calculations.

Unlike at 200 GeV, scale choice of $\mu=p_T$ underpredicts the data.
→ Threshold logarithm effects become relevant at this intermediate energy?

Data points from arXiv:0801.4555, submitted to PRL

From soft to hard

PRD76, 051106 (2007)



Exponent ($e^{-\alpha p_T}$) describes our pion cross section data perfectly well at p_T<~1 GeV/c (dominated by soft physics):

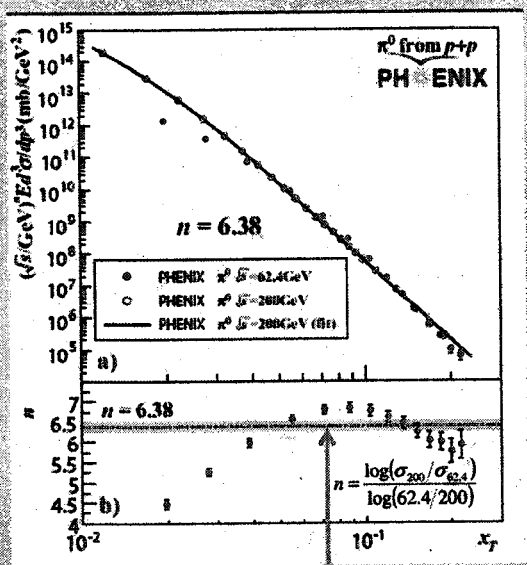
α=5.56±0.02 (GeV/c)$^{-1}$

χ^2/NDF=6.2/3

Assume that exponent describes soft physics contribution also at higher pTs ⇒ soft physics contribution at pT>2 GeV/c is <10%

pT>2 GeV/c – hard scale?

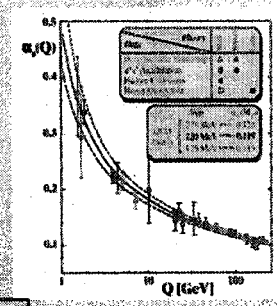
From soft to hard



2 GeV/c at √s=62 GeV

xT scaling:

$$E\frac{d^3\sigma}{dp^3} = \frac{1}{\sqrt{s}^n} G(x_T)$$



Running $\alpha(Q^2)$
Evolution of PDF and FF
Higher order effects
Etc.

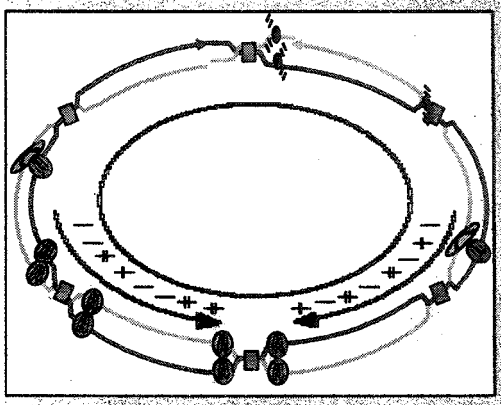
→ $n=n(x_T, \sqrt{s})$

Soft region: $n(x_T)$ increase with x_T
If $\sigma \sim \exp(-\alpha p_T)$

Hard region: $n(x_T)$ decrease with x_T
Stronger scale breaking at lower p_T

pT~2 GeV/c – transition from soft to hard scale?

Measuring A_N



- Look at left-right asymmetries relative to one transversely polarized proton beam

$$A_N = \frac{1}{P}\frac{N^{\uparrow}_{left} - R_{lum}N^{\downarrow}_{left}}{N^{\uparrow}_{left} + R_{lum}N^{\downarrow}_{left}} = \frac{R_{lum}N^{\downarrow}_{right} - N^{\uparrow}_{right}}{R_{lum}N^{\downarrow}_{right} + N^{\uparrow}_{right}},\ R_{lum} = \frac{L^{\uparrow}}{L^{\downarrow}}$$

$$A_N = \frac{1}{P}\frac{N^{\uparrow}_{left} - R_{det}N^{\uparrow}_{right}}{N^{\uparrow}_{left} + R_{det}N^{\uparrow}_{right}} = \frac{R_{det}N^{\downarrow}_{right} - N^{\downarrow}_{left}}{R_{det}N^{\downarrow}_{right} + N^{\downarrow}_{left}},\ R_{det} = \frac{\varepsilon_{left}}{\varepsilon_{right}}$$

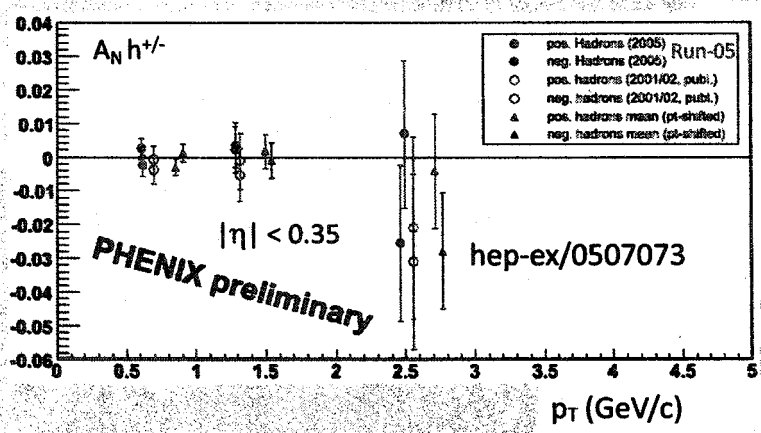
- To cancel acceptance and luminosity effects use so-called square root formula

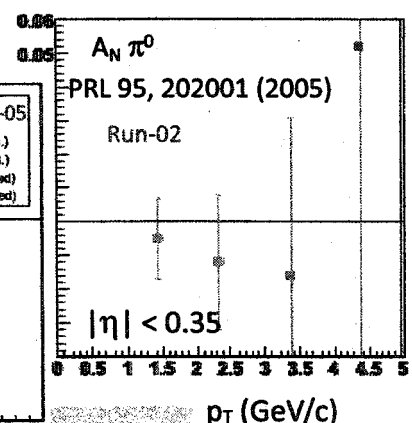
$$A_N = \frac{1}{P}\frac{\sqrt{N^{\uparrow}_{left}\cdot N^{\downarrow}_{right}} - \sqrt{N^{\downarrow}_{left}\cdot N^{\uparrow}_{right}}}{\sqrt{N^{\uparrow}_{left}\cdot N^{\downarrow}_{right}} + \sqrt{N^{\downarrow}_{left}\cdot N^{\uparrow}_{right}}}$$

✓ Bunch spin configuration alternates every 106 ns
✓ Data for all bunch spin configurations are collected at the same time

⇒ Possibility for false asymmetries are greatly reduced

A_N of midrapidity π^0 and $h^{+/-}$ at $\sqrt{s}$=200 GeV

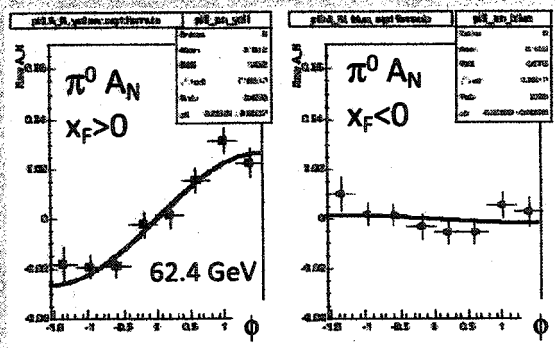


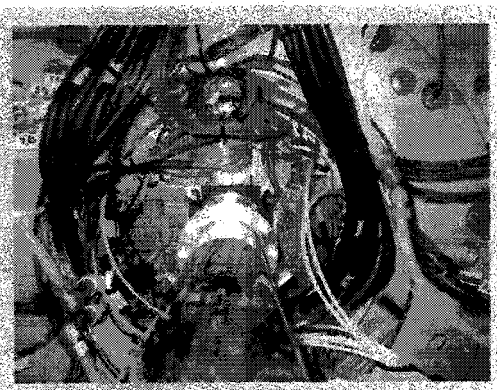


- A_N is zero within 1% → contrast with forward pions
- Constrains Sivers distribution function for gluons (Anselmino et al., PRD74, 094011 (2006))
- Updated π^0 analysis with ~200x improvement(!) in statistical figure-of-merit underway . . .

Expanded EMCal coverage

- Muon Piston Calorimeter (MPC): $PbWO_4$ calorimeter
- $3.1 < |\eta| < 3.7$
  - Region of large observed asymmetries
- Single arm commissioned in 2006
- Second arm took data in 2008

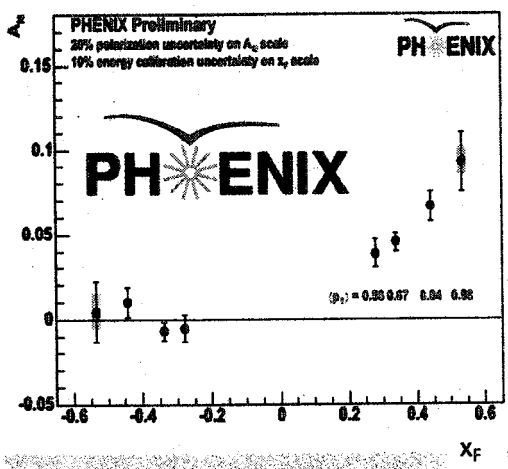


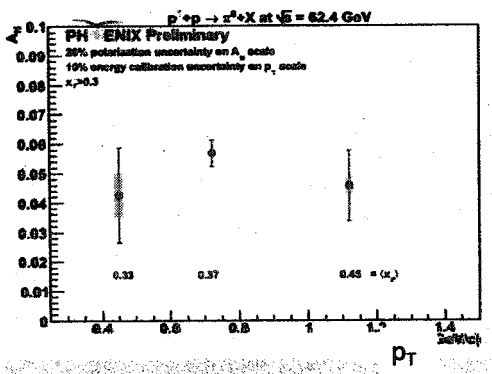


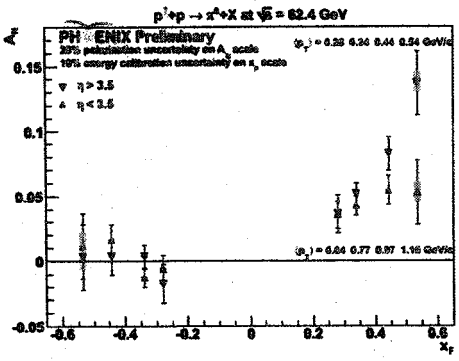
Full azimuthal coverage for $3.1 \leq \eta \leq 3.7$ and $2 < E(\pi^0) < 25$ GeV

Forward π^0 A_N at $\sqrt{s}$=62.4 GeV

PHENIX, Chiu et al., nucl-ex/0701031



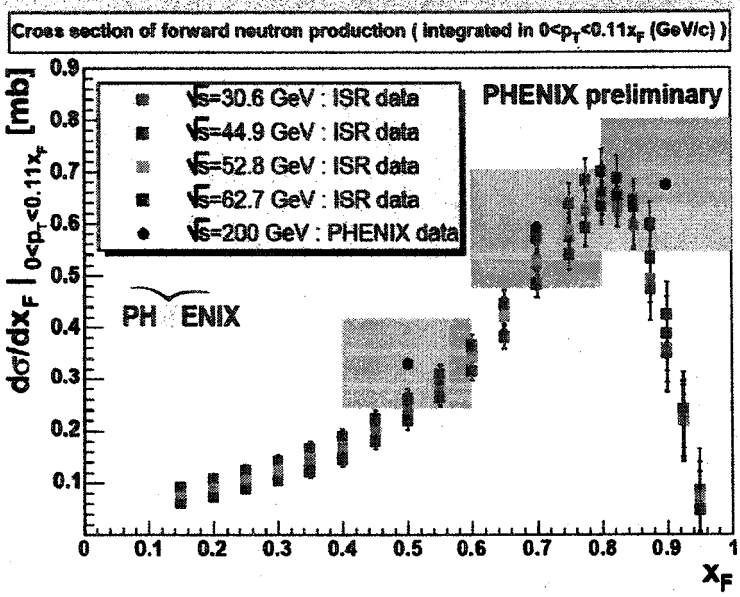


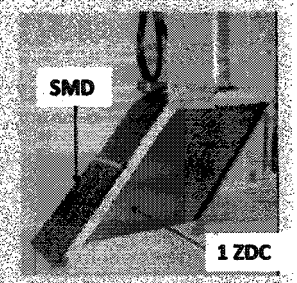


Sizable asymmetries in forward direction.
Need more data to understand p_T dependence

Forward neutrons at √s=200 GeV at PHENIX

Cross section at 200 GeV consistent with ISR data
→ suggests Feynman scaling holds

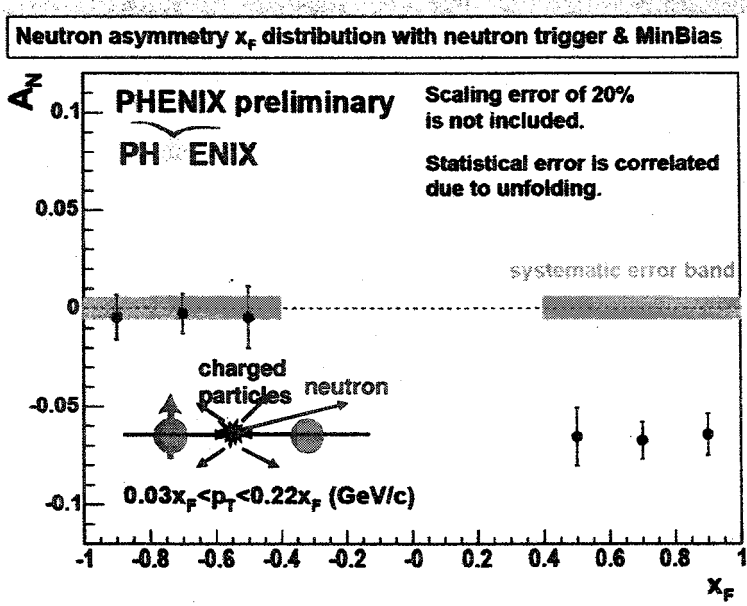




θ_n<2.8 mrad

Forward neutrons at √s=200 GeV at PHENIX

Large negative SSA observed for x_F>0, enhanced by requiring concidence with forward charged particles ("MinBias" trigger).
No x_F dependence seen.



Mean p_T
(Estimated by simulation assuming ISR p_T dist.)
0.4<|x_F|<0.6 0.088 GeV/c
0.6<|x_F|<0.8 0.118 GeV/c
0.8<|x_F|<1.0 0.144 GeV/c

preliminary	A_N
Without MinBias	-6.6 ±0.6 %
With MinBias	-8.3 ±0.4 %

MB: |η|=3.0-3.9

Probing Transversity with Interference Fragmentation Function in p+p Collisions

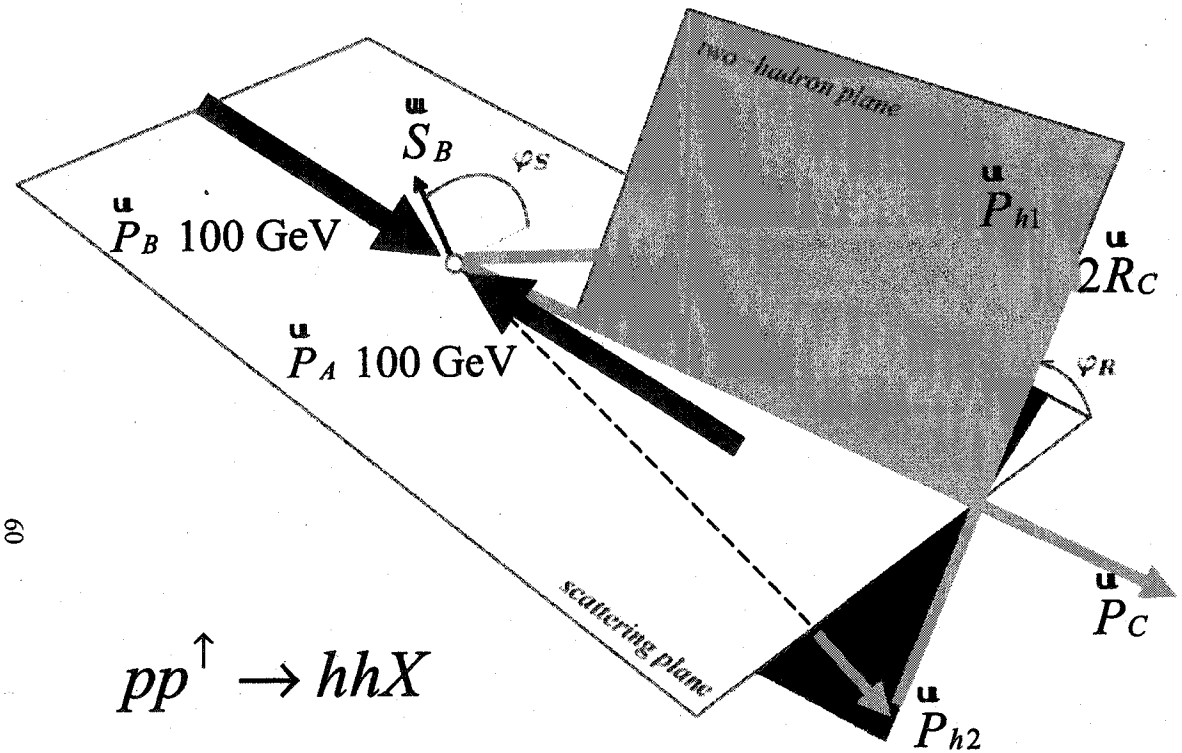
PHENIX

Ruizhe Yang, University of Illinois
(For the PHENIX Collaboration)

PKU-RBRC Workshop on Transverse Spin Physics, July 2008

Definition of Vectors and Angles

PHENIX



p+p c.m.s. = lab frame

$\vec{P}_A, \vec{P}_B$: momenta of protons

$\vec{P}_{h1}, \vec{P}_{h2}$: momenta of hadrons

$\vec{P}_C = \vec{P}_{h1} + \vec{P}_{h2}$

$\vec{R}_C = (\vec{P}_{h1} - \vec{P}_{h2})/2$

$\vec{S}_B$: proton spin orientation

hadron plane: $\vec{P}_{h1}, \vec{P}_{h2}$

scattering plane: $\vec{P}_C, \vec{P}_B$

ϕ_R : from scattering plane to hadron plane

ϕ_S : from polarization vector to scattering plane

Bacchetta and Radici, PRD70, 094032 (2004)

Transversity from di-hadron SSA

PHENIX

Physics asymmetry $A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} = \frac{\sigma_{UT}}{\sigma_{UU}}$

$$d\sigma_{UU} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a)\, f_1^b(x_b)\, \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}}\, D_{1,oo}(\bar{z}_c, M_C^2)$$

Unpolarized quark distribution
Known from DIS

Transversity
to be extracted

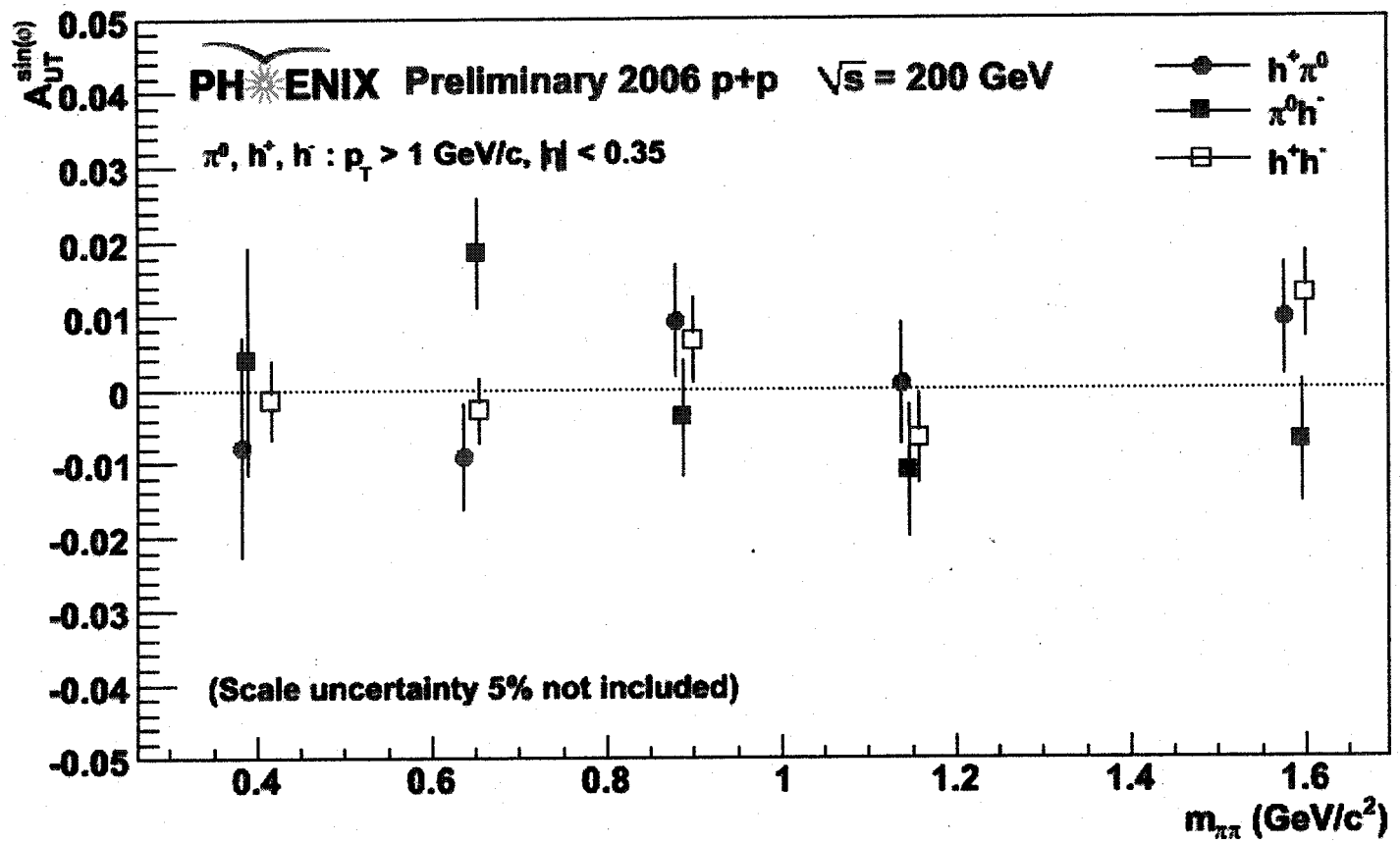
Hard scattering cross section
from pQCD

IFF + Di-hadron FF
to be measured in e+e-

$$d\sigma_{UT} = 2\,|\mathbf{P}_{C\perp}| \sum_{a,b,c,d} \frac{|\mathbf{R}_C|}{M_C} |\mathbf{S}_{BT}| \sin(\phi_{S_B} - \phi_{R_C}) \int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a)\, h_1^b(x_b)\, \frac{d\Delta\hat{\sigma}_{ab^{\uparrow}\to c^{\uparrow}d}}{d\hat{t}}\, H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

$A_{UT}^{\sin\phi}$ vs invariant mass of the pair

PHENIX



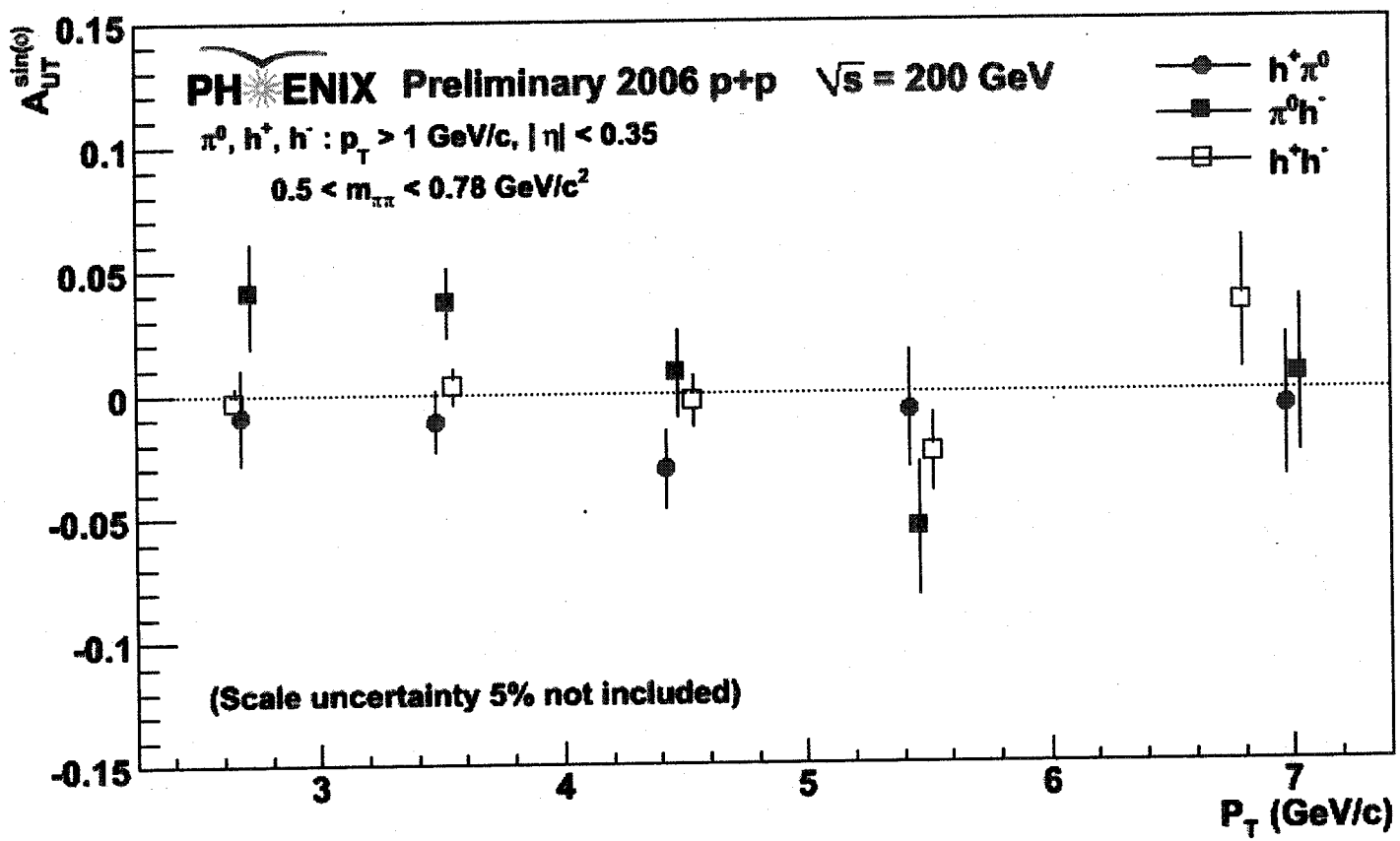
Systematic errors
Polarization 5%
Relative lumi. 5×10^{-4}
No systematic effects detected from bunch shuffling

Consistent with 0, despite the second bin of π^0h^- pairs and the last bin of h^+h^- pairs are 2σ from 0

62

$A_{UT}^{\sin\phi}$ vs p_T of the pair ($0.5 < m < 0.78$)

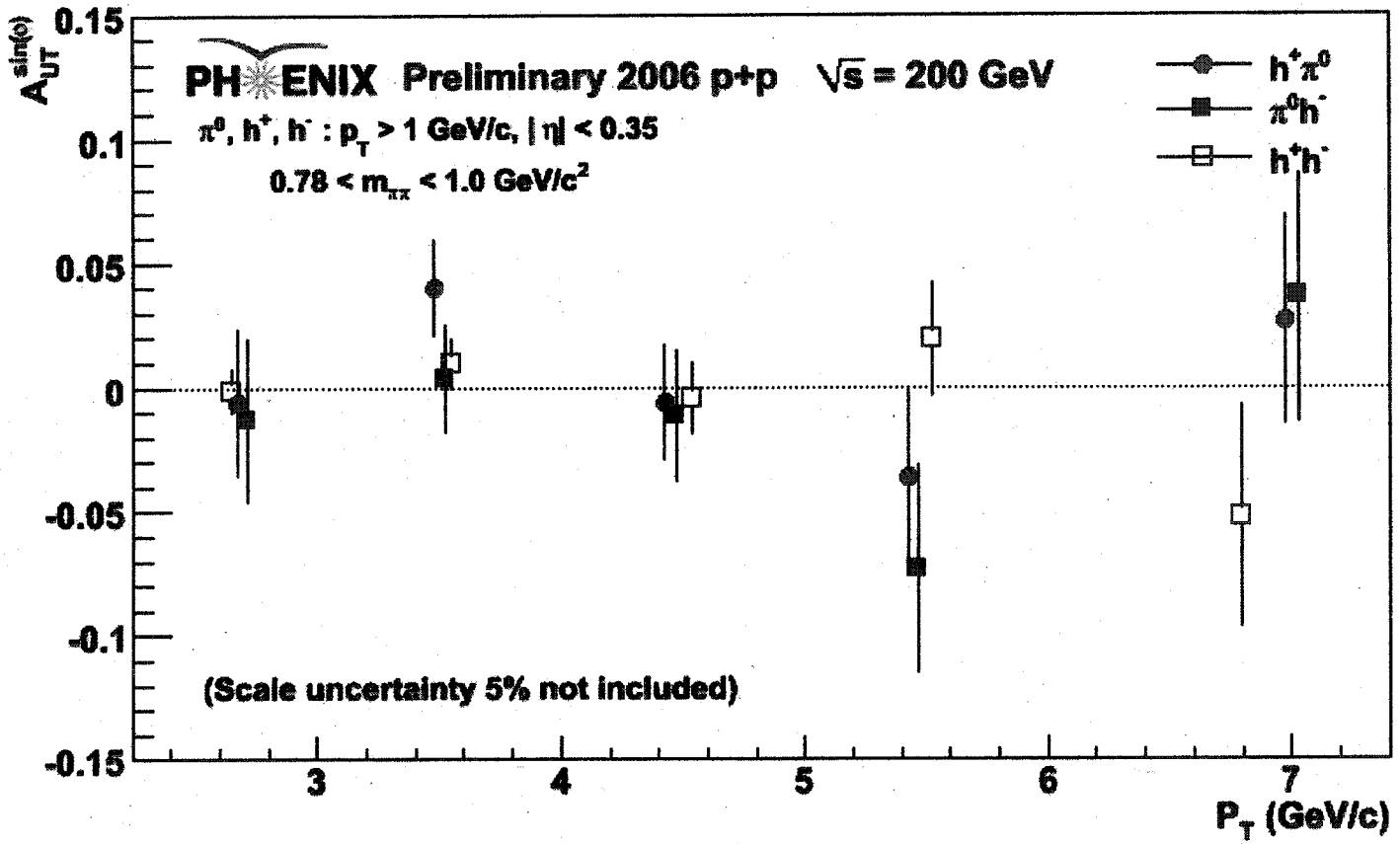
PHENIX



Soft physics contributions at at low p_T, may be non-neglegible

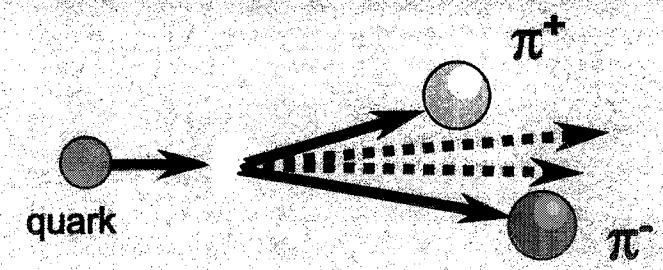
$A_{UT}^{\sin\phi}$ vs p_T of the pair ($0.78 < m < 1.0$)

PHENIX



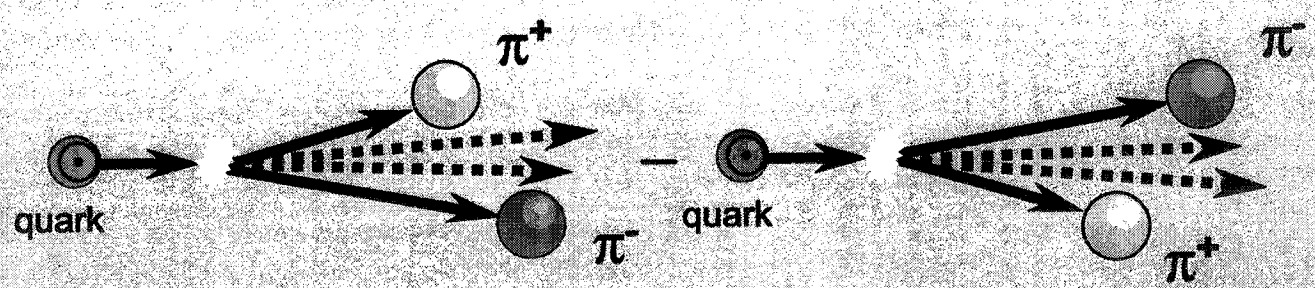
Soft physics contributions at at low p_T, may be non-neglegible

Dihadron fragmentation functions



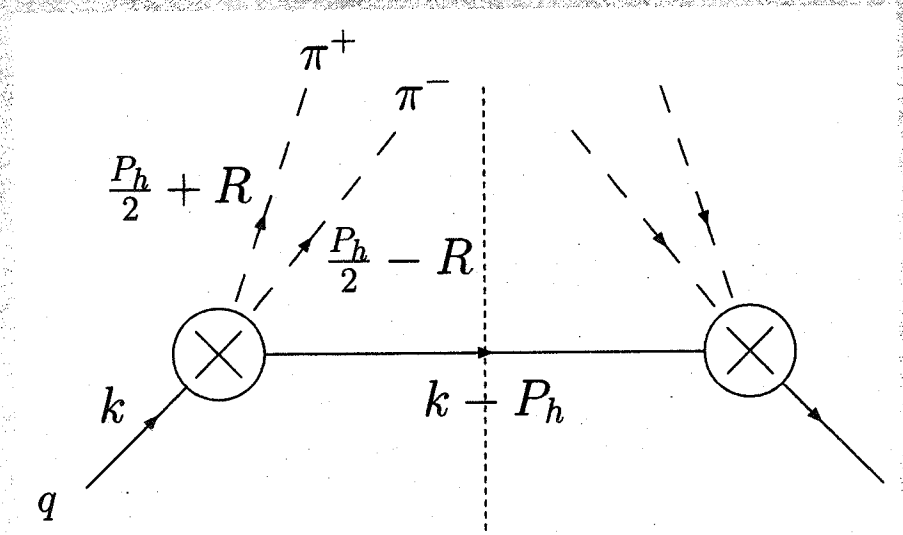
$$D_1^q(z, \cos\theta, M_h^2) = 4\pi\, \mathrm{Tr}[\Delta^q(z, \cos\theta, M_h^2, \phi_R)\, \gamma^-],$$

$$\frac{\epsilon_T^{ij}\, R_{Tj}}{M_h}\, H_1^{\sphericalangle\, q}(z, \cos\theta, M_h^2) = 4\pi\, \mathrm{Tr}[\Delta^q(z, \cos\theta, M_h^2, \phi_R)\, i\, \sigma^{i-}\, \gamma_5].$$



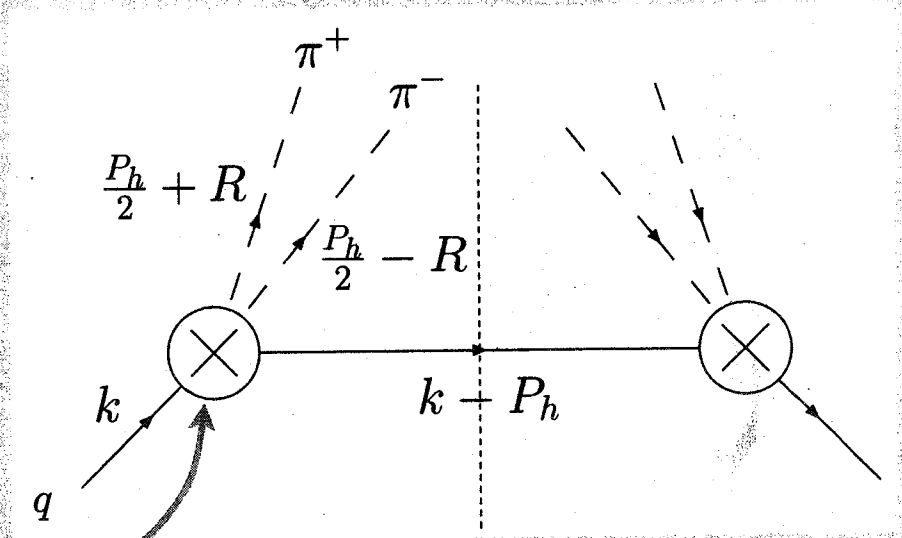
Model for dihadron fragmentation

A.B., M. Radici, PRD74 (06)



Model for dihadron fragmentation

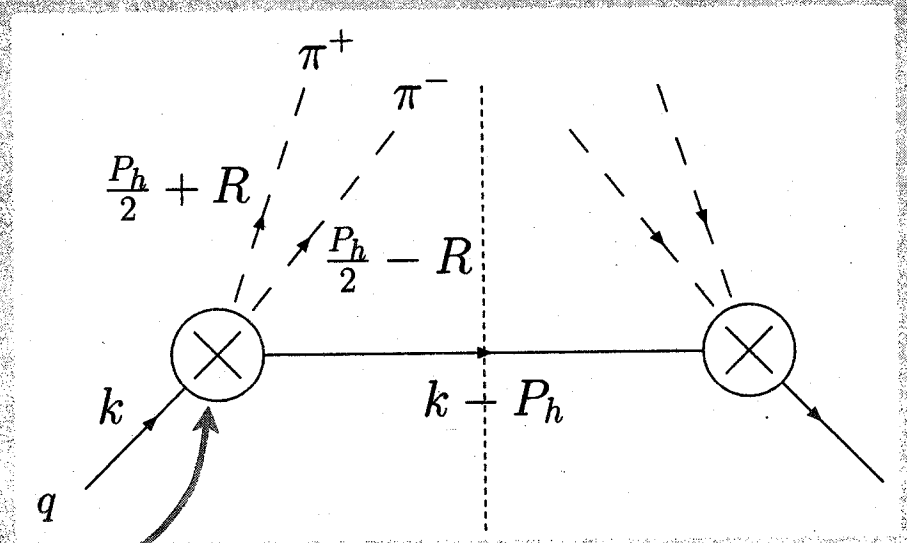
A.B., M. Radici, PRD74 (06)



$$\left(F^s e^{-\frac{k^2}{\Lambda_s^2}} + F^p e^{-\frac{k^2}{\Lambda_p^2}} \not{R}\right)$$

Model for dihadron fragmentation

A.B., M. Radici, PRD74 (06)



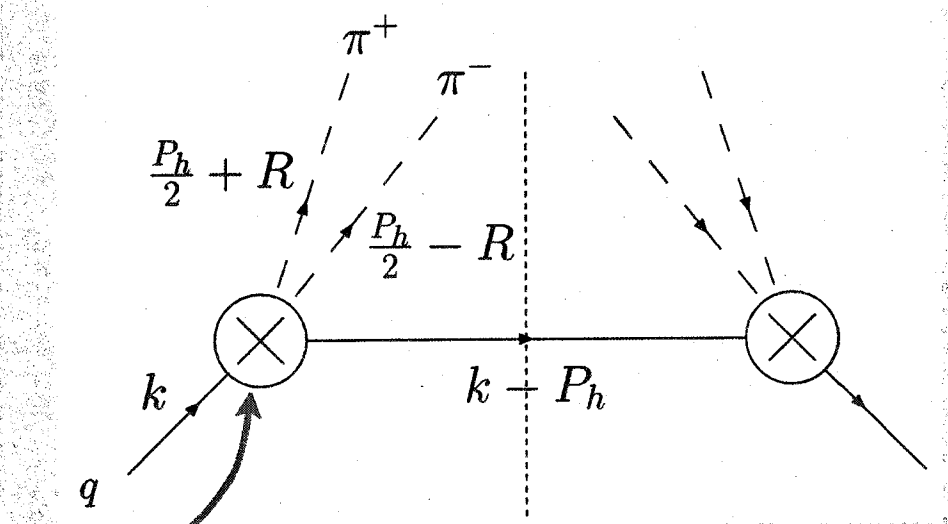
$$\left(F^s\, e^{-\frac{k^2}{\Lambda_s^2}} + F^p\, e^{-\frac{k^2}{\Lambda_p^2}}\, \not{R}\right)$$

$$F^s = f_s,$$

$$F^p = f_\rho \frac{(M_h^2 - M_\rho^2) - i\,\Gamma_\rho\, M_\rho}{(M_h^2 - M_\rho^2)^2 + \Gamma_\rho^2\, M_\rho^2} + f_\omega \frac{(M_h^2 - M_\omega^2) - i\,\Gamma_\omega\, M_\omega}{(M_h^2 - M_\omega^2)^2 + \Gamma_\omega^2\, M_\omega^2}$$
$$- i\, f'_\omega \frac{\sqrt{\lambda(M_\omega^2, M_h^2, m_\pi^2)}\, \Theta(M_\omega - m_\pi - M_h)}{4\,\pi\,\Gamma_\omega\, M_\omega^2 \sqrt[4]{4\, M_\omega^2\, m_\pi^2 + \lambda(M_\omega^2, M_h^2, m_\pi^2)}},$$

Model for dihadron fragmentation

A.B., M. Radici, PRD74 (06)



$$\left(F^s e^{-\frac{k^2}{\Lambda_s^2}} + F^p e^{-\frac{k^2}{\Lambda_p^2}} R\right)$$

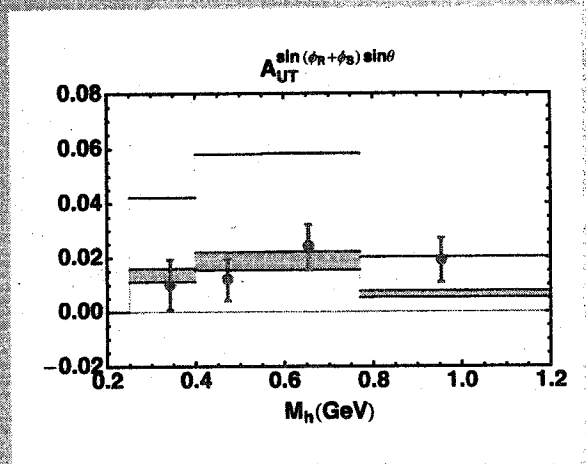
$$F^s = f_s,$$

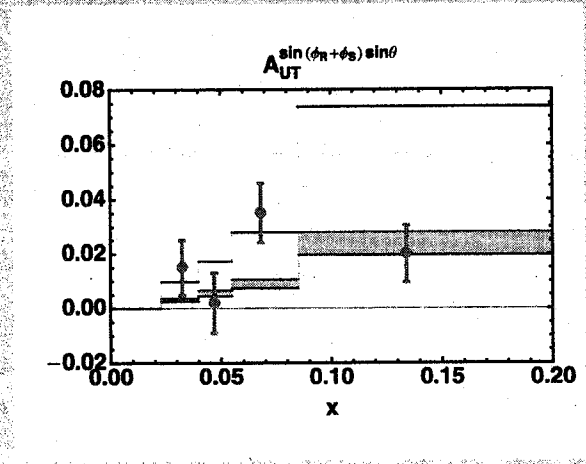
$$F^p = f_\rho \frac{(M_h^2 - M_\rho^2)\,\Gamma_\rho M_\rho}{(M_h^2 - M_\rho^2)^2 + \Gamma_\rho^2 M_\rho^2} + f_\omega \frac{(M_h^2 - M_\omega^2)\,\Gamma_\omega M_\omega}{(M_h^2 - M_\omega^2)^2 + \Gamma_\omega^2 M_\omega^2}$$

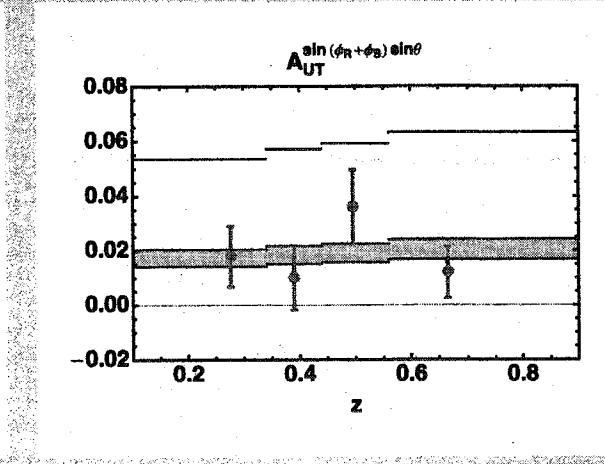
$$\Gamma_\omega = \frac{\sqrt{\lambda(M_\omega^2, M_h^2, m_\pi^2)}\,\Theta(M_\omega - m_\pi - M_h)}{4\pi\,\Gamma_\omega M_\omega^2 \sqrt[4]{4 M_\omega^2 m_\pi^2 + \lambda(M_\omega^2, M_h^2, m_\pi^2)}},$$

Fit to HERMES data

A.B., F. Ceccopieri, A. Mukherjee, M. Radici, work in progress







GPDS – towards a 3D imaging of hadrons

Delia Hasch (INFN-Frascati)

Over the last years, the very interesting field of Generalised Parton Distributions (GPDs) has been developed. The new formalism provides a coherent and homogenous description of the structure of hadrons as it reveals simultaneously (transverse) position distributions and (longitudinal) momentum distributions of partons. They therefore offer a three-dimensional representation of hadrons at the parton level. The ordinary parton distribution functions and elastic form factors appear as kinematic limits and moments of GPDs, respectively. Strong interest in the formalism of GPDs has emerged after GPDs were found to offer the first possibility to reveal the total angular momentum carried by the quarks in the nucleon.
There is an exciting relation between TMDs and GPDs, they both originate from the same Wigner function. However, direct relations between TMDs and GPDs have not yet been established in a model independent way (for model dependent relations see recent works of M. Burkardt and A. Metz et.al. and the talks at this workshop by M. Burkardt and M. Schlegel). A very interesting way of using the *chiral-odd* GPDs for gaining information about *transversity* was discussed at this workshop by G. Goldstein.

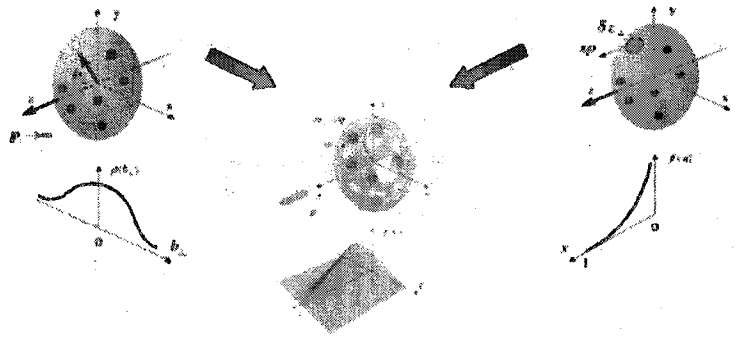
This talk attempts for presenting an overview about the experimental situation for gaining information about GPDs. It presents a personal point of view to this broad field and is not aiming for completeness. Instead, we try to discuss the recent trends, the important achievements and open questions.
GPDs are measured in hard exclusive leptoproduction of mesons or real photons. Hard exclusive processes are challenging to measure as they require high beam energies (to ensure the hard regime), very high luminosities (due to the small cross sections) and an excellent resolution of the spectrometer (to ensure the exclusivity of the process). There is no such experiment that fulfills all criteria. Nevertheless, important experimental information has been gained over the last years.
We discuss here two channels: exclusive vector meson production and deeply virtual Compton scattering (DVCS). While DVCS is the theoretically cleanest way for gaining information about GPDs, only meson production provide additional information about the quark flavours, and gluon GPDs appear at the same order α_s.
Vector meson production has been measured over a wide kinematic range by the HERA collider experiments H1 and ZEUS, at intermediate energies by COMPASS and HERMES and at low energy by JLAB experiments. This results in a wide kinematic range, from low x where gluon contributions are dominant till high x where quark contributions dominate. The interpretation of these data is complicated by large NLO corrections and by possible power corrections (at low Q^2). Despite these caveats, recently a very interesting GPD model calculation (including power corrections) by Goloskokov and Kroll succeeded to describing the data over this wide kinematic range.
For DVCS, we will not discuss the HERA collider results as they cannot be interpreted within the handbag approach. Very interesting data is coming from HERMES and from JLAB HallA and B. There are two new experimental trends. The JLAB experiments aim with dedicated measurements for very high statistics which provides data that are differential in three kinematic variables. HERMES aims for new analysis methods that utilize simultaneously polarisation observables and different beam charges. This allows a separation of different terms and facilitates the interpretation of the data. These new high quality data make limitations of current GPD models clear – there is no such model that is able to describe all available DVCS observables. This clearly calls for new, more sophisticated parameterisations of GPDs.

There is a bright future for GPDs: much more high quality data will become available soon and the theory community is extremely active for providing new GPD models. It would be very exciting to find relations between TMDs and GPDs that help extracting information about the hot objects discussed mainly during this workshop: transversity and functions that describe spin-orbit couplings.

nucleon studied for decades:

form factors
location of partons in nucleon

parton distributions
longitudinal momentum fraction x



generalised parton distributions (GPDs)
longitudinal momentum fraction x at transverse location $b_\perp$

only known framework to gain information on 3D picture of hadrons

why GPDs ?

→ **3D structure of hadrons** : nucleon tomography

→ **complementary to TMDs** :

Wigner distribution: ("mother" function)

$$W_p^u(\vec{r},k)$$

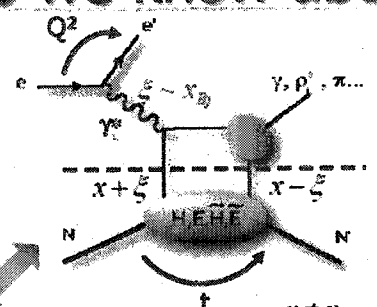
probability to find a quark **u** in a nucleon **P** with a certain polarisation in a position **r** and momentum **k**

$\xrightarrow{d^3r}$ TMD

$\xrightarrow{FT\ (d^2k_T)}$ GPD

→ **phenomena of single-spin asymmetries**

what do we know about GPDs ?



$Q^2 >>, t <<$

appear in factorisation theorem for *hard exclusive processes*

$H(x,\xi,t)$ $\quad x \neq x_{Bj}$, $\xi \sim x_{Bj}$

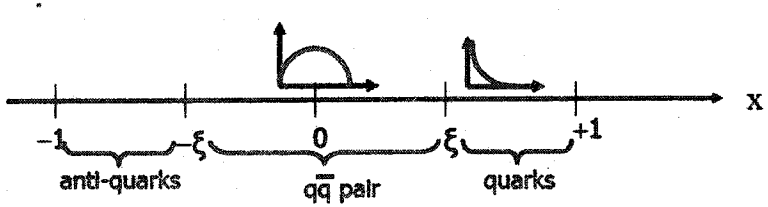
form factors

$$\sum_q e_q \int dx\, H^q(x,\xi,t) = F_1(t)$$

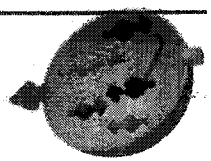
⋮

PDFs

$$H^{q,g}(x,0,0) = q(x)$$
$$\tilde{H}^{q,g}(x,0,0) = \Delta q(x)$$



GPDs and the spin puzzle



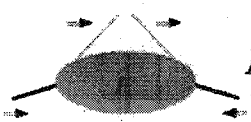
nucleon spin:

$$s_z^n = \frac{1}{2} = \frac{1}{2}\sum_q \Delta q + L_z^q + \Delta G + L_z^g = J_q + J_g$$

↑ ≈30% ↑ ≈zero

[X. Ji, 1997]

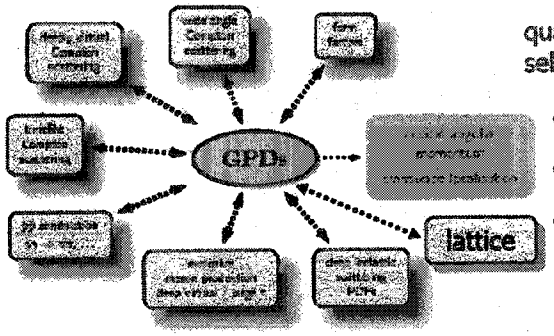
$$J_q = \lim_{t\to 0}\frac{1}{2}\int x\,dx\left[H^{q,g}(x,\xi,t) + E^{q,g}(x,\xi,t)\right]$$



$E^q \neq 0$ *requires* orbital angular momentum

proton helicity flipped but quark helicity conserved

how to access GPDs ?



quantum number of final state selects different GPDs:

- VM (ρ, ω, ϕ): H E
- PS mesons (π, η): $\tilde{H}$ $\tilde{E}$
- DVCS (γ): H, E, $\tilde{H}$, $\tilde{E}$

π^0	$2\Delta u+\Delta d$
η	$2\Delta u-\Delta d$
ρ^0	2u+d, 9g/4
ω	2u−d, 3g/4
ϕ	s, g
ρ^+	u−d
J/ψ	g

→ DVCS most clean process for gaining information on GPDs

→ meson provide info on quark flavours
VM: quark and gluon GPDs appear at same order α_s

accessing GPDs: caveats

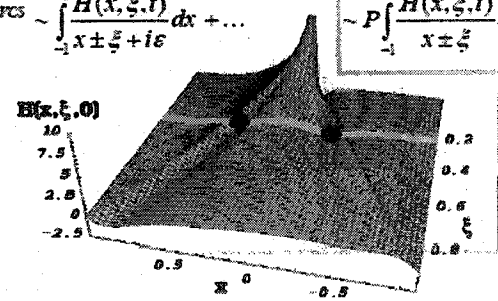
- $H(x,\xi,t)$ but only ξ and t accessible experimentally
- x is mute variable (integrated over):

→ apart from cross-over trajectory (ξ=x) GPDs not directly accessible: deconvolution needed ! (model dependent)

→ GPD moments cannot be directly revealed, extrapolations t → 0 are model dependent

e.g.

$$T^{DVCS} \sim \int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi + i\varepsilon} dx + \ldots \quad \sim P\int_{-1}^{+1} \frac{H(x,\xi,t)}{x \pm \xi} dx - i\pi H(\pm\xi,\xi,t) + \ldots$$



cross sections & beam-charge asymmetry ~ Re(T^{DVCS})

beam or target-spin asymmetries ~ Im(T^{DVCS})

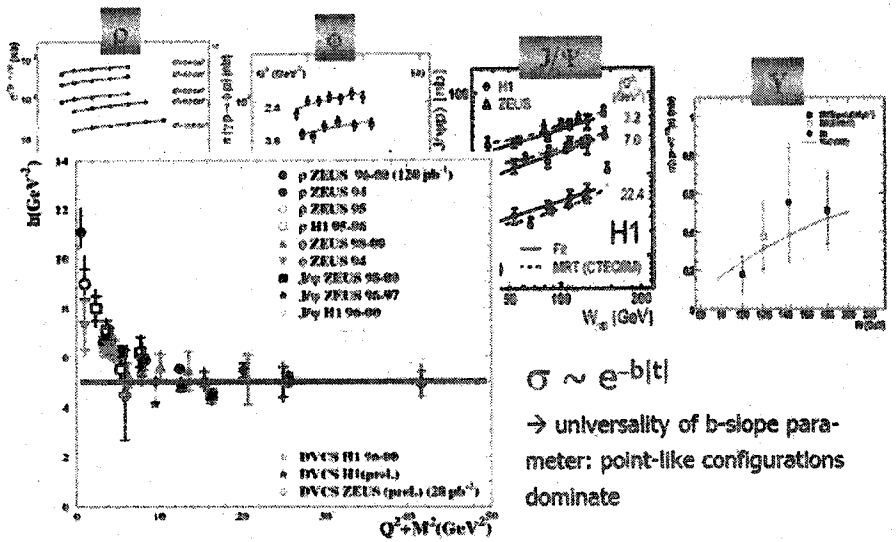
the ideal experiment for measuring hard exclusive processes

- high+variable beam energy
  - → hard regime
  - → wide kinematic range
- high luminosity
  - → small cross sections
  - → measure in 3 kinematic variables simultanously
- complete event reconstruction
  - → ensure exclusivity

... doesn't exist (yet)...

VM production @small x

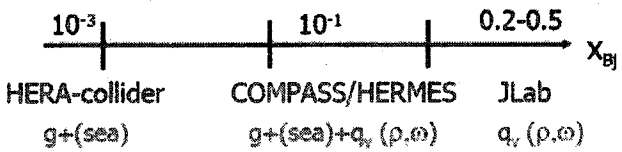
W & t **dependences**: probe transition from soft → hard regime



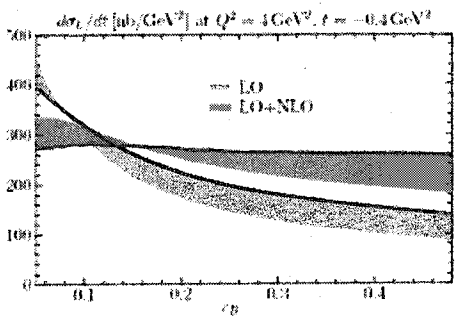
$\sigma \sim e^{-b|t|}$

→ universality of b-slope parameter: point-like configurations dominate

VM production: small → high x

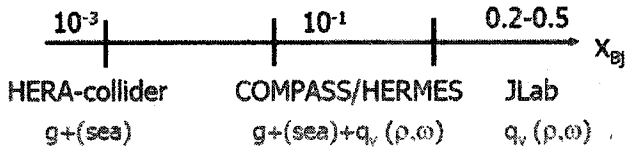


- NLO corrections to VM production are large: [M.Diehl, W.Kugler arXiv0708.1121]

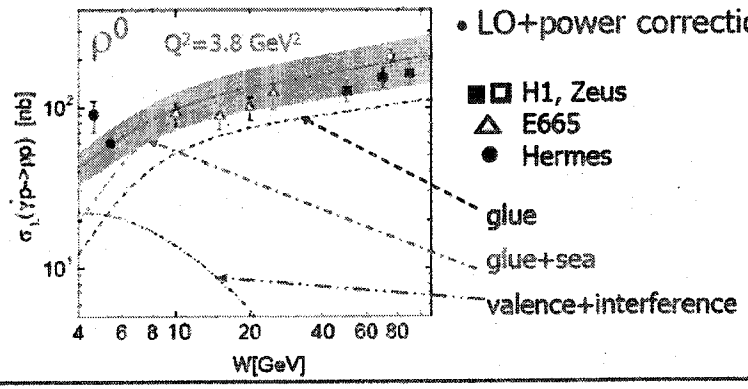


- ρ^0 cross section @typical kinematics of compass / hermes / jlab12

VM production: small → high x



- ...despite: LO GPD model (handbag fact.) [S.Goloskokov, P.Kroll arXiv0711.4736]



- LO+power corrections

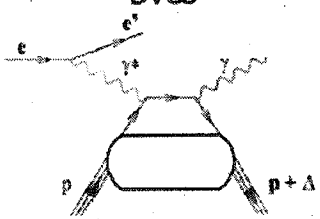
deeply virtual compton scattering

DVCS

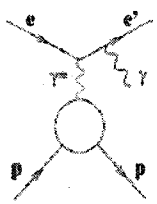
→ $H, \tilde{H}, E, \tilde{E}$

most clean channel for interpretation in terms of GPDs (full factorisation proof)

DVCS



Bethe-Heitler



@HERMES/JLab:

DVCS << Bethe-Heitler

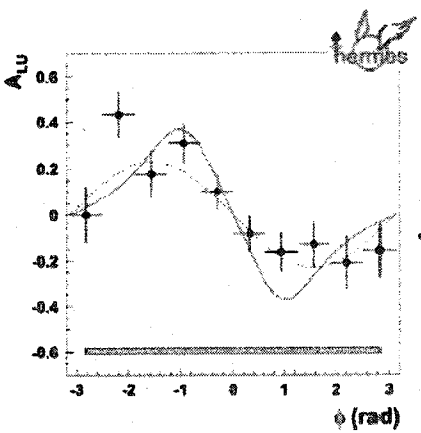
$$\frac{d^4\sigma}{dx_B\, dQ^2\, d|t|\, d\phi} \propto |T_{DVCS} + T_{BH}|^2 = |T_{DVCS}|^2 + |T_{BH}|^2 + \underbrace{T_{DVCS}T^*_{BH} + T^*_{DVCS}T_{BH}}$$

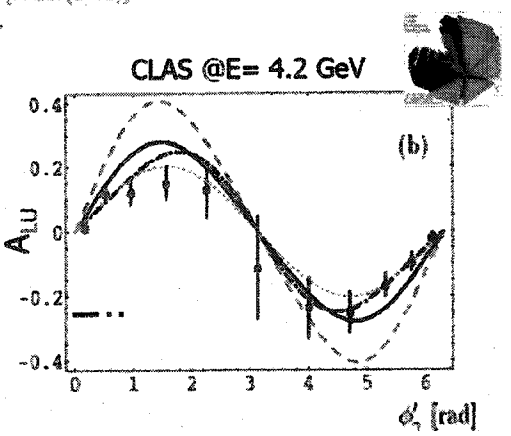
→ leads to non-zero azimuthal asymmetries:

first DVCS signals: A_{LU}

-- from interference term --

[PRL87(2001)]

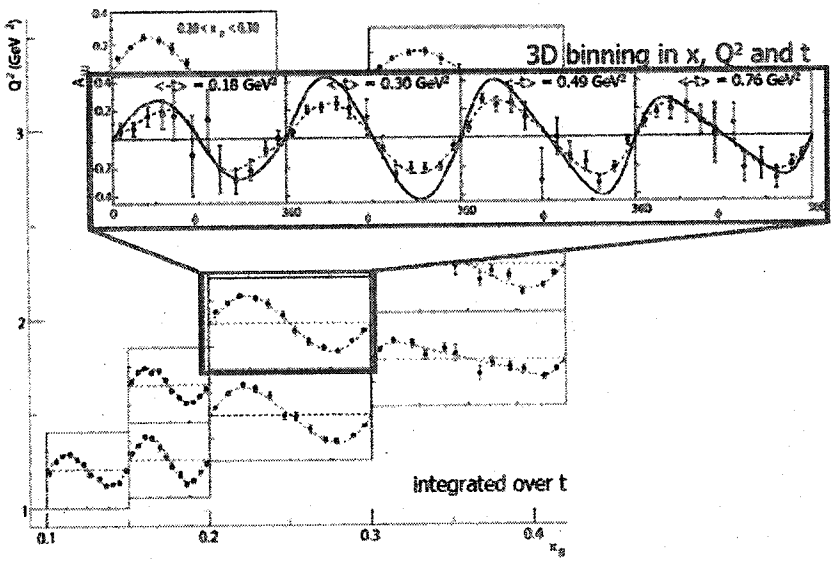




→ sinφ dependence indicates dominance of handbag contribution

call for high statistics

JLab: E1-DVCS beam-spin asymmetry



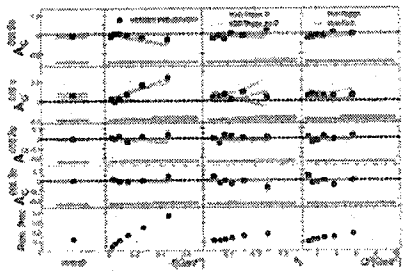
call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ **separation of interference term + DVCS²**

$$\sigma_{LU}(\phi; P_l, e_l) = \sigma_{UU}(\phi) \cdot \{1 + P_l A_{LU}^{DVCS}(\phi) + e_l P_l A_{LU}^{I}(\phi) + e_l A_C(\phi)\}$$

$\sum_{n=1}^{2} s_n^l sin(n\phi)$ $\sum_{n=0}^{3} c_n^l cos(n\phi)$

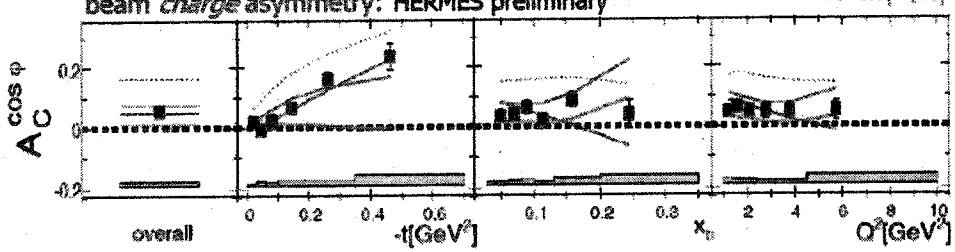


call for new analysis methods

HERMES: combined analysis of charge & polarisation dependent data

→ **separation of interference term + DVCS²**

beam *charge* asymmetry: HERMES preliminary $\propto Re[F_1 \mathcal{H}]$



GPD models: VGG ——— w/o D-term; - - - - with D-term — regge-ansatz for t-depend.

dual ——— regge-ansatz for t-dependence; ——— factorised t-dependence

[Guzey, Teckentrup 2006]

a word about GPD models

VGG: [Vanderhaegen, Guichon, Guidal 1999]

- double distributions ; fa → describes well A_C and A_U data
- D-term to restore full po → fails for A_{LU}
- skweness depending on → A_C favour 'no D-term' ← contradicts
- includes tw-3 (WW appro QCM & lattice results

dual: [Guzey, Teckentrup 2006]

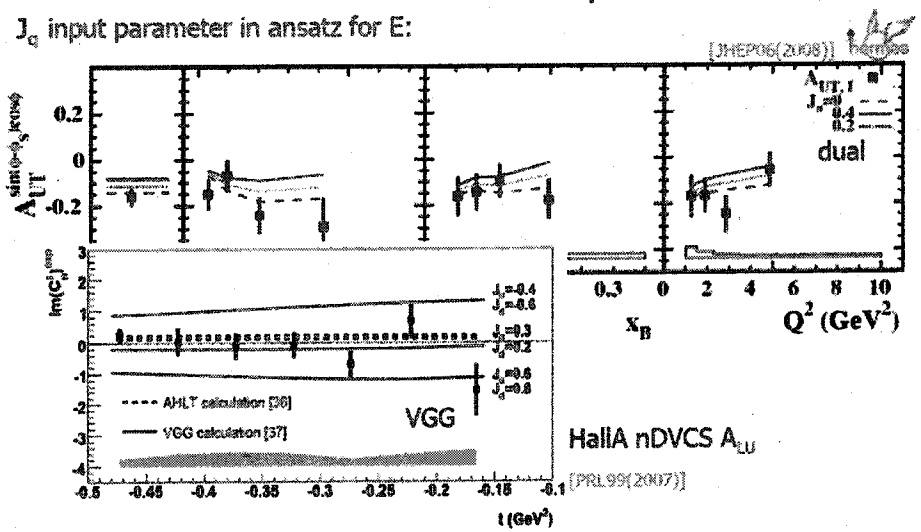
- GPDs based on infinite s → describes well spin-asymmetries
- factorised or regge-insp → fails for unpol. cross sections (HallA)
- tw-2 only

→ call for new, more sophisticated parametrisations of GPDs

... more models on the way: e.g. generalisation of Mellin transform technique

...nevertheless: first attempts to constrain J_q

J_q input parameter in ansatz for E:



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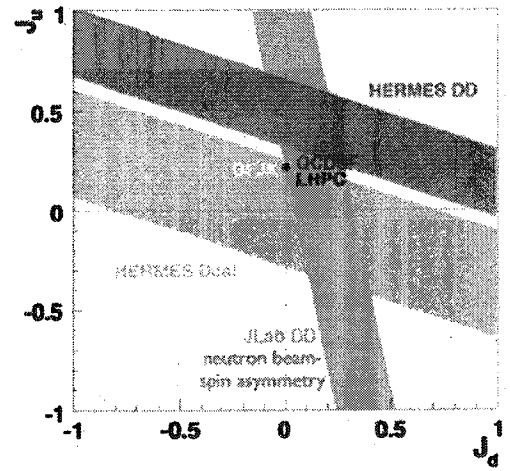


→ demonstrates model dependence of these analyses

→ data are free to be re-used at any time with new models ☺

conclusions

GPDs

contain a wealth of new information on hadron structure at parton level

→ only known framework allowing a 3D imaging of hadrons ←

... BUT they are intricate functions...

complementary to TMDs : relations GPDs ←→ TMDs [M. Burkardt, M. Schlegel]

GPDs offer a way to measure transversity! → see talk by G. Goldstein

- increasing amount and precision of experimental data
- large "flow" of new data expected soon (JLab, HERMES, COMPASS)
- 'standard' models/parametrisations of GPDs too simple
  - → models should describe large variety of different observables over wide kinematic range

prior to any conclusion about GPDs from data: call for new, more sophisticated parametrisations

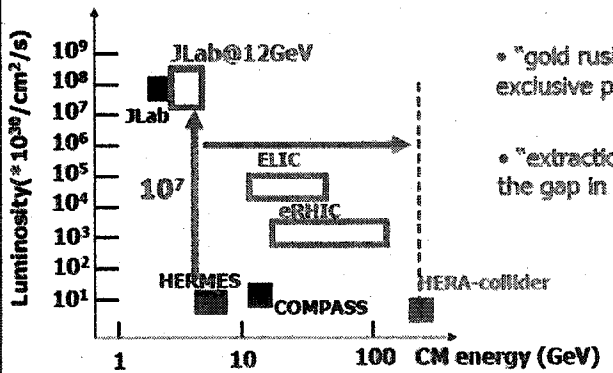
perspectives for GPDs & TMDs

@ new facilities:

- high beam energy (hard regime, wide kinematic range)
- very high luminosity (small xsections, multi-D analyses)
- complete event reconstruction (ensure exclusivity)

→ exploration of new channels: WACS, time like DVCS, ...

→ ideas for accessing GPDs @LHC, @GSI, ...



- "gold rush" for studying hard exclusive processes & GPDs
- "extraction" of GPDs requires filling the gap in kinematic coverage

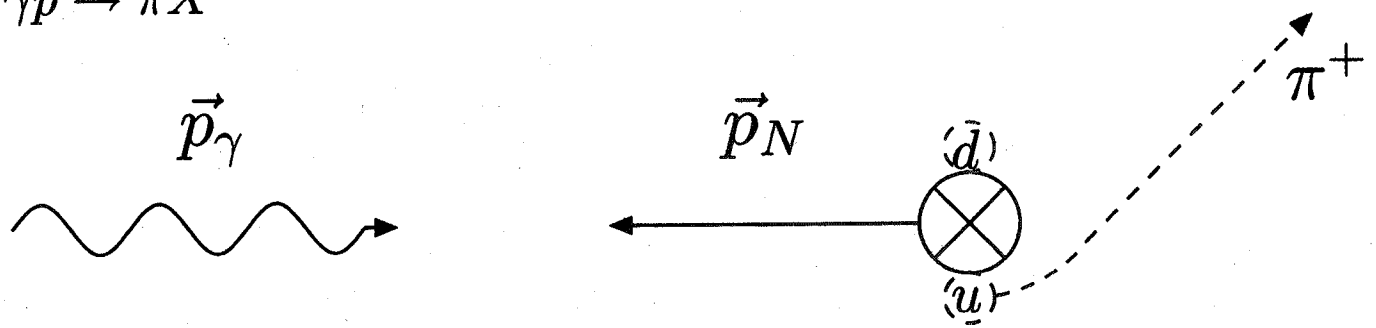
burkardt_abstract

`Parton Distributions in Impact Parameter Space'

Parton distributions in impact parameter space, which are obtained by Fourier transforming GPDs, are exhibit a significant deveiation from axial symmetry when the target and/or quark is transversely polarized. In combination with the final state interactions, this transverse deformation provides a natural mechanism for naive-T odd transverse single-spin asymmetries in semi-inclusive DIS. The deformation can also be related to the transverse force acting on the active quark in polarized DIS at higher twist.

GPD $\longleftrightarrow$ SSA (Sivers)

- example: $\gamma p \to \pi X$



- u, d distributions in $\perp$ polarized proton have left-right asymmetry in $\perp$ position space (T-even!); sign "determined" by κ_u & κ_d
- attractive FSI deflects active quark towards the center of momentum

$\hookrightarrow$ FSI translates position space distortion (before the quark is knocked out) in $+\hat{y}$-direction into momentum asymmetry that favors $-\hat{y}$ direction

$\hookrightarrow$ correlation between sign of κ_q^p and sign of SSA: $f_{1T}^{\perp q} \sim -\kappa_q^p$

- $f_{1T}^{\perp q} \sim -\kappa_q^p$ confirmed by HERMES results (also consistent with COMPASS $f_{1T}^{\perp u} + f_{1T}^{\perp d} \approx 0$)

Quark-Gluon Correlations

- (chirally even) higher-twist PDF $g_2(x) = g_T(x) - g_1(x)$

$$\int \frac{d\lambda}{2\pi} e^{i\lambda x} \langle PS|\bar{\psi}(0)\gamma^\mu\gamma_5\psi(\lambda n)|_{Q^2}|PS\rangle$$
$$= 2\left[g_1(x,Q^2)p^\mu(S\cdot n) + g_T(x,Q^2)S_\perp^\mu + M^2 g_3(x,Q^2)n^\mu(S\cdot n)\right],$$

- neglecting m_q: $g_2(x) = g_2^{WW}(x) + g_2^{int}(x)$, with $g_2^{WW}(x) = -g_1(x) + \int_x^1 \frac{dy}{y} g_1(y)$
- $g_2^{int}(x)$ involves quark-gluon correlations, e.g.

$$\int dx x^2 g_2^{int}(x) = \frac{1}{6} d_2 = \frac{g}{16M^2P^{+2}S^x} \left\langle P,S \left|\bar{q}(0)G^{+y}(0)\gamma^+ q(0)\right| P,S\right\rangle$$

- $\sqrt{2}G^{+y} = B^x - E^y$ and the matrix elements of $\bar{q}B^x\gamma^+q$ and $\bar{q}E^y\gamma^+q$ are sometimes called 'color-magnetic and electric polarizabilities' or 'spin-polarizabilities' — but these names are misleading

Quark-Gluon Correlations

- $g_2^{int}(x)$ involves quark-gluon correlations, e.g.

$$\int dx x^2 g_2^{int}(x) = \frac{1}{6} d_2 = \frac{g}{16 M^2 P^{+2} S^x} \langle P, S \left| \bar{q}(0) G^{+y}(0) \gamma^+ q(0) \right| P, S \rangle$$

- compare to average $k_\perp$ in SIDIS (Qiu, Sterman)

$$\langle k_\perp^y \rangle = -\frac{1}{2p^+} \left\langle P, S \left| \bar{q}(0) \int_0^\infty dx^- G^{+y}(x^-) \gamma^+ q(0) \right| P, S \right\rangle$$

semi-classical interpretation: average $k_\perp$ in SIDIS obtained by correlating the quark density with the transverse impulse acquired from (color) Lorentz force acting on struck quark along its trajectory to (light-cone) infinity

$\hookrightarrow$ d_2 a measure for the **average color Lorentz force** acting on the struck quark in SIDIS in the instant **right after being hit by the virtual photon**

$$\langle F^y(0) \rangle = -\frac{4}{3} M^2 d_2 \qquad \text{(rest frame; } S^x = 1\text{)}$$

Probing nucleon's internal structure with transversely polarized proton beams

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Single-transverse-spin asymmetries (SSAs) have received much attention in recent years, both experimentally and theoretically. Large SSAs have been consistently observed in various experiments at different collision energies. As a consequence of the parity and time-reversal invariance of the strong interaction, the SSA is directly connected to the transverse motion of partons inside a polarized hadron. Understanding the QCD dynamics behind the measured asymmetries should have the profound impact on our knowledge of strong interaction and hadron structure.

Within the QCD collinear factorization formalism for cross sections with a large momentum transfer, we attribute the SSA to the twist-3 transverse-spin dependent quark-gluon correlation functions. So far, most studies have been concentrated on the SSAs generated by the twist-3 quark-gluon correlation function,

$$T_F(x,x) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ixP^+y_1^-} \langle P, s_\perp | \bar{\psi}(0)\gamma^+ \left[\epsilon^{s_\perp \sigma n \bar{n}} F_\sigma{}^+(y_2^-)\right] \psi(y_1^-) | P, s_\perp \rangle \,, \tag{1}$$

with the gauge links suppressed. In this talk [1], we propose to use the SSA of D- or $\bar{D}$-meson production in the semi-inclusive lepton-hadron deep inelastic scattering (SIDIS) to study the twist-3 tri-gluon correlation function,

$$T_G(x,x) = \int \frac{dy_1^- dy_2^-}{2\pi} e^{ixP^+y_1^-} \frac{1}{xP^+} \langle P, s_\perp | F^+{}_\alpha(0) \left[\epsilon^{s_\perp \sigma n \bar{n}} F_\sigma{}^+(y_2^-)\right] F^{\alpha +}(y_1^-) | P, s_\perp \rangle \,. \tag{2}$$

Unlike the $T_F(x,x)$, there are two independent tri-gluon correlation functions, $T_G^{(f)}$ and $T_G^{(d)}$, because of the fact that the color of the three gluons can be neutralized by contracting either the antisymmetric if^{ABC} or the symmetric d^{ABC} tensor with color indices, A, B, and C.

The D- or $\bar{D}$-meson production at a large enough transverse momentum $P_{h\perp}$ in SIDIS is dominated by the photon-gluon fusion subprocess, and therefore, the SSA is directly proportional to the $T_G^{(f)}$ or $T_G^{(d)}$ and gets no contribution from the Collins effect. We calculate the SSA in D- and $\bar{D}$-meson production and find that the difference between the SSA of D- and $\bar{D}$-production can uniquely separate contributions from these two tri-gluon correlation functions. With a simple model for the tri-gluon correlation function, we estimate the asymmetry for both COMPASS and eRHIC kinematics, and find that extracting the tri-gluon correlation function in these experiments are promising.

References

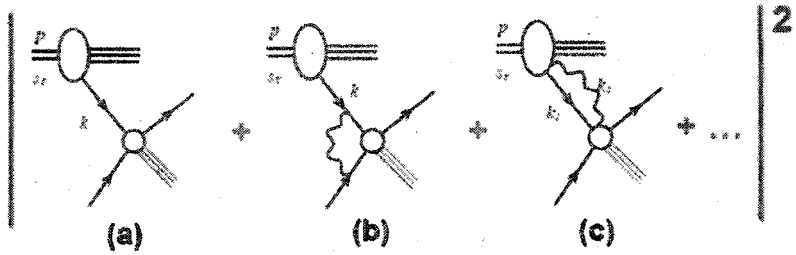
[1] Z. B. Kang and J. W. Qiu, Phys. Rev. D (in press), arXiv:0806.1970 [hep-ph].

SSA in collinear factorization

Efremov, Teryaev, 1982, Qiu, Sterman, 1991

- When all observed scales >> Λ_{QCD}, collinear factorization should work:

$\sigma(s_T) \sim$

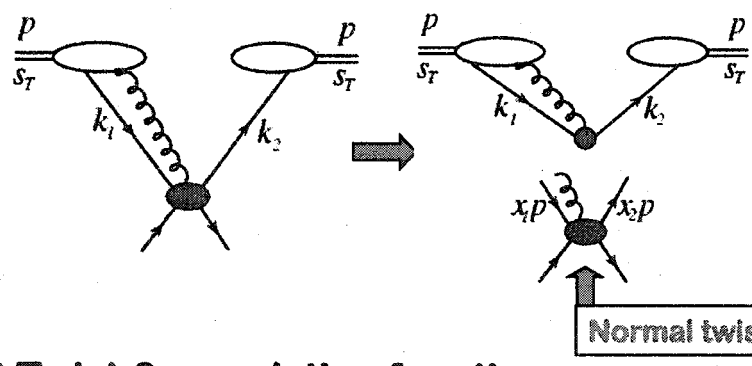


- **Leading spin dependent part of the cross section**
  - ➡ **Interference between amplitudes (a) and (b) or (c)**
- **The hadronic phase – the "i"**
  - ➡ Re[(a)] interferes with Im[(b)] or Im[(c)]
- Re[(a)] $\times$ Im[(b)] $\propto$ $m_Q\ \delta q(s_\perp)$

Twist-3 quark-gluon correlations

Qiu, Sterman, 1991, 1999

- **Factorization:**



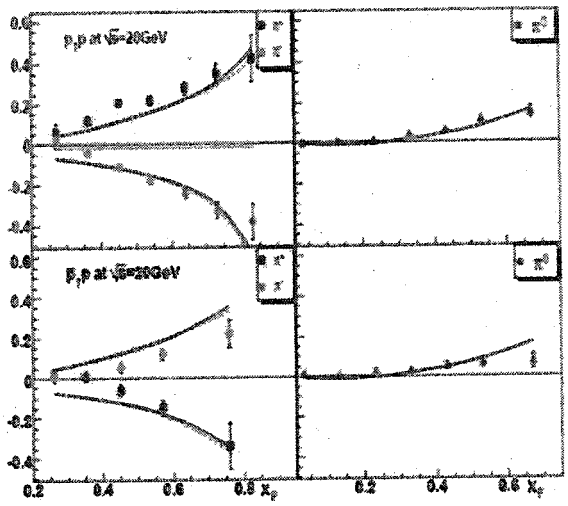
$$T_F(x_1,x_2) \propto \langle \bar{\psi}\gamma^+ F^{+\perp}\psi \rangle$$
$$T_D(x_1,x_2) \propto \langle \bar{\psi}\gamma^+ D_\perp \psi \rangle$$

- **Twist-3 correlation functions:**
  - Only $T_F(x_1,x_2)$ contributes to SSA due to P and T invariance
  - Two gluonic twist-3 correlation functions:

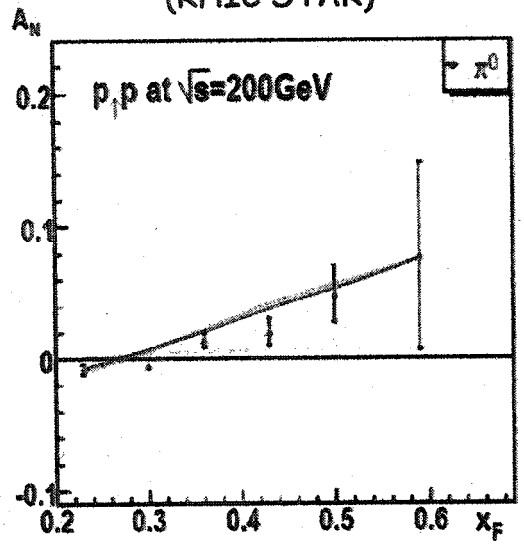
$T_G^{(f)}(x_1,x_2)$ and $T_G^{(d)}(x_1,x_2)$ **due two independent color contractions**

Asymmetries from the $T_F(x,x)$

(FermiLab E704)



(RHIC STAR)



Kouvaris, Qiu, Vogelsang, Yuan, 2006

$T_F(x_1, x_2)$ only in forward region

Nonvanish twist-3 function ⟹ Nonvanish transverse motion

Twist-3 gluon correlations

JI, PLB289 (1992)

- Diagonal tri-gluon correlations:

$$T_G(x,x) = \int \frac{dy_1^- dy_2^-}{2\pi} e^{ixP^+y_1^-} \times \frac{1}{xP^+} \langle P, s_\perp | F^+{}_\alpha(0) \left[\epsilon^{s_\perp \sigma n \bar{n}} F_\sigma{}^+(y_2^-)\right] F^{\alpha+}(y_1^-) | P, s_\perp \rangle$$

- Two tri-gluon correlation functions – color contraction:

$$T_G^{(f)}(x,x) \propto i f^{ABC} F^A F^C F^B = F^A F^C (\mathcal{T}^C)^{AB} F^B$$

$$T_G^{(d)}(x,x) \propto d^{ABC} F^A F^C F^B = F^A F^C (\mathcal{D}^C)^{AB} F^B$$

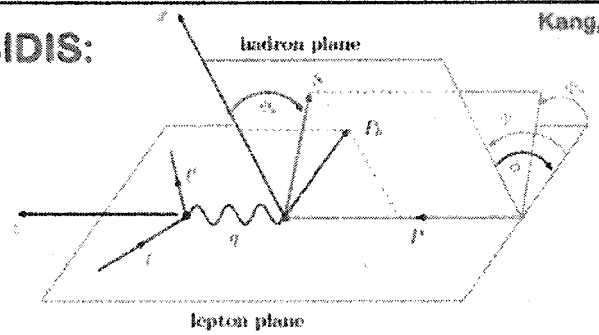
Fermionic correlation: $T_F(x,x) \propto \overline{\psi}_i F^C (T^C)_{ij} \psi_j$

- D-meson production in SIDIS:
  - Clean probe for gluonic twist-3 correlation functions
  - $T_G^{(f)}(x,x)$ could be connected to the gluonic Sivers function

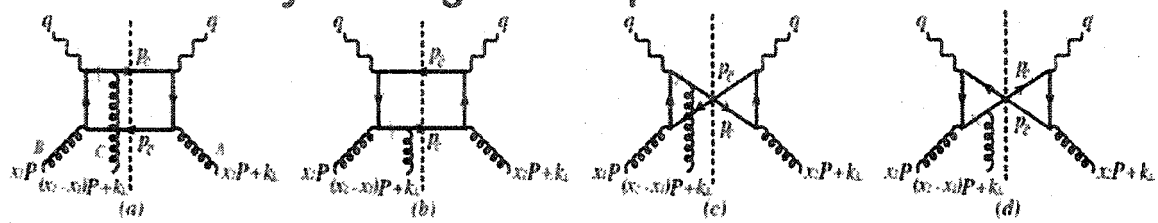
D-meson production in SIDIS

Kang, Qiu, 0806.1970 (hep-ph)

- Frame for SIDIS:



- Dominated by the tri-gluon subprocess:



- Single transverse-spin asymmetry:

$$A_N = \frac{\sigma(s_\perp) - \sigma(-s_\perp)}{\sigma(s_\perp) + \sigma(-s_\perp)} = \frac{d\Delta\sigma(s_\perp)}{dx_B dy dz_h dP_{h\perp}^2 d\phi} \Bigg/ \frac{d\sigma}{dx_B dy dz_h dP_{h\perp}^2 d\phi}$$

Spin-dependent cross section

- Contribution from $T_G^{(f)}$:

Color factor

$$\frac{d\Delta\sigma(s_\perp)}{dx_B dy dz_h dP_{h\perp}^2 d\phi} = \sigma_0 \int_{x_{min}}^1 dx \int \frac{dz}{z} D(z) \delta\left(\frac{P_{h\perp}^2}{z_h^2} - \frac{(1-\hat{x})(1-\hat{z})}{\hat{x}\hat{z}} Q^2 + \hat{z}^2 m_c^2\right)\left(\frac{1}{4}\right)$$
$$\times \left[\epsilon^{P_h s_\perp n\bar{n}}\left(\frac{\sqrt{4\pi\alpha_s}}{z\hat{t}}\right)\left(1+\frac{\hat{t}}{\hat{u}}\right)\right]\sum_{i=1}^4 \mathcal{A}_i\left[-x\frac{d}{dx}\left(\frac{T_G(x,x)}{x}\right)\hat{W}_i + \left(\frac{T_G(x,x)}{x}\right)\hat{N}_i\right]$$

- Partonic hard parts: $\hat{W}_i \neq \hat{N}_i$

$$\mathcal{A}_1 = 1 + \cosh^2\psi \quad \mathcal{A}_2 = -2 \quad \mathcal{A}_3 = -\cos\phi\sinh 2\psi \quad \mathcal{A}_4 = \cos 2\phi \sinh^2\psi$$

$$\cosh\psi = \frac{2x_B S_{ep}}{Q^2} - 1 = \frac{2}{y} - 1$$

$$\hat{W}_1 = 2\left[\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} - \frac{2\hat{s}Q^2}{\hat{t}\hat{u}} + \frac{4\hat{s}^2 m_c^2}{Q^2}\right] + 4m_c^2\left[\frac{Q^2-2\hat{t}}{\hat{t}^2} + \frac{Q^2-2\hat{u}}{\hat{u}^2} - \frac{2\hat{s}^2}{Q^2}\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} + 2\right)\right] - 8m_c^4\left[\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right]^2$$

$$\hat{W}_2 = \frac{16\hat{s}^2}{Q^2}\left[\hat{s} - m_c^2\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} + 2\right)\right].$$

$$\hat{W}_3 = 4\hat{s}\hat{z}\frac{8\hat{s}}{Q}(\hat{u}-\hat{t})\left[\frac{\hat{s}-Q^2}{\hat{t}\hat{u}} - 2m_c^2\left(\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right)^2\right]$$

$$\hat{W}_4 = 8\hat{s}^2\hat{z}_\perp^2\left[\frac{Q^2}{\hat{t}\hat{u}} + m_c^2\left(\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right)^2\right].$$

$$\hat{N}_1 = 4\left[\frac{2m_c^2 - Q^2}{\hat{t}\hat{u}} + \frac{6\hat{s}^2}{Q^2}\right]\left[(\hat{s} - Q^2) - 2m_c^2\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} + 2\right)\right].$$

$$\hat{N}_2 = \frac{16\hat{s}^2}{Q^2}\left[(\hat{s} - Q^2) - 2m_c^2\left(\frac{\hat{u}}{\hat{t}} + \frac{\hat{t}}{\hat{u}} + 2\right)\right].$$

$$\hat{N}_3 = \frac{2Q}{\hat{s}\hat{q}_\perp}(\hat{u}-\hat{t})\left[\left(\frac{4\hat{s}^2\hat{q}_\perp^2}{\hat{t}\hat{u}} - \frac{1}{Q^2+\hat{s}}\right)\left(2m_c^2\left(\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right) - \frac{Q^2-\hat{s}}{Q^2+\hat{s}}\right) - 2\hat{s}\hat{q}_\perp^2\right]$$

$$\hat{N}_4 = 8\left[2\hat{s}\hat{q}_\perp^2 - \frac{\hat{t}\hat{u}}{Q^2+\hat{s}}\right]\left[\frac{Q^2}{\hat{t}\hat{u}} + m_c^2\left(\frac{1}{\hat{t}} + \frac{1}{\hat{u}}\right)^2\right].$$

- Contribution from $T_G^{(d)}$ is the same except the color factor

Estimation of the SSA

- Dependence on tri-gluon correlation functions:

$$D-\text{meson} \propto T_G^{(f)} + T_G^{(d)} \qquad \overline{D}-\text{meson} \propto T_G^{(f)} - T_G^{(d)}$$

Separate $T_G^{(f)}$ and $T_G^{(d)}$ by the difference between D and $\bar{D}$

- Model for tri-gluon correlation functions:

$$T_G^{(f,d)}(x,x) = \lambda_{f,d} G(x) \qquad \lambda_{f,d} = \pm\lambda_F = \pm 0.07\text{GeV}$$

- Kinematic constraints:

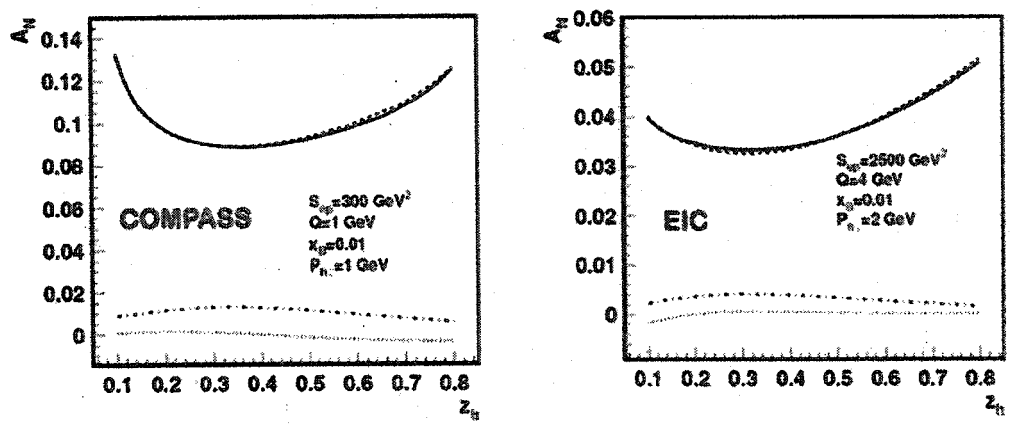
$$x_{min} = \begin{cases} x_B\left[1 + \frac{P_{h\perp}^2 + m_c^2}{z_h(1-z_h)Q^2}\right], & \text{if } z_h + \sqrt{z_h^2 + \frac{P_{h\perp}^2}{m_c^2}} \geq 1 \\ x_B\left[1 + \frac{2m_c^2}{Q^2}\left(1 + \sqrt{1 + \frac{P_{h\perp}^2}{z_h^2 m_c^2}}\right)\right], & \text{if } z_h + \sqrt{z_h^2 + \frac{P_{h\perp}^2}{m_c^2}} \leq 1 \end{cases}$$

Note: The $z_h(1-z_h)$ has a maximum

SSA should have a minimum if the derivative term dominates

Minimum in the SSA of D-meson production

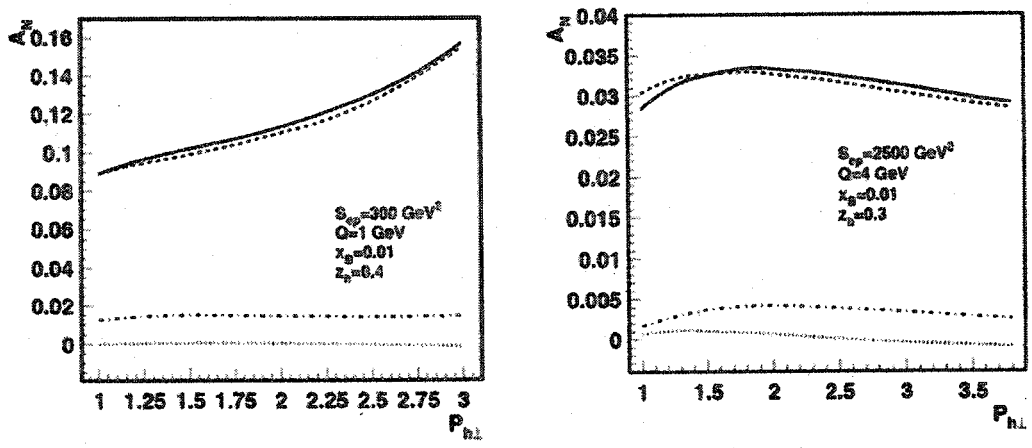
- SSA for D^0 production (λ_f only):



- **Derivative term dominates, and small φ dependence**
- **Asymmetry is twice if $T_G^{(f)} = +T_G^{(d)}$, or zero if $T_G^{(f)} = -T_G^{(d)}$**
- **Opposite for the $\bar{D}$ meson**
- **Asymmetry has a minimum ~ z_h ~ 0.5**

Maximum in the SSA of D-meson production

- SSA for D^0 production (λ_f only):



- **The SSA is a twist-3 effect, it should fall off as $1/P_T$ when $P_T >> m_c$**
- **For the region, $P_T \sim m_c$,**

$$A_N \propto \epsilon^{P_h s_\perp n\bar{n}} \frac{1}{\tilde{t}} = -\sin\phi_s \frac{P_{h\perp}}{\tilde{t}}$$

$$\tilde{t} = (p_c - q)^2 - m_c^2 = -\frac{1-\hat{z}}{\hat{x}} Q^2$$

$$\hat{z} = z_h/z, \quad \hat{x} = x_B/x$$

Summary

- After more than 20 years of effort, the universality of PDFs has been well-tested

  But, there are still large uncertainties, in particular, in large x region

- Single transverse-spin asymmetry is directly connected to the parton's transverse motion (P and T invariance)
  - an excellent probe for the parton's transverse motion

  Two complementary approaches: TMD and Collinear factorization

  TMD: direct P_T information
  Collinear: net spin-dependence of all P_T

- D-meson production in SIDIS, as well as in hadron-hadron production (Kang, Qiu, Yuan, Vogelsang), is an excellent observable to measure tri-gluon correlation functions

  ⟹ QCD global analysis of twist-3 distributions: $T_F, T_G^{(f)}, T_G^{(d)}$

Spin physics with the EIC: Ideas and Aspirations

Abhay Deshpande
Stony Brook University & RBRC

PKU-RBRC Workshop
Transverse Spin Physics @ Peking University
July 2008

Fundamental Questions in QCD

- How do gluons contribute to the structure of the nucleon?
- What role do the gluons play in determining the spin structure of the nucleon?
- What is the spatial distribution of the gluons and sea quarks in the nucleon?
- How do the gluons contribute to the structure of the nuclei?
- What are the properties of *high density* gluon matter?
- How do fast quarks and gluons interact when they traverse through nuclear matter?

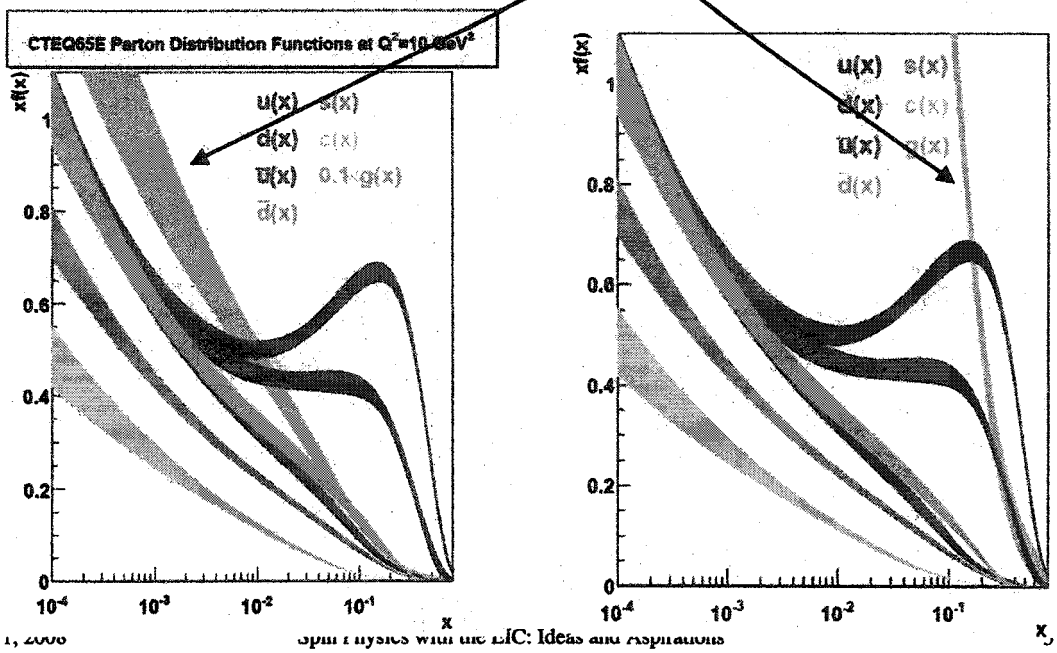
How do we get to the answers?

Precise imaging of the sea-quarks and gluons in the nucleon

Need to explore a new QCD frontier: of strong color fields in nuclei

Where is the glue?

LOW x!



Status of the Nucleon Spin puzzle

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + L_q + \Delta G + L_g$$

??

DIS fixed target Experiments

~0.24

DIS & RHIC Spin Transverse Spin GPDs, TMDs

~??

Not 0?

RHIC Spin DIS experiments

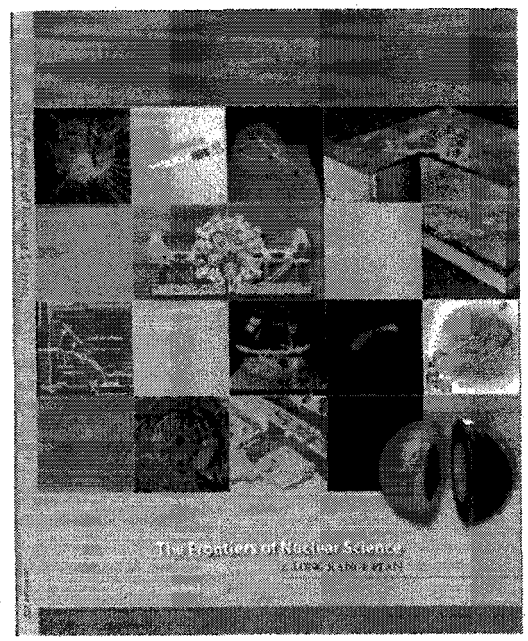
~0.04± (unknown)

0.02<x<0.3

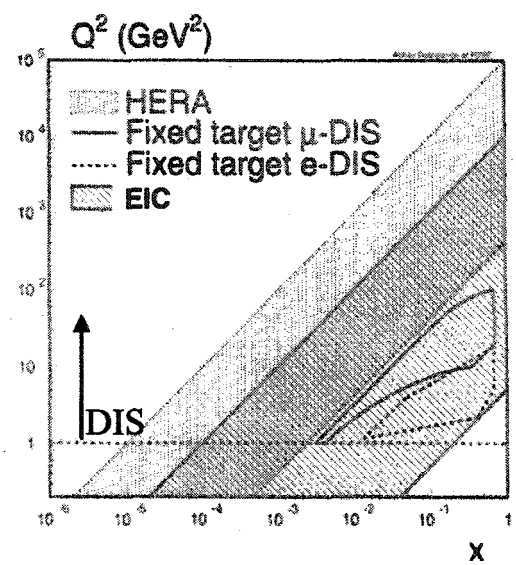
NSAC 2007 Long Range Plan

"An **Electron-Ion Collider (EIC)** with polarized beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia. In support of this new direction:

We recommend the allocation of resources to develop accelerator and detector technology necessary to lay the foundation for a polarized Electron Ion Collider. The EIC would explore the new QCD frontier of strong color fields in nuclei and precisely image the gluons in the proton."



EIC/eRHIC vs. Other DIS Facilities



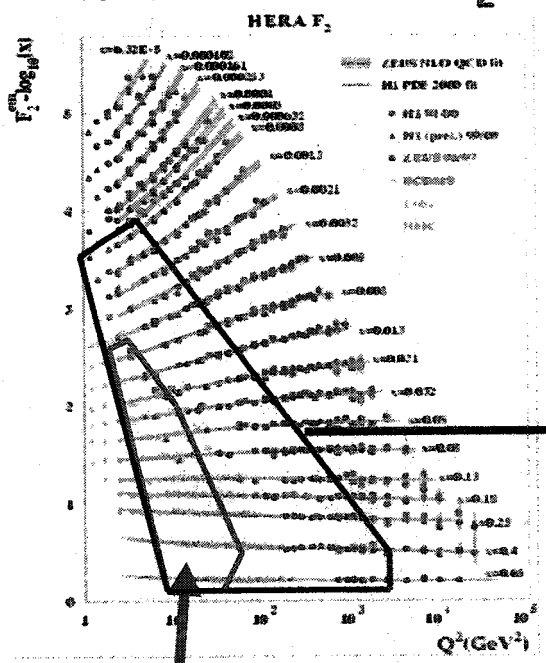
- **New kinematic region**
- E_e = 10 GeV (~5-20 GeV variable)
- E_p = 250 GeV (~50-250 GeV)
- E_A= 100 GeV
- Sqrt[S_{ep}] = 30-100 GeV
- Kinematic reach of EIC:
  - $X = 10^{-4} \rightarrow 0.7$ ($Q^2 > 1$ GeV^2)
  - $Q^2 = 0 \rightarrow 10^4$ GeV^2
- Polarization of e,p and light ion beams at least ~ 70% or better
- Heavy ions of ALL species
- Machine Luminosities envisioned
  - L(ep) ~$10^{33\text{-}34}$ cm^{-2} sec^{-1}
- Integrated Luminosity goal:
  - 50 fb^{-1} in 10 years
  - possible with 10^{33} cm^{-2} sec^{-1}

A Detector for EIC
A 4π Detector

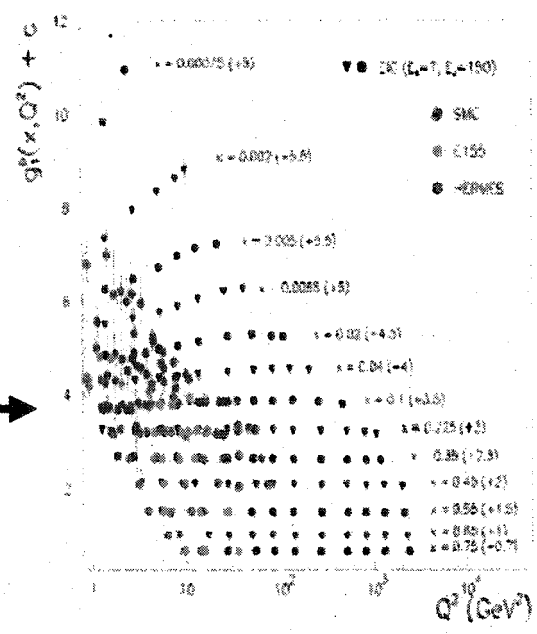
- Scattered electrons to measure kinematics of DIS
- Scattered electrons at small (~zero degrees) to tag photo production
- Central hadronic final state for kinematics, jet measurements, quark flavor tagging, fragmentation studies, particle ID
- Central hard photon and particle/vector detection (DVCS)
- ~Zero angle photon measurement to control radiative corrections and in e-A physics to tag nuclear de-excitations
- Missing E_T for neutrino final states (W decays)
- Forward tagging for 1) nuclear fragments, 2) diffractive physics
- ***Lot of experience from HERA... use it!***
  - What was good about HERA detectors?
  - What was bad? How/What can we improve?
- **Recent new ideas from BaBar/Belle & LHC detectors**

Detector integration with the beam lines and interaction region of paramount importance!

World Data on F_2^p



EIC Data on g_1^p

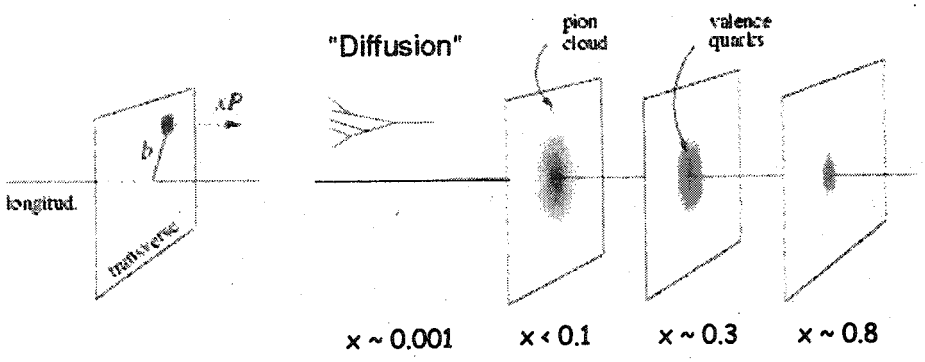


Region of existing g_1^p data

An [illegible] makes it possible!

GPDs and Transverse Gluon Imaging

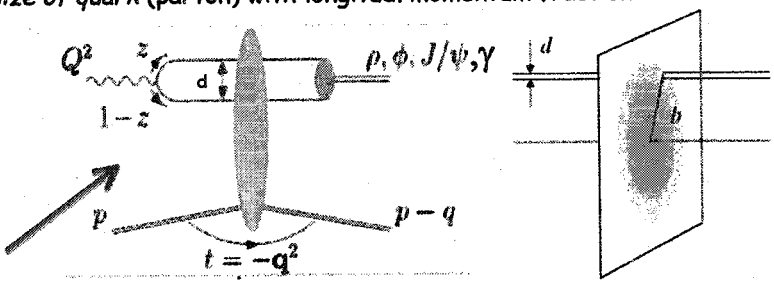
Fourier transform in momentum transfer



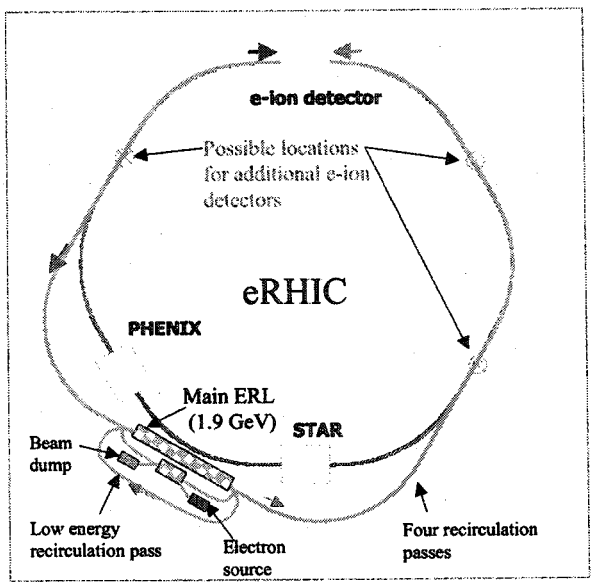
gives *transverse size of quark* (parton) with longitud. momentum fraction x

EIC:

1) x < 0.1: gluons!
2) ξ ~ 0 → the "take out" and "put back" gluons act coherently.

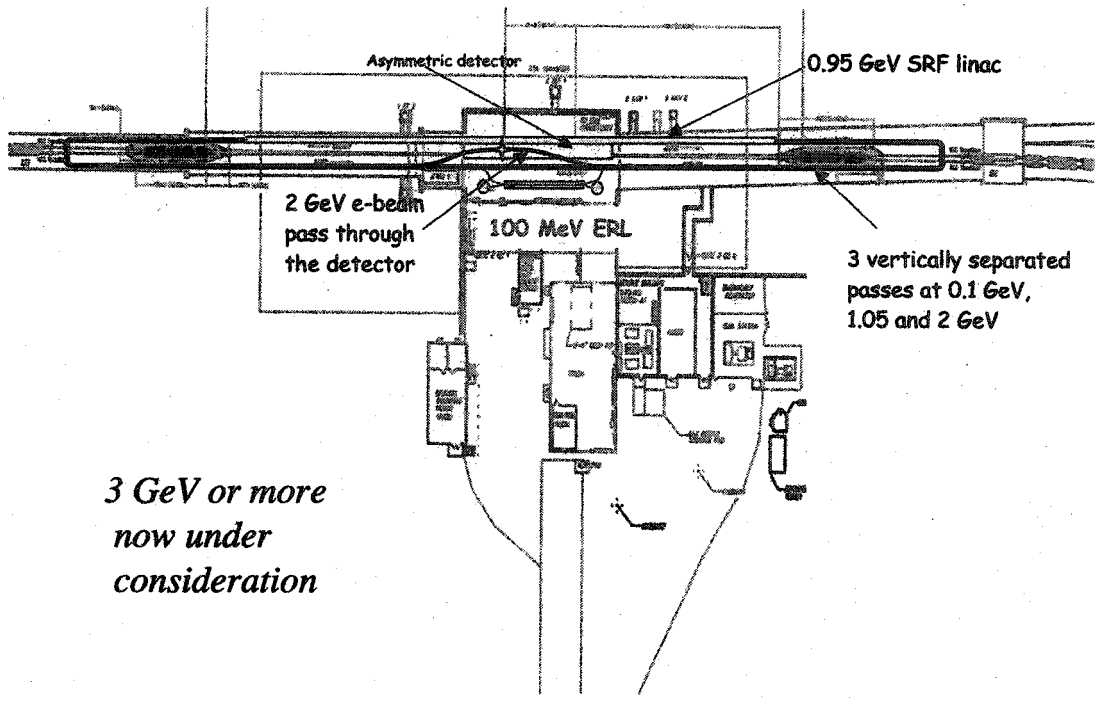


ERL-based eRHIC Design

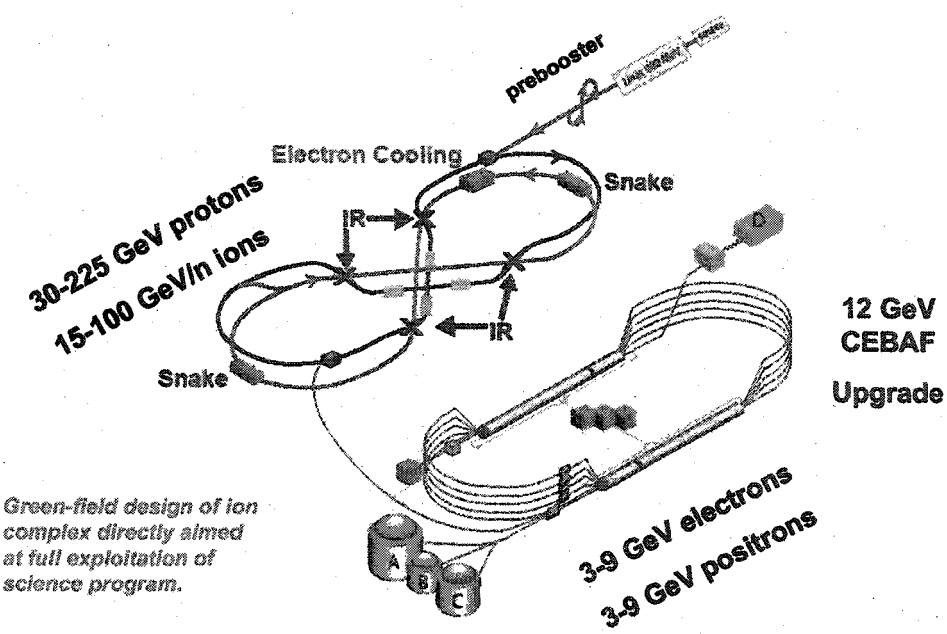


- 10 GeV electron design energy. Possible upgrade to 20 GeV by doubling main linac length.
- 5 recirculation passes (4 of them in the RHIC tunnel)
- Multiple electron-hadron interaction points (IPs) and detectors;
- Full polarization transparency at all energies for the electron beam;
- Ability to take full advantage of transverse cooling of the hadron beams;
- Possible options to include polarized positrons: compact storage ring

MEIC with 2 GeV ERL @ IP2



ELIC Conceptual Design



Green-field design of ion complex directly aimed at full exploitation of science program.

ERL-based eRHIC Parameters: e-p

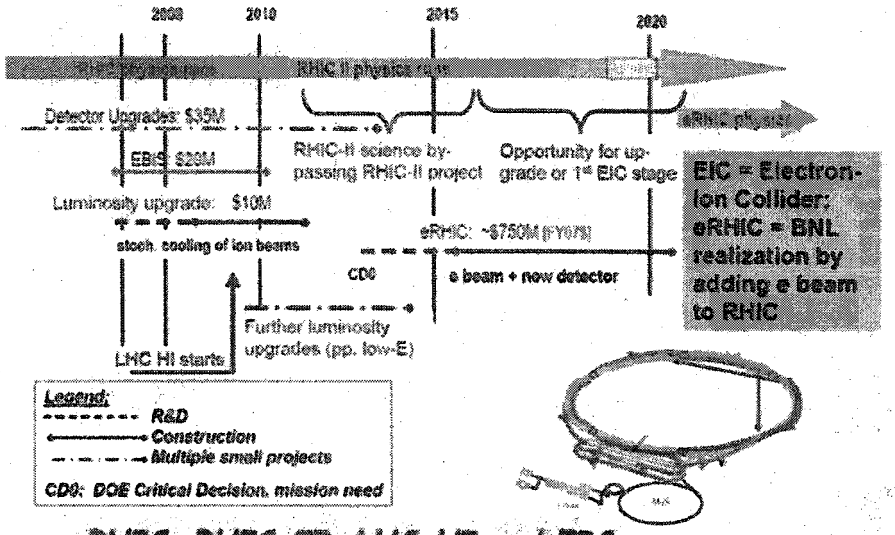
	High energy setup		Low energy setup	
	p	e	p	e
Energy, GeV	250	10	50	3
Number of bunches	166		166	
Bunch spacing, ns	71	71	71	71
Bunch intensity, 10^{11}	2	1.2	2	1.2
Beam current, mA	420	260	420	260
Normalized 95% emittance, π mm.mrad	6	460	6	570
Rms emittance, nm	3.8	4	19	16.5
β^*, x/y, cm	26	25	26	30
Beam-beam parameters, x/y	0.015	0.59	0.015	0.47
Rms bunch length, cm	20	1	20	1
Polarization, %	70	80	70	80
Peak Luminosity, 1.e33 $cm^{-2}s^{-1}$	2.6		0.53	
Aver.Luminosity, 1.e33 $cm^{-2}s^{-1}$	0.87		0.18	
Luminosity integral /week, pb^{-1}	530		105	

ELIC (e/p) Design Parameters

Parameter	Unit	Ring-Ring			
Beam energy	**GeV**	**225/9**	**150/7**	**100/5**	**30/3**
e/A ring circumference	**km**	**1.5**			
Bunch collision frequency	**GHz**	**1.5**			
Number of particles/bunch	**10^{10}**	**0.42/.77**	**0.4/1**	**0.4/1.1**	**0.12/1.7**
Beam current	**A**	**1/1.85**	**1/2.4**	**1/2.7**	**0.3/4.1**
Energy spread, rms	**10^{-4}**	**3/3**			
Bunch length, rms	**mm**	**5/5**			
Beta*	**mm**	**5/5**			
Horizontal emittance, norm	**?m**	**1.25/90**	**1/90**	**.7/70**	**.2/43**
Vertical emittance, norm	**?m**	**.05/3.6**	**.04/3.6**	**.06/6**	**.2/43**
Beam-beam tune shift (vertical) per IP		**.006/.086**	**.01/.086**	**.01/.078**	**.009/.008**
Peak luminosity per IP, 10^{34} (*including hour glass effect*)	**$cm^{-2}s^{-1}$**	**5.7**	**6.0**	**5.0**	**.7**
Number of IPs		**4**			
Core & lumi. IBS lifetime	**hrs**	**24**			

S. Vigdor, BNL Associate Laboratory Director, NP/HE
RHIC-AGS User's Meeting June, 2008

A Long Term (Evolving) Strategic View for RHIC



RHIC, RHIC-II, LHC-HI and EIC science share a common theme...

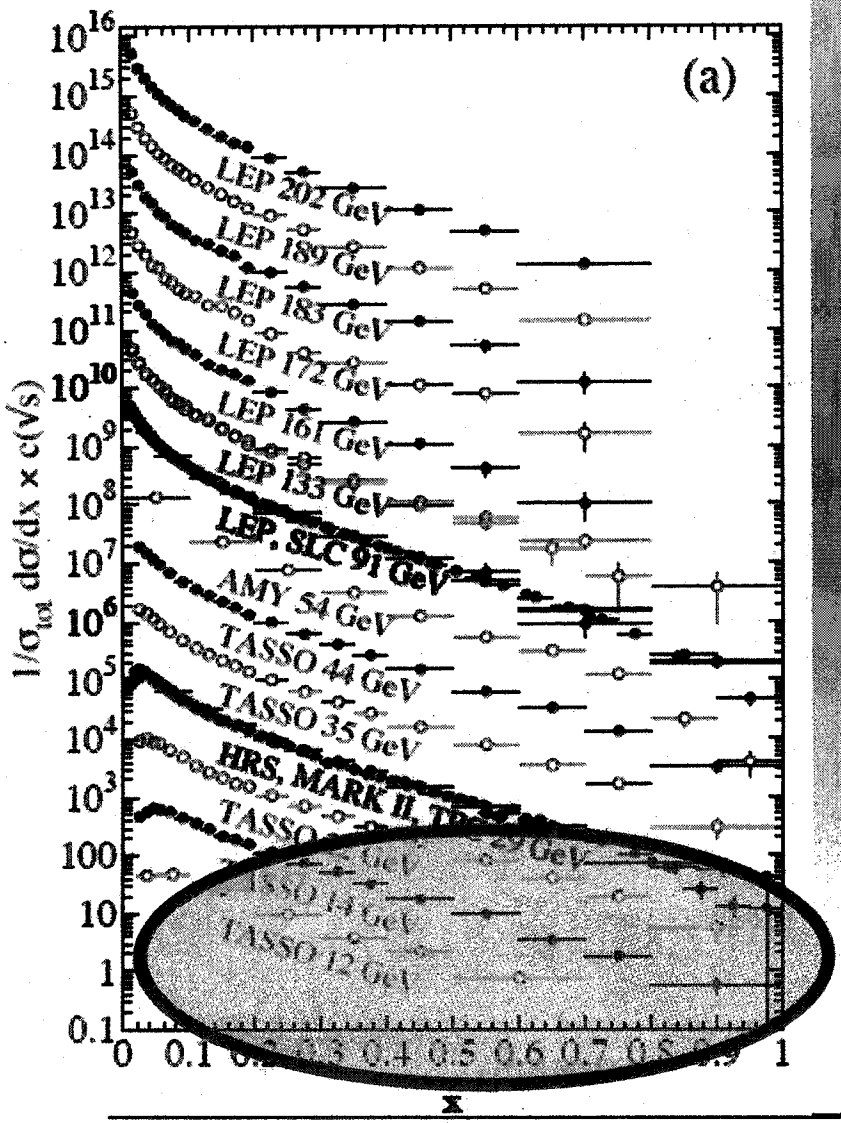
Light quark and spin dependent fragmentation function measurements at Belle

Transverse spin workshop,
PKU, China July 1st, 2008

M. Grosse Perdekamp
(University of Illinois)
M. Leitgab (University of Illinois)
A. Ogawa (BNL/RBRC)
R. Seidl (RBRC)

representing the Belle collaboration

World data and motivation for precise unpolarized FFs



- Most data obtained at LEP energies,
- At lower CMS energies very little data available
- 3-jet fragmentation to access gluon FF theoretically difficult

➔ Gluon fragmentation from evolution not yet well constrained

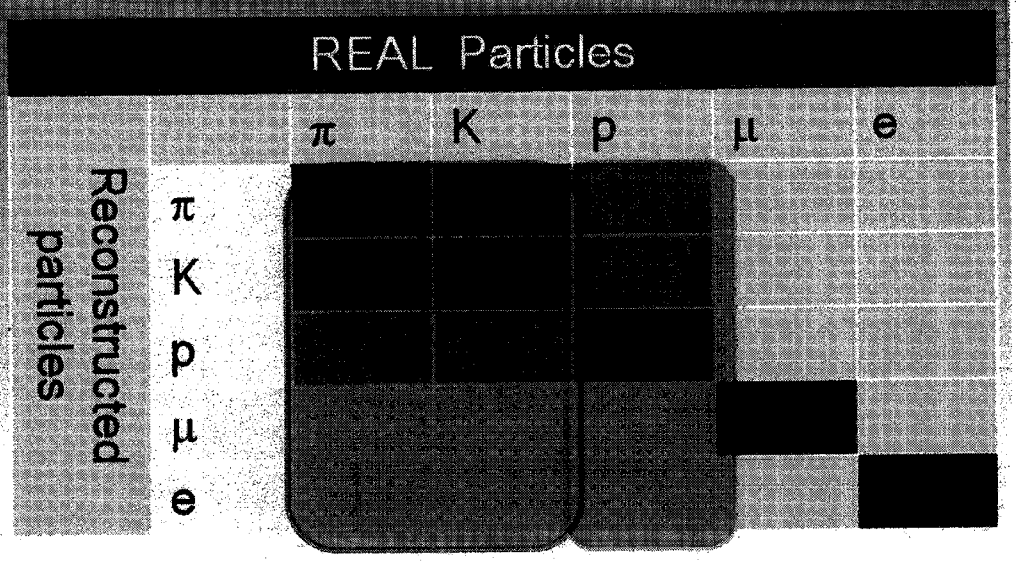
➔ Higher z FFs (>0.7) hardly available

Systematic studies: Particle identification

- Particle identification: create PID efficiency matrix for K,π,p,e,μ
- PID responses from MC not reliable, use well identified decays from data:
  - Use $D^* \rightarrow \pi_{slow}\, D^0 \rightarrow \pi_{slow}\pi_{fast} K$ for K,π identification
  - Use $\Lambda \rightarrow \pi p$ for p,π identification

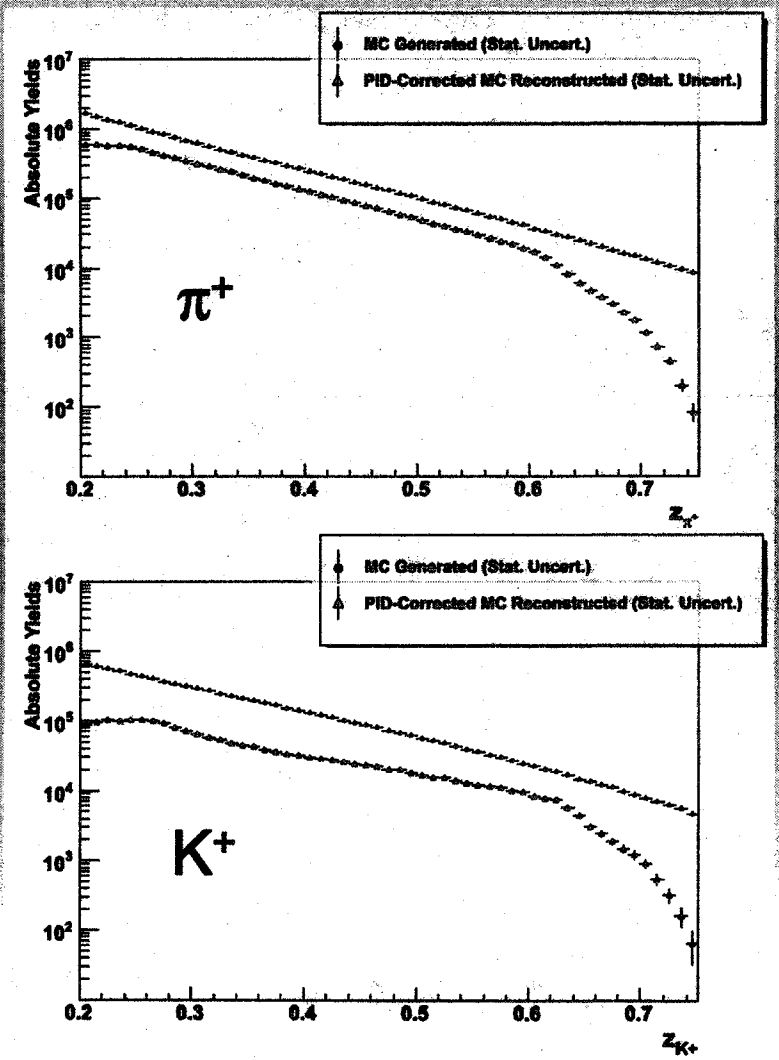
→ Unfolding

$$\begin{pmatrix} N_e^{likelihood-cut} \\ N_\mu^{likelihood-cut} \\ N_\pi^{likelihood-cut} \\ N_K^{likelihood-cut} \\ N_P^{likelihood-cut} \end{pmatrix} = \begin{pmatrix} \epsilon_{e\to e} & \epsilon_{e\to\mu} & \epsilon_{e\to\pi} & \epsilon_{e\to K} & \epsilon_{e\to P} \\ \epsilon_{\mu\to e} & \epsilon_{\mu\to\mu} & \epsilon_{\mu\to\pi} & \epsilon_{\mu\to K} & \epsilon_{\mu\to P} \\ \epsilon_{\pi\to e} & \epsilon_{\pi\to\mu} & \epsilon_{\pi\to\pi} & \epsilon_{\pi\to K} & \epsilon_{\pi\to P} \\ \epsilon_{K\to e} & \epsilon_{K\to\mu} & \epsilon_{K\to\pi} & \epsilon_{K\to K} & \epsilon_{K\to P} \\ \epsilon_{P\to e} & \epsilon_{P\to\mu} & \epsilon_{P\to\pi} & \epsilon_{P\to K} & \epsilon_{P\to P} \end{pmatrix} \begin{pmatrix} N_e^{real} \\ N_\mu^{real} \\ N_\pi^{real} \\ N_K^{real} \\ N_P^{real} \end{pmatrix}$$



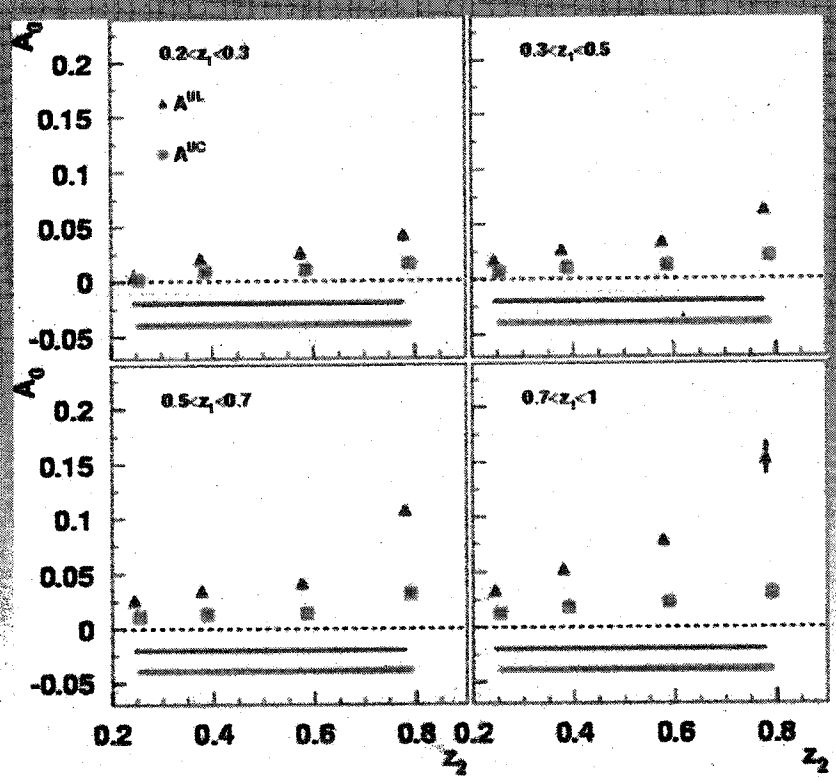
Acceptance correction, status

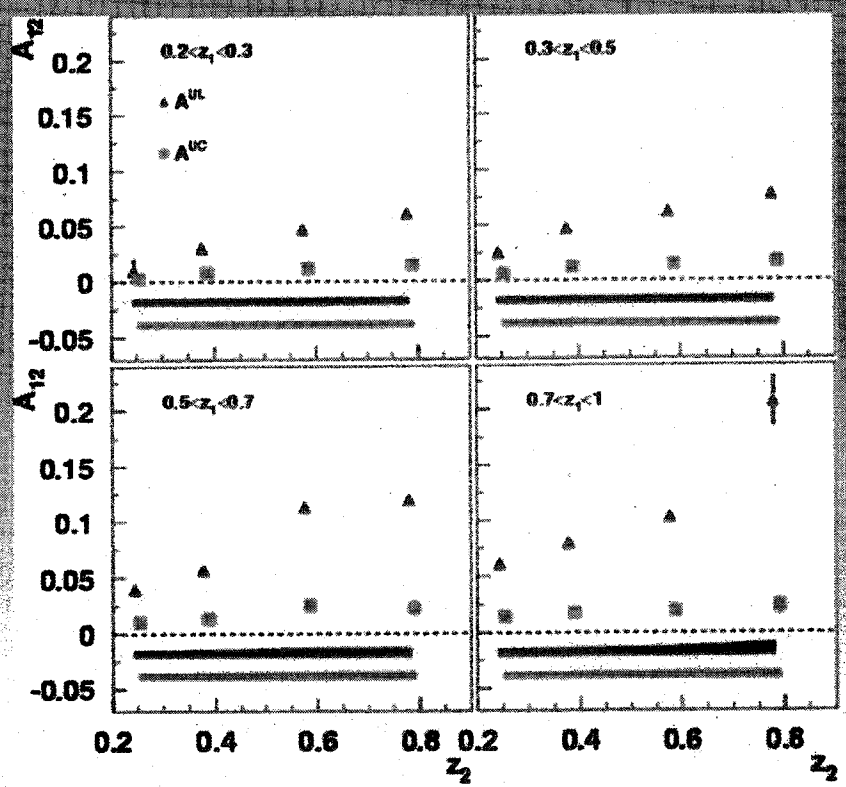
- Correction from MC for missing acceptance in forward/backward regions and empty PID matrix elements in (q_{Lab}, P_{Lab})
- Status:
  - π and K FFs in intermediate z-region close to being able to be released
  - P and higher z (>0.75) data need more studies (PID efficiency matrix)



Final Collins FF results

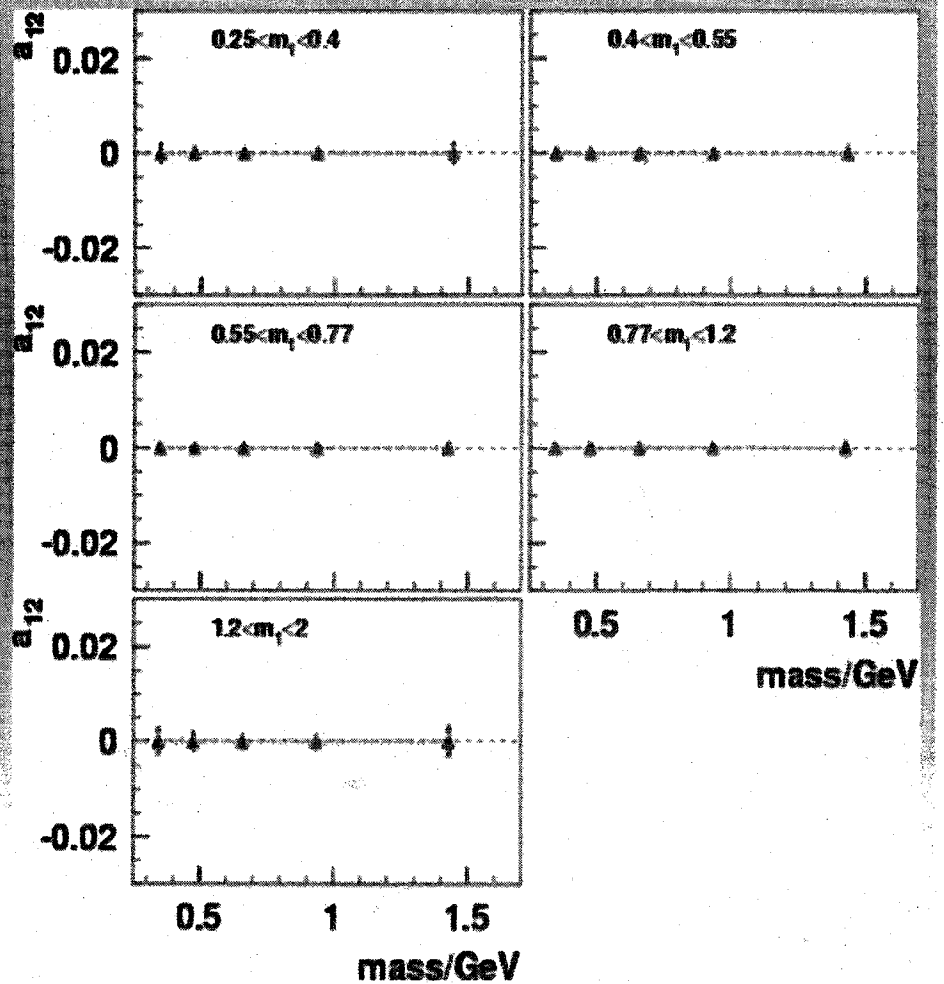
Belle 547 fb^{-1} data set (Phys.Rev.D78:032011,2008, arXiv:0805.2975)





Expected sensitivities for interference FFs for 60 fb^{-1}

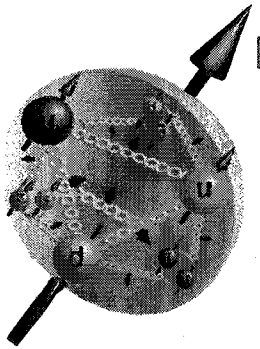
- $(\pi^+\pi^-)$ $(\pi^+\pi^-)$ pairs as a function of the invariant mass $m_{\pi\pi,1} \times m_{\pi\pi,2}$
- Similar distributions to be shown as a function of $z_{\pi\pi,1} \times z_{\pi\pi,2}$
- Other hadron combinations



Summary and outlook

- Measure precise unpolarized fragmentation functions of many final states
  → Important input for general QCD physics and helicity structure measurements
- Analysis approaches:
  - PDG studies
  - Acceptance correction
- Belle Collins data largely improved from 29 fb^{-1} → 547 fb^{-1}
- Significant, nonzero asymmetries → Collins function is large
- Long Collins paper submitted
- Data used already in Global analysis

- Continue to measure precise spin dependent fragmentation functions at Belle
  - kT dependence of Collins function
  - Artru model test with Vector meson Collins
  - Interference Fragmentation function measurements (started)
- Measure other interesting QCD-related quantities at Belle:
  - Chiral-odd Λ-fragmentation function
  - Λ single spin asymmetry
  - Event shapes
  - R-ratio with ISR



Novel extraction of Sivers, Collins and transversity distributions

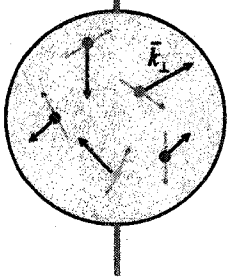
Mauro Anselmino, Torino University and INFN,
Beijing, July 1, 2008

PKU-RBRC Workshop on Transverse Spin Physics

M.A., M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin, S. Melis, C. Türk

The nucleon transverse structure: more interesting and less studied

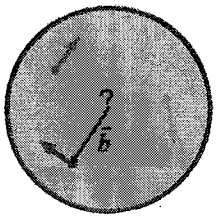
spin-$k_\perp$ correlations?



Transverse Momentum Dependent distribution functions

$$q(x,\boldsymbol{k}_\perp;Q^2)$$

orbiting quarks?

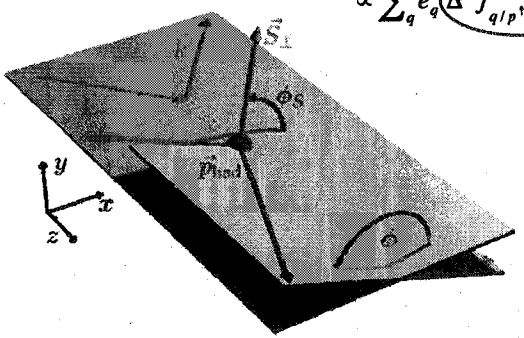


Space dependent distribution functions

$$q(x,\boldsymbol{b};Q^2)$$

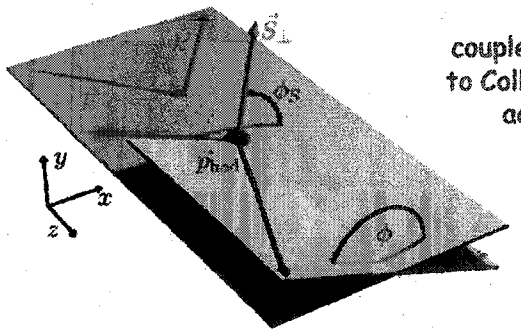
approach to Sivers function, SSA

$$2\langle\sin(\Phi-\Phi_S)\rangle = A_{UT}^{\sin(\Phi-\Phi_S)}$$
$$= 2\frac{\int d\Phi\, d\Phi_S (d\sigma^\uparrow - d\sigma^\downarrow)\sin(\Phi-\Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^\uparrow + d\sigma^\downarrow)}$$
$$\propto \sum_q e_q^2 \Delta^N f_{q/p^\uparrow}(x,k_\perp) \otimes D_{\pi/q}(z,p_\perp)$$



approach to Collins function ⊗ transversity

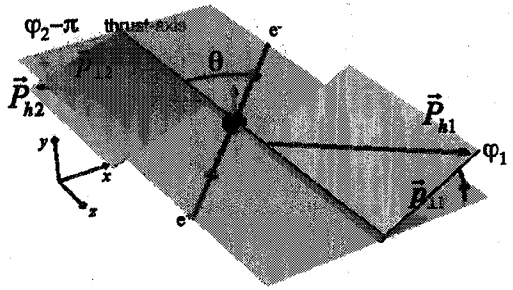
$$2\langle\sin(\Phi+\Phi_S)\rangle = A_{UT}^{\sin(\Phi+\Phi_S)}$$
$$= 2\frac{\int d\Phi\, d\Phi_S (d\sigma^\uparrow - d\sigma^\downarrow)\sin(\Phi+\Phi_S)}{\int d\Phi\, d\Phi_S (d\sigma^\uparrow + d\sigma^\downarrow)}$$
$$\propto \sum_q e_q^2 h_{1q}(x,k_\perp) \otimes \Delta^N D_{h/q^\uparrow}(z,p_\perp)$$



couples transversity to Collins: so far only access to h_1

Collins function from e^+e^- processes

(spin effects without polarization, D. Boer)



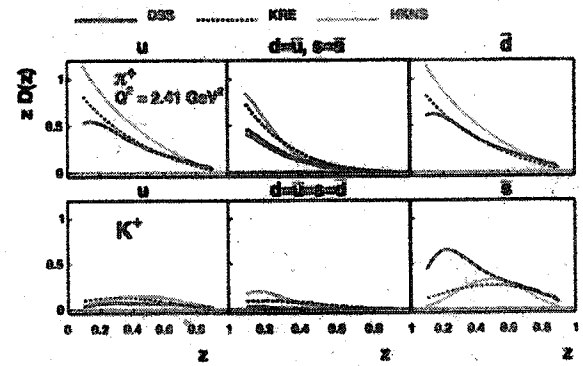
$$e^+e^- \to q\,\bar{q} \to h_1 h_2\, X$$

[redacted] BELLE @ KEK [redacted]

New set of fragmentation functions

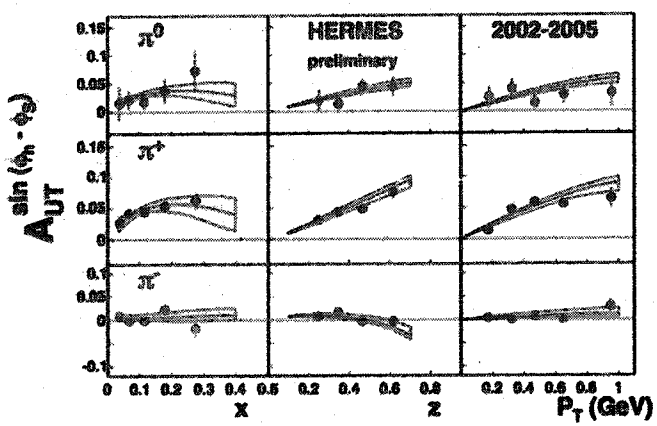
D. de Florian, R. Sassot, and M. Stratmann, Phys. Rev. D75, 114010 (2007)

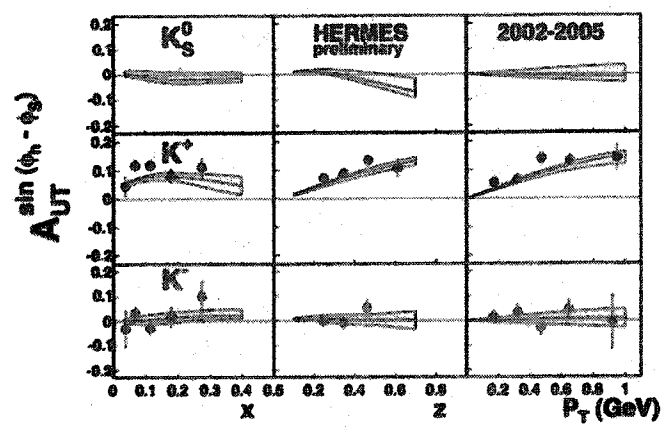
KRE = Kretzer, HKNS = Hirai, Kumano, Nagai, Sudoh



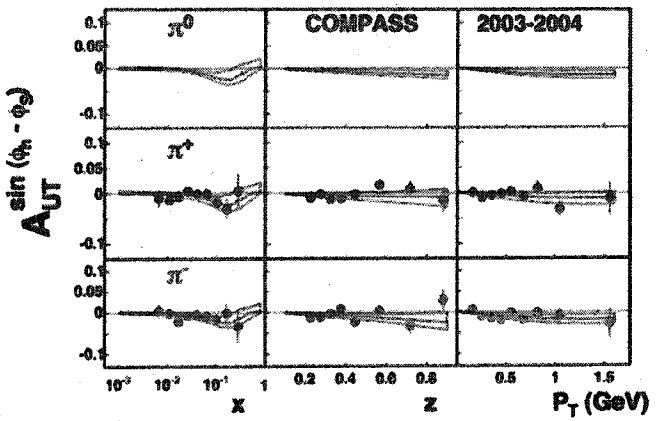
Sivers asymmetry best fits

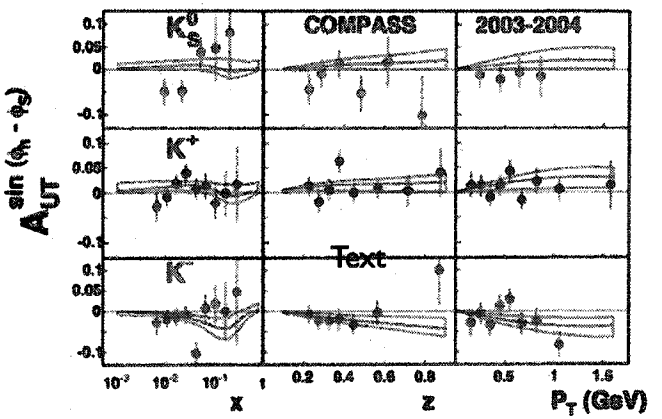
M.A., M. Boglione, U. D'Alesio, A. Kotzinian, S. Melis, F. Murgia, A. Prokudin, C. Turk
arXiv:0805.2677 [hep-ph]



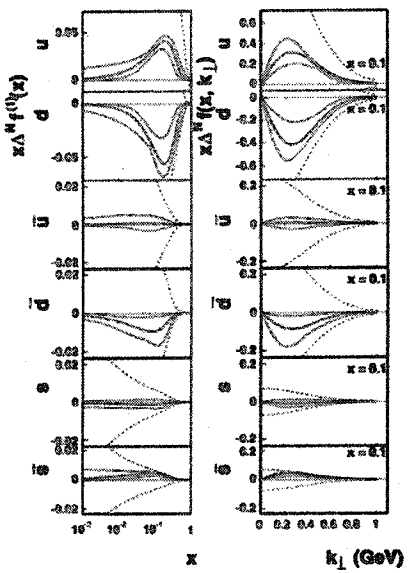


$$D_d^{K_S^0} = D_{\bar{d}}^{K_S^0} = \frac{1}{2}\left[D_u^{K^+} + D_{sea}^{K^+}\right]$$





K_S^0 not included in the fit: computed



extracted Sivers functions

$\Delta^N f_{u/p^\uparrow} > 0$

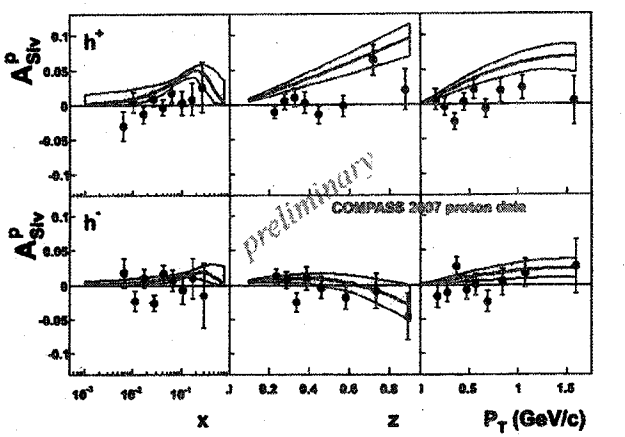
$\Delta^N f_{d/p^\uparrow} < 0$

$\Delta^N f_{\bar{u}/p^\uparrow} > 0$

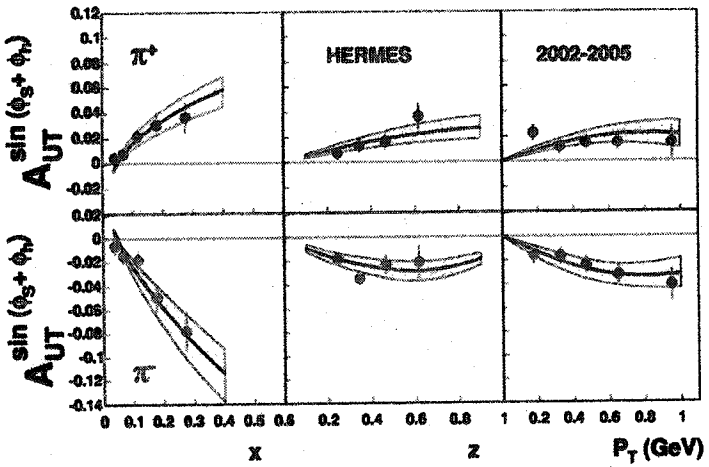
11 parameters

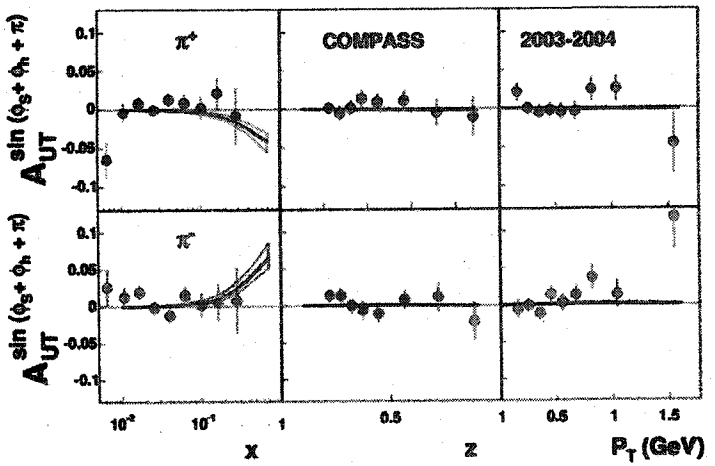
N_u	N_d	N_s
$N_{\bar{u}}$	$N_{\bar{d}}$	$N_{\bar{s}}$
α_u	α_d	α_{sea}
β	$M_1(\mathrm{GeV}/c)$.	

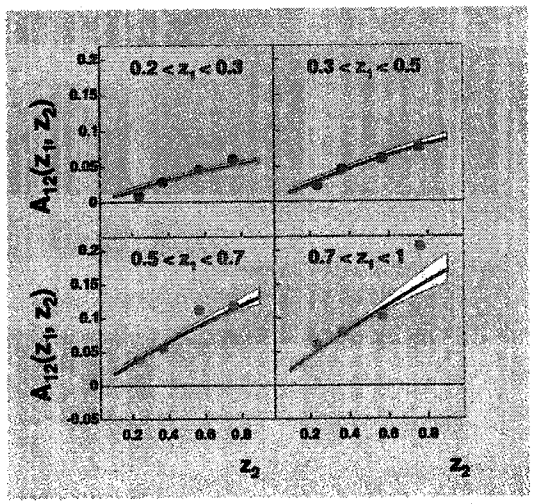
Comparison of predictions with COMPASS data, proton target



Collins asymmetry best fit







best fit of Belle data

9 parameters alltogether in fit of Collins + transversity

$N_u^T \quad N_d^T$

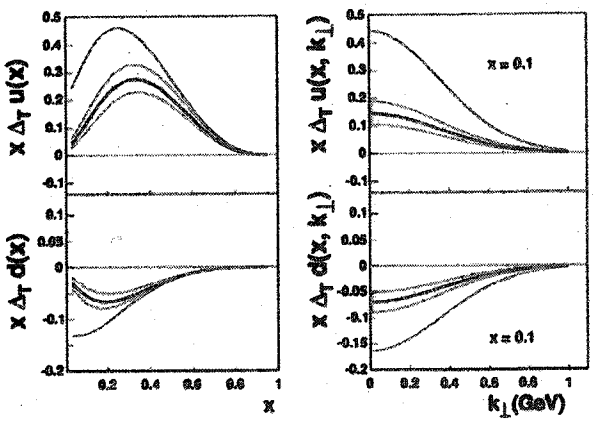
$N_{fav}^C \quad N_{unf}^C$

$\alpha \quad \beta$

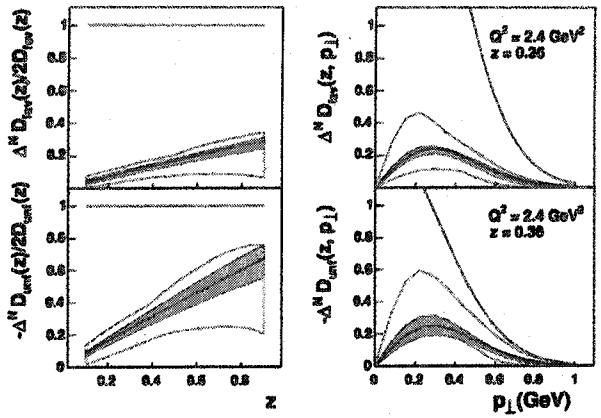
$\gamma \quad \delta \quad M_1$

extracted transversity distributions

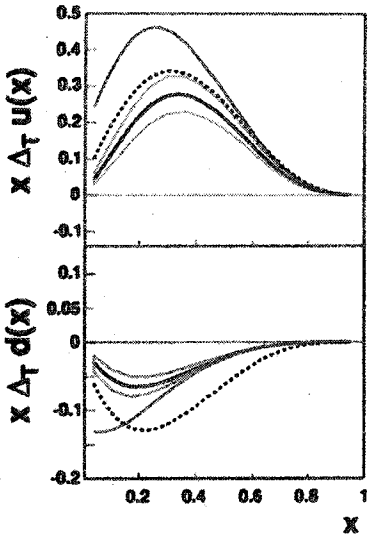
(blue lines = Soffer's bound)



extracted Collins functions



transversity vs. helicity



- Solid red line – transversity distribution

  $\Delta_T q(x)$

  this analysis at $Q^2 = 2.4$ GeV^2.
- Solid blue line – Soffer bound

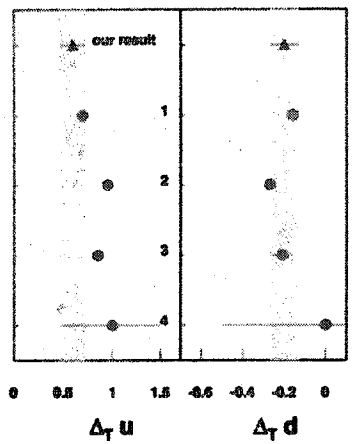
  $$\frac{q(x) + \Delta q(x)}{2}$$

  GRV98LO + GRSV98LO
- Dashed line – helicity distribution

  $\Delta q(x)$

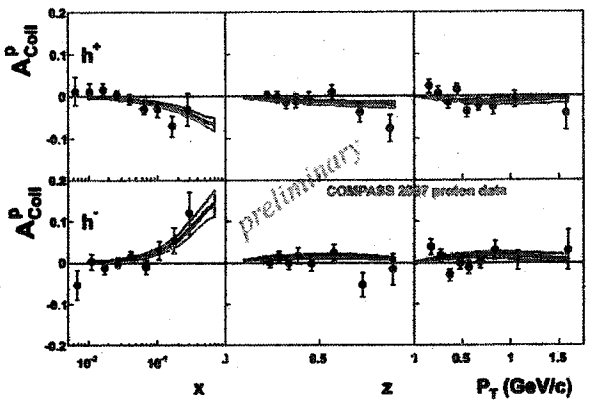
Tensor charges ($\Delta_T \bar{q} = 0$)

$\Delta_T u = 0.59^{+0.14}_{-0.13}$, $\Delta_T d = -0.20^{+0.05}_{-0.07}$ at $Q^2 = 0.8$ GeV^2



- Quark-diquark model:
  Cloet, Bentz and Thomas
  PLB 659, 214 (2008), $Q^2 = 0.4$ GeV^2
- CQSM:
  M. Wakamatsu, PLB B 653 (2007) 398
  $Q^2 = 0.3$ GeV^2
- Lattice QCD:
  M. Gockeler et al.,
  Phys.Lett.B627:113-123,2005 , Q^2 = GeV^2
- QCD sum rules:
  Han-xin He, Xiang-Dong Ji,
  PRD 52:2960-2963,1995, $Q^2 \sim 1$ GeV^2

Comparison of predictions with COMPASS data, proton target



k_T Asymmetry In Longitudinally Polarized p+p Collisions at PHENIX

Researchers in the PHENIX experiment at RHIC have developed a method for measuring the average net pair transverse momentum of hard scattering jets at central rapidity [1]. This method utilizes the azimuthal correlation between a leading high p_T π° and another charged hadron. The widths of the resulting near- and far- side peaks can then be related to the fragmentation transverse momentum, j_T (the transverse momentum of the fragmented hadron relative to the hard-scattered parton) and the net pair transverse momentum, k_T in a straight forward manner. The net pair transverse momentum can be produced from parton intrinsic transverse momentum inside the proton, from soft gluon emission, or from next-to-leading order processes of the perturbative QCD. In addition, one can consider the possibility that spin-correlated transverse momentum (orbital angular momentum) may contribute to k_T, as discussed in [2]. Coherent spin-dependant parton transverse momentum adds to k_T an amount dependent upon the helicity combination of the colliding partons, and upon the impact parameter of the collision. However, integrating over impact parameter will likely leave a residual effect that is dependant only on the helicity combination, a signal that could, be examined in the present data from past RHIC runs.

We have examined this k_T asymmetry in the data from 2005 RHIC run. Figure on slide number 5, (slides on next few pages are not numbered sequentially), shows the azimuthal angle distribution between triggered π° in the transverse momentum range of 3.0 - 3.5 GeV and an associated charged hadron in 1.4 - 5.0 GeV range. The jet fragmentation transverse momentum, j_T, and the partonic transverse momentum k_T can be extracted from the width of the near side peak (around $\Delta\phi$=0) and that of the far side peak (around $\Delta\phi=\pi$). However, as explained in [1], the raw $dN_{real}/d\Delta\phi$ distributions are fit with the function given on slide 14 to obtain σ_{near} and $v<p_{out}^2>$, which are then used to extract j_T and k_T.

The difference in the extracted $v<k_T^2>$ values from the same helicity minus the opposite helicity events is shown in Figure on the last slide (no. 18). This preliminary result shows a difference of 673 ± 387 MeV. However, in the final results (soon to be published) the uncertainty on k_T asymmetry is reduced by almost a factor of 2, and the average is consistent with zero within one sigma.

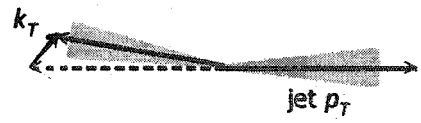
[1] S.S. Adler *et al.* Phys Rev D 74, 072002 (2006)

[2] Meng Ta-Chung *et al.* Phys Rev D 40 (1989)

Origin of Jet k_T

Net transverse momentum of a dilepton or dijet pair

$$\frac{1}{2}\left\langle p_T^2\right\rangle_{pair} = \left\langle k_T^2\right\rangle = \left\langle k_T^2\right\rangle_{intrinsic} + \left\langle k_T^2\right\rangle_{NLO} + \left\langle k_T^2\right\rangle_{soft}$$

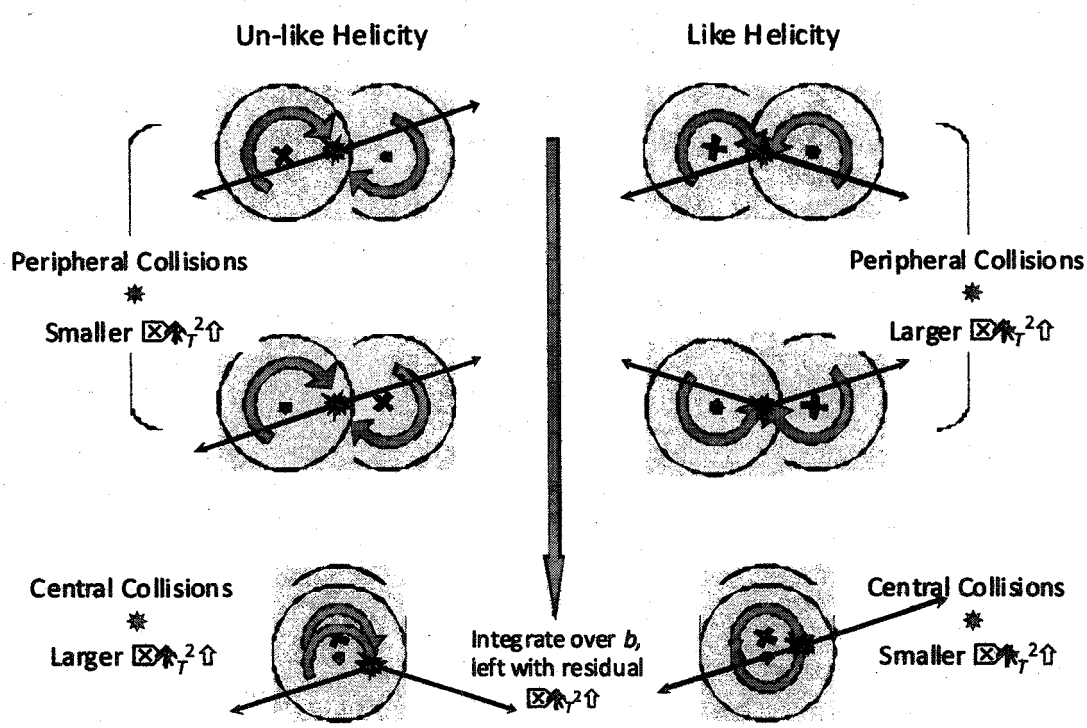


- *intrinsic* – fermi motion of the confined quarks or gluons
- *NLO* – radiation of an initial state or final state hard gluon
- *soft* – Gausian like distribution observed as p_{Tpair} ? 0; resummation.

Another Possibility:

- Spin-Correlated transverse momentum – partonic orbital angular momentum
- Assume other contributions have no spin dependence…
- We can perhaps measure using jet k_T spin asymmetry.
- Possible Effect in double longitudinal spin
  - Idea proposed for the Drell-Yan process by M.Ta-chung et. al. (Phys. Rev. D40 p.769, 1989)
  - Same idea for jets suggested by Douglas Fields.

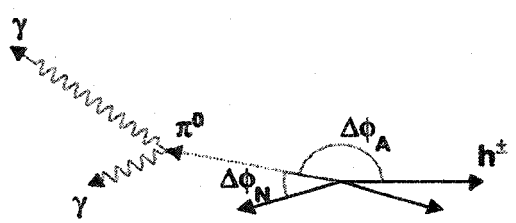
Accessing Orbital Angular Momentum

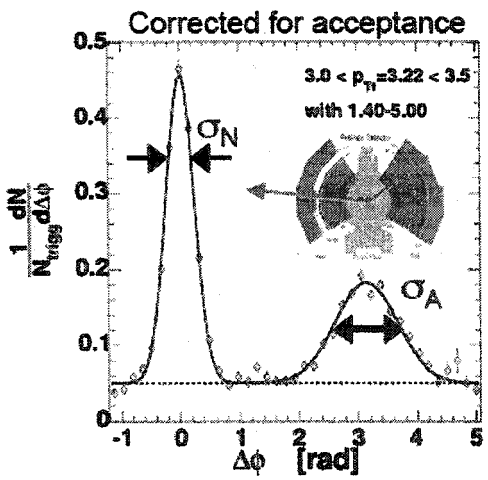


Measuring jet k_T – dihadron correlation

π^0- $h^\pm$ azimuthal correlation

Trigger on a particle, e.g. π^0, with transverse momentum p_{Tt}. Measure azimuthal angular distribution *w.r.t.* the azimuth of associated (charged) particle with transverse momentum p_{Ta}. The strong ***same*** and ***away*** **side peaks** in p-p collisions indicate di-jet origin from hard scattering partons.



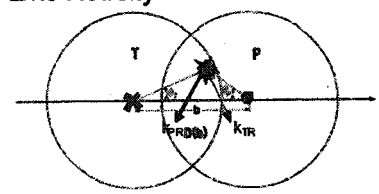


Integrating over Impact Parameter

Drell-Yan pair production in polarized *p+p* collisions.
(Meng Ta-Chung et al. Phys. Rev. D 1989)

$$p_t^2(b,\theta_P,\theta_T;\pm) = \left|\vec{k}_{PR}\right|^2 + \left|\vec{k}_{TR}\right|^2 \pm \left|\vec{k}_{PR}\right|\left|\vec{k}_{TR}\right|\cos(\theta_P+\theta_T)$$

Like Helicity



Averaging over *D(b)*:

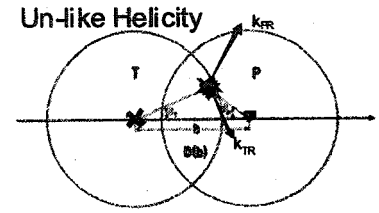
$$\Delta\left\langle p_t^2(b)\right\rangle = \left\langle p_t^2(b,+)\right\rangle - \left\langle p_t^2(b,-)\right\rangle$$

Integrating over impact parameter *b*:

$$\Delta\left\langle p_t^2\right\rangle \approx 1.9\left\langle k_R\right\rangle^2$$

$$\left\langle k_R\right\rangle \equiv \left\langle\left|\vec{k}_{PR}\right|\right\rangle = \left\langle\left|\vec{k}_{TR}\right|\right\rangle$$

Un-like Helicity

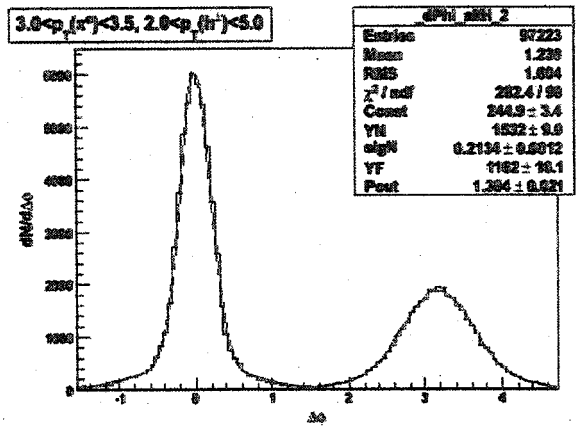


Fit Function

$$\frac{dN_{real}}{d\Delta\phi} = \frac{1}{N}\frac{dN_{mix}}{d\Delta\phi}\cdot\left(C_o + C_1\cdot Gaus(0) + C_2\cdot\left.\frac{dN_{away}}{d\Delta\phi}\right|_{\pi/2}^{3\pi/2}\right)$$

$$\left.\frac{dN_{away}}{d\Delta\phi}\right|_{\pi/2}^{3\pi/2} = \frac{-p_{Ta}\cos\Delta\phi}{\sqrt{2\pi\left\langle p_{out}^2\right\rangle}Erf\left(\sqrt{2}\,p_{Ta}/\sqrt{\left\langle p_{out}^2\right\rangle}\right)}\exp\left(-\frac{p_{Ta}^2\sin^2\Delta\phi}{2\left\langle p_{out}^2\right\rangle}\right)$$

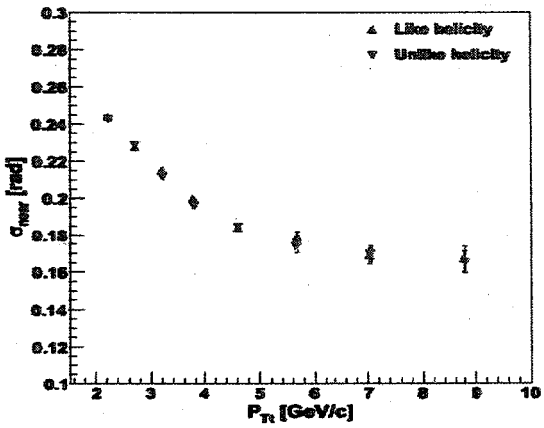
- Blue – real (raw ? f)
- Red – Fit from above equation

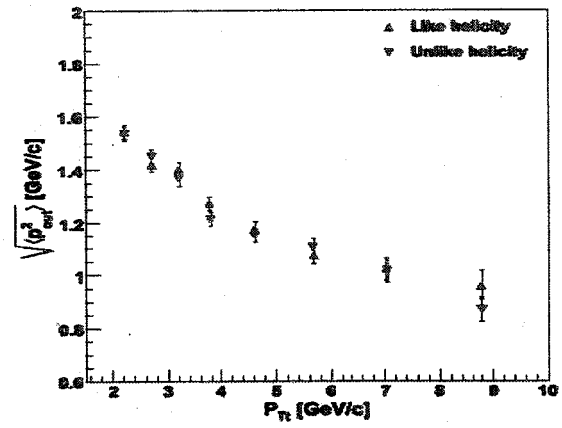


Spin sorted dihadron correlations

Fit Results

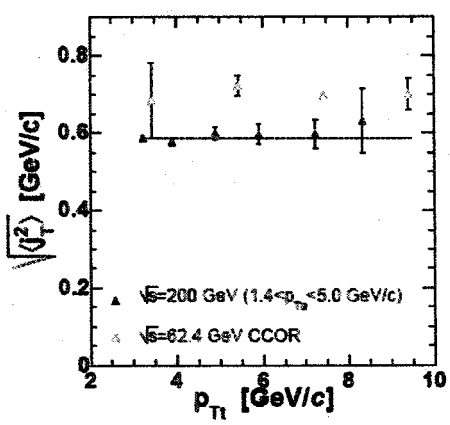
- Red ▲– Like helicity (++ & --)
- Blue ▼– Unlike helicity (+- & -+)

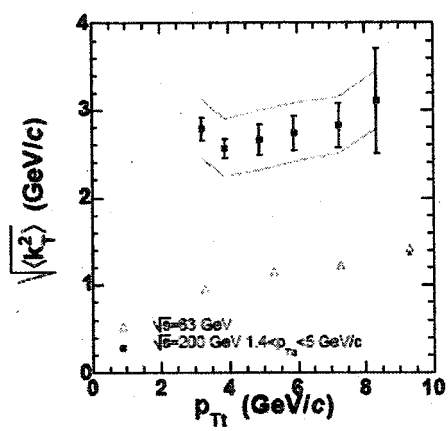




k_T results for unpolarized case

$\langle j_T \rangle$ = 585 ± 6(*stat*) ± 15(*syst*) MeV
$\langle k_T \rangle$ = 2.68 ± 0.07(*stat*) ± 0.34 (*syst*) GeV





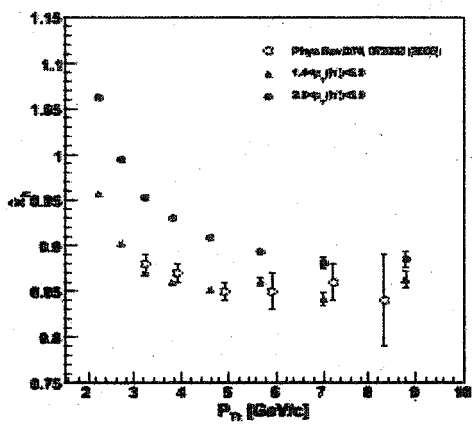
Phys. Rev. D 74, 072002 (2006)

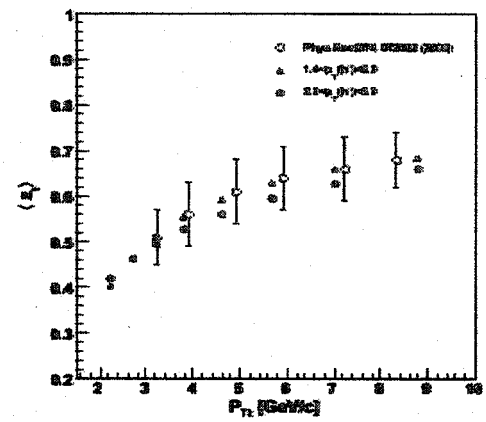
Need $\langle z_t \rangle$ and x_h

$$\frac{\langle z_h(k_T, x_h)\rangle \sqrt{\langle k_T^2 \rangle}}{x_h(k_T, x_h)} = \frac{1}{x_h}\sqrt{\langle p_{out}^2 \rangle - \langle j_{T_\gamma}^2 \rangle (1 + x_h^2)}$$

$\langle k^2_T \rangle$ asymmetry results are not sensitive to this $\hat{x}_h$ and $\langle z_t \rangle$ valuse – only needed to set the scale.

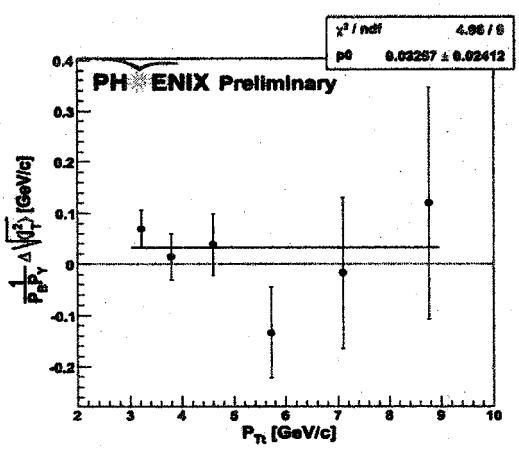
$\hat{x}_h$ and $\langle z_t \rangle$ are determined through a combined analysis of the p° inclusive cross section and using jet fragmentation function measured in e^+e^- collisions. *Ref.* PRD 74, 072002 (2006)

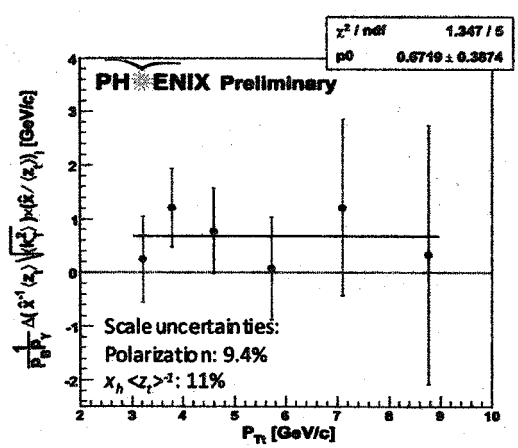




Preliminary Results

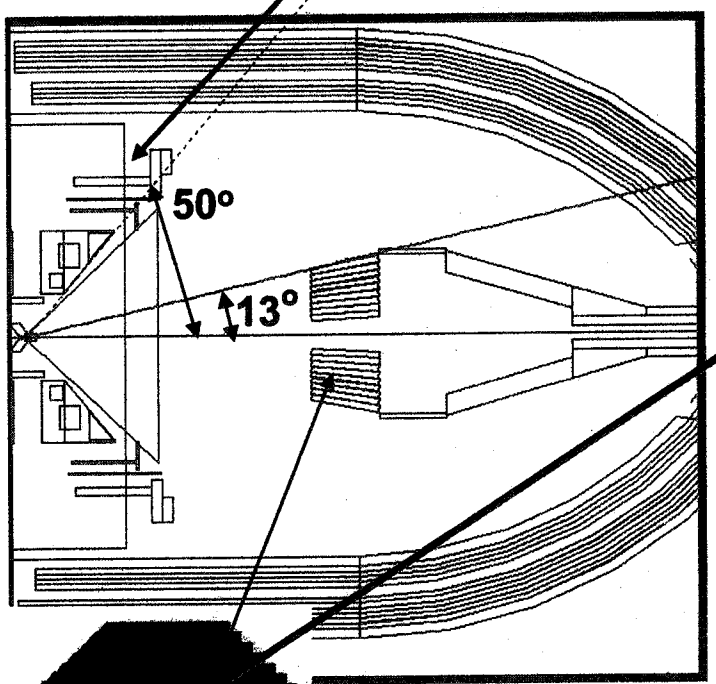
- Take the difference Like – Unlike helicities
- Normalized by beam polarizations
- $\langle j^2_T \rangle$ asymmetry small (32 ± 24 MeV out of ~580 MeV for unpolarized)
- $\langle k^2_T \rangle$ asymmetry not small (672 ± 387 MeV out of ~2.7 GeV for unpolarized)
- Final results soon to be published.
- **Final uncertainty on k_T asymmetry is reduced by almost a factor of 2, and the average is consistent with zero within one sigma.**

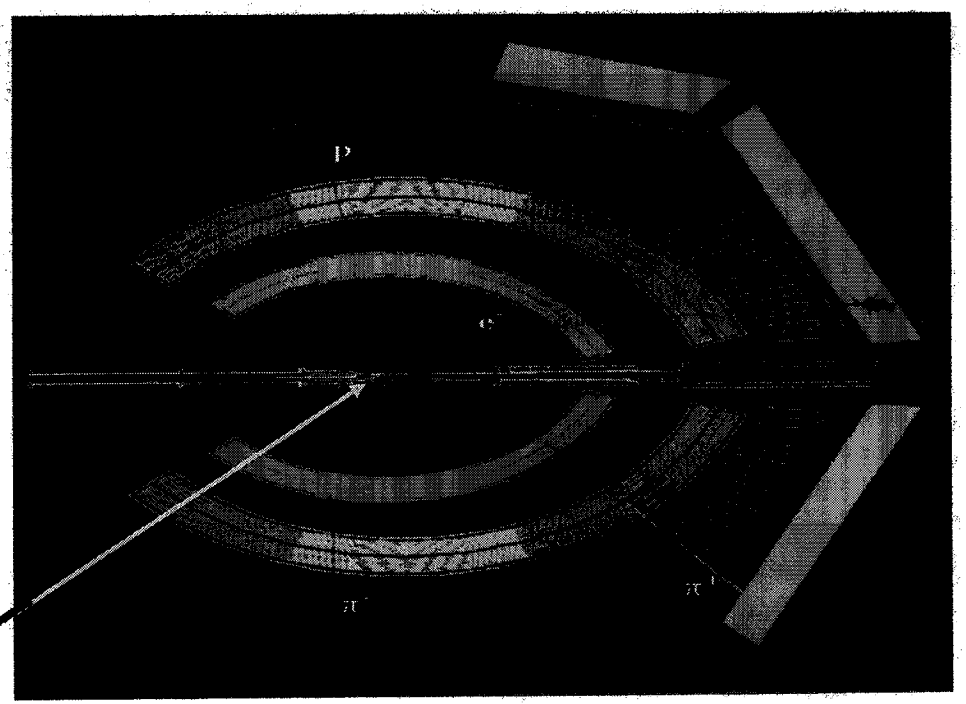




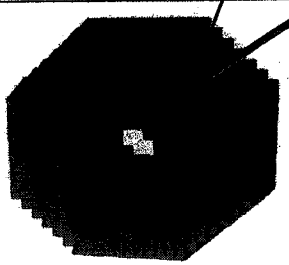
Harut Avakian

Studies of spin-orbit correlations at CLAS





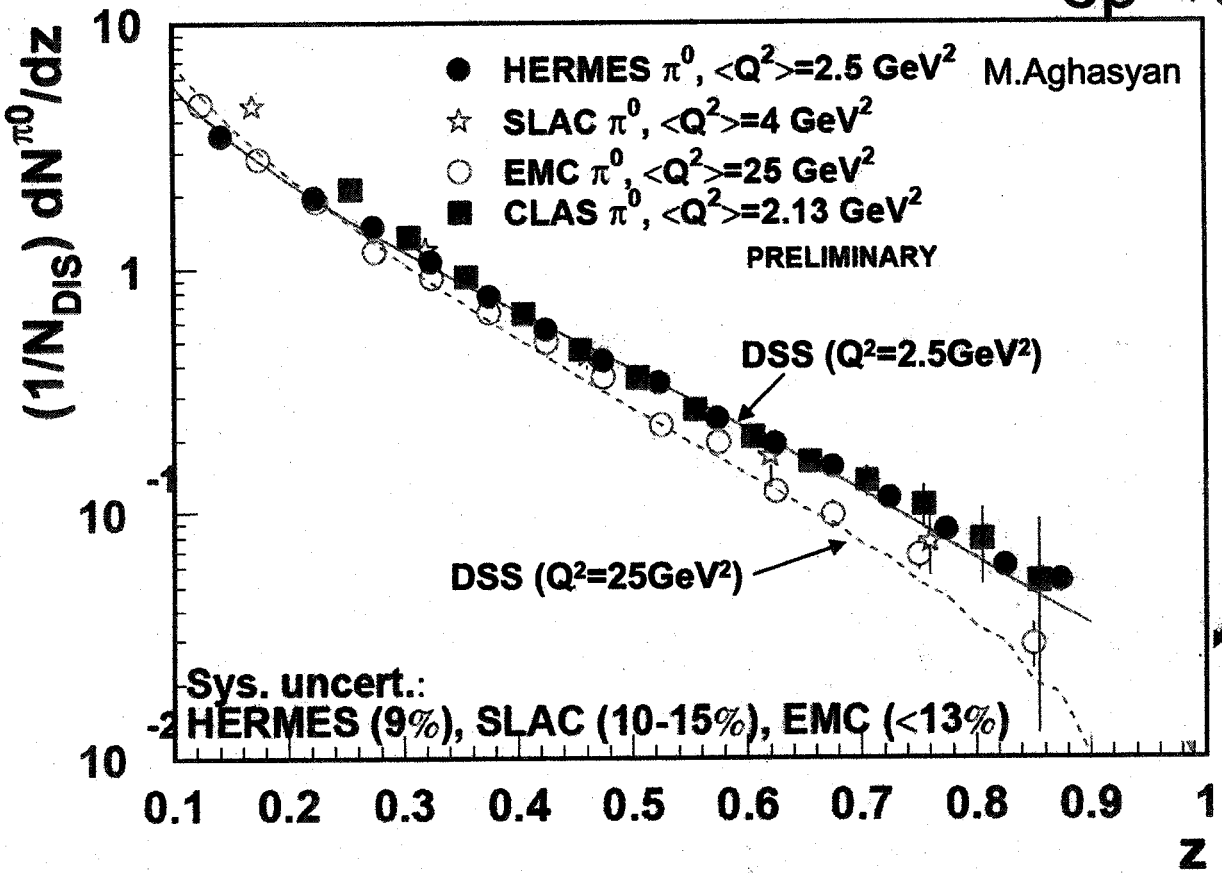
1) Polarized NH3/ND3 (no IC, ~5 days)
2) Polarized NH3 with IC 60 days
3) Unpolarized H with IC 30+30 days
4) Polarized HD-Ice (no IC, 25 days)



Inner Calorimeter (424 $PbWO_4$ crystals) to detect high energy photons at forward lab angles.

π^0 multiplicities

$ep \rightarrow e'\pi^0 X$



P.Bertin
(Hall-A preliminary)

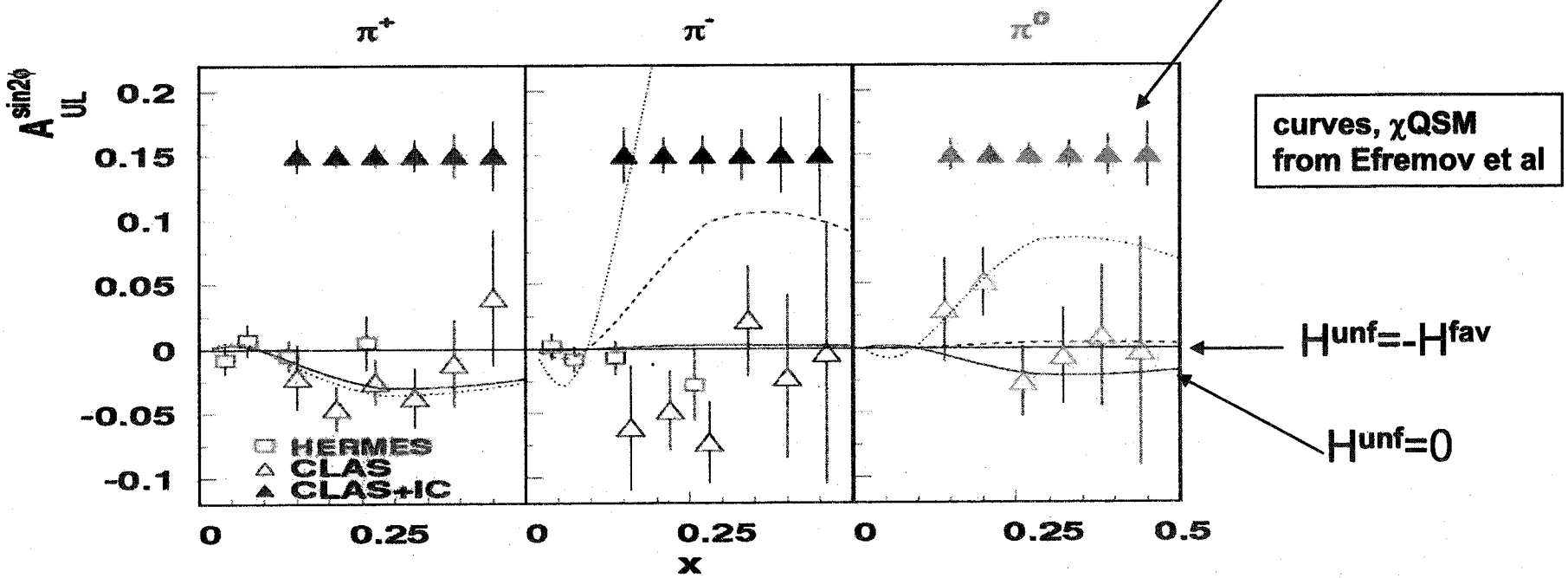
π^0 multiplicities consistent with SIDIS predictions

Kotzinian-Mulders asymmetry

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$$A_{UL}^{\sin 2\phi} \sim h_{1L}^\perp H_1^\perp \sin 2\phi$$

60 days of CLAS+IC
(L=1.5.10^{34}cm^{-2}s^{-1})



- Provide measurement of SSA for all 3 pions, extract the RSMT TMD and study Collins fragmentation with longitudinally polarized target
- Allows also measurements of 2-pion asymmetries

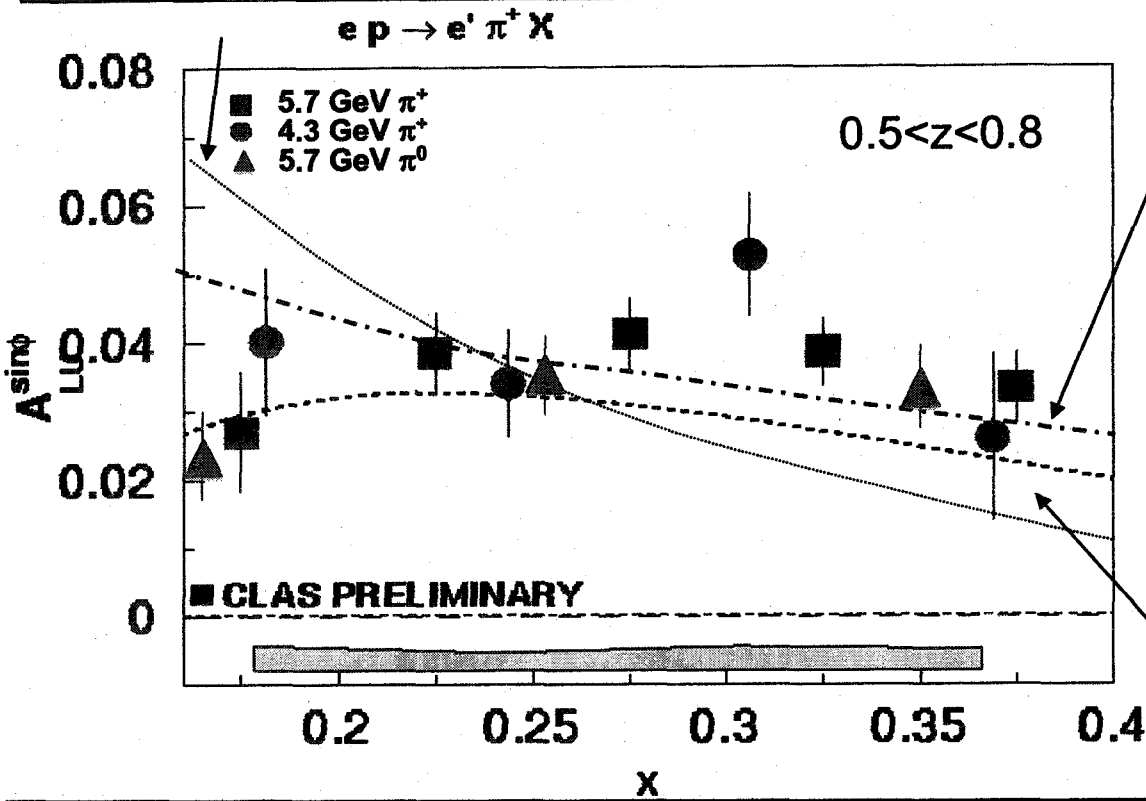
Beam SSA: A_{LU} from CLAS @ JLab

$$A_{LU}^{\sin\phi} \sim g^{\perp} D_1(z)$$

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel

$$A_{LU}^{\sin\phi} \sim h_1^{\perp}(x) E(z)$$

Beam SSA from initial distribution (Boer-Mulders TMD) F.Yuan using $h_1^{\perp}$ from MIT bag model



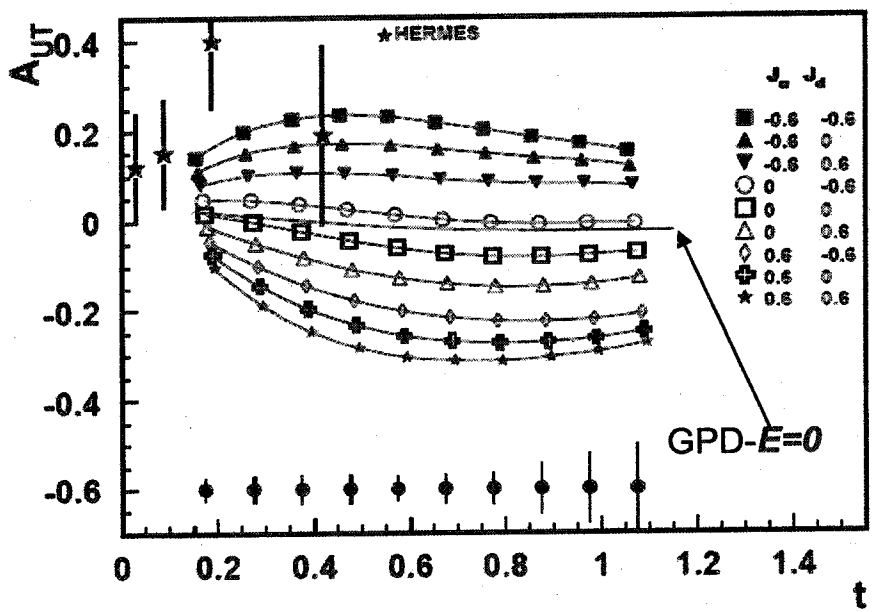
$$A_{LU}^{\sin\phi} \sim e(x) H_1^{\perp}(z)$$

Beam SSA from hadronization (Collins effect) by Schweitzer et al.

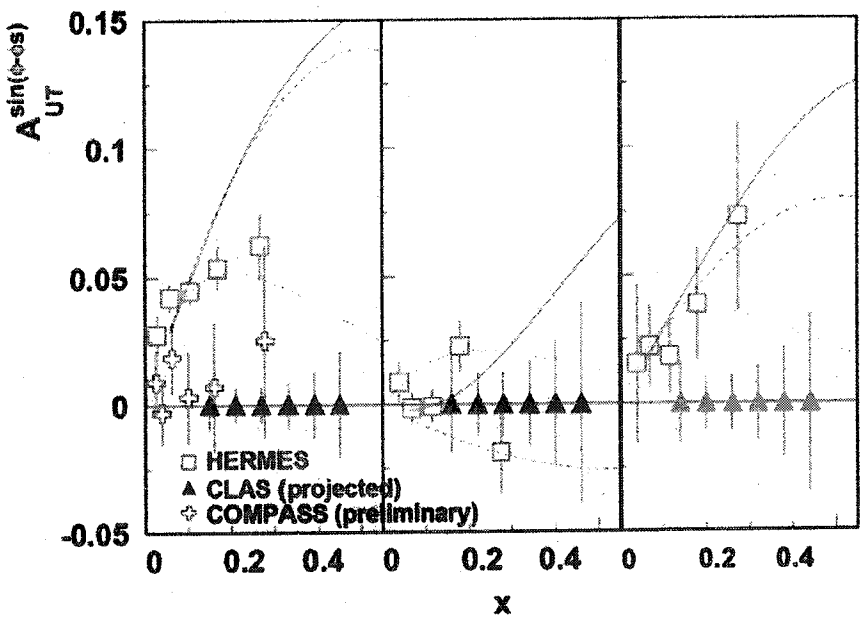
Beam SSA for π^0 and π^+ are comparable indicating small Collins type contributions

Measurement of Sivers function and GPD-E

(DVCS)



(SIDIS) CLAS6 (25 days-2011)



DVCS Transverse asymmetry (function of momentum transfer to proton is large and has strong sensitivity to GPD-*E*

CLAS will provide a measurements of Sivers asymmetry at large x, where the effect is large and models unconstrained by previous measurements.

$$\int d^2\vec{k}_T \vec{k}_T^2 f_{1T}^{\perp}(x,\vec{k}_T^2) = -e_s e_q \frac{(1-x)}{4\pi} \int d^2\vec{b}_T (E(x,\vec{b}_T^2))'$$

Meissner, Metz & Goeke (2007)

Summary

Significant azimuthal moments in pion production in SIDIS were measured at CLAS providing information on leading and sub-leading transverse momentum dependent distributions of quarks.

➢ ***Large acceptance of CLAS allows simultaneous measurements of exclusive and semi-inclusive processes in a wide kinematical range important for understanding of underlying physics processes***

Incoming runs at CLAS at 6 GeV will provide high statistics data for studies of correlations of spin and transverse momentum of partons (access all 8 TMDs).

1)Unpolarized SIDIS (30 days-2008, with IC)
2)Longitudinally polarized SIDIS (60 days-2009, with IC)
3)Transversely polarized HD (25 days-2011)

Nucleon Transversity Study Using a Polarized ^{3}He Target in Hall A at JLab

PKU-RBRC Workshop on Transverse Spin Physics
June 30 – July 4, 2008
Beijing, China

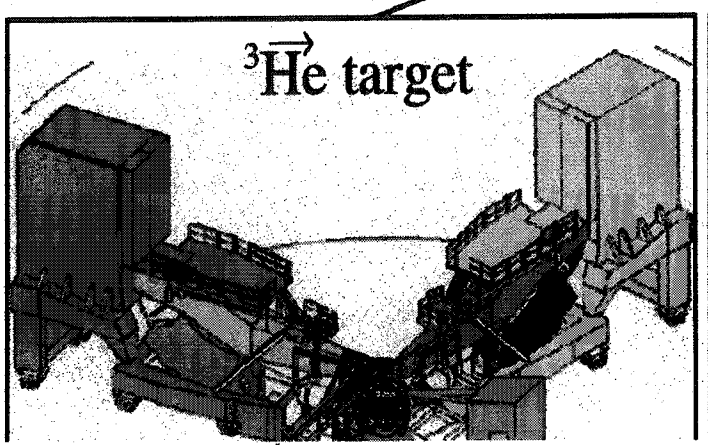
Haiyan Gao

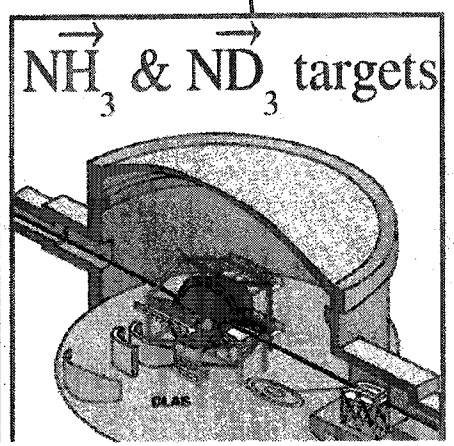
Duke University/TUNL

Durham, NC, U.S.A.

Jefferson Lab Experimental Halls

6 GeV pol. e beam
Pol=85%, 100μA





HallA: two HRS' **Hall B:CLAS** **Hall C: HMS+SOS**

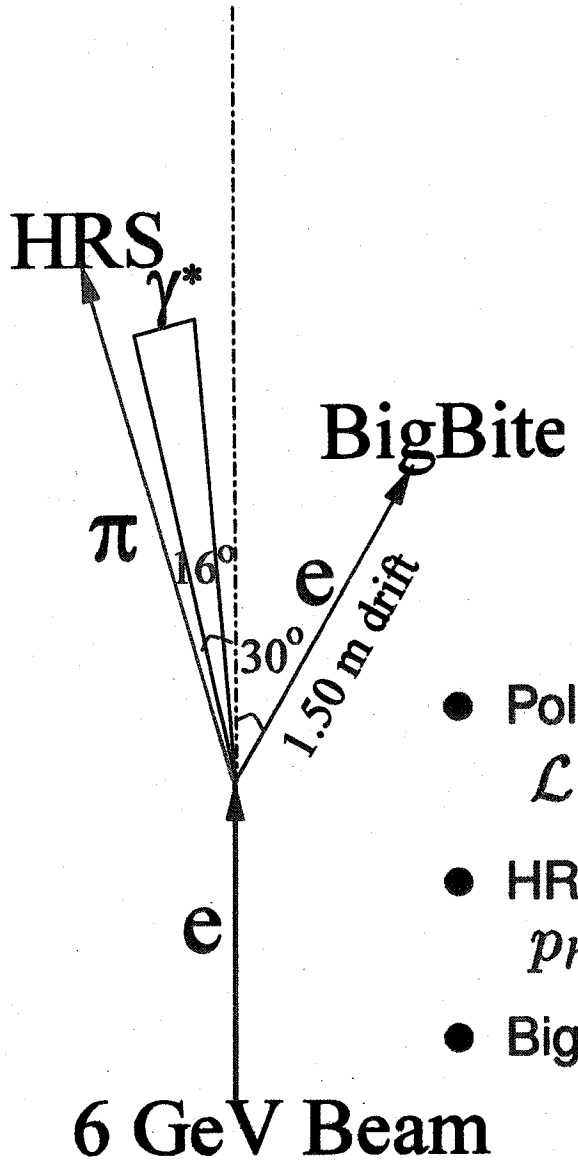
Jefferson Lab Hall A E06-010/E06-011
Collaboration

California State Univ., Duke Univ., Florida International. Univ., Univ. Illinois, JLab, Univ. Kentucky, LANL,Univ. Maryland, Univ. Massachusetts, MIT, Old Dominion Univ., Rutgers Univ., Temple Univ., Penn State Univ., Univ. Virginia, College of William & Mary, Univ. Sciences & Tech, China Inst. Of Atomic Energy, Beijing Univ., Seoul National Univ., Univ. Glasgow, INFN Roma and Univ. Bari, Univ. of Ljubljana, St. Mary's Univ., Tel Aviv Univ.

Collaboration members

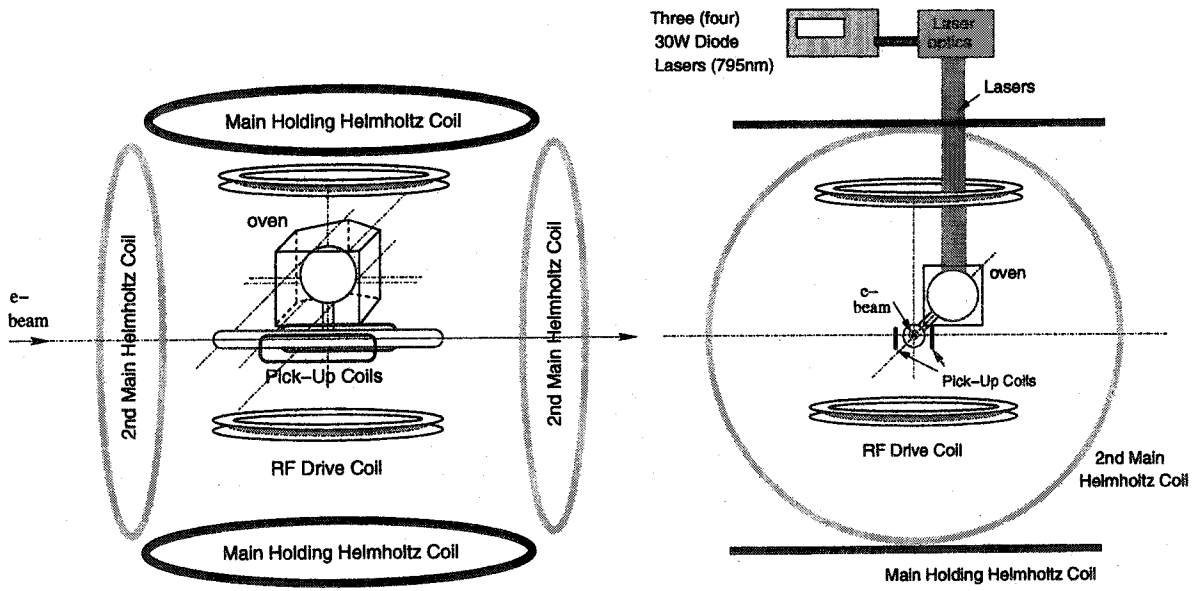
A.Afanasev, K. Allada, J. Annand, T. Averett, F. Benmokhtar, W. Bertozzi, F. Butaru, G. Cates, C. Chang, J.-P. Chen (Co-SP), W. Chen, S. Choi, C. Chudakov, E. Cisbani(Co-SP), E. Cusanno, R. De Leo, A. Deur, C. Dutta, D. Dutta, R. Feuerbach, S. Frullani, L. Gamberg, H. Gao(Co-SP), F. Garibaldi, S. Gilad, R. Gilman, C. Glashausser, J. Gomez, M. Grosse-Perdekamp, D. Higinbotham, T. Holmstrom, D. Howell, M. Iodice, D. Ireland, J. Jansen, C. de Jager, X. Jiang (Co-SP), Y. Jiang, M. Jones, R. Kaiser, A. Kalyan, A. Kelleher, J. Kellie, J. Kelly, A. Kolarkar, W. Korsch, K. Kramer, E. Kuchina, G. Kumbartzki, L. Lagamba, J. LeRose, R. Lindgren, K. Livingston, N. Liyanage, H. Lu, B. Ma, M. Magliozzi, N. Makins, P. Markowitz, Y. Mao, S. Marrone, W. Melnitchouk, Z.-E. Meziani, R. Michaels, P. Monaghan, S. Nanda, E. Nappi, A. Nathan, V. Nelyubin, B. Norum, K. Paschke, J. C. Peng (Co-SP), E. Piasetzky, M. Potokar, D. Protopopescu, X. Qian, Y. Qiang, B. Reitz, R. Ransome, G. Rosner, A. Saha, A. Sarty, B. Sawatzky, E. Schulte, S. Sirca, K. Slifer, P. Solvignon, V. Sulkosky, P. Ulmer, G. Urciuoli, K. Wang, Y. Wang, D. Watts, L. Weinstein, B. Wojtsekhowski, H. Yao, H. Ye, Q. Ye, Y. Ye, J. Yuan, X. Zhan, X. Zheng, S. Zhou.

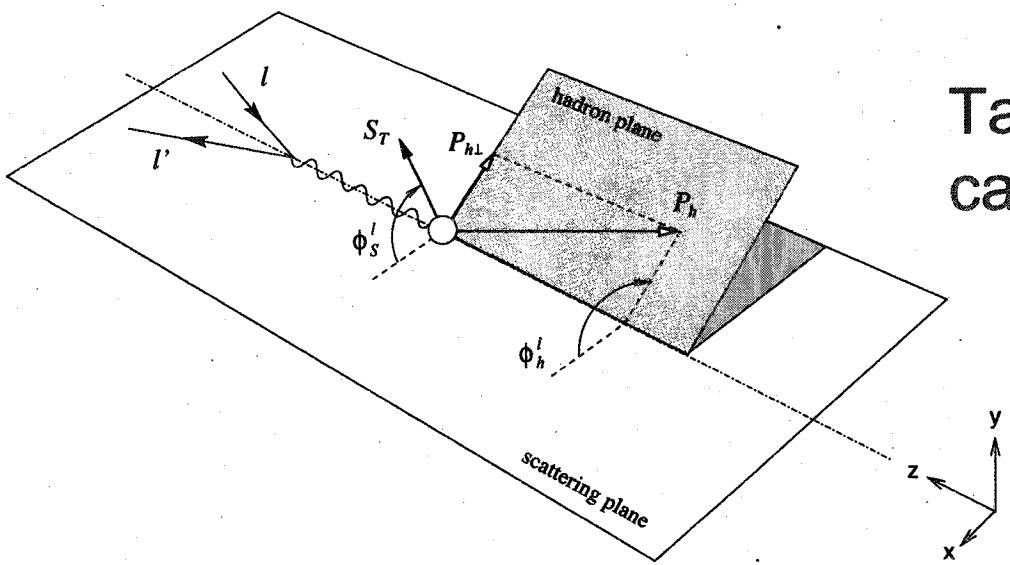
SIDIS: N(e,e'h)
h=π⁺/K⁺ or π⁻/K⁻



- Polarized ^{3}He target, 10 atm pressure. $\mathcal{L}(\vec{n}) = 10^{36}$ cm^{-2}s^{-1}.
- HRS$_L$ at 16° as h-arm ($\pi^{+/-}$ or $K^{+/-}$ with RICH for PID.). $p_h = 2.4$ GeV/c, $z = 0.5$.
- BigBite spectrometer at 30° as e-arm. $\Delta\Omega = 64$ msr.

Transversely polarized ^{3}He target



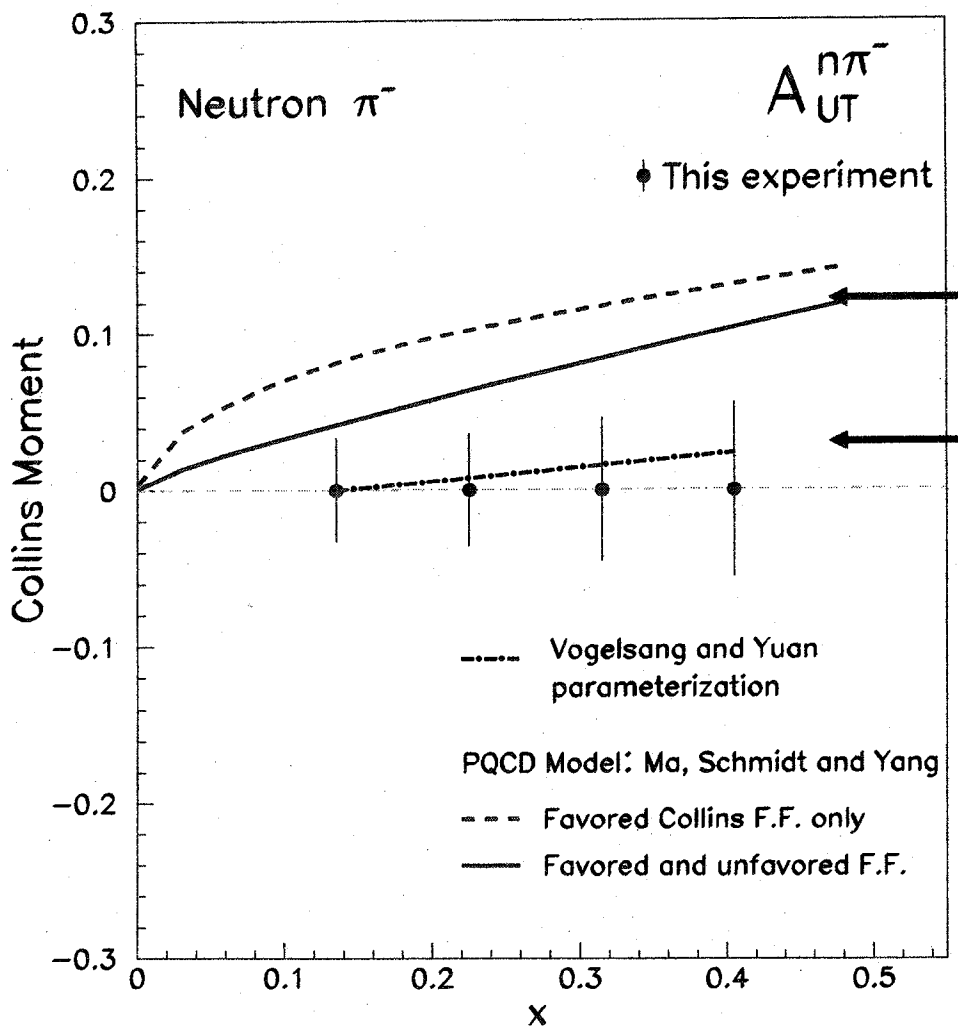


Target polarization orientation can be rotated to increase the coverage in Φ_S^l

Projections of Collins asymmetry on neutron

$$A_{UT}^{n\pi^+} \propto 4\delta d \cdot H_1^{\perp fav} + \delta u \cdot H_1^{\perp unfav}$$

$$A_{UT}^{n\pi^-} \propto 4\delta d \cdot H_1^{\perp unfav} + \delta u \cdot H_1^{\perp fav}$$



$$H_1^{\perp unfav} / H_1^{\perp fav} \approx D_1^{unfav} / D_1^{fav}$$

$$H_1^{\perp unfav} / H_1^{\perp fav} \approx -1$$

Single Transverse-Spin Asymmetry in QCD

Yuji Koike

Department of Physics, Niigata University, Ikarashi, Niigata 950-2181, Japan

Two mechanism in QCD have been often used to describe the large single transverse-spin asymmetries (SSA) observed in various hard inclusive processes. One is the so-called "naively T-odd" distribution and fragmentation functions in the transverse-momentum-dependent (TMD) factorization approach. The other one is the twist-3 effect in the framework of collinear factorization [1, 2, 3, 4, 5]. In this talk I discussed the recent developments in the theory of the latter approach, and also the connection between the two formalisms.

I first discussed the outline of the twist-3 formalism for SSA following the line of our recent paper [5]. There are two independent twist-3 quark-gluon correlation functions in the transversely polarized nucleon. In this formalism, the phases necessary for SSA are provided as pole contributions from the internal propagators. They are classified as soft-gluon-pole (SGP), hard-pole (HP) and soft-fermion-pole (SFP) contributions. In [5], we have presented a formalism which leads to the complete cross section formula from these poles in terms of the complete set of the twist-3 distribution functions. In particular, we have emphasized that the Ward identities satisfied by each pole contribution leads to the gauge-invariant factorized expression for the cross section. We have applied the formalism to SIDIS, $ep^\uparrow \to e\pi X$, and derived the twist-3 single-spin-dependent cross section.

With the obtained cross section, we have discussed the matching of the two mechanisms for SSA at intermediate q_T [6]. First we took the limit of $q_T \to 0$ of the twist-3 cross section and extracted its dominant part at $q_T \to 0$. We found the SGP and HP contributions from $G_F(x_1, x_2)$ and $\widetilde{G}_F(x_1, x_2)$ survive in this limit, but not from the SFP. Next we have performed a perturbative calculation of the Sivers function $q_T(x, k_\perp)$ at large transverse momentum $k_\perp \gg \Lambda_{\rm QCD}$. We found that the Sivers function can also expressed in terms of G_F and $\widetilde{G}_F$ in this limit, and that the TMD factorization formula with the obtained Sivers function gives the cross section which is identical to the twist-3 cross section at $q_T \to 0$. This study is supplementary to the previous one [3] which investigated the consistency refering to the SGP and HP contributions from G_F, and establishes the consistency of the two frameworks for SSA.

Next I discussed the special property of the SGP contribution in the twist-3 cross section [7]. We have shown that the partonic hard cross section for the *total* SGP contribution has a simple relation with a certain twist-2 cross section up to kinematic and color factors. This applies to any processes such as $ep^\uparrow \to e\pi X$, $p^\uparrow p \to \gamma^{(*)} X$, $p^\uparrow p \to \pi X$, $pp \to \Lambda^\uparrow X$ etc. We have further shown that the scale invariance of the twist-2 cross section among *massless* partons in pp collisions (e.g. $p^\uparrow p \to \pi X$, $p^\uparrow p \to \gamma X$) leads to a compact formula for the SGP cross section.

References

[1] A. V. Efremov and O. V. Teryaev, Sov. J. Nucl. Phys. **36**, 140 (1982) [Yad. Phiz. **36**, 242 (1982)]; Phys. Lett. **B150**, 383 (1985). J. Qiu and G. Sterman, Phys. Rev. Lett. **67**, 2264 (1991); Nucl. Phys. **B378**, 52 (1992); Phys. Rev. **D59**, 014004 (1999). Y. Kanazawa and Y. Koike, Phys. Lett. **B478**, 121 (2000); Phys. Lett. **B490**, 99 (2000); Phys. Rev. **D64**, 034019 (2001).

[2] H. Eguchi, Y. Koike and K. Tanaka, Nucl. Phys. **B752**, 1 (2006).

[3] X. D. Ji, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. Lett. **97**, 082002 (2006); Phys. Rev. **D73**, 094017 (2006); Phys. Lett. B **638**, 178 (2006).

[4] C. Kouvaris, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. **D74**, 114013 (2006).

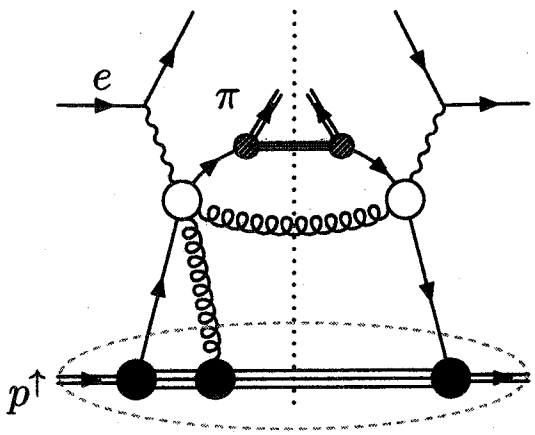
[5] H. Eguchi, Y. Koike and K. Tanaka, Nucl. Phys. **B763**, 198 (2007).

[6] Y. Koike, W. Vogelsang and F. Yuan, Phys. Lett. B **659**, 878 (2008).

[7] Y. Koike and K. Tanaka, Phys. Lett. **B646**, 232 (2007); Phys. Rev. D **76**, 011502 (2007).

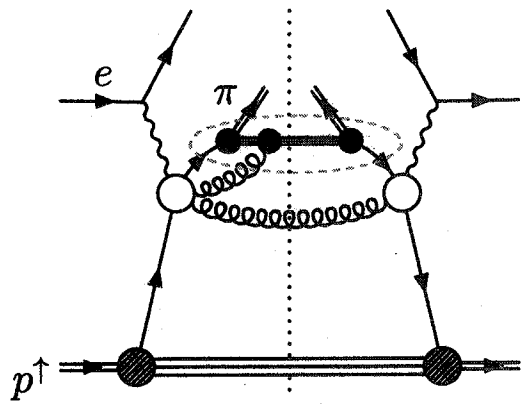
- SSA in $e + p^{\uparrow} \to e + \pi(P_h) + X$.

Sivers type
Twist-3 distribution



(A)

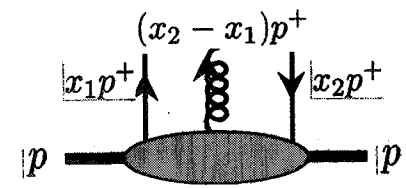
Collins type
Twist-3 fragmentation function



(B)

Focus on this term.

⋆ Twist-3 formalism for SSA.



· Complete set of twist-3 quark-gluon correlation functions.

Two expressions: $\{G_F(x_1,x_2),\ \widetilde{G}_F(x_1,x_2)\} \sim \langle\bar{\psi}gF^{\alpha+}\psi\rangle$ F-type

$\{G_D(x_1,x_2),\ \widetilde{G}_D(x_1,x_2)\} \sim \langle\bar{\psi}D_\perp^\alpha\psi\rangle$ D-type

Not independent: $\{G_D,\ \widetilde{G}_D\}$ can be expressed in terms of $\{G_F,\ \widetilde{G}_F\}$.

· All the twist-3 single-spin-dependent cross section can be written in terms of $\{G_F(x_1,x_2), \widetilde{G}_F(x_1,x_2)\}$.

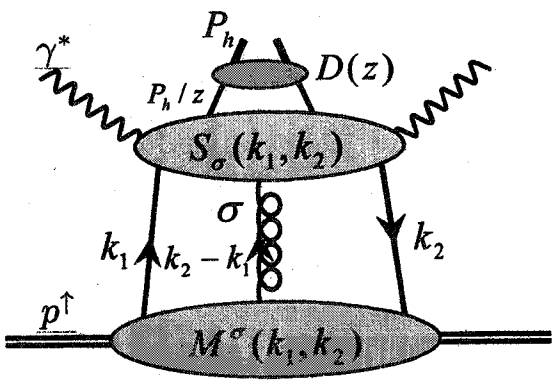
$$d\sigma^A \sim \epsilon^{\alpha pnS_\perp}\mathrm{Tr}\left[i\,\frac{\partial S_\sigma(k_1,k_2)p^\sigma}{\partial k_{2\perp}^\alpha}\bigg|_{k_i=x_ip}\not{p}\right]\otimes G_F(x_1,x_2)\otimes D(z),$$

(in Feynman gauge)

(Likewise for $\widetilde{G}_F$-contribution)

$M^\sigma(k_1,k_2) \sim \langle\bar{\psi}A^\sigma\psi\rangle$

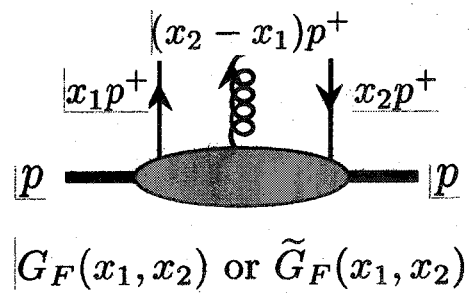
$S_\sigma(k_1,k_2)$: hard scattering part for $M^\sigma(k_1,k_2)$.



· All other gauge-noninvariant terms cancel out due to the Ward identities satisfied by each pole contribution!

· The cross section for $ep^{\uparrow} \to e\pi X$ occurs from Hard-pole (HP), Soft-fermion-pole (SFP), Soft-gluon-pole (SGP).

SGP: $x_2 - x_1 = 0$,
SFP: $x_1 = 0$ or $x_2 = 0$,
HP: $x_i \neq 0$, $x_1 \neq x_2$.



· For the HP and SFP contributions ($x_1 - x_2 \neq 0$), one has from Ward identity

$$\left.\frac{\partial S_\sigma^{HP/SFP}(k_1, k_2)p^\sigma}{\partial k_{2\perp}^\alpha}\right|_{k_i = x_i p} = \frac{1}{x_1 - x_2} S_\alpha^{HP/SFP}(x_1 p, x_2 p).$$

This guarantees that HP and SFP do not receive derivative contributions. Calculation is also simplified.

⋆ Structure of the cross section for $ep^{\uparrow} \to e\pi X$

SGP

$$\frac{d^5\sigma}{dx_{bj}dQ^2dz_f dq_T^2 d\phi} \sim \sum_{a=q,\bar{q}} \Big[\hat{\sigma}^{SGP1}_{q,g} \otimes \Big(x\frac{d}{dx}G^a_F(x,x)\Big) + \hat{\sigma}^{SGP2}_{q,g} \otimes G^a_F(x,x)$$

$$+\hat{\sigma}^{HP}_{q,g} \otimes G^a_F(x_{bj},x) + \hat{\sigma}^{SFP}_{q,g} \otimes G^{\bar{a}}_F(0,x)\Big] \otimes D_{a,g}(z)$$

$$+ \sum_{a=q,\bar{q}} \Big[\hat{\sigma}^{HP'}_{q,g} \otimes \widetilde{G}^a_F(x_{bj},x) + \hat{\sigma}^{SFP'}_{q,g} \otimes \widetilde{G}^{\bar{a}}_F(0,x)\Big] \otimes D_{a,g}(z),$$

HP SFP

· For HP and SFP terms, one can use $G^a_D(x_1,x_2) = G^a_F(x_1,x_2)/(x_1-x_2)$, $\widetilde{G}^a_D(x_1,x_2) = \widetilde{G}^a_F(x_1,x_2)/(x_1-x_2)$.

· $G^{\bar{a}}_F(x_1,x_2)$: anti-quark distribution $\sim \langle\bar{\psi}^c gF^{\perp+}\psi^c\rangle$.

Note: SGP&HP$\sim q\otimes q$, while SFP $\sim q\otimes\bar{q}$.

• Azimuth. dep. of SSA for $ep^{\uparrow} \to e\pi X$ (EKT'07 and YK-Tanaka in preparation)

⋆ G_F and $\tilde{G}_F$ contribution

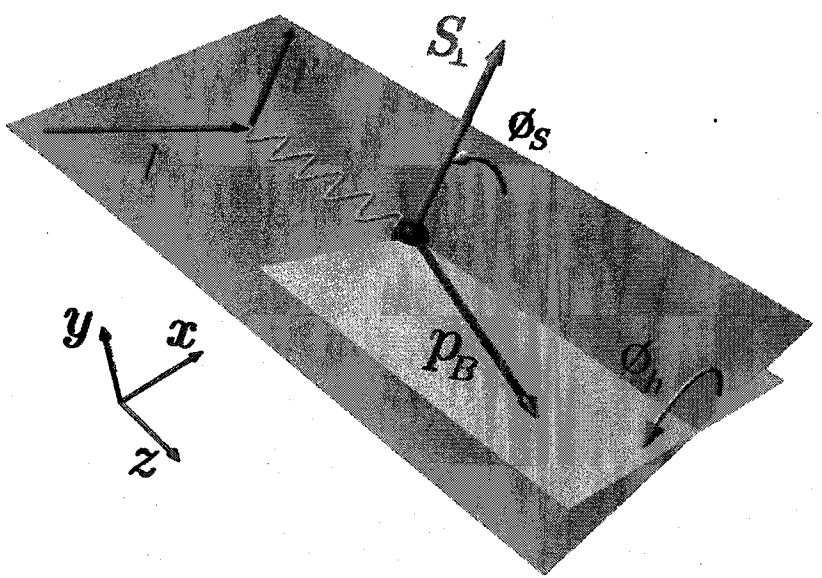
Same as Sivers effect:

$$\frac{d^5\sigma^A}{dQ^2 dx_{bj} dz_f dq_T{}^2 d\phi} = \sin(\phi_h - \phi_S)(\sigma_1 + \sigma_2 \cos(\phi_h) + \sigma_3 \cos(2\phi_h))$$
$$+\cos(\phi_h - \phi_S)(\sigma_4 \sin(\phi_h) + \sigma_5 \sin(2\phi_h))$$

$P_T = z_f q_T$

Second line missed in EKT('07).

(Agrees with JQVY'06 for σ_1.)



5 independent components.

(cf. Bachetta et. al. JHEP('07))

• **Unpol. cross section**

$$\frac{d^5\sigma^U}{dQ^2 dx_{bj} dz_f dq_T{}^2 d\phi}$$
$$= \sigma_1^U + \sigma_2^U \cos(\phi) + \sigma_3^U \cos(2\phi)$$

⋆ Comparison of the two approaches.

(1) Derive the expression for the Twist-3 cross section at $q_T \ll Q$.

- Both from G_F and $\widetilde{G}_F$ including all kinds of poles (SGP, SFP, HP).

(2) Perturbative calculation of the Sivers function $q_T(x, k_\perp)$ at $k_\perp \gg \Lambda_{\rm QCD}$:
Include SFP and $\widetilde{G}_F$ contributions as well.

$\rightarrow$ $q_T(x, k_\perp)$ in terms of $G_F(x_1, x_2)$ and $\widetilde{G}_F(x_1, x_2)$.

$\rightarrow$ Insert it into the TMD factorization formula to get the cross section.

Note :

Only one Sivers function in the TMD factroization.

$\leftrightarrow$ Two functions G_F and $\widetilde{G}_F$ in the Twist-3 mechanism.

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Multi-parton coherence at high x

Paul Hoyer
University of Helsinki

PKU-RBRC Workshop
on Transverse Spin Physics

CHEP, Peking University, 2 July 2008

Abstract:

We consider QCD factorization between hard and soft subprocesses in inclusive reactions where the momentum fraction x of one parton approaches unity as the hard scale $Q^2 \to \infty$, such that $Q^2(1-x)$ is fixed. In this "BB limit" the entire (multi-parton) Fock state containing the high x parton is coherent with the hard subprocess. The soft contribution is given by a forward multiparton matrix element. The BB limit corresponds to a fixed (large or small) missing mass and is thus closely connected to exclusive production. We analyze the Drell-Yan process $h+N \to \gamma^* + X$ in detail, explaining why the virtual photon is longitudinally polarized for $h=\pi$ and transversely polarized for $h=p$. The BB limit may be relevant also for other phenomena observed at high x, such as the large single spin asymmetries of $pp \to \Lambda^\uparrow X$ and in $pp^\uparrow \to \pi X$.

Work in progress with:
M. Järvinen, U. of Southern Denmark
S. Kurki, U. of Helsinki

Summary

Hard inclusive processes have interesting features at high x_F

Large single spin asymmetries $p^\uparrow p \to \pi + X$, ...

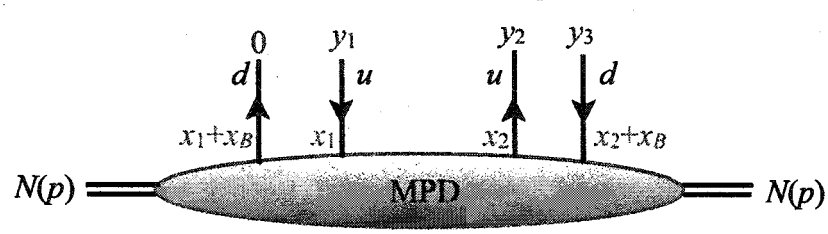
Angular distribution of muon pairs in Drell-Yan $\pi^- N \to \mu^+\mu^- X$

"Higher twist" contributions are suppressed only by $1/Q^2(1-x_F)$

⇒ Consider QCD factorization in a new limit: $Q^2 \to \infty$ with $Q^2(1-x_F)$ fixed

The hard subprocess is coherent with the entire projectile Fock state

Soft matrix element is a forward multi-parton distribution:



Motivation: Photon polarization in Drell-Yan at high x_B

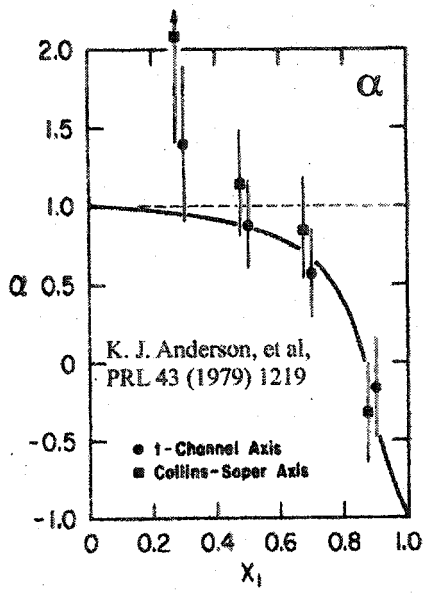


FIG. 2. The dependence of α on x_1 for data with $M > 4$ GeV. The dashed line is the expected result for the naive Drell-Yan model. The solid curve is the QCD prediction of Berger and Brodsky (Ref. 8).

E615: $\pi^- N \to \mu^+\mu^- + X$

$p_{lab} = 263$ GeV/c, $Q > 4$ GeV

$$\frac{d\sigma}{d\cos\theta^*} \propto 1 + \alpha\cos^2\theta^* \to \sin^2\theta^* \text{ as } x_F \to 1$$

Berger and Brodsky, PRL 42 (1979) 940

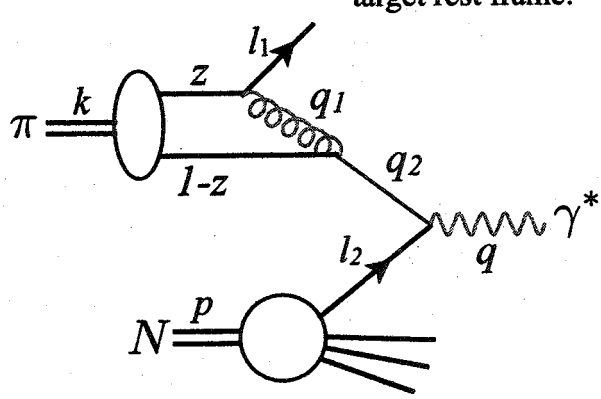
⇒ colliding quark(s) are far off-shell: new subprocess

How does the hard subprocess factorize from the soft matrix element?

Drell-Yan in the BB limit: $Q^2 \to \infty$ at fixed $Q^2(1-x_F)$

Kinematics in the target rest frame:

$k^- = k^0 - k^z \to \infty,\ k^+ = 0$
$p^+ = p^- = m_N$
l_1, l_2 finite



$$\left.\begin{aligned} q_1^2 &\approx -zk^- l_1^+ \\ q_2^2 &\approx -k^- l_1^+ \\ q^2 &\approx k^-(l_2^+ - l_1^+) \end{aligned}\right\} \to \infty$$

Note:
q^2, q_1^2, q_2^2 are independent of *minus* and $\perp$ components of $l_{1,2}$

$$x_F = \frac{q^-}{k^-} \to 1 \qquad x_B \equiv \frac{q^+}{p^+} = \frac{Q^2}{2q\cdot p} = \frac{Q^2}{s} \quad \text{fixed}$$

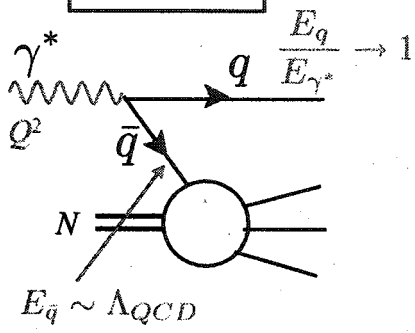
The hadronic mass

$$M_X^2 \equiv (k+p-q)^2 \simeq (1-x_B)[s(1-x_F)+m_N^2] \quad \text{fixed}$$

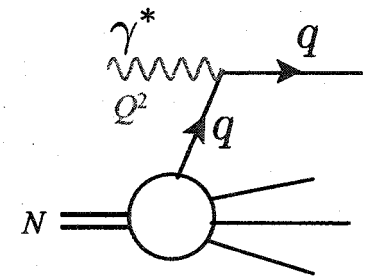
Paul Hoyer CHEP 2 July 2008

Analogy to DIS: "Target rest frame" vs. Handbag

$\boxed{\gamma^* \to q\bar{q}}$



$\boxed{\gamma^* q \to q}$



DIS viewed as photon splitting:

The antiquark is comoving with the target. Its scattering in the target determines DIS σ

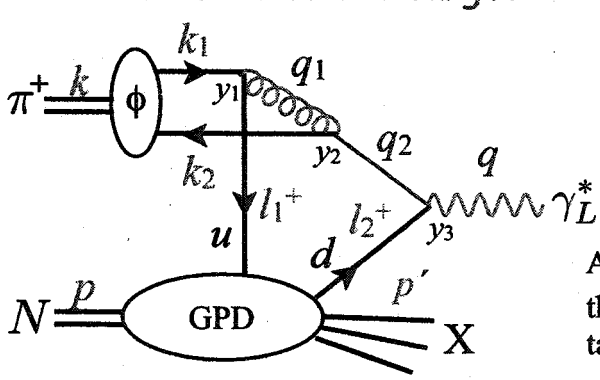
DIS viewed as photon scattering:

The DIS cross section determined by the "probability of finding the quark in the target"

In either case, the large photon virtuality Q^2 arises from the difference in longitudinal momenta of the quarks, not from their transverse momentum

Hence the stopped quark should be connected to the target:

$k_1 = (0^+, zk^-, \boldsymbol{k}_\perp)$
$k_2 = (0^+, (1-z)k^-, -\boldsymbol{k}_\perp)$



Since $q_1^2 \approx -zk^- l_1^+ \to \infty$

the pion wave function contributes through its *distribution amplitude* ϕ

Also q_2^2, q_1^-, $q_2^- \to \infty$, hence the space-time separation of the target interaction points y_1, y_3 is

$$|y_{1\perp} - y_{3\perp}| = \mathcal{O}(1/Q)$$
$$|y_1^+ - y_3^+| = \mathcal{O}(1/Q^2)$$
$$|y_1^- - y_3^-| = \mathcal{O}(1/\ell_1^+)$$

For each final state X the target matrix element is give by a GPD with skewness

$$l_2^+ - l_1^+ = q^+ = x_B\, p^+$$

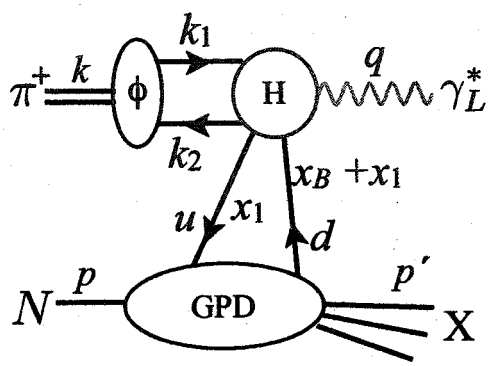
Assuming perturbative propagators for the gluon q_1 and d-quark q_2 and adding three more diagrams we get

$$T(\pi^+ N \to \gamma_L^* X) = \frac{-ieg^2\, C_F}{2\pi Q\sqrt{2N_c}} \int dx_1 C(x_B, x_1)$$

$z = k_1^-/k^-$
$x_B = q^+/p^+$
$x_1 = l_1^+/p^+$

$$\times \int dy_1^-\, e^{-iy_1^- x_1 p^+/2} \langle X(p')|\bar{\psi}_u(y_1)\gamma^+\gamma_5\, \psi_d(0)|p\rangle_{y_1^+ = y_{1\perp} = 0}$$

where $\quad C(x_B, x_1) = \int dz\, \phi_\pi(z) \left(\frac{e_d}{z} \frac{1}{x_1 - i\varepsilon} + \frac{e_u}{1-z} \frac{1}{x_B + x_1 + i\varepsilon} \right)$



For $X = p$ we recognize the time-reversed amplitude for deeply virtual pion production, $\gamma^* + p \to \pi^+ + n$

For $X \neq p$ we have a "transition" GPD L.L. Frankfurt *et al*, PRD **60** (1999) 014010

Next we need to sum over all states X

The $\pi^+ N \to \gamma^* + X$ cross section

$$(2\pi)^3 \frac{d\sigma}{dx_F d^2 q_\perp} = \frac{1}{8sp'^-} \sum_X |T(\pi^+ N \to \gamma^* X)|^2 2\pi\delta(p^+ - q^+ - p'^+)$$

The δ-function can be included in $T^\dagger(\pi^+ N \to \gamma^* X)$ using translation invariance:

$$\frac{1}{2} \int dy_3^-\, e^{iy_3^-(p^+ - q^+ - p'^+)/2} \langle p|\bar{\psi}_d(0)\gamma^+\gamma_5\psi_u(y_2)|p'\rangle$$

$$= \frac{1}{2} \int dy_3^-\, \langle p|\bar{\psi}_d(y_3)\gamma^+\gamma_5\psi_u(y_2 + y_3)|p'\rangle e^{-iy_3^- q^+/2}$$

After the completeness sum $\sum_X |X(p')\rangle\langle X(p')| = 1$

we find the multi-parton distribution

The photon helicity

Naïvely: In the BB limit of $\pi^+ N \to \gamma^* + X$ the photon carries the helicity of the pion ($\lambda = 0$), since the process is coherent on the pion wave function

But: In p $N \to \gamma^* + X$ the photon helicity differs from the proton helicity by $|\Delta\lambda| \geq 1/2$, whether it is longitudinal or transverse. What is then the photon polarization?

Helicity systematics in the BB limit is a consequence of the low transverse momenta, $q_\perp \sim \Lambda_{QCD}$ and the conservation of $J_z = L_z + S_z$

Each unit of L_z brings a suppression $q_\perp/Q \sim \Lambda_{QCD}/Q$

$\Rightarrow$ Leading contribution obtained by setting all $q_\perp = 0$ (when possible)

Helicity conservation for the (massless) quarks then implies
longitudinal photons in $\pi^+ N \to \gamma^* + X$
transverse photons in $p N \to \gamma^* + X$ Consistent with pN DY data (J. C. Peng, private comm.)

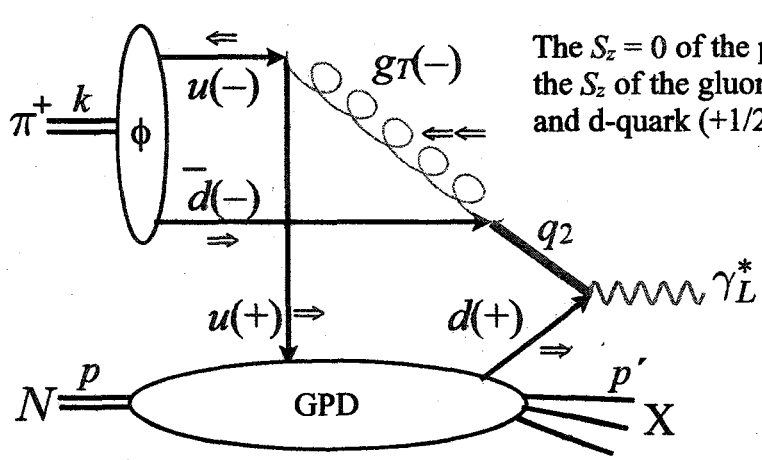
Conservation of S_z

Up to terms $\sim m_q/Q$ the helicity of the quark line is conserved:

Contribution to S_z ($\Rightarrow$ or $\Leftarrow$)determined by direction of motion ($\pm$) for on-shell quarks and antiquarks:

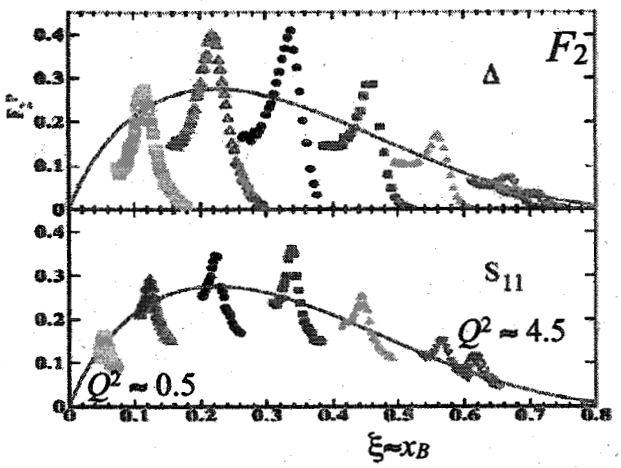
The spin direction of the off-shell quark line q_2 is indefinite.

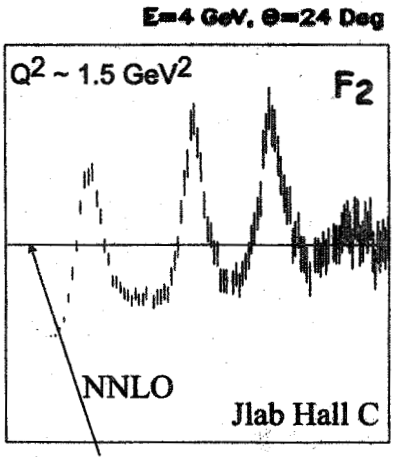
The $S_z = 0$ of the photon is the sum of the S_z of the gluon (–1), the anti-d (+1/2) and d-quark (+1/2)



Bloom - Gilman duality in eN DIS

Jlab Hall C





S. Alekhin, PRD 68 (2003) 014002

Smooth curves: Scaling F_2 at large Q^2 at fixed x_B — Bj limit

Peaks: Δ and S_{11} contributions for increasing Q^2 at fixed $(1\text{-}x_B)\,Q^2$ — BB limit

Duality shows that the Bj and BB limits are simultaneously valid

Summary

Data reveals qualitatively new features of scattering at high x
- Longitudinal photons in πN Drell-Yan
- Large single spin asymmetries

This suggests to consider hard processes at fixed $Q^2(1\text{-}x)$
- Hard subprocess coherent with entire wave function of projectile
- Approaching exclusive processes from better understood region

Cross sections given by forward multi-parton distributions
- Previously studied as a higher-twist contribution in the limit of fixed x
- Physical interpretation analogous to usual 2-parton distributions

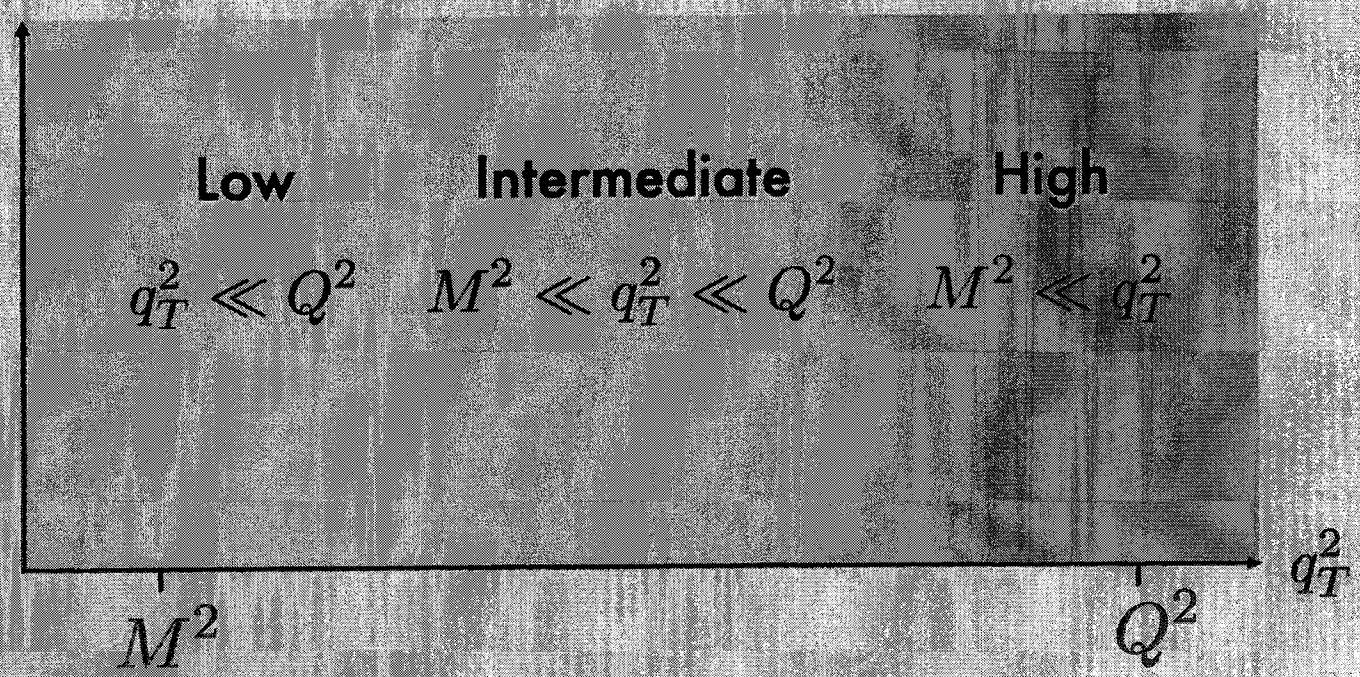
Higher orders in α_s, Q^2-evolution, gluonic distributions;

Phenomenology of multi-parton distributions;

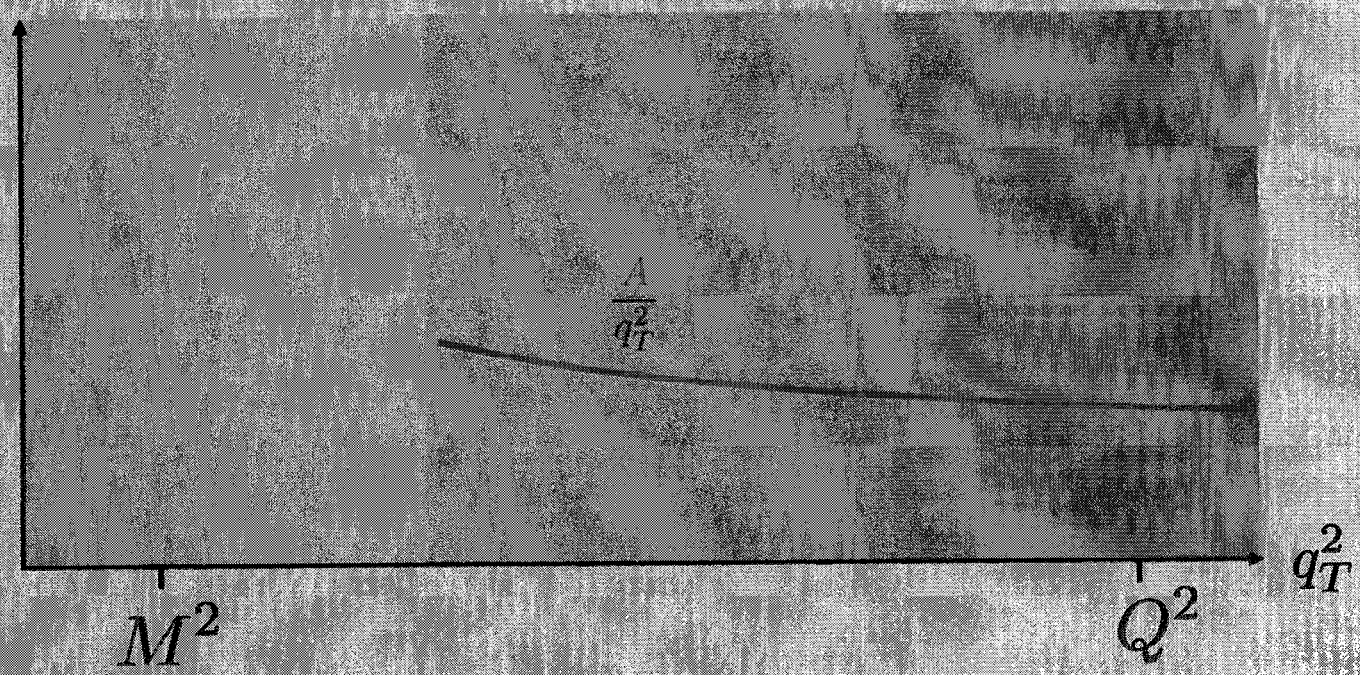
Applications to SSA in $p^{\uparrow}p \to \pi + X$ and other processes...

Remain to be considered

High and low transverse momentum



Matching



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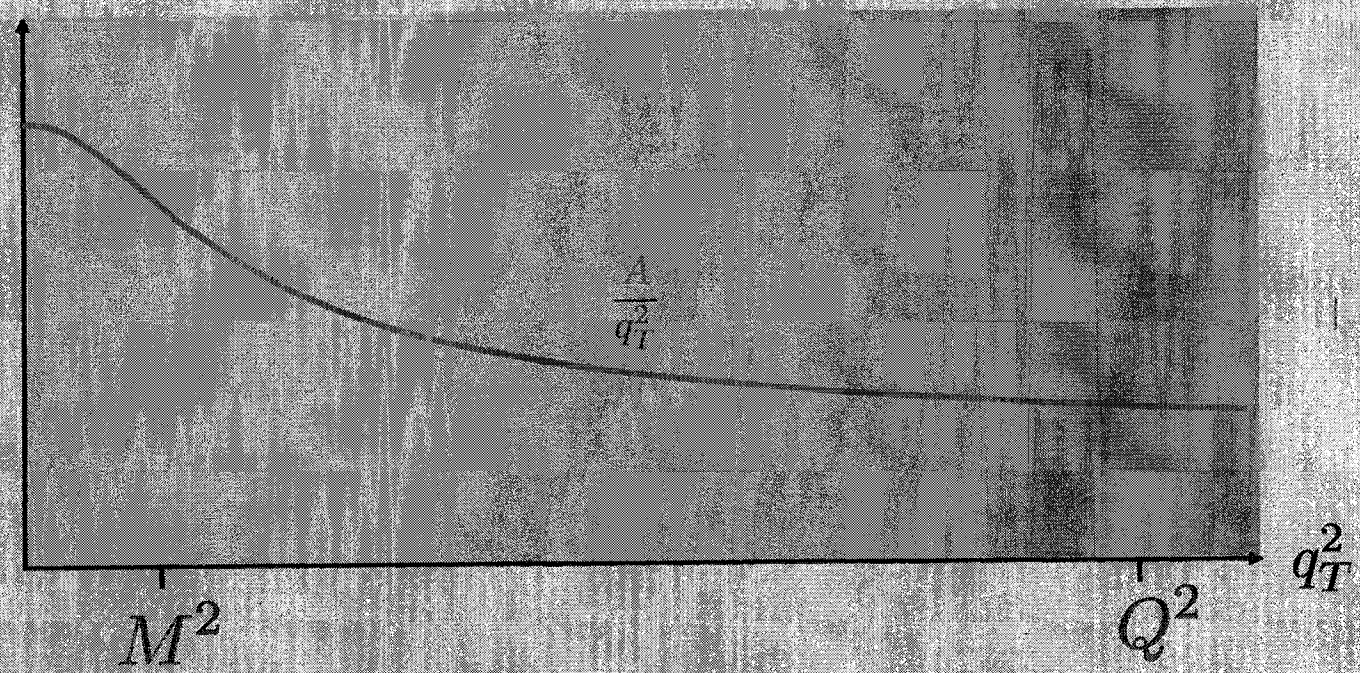

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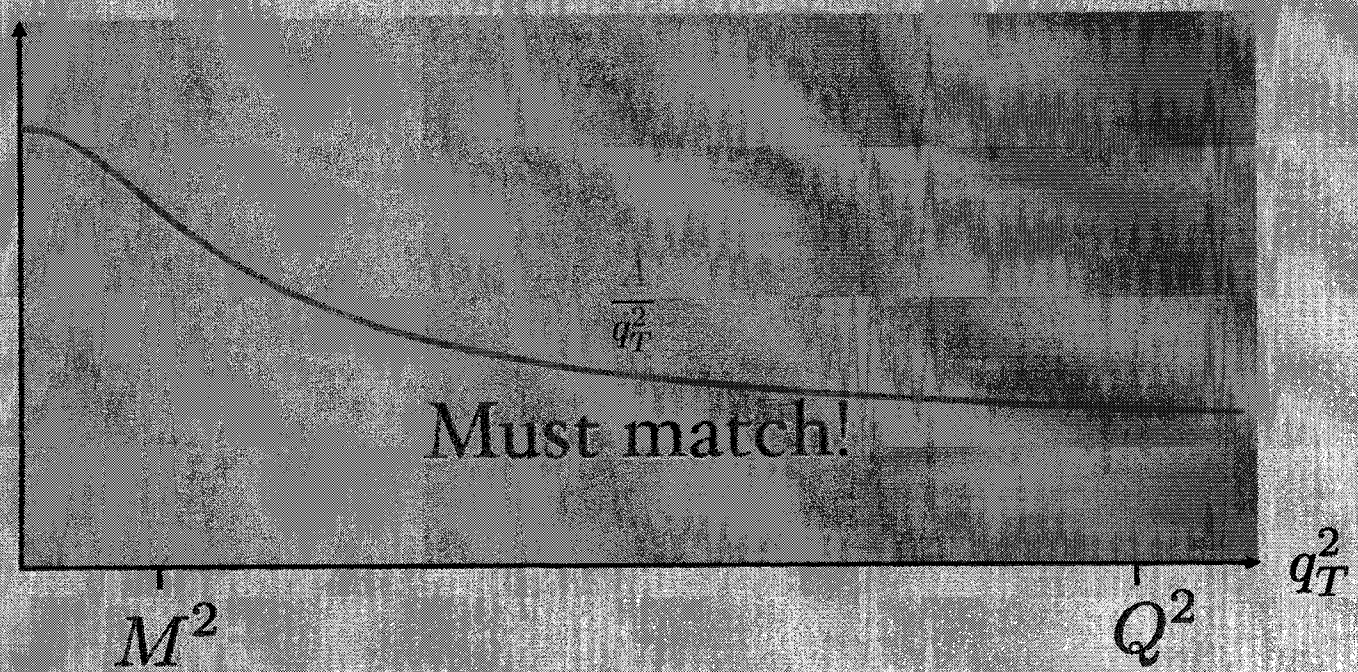

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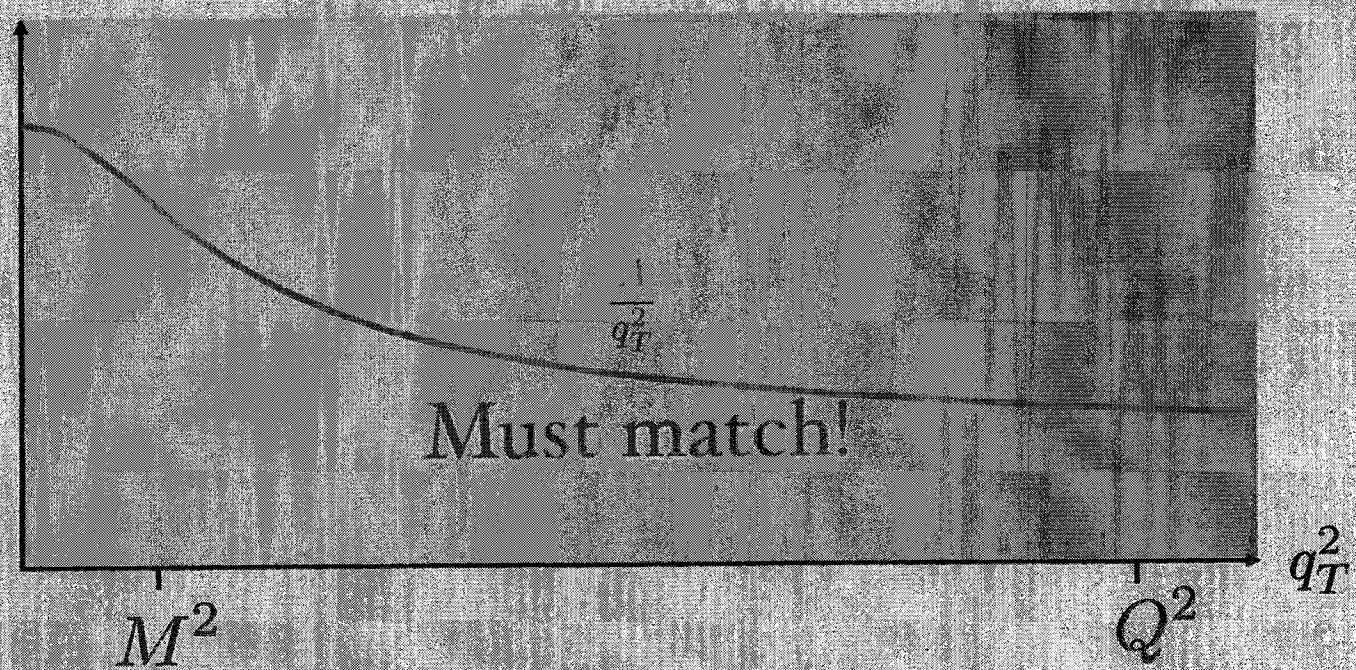
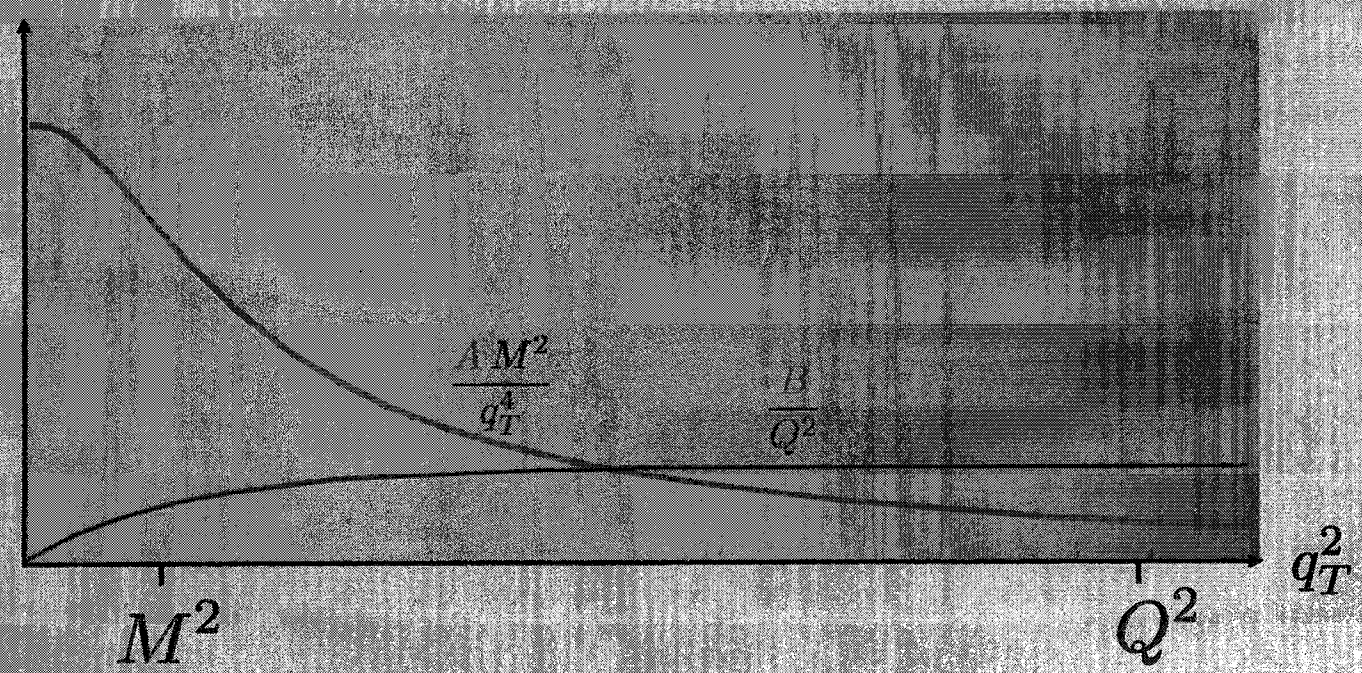


The leading high-q_T part is just the "tail" of the leading low-q_T part

Expected mismatch

The leading terms in the two expansions
CANNOT and MUST not match!



GMC_TRANS
– A Monte Carlo Generator for TMDs –

G. SCHNELL [on behalf of the HERMES Collaboration]

Universiteit Gent, Subatomaire en Stralingsfysica, Proeftuinstraat 86, 9000 Gent, Belgium

Transverse-momentum-dependent parton-distribution as well as fragmentation functions (TMDs) experience a continuing growth of attention, both in experiments and in theory. They were found to provide unique information about the structure of the nucleon, be it spin-orbit correlations of partons inside the nucleon, e.g., the Sivers distribution function, or as probes of otherwise difficult to measure properties, e.g., the Collins fragmentation function giving access to transversity or the Boer-Mulders distribution.

One common aspect of TMDs is their appearance in azimuthal asymmetries. For experimentalists this constitutes a particular challenge: the reliable evaluation of detector-acceptance effects in the course of extracting the particular Fourier and/or Legendre components of the cross section. An acceptance correction can be performed reliably only when the detector acceptance is known fully differential in all relevant variables. Moreover, a satisfactory description of the underlying physics is needed for the kinematic region that lies outside the acceptance but could contribute to the signal, e.g., via smearing.

From this it becomes clear that for the experimental determination of TMDs a reliable Monte Carlo generator is needed. GMC_trans aims at providing just that. Based on a Gaussian Ansatz for the transverse-momentum dependences, analytic expressions are used for the underlying cross section. This allows for a fast physics generator for pseudoscalar production in semi-inclusive DIS that includes contributions from TMDs like the Sivers and Collins functions and that allows direct comparison of implemented (model) and reconstructed azimuthal amplitudes. Various models and fits can be used for the TMDs and the integrated distribution and fragmentation functions.

A satisfactory description for the hadron's transverse momentum was found for pions at HERMES kinematics. A fixed average intrinsic transverse quark momentum and a z-dependent average fragmentation transverse momentum were used for that.

The Collins amplitudes measured at HERMES are reproduced to a very good degree, while the Sivers amplitudes are difficult to reproduce in magnitude but not in shape. One particular problem encountered here is related to the positivity requirements for TMDs. These were derived based on the spin-density matrix for TMDs. While exact inequalities can only be given when considering all TMDs, in GMC_trans approximate expressions were derived by setting all TMDs to zero that were not used in GMC_trans. In that case larger Sivers function then the one used, e.g., the fits by Anselmino et al. that describe the HERMES data quite well, always resulted in violations of the approximate positivity inequalities. Hence, if the Anselmino fits are a good representation of the Sivers function, some of the TMDs that were neglected in GMC_trans must not vanish.

Another outcome of the GMC_trans studies at HERMES is an apparent flaw in the helicity distribution of strange quarks in the GRSV fits. At Q^2 close to 1 GeV^2 it is equal to the number density for a certain range in x. While not of utterly importance it should be taken with care when using these functions as inputs to calculations.

Falsified Lemma I

- **"acceptance cancels in asymmetries"**

$$
\begin{aligned}
A_{UT}(\phi,\Omega) &= \frac{\sigma_{UT}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} && \Omega = x, y, z, \ldots \\
&= \frac{\sigma_{UT}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)} && \epsilon : \textbf{detection efficiency} \\
&\neq \frac{\int \mathrm{d}\Omega\, \sigma_{UT}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)} \neq \frac{\int \mathrm{d}\Omega\, \sigma_{UT}(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)} \equiv A_{UT}(\phi)
\end{aligned}
$$

Acceptance does **not cancel** in general when **integrating** numerator and denominator over (large) ranges in kinematic variables!

Falsified Lemma II

- **use Monte Carlo (physics generator * detector model) to extract acceptance function**
- **"projected acceptance function is independent from cross-section model"**

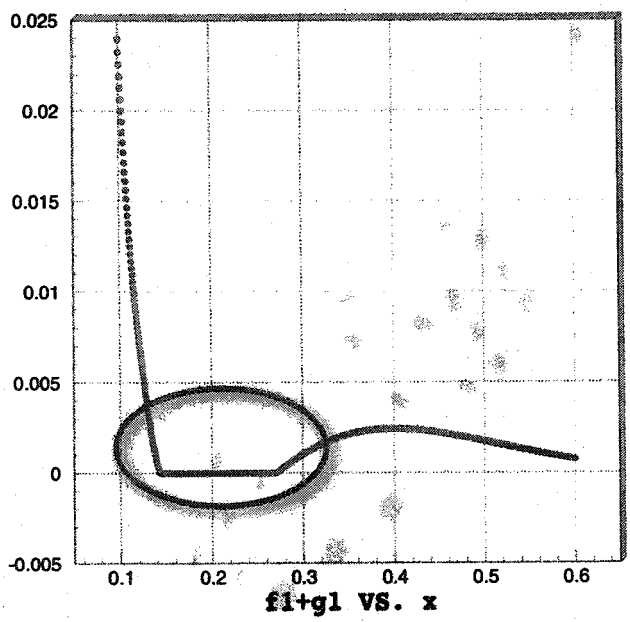
$$
\begin{aligned}
\epsilon(\phi,\Omega) &= \frac{\epsilon(\phi,\Omega)\sigma_{UU}(\phi,\Omega)}{\sigma_{UU}(\phi,\Omega)} && \Omega = x, y, z, \ldots \\
&\neq \frac{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)\,\epsilon(\phi,\Omega)}{\int \mathrm{d}\Omega\, \sigma_{UU}(\phi,\Omega)} \\
&\neq \int \mathrm{d}\Omega\, \epsilon(\phi,\Omega) \equiv \epsilon(\phi)
\end{aligned}
$$

Cross-section model does **not cancel** in general when **integrating** numerator and denominator over (large) ranges in kinematic variables!

Basic workings

- use cross section that can (almost) be calculated analytically
- start from 1-hadron SIDIS expressions of Mulders & Tangerman (Nucl.Phys.B461:197-237,1996) and others
- use Gaussian Ansatz for all transverse-momentum dependencies of DFs and FFs
- unpolarized DFs (as well as helicity distribution) and FFs from fits/parametrizations (e.g., Kretzer FFs etc.)
- "polarized" DFs and FFs either related to unpolarized ones (e.g., saturation of Soffer bound for transversity)or some parametrizations used

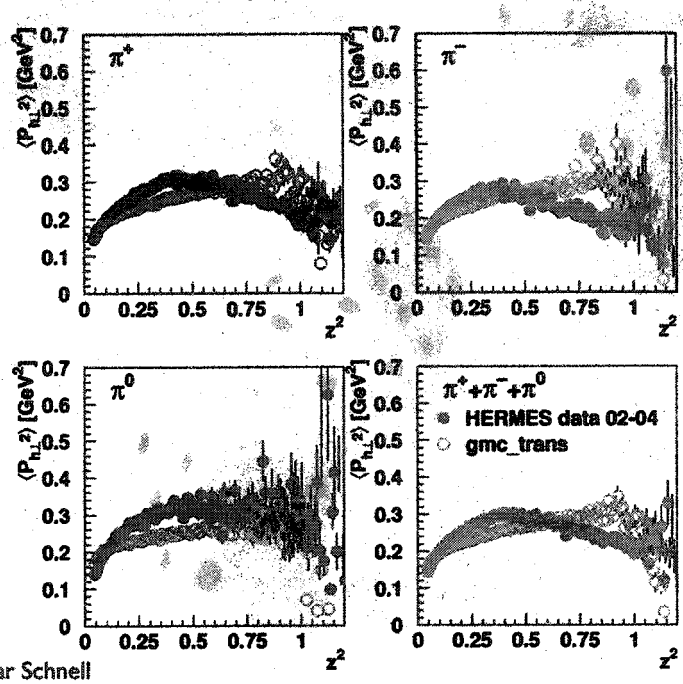
The Strange(!) Sea



- $f_1(x) + g_1(x)$ for strange quarks
- LST(15) = 118; 'standard' scenario, leading order GRSV
- $Q^2=1$
- Soffer bound: $|h_1(x)| < 0.5\{f_1(x)+g_1(x)\}$ can't be fulfilled for nonzero h_1

Tuning the Gaussians in gmc_trans

so far: $\langle P_{h\perp}^2(z)\rangle = z^2 \langle p_T^2\rangle + \langle K_T^2\rangle$



$\langle p_T\rangle = 0.38$

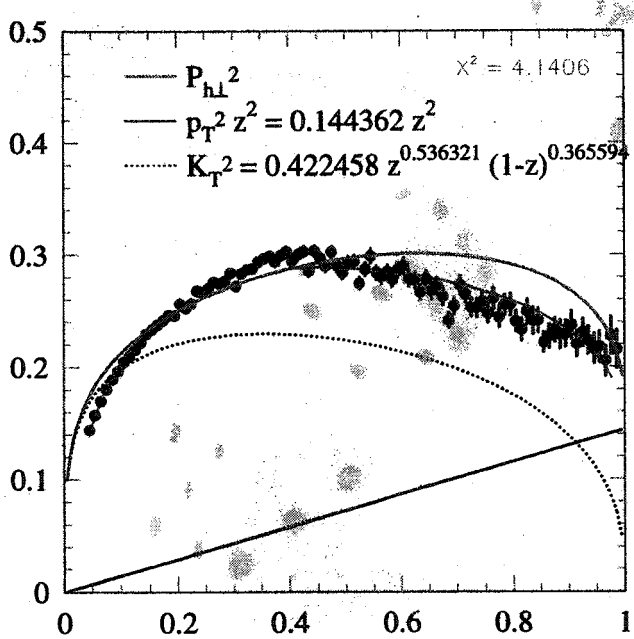
$\langle K_T\rangle = 0.38$

$\langle p_T^2\rangle \simeq 0.185$

$\langle K_T^2\rangle \simeq 0.185$

Tuning the Gaussians in gmc_trans

now: $\langle P_{h\perp}^2(z)\rangle = z^2 \langle p_T^2\rangle + \langle K_T^2(z)\rangle$

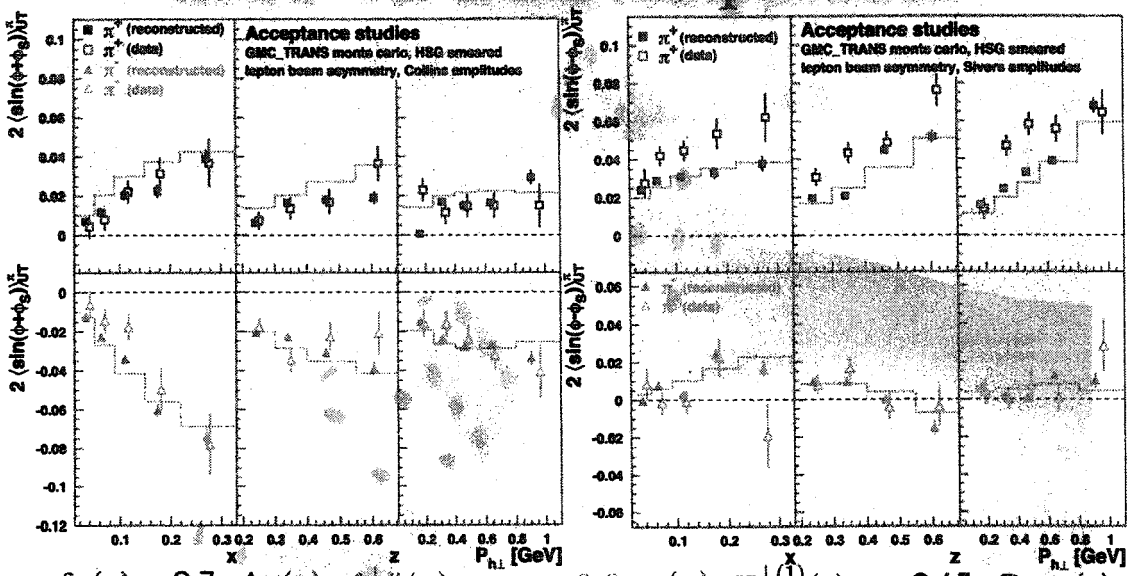


now z-dependent!

tuned to HERMES data in acceptance

"Hashi set"

GMC vs. Data Amplitudes



$$\delta u(x) = 0.7 \cdot \Delta u(x) \quad f_{1T}^{\perp u}(x) = -0.6 \cdot u(x) \quad H_{1,\mathrm{fav}}^{\perp(1)}(z) = 0.65 \cdot D_{1,\mathrm{fav}}(z)$$

$$\delta d(x) = 0.7 \cdot \Delta d(x) \quad f_{1T}^{\perp d}(x) = 1.05 \cdot d(x) \quad H_{1,\mathrm{dis}}^{\perp(1)}(z) = -1.30 \cdot D_{1,\mathrm{dis}}(z)$$

$$\delta q(x) = 0.3 \cdot \Delta q(x) \quad f_{1T}^{\perp q}(x) = 0.3 \cdot q(x) \quad q = \bar{u}, d, s, \bar{s}$$

"hashi" set III for transverse momentum widths $\quad C_S = C_C = 0.25$

Positivity Limits Revisited

- **least stringent positivity constraints only involve considered 'polarized' function and the corresponding unpolarized function, e.g., Sivers vs. f_1**
- **more stringent relations arise from full density density matrix (e.g., Soffer relation for h_1 vs. g_1 and f_1):**

A. Bacchetta, M. Boglione, A. Henneman, and P. Mulders, Phys. Rev. Lett. **85**, 712 (2000).

$$\begin{pmatrix} f_1 + \not{S}_L & \frac{|p_T|}{M} e^{i\phi}(\not{S}_T + i f_{1T}^{\perp}) & \frac{|p_T|}{M} e^{-i\phi}(\not{h}_L^{\perp} + i\not{h}_T^{\perp}) & 2h_1 \\ \frac{|p_T|}{M} e^{-i\phi}(\not{S}_T - i f_{1T}^{\perp}) & f_1 - \not{S}_L & \frac{|p_T|^2}{M^2} e^{-2i\phi} \not{h}_T & -\frac{|p_T|}{M} e^{-i\phi}(\not{h}_T^{\perp} - i\not{h}_L^{\perp}) \\ \frac{|p_T|}{M} e^{i\phi}(\not{h}_T^{\perp} - i\not{h}_L^{\perp}) & \frac{|p_T|^2}{M^2} e^{2i\phi} \not{h}_T & f_1 - \not{S}_L & -\frac{|p_T|}{M} e^{i\phi}(\not{S}_T - i f_{1T}^{\perp}) \\ 2h_1 & -\frac{|p_T|}{M} e^{i\phi}(\not{h}_T^{\perp} + i\not{h}_L^{\perp}) & -\frac{|p_T|}{M} e^{-i\phi}(\not{S}_T + i f_{1T}^{\perp}) & f_1 + \not{S}_L \end{pmatrix}$$

has to be positive definite!

"Critique de Ferrara"

- "positivity limit has to involve either only f_1 or (almost) all PDFs"
- implemented positivity limit in gmc_trans (self-consistently) involves only all in gmc_trans non-zero PDFs: f_1, h_1, Sivers (and if wanted BM)
- however, we know g_1 is not zero, thus at least g_1 has to be considered as well for gmc_trans to be realistic:

$$\frac{p_T^2}{M^2}\left(f_{1T}^{\perp}(x,p_T^2)\right)^2 \leq \left\{\left(f_1(x,p_T^2)\right)^2 - \left(g_1(x,p_T^2)\right)^2\right\}\left\{1 - \frac{2\,|h_1(x,p_T^2)|}{f_1(x,p_T^2)+g_1(x,p_T^2)}\right\}$$

- which positivity constraint is stronger and what about other PDFs?

Sivers & Transversity Fits by Anselmino et al.

g_1=0

```
======  Check positivity limit for Transversity:
iquark= -3: lhs=  0. < rhs=  0.5
iquark= -2: lhs=  0. < rhs=  0.5
iquark= -1: lhs=  0. < rhs=  0.5
iquark= 1: lhs=  0.221290307 < rhs=  0.5
iquark= 2: lhs=  0.356384362 < rhs=  0.5
iquark= 3: lhs=  0. < rhs=  0.5

======  Check positivity limit for T-odd D
iquark= -3: lhs=  0.38756798 < rhs=  0.
iquark= -2: lhs=  0.01550272 < rhs=
iquark= -1: lhs=  0.15502719 <

==========  positiv
iquark= 1: lhs=  0.4
iquark= 2: lhs=
iquark= 3:
```

```
======  Check positivi
iquark= -3: lhs=  0. <
iquark= -2: lhs=
iquark= -1: l
iquark=
iqua
```

```
Check positivity limit for T-odd DFs:
iquark= -3: lhs=  0.38756798 < rhs=  0.38756827
iquark= -2: lhs=  0.01550272 < rhs=  0.38756827
iquark= -1: lhs=  0.15502719 < rhs=  0.38756827

==========  positivity violation!
iquark= 1: lhs=  0.58568429 > rhs=  0.38756827
iquark= 2: lhs=  0.21341756 < rhs=  0.38756827
iquark= 3: lhs=  0.09301631 < rhs=  0.38756827
```

Non-Trivial Role of other TMDs!?

- Si ction rather close to positivity limit for **anti-s**
- Sive s function for **d quarks 20% too large**

T-odd Fragmentation and Gluonic Pole Matrix Elements

Leonard Gamberg† Penn State Berks

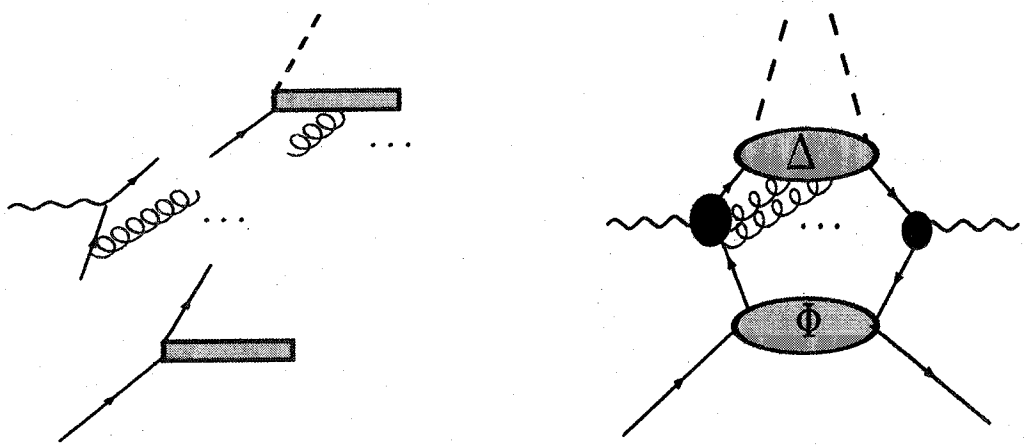
PKU-RBRC Workshop on Transverse Spin Physics

July 2, 2008
Peking University

With A. Mukherjee(IIT Mumbai) and P. J. Mulders (VU Univ.Amsterdam)
based on arXiv:0803.2632 to appear in PRD

T-Odd Effects Process Dependence and QCD-Wilson Line

- ***Sub-class of interactions*** **of** ***colinear & transverse*** **gluons re-summed to render** ***physical process*** **color gauge invariant**
  Boer, Mulders: NPB 2000, Ji et al, PLB: 2002, NPB 2003, Boer et al NPB 2003



etc . . .

- **Wilson line emerges from resummation of gluon ISI and FSI** ***btw. active quark and hadron remnants*** $\rightarrow U^{[C]}_{[0,\xi]} = \mathcal{P}exp(-ig\int_0^\xi ds^\mu A_\mu)$

- **The path $[C]$ is fixed by hard subprocess within hadronic process.**

$$\Phi^{[\mathcal{U}[C]]}(x, p_T) = \int \frac{d\xi^- d^2\xi_T}{2(2\pi)^3} e^{ip\cdot\xi} \langle P|\overline{\psi}(0)\mathcal{U}^{[C]}_{[0,\xi]}\psi(\xi^-, \xi_T)|P\rangle|_{\xi^+=0}$$

$$\Delta^{[\mathcal{U}[C]]}(z, k_T) = \int \frac{d\xi^+ d^2\xi_T}{4z(2\pi)^3} e^{ik\cdot\xi} \langle 0\,|\mathcal{U}^{[C]}_{[0,\xi]}\psi(0)|x; P_h\rangle\langle x; P_h|\overline{\psi}(\xi^+, \xi_T)|0\rangle|_{\xi^-=0}$$

- **See Ch. 3 Ph.D Thesis C. Bomhof**

Process Dependence. . . & Qiu Sterman Mech. from Gauge Links

- **For the weighted cross sections the process dependence is in *gluonic pole factors*** *Bomhof, Mulders 2006-2008 JHEP,NPB...* **see talk of Piet Mulders**

$$
\begin{aligned}
< q_T^\alpha \sigma > &\sim \tilde{\Phi}_\partial^{\alpha[\not{C}]}(x)\hat{\sigma}_{lq\to lq}\Delta(z) + \pi\Phi_G^{\alpha[\not{C}]}(x,x)\hat{\sigma}_{lq\to lq}\Delta(z) \\
< q_T\ \sigma^{\text{Sivers}}_{lH\to lhX} > &\sim +f_{1T}^{\perp(1)}(x)\hat{\sigma}_{lq\to lq}D_1(z) \\
< q_T\ \sigma^{\text{Sivers}}_{H\bar{H}\to l\bar{l}X} > &\sim -f_{1T}^{\perp(1)}(x_1)\hat{\sigma}_{q\bar{q}\to l\bar{l}}\bar{f}_1(x_2) \\
f_{1T}^{\perp(1)}(x) &= -\frac{g}{2M}T_F(x)
\end{aligned}
$$

Boer,Pijlman,Mulders 2003 NPB

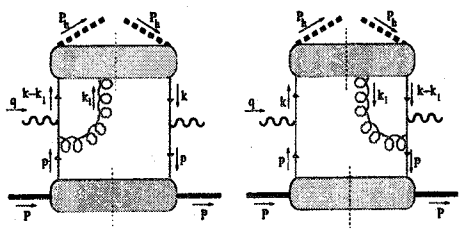
- **For more complicated processes one gets gluonic pole factors "$[C]$"**

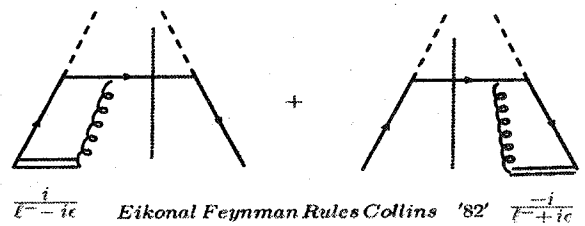
$$
\begin{aligned}
\Phi_\partial^{\alpha[C]}(x) &= \tilde{\Phi}_\partial^{\alpha[\not{C}]}(x) + C_G^{[U(C)]}\pi\Phi_G^{\alpha[\not{C}]}(x,x) \\
\Delta_\partial^{\alpha\,[C]}(z) &= \tilde{\Delta}_\partial^{\alpha[\not{C}]}\left(\tfrac{1}{z}\right) + C_G^{[U(C)]}\pi\Delta_G^{\alpha[\not{C}]}\left(\tfrac{1}{z},\tfrac{1}{z}\right).
\end{aligned}
$$

- **Universality violated from gluonic pole matrix elements Sivers asymmetry**
  Collins Qui, Collins PRD 2007,2008 $H\,H \to\ h\,h\,X$ **at high** P_T

"Gluonic Poles" & Gauge Link for T-Odd Collins Function "some history"

$$\Delta^{[\sigma^{\perp -}\gamma_5]}(z, k_\perp) = \frac{1}{4z}\int dk^+ Tr(\gamma^-\gamma^\perp\gamma_5\Delta)\Big|_{k^-=P_\pi^-/z}$$





- ***Motivation: color gauge .inv frag. correlator* "pole contribution"**

- **Gribov-Lipatov Reciprocity 1974, Mulders et al. 1990s for T-even Fragmentation. Applied to T-odd Fragmentation L.G.,Goldstein,Oganessyan PRD68,2003**

★ **Metz 2002 PLB to 1-loop-same sign $H_1^\perp$ for e^+e^- and SIDIS: result, implies universality preserved**

★ **Collins Metz PRL 2004 demonstrate to universality in "spectator field theory"**

★ **Basis for cut method and pheno. Bacchetta, Metz, Yang, PLB 2003, Amrath Bacchetta, Metz : PRD 2005, Bacchetta, L.G. Goldstein, Mukherjee PLB 2008**

★ **Reciprocity Fails, "T-odd" Fragmentation Function Universal between e^+e^- and SIDIS to *one loop.***

★ ***Yuan, PRL 2008 Universality to two loops of fragmentation in azimuthal distr. of hadrons in a high energy jet $p\ p^\uparrow$***

Revisit Gluonic Poles contributions-Fragmentation & Universality

(L.G. Mukherjee, Mulders to appear PRD-2008)

- **By contrast to one and two loop calcs. studying cuts we explore parton correlator with one additional gluon taking the zero $k_1^{\pm} \to 0$ limit; gluonic pole matrix element/Efremov-Terayev-Qiu Sterman Matrix elements**

- **Gluonic Poles Identify the T-odd sources and possible non-universal or process dependent contributions in PDFs and FFs**
  Boer, Pijlman, Mulders NPB 03, Bacchetta, Bomhof, Mulder, Pijlman PRD 05, Bomhof Mulders 07, 08, Bomhof, Mulders, Vogelsang, Yuan PRD 07.

$$\Phi_\partial^{\alpha\,[\mathcal{U}]}(x) = \int d^2k_T\; k_T^\alpha\, \Phi^{[\mathcal{U}]}(x,k_T) = \tilde{\Phi}_\partial^\alpha(x) + C_G^{[\mathcal{U}]}\, \pi \Phi_G^\alpha(x,x)$$

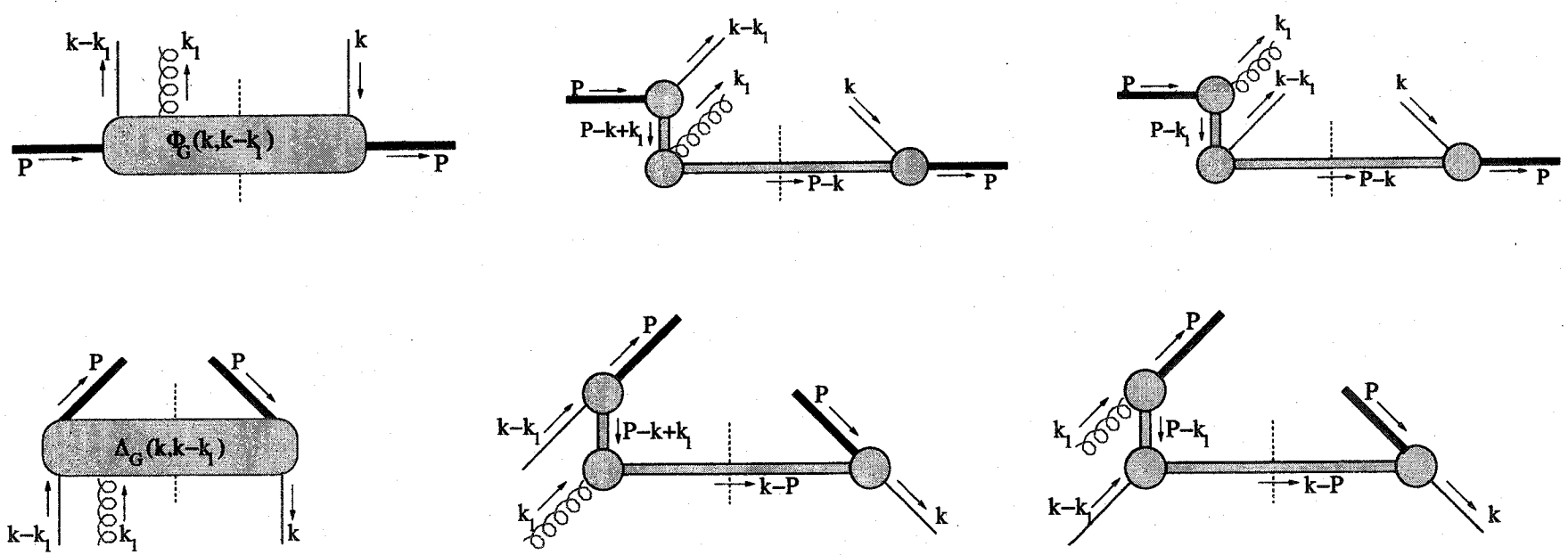
$$\Delta_\partial^{\alpha\,[\mathcal{U}]}(z) = \int d^2k_T\; k_T^\alpha \Delta^{[\mathcal{U}]}(z,k_T) = \tilde{\Delta}_\partial^\alpha\left(\tfrac{1}{z}\right) + C_G^{[\mathcal{U}]}\, \pi \Delta_G^\alpha\left(\tfrac{1}{z},\tfrac{1}{z}\right).$$

- **In doing so we investigated the "reciprocity" btwn distrb. and frag. functions $x \to 1/z$**
  $h_1^{\perp(1)}$ and $H_1^{\perp(1)}$ for example

Spectral Analysis Gluonic Poles-Fragmentation

- **In this approach rather than integrating over the longitudinal component of the "loop momenta" we look at the limit of a zero gluon momentum in quark-gluon-quark matrix element, Qiu Sterman matrix element**

- **We calculate them by considering the multi-parton correlators $\Phi_G(k, k-k_1)$ and $\Delta_G(k, k-k_1)$ in light-cone gauge**



Calculate the Weighted Frag. correlator

- The T-odd operator-combination that appears in the transverse moment,

$$\Delta^{\alpha}_{\partial}(z;n,C) = \int d^2k_T k_T^{\alpha} \Delta(x,k_T;n,C) = \tilde{\Delta}^{\alpha}_{\partial}(z) + \pi \Delta^{\alpha}_{G}(z)$$

yields the gluonic pole matrix element which is characterized by the difference of the transverse gluon field at $\pm\infty$,

$$\begin{aligned}\Delta^{\alpha}_{G\,ij}(z;n,C) &= \sum_X \int \frac{d(\xi\cdot P_h)}{2\pi} e^{ik\cdot\xi} \langle 0| \left(A^{\alpha}_T(\infty) - A^{\alpha}_T(-\infty)\right) \\ &\quad \times \psi_i(\xi)|P_h,X\rangle\langle P_h,X|\bar{\psi}_j(0)|0\rangle\Big|_{\xi\cdot n_h=\xi_T=0}\end{aligned}$$

where

$$A^{\alpha}_T(\infty) - A^{\alpha}_T(-\infty) = \int_{-\infty}^{\infty} d(\eta\cdot P_h) G^{n_h\alpha}(\eta)\Big|_{\eta\cdot n_h=\eta_T=0}.$$

Straightforward Integration

$$\Phi_G(x, x_1 - x) \sim \frac{1}{(k^2 - m^2)} \left\{ \int \frac{dk_1^-}{2\pi i} \frac{F_1\left(k_1^-, x, x_1, k_T, k_{1T}\right)}{(k_1^2 - m_1^2 + i\epsilon)((k - k_1)^2 - m^2 + i\epsilon)((P - k + k_1)^2 - M_{s1}^2 + i\epsilon)} \right.$$
$$\left. + \int \frac{dk_1^-}{2\pi i} \frac{F_2\left(k_1^-, x, x_1, k_T, k_{1T}\right)}{(k_1^2 - m_1^2 + i\epsilon)((k - k_1)^2 - m^2 + i\epsilon)((P - k_1)^2 - M_{s2}^2 + i\epsilon)} \right\}$$

where, $F_i\left(k_1^-, x, x_1, k_T^2, k_{1T}^2\right)$ **contain numerators and vertex functions**

- **Assume numerator doesn't grow with** k_1^- **can perform** k_1^- **integrations**

$$\Theta^m_{n_1 n_2 \ldots}(x_1, x_2, \ldots) = \int \frac{d\alpha}{2\pi i} \frac{\alpha^m}{(\alpha x_1 - 1 + i\epsilon)^{n_1} (\alpha x_2 - 1 + i\epsilon)^{n_2} \ldots},$$

- **Take** $x_1 \to 0$ **we get gluonic pole correlators, distribution and** $(0 \leq x \leq 1)$ **and Fragmentation functions** $(x = 1/z \geq 1)$

$$\Delta_G(x, x) = 0 \quad \text{and} \quad \Phi_G(x, x) \neq 0$$

SUMMARY

- Going beyond the collinear approximation in PQCD progress has been achieved characterizing transverse SSA and azimuthal asymmetries through "rescattering" mechanisms which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist
- Central to this understanding is the role of correlations between transverse momentum and transverse spin in QCD hard scattering
- In spectator framework we find the contribution to gluonic pole matrix element vanishes for fragmentation functions and survives for PDFs
- Outcome important for the study of universality for fragmentation functions and confirms the findings of different approaches.
- Universal Collins and Sivers Fragmentation function have impact on the transversity programs Belle, COMPASS, HERMES, RHIC, have uncovered large effects and near term Hall-A Transversity will start to check flavor structure of T-odd TMDs
- Future experiments to uncover the Boer Mulders function was approved at JLAB- Hall B-CLAS12 proposal and also possibilities at GSI, RHIC, JPARC . . . on $\cos 2\phi$.

Transverse Momentum Dependent Distribution and Fragmentation Functions

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Sejong University

PKU-RBRC Workshop on Transverse Spin Physics
Beijing, June 30 - July 4, 2008

1. Light-Cone WF Reps. of $f_{1T}^{\perp}$ and $h_1^{\perp}$

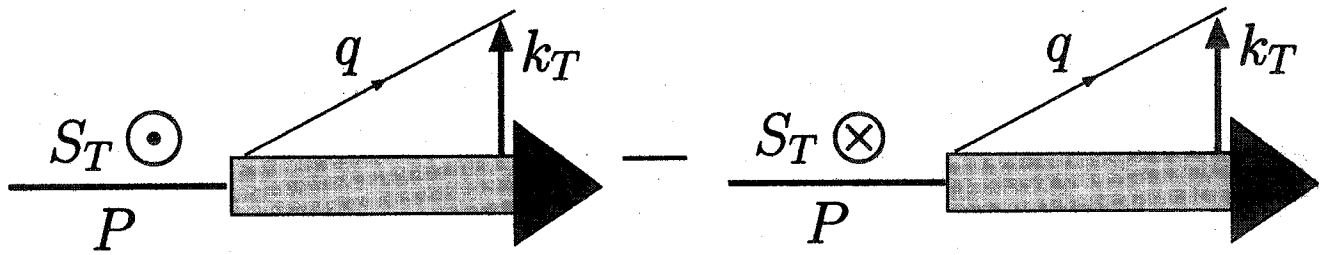


Figure 1: Sivers distribution function $f_{1T}^{\perp}$.

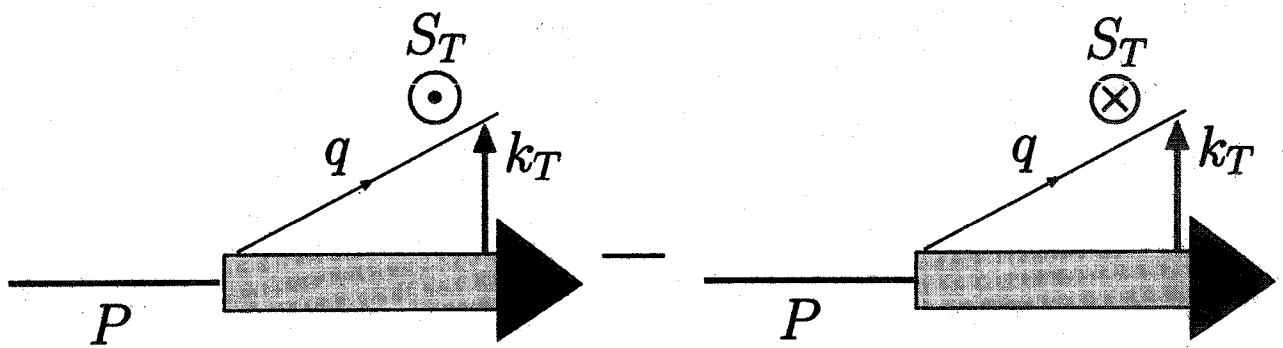


Figure 2: Boer-Mulders distribution function $h_1^{\perp}$.

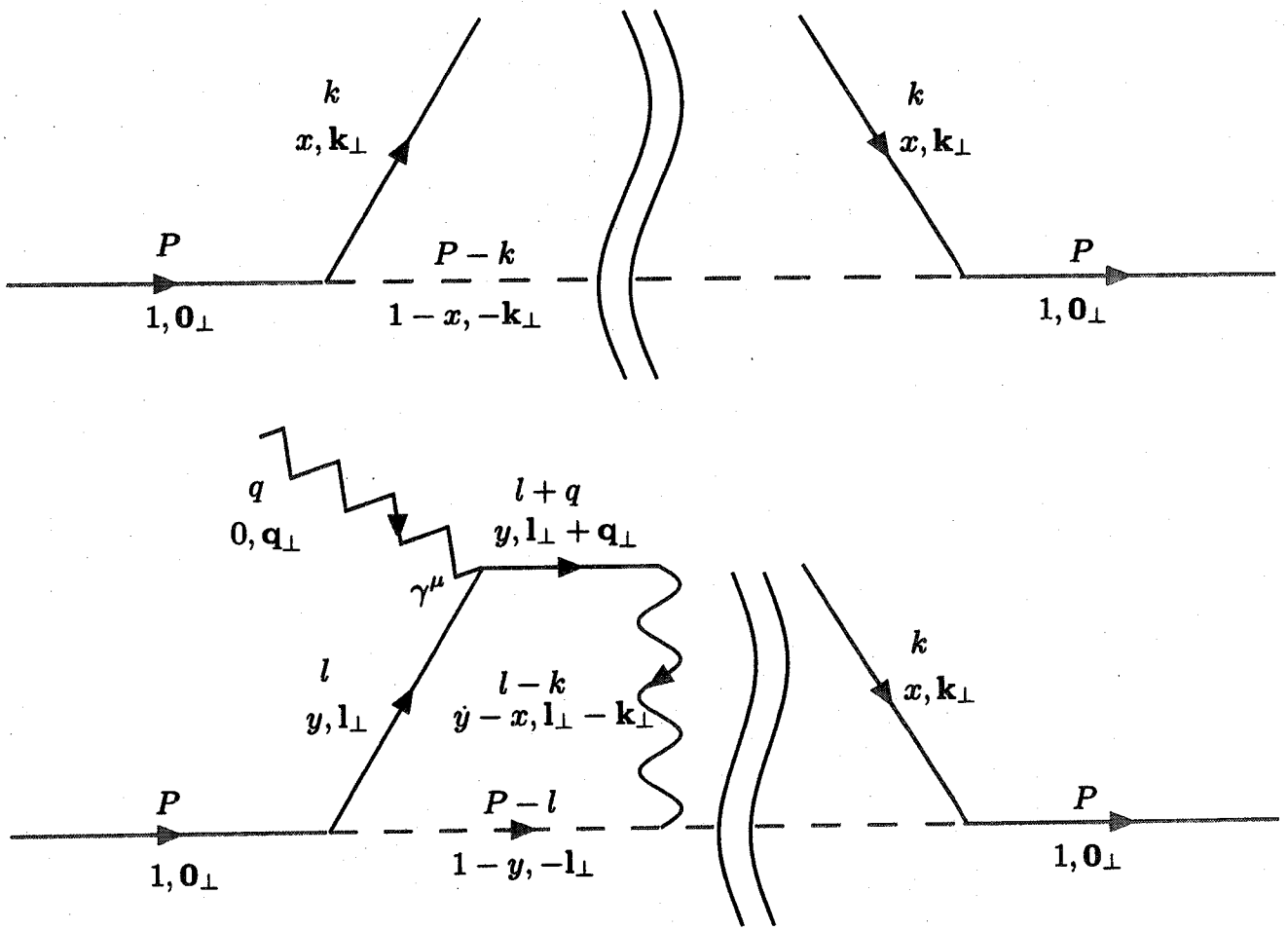
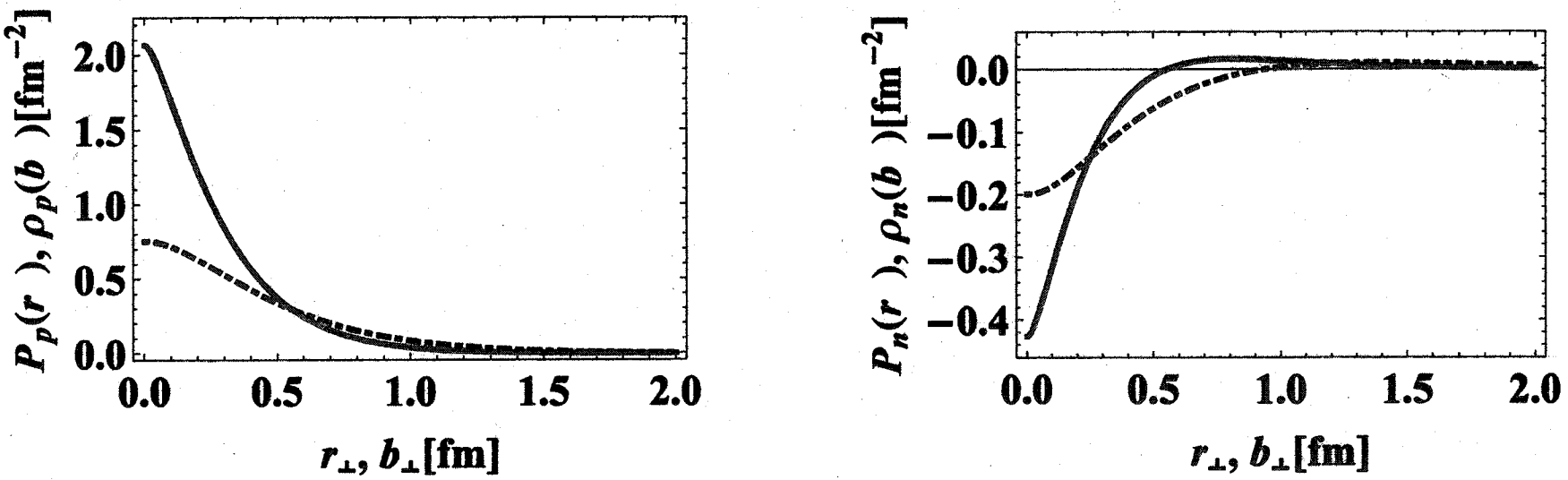


Figure 3: Diagrams for f_1, $f_{1T}^\perp$ and $h_1^\perp$.



(a) (b)

Figure 7: The results of $P(\mathbf{r}_\perp)$ (dash-dot line) and $\rho^{\mathrm{Imp}}(\mathbf{b}_\perp)$ (solid line) for proton and neutron for the fitted scalar diquark model.

3. $D_1(z, \mathbf{p}_\perp)$ Dependence of σ_0

(With Hyungsuk Son)

$$\sigma_0 = \frac{\pi}{xy^2}\left[1+(1-y)^2\right]\Sigma_q e_q^2 \int d^2\mathbf{k}_\perp\, f_1^q(x,\mathbf{k}_\perp)\, D_{1q}^h(z, \mathbf{P}_{hT} - z\mathbf{k}_\perp)\,.$$

$$f_1^q(x,\mathbf{k}_\perp) = f_1^q(x)\frac{1}{\pi\mu_0^2}\exp\left(-\frac{\mathbf{k}_\perp^2}{\mu_0^2}\right),$$

(1) $$D_{1q}^h(z,\mathbf{p}_\perp) = D_{1q}^h(z)\frac{1}{\pi\mu_D^2}\exp\left(-\frac{\mathbf{p}_\perp^2}{\mu_D^2}\right),$$

(2) $$D_{1q}(z,\mathbf{p}_\perp) = \frac{1}{z}\frac{g_A^2}{4F_\pi^2}\frac{1}{16\pi^3}\left(1-4\frac{1-z}{z^2}\frac{m^2\, m_\pi^2}{(\frac{\mathbf{p}_\perp^2}{z^2}+m^2+\frac{(1-z)}{z^2}m_\pi^2)^2}\right).$$

(1) Anselmino, Efremov, Kotzinian, and Parsamyan, Phys. Rev. D 74, 074015 (2006).

(2) Bacchetta, Kundu, Metz, Mulders, Phys. Rev. D 65, 094021 (2002).

HERMES (0.1<x<0.6, 0.45<y<0.85 and 0.4<z<0.7)

COMPASS (0.1<x<0.6, 0.5<y<0.9 and 0.4<z<0.9)

JLAB (0.2<x<0.6, 0.4<y<0.85 and 0.4<z<0.7)

[Parameter values used in (1).]

Conclusion

1. Light-cone wavefunction representations are useful for understanding the properties of Sivers and Boer-Mulders distribution functions.

2. Charge distributions of quarks inside nucleons are studied in the transverse coordinate and impact parameter spaces.

3. Measurement of $\mathbf{P}_{hT}$ dependence of σ_0 can be used as an experimental method for distinguishing $\mathbf{p}_\perp$ dependent $D_1(z, \mathbf{p}_\perp)$ models.

SIDIS asymmetries in Quark-Diquark model for Distribution Functions

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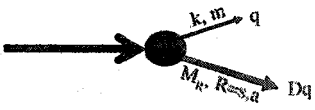
Abstract

Some properties of intrinsic transverse momentum dependent nucleon distribution functions are considered in the simple quark-diquark model. The transverse target polarization dependent asymmetries for SIDIS are calculated and compared with recent results of COMPASS. The model describes well the measured asymmetries. Predictions for transversely polarized target asymmetries are presented.

Generalization of quark-diquark model for Sivers function is discussed. We note, that the Sivers function calculated using the mechanism of final state interaction in SIDIS for some choices of formfactor in quark-diquark model violates the positivity constraint.

Quark-Diquark model for DFs

R. Jakob, P. Mulders & Rodrigues NP A626, 937 (1997)



Choose exponential form-factor:

$$N\frac{k^2-m^2}{|k^2-\Lambda^2|^\alpha} \Rightarrow N(k^2-m^2)\exp\left(\frac{k^2}{2\Lambda^2}\right)$$

$$f_1^R(x,k_T^2) = f_0^R(x,k_T^2)\left[(xM+m)^2+k_T^2\right]$$

$$g_1^R(x,k_T^2) = a_R f_0^R(x,k_T^2)\left[(xM+m)^2-k_T^2\right]$$

$$f_0^R(x,k_T^2) = N_R^2 \exp\left(\frac{x(1-x)M^2 - xM_R^2}{\mu^2(x)}\right)\left(\frac{1}{\pi\mu^2(x)}\exp\left(-\frac{k_T^2}{\mu^2(x)}\right)\right)$$

$$\mu^2(x) = \Lambda^2(1-x),\quad a_s = 1,\quad a_v = -\frac{1}{3}$$

Only few common parameters, m_q=0.36, M_A=0.8, M_S=0.6, Λ=0.5 (GeV/c), for all DFs

No x-k_T factorization and width of intrinsic transverse momentum depends on x

$A_{UT}^{\sin(\varphi_h-\varphi_s)}$ Sivers asymmetry

$$A_{UT,T}^{\sin(\varphi_h-\varphi_s)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h = 0$$

Since

$$f_{1T}^{\perp q} = 0 \text{ in this model}$$

$$F_{UU} = F_{UU,T} + \varepsilon F_{UT,L}$$

$$A_{UT}^{\sin(\varphi_h-\varphi_s)} = A_{UT,T}^{\sin(\varphi_h-\varphi_s)} + \varepsilon A_{UT,L}^{\sin(\varphi_h-\varphi_s)}$$

$$F_{UT,L} \propto \frac{1}{Q^2},\quad A_{UT,L}^{\sin(\varphi_h-\varphi_s)} \propto \frac{1}{Q^2}$$

Further comments later

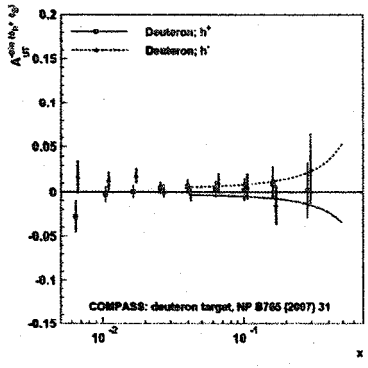
$A_{UT}^{-\sin(\varphi_h+\varphi_s)}$ Collins asymmetry @ COMPASS

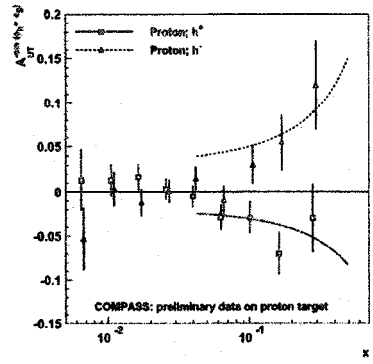
$$A_{UT}^{\sin(\varphi_h+\varphi_s)} \propto h_1^q \otimes H_{1q}^{\perp h}$$

$$h_1^q(x,k_T^2) = a_k f_0^q(x)(xM+m)^2 \exp\left(-\frac{k_T^2}{(1-x)\Lambda^2}\right)$$

$H_{1q}^{\perp h}$ from Anselmino *et al.* global analysis

$$f_0^q(x) = \frac{N^2}{(1-x)^2} \exp\left(-\frac{x(1-x)M^2 - xM_R^2}{(1-x)\Lambda^2}\right)$$





Beijing, July 2, 2008 Aram Kotzinian 3

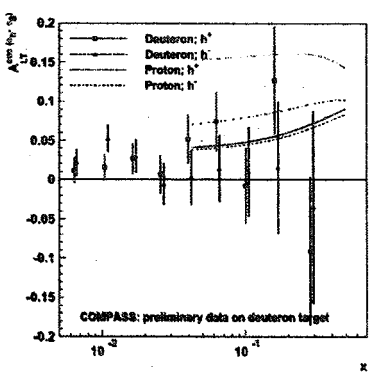
$A_{LT}^{\cos(\varphi_h-\varphi_s)}$ and $A_{UT}^{\sin(3\varphi_h-\varphi_s)}$ @ COMPASS

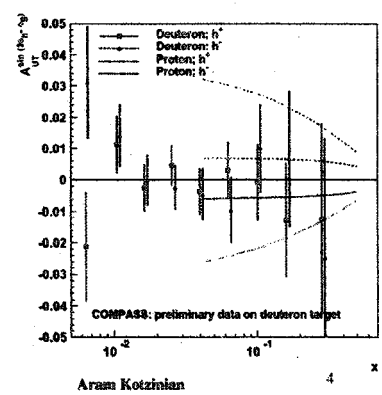
$$A_{LT}^{\cos(\varphi_h-\varphi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$g_{1T}^q(x,k_T^2) = 2a_k f_0^q(x) M(xM+m) \exp\left(-\frac{k_T^2}{(1-x)\Lambda^2}\right)$$

$$A_{UT}^{\sin(3\varphi_h-\varphi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

$$h_{1T}^{\perp q}(x,k_T^2) = -2a_k f_0^q(x) M^2 \exp\left(-\frac{k_T^2}{(1-x)\Lambda^2}\right)$$





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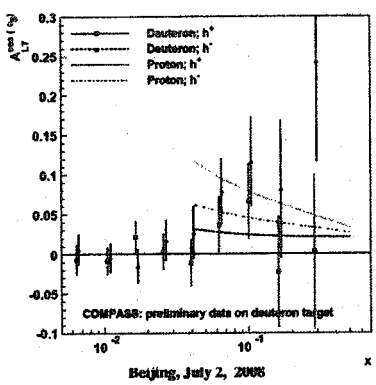
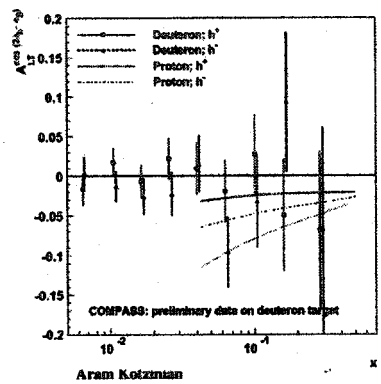
$A_{LT}^{\cos\varphi_s}$ and $A_{LT}^{\cos(2\varphi_h-\varphi_s)}$ @ COMPASS

$$A_{LT}^{\cos(\varphi_s)} \propto \frac{M}{Q} g_{1T}^{q} \otimes D_{1q}^{h}$$

$$A_{LT}^{\cos(2\varphi_h-\varphi_s)} \propto \frac{M}{Q} g_{1T}^{q} \otimes D_{1q}^{h}$$





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$A_{UT}^{\sin\varphi_s}$ and $A_{UT}^{\sin(2\varphi_h-\varphi_s)}$ @ COMPASS

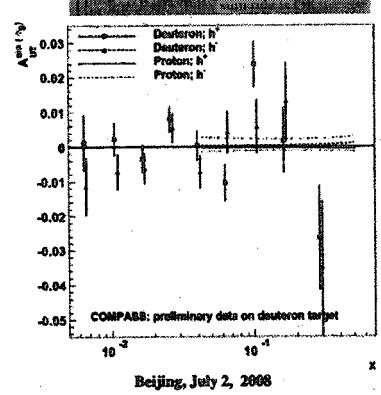
$$A_{UT}^{\sin(\varphi_s)} \propto \frac{M}{Q}\left[h_{1T}^{q} \otimes H_{1q}^{\perp} + f_{1T}^{\perp} \otimes D_{1q}^{h}\right]$$

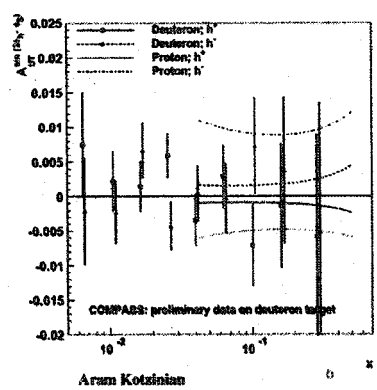
$$F_{UT}^{\sin(\phi_S)} \propto \frac{2(\mu_s^2 - P_T^{h^2})}{Qm_\pi} G(P_T^h) \sum_q h_1^q(x) \otimes H_{1q}^{\perp h}(z)$$

$$G(P_T^h) = \frac{\exp(P_T^{h2}/\mu_s^2)}{\pi\mu_s^2}$$

$$A_{UT}^{\sin(2\varphi_h-\varphi_s)} \propto \frac{M}{Q}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^{h}\right)$$

$f_{1T}^{\perp q} = 0$ in q-diq model





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Analyzing power of Sivers functions: Positivity Bound

A. Bacchetta, M. Boglione, A. Henneman and P. J. Mulders, Phys. Rev. Lett. **85**, 712 (2000)

$$\frac{\mathbf{k}_T^2}{M^2}\left(g_{1T}^{\perp}(x,k_T^2)\right)^2 + \frac{\mathbf{k}_T^2}{M^2}\left(f_{1T}^{\perp}(x,k_T^2)\right)^2 \le \left(f_1^q(x,k_T^2)\right)^2 - \left(g_{1L}^q(x,k_T^2)\right)^2$$

$$A_{Siv}(x,k_T) = \frac{k_T}{M}\frac{f_{1T}^{\perp}(x,k_T)}{f_1(x,k_T)} \quad \Longrightarrow \quad \left|A_{Siv}(x,k_T) \le 1\right|$$

Consider large k_T limit $\quad k_T \to \infty$ limit

Brodsky, Hwang & Schmidt

$$f_1(x,\vec{k}_\perp) = g^2(1-x)\frac{(xM+m)^2 - \vec{k}_\perp^2}{(\vec{k}_\perp^2 - B)^2}$$

$$f_{1T}^{\perp}(x,\vec{k}_\perp) = \frac{C_F g^2}{4\pi} g^2(1-x)\frac{M(xM+m)}{(\vec{k}_\perp^2 - B)}\frac{1}{\vec{k}_\perp^2}\ln\frac{\vec{k}_\perp^2 - B}{B}$$

$$A_{Siv}(x,k_T) \propto \frac{1}{k_T}\log(k_T^2) \to 0$$

Analyzing power of Sivers functions, 3

Gaussian form-factor (J.Ellis, D.Hwang, A.K.)

$$A_{Siv}(x,k_T) \propto \frac{1}{k_T^3}\exp\left(\frac{k_T}{2\Lambda^2(1-x)}\right) \to \infty$$

Transverse Quark Spin Effects and the Flavor Dependence of the Boer-Mulders Function

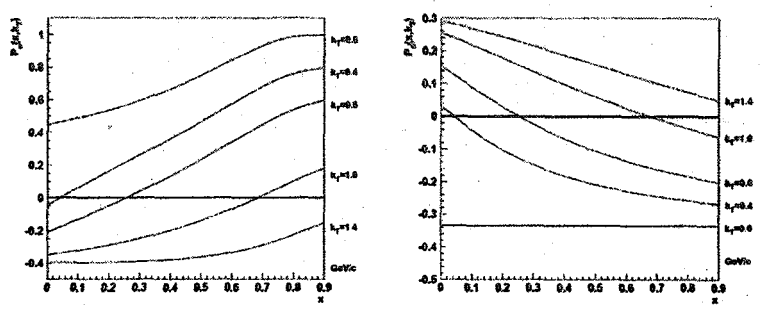
L.Gamberg, G.Goldstein & M.Schlegel, 0708.0324v2

$$A_{Siv}^S(x,k_T) \propto k_T^3\exp(\tilde{b}k_T) \to \infty, \quad A_{Siv}^A(x,k_T) \propto k_T^5\exp(\tilde{b}k_T) \to \infty$$

$$\tilde{b} = \frac{b}{(1-x)}, \quad g(p^2) = N\frac{p^2 - m_q^2}{(p^2-\Lambda^2)^3}\exp(bk^2), \quad b > 0$$

Quark longitudinal polarization

$$P_q(x,k_T^2)=\frac{g_1^q(x,k_T^2)}{f_1^q(x,k_T^2)}$$



For given x the sign of the polarization is changing at high k_T

Concluding remarks

- JMR q-dq model is a good tool for guidance
  - The $\mathbf{k_T}$ and $\mathbf{p_T}$ dependences of (polarized) DFs and FFs can be nontrivial.
    - No x-k_T factorization in DFs, flavor dependence of $\langle k_T\rangle(x)$, $\langle p_T\rangle(z)$
  - The $\mathbf{k_T}$ dependence of DF g_1 is tightly related to quark orbital momentum
  - In valence region this model is able to describe the x-dependence of new 6 transverse spin dependent azimuthal asymmetries
  - Do we understand well dynamical origin of Sivers effect?
    - FSI?
      - Why changing form-factor of nucleon-quark-diquark vertex brings to unphysical k_T behavior?
      - How one can resolve this problem?
    - Twist-four?
- More measurements are needed for better understanding TMD DFs
  - HERMES: 6 asymmetries transversely polarized proton target?
  - For better understanding of SIDIS we need the data for unpolarized x-sections and asymmetries ($R^h(x,z,p_T)$, $A_{LL}(p_T)$...) as a function of all kinematical variables (x, z, P_T, Q^2) or (x, P_T), (z, P_T), (x_F, P_T) ...

Transversity workshop
Beijing
June 29 – July 4, 2008

Universality of T-odd phenomena

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See also Mulders, WHEPP X talk, arXiv:0806.1134 [hep-ph]

Abstract

Single-spin asymmetries were long thought to vanish in high-energy scattering processes because of their specific time-reversal behavior. Time-reversal-odd phenomena, however, appear naturally when one includes effects of intrinsic transverse momenta of partons. The partons, quarks and gluons, enter the description of high-energy scattering processes in correlators which contain quark and gluon fields. The correlators, parameterized in terms of distribution and fragmentation functions, constitute matrix elements of non-local field configurations. For transverse momentum dependent (TMD) correlators the non-locality is along a light-front, in contrast to the non-locality along the light-cone for collinear correlators, integrated over transverse momenta. The TMD correlators require a careful treatment to assure color gauge invariance, leading to nontrivial gauge links connecting the parton fields. These give rise to time-reversal-odd phenomena, showing up as single spin and azimuthal asymmetries. The gauge links, arising from multi-gluon initial and final state interactions, depend on the color flow in the process, which has consequences for issues like universality and factorization.

Motivation

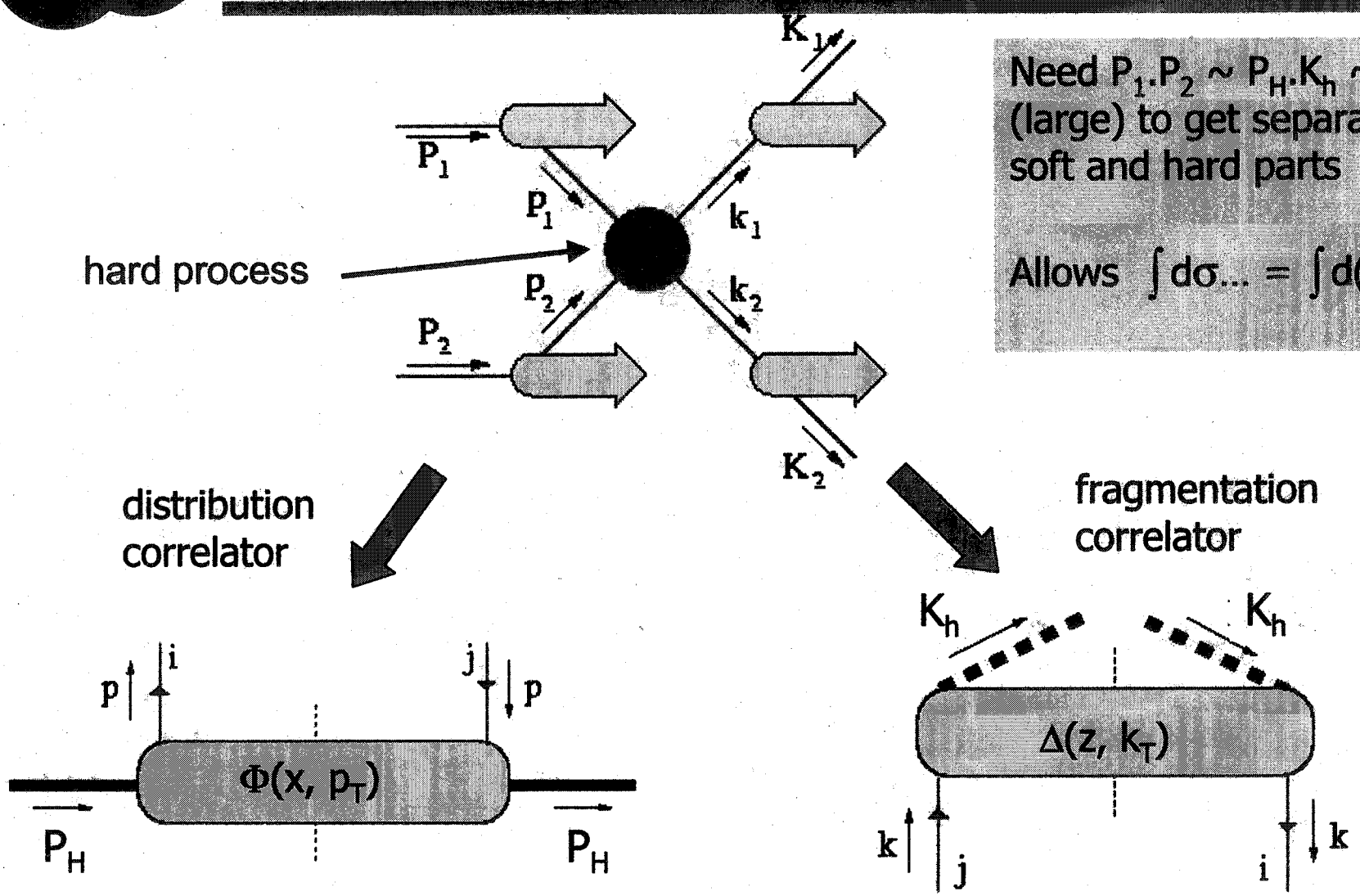
CONTEXT

- Single spin asymmetries are a specific example of T-odd observables
- They appear in processes in which T cannot be used as a constraint, such as hadron-hadron collisions or fragmentation processes (in contrast to inclusive DIS!)
- For spin 0 and spin ½ hadrons all (leading twist) collinear quark distribution functions (DF) and fragmentation functions (FF) are T-even
- T-odd in hard parts comes in at $O(\alpha_s)$
- Collinear description of T-odd effects requires gluonic pole matrix elements (Qiu-Sterman) or inclusion of soft gluon exchange (Brodsky...)

CONTENT

- There are several T-even and T-odd (leading) transverse momentum dependent (TMD) DFs and FFs, appearing in azimuthal asymmetries
- The TMD functions contain process-dependent gauge links
- The moments of the TMD distribution functions are universal and T-odd parts correspond with gluonic pole matrix elements
- Vanishing of gluonic pole matrix elements for fragmentation functions?

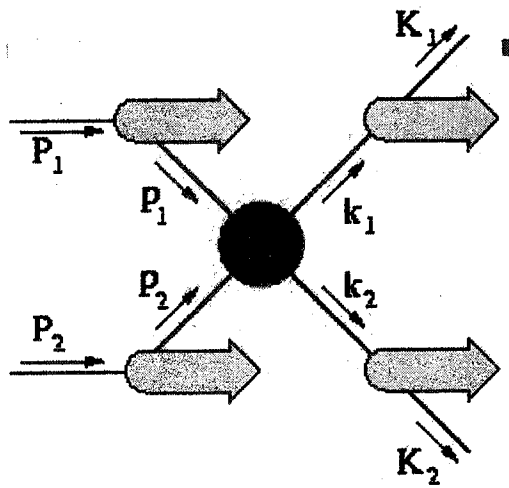
Leading partonic structure of hadrons



Need $P_1.P_2 \sim P_H.K_h \sim s$ (large) to get separation of soft and hard parts

Allows $\int d\sigma... = \int d(p.P)...$

Partonic correlators



The cross section can be expressed in hard squared QCD-amplitudes and distribution and fragmentation functions entering in **forward** matrix elements of **nonlocal** combinations of quark and gluon field operators ($\phi \rightarrow \psi$ or G).

Distribution functions

$$p^\mu = xP^\mu + p_T^\mu + (p.P - xM^2)n^\mu$$

$$\Phi(x, p_T) = \int \frac{d(\xi.P)d^2\xi_T}{(2\pi)} e^{ip.\xi} \langle P|\phi^\dagger(0)\,\phi(\xi)|P\rangle_{\xi.n=0}$$

Fragmentation functions

$$k^\mu = \frac{1}{z}K^\mu + k_T^\mu + (k.K - z^{-1}M_h^2)n^\mu$$

$$\Delta(z, k_T) = \sum_X \int \frac{d(\xi.K)d^2\xi_T}{(2\pi)^3} e^{-ik.\xi} \langle 0|\phi(0)|K, X\rangle\langle K, X|\phi^\dagger(\xi)|0\rangle_{\xi.n=0}$$

Relevance of transverse momenta

$$p \approx xP + p_T$$
$$k \approx z^{-1}P + k_T$$

- In a hard process one probes quarks and gluons
- Parton momenta fixed by kinematics (external momenta)

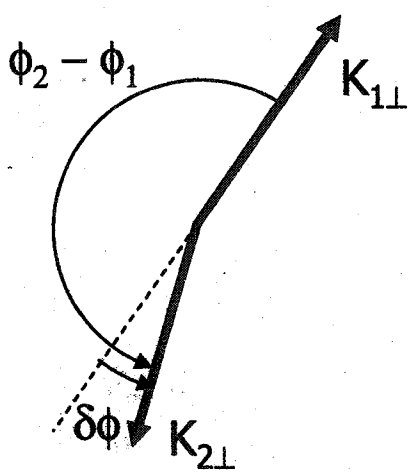
DIS $\quad x = x_B = Q^2 / 2P.q$

SIDIS $\quad z = z_h = P.K_h / P.q$

- Also possible for transverse momenta of partons

SIDIS
$$q_T = q + x_B P - z_h^{-1} K_h$$
$$= k_T - p_T$$

2-particle inclusive hadron-hadron scattering
$$q_T = z_1^{-1} K_1 + z_2^{-1} K_2 - x_1 P_1 - x_2 P_2$$
$$= p_{1T} + p_{2T} - k_{1T} - k_{2T}$$



pp-scattering

We need more than one hadron and knowledge of hard process(es)!

Collinear Expansion and Azimuthal Asymmetries In Semi-inclusive DIS

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Abstract

This talk is based on the following three recent publications [1-3] in collaboration with X. N. Wang, and J. Zhou. We derive a general framework for describing semi-inclusive deep-inelastic lepton-nucleon scattering in terms of the unintegrated parton distributions and other higher twist parton correlations. Such a framework provides a consistent approach to the calculation of inclusive and semi-inclusive cross sections including higher twist effects. As an example, we calculate the azimuthal asymmetries to the order of 1/Q in semi-inclusive process with transversely polarized target. A non-vanishing single-spin asymmetry in the ``triggered inclusive process" is predicted to be 1/Q suppressed with a part of the coefficient related to a moment of the Sivers function. We also show that the gauge-invariant transverse-momentum-dependent (TMD) quark distribution function can be expressed as a sum of all higher-twist collinear parton matrix elements in terms of a transport operator. From such a general expression, we derive the nuclear broadening of the transverse momentum distribution. Under the maximal two-gluon correlation approximation, in which all higher-twist nuclear multiple-parton correlations with the leading nuclear enhancement are given by products of twist-two nucleon parton distributions, we find the nuclear transverse momentum distribution as a convolution of a Gaussian distribution and the nucleon TMD quark distribution. The width of the Gaussian, or the mean total transverse momentum broadening squared, is given by the path integral of the quark transport parameter $\hat{q}_F$ which can also be expressed in a gauge invariant form and is given by the gluon distribution density in the nuclear medium.

Within the framework, twist-4 contributions to DIS off a large nucleus can be factorized as a convolution of hard parts and two-parton correlation functions. The hard parts for the quark scattering in the light-cone gauge correspond to interaction with a transverse (physical) gluon in the target, while they are given by the second derivative of the cross section with a longitudinal gluon in the covariant gauge. We provide a general proof of the equivalence of the hard parts in the light-cone and covariant gauge. We further demonstrate the equivalence in calculations of twist-4 contributions to semi-inclusive cross section of DIS in both lowest order and next leading order. Calculations of the nuclear transverse momentum broadening of the struck quark in the light-cone and covariant gauge are also discussed.

References

[1] Z.T. Liang and X.N. Wang, Phys. Rev. D75, 094002 (2007);

[2] Z.T. Liang, X.N. Wang, and J. Zhou, Phys.Rev.D77, 125010 (2008);

[3] Z.T. Liang, X.N. Wang, and J. Zhou, arXiv:0805.4030 [hep-ph] (2008).

Azimuthal asymmetry in unpolarized SIDIS

1978: Cahn, Intrinsic momentum effects, Phys. Lett. B78B, 269 (1978).

Generalized parton model to include an intrinsic transverse momentum $\vec{k}_\perp$ but no gluon radiation in the final state:

$$\langle \cos\varphi \rangle = -\frac{|\vec{k}_\perp|}{Q}\frac{B(y)}{A(y)}$$

"Realistic studies": Monte-Carlo, experiments etc.

small $p_{h\perp}$, moderate Q, intrinsic $k_\perp$ contribution dominates;
large $p_{h\perp}$, large Q, Georgi-Politzer mechanism dominates.

$\Longrightarrow$ In DIS at intermediate energies: intrinsic transverse momentum $k_\perp$ effects have to be taken into account.

Azimuthal asymmetry in polarized SIDIS

History: theoretical studies on single-spin asymmetry in $p(\uparrow)+p \to \pi+X$

Factorization $d\sigma_{p(\uparrow)+p\to\pi+X} \propto (p.d.f.) \otimes d\hat{\sigma}_{q(\uparrow)+q\to q+X} \otimes (frag.fun.)$

1978, Kane, Pumplin, R[illegible]: pQCD $a_N[q(\uparrow)+q\to q+q]=0$.

1991, Sivers: asymmetric quark distribution (Sivers effect)

1993, Boros, Liang, Meng: quark orbital angular momentum & "surface effect"

Collins: Proof of non-existence of Sivers effect.
asymmetric fragmentation function (Collins effect)

2002, Brodsky, Hwang, Schmidt: quark orbital angular momentum & "final state interaction".

[illegible]: "final state interaction" = "gauge link"

[illegible]: 1993's proof is wrong because forgot gauge link

Azimuthal asymmetry in polarized SIDIS

Conclusion:

both Sivers and Collins effects can exist when gauge link is taken into account.

⟹ intrinsic transverse momentum and gauge link are important in studying azimuthal asymmetries in SIDIS

Semi-inclusive DIS with $k_\perp$: A BASIC QUESTION

The general framework to write the cross section

Cross section for $ep \to ehX$: $d\sigma(e+p \to e+h+X)$

$=$ Parton distributions $q(x)$ $\otimes$ Cross section for $eq \to eq$ without $k_\perp$: $d\sigma(eq \to eq)|_{k_\perp=0}$ $\otimes$ Fragmentation function for $q \to h+X$: $D^{q\to h+X}(z)$

(without transverse momentum: collinear approximation)

$\Longrightarrow q(x,k_\perp) \otimes d\sigma(eq \to eq)|_{k_\perp \neq 0, k_\perp} \otimes D^{q\to h+X}(z,\vec{k}_{F\perp})$

(with transverse momentum, with gauge link)

Inclusive DIS with QCD interaction

$$W_{\mu\nu}(q,p,S) = \widetilde{W}^{(0)}_{\mu\nu}(q,p,S) + \widetilde{W}^{(1)}_{\mu\nu}(q,p,S) + \widetilde{W}^{(2)}_{\mu\nu}(q,p,S) + \cdots$$

$$\widetilde{W}^{(0)}_{\mu\nu}(q,p,S) = \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\left[\hat{\Phi}^{(0)}(k,p,S)\, \hat{H}^{(0)}_{\mu\nu}(xp)\right]$$

$$\hat{\Phi}^{(0)}(k,p,S) = \int d^4z\, e^{ik\cdot z} \langle p,S|\bar{\psi}(0)\mathcal{L}(0,z)\psi(z)|p,S\rangle$$

$$\mathcal{L}(0,z) = P\exp\left[-ig\int_0^z d\eta^\mu A^a(0,\eta^\mu,\vec{0}_\perp)\right] = 1 - ig\int_0^z d\eta^\mu A^a(0,\eta^\mu,\vec{0}_\perp) + (ig)^2\int_0^z d\eta^\mu A^a(0,\eta^\mu,\vec{0}_\perp)\int_0^{\eta^\mu} d\eta'^\nu A^a(0,\eta'^\nu,\vec{0}_\perp) + \cdots$$

$$\widetilde{W}^{(1)}_{\mu\nu}(q,p,S) = \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4} \mathrm{Tr}\left[\hat{\Phi}^{(1)}_\rho(k_1,k_2,p,S)\, \hat{H}^{(1)\rho}_{\mu\nu}(x_1p,x_2p)\right]$$

$$\hat{\Phi}^{(1)}_\rho(k_1,k_2,p,S) = \int d^4z\, d^4y\, e^{ik_1\cdot y + ik_2\cdot z} \langle p,S|\bar{\psi}(0)\mathcal{L}(0,y)D_\rho(y)\mathcal{L}(y,z)\psi(z)|p,S\rangle$$

$$D_\rho(y) = -i\partial_\rho + gA_\rho(y)$$

Contain QCD interactions.
(Color) gauge invariant !

Semi-Inclusive DIS with QCD interaction

The same collinear expansion technique leads to

$$W^{(0)}_{\mu\nu}(q,p,S,k') = \widetilde{W}^{(0,a)}_{\mu\nu}(q,p,S,k') + \widetilde{W}^{(0,b)}_{\mu\nu}(q,p,S,k') + \widetilde{W}^{(0,c)}_{\mu\nu}(q,p,S,k') + \cdots$$

$$\widetilde{W}^{(0,a)}_{\mu\nu}(q,p,S,k') = \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}[\hat{\Phi}^{(0)}(k,p,S)\, H^{(0)}_{\mu\nu}(xp)](2E_{k'})(2\pi)^4\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

$$\widetilde{W}^{(0,b)}_{\mu\nu}(q,p,S,k') = \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4} \sum_{a=u,\bar{u}} \mathrm{Tr}[\hat{\Phi}^{(0)}_a(k_1,k_2,p,S)\, H^{(1,a)\rho}_{\mu\nu}(x_1p,x_2p)\, \omega_\rho^{\mu\nu}]$$
$$\times (2E_{k'})(2\pi)^4\delta^3(\vec{k}'-\vec{k}_2-\vec{q})$$

$$\widetilde{W}^{(0,c)}_{\mu\nu}(q,p,S,k') = \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k}{(2\pi)^4} \sum_{a=u,\bar{u}} \mathrm{Tr}[\hat{\Phi}^{(2)}_{a,\rho\sigma}(k_1,k_2,k,p,S)\, H^{(2,a)\rho\sigma}_{\mu\nu}(x_1p,x_2p,xp)\, \omega_\rho^{\mu\nu}\omega_\sigma^{\mu\nu}]$$
$$\times (2E_{k'})(2\pi)^4\delta^3(\vec{k}'-\vec{k}_2-\vec{q})$$

Gauge invariant parton distributions/correlations (with gauge link)

SIDIS with $k_\perp$: Direct consequence I

Consider the contribution from $\tilde{W}^{(0,x)}_{\mu\nu}(q,p,S,k^+)$

Cross section for $ep \to eqX$: $d\sigma(e+p \to e+q+X)$

$=$ Parton distributions $q(x)$ $\otimes$ Cross section for $eq \to eq$ without $k_\perp$: $d\sigma(eq \to eq)|_{k_\perp=0}$

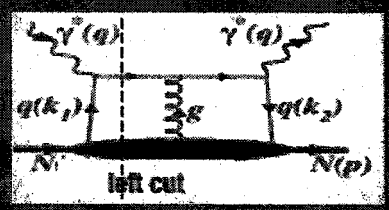
(without transverse momentum)

$\Longrightarrow q(x,k_\perp) \otimes d\sigma(eq \to eq)|_{k_\perp=0}$

(with transverse momentum)

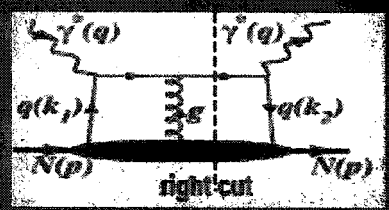
SIDIS with $k_\perp$: Direct consequence II

A simplification of $\tilde{W}^{(1,x)}_{\mu\nu}(q,p,S,k^+)$



$$\hat{H}^{(1,x)\mu}_{\mu\nu}(x_1p,x_2p)\omega_p^{\nu'} = \frac{\pi}{2q\cdot p}\delta(x_1-x_B)\omega_p^{\nu'}\gamma_\nu \not{n}\gamma^\mu \not{\bar{n}}\gamma_\nu = \hat{H}^{(0)\nu'}_{\mu\nu}(x_1p)$$

independent of x_2!



$$\hat{H}^{(1,x)\nu}_{\mu\nu}(x_1p,x_2p)\omega_p^{\nu'} = \frac{\pi}{2q\cdot p}\delta(x_2-x_B)\omega_p^{\nu'}\gamma_\nu \not{\bar{n}}\gamma^\mu \not{n}\gamma_\nu = \gamma_0 H^{(1)\mu\nu\dagger}_{\mu\nu}(x_1p)\gamma_0$$

independent of x_1!

SIDIS with $k_\perp$: Direct consequence II

This leads to

$$\tilde{W}^{(1,\omega)}_{\mu\nu}(q,p,S,k') = \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4} \sum_{\alpha,\beta,\kappa} \mathrm{Tr}[\hat{\Phi}^{(1)}_\beta(k_1,k_2,p,S)\, \hat{H}^{(1,\omega)\alpha}_{\mu\nu}(x_1p,x_2p)\, \omega^{\beta\alpha}_\kappa]$$

$$\times (2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}_\kappa-\vec{q})$$

$$= 2\,\mathrm{Re}\int \frac{d^4k}{(2\pi)^4}\mathrm{Tr}[\hat{\varphi}^{(1)}_\beta(k,p,S)\hat{H}^{(1,\omega)\alpha}_{\mu\nu}(xp)](2E_{k'})(2\pi)^3\delta^3(\vec{k}'-\vec{k}-\vec{q})$$

Only $\hat{\varphi}^{(1)}_\beta(k,p,S) = \int \frac{d^4k_1}{(2\pi)^4}\hat{\Phi}^{(1)}_\beta(k,k_1,p,S)$

$$= \int d^4z e^{ikz}\langle p,S|\overline{\psi}(0)\mathcal{L}(0,z)D_\beta(z)\psi(z)|p,S\rangle$$

is relevant in semi-inclusive deep-inelastic lepton-nucleon scattering.

Summary

- Collinear expansion can be extended to SIDIS.
- Naive extension of parton distribution function convoluting with $eq \to eq$ cross section to include intrinsic transverse momentum is incorrect.
- The existence of the projection operator $\omega^{\beta\alpha}_\kappa$ simplifies $\tilde{W}^{(1,\omega)}_{\mu\nu}(q,p,S,k')$ very much.
- New single-spin asymmetries are predicted to 1/Q.
- In "maximal two gluon approximation",

$$f_\kappa^{\alpha}(x,\vec{k}_\perp) = \frac{A}{\pi\Delta_{\perp r}}\int d^2l_\perp e^{-(\vec{k}_\perp-\vec{l}_\perp)^2/\Delta_{\perp r}^2} f_\kappa^{\alpha}(x,\vec{l}_\perp), \quad \Delta_{\perp r}^2 = \frac{3\pi^2\alpha_s}{N_c}\int d\xi_\perp^2 \rho_A^2(\xi_\perp)|\nabla_\perp^2 f_\kappa^{\alpha}(x)| \to$$

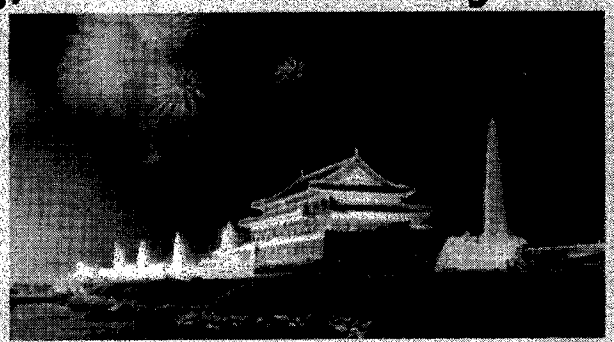
- A number of identities have been derived, with them gauge invariance of twist-4 contributions to eA has been proven.

Boer-Mulders functions in SIDIS and Drell-Yan

Alexei Prokudin

Università di Torino and INFN Sezione di Torino

PKU-RBRC Workshop on Transverse Spin Physics
Beijing, June 30th-July 4th, 2008



In collaboration with Vincenzo Barone, Bo-Qiang Ma and Stefano Melis

arXiv:0804.3024

Boer-Mulders functions and $\cos 2\phi_h$ asymmetry

Three sources of $\cos 2\phi_h$ asymmetry

- Cahn effect $\propto f_q(x, k_\perp^2) \otimes D_h^q(z, p_\perp^2)$. Kinematical higher twist effect $1/Q^2$ suppressed.
- Boer-Mulders $\otimes$ Collins FF contribution $\propto h_1^\perp(x, k_\perp^2) \otimes H_1^\perp(z, p_\perp^2)$. Leading twist effect.
- Gluon radiation QCD effect. Important for high P_T hadrons.

Boer-Mulders functions and $\cos 2\phi_h$ asymmetry

Boer-Mulders function $h_1^\perp(x, k_\perp)$ describes distribution of transversely polarised quarks in an unpolarised hadron.
$\cos(2\phi_h)$ asymmetry is generated in SIDIS by convolution with Collins FF.

- Large-N_c predictions $h_1^{\perp u} \simeq h_1^{\perp d}$
- Burkardt's approach $h_1^\perp$ and $f_{1T}^\perp$ are connected to GPD's.
  $h_1^{\perp u,d} \simeq \frac{\mathcal{K}_T{}^{u,d}}{\mathcal{K}^{u,d}} f_{1T}^{\perp u,d}$, $h_1^{\perp u,d} < 0$
  arXiv:0705.1573 [hep-ph], Phys.Rev.**D 72**,094020
- Lattice QCD result: $\frac{\mathcal{K}_T{}^u}{\mathcal{K}^u} \simeq \frac{3}{1.67}$, $\frac{\mathcal{K}_T{}^d}{\mathcal{K}^d} \simeq \frac{1.9}{2.03}$
  hep-lat/0612032

We use these relations and Collins FF from

Anselmino et al Phys.Rev.**D75** 054032,2007.

Sivers functions from

Anselmino et al Phys.Rev.**D72** 094007,2005 or arXiv:0805.2677

How to study Boer-Mulders functions in SIDIS?

Charge separation of produced hadrons can give information on B-M functions.

Collins FF are known $H_1^{\perp fav} > 0$, $H_1^{\perp unfav} < 0$

Anselmino et al Phys.Rev.**D75** 054032,2007.

B-M functions are believed to be negative $h_1^{\perp u,d} < 0$

arXiv:0705.1573 [hep-ph], Phys.Rev.**D 72**,094020

Thus we have

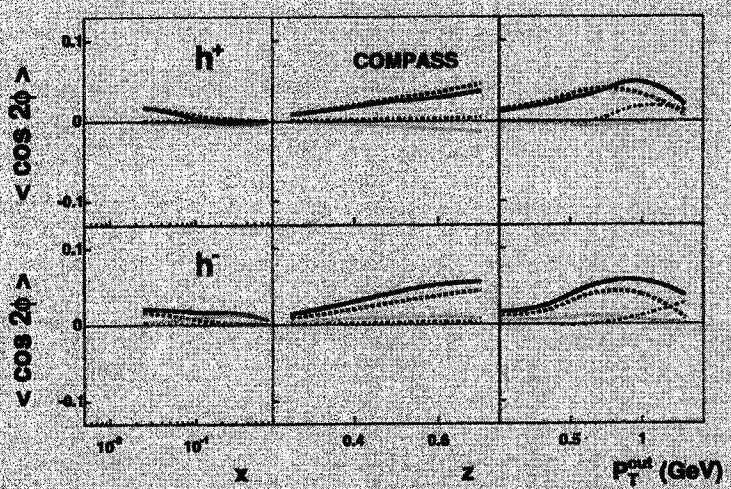
π^+ and π^- are of different sign

$$\langle \cos 2\phi_h \rangle^{\pi^+}_{BM} \sim 4h_1^{\perp u} H_1^{\perp fav} + h_1^{\perp d} H_1^{\perp unfav} < 0$$
$$\langle \cos 2\phi_h \rangle^{\pi^-}_{BM} \sim 4h_1^{\perp u} H_1^{\perp unfav} + h_1^{\perp d} H_1^{\perp fav} > 0$$

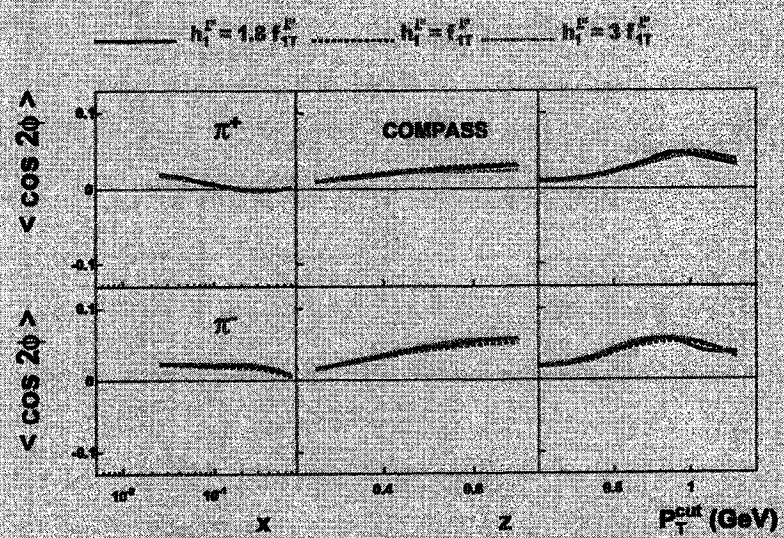
As far $\langle \cos 2\phi_h \rangle^{\pi^\pm}_{Cahn,QCD} > 0$ and
$\langle \cos 2\phi_h \rangle = \langle \cos 2\phi_h \rangle_{Cahn} + \langle \cos 2\phi_h \rangle_{QCD} + \langle \cos 2\phi_h \rangle_{B-M}$

Boer-Mulders functions and $\cos 2\phi_h$ asymmetry

$\mu D \to \mu h X$, 160 GeV, COMPASS



$\mu D \to \mu \pi X$, COMPASS



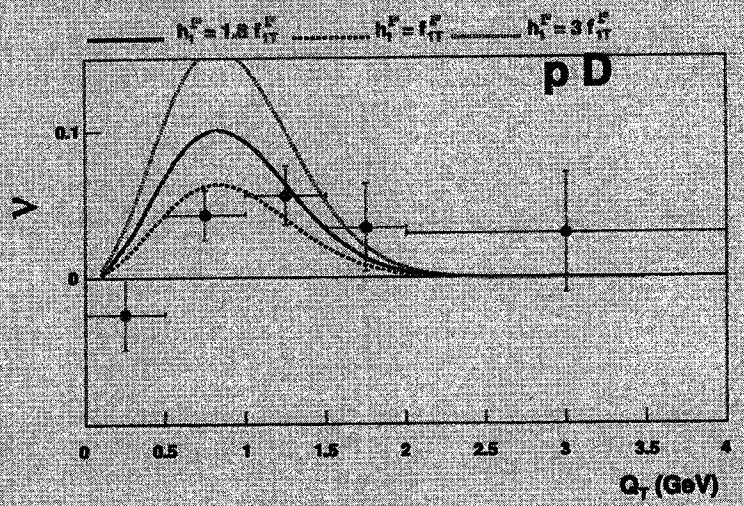
The dotted line corresponds to Boer-Mulder contribution and the dashed line corresponds to higher twist contribution. The continuous line corresponds to the sum of all contributions.

Full = Cahn(HT) + Boer-Mulders + QCD

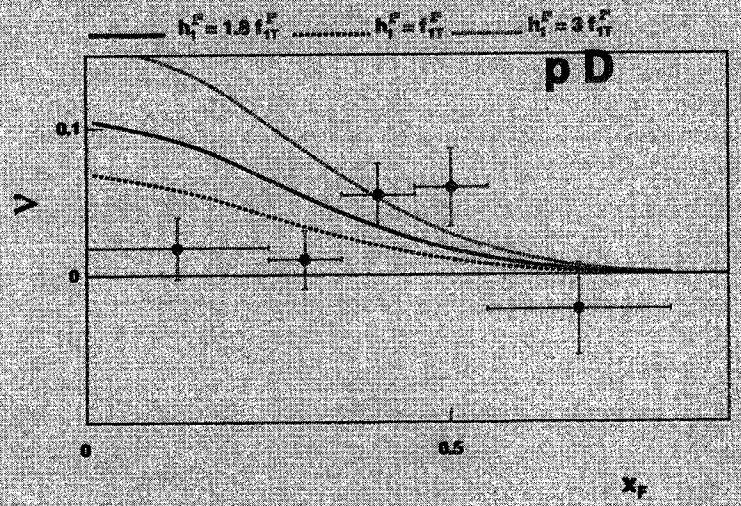
Barone, Ma, A.P. arXiv:0804.3024 (2007)

Boer-Mulders functions in Drell-Yan process

$PD \to l^+ l^- X$, 800 GeV, E866



$PD \to l^+ l^- X$, 800 GeV, E866



L.Y.Zhu et al, FNAL E866/NuSea Coll., Phys. Rev. Lett. 99, 082301 (2007)

Light-Front Holography and Novel QCD Phenomena

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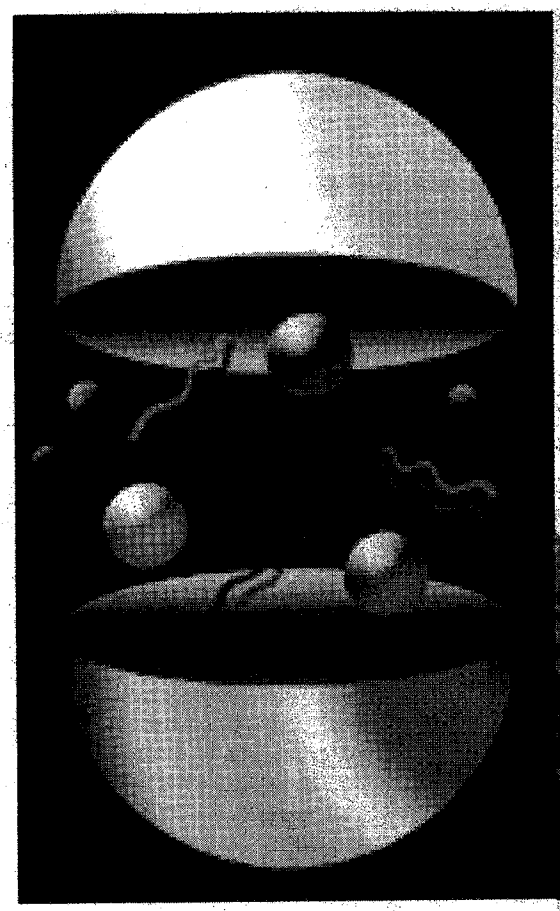
This research is supported by the Department
of Energy contract DE--AC02--76SF00515.

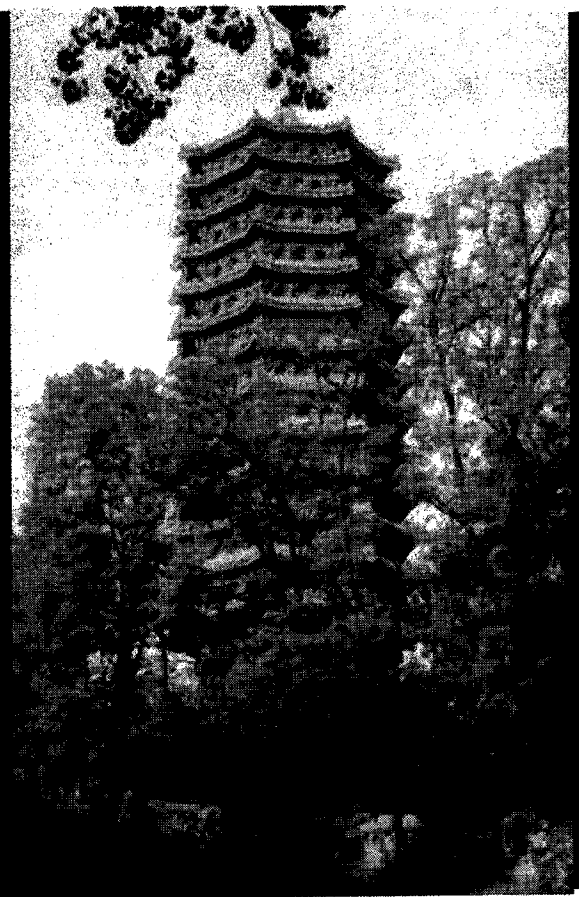
Abstract

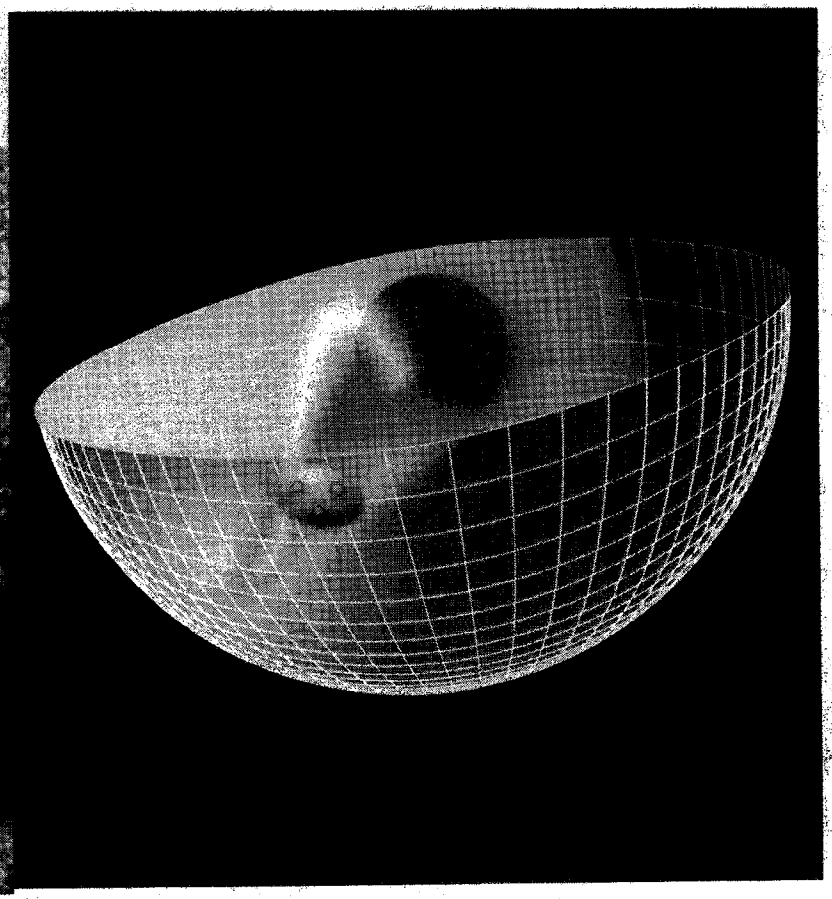
The AdS/CFT correspondence between Anti-de Sitter space and conformal gauge theories provides an analytically tractable approximation to QCD in the regime where the QCD coupling is large and constant. ``Light-front Holography" is a remarkable feature of AdS/QCD: it allows hadronic amplitudes in the AdS fifth dimension to be mapped to frame-independent light-front wavefunctions of hadrons in physical space-time, thus providing a relativistic description of hadrons at the amplitude level. In particular, as shown by Guy de Teramond and myself, there is an exact correspondence between the fifth-dimension coordinate z of AdS space and a specific impact variable ζ which measures the separation of the quark constituents within the hadron in ordinary space-time. This connection allows one to compute the analytic form of the frame-independent light-front wavefunctions of mesons and baryons, the fundamental entities which encode hadron properties such as spin-correlations and transversity and allow the computation of hadronic scattering amplitudes. The light-front Schrodinger equations predicted from AdS/QCD give a good representation of the observed meson and baryon spectra and give excellent phenomenological predictions for hadronic amplitudes such as electromagnetic form factors and decay constants. The hadronic light-front wavefunctions can be systematically improved by diagonalizing the QCD Light-Front Hamiltonian on the AdS/QCD basis. Robert Shrock and I have noted that the AdS/QCD model predicts that QCD condensates are restricted to the interior of hadrons since they arise due to the interactions of confined quarks and gluons. Chiral symmetry is thus broken in a limited domain of size $1/ m_\pi$, in analogy to the limited physical extent of superconductor phases.

I also discuss a number of novel phenomenological features of QCD. The effect of orbital angular momentum on the valence quark distributions leads to a new perspective for counting rules for helicity-dependent structure functions at large $x_{bj}.$ Initial- and final-state interactions from gluon-exchange, normally neglected in the parton model, have a profound effect in QCD hard-scattering reactions, leading to leading-twist single-spin asymmetries such as the Sivers effect, diffractive deep inelastic scattering, diffractive hard hadronic reactions, the breakdown of the Lam-Tung relation in Drell-Yan reactions, and nuclear shadowing and non-universal antishadowing---leading-twist physics not incorporated in the light-front wavefunctions of the target computed in isolation. Diffractive events in high energy collisions can be used to materialize the Fock states of a hadronic projectile, test QCD color transparency, and reveal anomalous heavy quark effects, such as Higgs production at large x_F. The intrinsic s vs $\bar s$ asymmetry of the proton wavefunction can be tested in jet fragmentation. The presence of direct higher-twist processes where a proton is produced in the hard subprocess can explain the large proton-to-pion ratio seen in high centrality heavy ion collisions. A new method for computing the hadronization of quark and gluon jets at the amplitude level, an ``event amplitude generator", is also discussed.

Light-Front Holography and Novel QCD Phenomena



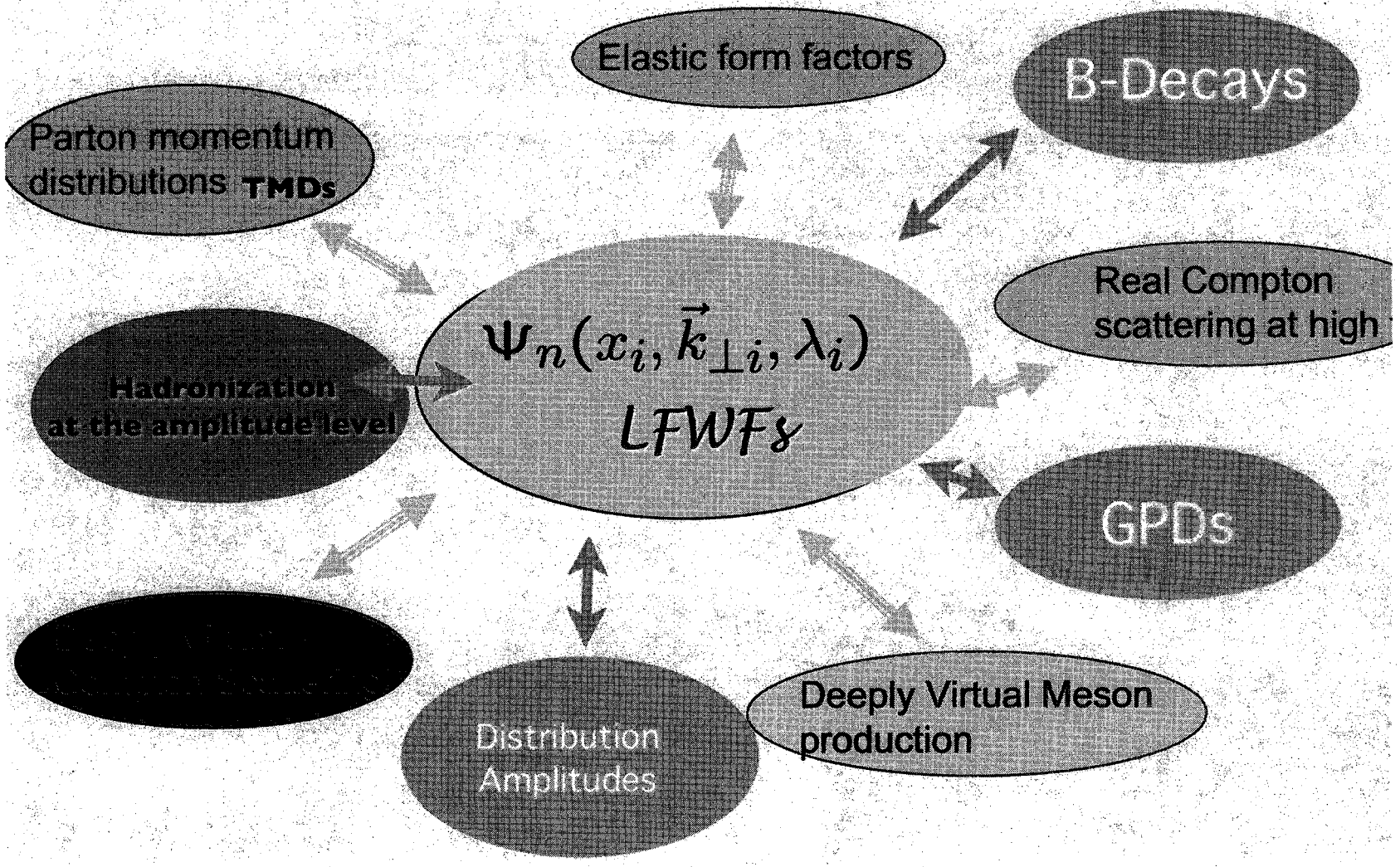




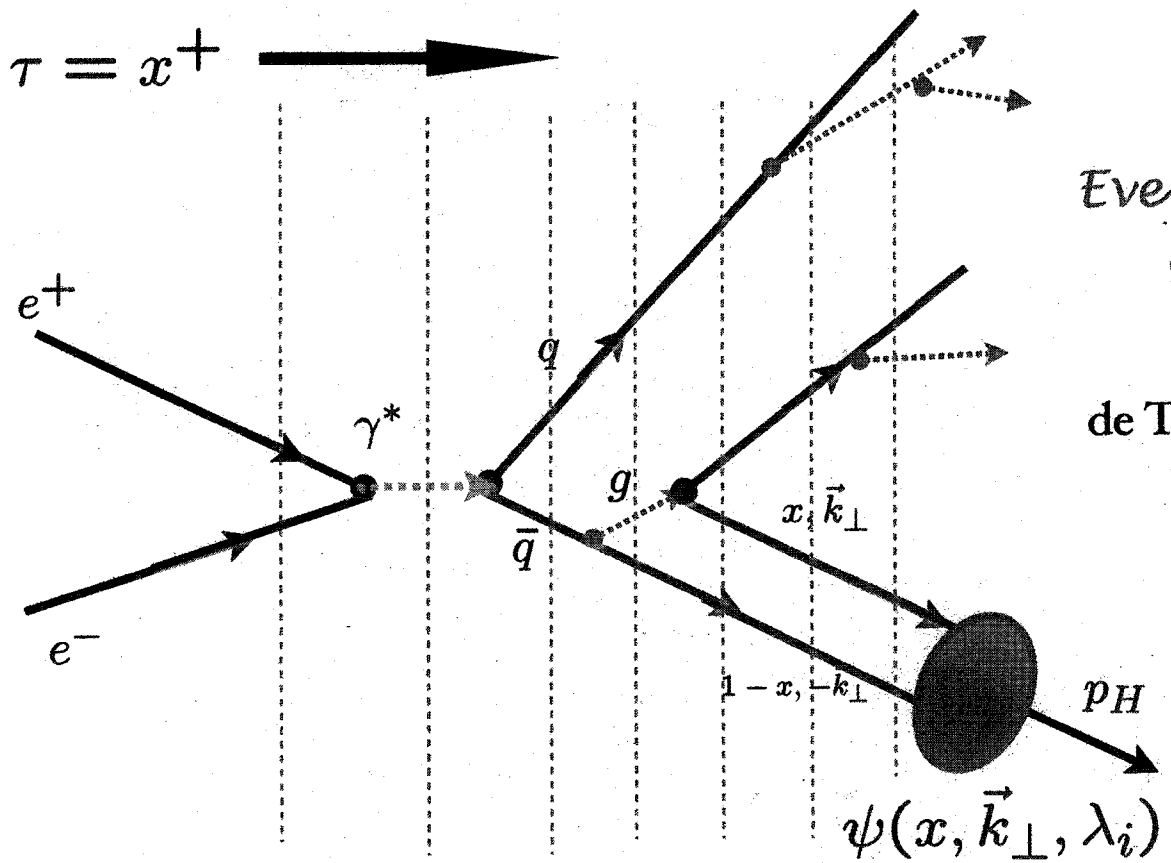
Stan Brodsky, SLAC/IPPP

PKU-RBRC Workshop on Transverse Spin Physics
CHEP, Peking University, July 3, 2008

A Unified Description of Hadron Structure



Hadronization at the Amplitude Level



Event amplitude generator

de Teramond, Shrock, sjb

AdS/QCD Hard Wall Confinement:

Capture if $\zeta^2 = x(1-x)b_\perp^2 > \frac{1}{\Lambda^2_{QCD}}$

i.e.,

$$\mathcal{M}^2 = \frac{k_\perp^2}{x(1-x)} < \Lambda^2_{QCD}$$

Single-spin asymmetries

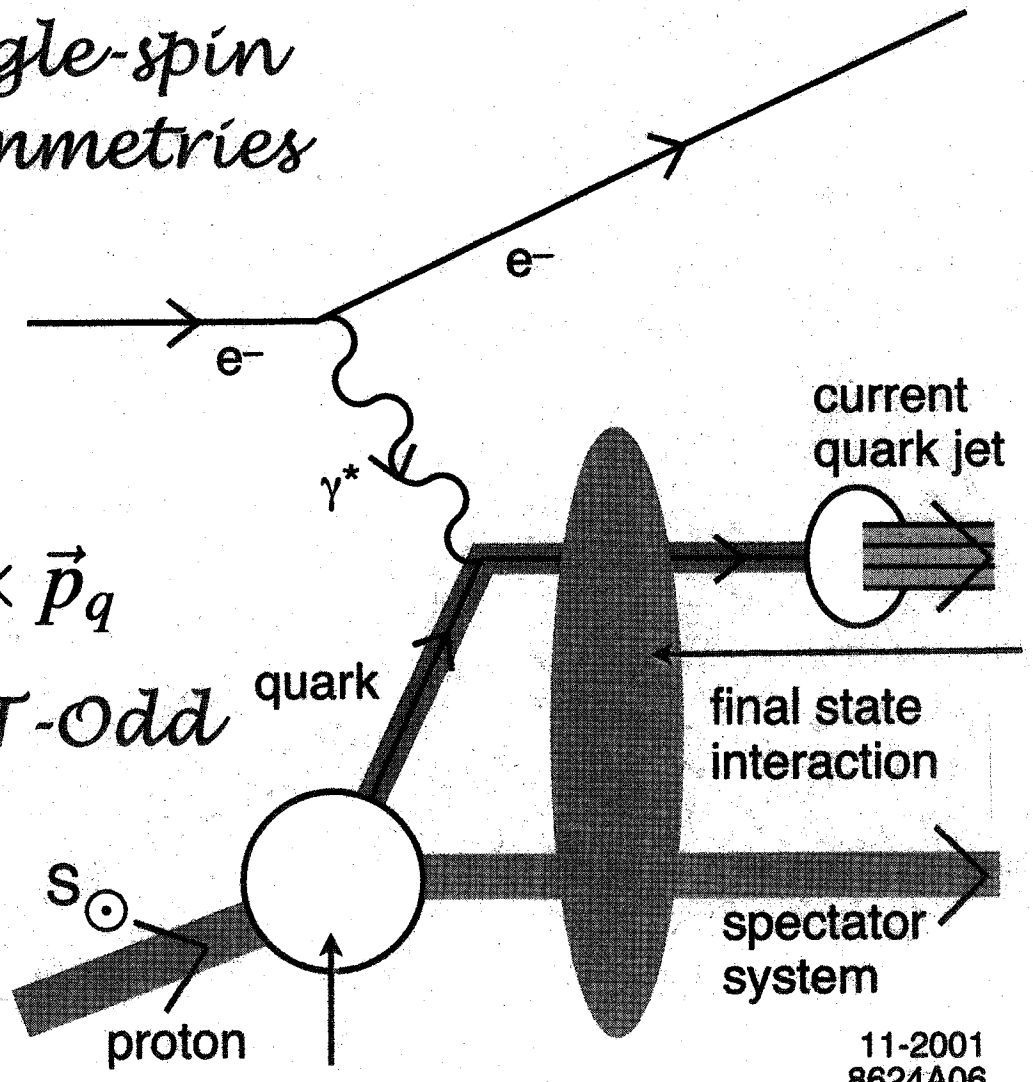
Leading Twist Sivers Effect

Hwang, Schmidt, sjb

Collins, Burkardt Ji, Yuan

$$i\,\vec{S}_p \cdot \vec{q} \times \vec{p}_q$$

Pseudo-T-Odd



QCD S- and P- Coulomb Phases --Wilson Line

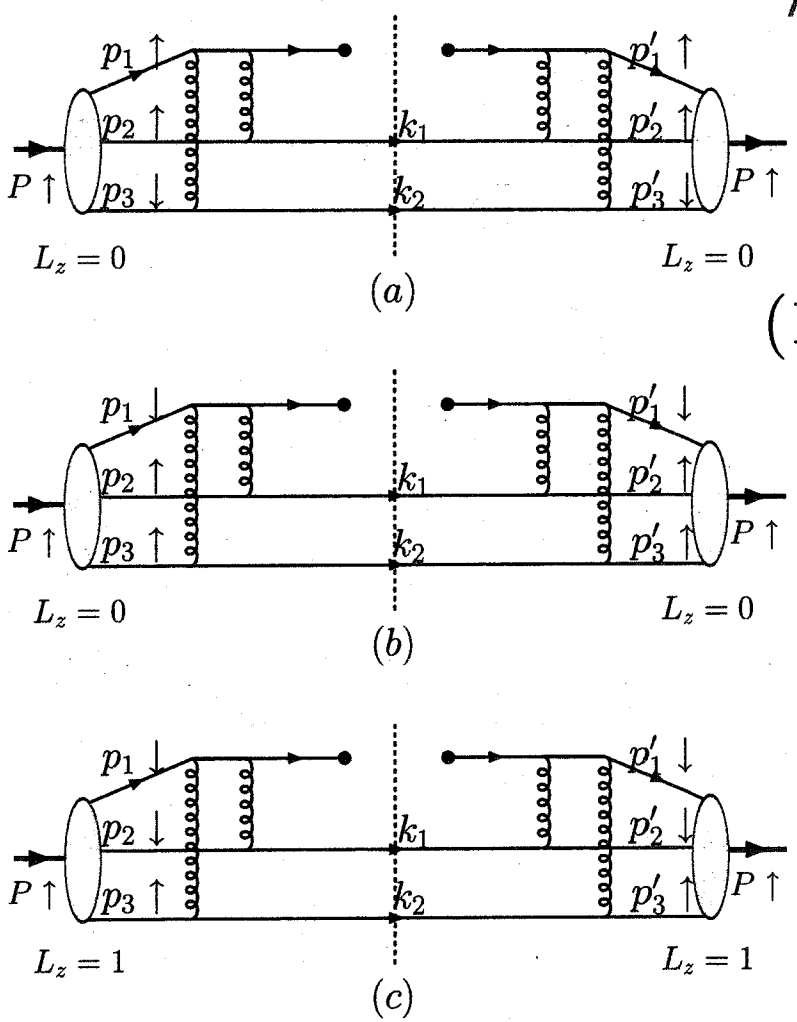
Light-Front Wavefunction S and P- Waves

Perturbative analysis of LFWFs at large x

Avakian, Deur, Yuan, sjb

DGLAP Evolution
Quenched at Large x

Lepage, sjb



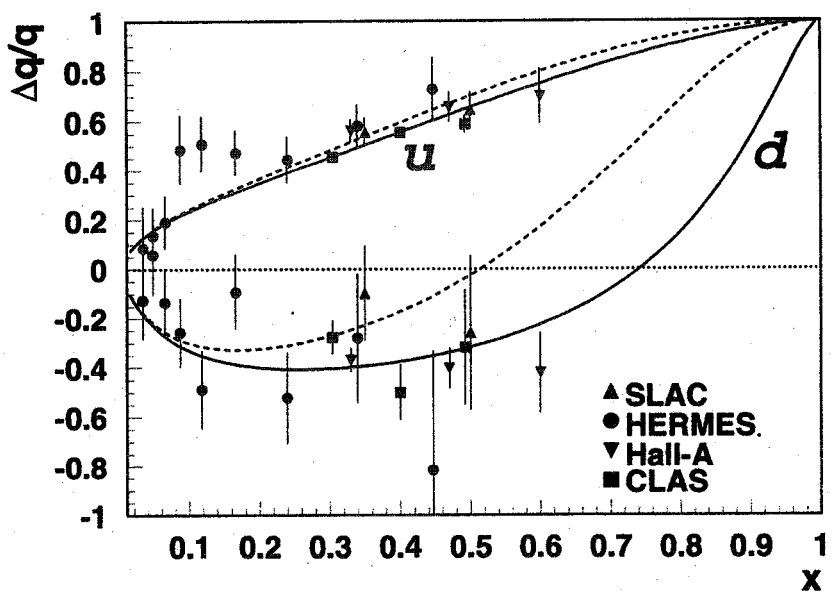
$$(1-x)^{2n_s-1+2|\Delta S^z|}$$

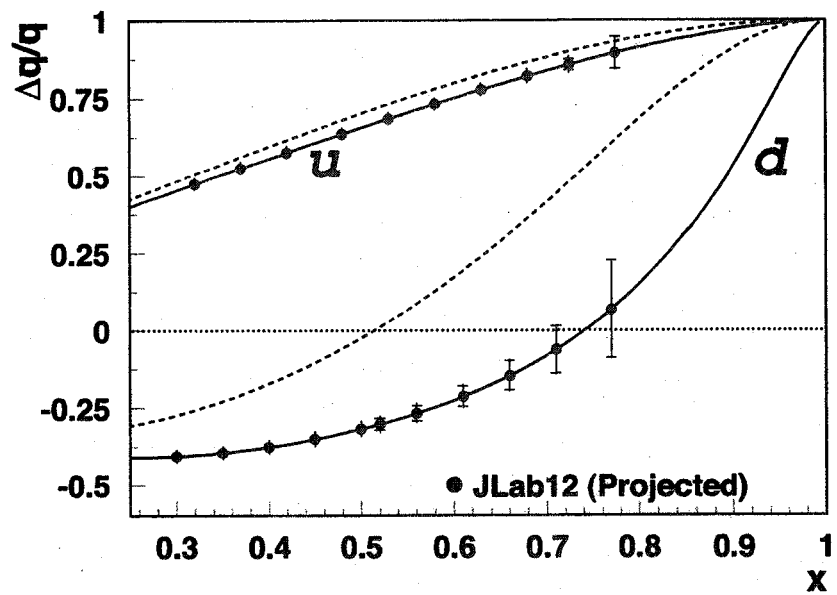
Burkardt, Schmidt, sjb

Spectator counting rules at $x \to 1$

Effect of Orbital Angular Momentum on Valence-Quark Helicity Distributions

Effect of Orbital Angular Momentum on Valence-Quark Helicity Distributions





Avakian, Deur, Yuan, sjb

Parametrization of Boer-Mulders functions and the application

Bin Zhang

Peking University

Contribuions

- We extract Boer-Mulders functions for the first time with two sets from the unpolarized p+D Drell-Yan process in FNAL E866/NuSea Experiment.
- The incoming unpolarized p+p data from FNAL E866/NuSea will distinguish which set is preferred by data.
- The unpolarized p+pbar data from GSI in future will pin down the free coefficient omega.
- In SIDIS , we show a larger asymmetries in π^- production, compared to π^+ production.
- We suggest to measure these processes separately to get more detail information on the Boer-Mulders functions.
- More experiments for measuring the Cos2phi asymmetries in the unpolarized SIDIS and Drell-Yan processes are needed to pin down the Boer-Mulders functions.

Papers:

1 Cos 2 phi asymmetries in unpolarized semi-inclusive DIS.
Bing Zhang (Peking U.) , Zhun Lu (Santa Maria U., Valparaiso) , Bo-Qiang Ma (Peking U.) , Ivan Schmidt (Santa Maria U., Valparaiso) .
Jul 2008. 9pp.
e-Print: arXiv:0807.0503 [hep-ph]

2 Extracting Boer-Mulders functions from p+D Drell-Yan processes.
Bing Zhang (Peking U.) , Zhun Lu (Santa Maria U., Valparaiso) , Bo-Qiang Ma (Peking U.) , Ivan Schmidt (Santa Maria U., Valparaiso) .
Mar 2008. 6pp.
Published in Phys.Rev.D77:054011,2008.

Parameterization of the Boer-Mulders functions for the proton as :

Gaussian form ,suitable to describe non-perturbative effects at small Pt values and simple enough to allow analytical integration over the intrinsic transverse momenta. **1-x** follows the large-x behavior of BM functions compared with the unpolarized distribution.

$$f_1^a(x, \mathbf{p}_T^2) = f_1^a(x) \frac{exp(-\mathbf{p}_T^2 / p_{unp}^2)}{\pi p_{unp}^2}$$

0.25 Anselmino

Unpolarized distribution function MRST2001(LO set)

$$h_1^{\perp,a}(x, \mathbf{p}_T^2) = h_1^{\perp,a}(x) \frac{exp(-\mathbf{p}_T^2 / p_{BM}^2)}{\pi p_{BM}^2}$$

$$h_1^{\perp,u}(x) = H_u x^c (1-x) f_1^u(x)$$

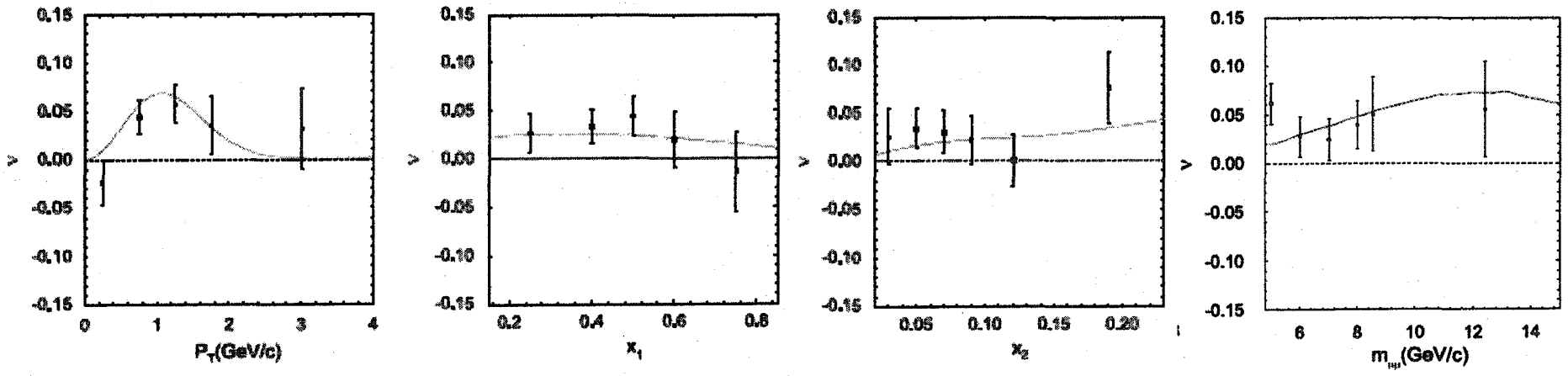
$$h_1^{\perp,d}(x) = H_d x^c (1-x) f_1^d(x)$$

$$h_1^{\perp,\bar{u}}(x) = H_{\bar{u}} x^c (1-x) f_1^{\bar{u}}(x)$$

$$h_1^{\perp,\bar{d}}(x) = H_{\bar{d}} x^c (1-x) f_1^{\bar{d}}(x)$$

Best fit values of Boer-Mulders functions

E866 Drell-Yan pD Process (CERN program library MINUIT)



	Set I	Set II
H_u	3.99	4.44
H_d	3.83	-2.97
$H_{\bar{u}}$	0.91	4.68
$H_{\bar{d}}$	-0.96	4.98
p_{bm}^2	0.161	0.165
c	0.45	0.82
$\chi^2/d.o.f.$	0.79	0.79

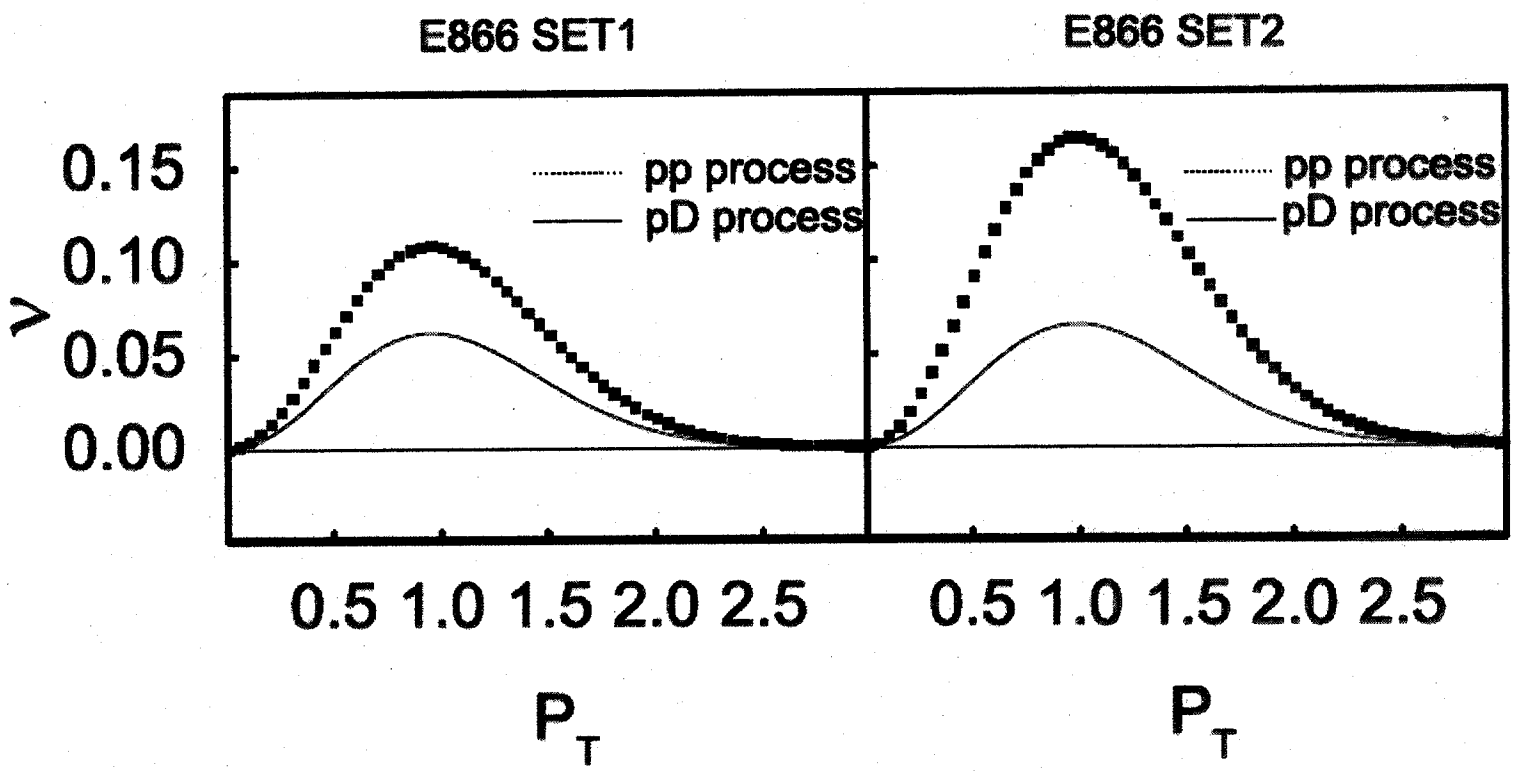
Set I
- Large Nc (Pobylitsa)
- Lattice calculation (QCDSF)
- GPD approach (Buikardt,Gamberg)

$h_1^{\perp,u} \approx h_1^{\perp,d}$

Set II
- Axial-diquark model (Bacchetta,Schafer, Yang)

$h_1^{\perp,u}$ and $h_1^{\perp,d}$ nearly have different sign

E866 Drell-Yan p+D Process vs p+p Process



50% difference for the p+p process to distinguish which Set is preferred by the forthcoming p+p data.

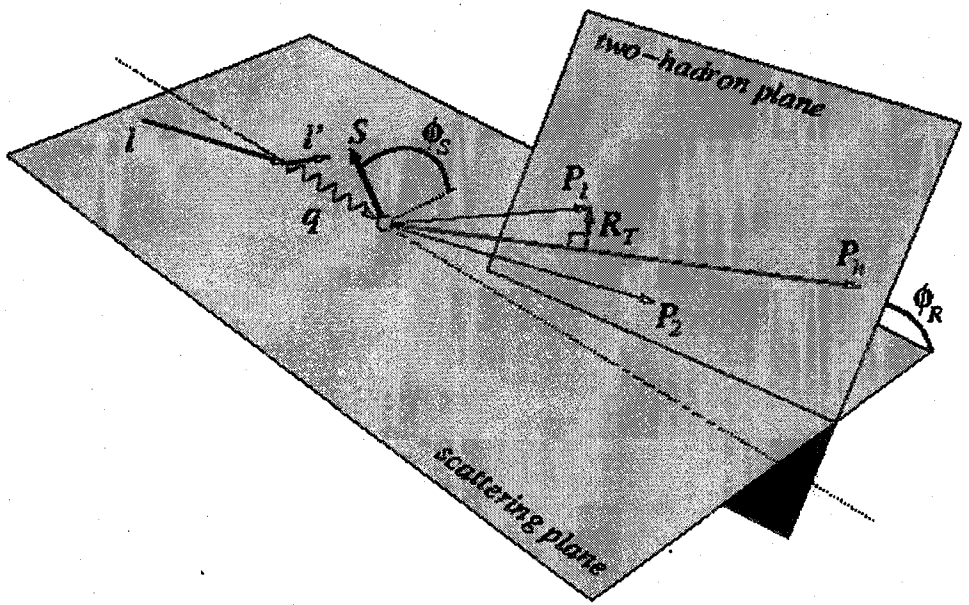
Transversity from two pion interference fragmentation

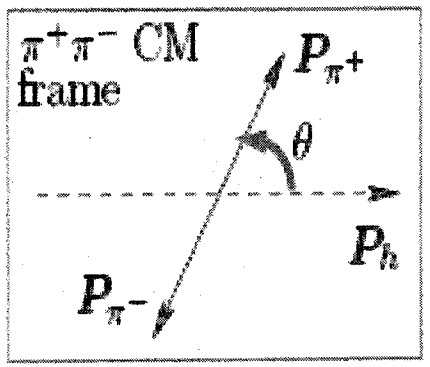
Speaker: Jun She (Peking University)
Supervisor: Prof. Bo-Qiang Ma (Peking University)

Abstract

- We calculate the SSA for pion pair production in SIDIS process, using a new parameterized interference FF to study transversity. We find that different approaches to transversity give different predictions on the neutron target, which may help us know more about transversity.
- This work has been published in Phys. Rev. D **77,** 014035 (2008).

2-Hadron production





$$P_h = P_1 + P_2, \quad R = (P_1 - P_2)/2, \quad M_h^2 = (P_1 + P_2)^2$$

$$x = \frac{p^+}{P^+}, \quad z = \frac{P_h^-}{k^-}, \quad \zeta = \frac{2R^-}{P_h^-} = -\frac{2|\vec{R}|}{M_h}\cos\theta$$

Bacchetta and Radici, PRD 67, 094002 (2003)

- Cross section:

Bacchetta and Radici, PRD 69, 074026 (2004)

$$\frac{d^7\sigma}{d\zeta\, dM_h^2 d\phi_R dz dx dy d\phi_S} = \frac{\alpha^2}{2\pi Q^2 y}\Bigg[\sum_a e_a^2 (1-y+\frac{y^2}{2}) f^a(x) D_1^a(z,\zeta,M_h^2)$$

$$-S_T \sin(\phi_R+\phi_S)\sin\theta \sum_a e_a^2 (1-y)\delta f^a(x) H_1^{\sphericalangle a}(z,\zeta,M_h^2)\Bigg]$$

$$A_{UT}^{\langle 2\sin(\phi_R+\phi_S)/\sin\theta\rangle} : -\frac{\sum_a e_a^2 \delta f^a(x)\int d\zeta \frac{|\vec{R}|}{M_h} H_1^{\sphericalangle a}(z,\zeta,M_h^2)}{\sum_a e_a^2 f^a(x)\int d\zeta D_1^a(z,\zeta,M_h^2)}$$

New fragmentation functions are introduced: the dihadron FFs, including the chiral odd interference FF.

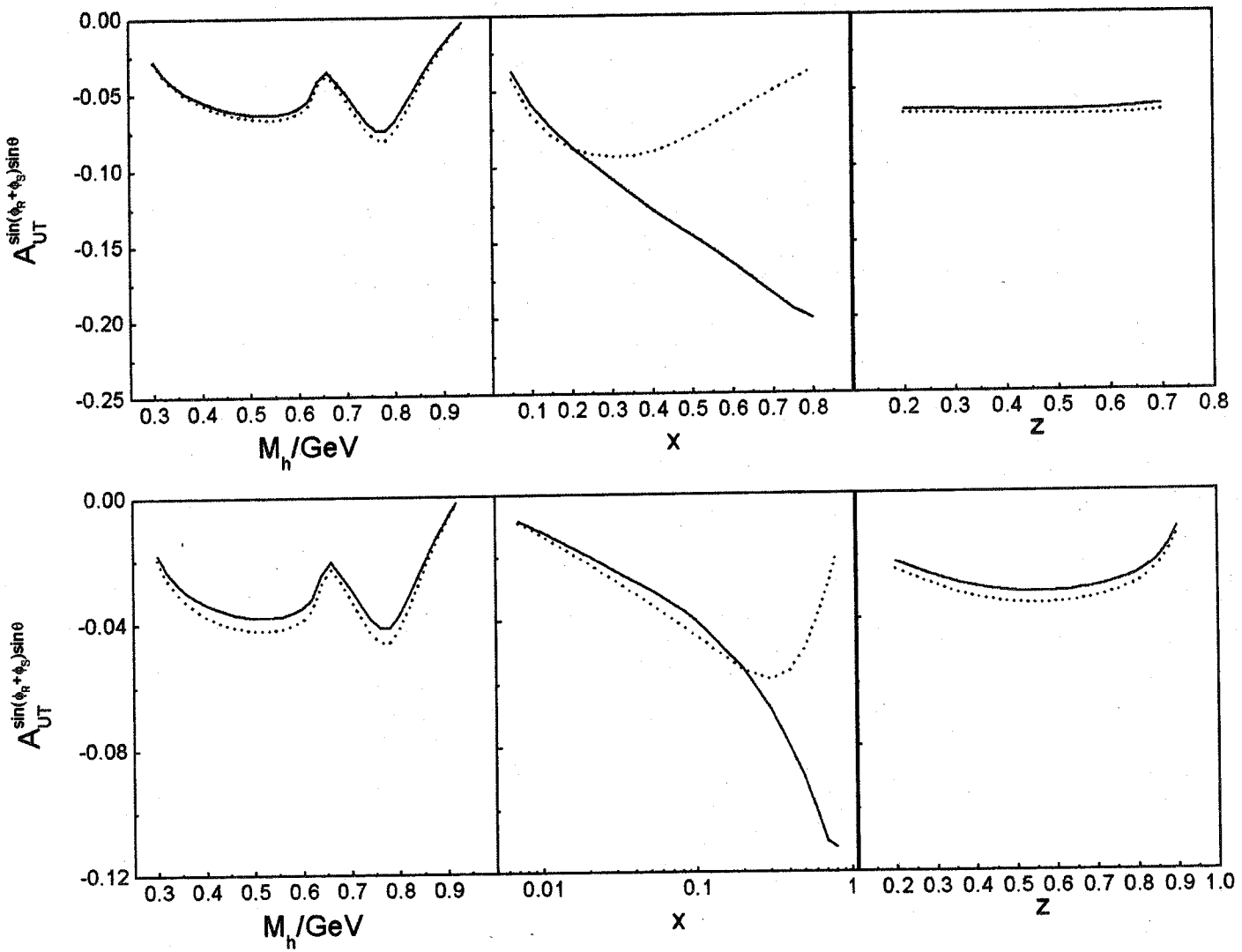
Comparison to 1-hadron analysis

- Advantages:
  - No convolution, simpler factorization.
  - No Collins and Sivers entanglement.
  - The FFs can be measured independently.
- Disadvantages:
  - Unknown FFs are introduced.
  - Less statistics in experiment.

$x \to 1$

	SU(6)	pQCD
d/u	0	1/5
$\delta u/u$	1	1
$\delta d/d$	-1/3	1
$A_p : \dfrac{4\delta u - \delta d}{4u + d}$	—	—
$A_d : \dfrac{1.5(\delta u + \delta d)}{2.5(u + d)}$	$\frac{3}{5} A_p$	$\frac{3}{5} A_p$
$A_n : \dfrac{4\delta d - \delta u}{4d + u}$	$-A_p$	$-\frac{1}{9} \times \frac{19}{21} A_p$

Prediction III (neutron target)



Transverse Spin and Drell-Yan Process

Jen-Chieh Peng
University of Illinois at Urbana-Champaign

- The Drell-Yan process compliments the SIDIS as a powerful independent tool for measuring transversity and TMD PDFs.
- First results on azimuthal decay angular distributions on unpolarized p-p or p-d Drell-Yan are now available.
- Pronounced cos2Φ azimuthal dependence previously observed in pion-induced Drell-Yan is not observed in p-p or p-d Drell-Yan
- These results suggest that the Boer-Mulders functions $h_1^{\perp}$ for sea quarks are smaller than for valence quarks.
- Future Drell-Yan experiments at Fermilab, J-PARC and other facilities can provide new information (flavor dependence of valence and sea, opposite sign for SIDIS and D-Y) on Boer-Mulders and other TMDs.

Transversity and TMD PDFs are also probed in Drell-Yan

Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}\bar{h}_1^{\perp}\cos(2\phi)$

Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$

Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

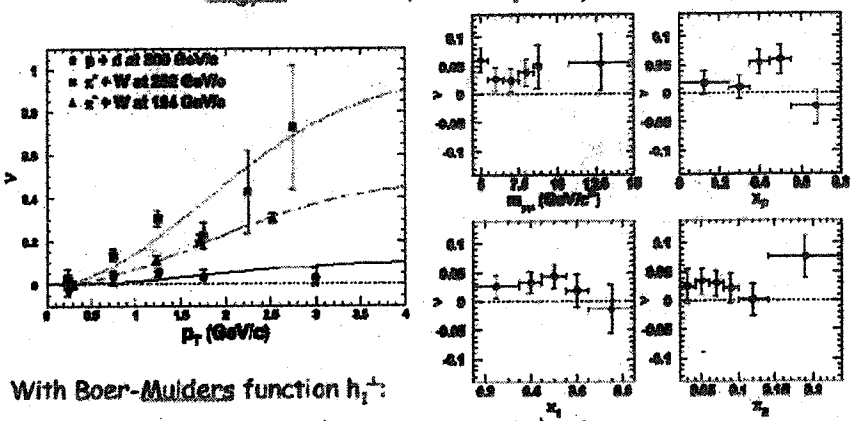
$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$

- Drell-Yan and SIDIS involve different combinations of TMDs
- Drell-Yan does not require knowledge of the fragmentation functions
- T-odd TMDs are predicted to change sign from DIS to DY (Boer-Mulders and Sivers functions)

  Remains to be tested experimentally!

Azimuthal cos2Φ Distribution in p+d Drell-Yan

Lingyan Zhu et al., PRL 99 (2007) 082301



With Boer-Mulders function $h_1^{\perp}$:

$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

$\nu > 0$ suggests same sign for the valence and sea BM functions

19

Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, arXiv:0803.1692)

Parametrization of the BM functions:

$$h_1^{\perp q}(x, p_\perp^2) = H_q x^c (1-x) f_1^q(x) \exp(-p_\perp^2 / p_{BM}^2)$$

H_u	H_d	$H_{\bar{u}}$	$H_{\bar{d}}$	p_{BM}^2	c	χ^2 / dof
3.99	3.83	0.91	-0.96	0.16	0.45	0.79

- H_u and H_d have the same sign and similar magnitude (in agreement with model calculations (bag-model, quark-diquark, relativistic CQM, Lattice) and the picture given by M. Burkardt)
- $H_{\bar{u}}$ and $H_{\bar{d}}$ are smaller by factor of 4 and have opposite sign

A simple explanation for the signs of the up- and down-quark Boer-Mulders functions

From fits to SIDIS data, we know that

1) transversity

$h_1(u) > 0 \quad h_1(d) < 0$

2) Sivers function

$f_{1T}^{\perp}(u) < 0 \quad f_{1T}^{\perp}(d) > 0$

3) Boer-Mulders function

One expects

$h_1^{\perp}(u) < 0 \quad h_1^{\perp}(d) < 0$

1) Transversity

Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

2) Sivers function

Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

3) Boer-Mulders function

Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

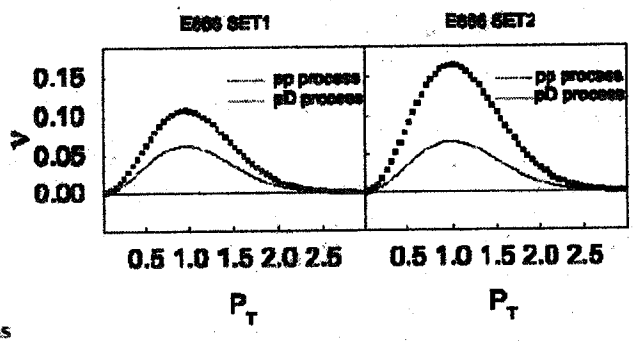
Extraction of Boer-Mulders functions from p+d Drell-Yan

(B. Zhang, Z. Lu, B-Q. Ma and I. Schmidt, Private communication)

	Set I	Set II
H_u	3.99	4.44
H_d	3.83	-2.97
$H_{\bar{u}}$	0.91	4.68
$H_{\bar{d}}$	-0.96	4.98
p_{bm}^2	0.161	0.165
c	0.45	0.82
$\chi^2/d.o.f.$	0.79	0.79

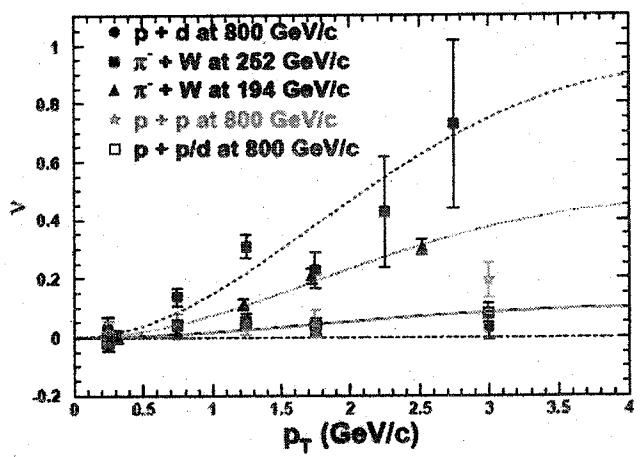
Set I: H_u, H_d have same signs

Set II: H_u, H_d have opposite signs



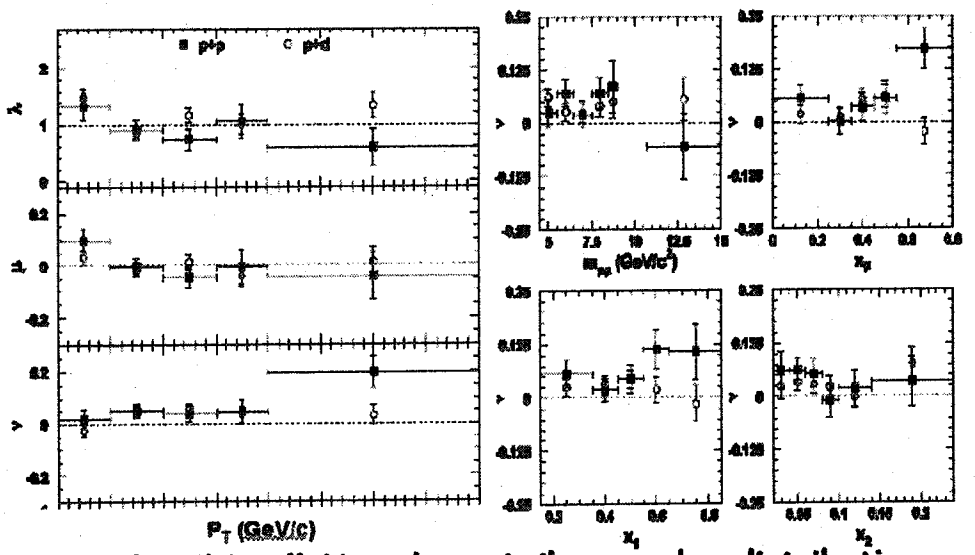
Predict larger values of ν for p+p than for p+d

New results on the Azimuthal cos2Φ Distribution in p+p Drell-Yan



- p+p is similar to p+d
- A global fit to all pion and proton data is needed

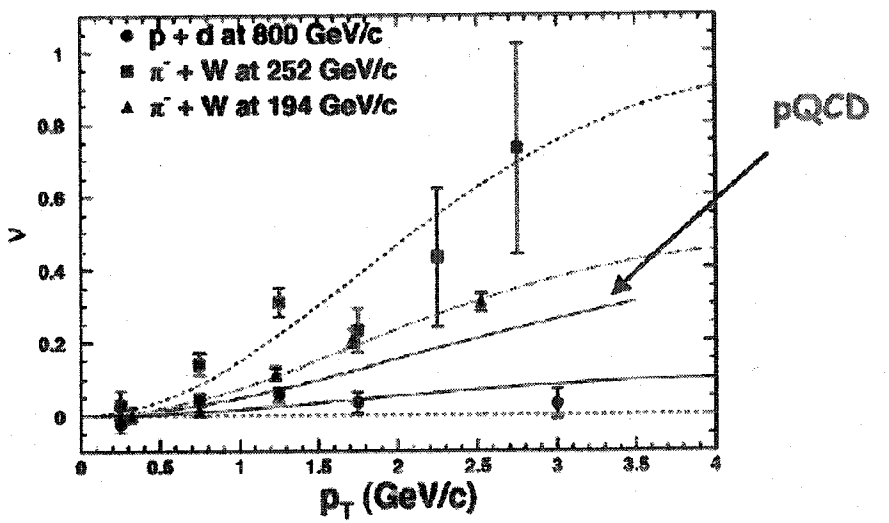
Angular Distribution in E866 p+p/p+d Drell-Yan



p+p and p+d Drell-Yan show similar angular distributions. Should be analysed togther for better constraints on BM.

QCD correction

(Talk by Werner Vogelsang)



Future prospect for Drell-Yan experiments

- Fermilab p+p, p+d, p+A
  - Unpolarized beam and target
- RHIC
  - Polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarizied proton beam and target

Outstanding questions to be addressed by future Drell-Yan experiments

- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

Transverse Single Spin Asymmetry in Drell-Yan Production at RHIC

Ming X. Liu

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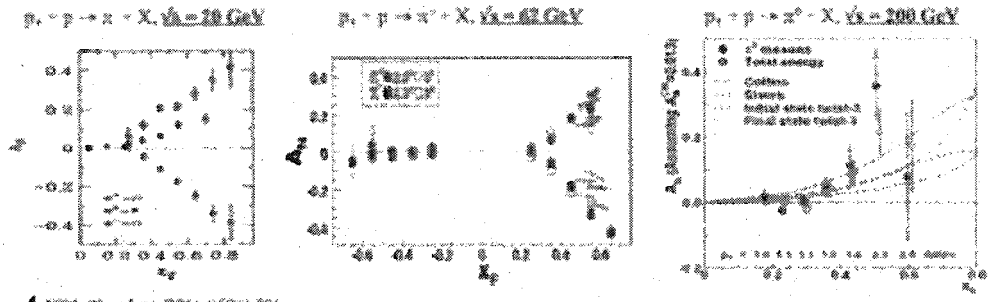
We discuss the science case and opportunities for the future study of the transverse single spin asymmetry in Drell-Yan process at Relativistic Heavy Ion Collider (RHIC) at BNL. In the last a few years, there has been tremendous progress in understanding the underlying physics mechanisms of the very large "left-right" asymmetries observed in hadronic reactions with transversely polarized beams. Particularly, the Sivers-type and Collins-type single-spin asymmetries have been observed in semi-inclusive DIS at HERMES and COMPAS.

Although most model calculations agree impressively with observed A_N vs X_F at RHIC, they failed to reproduce the recent more detailed pT dependent behavior of A_N in the forward rapidity. It is clear that our current understanding of the origin of single spin asymmetry is not complete and needs further investigation. There is a fundamental QCD prediction on Sivers asymmetries in Drell-Yan processes that the asymmetries carry the opposite sign of what observed in DIS processes. Confirmation of this prediction will allow us to test ALL concepts used for analyzing hard-scattering reactions that we know of. I will show that RHIC offers extremely favorable possibilities for studying the Drell-Yan transverse single spin asymmetries with RHIC luminosity and detector upgrade.

Ref: http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Large Asymmetries Persist at High √s

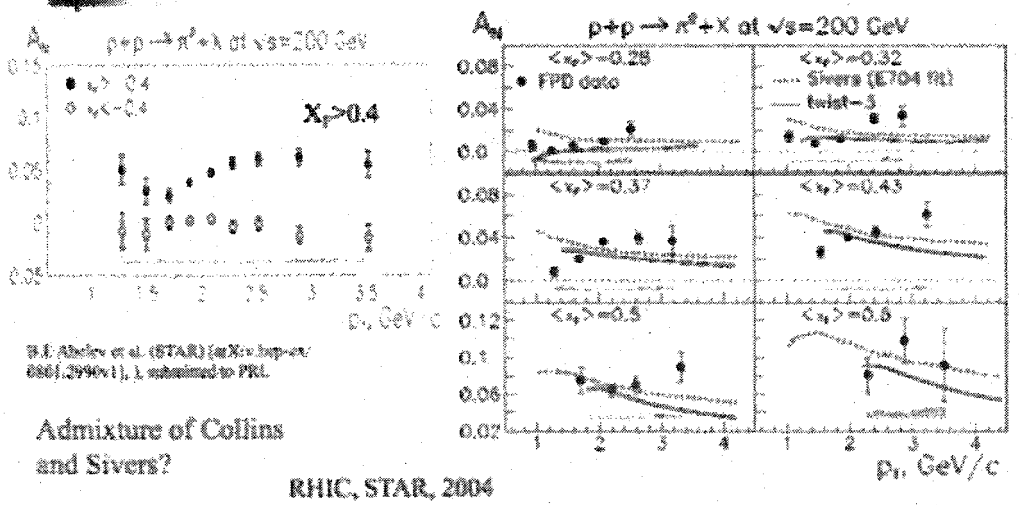


Fermilab, E704, 1991 | RHIC, Brahma, 2007 | RHIC, STAR, 2004

Non-Perturbative cross section ⟶ Perturbative cross section

Gordon AGS/RHIC 2008

...but rising P_T dependence is not predicted by the same fits



Admixture of Collins and Sivers?

RHIC, STAR, 2004

Attractive vs Repulsive "Sivers" Effects

Unique Prediction of Gauge Theory !

DIS: attractive | **Drell-Yan: repulsive**

$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Drell-Yan Production @RHIC

- Rapidity and Collision Energy Dependence

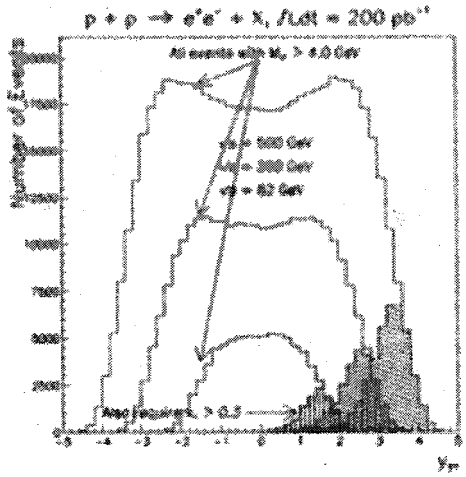
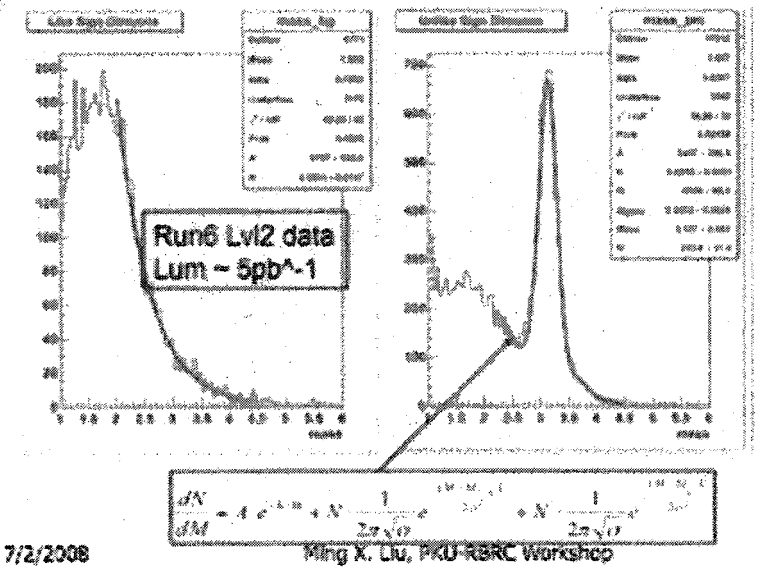


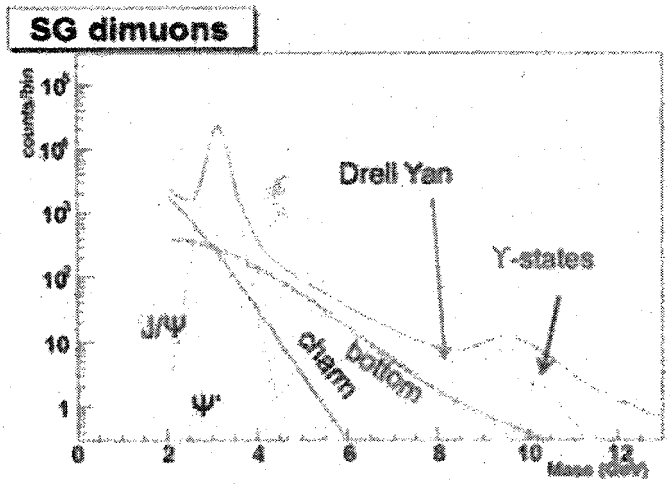
Figure 5: PYTHIA simulation of the rapidity distribution of e^+e^- dileptons produced through the Drell-Yan process. The importance of large rapidity to probe the valence region is illustrated by selecting events with $x_1 > 0.3$.

Dimuon Mass Spectra from PHENIX @200GeV



DY Background @200GeV

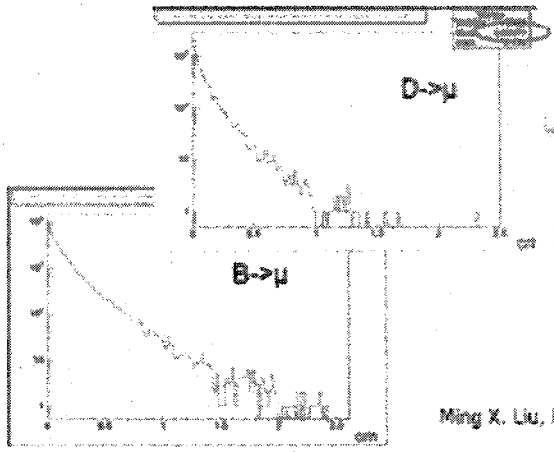
(PYTHIA Simulation benchmarked to PHENIX Data)

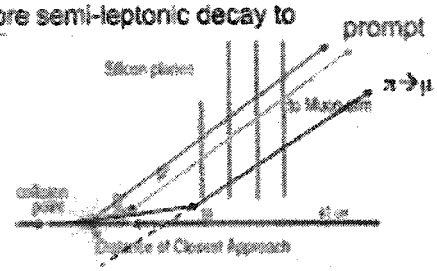


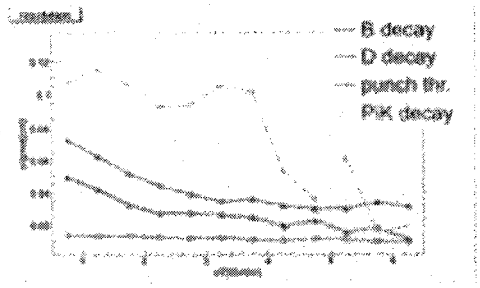
Impact Parameters for muons from D,B and DY

Measuring Charm and Beauty

- D, B mesons travel ~1 mm (with boost) before semi-leptonic decay to muons
- By measuring DCA to primary vertex, can separate D and B from prompt particles and long-lived decays like π, K



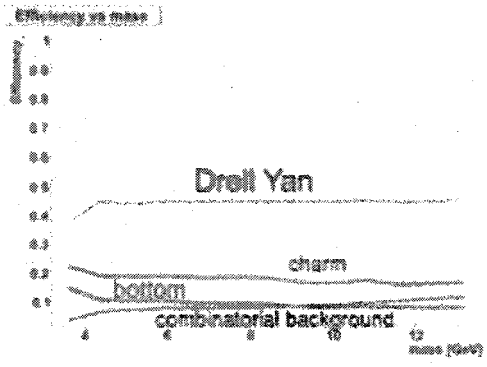




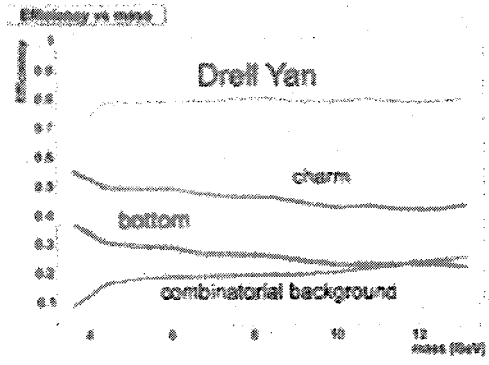
Ming X. Liu, PKU-RBRC Workshop 20

Reduce Heavy Quark Background by DCA cut

DCA < 1 σ cut:
Increase DY/bb ~ 5



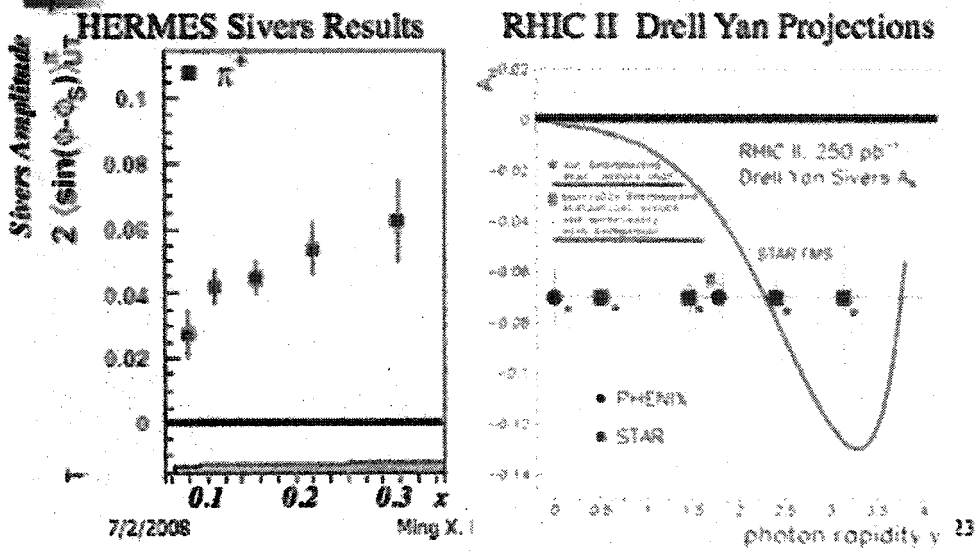
DCA < 2 σ
Increase DY/bb ~ 3



7/2/2008 Ming X. Liu, PKU-RBRC Workshop 21

Experiment SIDIS vs Drell Yan: $\text{Sivers}|_{DIS} = -\text{Sivers}|_{DY}$

***** Probes QCD attraction and QCD repulsion *****



Summary

- Exciting Physics
  - A new fundamental test of QCD prediction
- Experimentally challenge
  - Need RHIC-II luminosity
  - Detector Upgrade
- Can do it at RHIC!

Polarized Drell-Yan experiment at J-PARC

Y. Goto

RIKEN and *RIKEN BNL Research Center*

We propose to make the J-PARC facility allow acceleration of polarized proton beams to 30-50 GeV with some modifications for experiments using this primary beam.[1, 2] The modifications would consist of the addition of a polarized H^- source, an rf dipole in the 3 GeV Rapid Cycling Synchrotron (RCS) and two strong superconducting partial Siberian snakes in the 50 GeV Main Ring (MR). In addition, several external and internal polarimeters are needed for commissioning and operation of polarized proton acceleration. The proposed scheme for the acceleration of polarized protons is based on the successful experience of accelerating polarized protons to 25 GeV at the Brookhaven AGS [3], which is very similar to the J-PARC complex. To meet the requirements of spin physics program the MR should deliver about 10^{12} p/spill. The required beam bunch parameters that allow the acceleration of polarized protons to 50 GeV are a normalized 95% emittance of 10π mm mrad and 0.3 eVs longitudinal emittance. With the present available source intensity of 10^{12} H^- for a 0.5 ms pulse it is easily possible to produce a bunch intensity of 2×10^{11} protons for a single bunch in the RCS.

Polarized Drell-Yan measurement by the dimuon experiment which has been proposed [4] will provide us valuable new experimental data of the polarized nucleon structures, e.g. flavor structure of the sea-quark polarization, orbital angular momentum and transversity of quarks inside the nucleon. Since we know relatively well the contribution of the quark and gluon to the nucleon spin, and it is not enough to explain the entire contents, we want to measure the contribution of the orbital angular momentum of the quark and gluon to the nucleon spin as the final object. To restrict the quark and gluon contribution to the nucleon spin with high precision, it is also important to know the flavor-sorted sea-quark contribution to the nucleon spin directly. The polarized proton acceleration at J-PARC will provide a new and unique tool to study the nucleon structure and hadron interactions based on QCD.

References

[1] Y. Goto, H. Sato *et al.*, Proposal "Polarized Proton Acceleration at J-PARC", November 2007.

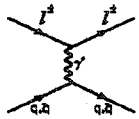
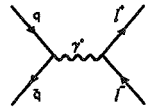
[2] A. U. Luccio *et al.*, SPIN2006, AIP Conf. Proc. 915, p.944.

[3] H. Huang *et al.*, Proceedings of EPAC2006, Edinburgh, Scotland, p.273: H. Huang *et al.*, Phys. Rev. Lett. **99**, 154801 (2007).

[4] J.-C. Peng, S. Sawada *et al.*, Proposal "Measurement of High-Mass Dimuon Production at the 50-GeV Proton Synchrotron", April 2006: Addendum to the Proposal, June 2007.

Drell-Yan experiment

- The simplest process in hadron-hadron reactions

DIS  Drell-Yan 

  - no QCD final-state effect
  - no polarized Drell-Yan experiment done yet
  - flavor asymmetry of the sea-quark distributions
    - unpolarized and longitudinally-polarized measurements
  - orbital angular momentum in the nucleon
    - Sivers effect (no Collins effect)
  - transversity distribution function, etc.
- Why at J-PARC ?
  - polarized beam feasible in discussions with J-PARC and BNL accelerator physicists
  - high intensity/luminosity for small Drell-Yan cross section

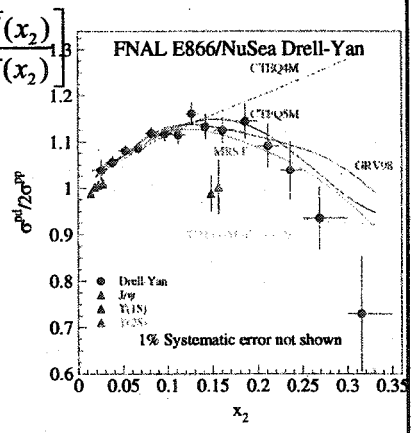
Flavor asymmetry of sea-quark distribution

- Fermilab E866 $\frac{\sigma^{pd}}{2\sigma^{pp}} \sim \frac{1}{2}\left[1+\frac{\bar{d}(x_2)}{\bar{u}(x_2)}\right]$
- Possible origins
  - meson-cloud model
    - virtual meson-baryon state

$$p \to p\pi^0, n\pi^+, \Delta\pi$$

  - chiral quark model

  - instanton model
  - chiral quark soliton model
- Is π^+ the origin of $\bar{d}$ -quark excess in the proton?



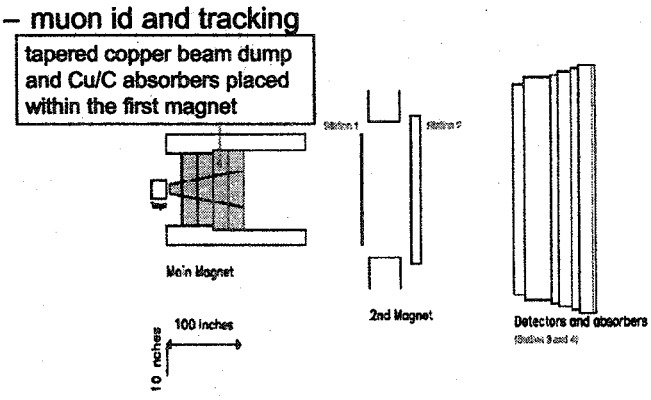
with CTEQ5M

$$\int_{0.015}^{0.35} dx[\bar{d}(x)-\bar{u}(x)] = 0.0803 \pm 0.011$$

$$\int_0^1 dx[\bar{d}(x)-\bar{u}(x)] = 0.118 \pm 0.012$$

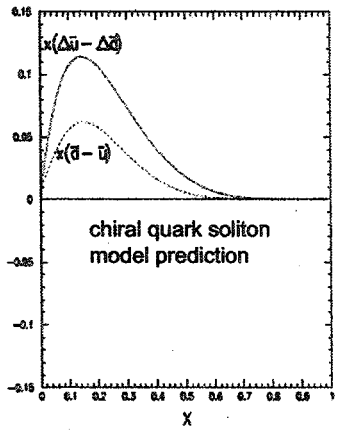
Dimuon experiment at J-PARC (P04)

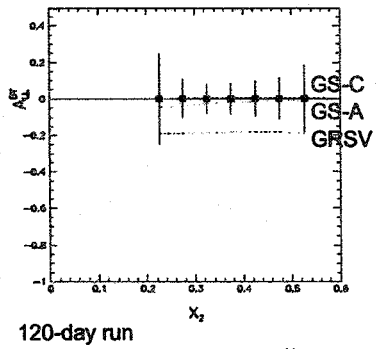
- based on the Fermilab spectrometer for 800 GeV
- length to be reduced but the aperture to be increased
- two bending magnets with p_T kick of 2.5 GeV/c and 0.5 GeV/c
- tracking by three stations of MWPC and drift chambers
- muon id and tracking



Polarized Drell-Yan experiment at J-PARC

- Longitudinally-polarized measurement
  - A_{LL} measurement
  - flavor asymmetry of sea-quark polarization

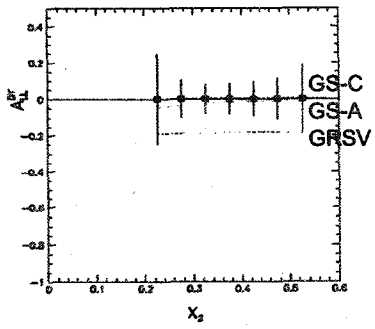


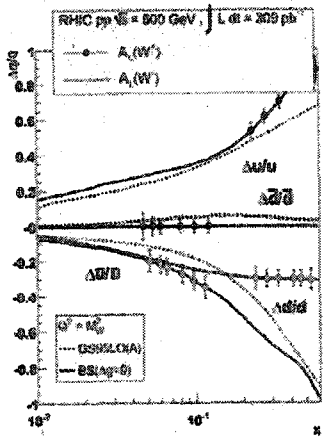


120-day run
75% polarization for a 5×10^{11} protons/spill polarized solid NH3 target, 75% hydrogen polarization and 0.15 dilution factor

Flavor asymmetry of sea-quark polarization

- Polarized Drell-Yan experiment at J-PARC
  - x = 0.25 – 0.5
- $W^{\pm}$ production at RHIC
  - x = 0.05 – 0.1

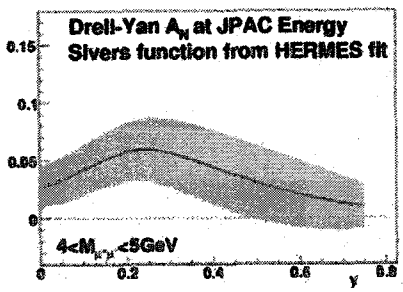




reduction of uncertainties to determine the quak spin contribution $\Delta\Sigma$ and gluon spin contribution ΔG to the proton spin

Polarized Drell-Yan experiment at J-PARC

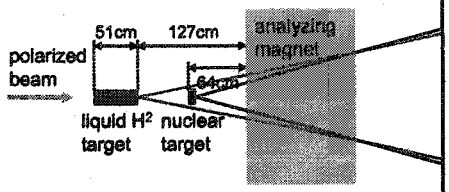
- Orbital angular momentum
  - in hadron-hadron reaction, no direct link between measurement and theory (yet)
  - but, any partonic transverse motion and correlation should be related
    - Sivers effect / higher-twist effect
- *SSA (A_N)* measurement
  - Sivers effect and higher-twist effect provide the same description of SSA on Drell-Yan and semi-inclusive DIS at moderate q_T: $\Lambda_{QCD} << q_T << Q$
  - Sivers function in Drell-Yan should have a sign opposite to that in DIS
    - sensitive QCD test between e+p data and p+p data



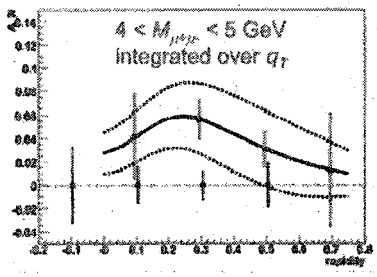
Theory calculation by Ji, Qiu, Vogelsang and Yuan based on Sivers function fit of HERMES data (Vogelsang and Yuan: PRD 72, 054028 (2005))

Polarized Drell-Yan experiment at J-PARC

- Experimental condition
  - higher beam intensity is possible for unpolarized liquid H_2 target, or nuclear target
    - 5×10^{12} ppp = $2.5\times10^{12}\times2$sec in 1pulse (5sec) possible?
  - PYTHIA simulation
    - 75% polarization beam
    - 120 days, beam on target 5×10^{17} (with 50% duty factor)
    - ~5% reaction target
    - 10000 fb^{-1} luminosity
    - mass 4 – 5 GeV/c^2



red liquid H2 target
blue nuclear target



Polarized Drell-Yan experiment at J-PARC

- A_{TT} measurement
  - $h_1(x)$: transversity
    - remaining leading-order distribution function of the nucleon

$$A_{TT} = \hat{a}_{TT} \cdot \frac{\sum_q e_q^2 (\bar{h}_{1q}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

$$\hat{a}_{TT} = \frac{\sin^2\theta \cos(2\phi - \phi_{S_1} - \phi_{S_2})}{1+\cos^2\theta}$$

- SSA measurement, $\sin(\phi+\phi_S)$ term
  - $h_1(x)$: transversity
  - $h_1^{\perp(1)}(x)$: Boer-Mulders function (1st moment of)

$$\hat{A} = -\frac{1}{2} \frac{\sum_q e_q^2 (\bar{h}_{1q}^{\perp(1)}(x_1) h_{1q}(x_2) + (1 \leftrightarrow 2))}{\sum_q e_q^2 (\bar{f}_{1q}(x_1) f_{1q}(x_2) + (1 \leftrightarrow 2))}$$

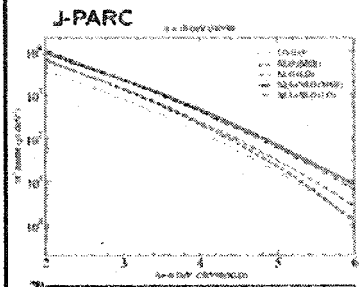
- Unpolarized measurement
  - angular distribution of unpolarized Drell-Yan
  - Boer-Mulders function
    - valence $h_1^{\perp}(x) \otimes$ sea $h_1^{\perp}(x)$

$$N(\phi) \propto h_1^{\perp q}(x_1, k_\perp^2) \cdot \frac{(\hat{P} \times \vec{k}_\perp) \cdot \vec{S}_q}{M} \cdot h_1^{\perp \bar{q}}(x_2, \bar{k}_\perp^2) \cdot \frac{(\hat{P} \times \vec{\bar{k}}_\perp) \cdot \vec{S}_{\bar{q}}}{M}$$

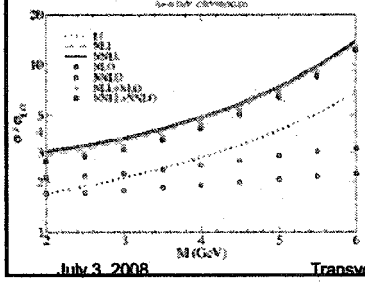
pQCD studies of Drell-Yan cross section

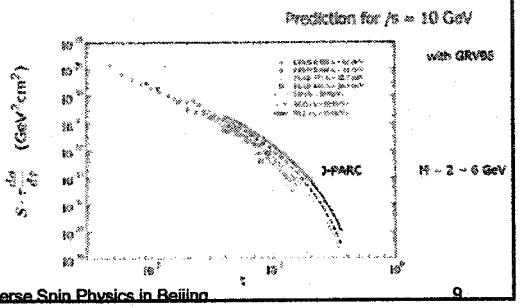
- pQCD correction can be controlled at J-PARC energy

J-PARC



NNLO calculation
Hamberg, van Neerven, Matsuura, Harlander, Kilgore
NLL, NNLL calculation
Yokoya, et al...





Summary

- Polarized Drell-Yan experiment with dimuon measurment using polarized proton beam at J-PARC has a rich physics programs
  - flavor asymmetry of sea-quark polarization → higher precision for $\Delta\Sigma$ and ΔG
  - SSA measurements for Sivers and higher-twist effects → link to orbital-angular momentum
  - transversity and Boer-Mulders distribution functions
  - theoretical studies at J-PARC energy has shown convergence to compare with experimental data
- We have proposed to make the J-PARC facility allow acceleration of polarized proton beams to 30-50 GeV
  - feasible in discussion with J-PARC and BNL accelerator physicists
  - technically, there is no showstopper so far
- More studies for experimental condition to be done
  - For the next proposal

Round table discussion on Drell-Yan

Werner Vogelsang and Jen-Chieh Peng

PKU-RBRC Workshop on Transverse Spin Physics,
Beijing, June 30 – July 4, 2008

agenda

- Goals of future D-Y experiments (Jen-Chieh Peng)
- Theoretical issues (Werner Vogelsang)
- Future D-Y at COMPASS (Franco Bradamante)
- Future D-Y at STAR (Les Bland)
- Other discussions/presentations

Future prospect for Drell-Yan experiments

- Fermilab
  - Unpolarized proton beam and target
- RHIC
  - Polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarizied proton beam and target

Outstanding questions to be addressed by future Drell-Yan experiments

- Does Sivers function change sign between DIS and Drell-Yan?
- Does Boer-Mulders function change sign between DIS and Drell-Yan?
- Are all Boer-Mulders functions alike (proton versus pion Boer-Mulders functions)
- Flavor dependence of TMD functions
- Independent measurement of transversity with Drell-Yan

Outstanding questions to be addressed by future Drell-Yan experiments

- Does Sivers function change sign between DIS and Drell-Yan?
  - Need single transversely polarizied Drell-Yan. ($\sin(\Phi-\Phi_s)$ moment ~ product of Sivers and unpolarzied pdf)
  - Possible at RHIC, J-PARC, FAIR

- Does Boer-Mulders function change sign between DIS and Drell-Yan?
  - Unpolarized D-Y is insensitive to the sign of B-M function
  - Need single transversely polarizied D-Y ($\sin(\Phi+\Phi_s)$ moment ~ product of transversity and B-M)
  - Possible at RHIC, J-PARC, FAIR

Outstanding questions to be addressed by future Drell-Yan experiments

- Are all Boer-Mulders functions alike (proton and pion Boer-Mulders functions are predicted to have same signs)
- Flavor dependence of TMD functions
  - Fermilab, RHIC, COMPASS, J-PARC, FAIR

Outstanding questions to be addressed by future Drell-Yan experiments

- Independent measurement of transversity with Drell-Yan
  - FAIR, using double transversely polarized D-Y in p-bar-p collision
  - RHIC, using double transversely polarized D-Y in p-p collision. Sensitive to sea-quark transversity
  - FAIR, using singly transversely polarizied D-Y ($\sin(\Phi+\Phi_s)$ term is sensitive to product of transversity and B-M function)

Transversity

from a relativistic viewpoint

Bo-Qiang Ma (马伯强)
PKU (北京大学物理学院)

Transversity 2008 Beijing

The proton "spin crisis" or "spin puzzle" can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation.

New way to access quark orbital angular momentum is suggested.

The proton spin crisis

& the Melosh-Wigner rotation

- It is shown that the proton "spin crisis" or "spin puzzle" can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation.
- The quark helicity Δq measured in polarized deep inelastic scattering is actually the quark spin in the infinite momentum frame or in the light-cone formalism, and it is different from the quark spin in the nucleon rest frame or in the quark model.

B.-Q. Ma, J.Phys. G 17 (1991) L53

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

A general consensus

The quark helicity Δq defined in the infinite momentum frame is generally not the same as the constituent quark spin component in the proton rest frame, just like that it is not sensible to compare apple with orange.

H.-Y.Cheng, hep-ph/0002157,
Chin.J.Phys.38:753,2000

The Melosh-Wigner Rotation in Quark Orbital Angular Moment

$$\hat{L}_q = -i\left(k_1 \frac{\partial}{\partial k_2} - k_2 \frac{\partial}{\partial k_1}\right).$$

$$L_q(x) = \int [d^2k_\perp] M_L(x,k_\perp) \Delta q_{QM}(x,k_\perp)$$

$$M_L(x,k_\perp) = \frac{k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

The Melosh-Wigner Rotation in Pretrelosity

$$g_1^q(x, k_\perp) - h_1^q(x, k_\perp) = h_{1T}^{\perp(1)q}(x, k_\perp) \ .$$

$$\frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} - \frac{(k^+ + m)^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} = -\frac{\mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2}$$

$$\mathrm{Pretrelocity} = \Delta \mathrm{q} - \delta \mathrm{q} = -\mathrm{L_q}$$

$$\mathrm{Pretrelocity} = -\int [\mathrm{d}^2\mathbf{k}_\perp] \frac{\mathbf{k}_\perp^2}{(\mathrm{k}^+ + \mathrm{m})^2 + \mathbf{k}_\perp^2} \Delta \mathrm{q_{QM}}(\mathrm{x}, \mathbf{k}_\perp)$$

Conclusions

- Relativistic effect of Melosh-Winger rotation is important in hadron spin physics.
- Transversity is being accessed in SIDIS and two pion inteference fragmentation processes
- The unfavored Collins fragmentation plays a surprising role to reproduce the data, than naively expected.
- Further constraints on Collins functions and interference fragmentation functions are needed for reliable determination of transversity.
- New way to access quark orbital angular momentum is suggested.

Correlation functions in hard exclusive and (semi-) inclusive processes

Marc Schlegel,
Theory Center, Jefferson Lab

in collaboration with
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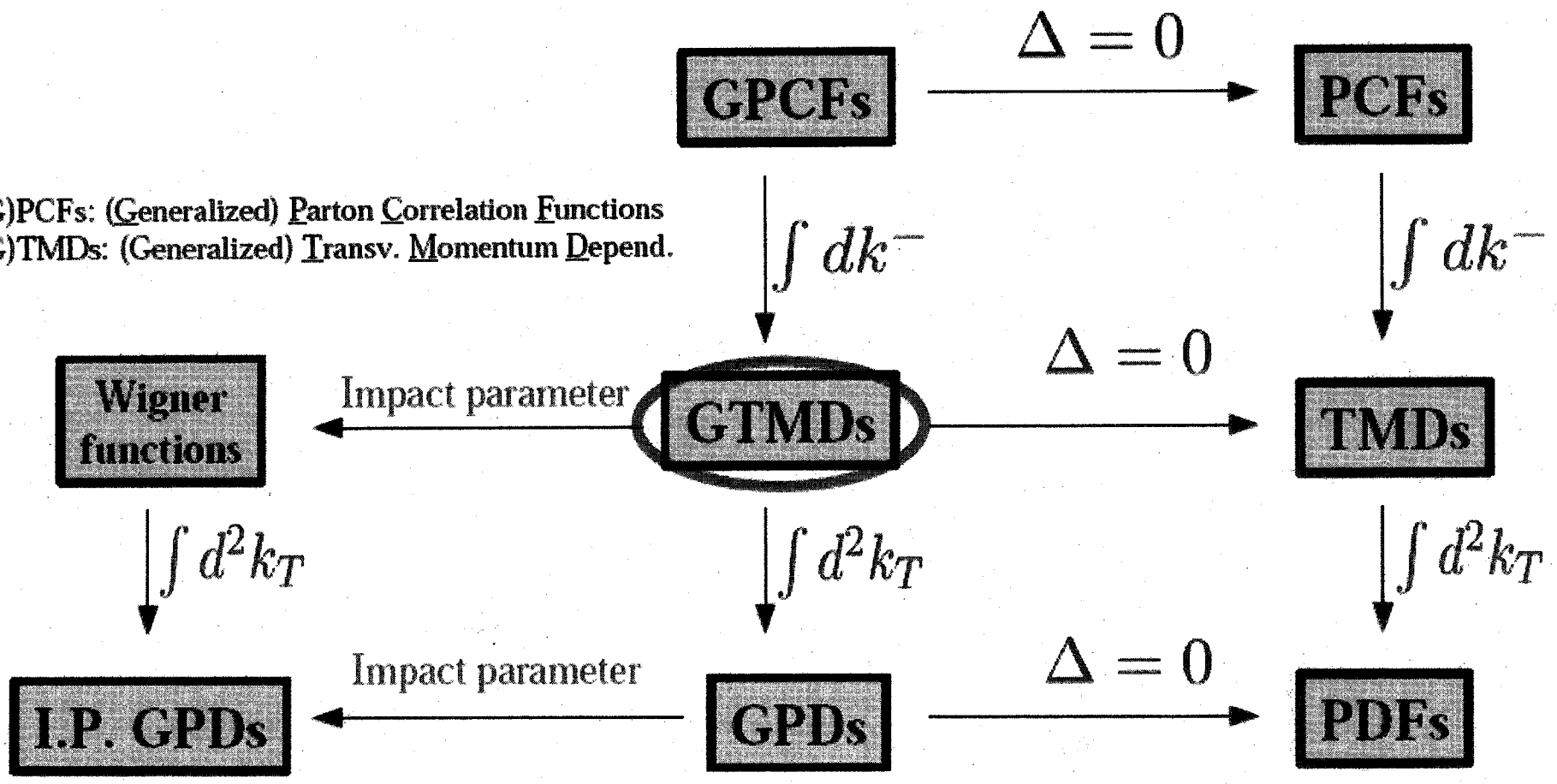
and S. Meissner, K. Goeke (Ruhr-University, Bochum, Germany)

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Mother functions

Relations between functions:

(G)PCFs: (Generalized) Parton Correlation Functions
(G)TMDs: (Generalized) Transv. Momentum Depend.



Which GPDs and TMDs have the same mother functions?

Classification of GPCFs

[Goeke, Meissner, Metz, M.S., 0805.3165 [hep-ph], spin-0]

[Goeke, Meissner, Metz, M.S., in preparation, spin-1/2]

Generalized, fully unintegrated quark-quark correlator:

$$W_{ij}(P,k,\Delta,N;\eta) = \int \frac{d^4z}{(2\pi)^4}\, e^{ik\cdot z} \langle p' | \bar{\psi}_j(-\tfrac{z}{2}) \mathcal{W}(-\tfrac{z}{2},\tfrac{z}{2}\,|\,n) \psi_i(\tfrac{z}{2}) | p \rangle$$

- Wilson line chosen 'by hand': TMDs in *SIDIS / DY* can be recovered.
- Encodes the maximum amount of information on two-parton structure.
- *W* depends on a *light cone direction N*, $N^\mu = n^\mu M^2/(Pn)$,
  Parameter $\eta = \mathrm{sign}(n^0) \in \{-1,1\} \Longrightarrow$ ISI / FSI

Generalized TMDs

- Integration over a light cone direction (k^-) $\longrightarrow$ *GTMDs:*

$$\tilde{W} = \int dk^- \, W$$

<u>For spin-0</u>: Classification with respect to P^+

$$\mathrm{Tr}[\tilde{W}\gamma^+] = 2F_1(x, \xi, \vec{\Delta}_T^2, \vec{k}_T^2, \vec{\Delta}_T \cdot \vec{k}_T; \eta)$$ [unpol. quark]

$$\mathrm{Tr}[\tilde{W}\gamma^+\gamma_5] = 2\frac{\vec{k}_T \times \vec{S}_T}{M^2}\tilde{G}_1$$ [long. pol. quark]

$$\mathrm{Tr}[\tilde{W}i\sigma^{i+}\gamma_5] = -\frac{2i}{M}\left(\epsilon_T^{ij}k_T^j H_1^k - \epsilon_T^{ij}\Delta_T^j H_1^\Delta\right)$$ [transv. pol. quark]

- GTMDs are complex-valued of the form (Time-reversal)

$$X(\eta) = \Re[X] + i\eta\Im[X]$$

Limiting cases of Generalized TMDs

- TMDs in terms of GTMDs: $\Delta = 0$

$$f_1(x, \vec{k}_T^2) = \Re[F_1](x, 0, 0, 0, \vec{k}_T^2)$$

$$h_1^\perp(x, \vec{k}_T^2) = \eta \Im[H_1^k](x, 0, 0, 0, \vec{k}_T^2)$$

- GPDs in terms of GTMDs: $\int d^2 k_T$

$$F_1^\pi(x, \xi, t) = \int d^2 k_T \, \Re[F_1](x, \xi, \vec{\Delta}_T^2, \vec{\Delta}_T \cdot \vec{k}_T, \vec{k}_T^2)$$

$$H_1^\pi(x, \xi, t) = \int d^2 k_T \left[\frac{\vec{\Delta}_T \cdot \vec{k}_T}{\vec{\Delta}_T^2} \Re[H_1^k] + \Re[H_1^\Delta] \right]$$

- Trivial relation fulfilled.
- No *exact* model-independent relations. Approximate relations?

Limiting cases: Spin 1/2

Example: Sivers function:

GTMDs:

$$\mathrm{Tr}\left[\tilde{W}_{\lambda'\lambda}\gamma^-\right] = \frac{1}{p^-}\bar{u}(p',\lambda')\left[\frac{p^-}{M}\mathcal{F}_1 + \frac{i\sigma^{j-}k_T^j}{M}\mathcal{F}_1^- + \frac{i\sigma^{j-}\Delta_T^j}{M}\mathcal{F}_1^\Delta + \frac{p^+}{M}\frac{i\sigma^{ij}k_T^i\Delta_T^j}{M^2}\mathcal{F}_1^{-\Delta}\right]u(p,\lambda)$$

4 GTMDs: Amount of structures are doubled.

TMD-limit: $\Delta = 0$

$$f_{1T}^\perp(x,\vec{k}_T^2) = \Im[\mathcal{F}_1^\perp](x,0;\vec{k}_T^2,0,0)$$

GPD-limit: $\int d^2k_T\ ,\ \xi = 0$

$$(E+H)(x,0,\vec{\Delta}_T^2) = 2\int d^2k_T\left[\Re[\mathcal{F}_1^\Delta] + \frac{\vec{k}_T\cdot\vec{\Delta}_T}{\vec{\Delta}_T^2}\Re[\mathcal{F}_1^\perp]\right]$$

No model-independent *exact* relation! Approximate relations?

Comments on Sivers and Collins effects in pp collisions

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Dipartimento di Fisica and INFN, Università di Cagliari, C.P. 170, I-09042 Monserrato (CA), Italy

Two common approaches are currently adopted for the description of transverse single spin asymmetries (SSA) in proton-proton collisions: *i*) the twist-three formalism in a collinear factorization scheme; *ii*) the generalized parton model (GPM) approach with transverse momentum dependent (TMD) distributions [1]. In the first case factorization has been established, whereas in the second case it is assumed as a phenomenological ansatz. On the other hand the TMD factorization, with proper inclusion of colour-gauge links, has been proved for SIDIS, Drell-Yan and $e^+e^- \to hhX$ processes and, at least for $k_\perp$-weighted quantities, also for double inclusive particle production in pp collisions. Violation of universality, with non factorizable terms, is expected in the TMD approach to $pp \to hhX$, while the single inclusive case is still under debate. For these reasons a phenomenological analysis of SSAs in $pp \to \pi X$ in the TMD approach, besides its intrinsic interest, could be considered a guidance towards our understanding of factorization and universality breaking effects.

Among the main features of the GPM approach [1] we recall: use of full $k_\perp$ kinematics; fair agreement between leading order unpolarized cross sections and high-energy data; use of leading-twist TMD distributions with higher-twist effects going like $k_\perp/p_T$; role of azimuthal phases.

In this talk we address the following issues:

- *Reassessment of the Collins effect in pp collisions* [slides 7, 8]. The correction of a sign mistake in the double spin transfer for the $qg \to qg$ channel implies a revision of our previous findings [2]. Although the role of azimuthal phases is still confirmed, Collins effect is not suppressed anymore (see also Ref. [3]). Notice that this has no implication in various other results obtained in the TMD approach.
- *Role of Sivers and Collins effects in $pp \to \pi X$.* In principle they are both able to describe the SSAs observed at RHIC (STAR, BRAHMS) [slides 10, 13]. Among some relevant aspects we mention: sizeable SSAs for neutral pions could be obtained only if the Sivers functions for up and down quarks or the favoured and unfavoured Collins functions are not comparable in size and opposite in sign, in particular at large x or z [slides 12, 14]; for both positive and negative pion SSAs a relevant role is played by the fragmentation function (FF) set adopted (gluon and favoured vs. unfavoured FFs).
- *Sivers and Collins effects from SIDIS to $pp \to \pi X$.* Adopting the Sivers, Collins and transversity functions as extracted in Refs. [4, 5] (and correcting the sign mistake in the Collins effect), the agreement is still good for STAR data and is now a bit worse for BRAHMS data w.r.t. what shown in Ref. [6] [slide 17]. Even if this is an extrapolation to a region not covered by SIDIS data ($x < 0.3$), the degree of compatibility of the TMD approach in such different processes is amazing. A new updated analysis of the Sivers effect in SIDIS [7] has been recently released. Being focused on kaon production and sea quark contributions, this is not directly usable in $pp \to \pi X$: indeed here the large x behaviour, still not covered by SIDIS data, is "over-constrained", and would imply a negligible SSA for $pp \to \pi^0 X$ [8]. Therefore a new strategy has been adopted: *i*) grid of the parameters β_u, β_d governing the large x behaviour of the Sivers function for up and down quarks [$\simeq (1-x)^{\beta_q}$]; *ii*) fit of SIDIS data at fixed β_q; *iii*) exclusion of fits with $\chi^2 > 1.2$; *iv*) spanned region in $pp \to \pi X$ from SIDIS fits with $\chi^2 < 1.2$ [slide 21]. From this preliminary study the compatibility of SSA in SIDIS and $pp \to \pi X$ processes in terms of the Sivers effect alone is not excluded [slide 22]. A similar study for the Collins effect could be performed and is in progress.

More consistently, since both the Sivers and the Collins effects could in principle mix in $pp \to \pi X$, the future goal is a global analysis of SSAs in SIDIS, e^+e^- and pp processes.

These results are based on ongoing work in collaboration with M. Anselmino, M. Boglione, E. Leader, S. Melis, F. Murgia, and A. Prokudin.

---

[1] M. Anselmino *et al.*, Phys. Rev. **D 73**, 014020 (2006), hep-ph/0509035.
[2] M. Anselmino, M. Boglione, U. D'Alesio, E. Leader and F. Murgia, Phys. Rev. **D 71**, 014002 (2005), hep-ph/0408356.
[3] F. Yuan, Phys. Lett. **B666**, 44 (2008), arXiv:0804.3047 [hep-ph].
[4] M. Anselmino *et al.*, Phys. Rev. **D 72**, 094007 (2005), hep-ph/0507181.
[5] M. Anselmino *et al.*, Phys. Rev. **D 75**, 054032 (2007), hep-ph/0701006.
[6] M. Boglione, U. D'Alesio and F. Murgia, Phys. Rev. **D 77**, 051502 (2008), arXiv:0712.4240 [hep-ph].
[7] M. Anselmino *et al.*, arXiv:0805.2677 [hep-ph].
[8] M. Anselmino *et al.*, arXiv:0809.3743 [hep-ph].

Reassessment of the Collins effect in pp collisions (thanks to *Yuan '08*)

$$A_N \simeq h_1 \otimes f \otimes \Delta\hat{\sigma} \otimes \Delta^N D_{h/q^\uparrow}$$

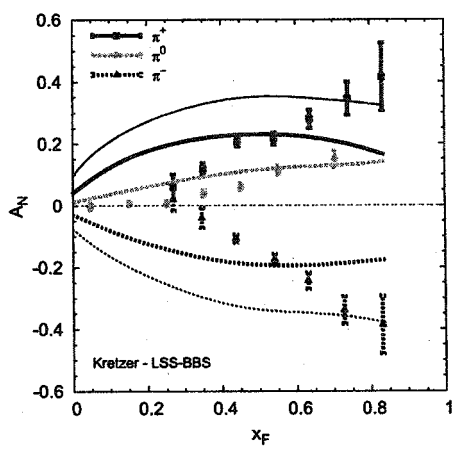
- $q^\uparrow g \to q^\uparrow g$ (leading contribution at large x_F):
double spin transfer $d\hat{\sigma}^{\uparrow\uparrow} - d\hat{\sigma}^{\uparrow\downarrow}$: wrong SIGN in *Anselmino et al. PRD71 '05*
(*strong cancelation between qq and qg subprocesses*)

NOTICE: nothing to do with full $k_\perp$ kinematics and role of azimuthal phases

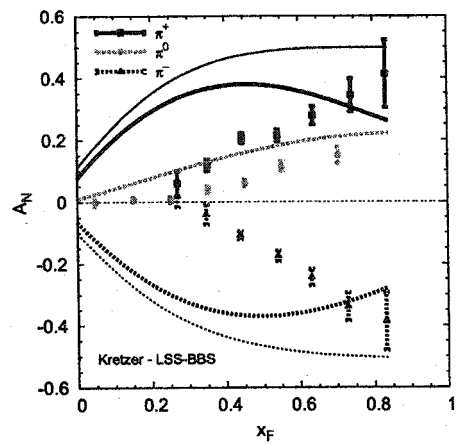
No consequences in:
- Sivers effect in $p^\uparrow p \to \pi + X$, $p^\uparrow p \to \ell^+\ell^- + X$ and $p^\uparrow p \to D + X$ (ok!)
- Λ transverse polarization in $pp \to \Lambda^\uparrow + X$ (ok!)
- SIDIS A_{UT} (ok!)
- bounds on gluon Sivers function from PHENIX data at $\eta = 0$ (ok!).

BUT crucial against Collins suppression argument:
Collins effect in pp collision: RESURRECTED

$A_N(\pi)$ for E704 setup (Maximized Collins effect): thin lines (phases set to zero)



PRD 71 (2005): Wrong



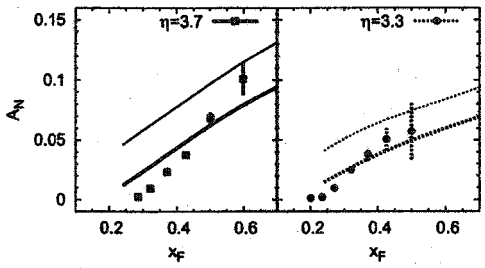
Corrected

Potential role of Sivers effect at RHIC

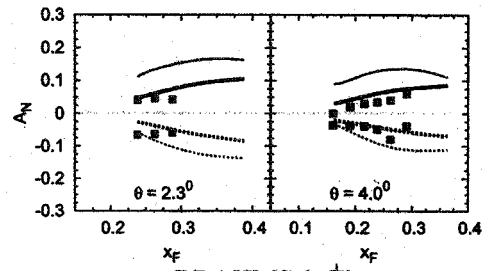
- maximized effect (proper sign):

$$\Delta^N f_u = +(2) f_u \qquad \Delta^N f_d = -2 f_d$$

KRE (thin) vs. DSS (thick) lines



STAR (π^0)



BRAHMS ($\pi^\pm$)

- both FF sets allow a description of RHIC data in terms of Sivers effect alone

- KRE set shows a capability larger than DSS set:
relative role of quark and gluon FFs in unpolarized cross sections

Role of *up* and *down* Sivers functions in $p^\uparrow\ p \to \pi + X$: $[\Delta^N f_d < 0]$

Remember: large $x_F \to \hat{t}$- channel dominance ($qb \to qb$)

$$A_N(\pi^+) \simeq \Delta^N f_u D_{\rm fav} + \Delta^N f_d D_{\rm unf} = \Delta^N f_u D_{\rm fav} - |\Delta^N f_d| D_{\rm unf}\ (>0)$$

$$A_N(\pi^-) \simeq \Delta^N f_u D_{\rm unf} + \Delta^N f_d D_{\rm fav} = \Delta^N f_u D_{\rm unf} - |\Delta^N f_d| D_{\rm fav}\ (<0)$$

$$A_N(\pi^0) \simeq (\Delta^N f_u + \Delta^N f_d) D_{\pi^0} = \left(\Delta^N f_u - |\Delta^N f_d|\right) D_{\pi^0}$$

- *only* if $D_{\rm unf} \ll D_{\rm fav} \to A_N(\pi^+)$ and $A_N(\pi^-)$ are UNcorrelated

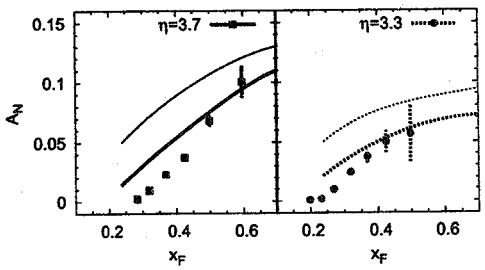
- potentially large cancellation in $A_N(\pi^0)$:
$\Delta^N f_d = -\Delta^N f_u \Rightarrow A_N^{\rm Sivers}(\pi^0) \simeq 0$ (large N_c; COMPASS $A_{UT} \simeq 0$ on D)

Potential role of Collins effect at RHIC

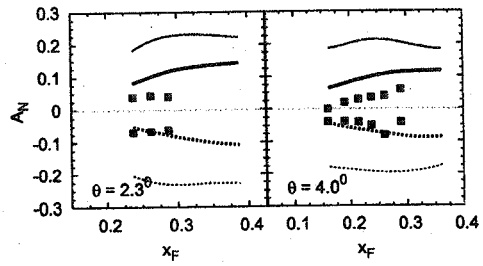
- maximized transversity and Collins function (proper signs): KRE vs. DSS

$$h_1^u = +\frac{1}{2}(u+\Delta u) \qquad h_1^d = -\frac{1}{2}(d+\Delta d) \qquad \text{(Soffer bounds)}$$

$$\Delta^N D_{\rm fav} = +2D_{\rm fav} \qquad \Delta^N D_{\rm unf} = -2D_{\rm unf} \qquad \text{(positivity bounds)}$$



STAR (π^0)



BRAHMS ($\pi^\pm$)

Again KRE (better) vs. DSS set:
role of gluons in the denominator (unpol. cross sections).

But now [$h_1^d < 0$ and $\Delta^N D_{\rm unf} < 0$]:

$$A_N(\pi^+) = h_1^u \Delta^N D_{\rm fav} + h_1^d \Delta^N D_{\rm unf} = h_1^u \Delta^N D_{\rm fav} + |h_1^d||\Delta^N D_{\rm unf}| > 0$$

$$A_N(\pi^-) = h_1^u \Delta^N D_{\rm unf} + h_1^d \Delta^N D_{\rm fav} = -h_1^u|\Delta^N D_{\rm unf}| - |h_1^d|\Delta^N D_{\rm fav} < 0$$

$$A_N(\pi^0) = (h_1^u + h_1^d)\frac{1}{2}\left[\Delta^N D_{\rm fav} + \Delta^N D_{\rm unf}\right] = \left[h_1^u - |h_1^d|\right]\frac{1}{2}\left[\Delta^N D_{\rm fav} - |\Delta^N D_{\rm unf}|\right]$$

- up and down terms add in sign in $A_N(\pi^\pm)$ while
- still cancel each other in $A_N(\pi^0)$

Notice: if $\Delta^N D_{\rm unf} = -\Delta^N D_{\rm fav} \Rightarrow A_N^{\rm Collins}(\pi^0) = 0$ (to be kept in mind!)

OLD vs. NEW SIDIS SSA fits

- larger data set and more accurate data both for Collins and Sivers asymmetries

- change of FF set: from KRE to DSS

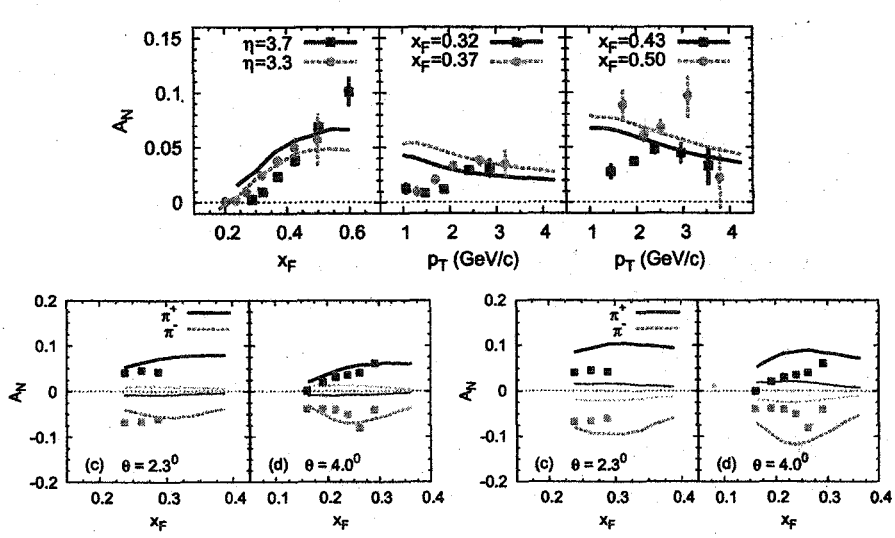
in particular for the Sivers effect:

- old fit: only up and down Sivers functions & independent large x behaviour

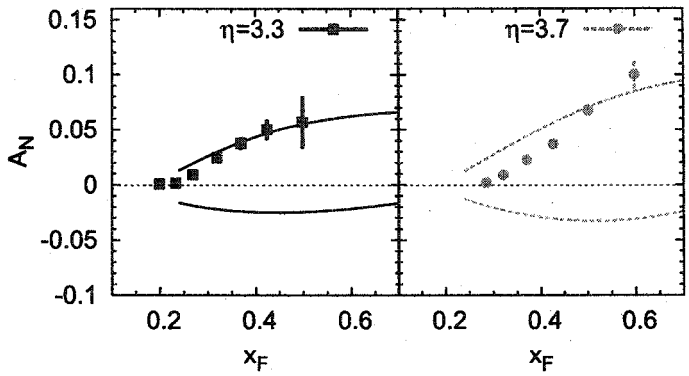
- new fit: up, down and broken-sea extraction & same large x behaviour (to reduce the number of parameters)

covered experimental region: $x < 0.3$

adopting Sivers & Collins functions as in the old fits with KRE set
(*Boglione, UD, Murgia '08*)

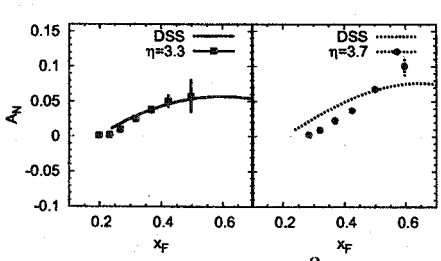


Sivers + Collins ((wrong) Sivers + Collins (corrected)

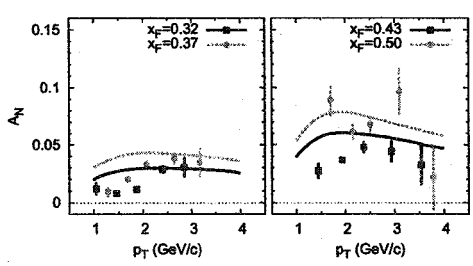


covered region (STAR) via scan + SIDIS fit: compatible with data BUT:
Is there a definite Sivers function parameterization able to describe RHIC data?

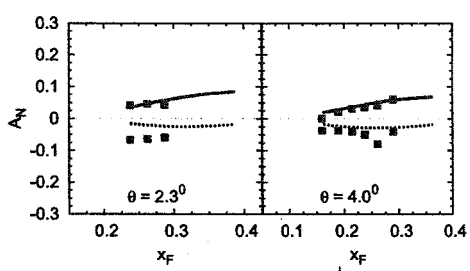
Sivers effect from SIDIS ($\chi_{\rm dof} \simeq 1.2$ & DSS)



STAR π^0



STAR π^0



BRAHMS $\pi^{\pm}$

Transverse momentum dependent parton distributions in a light-cone quark model

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In this talk we present a study of the leading-twist transverse momentum dependent parton distributions (TMDs) in a light-cone description of the nucleon, following the work of Ref. [1]. The light-cone Fock expansion of a hadron state is completely defined by the matrix elements of a special class equal light-cone time quark-gluon operators between the QCD vacuum $|0\rangle$ and the hadron [2]. The authors of Refs. [3–5] considered the wave-function amplitudes keeping full transverse-momentum dependence of partons and proposed a systematic way to enumerate independent amplitudes of a LCWF given a particular parton combination. If one truncates the light-cone expansion of the proton state to the minimum Fock sector with just three valence quarks, one can write down the matrix elements of a class of three-quark light-cone operators which serve to define a complete set of light-cone amplitudes within the truncation. These matrix elements can be simplified using color, flavor, spin and discrete symmetries, and at the end one finds that six amplitudes are needed to describe the three-quark sector of the nucleon LCWF. Depending on the imposed gauge fixing conditions such amplitudes are real or complex. In the latter case, the amplitudes contain final state interaction effects. With such amplitudes one can calculate nucleon observables. One could choose a phenomenological approach parametrizing and fitting them to data. Here, the wave-function amplitudes are modeled in a light-cone constituent quark model which has been successfully applied in the calculation of the electroweak properties of the nucleon [6], generalized parton distributions [7–10] and spin densities [11]. This representation is well suited to disentangle the contribution from the different orbital angular momentum components of the nucleon wave function, and therefore to study the spin-spin and spin-orbit correlations encoded in the different TMDs. Analytic formulae have been derived for the T-even TMDs in terms of the momentum dependent part of the LCWF. By simple inspection of such formulae we have found that among the six twist-two T-even TMDs there are three relations, so that only three TMDs are in fact independent when assuming SU(6) spin-flavor symmetry in the three-quark sector of the Fock expansion. Two of such relations were already known [12, 13], whereas the third one, was first found in the diquark spectator model [14] and shown here to be valid in a larger class of relativistic quark models with SU(6) symmetry.
Estimates for azimuthal spin asymmetries due to the so-called T-even transverse momentum dependent parton distributions functions are also shown and compared to available experimental data [15]. In particular, perspectives to access experimental information on the distributions $h_{1T}^{\perp}$ from the azimuthal single spin asymmetry proportional to $\sin(3\phi - \phi_S)$ are discussed.

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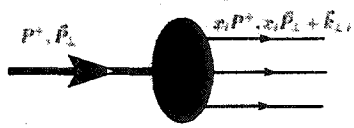
[1] B. Pasquini, S. Cazzaniga, S. Boffi, Phys. Rev. **D 78**, 034025 (2008).
[2] M. Burkardt, X. Ji, F. Yuan, Phys. Lett. **B 545**, 345 (2002).
[3] X. Ji, J.-P. Ma, and F. Yuan, Nucl. Phys. **B 652**, 383 (2003).
[4] X. Ji, J.-P. Ma, and F. Yuan, Eur. Phys. J. **C 33**, 75 (2004).
[5] X. Ji, J.-P. Ma, and F. Yuan, Phys. Rev. Lett. **90**, 241601 (2003).
[6] B. Pasquini, and S. Boffi, Phys. Rev. **D 76**, 074011 (2007).
[7] S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. **B 649**, 243 (2003).
[8] S. Boffi, B. Pasquini and M. Traini, Nucl. Phys. **B 680**, 147 (2004)
[9] B. Pasquini, M. Pincetti, and S. Boffi, Phys. Rev. **D 72**, 094029 (2005)
[10] B. Pasquini, and S. Boffi, Phys. Rev. **D 73**, 094001 (2006).
[11] B. Pasquini, and S. Boffi, Phys. Lett. **B 653**, 23 (2007).
[12] B. Pasquini, M. Pincetti, and S. Boffi, Phys. Rev. **D 76**, 034020 (2007)
[13] H. Avakian, A. V. Efremov, P. Schweitzer, F. Yuan, arXiv:0805.3355 [hep-ph].
[14] R. Jakob, P.J. Mulders, and J. Rodrigues, Nucl. Phys. **A 626**, 937 (1997).
[15] S. Boffi, A.V. Efremov, B. Pasquini, P. Schweitzer, in preparation.

Three Quark Light Cone Amplitudes



LCWF: $\Psi^f_{\lambda,\beta}(x_i, \vec{k}_{\perp,i})$

invariant under boost, independent of P^μ

internal variables: $\sum_{i=1}^{3} x_i = 1 \qquad \sum_{i=1}^{3} \vec{k}_{\perp,i} = \vec{0}_\perp$

[Brodsky, Pauli, Pinsky, '98]

$$|P,\lambda\rangle = \sum_\beta \int d[1]d[2]d[3]\, \Psi^f_{\lambda,\beta}(x_i,\vec{k}_{\perp,i})\, \frac{\varepsilon^{ijk}}{\sqrt{6}}\, u^\dagger_{i\lambda_1}(1) u^\dagger_{j\lambda_2}(2) d^\dagger_{k\lambda_3}(3)|0\rangle$$

❖ classification of LCWFs in angular momentum components

[Ji, J.P. Ma, Yuan, 03; Burkardt, Ji, Yuan, 02]

$$|P,\uparrow\rangle = |P,\uparrow\rangle^{L_z=2}_{-\frac{1}{2}} + |P,\uparrow\rangle^{L_z=1}_{-\frac{1}{2}} + |P,\uparrow\rangle^{L_z=0}_{\frac{1}{2}} + |P,\uparrow\rangle^{L_z=-1}_{\frac{1}{2}}$$

total quark helicity J^q

$$J_z = J_z^q + L_z$$

$$\langle 0|\varepsilon^{ijk} u^\dagger_{i\lambda_1}(1)\Gamma u^\dagger_{j\lambda_2}(2) d^\dagger_{k\lambda_3}(3)|P\rangle$$

parity
time reversal
isospin symmetry

6 independent wave function amplitudes: $\psi^{(i)}\ i = 1,..,6$

Light Cone Amplitudes Overlap Representation of TMDs

$f_1 =$

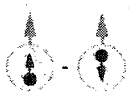
$$f_1^q(x,k_\perp^2) = {}^{L_z=0}\langle P\uparrow|\sum_\lambda q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=0} + {}^{L_z=1}\langle P\uparrow|\sum_\lambda q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=1}$$

$$+ {}^{L_z=-1}\langle P\uparrow|\sum_\lambda q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=-1} + {}^{L_z=2}\langle P\uparrow|\sum_\lambda q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=2}$$

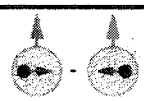
$g_{1L} =$

$$g_{1L}^q(x,k_\perp^2) = {}^{L_z=0}\langle P\uparrow|\sum_\lambda (-1)^{1/2-\lambda} q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=0} + {}^{L_z=1}\langle P\uparrow|\sum_\lambda (-1)^{1/2-\lambda} q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=1}$$

$$+ {}^{L_z=-1}\langle P\uparrow|\sum_\lambda (-1)^{1/2-\lambda} q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=-1} + {}^{L_z=2}\langle P\uparrow|\sum_\lambda (-1)^{1/2-\lambda} q^\dagger_\lambda q_\lambda|P\uparrow\rangle^{L_z=2}$$

$h_1 =$ 

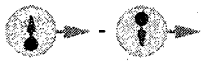
$$h_1^q(x,k_\perp^2) = \mathrm{Re}[{}^{L_z=0}\langle P\downarrow|q^\dagger_\uparrow q_\uparrow|P\uparrow\rangle^{L_z=0}] + 2\mathrm{Re}[{}^{L_z=-1}\langle P\uparrow|q^\dagger_\uparrow q_\uparrow|P\downarrow\rangle^{L_z=-1}]$$

g_{1T} = 

$$g_{1T}^{q}(x,k_\perp^2) = \frac{2M}{k_\perp^2}\Big(k^x \mathrm{Re}[^{L_z=0}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|P\downarrow\rangle^{L_z=-1}] + k^y \mathrm{Im}[^{L_z=0}\langle P\uparrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|P\downarrow\rangle^{L_z=-1}]$$

$$+k^x \mathrm{Re}[^{L_z=-2}\langle P\downarrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|P\uparrow\rangle^{L_z=-1}] + k^y \mathrm{Im}[^{L_z=-2}\langle P\downarrow|\sum_\lambda(-1)^{1/2-\lambda}q_\lambda^\dagger q_\lambda|P\uparrow\rangle^{L_z=-1}]\Big)$$

P→S P→S P→D P→D

$h_{1L}^\perp$ = 

$$h_{1L}^{\perp q}(x,k_\perp^2) = \frac{2M}{k_\perp^2}\Big(\mathrm{Re}[^{L_z=1}\langle P\uparrow|q_1^\dagger q_1|P\uparrow\rangle^{L_z=0}] - k^y \mathrm{Im}[^{L_z=1}\langle P\uparrow|q_1^\dagger q_1|P\uparrow\rangle^{L_z=0}]$$

$$+k^x \mathrm{Re}[^{L_z=2}\langle P\uparrow|q_1^\dagger q_1|P\uparrow\rangle^{L_z=1}] - k^y \mathrm{Im}[^{L_z=2}\langle P\uparrow|q_1^\dagger q_1|P\uparrow\rangle^{L_z=1}]\Big)$$

S→P S→P P→D P→D

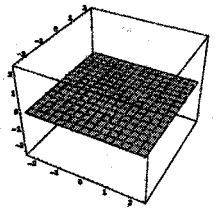
$h_{1T}^\perp$ =

$$h_{1T}^{\perp q}(x,k_\perp^2) = -\mathrm{Re}[^{L_z=1}\langle P\uparrow|q_1^\dagger q_1|P\downarrow\rangle^{L_z=-1}] - 2\mathrm{Re}[^{L_z=0}\langle P\uparrow|q_1^\dagger q_1|P\downarrow\rangle^{L_z=-2}]$$

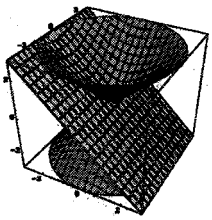
P→P D→S

Light Cone Constituent Quark Model

Instant form:
x^0 time;
x^1, x^2, x^3 space



Light-front form:
x^+ time;
$x^-, x_\perp$ space



- Instant Form (canonical) eigenvalue equation

$$M|\,M, j_c, \mu_c\rangle_c = [M_0 + V]|\,M, j_c, \mu_c\rangle_c$$

$M_0 = \sum_i^N \sqrt{m_i^2 + \vec{k}_i^2}$: free mass operator $\quad V$: interaction operator

- Light-front eigenvalue equation

$$\mathcal{M}|\,M, j_f, \mu_f\rangle_f = [M_0 + \mathcal{V}]|\,M, j_f, \mu_f\rangle_f$$

$\mathcal{M} = \mathcal{R}^\dagger M \mathcal{R} \Longrightarrow \mathcal{R} = \Pi_{i=1}^N R_M(\vec{k}_{\perp,i}, x_i, m_i)$: generalized Melosh rotations

$$\Downarrow$$

$$\Psi_N^f = \langle\{x_i, \vec{k}_{\perp,i}, \lambda_i\}_N\,|M, j_f, \mu_f\rangle_f = \frac{2(2\pi)^3}{\sqrt{M_0}}\Pi_{i=1}^N\sqrt{\frac{E_i}{x_i}}\sum_{\{\lambda_i'\}}\langle\{\lambda_i\}\,|\mathcal{R}^\dagger|\,\{\lambda_i'\}\rangle\Psi_N^c$$

Light Cone Spin

❖ Instant-form wave function: $\Psi = \Phi^I \otimes \Phi^S \otimes \tilde{\Psi}(\{\vec{k}_i\})$

✓ momentum-space component: S wave

✓ spin and isospin component: SU(6) symmetric

$$uud\,[\uparrow\downarrow\uparrow + \downarrow\uparrow\uparrow - 2\uparrow\uparrow\downarrow] \qquad J_z = J_z^q$$

$\boxed{\text{Melosh Rotations}}$

❖ Light-cone wavefunction

$$q_l^\uparrow = w\,[(k^+ + m_q)\,q_{LC}^\uparrow - (k_x + ik_y)\,q_{LC}^\downarrow]$$

$$q_l^\downarrow = w\,[(k_x - ik_y)\,q_{LC}^\uparrow + (k^+ + m_q)\,q_{LC}^\downarrow] \quad (w = [(k^+ + m_q)^2 + k_\perp^2]^{-1/2})$$

✓ non-zero quark orbital angular momentum: $J_z = J_z^q + L_z^q$

$\boxed{\text{Six independent wave function amplitudes}}$

$L_z^q = -1$	$L_z^q = 0$	$L_z^q = 1$	$L_z^q = 2$
$(\uparrow\uparrow\uparrow)_{LC}$	$(\uparrow\uparrow\downarrow)_{LC}$	$(\uparrow\downarrow\downarrow)_{LC}$	$(\downarrow\downarrow\downarrow)_{LC}$

The six independent wave function amplitudes obtained from the Melosh rotations satisfy the model independent classification scheme in four orbital angular momentum components

TMDs in a Light-Cone CQM

$$f_1^q(x,k_\perp^2) = N^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

$$g_{1L}^q(x,k_\perp^2) = P^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\frac{(m+xM_0)^2 - k_\perp^2}{(m+xM_0)^2 + k_\perp^2}\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

$$h_1^q(x,k_\perp^2) = P^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\frac{(m+xM_0)^2}{(m+xM_0)^2 + k_\perp^2}\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

$$g_{1T}^q(x,k_\perp^2) = P^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\frac{2M(m+xM_0)}{(m+xM_0)^2 + k_\perp^2}\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

$$h_{1L}^{\perp q}(x,k_\perp^2) = -P^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\frac{2M(m+xM_0)}{(m+xM_0)^2 + k_\perp^2}\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

$$h_{1T}^{\perp q}(x,k_\perp^2) = -P^q \int d[1]d[2]d[3]\sqrt{x_1x_2x_3}\,|\tilde{\Psi}(\{x_i\},\{k_{\perp,i}\})|^2\,\frac{2M^2}{(m+xM_0)^2 + k_\perp^2}\,\delta(x-x_3)\delta^2(\mathbf{k}_\perp - \mathbf{k}_{\perp,3})$$

➢ SU(6) symmetry ➡ $N^u = 2$ $N^d = 1$ $P^u = 4/3$ $P^d = -1/3$

➡ momentum dependent wf factorized from spin-dependent effects

➡ 3 relations between the TMDs

B.Pasquini, Cazzaniga, Boffi, PRD78 (2008)

Relations of TMDs in Valence Quark Models

(1) $$2h_1^q(x,k_\perp^2) = g_{1L}^q(x,k_\perp^2) + \frac{p^q}{N^q} f_1^q(x,k_\perp^2)$$

(2) $$\frac{p^q}{N^q} f_1^q(x,k_\perp^2) = h_1^q(x,k_\perp^2) - \frac{k_\perp^2}{2M^2} h_{1T}^{\perp q}(x,k_\perp^2)$$

(3) $$h_{1L}^{\perp q}(x,k_\perp^2) = -g_{1T}^q(x,k_\perp^2)$$

- (1), (2), and (3) hold in Light-Cone CQM Models
  BP, Pincetti, Boffi, PRD72, 2005;
  BP, Cazzaniga, Boffi, hep-ph:0806.2298
- (1) and (2) hold in Bag Model
  Avakian, Efremov, Yuan, Schweitzer, hep-ph: 0805.3355
- (3) holds in spectator model, (1) and (2) are recovered only if mass-axial-vector-diquark → mass-scalar- diquark
  Jakob, Mulders, Rodrigues, NPA626, 1997

✓ SU(6) symmetry
✓ no gluon dof
valid at low hadronic scale
✓ not restricted to S and P wave contributions

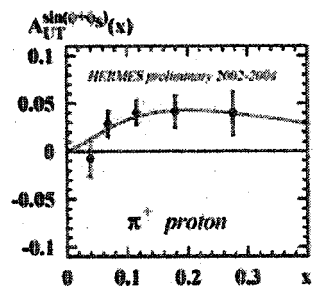
All 8 leading twist TMDs contain independent information on the nucleon structure and there are NO EXACT relations between TMDs in QCD

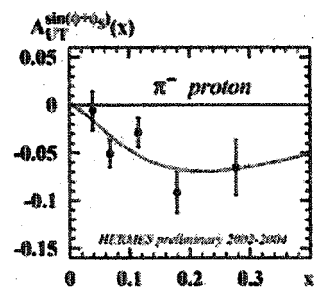
BUT

having well-motivated approximations is valuable!

Collins SSA

- Preliminary HERMES data $A_{UT}^{\sin(\phi+\phi_S)} \propto \sum_q e_q^2 h_1^q \otimes H_1^{\perp q}$
  HERMES data: Diefenthaler, hep-ex/0507013
- $h_1^q(x,Q^2)$ from Light-Cone CQM evolved at Q^2=2.5 GeV^2
- $H_1^{\perp q}$ from HERMES & BELLE data
  Efremov, Goeke, Schweitzer, PRD73 (2006);
  Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)





More recent HERMES, COMPASS and BELLE data not yet included in the fit of Collins function

Schweitzer, Boffi, Efremov, BP, in preparation

$A_{UL}^{\sin(2\phi)}$

- HERMES data on $A_{UL}^{\sin(2\phi)} \propto \sum_q e_q^2 h_{1L}^{\perp(1)q} \otimes H_1^{\perp q}$

Airapetian, PRL84, 2000; Avakian, Nucl. Phys. Proc. Suppl. 79 (1999)

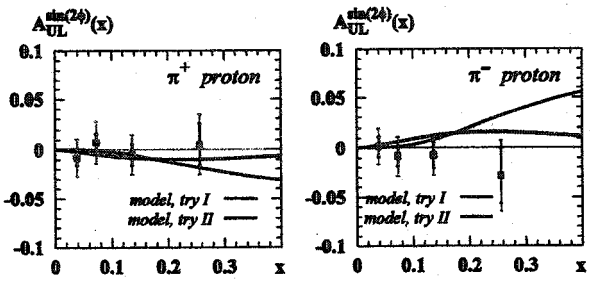
- $h_{1L}^{\perp(1)q}$ from Light-Cone CQM

- $H_1^{\perp q}$ from HERMES & BELLE

Efremov, Goeke, Schweitzer, PRD73 (2006);
Anselmino et al., PRD75 (2007); Vogelsang, Yuan, PRD72 (2005)

—— $h_{1L}^{\perp(1)q}(x, \mu_0^2)$
(no evolution)

—— $h_{1L}^{\perp(1)q}(x, \mu_0^2) \frac{h_1^q(x, Q^2)}{h_1^q(x, \mu_0^2)}$



Schweitzer, Boffi, Efremov, BP, in preparation

Pretzelosity in SIDIS: perspectives

At small x:

✓ There will be data from COMPASS proton target

✓ There will be data from HERMES

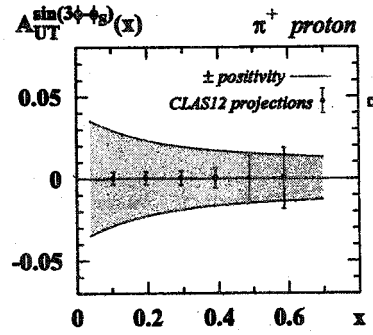
More favorable conditions at intermediate x ~ (0.2-0.6)

✓ experiment planned at CLAS with 12 GeV
(H. Avakian at al., LOI 12-06-108)

—— $|h_{1T}^{(1)\perp q}| \leq f_1^q - g_1^q$

—— Light Cone CQM

Error projections for 2000 hours run time at CLAS12



⟹ talk of P. Rossi

Schweitzer, Boffi, Efremov, BP, in preparation

Transversity in Exclusive Meson Electroproduction

Gary R. Goldstein (Tufts U.)
Simonetta Liuti & Saeed Ahmad (U.Va.)

ABSTRACT

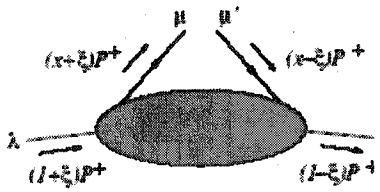
Exclusive π^0 & η meson electroproduction are described in terms of chiral odd Generalized Parton Distributions. These are constrained by transversity distribution functions and integrals of Transverse Momentum Distributions. Alternatively, in a hadronic picture, meson production amplitudes involve C-odd Regge exchanges with final state interactions. Helicity relates the partonic description and the hadronic description of C-odd processes. This contrasts with deeply virtual Compton scattering, and vector meson or charged π electroproduction. Spectator model calculations indicate how the tensor charge and other transversity parameters can be extracted from cross sections and spin asymmetry measurements over a broad range of kinematics.

See recent: Ahmad, GRG, Liuti, ArXiv hep-ph/0805.3568

Important ingredients for relating transversity to exclusive π^0 electroproduction

- Tensor charge couples via $\sigma^{\mu\nu}\gamma_5$ to nucleons
- Coupled quantum numbers 1^{+-} correspond to b_1 & h_1 couplings
  ($\gamma^\mu\ \gamma_5$ is opposite C-parity & does not contribute)
- $\gamma^* + \pi^0$ is C-parity odd eigenstate coupling to
  - 1^{+-} q+anti-q states (S=0, L=1...) ⇒ $b_1{}^0$ & h_1
  - 1^{--} q+anti-q states (S=1, L=1...) ⇒ ρ^0 & ω
  - 3 gluons or Odderon? ⇒ Pomeron-like diffraction (α~1)
    - **H1 HERA (Phys.Lett. B544 (2002) 35-43) searched for**
      $\gamma^*\ p \rightarrow \pi^0\ N^*(1/2)^-$ [<W> = 200 GeV |t|<0.3 GeV^2]
    - **$\sigma_{Tot}{}^{predicted}$ >200 nb $\sigma_{Tot}{}^{expt}$<49 nb ⇒ no odderon**
- $\gamma^* + \pi^0$ does not couple to ρ^0 & ω at small angles (small |t|), but $b_1{}^0$ & h_1 do couple
- $\gamma^*_T + \pi^0$ couples to <u>both</u> sets
- Note Isospin: $\gamma^* \sim \rho^0$ & ω .∃. ($\rho^0\ \omega\ \pi^0$) coupling &($b_1{}^0\ \omega\ \pi^0$) &($h_1\ \rho^0\ \pi^0$)
  What about $a_1{}^0(1230)$? Neither $\rho^0\ \pi^0$ (I) nor $\omega\ \pi^0$ (G).
  I=0 partner? $f_1(1285)$ [$0^+(1^{++})$] NOT $\rho^0\pi^0$(G) NOT $\omega\pi^0$(I)
  All due to **C-parity odd for $\gamma^* + \pi^0$**
- Different "transition form factors" $\rho^0 \rightarrow \pi^0$ & $b_1{}^0 \rightarrow \pi^0$
- Which picture - Regge or partons? Both connected . . . .

How does transversity enter?



- Quark helicity flip amps ⇒quark transversity

$$A_{++,+-} = \epsilon \frac{\sqrt{t_0 - t}}{2m}\left(\tilde{H}_T^q + (1-\xi)\frac{E_T^q + \tilde{E}_T^q}{2}\right),$$

$$A_{-+,--} = \epsilon \frac{\sqrt{t_0 - t}}{2m}\left(\tilde{H}_T^q + (1+\xi)\frac{E_T^q - \tilde{E}_T^q}{2}\right),$$

$$A_{++,--} = \sqrt{1-\xi^2}\left(H_T^q + \frac{t_0 - t}{4m^2}\tilde{H}_T^q - \frac{\xi^2}{1-\xi^2}E_T^q + \frac{\xi}{1-\xi^2}\tilde{E}_T^q\right)$$

$$A_{-+,+-} = -\sqrt{1-\xi^2}\,\frac{t_0 - t}{4m^2}\tilde{H}_T^q$$

$H_T^q(x,t=0,\xi=0)$
$=h_1(x)$ Norm δq
Also $H(x,0,0)=f_1(x)$
& $H^{\sim q}(x,0,0)=g_1(x)$ *Norm Δq*

GPDs parameterized via AHLT(2008),see S.Liuti talk

$$\int_{\zeta=1}^{1} dX\,[E(X,\zeta,t)]_{\zeta=t=0} = \kappa^q \qquad \int_{\zeta=1}^{1} dX\left[2\tilde{H}_T^q(X,\zeta,t) + E_T^q(X,\zeta,t)\right]_{\zeta=t=0} = \kappa_T^q$$

See M.Burkardt

$$\int d^2k_T\,dX\,f_{1T}^{\perp q}(X,k_T) = \kappa^q \qquad \int d^2k_T\,dX\,h_1^{\perp q}(X,k_T) = \kappa_T^q$$

times -1 A.Metz

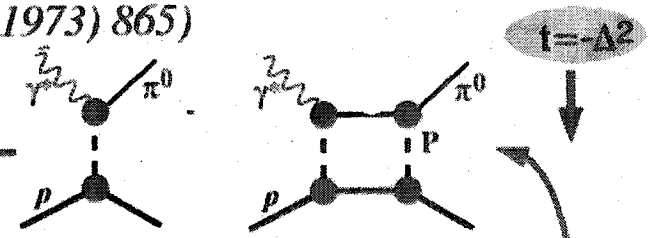
FSI: Hadronic Picture→Regge Model

GRG & Owens, PRD(1973) 865)

"weak Regge cut" model w. nonsense zeroes

$V = \rho,\ \omega$

$A = b_1, h_1$



"LO" → $f_{hA'\beta A} = \Delta^2 \frac{\beta_i}{\Gamma(\alpha_i)} \frac{1-e^{i\pi\alpha_i}}{\sin \pi\alpha_i} \left(\frac{s-u}{2}\right)^{\alpha_i} e^{-\Delta^2 c_i/2}$

LO + FSI → Elastc rescattering -> Eikonal form

Tensor Charge resides in b_1 & h_1 residue. Residue at Axial vector pole determines t<0 amps & sensitive observables

$\Gamma(b_1 \to \pi\gamma) \sim 230$ keV

$g_{b\pi\gamma} \sim 0.25/m_b$ Z.E.S. Uy PRD(1988) divide out

$g_{bNN} \sim 8$ & $\delta_b \sim \delta_{u-d} \sim 1.3$ modified by final state inter.w.s dependence factored out Need δ_h :$SU(3)_{flavor}$ $\delta_h \sim 0.87$ for mixed h_1 & h_1'

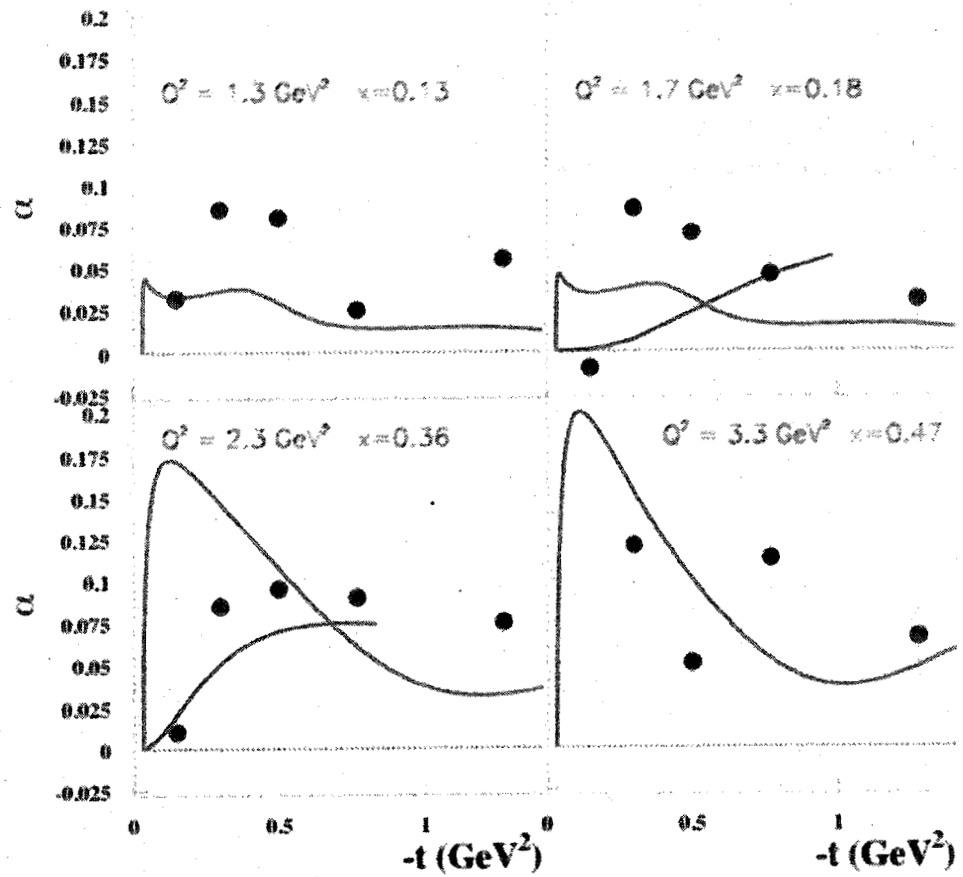
$\to \delta_u \sim 0.39$ & $\delta_d \sim -0.14$+/-30%

Regge-cut model Beam-spin asymmetry α

data R. De Masi et al.,Phys.Rev.C77, 042201 (2008).

Regge-cut predictions - comparisons involve ε_L, ε

Ahmad, GRG, Liuti, ArXiv hep-ph/0805.3568 blue



GPD predictions (preliminary) red

Chiral-odd generalized parton distributions

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The chiral quark soliton model (CQSM) is a unique model of baryons, which is consistent with large N_c QCD and $1/N_c$ expansion. We emphasize that the only one parameter of the model, i.e. the dynamically generated quark mass M, was already fixed from the low energy phenomenology. Furthermore, its field theoretical nature enables us to make reasonable predictions not only of the quark distributions but also of the antiquark distributions. We have shown, for instance, that its parameter-free prediction for the $\bar{d}(x)/\bar{u}(x)$ ratio is fairly close to the empirical data obtained from the E866 neutrino measurements. We have also pointed out that the new precise measurement of the deuteron spin-dependent structure function by the COMPASS and HERMES groups significantly reduced the error bars of the quark spin fraction $\Delta\Sigma$, and that the central values of their new fits are now remarkably close to the predictions of the CQSM.

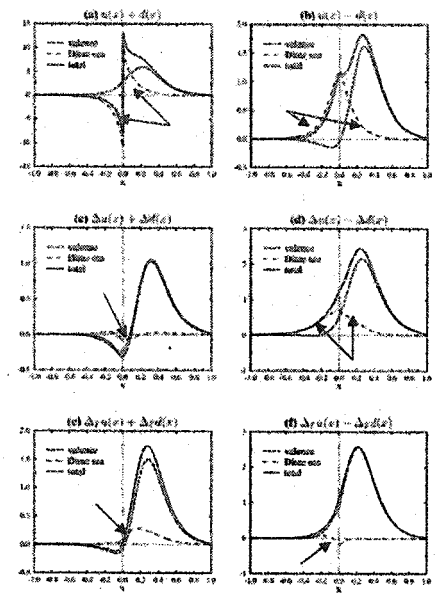
On the basis of this successful model of the nucleon structure, we investigated herte the parton distribution functions in the chiral-odd sector. First, we have carried out a comparative analysis of the transversities and the longitudinally polarized PDFs in light of the new global fit of transversities and the Collins fragmentation functions carried out by Anselmino et al. Their results, although with large uncertainties, already appears to indicate a remarkable qualitative difference between transversities and longitudinally polarized PDFs such that $|\Delta_T d(x)/\Delta d(x)| \ll |\Delta_T u(x)/\Delta u(x)|$, which is qualitatively consistent with the predictions of the CQSM. I have emphasized that the cause of this feature can be traced back to the relation $g_T^{(I=0)} / g_T^{(I=1)} \gg g_A^{(I=0)} / g_A^{(I=1)}$. Further combining with the BLT (Bakker-Leader-Trueman) sum rule, this indicates the following inequality $L^Q_{S_T} + L^g_{S_T} \ll L^Q + L^g$, that is, the transverse OAM may be much smaller than the longitudinal OAM.

We also gave CQSM predictions for the forward limit of the particular combination of the chiral-odd GPDs, $G_T(x,\xi,t) \equiv H_T(x,\xi,t) + 2\,\tilde{H}_T(x,\xi,t) + E_T(x,\xi,t)$. We found rather strong chiral enhancement near $x \sim 0$ for both of the isoscalar and isovector $G_T(x,0,0)$. From the 1st moment sum rules of G_T and H_T, we found an isoscalar dominance of the anomalous tensor moment, which indicates that Boer-Mulders functions for the u- and d-quarks are roughly equal with the same sign. It should be compared with the possible isovector dominance of the Sivers functions, or the anomalous magnetic moment of the nucleon. It is a very important experimental challenge to determine the relative sign and the magnitudes of the u- and d-quark Boer-Mulders functions.

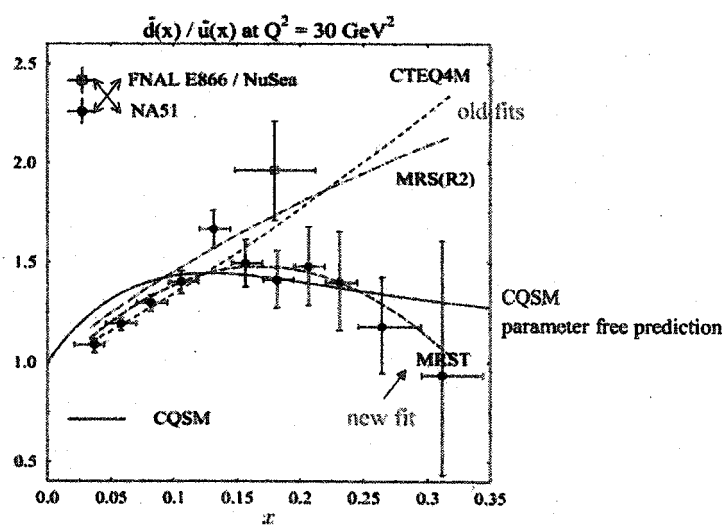
Parameter free predictions of CQSM for 3 twist-2 PDFs

- unpolarized PDFs
- longitudinally polarized PDFs
- transversities

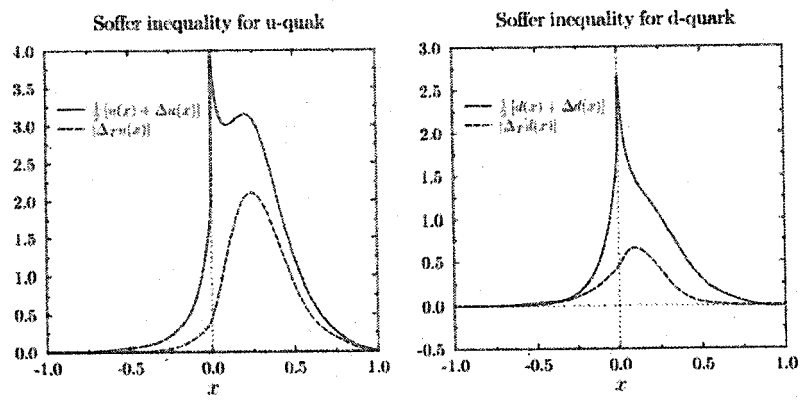
totally different behavior of the Dirac-sea contributions in different PDFs !



$\bar{d}(x)/\bar{u}(x)$ ratio in comparison with neutrino scattering data



Transversities and Soffer inequality in CQSM



We find that $|\Delta_T q(x)| \ll \frac{1}{2}[q(x) + \Delta q(x)]$

CQSM gives totally different predictions !

	NRQM	MIT bag	HO(LFCQ)	HYP(LFCQ)	CQSM
			Pasquini et al.		
$g_A^{(I=1)}$	1.5	1.06	1.25	0.76	1.31
$g_A^{(I=0)}$	1.0	0.64	0.75	0.46	0.35 ⇦
$g_T^{(I=1)}$	1.5	1.34	1.46	1.21	1.21
$g_T^{(I=0)}$	1.0	0.88	0.88	0.73	0.68
$g_A^{(I=0)}/g_A^{(I=1)}$	0.6	0.6	~ 0.6	~ 0.6	0.27 ⇦
$g_T^{(I=0)}/g_T^{(I=1)}$	0.6	0.6	~ 0.6	~ 0.6	0.56

3 quark model cannot resolve EMC observation ?

Chiral-odd GPDs

$$\mathcal{F} \equiv \frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \left\langle p',\lambda' \middle| \bar{\psi}(-z/2)\,\sigma^{+j}\gamma_5\,\psi(z/2) \middle| p,\lambda \right\rangle\Big|_{z^+=0,z_\perp=0}$$

$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[H_T\, i\sigma^{+j}\gamma_5 + \tilde{H}_T \frac{i\epsilon^{+j\alpha\beta}\Delta_\alpha P_\beta}{M_N^2} + E_T \frac{i\epsilon^{+3\alpha\beta}\Delta_\alpha\gamma_\beta}{2M_N} + \tilde{E}_T \frac{i\epsilon^{+j\alpha\beta}P_\alpha\gamma_\beta}{M_N}\right] u(p,\lambda)$$

in Breit frame with large N_c kinematics

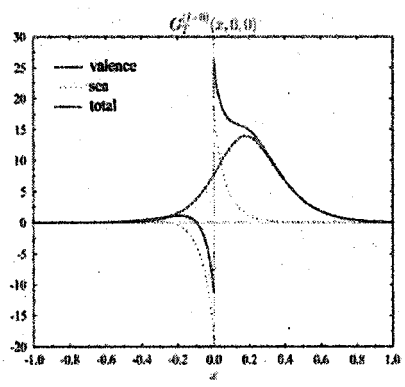
$$\mathcal{F} \sim H_T\,\sigma_1 + G_T \frac{i\Delta_2}{2M_N} + \tilde{E}_T\,(\boldsymbol{\sigma}\times\boldsymbol{\Delta})_2 + \tilde{G}_T \frac{1}{4M_N^2}[\boldsymbol{\Delta}\times(\boldsymbol{\Delta}\times\boldsymbol{\sigma})]$$

with

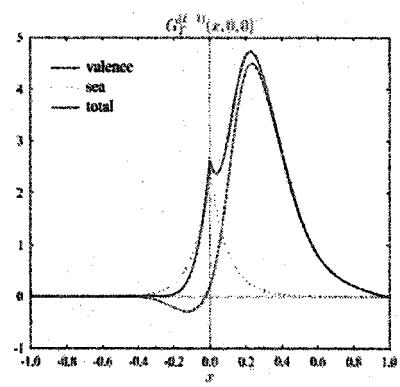
$$G_T \equiv H_T + 2\tilde{H}_T + E_T$$
$$\tilde{G}_T \equiv E_T - \frac{1}{2}H_T$$

Forward limit of $G_T(x,\xi,t)$

Isoscalar part



Isovector part



low x behavior of Dirac-sea contributions

$\sim f^{u+d}(x)$ $\sim f^{u-d}(x)$

transverse decomposition of quark angular momentum

$$\langle J_q^x \rangle = \langle J_{q,+\hat{x}}^x \rangle + \langle J_{q,-\hat{x}}^x \rangle$$

angular momentum carried by quarks with transverse polarization in the $\pm\hat{x}$ direction in an unpolarized nucleon at rest

transverse asymmetry

$$\langle \delta^x J_q^x \rangle = \langle J_{q,+\hat{x}}^x \rangle - \langle J_{q,-\hat{x}}^x \rangle$$

$\Updownarrow$

correlation between quark spin and angular momentum in an unpolarized target

Burkardt's sum rule

$$\langle J_q^x \rangle = \frac{S^x}{2} \int_{-1}^{1} [\, H(x,0,0) + E(x,0,0) \,]\, dx \quad \sim \quad \text{Ji's sum rule}$$

$$\langle \delta^x J_q^x \rangle = \frac{1}{2} \int_{-1}^{1} x\, [\, H_T(x,0,0) + 2, \tilde{H}_T(x,0,0) + E_T(x,0,0) \,]\, dx = \frac{1}{2} \int_{-1}^{1} x\, G_T(x,0,0)\, dx$$

Corresponding 2nd moment sum rule in CQSM

spin-orbit correlation

$\Updownarrow$

$$\int_{-1}^{1} x\, G_T^{(I=0)}(x,0,0)\, dx$$

$$= -\frac{N_c}{9} \sum_{n \in occ} \left\{ E_n \langle n | \begin{pmatrix} 0 & -i\,\boldsymbol{\sigma}\cdot\boldsymbol{x} \\ i\,\boldsymbol{\sigma}\cdot\boldsymbol{x} & 0 \end{pmatrix} | n \rangle + \frac{1}{2} \begin{pmatrix} \boldsymbol{\sigma}\cdot\boldsymbol{L} & 0 \\ 0 & -\boldsymbol{\sigma}\cdot\boldsymbol{L} \end{pmatrix} | n \rangle \right\}$$

Comparison with other model predictions

light-front constituent quark model (Pasquini, Pincetti, Boffi)

HO : harmonic oscillator model
HYP : hyper central model

asymmetry	HO	HYP	CQSM
$\langle \delta^x J_x^u \rangle$	0.68	0.39	0.49
$\langle \delta^x J_x^d \rangle$	0.28	0.10	0.22
$2\langle \delta^x J_x^{u+d} \rangle$	1.92	0.98	1.41
$2\langle \delta^x J_x^{u-d} \rangle$	0.80	0.58	0.54
$\langle \delta^x J_x^{u+d} \rangle / \langle \delta^x J_x^{u-d} \rangle$	2.40	1.69	2.61

1st moment sum rule

$$\int_{-1}^{1} G_T^q(x,0,0)\,dx \;=\; \int_{-1}^{1} H_T^q(x,0,0) \;+\; \int_{-1}^{1} \left[2\,\tilde{H}_T^q(x,0,0) + E_T^q(x,0,0)\right] dx$$

tensor moment tensor charge anomalous tensor moment

(Cf.) unpolarized GPD case

$$\int_{-1}^{1} H_M^q(x,0,0)\,dx \;=\; \int_{-1}^{1} H^q(x,0,0)\,dx \;+\; \int_{-1}^{1} E^q(x,0,0)\,dx$$

magnetic moment quark number anomalous magnetic moment

anomalous tensor moment	HO	HYP	CQSM
κ_T^u	3.60	1.98	3.47
κ_T^d	2.36	1.17	2.60
κ_T^{u+d}	5.96	3.15	6.07
κ_T^{u-d}	1.24	0.81	0.88
$\kappa_T^{u+d}/\kappa_T^{u-d}$	4.81	3.89	6.90

Impact on T-odd distributions (according to Burkardt's conjecture)

Sivers function $f_1^{\perp q}(x, k_\perp^2) \sim -\kappa^q$: anomalous magnetic moment

Boer-Mulders function $h_1^{\perp q}(x, k_\perp^2) \sim -\kappa_T^q$: anomalous tensor moment

This, combined with model predictions for κ_T^q, indicates

$$\left.\begin{array}{lll} \text{MIT bag :} & h_1^{\perp,d} = \frac{1}{2} h_1^{\perp,u} \\ \text{Large } N_c : & h_1^{\perp,d} = h_1^{\perp,u} \\ \text{CQSM :} & h_1^{\perp,d} \sim \frac{3}{4} h_1^{\perp,u} \end{array}\right\} \quad \text{all same sign !}$$

Compare

$$f_1^{\perp,d} \sim -f_1^{\perp,u} \quad \Leftarrow \quad \kappa^d \sim -\kappa^u \qquad \text{opposite sign !}$$

Origin ?

κ^q : isovector dominance $(\kappa^{u+d} \ll \kappa^{u-d})$

κ_T^q : isoscalar dominance $(\kappa_T^{u+d} \gg \kappa_T^{u-d})$

A Bottom-up Approach to Extract Transverse Spin GPDs from Experiment

Simonetta Liuti
University of Virginia

PKU Workshop on Transverse Spin

June 30th-July 4th, 2008. Beijing

Reaching a more advanced phase of extracting GPDs from data

(a bit of summary from ECT, June'08)*

- No longer simple models (D. Muller)
- Include Q^2 dependence (M. Diehl)
- Include all constraints from data DVCS, DVMP... (S.L.)
- Include new data as they become available... (S.L.)
- Use Lattice + Chiral Extrapolations (P. Hägler, A. Schaefer)
- Connect various experiments, separate valence from sea, flavors separation (T. Feldman)...
- New! Representation in terms of *dispersion relation* ⇒ only necessary to measure imaginary part? Stronger polynomiality constraint (M. Diehl and Yu. Ivanov)

A similar program exists for TMDs (simpler partonic interpretation than GPDs) ⇒ see M. Anselmino and collaborators

What goes into a theoretically motivated parametrization...?

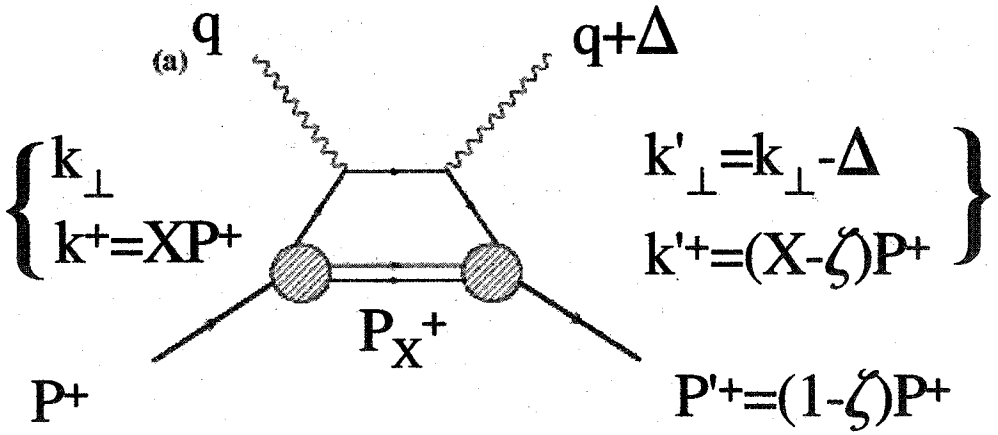
The name of the game: Devise a form combining essential dynamical elements with a flexible model that allows for a fully quantitative analysis constrained by the data

$$H_q(X,t) = R(X,t)\ G(X,t)$$

"Regge" — Quark-Diquark

Q2 Evolution is an essential element!!

In DGLAP region ⇒ partonic picture



Regge

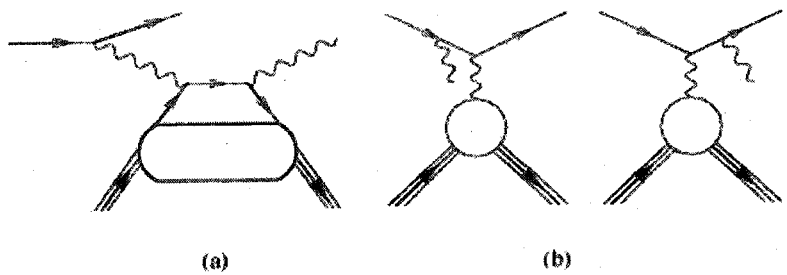
$$R^I_{1(2)} = X^{-\alpha^I - \beta^I_{1(2)}(1-X)^{p^I_{1(2)}} t}$$

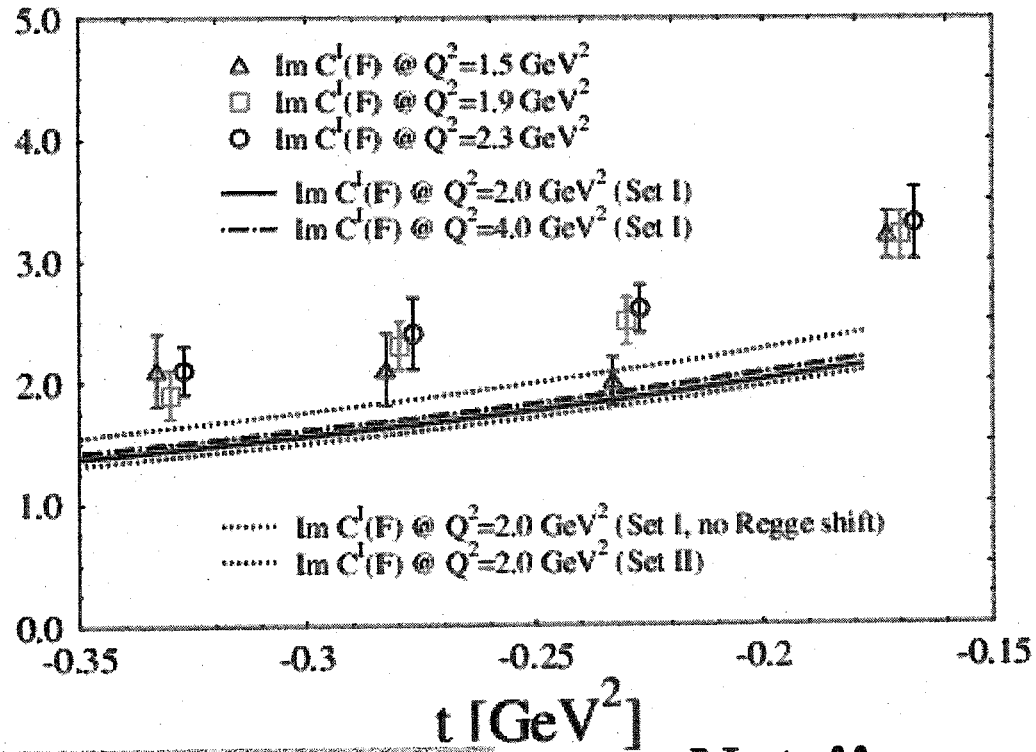
Quark-Diquark

$$G^\lambda_{M_X}(X,t) = \mathcal{N}\frac{X}{1-X}\int d^2\mathbf{k}_\perp \frac{\phi(k^2,\lambda)}{D(X,\mathbf{k}_\perp)}\frac{\phi(k'^2,\lambda)}{D(X,\mathbf{k}_\perp+(1-X)\mathbf{\Delta}_\perp)}$$

Comparison with Jlab Hall A data (proton)

Munoz Camacho et al., (2006)





- Observable given by Interference Term between DVCS (a) and BH(b):

$$d\sigma^{+} - d\sigma^{-} \propto \sin\phi \left[F_1(\Delta^2)\mathcal{H} + \frac{x}{2-x}(F_1 + F_2)\tilde{\mathcal{H}} + \frac{\Delta^2}{M^2} F_2(\Delta^2)\mathcal{E} \right]$$

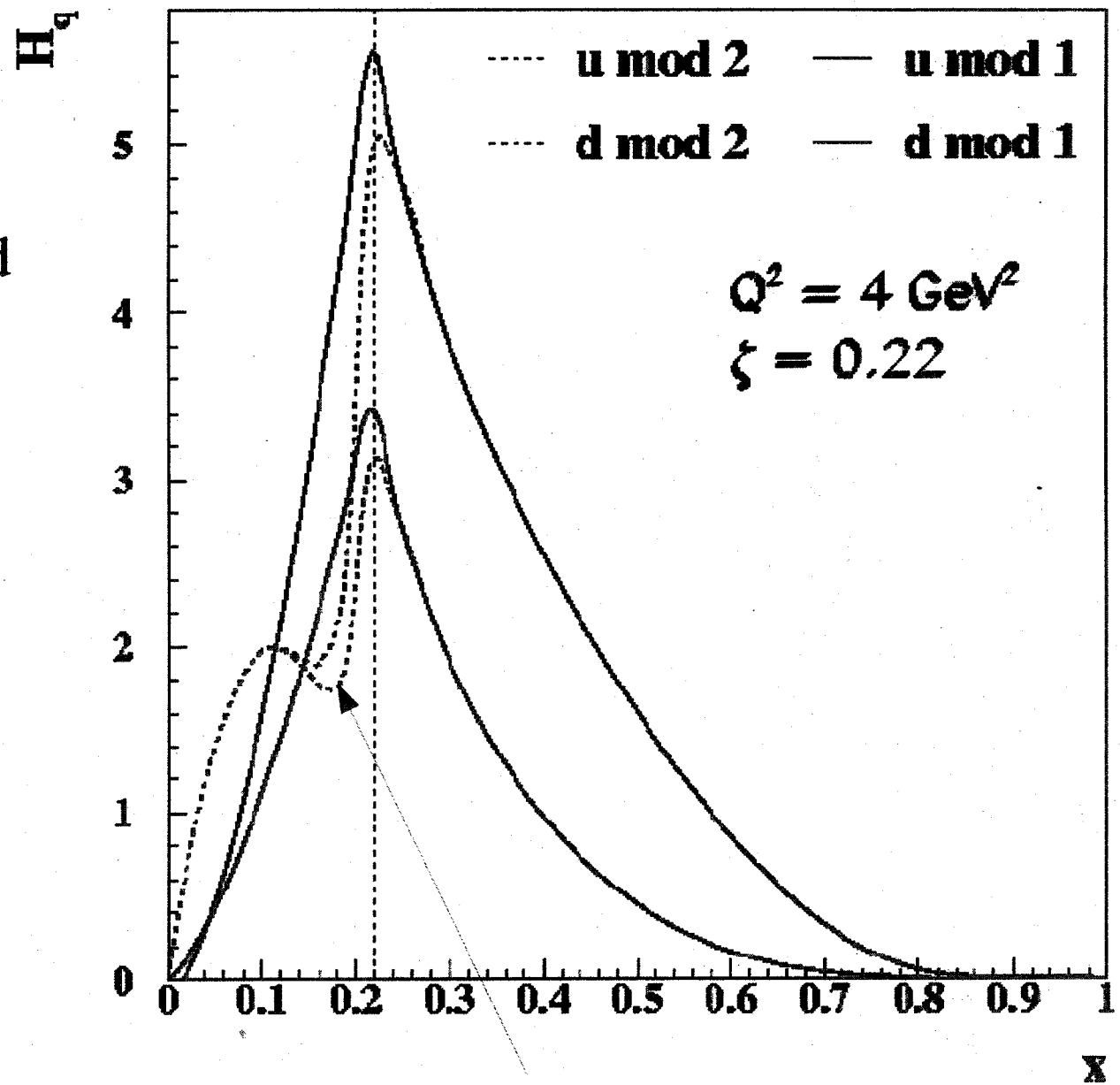
$$\mathcal{H} = \sum_q e_q^2 (H(\xi,\xi,\Delta^2) - H(-\xi,\xi,\Delta^2))$$

Note!!

Im $\mathcal{H}$ from asymmetry

Re $\mathcal{H}$ from x-section

S. Ahmad



- Behavior determined by Jlab data on Real Part and Q^2 dependence
- Consistent with lattice determination!

Neutron Transversity with 12 GeV JLab

Jian-ping Chen, Jefferson Lab

Transverse2008 Workshop, Beijing, China

- Transversity and *TMD*s
  - Multi-dimension, small asymmetries, precision → very high statistics
  - High luminosity AND large acceptance needed
  - A plan for a measurement of the tensor charge
- JLab 12 GeV energy upgrade
- New dedicated device for transversity study: A Large Solenoid Detector
  - Kinematical reach for *SIDIS*
  - Transversity and *TMD*s: unprecedented precision

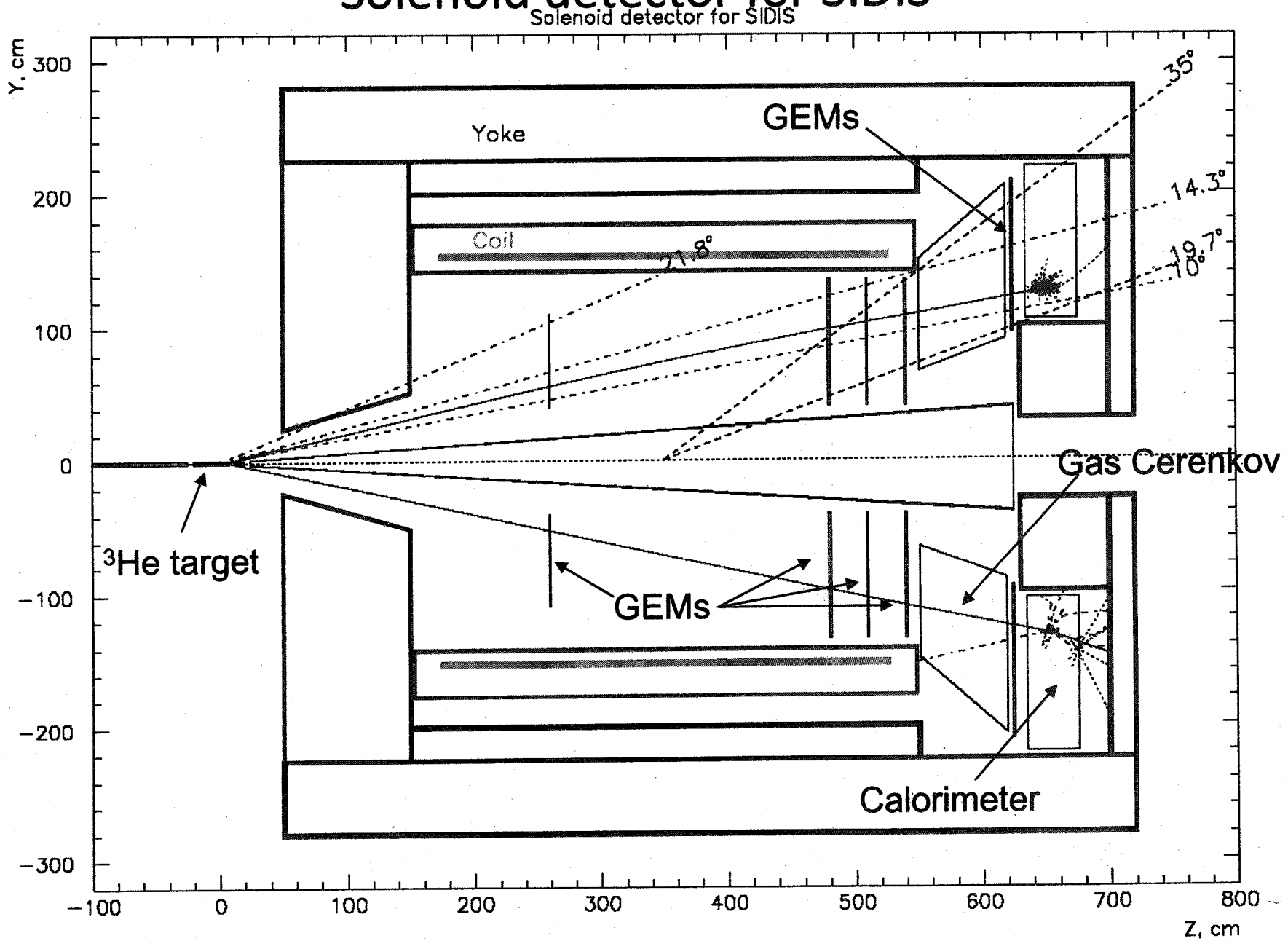
•***Acknowledgement: E. Chudakov, H. Gao, X. Qian, and many others***

Measurement of Tensor Charge

- Tensor charge is a fundamental quantity; *LQCD* prediction
- A plan for a measurement of the tensor charge
  - As much model independent as possible
  - Valence phenomena: *u* and *d* quarks dominant
  - To determine δu, δd, H_1^u, H_1^d
    - Need at least 4 measurements at each kinematical point
      → *SIDIS* of π^{+-} on both proton and neutron
  - Kinematical region: most contributions in $0.1 < x < 0.5$
  - 12 GeV JLab idea for this measurement
    - CLAS12 with proton and a new Solenoid with polarized neutron (^{3}He)

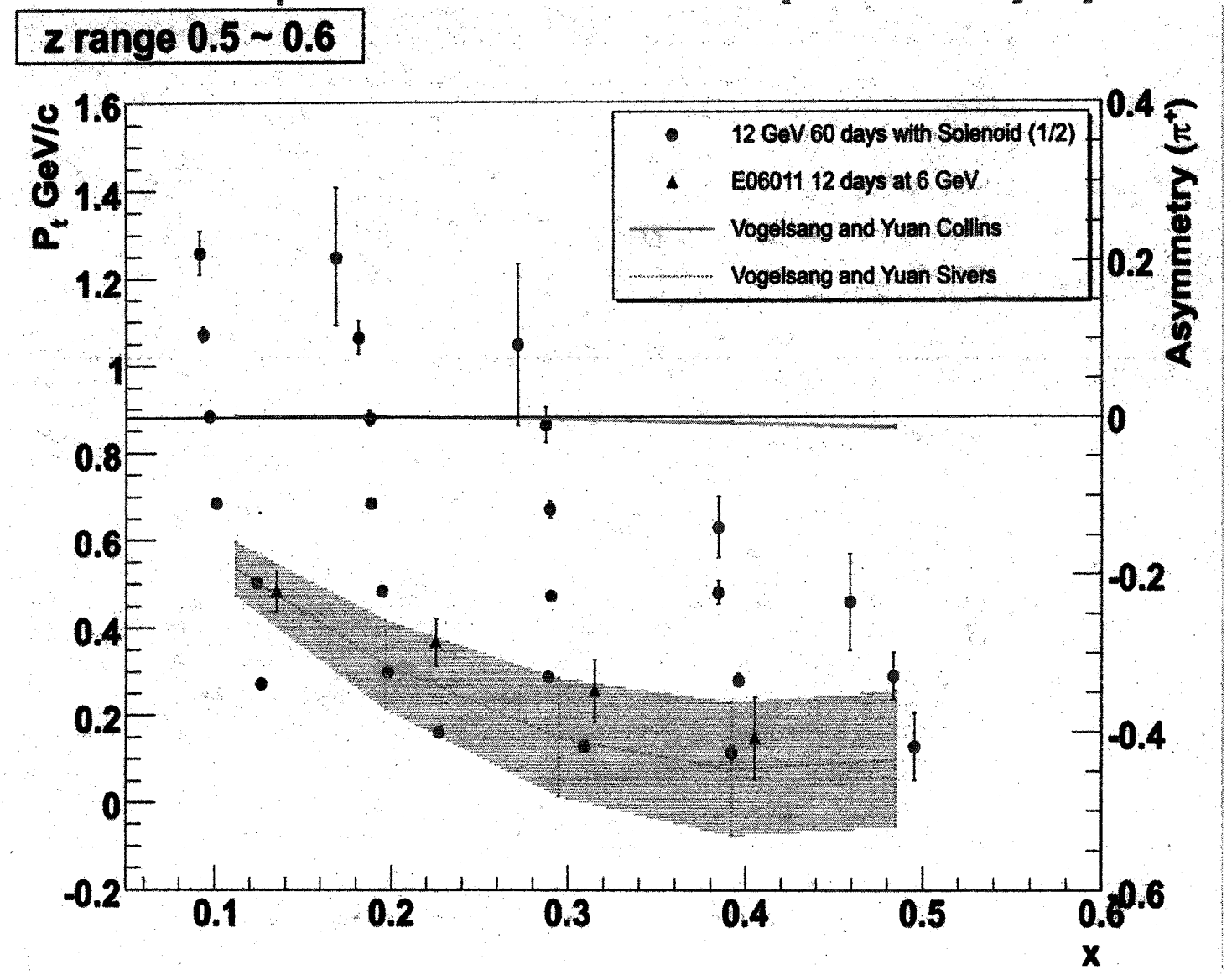
- Issues: factorization, Q^2 evolution, *NLO*, higher-twists, sea quarks
  e+e- (Belle), pp (RHIC, FAIR,...), ep (EIC) → global fit

Solenoid detector for SIDIS



Projection vs P_T and x for π+ (60 days)

- For one z bin (0.5-0.6)
- Will obtain 4 z bins (0.3-0.7)
- Also π- at same time
- With upgraded PID for K+ and K-



Discussion

- Unprecedented precision 3-d mapping of SSA
  - Collins and Sivers
  - π^+, π^- and K^+, K^-
- Study factorization with x and z-dependences
- Study P_T dependence
- Combining with CLAS12 proton and world data
  - extract transversity and fragmentation functions for both u and d quarks
  - determine tensor charge
  - study TMDs for both valence and sea quarks
  - study quark orbital angular momentum
- Combining with world data, especially data from high energy facilities
  - study Q^2 evolution
- Global efforts (experimentalists and theorists), global analysis
  - much better understanding of 3-d nucleon structure and QCD

From CLAS to CLAS12

- ***CLAS*** will be upgraded to ***CLAS12*** and optimized for studying exclusive and semi-inclusive reactions (GPDs & TMDs)

⇒ Large solid angle coverage

⇒ Use of polarized targets

- ***CLAS12*** will operate at higher energie

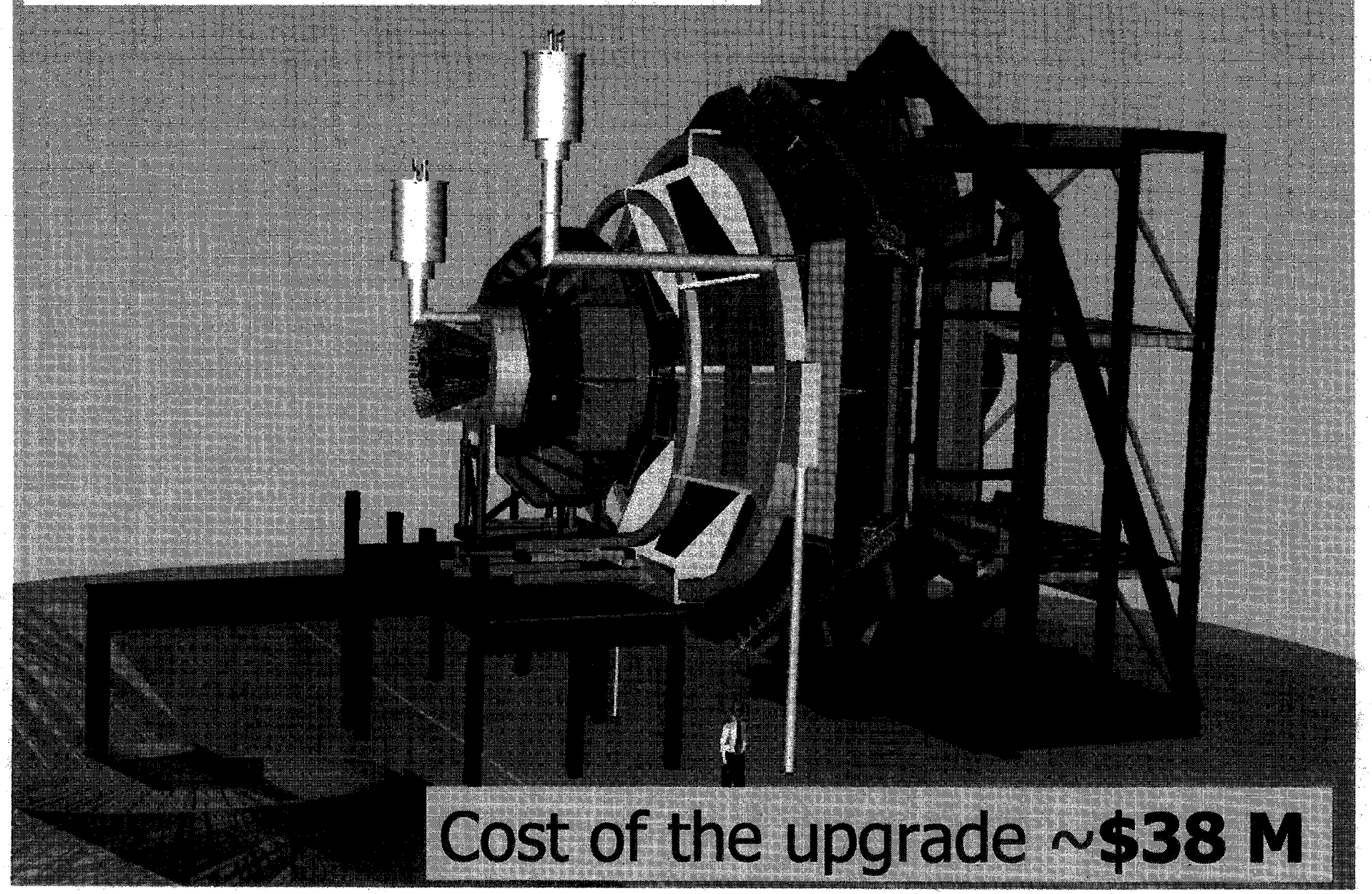
⇒ new requirements on particle identification improvements

- ❑ electron/pion separation
- ❑ particle timing
- ❑ calorimeter granularity

- ***CLAS12*** is expected to operate with an upgraded luminosity of $L=10^{35}cm^{-2}s^{-1}$, more than an order of magnitude increase over CLAS

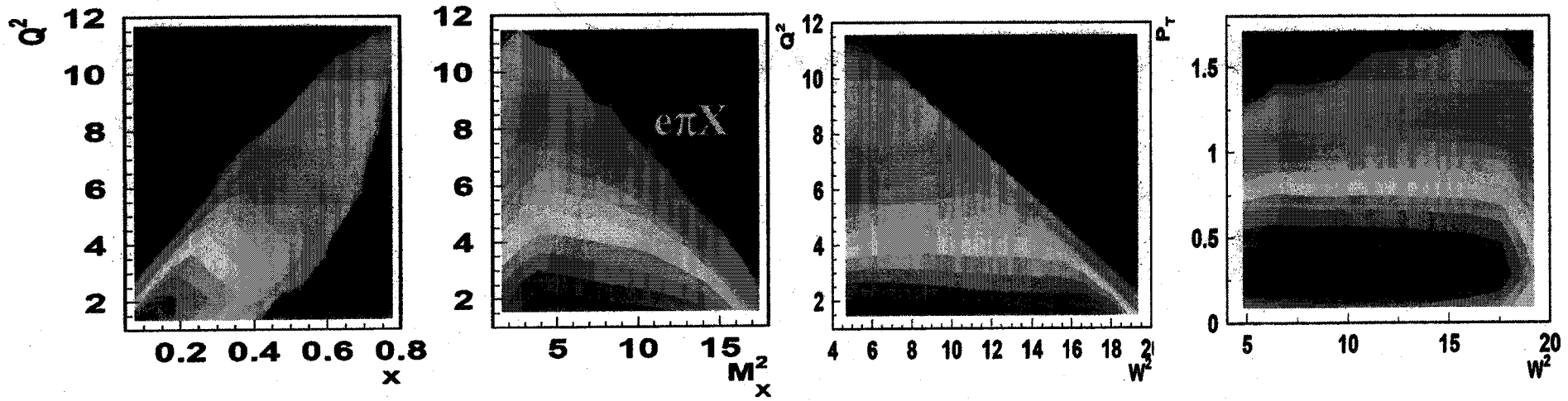
CLAS12 will be worldwide the only large acceptance, multi-purpose detector for fixed target electron scattering experiments.

CLAS12 - Detector



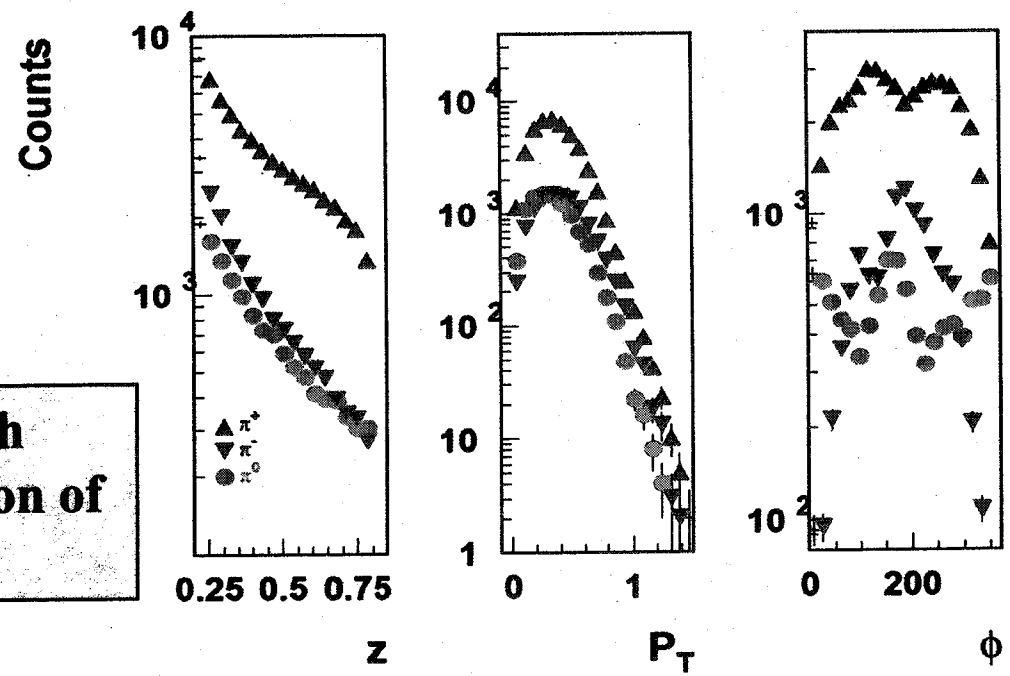
Cost of the upgrade ~**$38 M**

CLAS12: Kinematical coverage



SIDIS kinematics

$Q^2>1GeV^2$
$W^2>4\ GeV^2(10)$
$y<0.85$
$M_X>2GeV$



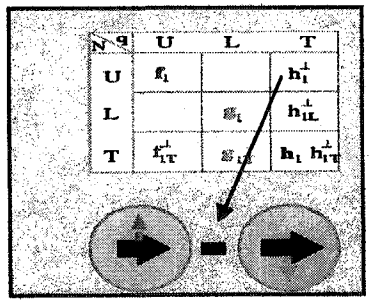
Large Q^2, M_X, and P_T accessible with CLAS12 are important for separation of Higher Twist contributions

E12-06-112: unpolarized target Collins asymmetry & Boer-Mulders Effect

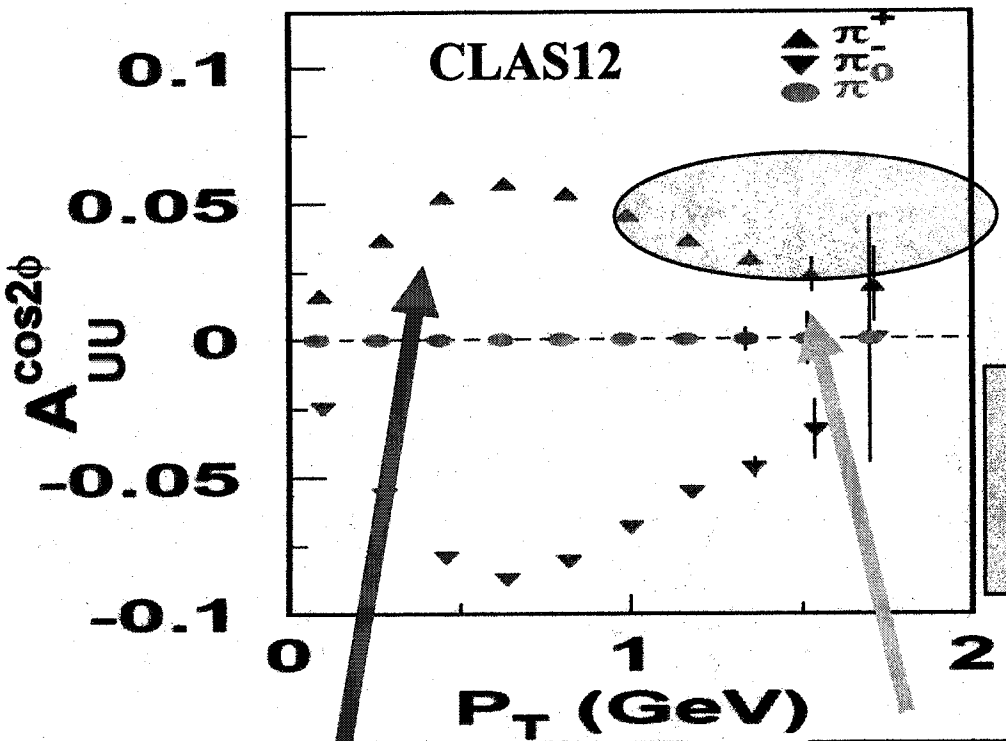
$F_{UU} \longrightarrow f_1 D_1$

$F_{UU} \longrightarrow h_1^{\perp} H_1^{\perp}$

$$A_{UU}^{\cos 2\phi} \propto h_1^{\perp} H_1^{\perp}$$



1500h @ 11 GeV with 10^{35}sec^{-1}cm^{-2})



P_T-dependence of BM asymmetry allows studies of transition from non-perturbative to perturbative description (Unified theory by Ji et al).

Non-perturbative TMD

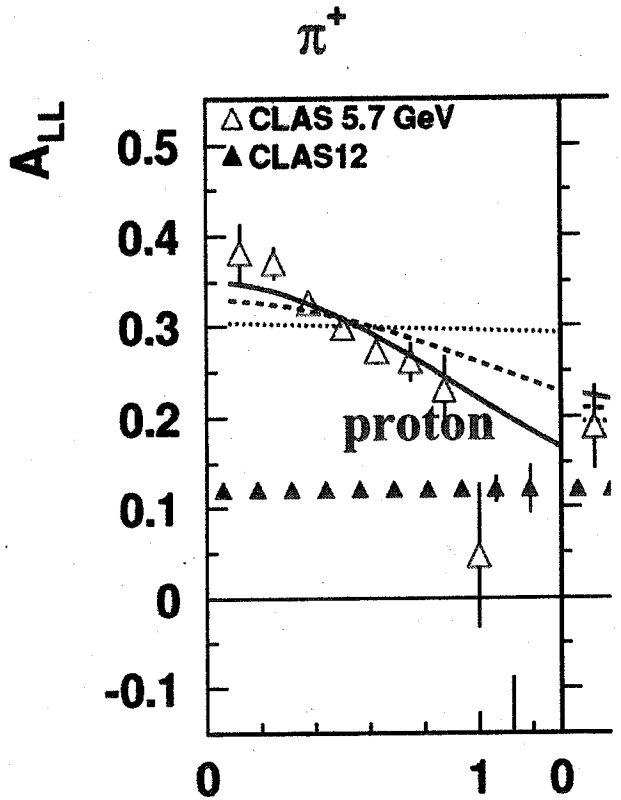
Perturbative region

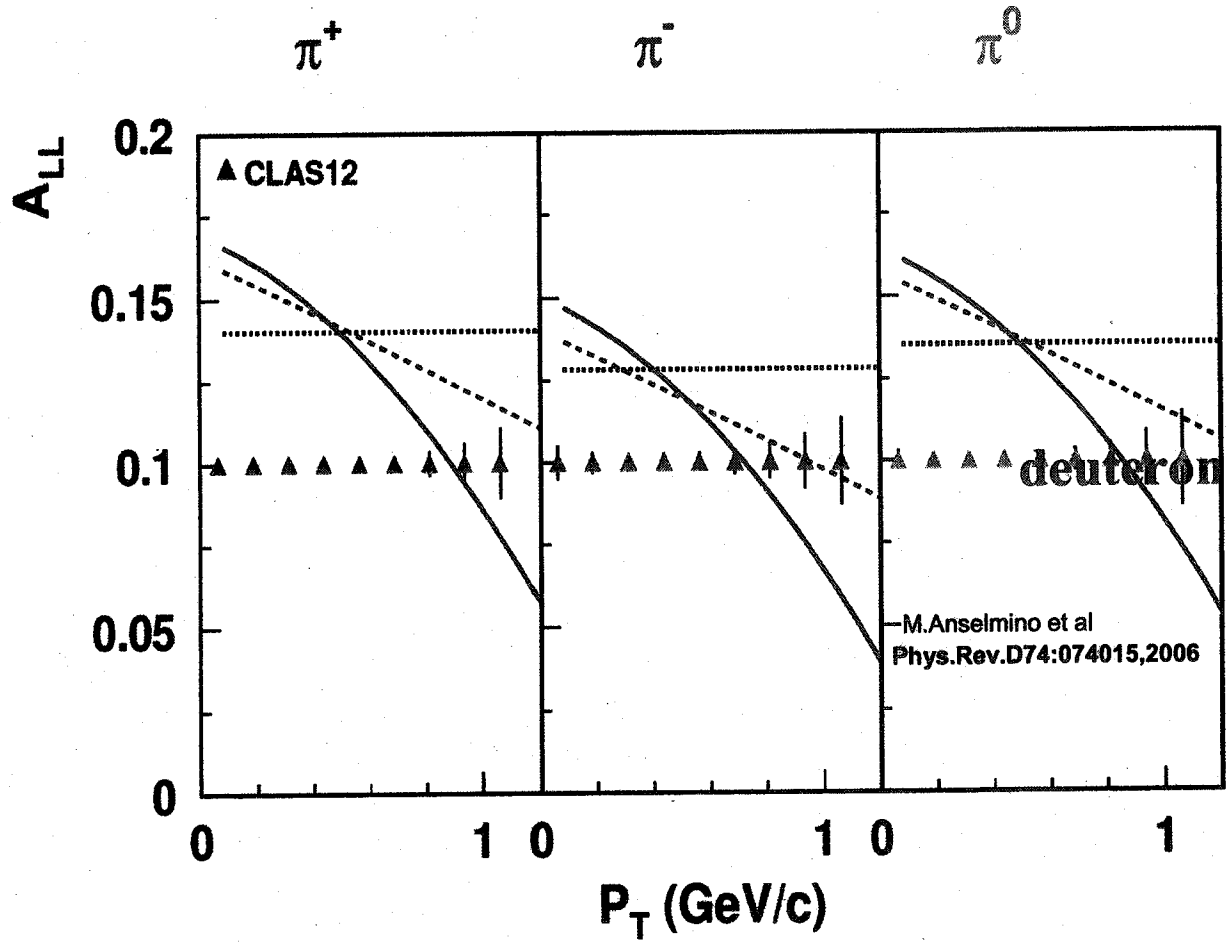
E12-07-107: A_{LL}-P_T-dependence

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

$F_{LL} \longrightarrow g_1 D_1$ $\qquad A_{LL} \propto \frac{g_1}{f_1}$

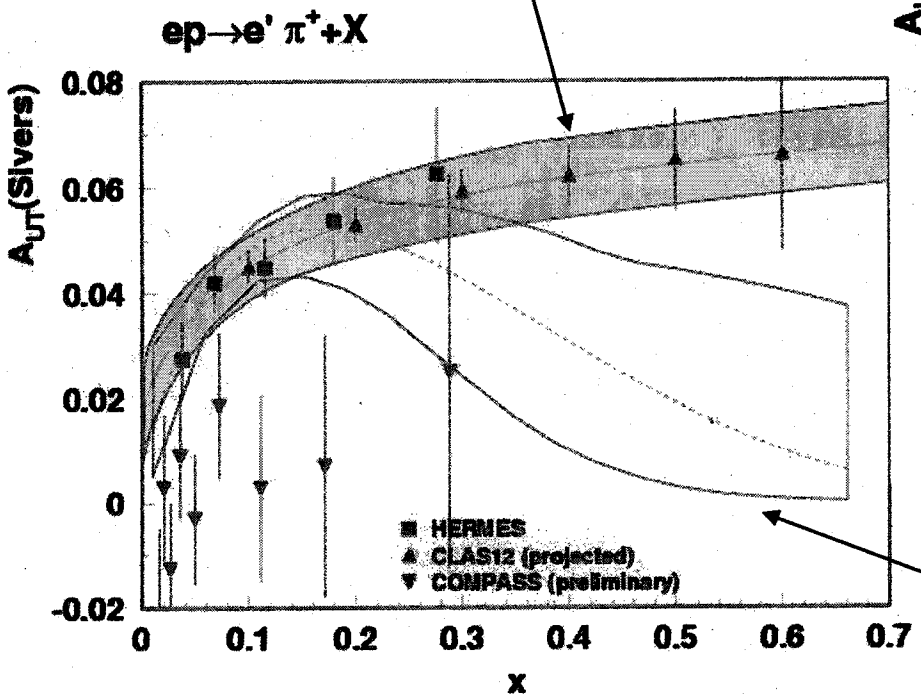
$F_{UL} \longrightarrow h_{1L}^\perp H_1^\perp$ $\qquad A_{UL}^{\sin 2\phi} \sim h_{1L}^\perp H_1^\perp$

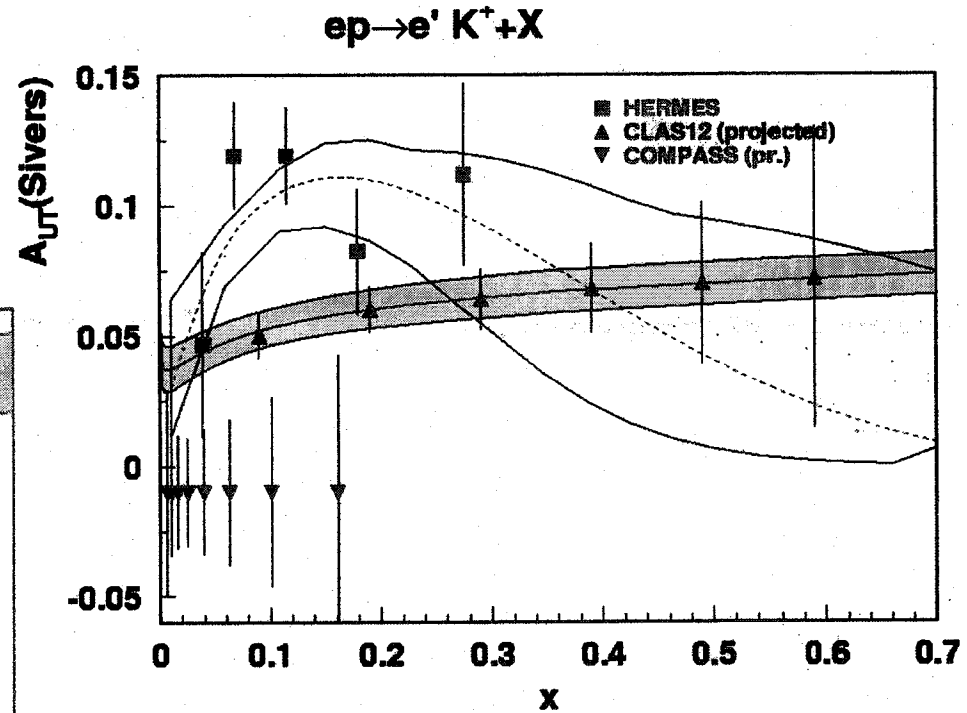




Sivers effect: pion & kaon electroproduction

S. Arnold et al
arXiv:0805.2137





M. Anselmino et al
arXiv:0805.2677

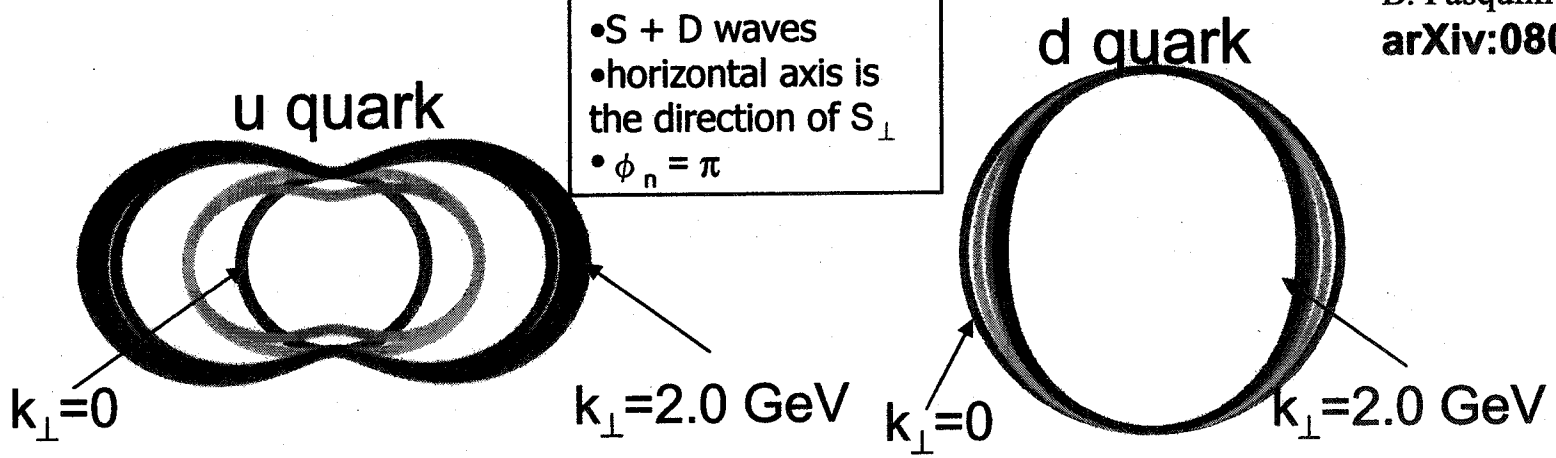
•CLAS12 data will provide superior measurement at large x and will cover intermediate range to solve the kaon puzzle.

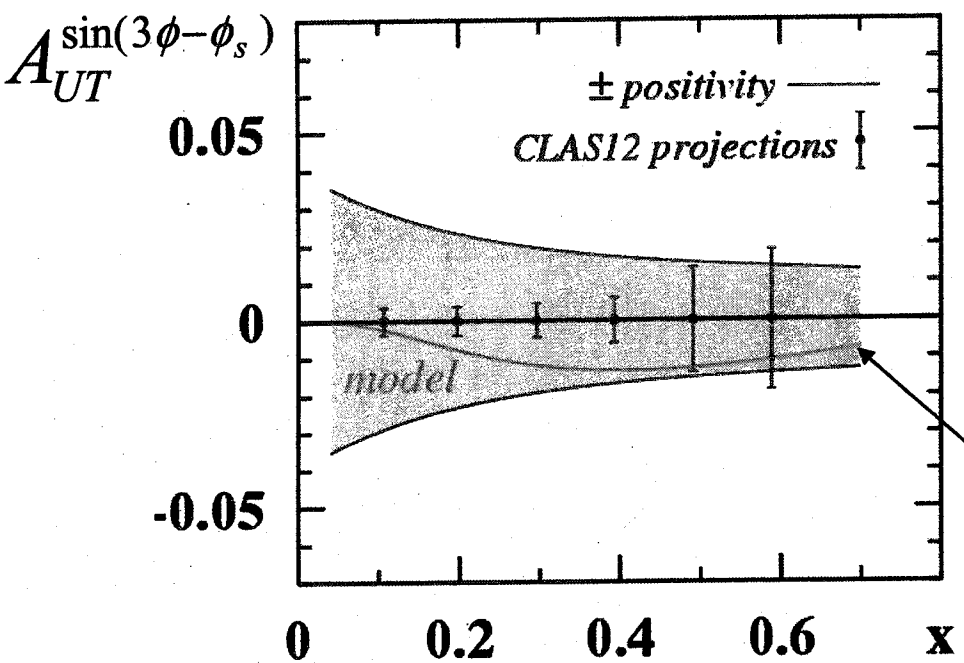
Pretzelosity

Role of pretzelosity investigated to produce a non spherical shape of the nucleon

B. Pasquini et al
arXiv:0806.2298

•S + D waves
•horizontal axis is the direction of $S_\perp$
• $\phi_n = \pi$





•CLAS12 will provide first pretzelosity measurement in the valence region for Kaons and pions.

2000 hours@11GeV

B. Pasquini et al.
arXiv:0806.2298

Participants

Reg. Number	Name	Affiliation
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2	Prof. Masashi Wakamats	Department of Physics, Faculty of Science, Osaka University
3	Prof. Dennis Wayne Sivers	Portland Physics Institute
4	Prof. Jacques Francis SOFFER	Physics Dept, Temple University, Philadelphia, PA, USA
5	Prof. Haiyan Gao	Dept. of Physics, Duke University
6	Prof. Abhay Lalit Deshpande	Stony Brook University, Department of Physics & Astronomy
7	Prof. Piet J Mulders	VU University Amsterdam
8	Prof. Yuji Koike	Phys. Dept., Niigata University
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PKU-RBRC Workshop on Transverse Spin Physics

June 30th-July 4th, 2008. Beijing

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Bo-Qiang Ma (Peking University)
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Conference Coordinator

Yu Zhu (Peking University)

Schedule

Monday, June 30

8:30- 9:00	Registration
Morning Session, Chair: Feng Yuan	
9:00-9:15	Introduction Remarks
9:15-10:00	Werner Vogelsang, Overview of Transverse Spin Physics
10:00-10:45	Les Bland, Experimental review and STAR results
10:45-11:10	Break
11:10-11:50	Franco Bradamante, Transverse Spin Effects at COMPASS
11:50-12:30	Markus Diefenthaler, The HERMES measurement of the Collins and Sivers mechanism
Afternoon Session, Chair: Jianping Chen	
14:00-14:40	Jacques Soffer, Single spin asymmetries: Past, Present and Future
14:40-15:10	Discussion on COMPASS results and its impact
15:10-15:40	J.H. Lee, Cross-section and SSA measurements at forward rapidities at RHIC
15:40-16:00	Break
16:00-16:30	Han Liu, Transverse Single Spin Asymmetry in heavy flavor production in Polarized p+p Collisions at RHIC
16:30-17:00	Alexsander Bazilevsky, Transverse single spin asymmetries in light hadron production from PHENIX
17:00-17:20	Ruizhe Yang, Probing transversity with interference fragmentation function in pp collision at $\sqrt{s}$ = 200 GeV
17:20-17:40	Alessandro Bacchetta, Predictions for observables involving dihadron fragmentation functions
18:30-20:00	Reception

Tuesday, July 1st

Morning Session, Chair: Werner Vogelang	
9:00-9:40	Delia Hasch, Overview of Generalized Parton Distributions
9:40-10:20	Matthias Burkardt, GPD and TMD
10:20-10:50	Break
10:50-11:30	Jianwei Qiu, Probing nucleon's internal structure with transversely polarized proton beam
11:30:12:10	Abhay Deshpande, Spin physics with the Electron Ion Collider (EIC): Ideas and Aspirations
Afternoon Session, Chair: Les Bland	
14:00-14:30	Ralf Seidl, light quark and spin dependent fragmentation functions at Belle
14:30-15:10	Mauro Anselmino, Novel extraction of Sivers, Collins and transversity distributions
15:10-15:30	Imran Younus, k_T asymmetry in longitudinally polarized p+p collisions at PHENIX
15:30-16:00	Break
16:00-16:30	Harut Avakian, Studies of spin-orbit correlations at CLAS
16:30-17:00	Haiyan Gao, Neutron Transversity study using a Polarized 3He Target
17:00-17:30	Zein-Eddine Meziani, The Transverse Nucleon Structure Function g2 and Quark-Gluon Correlations

Wednesday, July 2nd

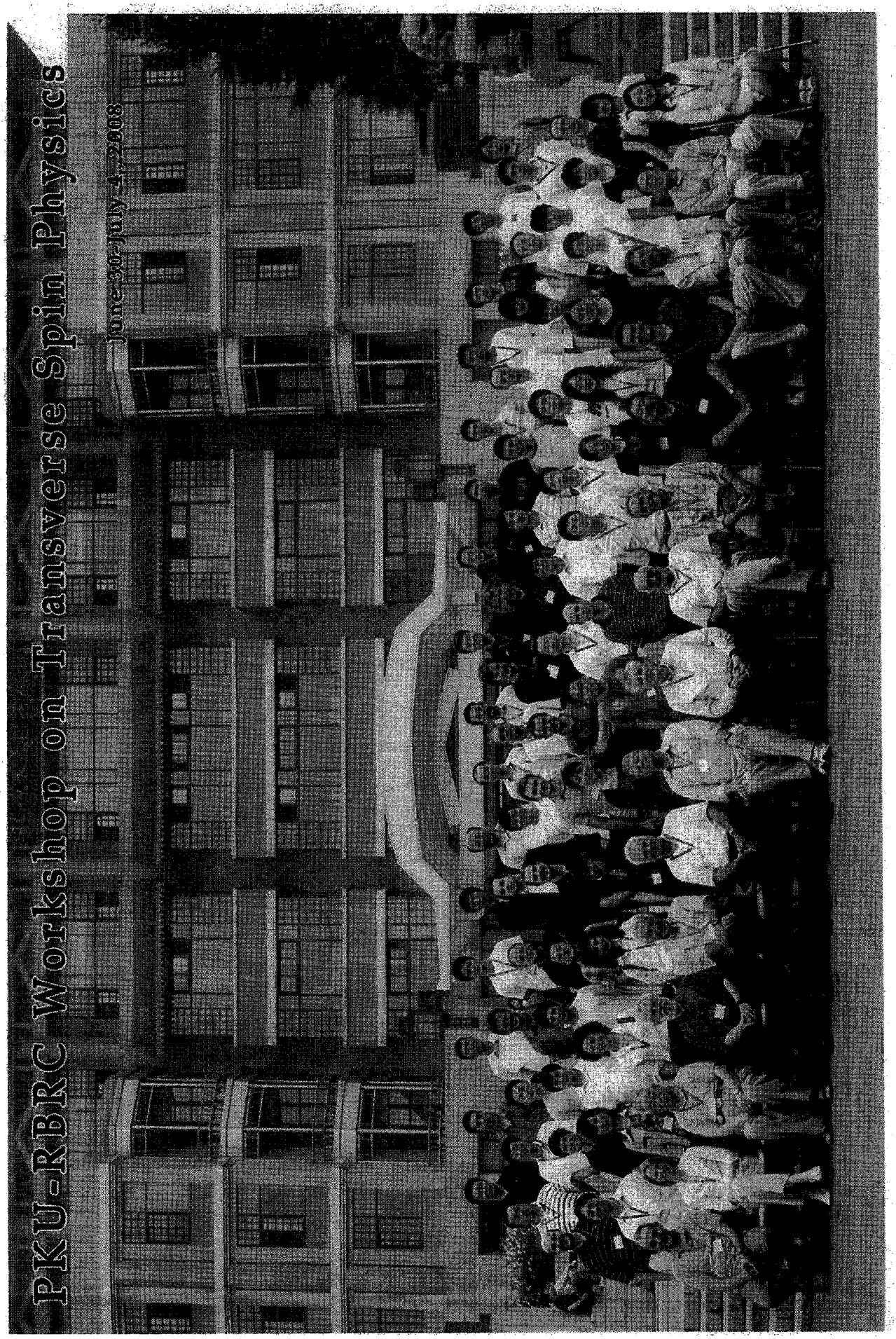
Morning Session, Chair: Jianwei Qiu	
9:00-9:40	Yuji Koike, Single Transverse-Spin Asymmetry in QCD
9:40-10:20	Paul Hoyer, Multi-parton coherence at high x
10:20-10:50	Break
10:50-11:30	Alessandro Bacchetta, DIS at low and high transverse momentum: matches and mismatches
11:30-12:10	Gunar Schnell, GMC_Trans -- A Monte Carlo Generator for TMDs
Afternoon Session, Chair: Piet Mulders	
14:00-14:40	Dennis Sivers, [talk omitted at speakers request] Chiral Dynamics of the Polarizing Fracture Functions for Baryon Productions
14:40-15:20	Oleg Teryaev, Relating DIS and Sivers function [NO SHOW]
15:20-15:50	Break
15:50-16:30	Leonard Gamberg, T-odd Fragmentation and Gluonic Pole Matrix Elements
16:30-17:00	Dae-Sunag Hwang, Transverse momentum dependent distribution and fragmentation functions
17:00-17:30	Aram Kotzinian, SIDIS asymmetries in Quark-diquark model for distribution functions
Social Event	Beijing Night Show

Thursday, July 3rd

Morning Session, Chair: Zein-Eddine Meziani	
9:00-9:40	Piet Mulders, Universality of T-odd phenomena
9:40-10:20	Zuo-tang Liang, Azimuthal asymmetry in SIDIS and collinear expansion
10:20-10:50	Alexei Prokudin, Boer-Mulders functions in SIDIS and Drell-Yan process
10:50-11:20	Break
11:20-12:20	CHEP-Physics Department Colloquium, chair: Kuangta Chao Stan Brodsky, Light-Front Holography and Novel QCD Phenomena
Afternoon Session, Chair: Abhay Deshpande	
14:00-14:20	Bing Zhang, Paremetrization of Boer-Mulders functions and the application
14:20-14:40	She Jun, Transversity from two pion interference fragmentation
14:40-15:20	J.C. Peng, Transverse spin and Drell-Yan process
15:20-15:50	Break
15:50-16:20	Ming Liu, Drell-Yan at RHIC
16:20-16:50	Yuji Goto, Polarized Drell-Yan Experiment at J-PARC
16:50-17:30	Round table discussion on Drell-Yan, chair: J.C. Peng and Werner Vogelsang
18:30-20:00	Banquet

Friday, July 4th

Morning Session, Chair: Mauro Anselmino	
9:00-9:40	Bo-qiang Ma, Transversity from a Relativistic Viewpoint
9:40-10:20	Marc Schlegel, Correlation functions in hard exclusive and inclusive processes
10:20-10:50	Break
10:50-11:30	Umberto D'Alesio, Comments on Sivers and Collins effects in pp collisions
11:30-12:10	Barbara Pasquini, TMD parton distributions in a light-cone quark mode
Afternoon Session, Chair: Harut Avakian	
14:00-14:40	Gary Goldstein, Transversity in Exclusive Meson Electroproduction
14:40-15:20	Massashi Wakamatsu, Chiral-odd generalized parton distributions
15:20-15:50	Break
15:50-16:30	Simonetta Liuti, Bottom-up Strategy to Extract Chiral Odd Generalized Parton Distributions
16:30-17:00	Jianping Chen, Neutron Transversity Study at JLab
17:00-17:30	Patrizia Rossi, Studies of Single-Spin Asymmetries with CLAS12
Adjourn	


PKU-RBRC Workshop on Transverse Spin Physics
June 30-July 4, 2008

Additional RIKEN BNL Research Center Proceedings

Volume 90 - PHENIX Spinfest School 2008 at BNL, August 4-8, 2008. BNL-81478-2008
Volume 89 - Understanding QGP through Spectral Functions and Euclidean Correlators, April 23-25, 2008 - BNL-81318-2008
Volume 88 - Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 - BNL-81307-2008
Volume 87 - RBRC Scientific Review Committee Meeting – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
Volume 85 – Parity Violating Spin Asymmetries at RHIC-BNL, April 26-27, 2007 – BNL – 79146-2007
Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 - BNL-77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL 75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
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Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDPC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 - Jet Correlations at RHIC, March 10-11, 2005 - BNL-73910-2005
Volume 72 - RHIC Spin Collaboration Meetings XXXI (January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) - BNL-73866-2005
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Volume 66 - RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino, Italy - BNL-73534-2004
Volume 65 - RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004) - BNL-73506-2004
Volume 64 - Theory Summer Program on RHIC Physics - BNL-73263-2004
Volume 63 - RHIC Spin Collaboration Meetings XXIV (05/21/04), XXV (05/27/04), XXVI (06/01/04) - BNL-72397-2004
Volume 62 - New Discoveries at RHIC, May 14-15, 2004 - BNL-72391-2004
Volume 61 - RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 - BNL-72336-2004
Volume 60 - Lattice QCD at Finite Temperature and Density - BNL-72083-2004
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Volume 58 - RHIC Spin Collaboration Meeting XX - BNL-71900-2004
Volume 57 - High pt Physics at RHIC, December 2-6, 2003 - BNL-72069-2004

Volume 56 - RBRC Scientific Review Committee Meeting - BNL-71899-2003
Volume 55 - Collective Flow and QGP Properties - BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX - BNL-71751-2003
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Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912
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Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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PKU-RBRC Workshop on Transverse Spin Physics

International Organizers: Harut Avakian, Gerry Bunce, Feng Yuan

June 30th – July 4th, 2008. Beijing, China

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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Speakers:

W. Vogelsang	A. Bazilevsky	R. Seidl	P. Hoyer	P. Mulders	B. Pasquini
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M. Liu	Y. Goto	B. Ma	M. Schegel	U. D'Alesio	