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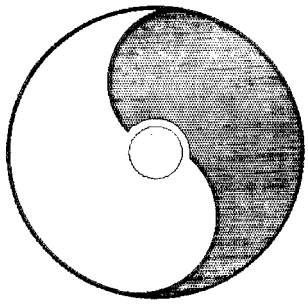
FORMAL REPORT

Proceedings of RIKEN BNL Research Center Workshop Volume 75

Single Spin Asymmetries

June 1-3, 2005



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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 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 currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen 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 ~40 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. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-three 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. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
May 2005

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

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Introduction

Single-transverse spin asymmetries (SSA) in strong interactions have a long history, starting from the 1970s and 1980s when surprisingly large single-transverse spin asymmetries were observed in $p_\uparrow p \to \pi X$ and $pp \to \Lambda_\uparrow X$, where really none were expected. They have again attracted much interest in recent years from both experimental and theoretical sides. In particular, first measurements by the STAR, PHENIX, and BRAHMS collaborations at RHIC have now become available which again reveal large single transverse spin asymmetries for hadron production in polarized proton proton scattering. This extends the SSA observations from the fixed target energy range to the collider regime. Meanwhile, experimental studies in Deep Inelastic Scattering by the HERMES collaboration at DESY, SMC at CERN, and CLAS at JLab also show a remarkably large SSA in semi-inclusive hadron production, $\gamma^* p \to \pi X$, when the proton is transversely polarized. On the theoretical side, there are several approaches to understanding SSA within Quantum Chromodynamics (QCD). For example, to explain the large SSAs for hadron production in hadron collisions, a mechanism that takes into account the contribution from quark-gluon-quark correlations (twist-3) in the nucleon was proposed. On the other hand, possible origins of SSA in DIS and hadronic scattering were also found in leading-twist transverse momentum dependent parton distributions. Current theoretical efforts aim at a better conceptual understanding of these two types of mechanisms, and of their connections.

We were very happy at this timely date to bring together the theorists and experimentalists of this field to review and discuss the current theoretical status and the latest experimental results. The whole workshop contained 25 formal talks, both experiment (15) and theory (10), and a few informal talks and many fruitful discussions. The topics covered all the relevant SSA observables, including in Deep Inelastic Scattering, the Drell-Yan process, and in inclusive hadron production and dijet correlations at hadron colliders. There were not only discussions on possible interpretations of the existing SSA data, but also on the future observables for the ongoing experiments as well as for planned experiments (such as RHIC II and eRHIC). On the theory side, the talks ranged from overviews and descriptions of the fundamental aspects of SSAs, to presentations of detailed phenomenological studies. All of the talks attracted much interest and initiated active discussions. Directions for future measurements were pointed out, in particular for studies at RHIC. Also, significant theoretical advances were made that may tie together some of the currently proposed mechanisms for single-spin asymmetries.

This was a very successful workshop. It stimulated many discussions and new collaborations. We are grateful to all participants and speakers for coming to the Center, and for their excellent work. The support provided for this workshop by Dr. N. Samios and his RIKEN-BNL Research Center has been magnificent, and we are very grateful for it. We thank Brookhaven National Laboratory and the U.S. Department of Energy for providing the facilities to hold the workshop. Finally, sincere thanks go to Pamela Esposito for her invaluable help in organizing and running the workshop.

BNL, June 2005

Werner Vogelsang, Feng Yuan

Results and Plans for Transverse Spin Effects at STAR

L.C. Bland, *Brookhaven National Laboratory*

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has a pair of helical dipole magnets in each ring known as Siberian Snakes. RHIC can be injected with polarized proton beams produced in a polarized ion source and accelerated to RHIC injection energies through the AGS. The helical dipole Siberian Snakes have been demonstrated to retain beam polarization in the acceleration of polarized protons to 100 GeV, and are designed for operation up to 250 GeV. This allows the study of polarized proton collisions at $\sqrt{s} = 200$ GeV. In RHIC run 5 (April through June, 2005) the energy range of polarized proton collisions will be extended to $\sqrt{s} = 410$ GeV. Spin rotator magnets around the PHENIX and STAR experiments allow for flexible orientation of the polarization direction of the colliding proton beams. Both vertical and longitudinal polarizations have been used for colliding beam studies at $\sqrt{s} = 200$ GeV.

Cross sections and analyzing powers for neutral π^0 mesons at large pseudorapidity ($\langle\eta\rangle$=3.8) were measured during the first year of polarized proton collisions at STAR using a prototype Forward π^0 Detector (FPD). The large analyzing power observed for π mesons produced at large Feynman x (x_F) by the FNAL E-704 experiment persist to RHIC collision energies. The forward calorimetry was replaced by the STAR FPD, consisting of matrices of lead-glass detectors deployed left, right, above and below the beam line on both sides of the STAR magnet. The STAR FPD has been used to measure the systematic variation of the cross section with x_F and p_T for the $p+p \rightarrow \pi^0+X$ reaction at $\sqrt{s} = 200$ GeV. In addition, azimuthal correlations of π^0 mesons observed at large rapidity with charged hadrons ($h^{\pm}$) at midrapidity have been observed. The inclusive π^0 cross sections are found to be in agreement with next-to-leading-order perturbative QCD calculations and PYTHIA simulations. Azimuthal correlations between forward π^0 and midrapidity $h^{\pm}$ are in agreement with PYTHIA simulations, except for the need for larger magnitude transverse momentum imbalance (k_T).

It is possible in the present RHIC run to substantially improve the statistical precision of the analyzing power for large rapidity π^0 production. An integrated luminosity of 1 pb^{-1} with the presently achieved beam polarization (>50%) would decrease the magnitude of the statistical errors (δA_N) by at least a factor of four. The increased precision can allow determination of the p_T dependence of A_N at fixed x_F.

In the longer term, there is a proposal to replace the FPD west of STAR by a Forward Meson Spectrometer (FMS). This proposal is described by Steve Heppelmann in a contribution to this workshop. Discussion of increased forward calorimetry as an interim step between the FPD and the FMS is also underway. The increased forward calorimetry could be used for large rapidity single photon detection.

Results and Plans for Transverse Spin Effects at STAR

OUTLINE

- Transverse single spin effects in p+p collisions at $\sqrt{s}$=200 GeV
- Towards understanding forward π^0 cross sections
- Plans for the near-term future

L.C. Bland
Brookhaven National Laboratory
RBRC Workshop on Single-Spin Asymmetries
Brookhaven 1 June 2005

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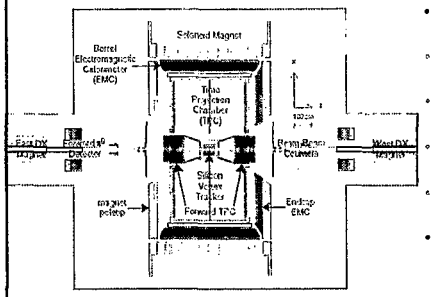
STAR detector layout

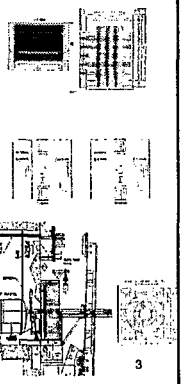


- TPC: $-1.0 < \eta < 1.0$
- FTPC: $2.8 < |\eta| < 3.8$
- BBC : $2.2 < |\eta| < 5.0$
- FEMC: $1 < \eta < 2$
- BEMC: $0 < \eta < 1$
- FPD: $|\eta| \sim 4.0$ & ~ 3.7

STAR Forward Calorimetry

Recent History and Plans

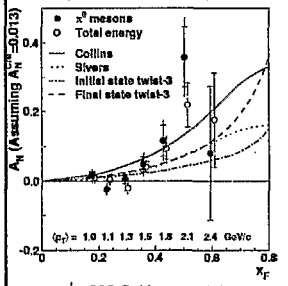
- Prototype FPD proposal Dec 2000
  - Approved March 2001
  - Run 2 polarized proton data (published 2004 spin asymmetry and cross section)
- FPD proposal June 2002
  - Review July 2002
  - Run 3 data pp dAu (Preliminary A_n Results)
- FMS Proposal Submitted Jan 2005. Near full Forward EM Coverage (hep-ex/0502040).
  - ⇒ See talk by Steve Heppelmann on 6/3



First A_N Measurement at STAR

prototype FPD results

STAR collaboration
Phys. Rev. Lett. 92 (2004) 171801



$\sqrt{s}$=200 GeV, $\langle\eta\rangle$ = 3.8

Similar to result from E704 experiment ($\sqrt{s}$=20 GeV, $0.5 < p_T < 2.0$ GeV/c)

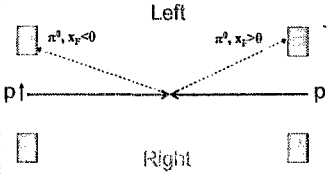
Can be described by several models available as predictions:

- Sivers: spin and $k_\perp$ correlation in parton distribution functions (initial state)
- Collins: spin and $k_\perp$ correlation in fragmentation function (final state)
- Qiu and Sterman (initial state) / Koike (final state): twist-3 pQCD calculations, multi-parton correlations

Single Spin Asymmetry

Definitions

- [illegible] $A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}}$
- [illegible] difference [illegible] to [illegible] of [illegible] polarized [illegible] (upward)



Two measurements:

- [illegible]

$$A_N = \frac{1}{P_{Beam}} \cdot \left(\frac{N^{\uparrow} - RN^{\downarrow}}{N^{\uparrow} + RN^{\downarrow}} \right) \qquad R = \frac{L^{\uparrow}}{L^{\downarrow}}$$

R = relative luminosity (by BBC)

P_{Beam} = beam polarization

- Two arms (left right) calorimeter

$$A_N = \frac{1}{P_{Beam}} \cdot \left(\frac{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} \cdot N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} \cdot N_L^{\downarrow}}} \right)$$

No relative luminosity needed

positive A_N: more π^0 going left to polarized beam

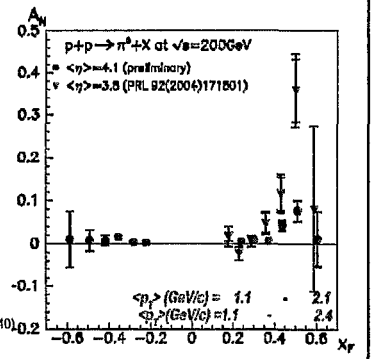
Caveats:
- -RHIC CNI Absolute polarization still preliminary.
- -Result Averaged over azimuthal acceptance of detectors.
- -Positive XF (small angle scattering of the polarized proton).

Run 2 Published Result.

Run 3 Preliminary Result.
- -More Forward angles.
- -FPD Detectors.
- - ~0.25 pb^{-1} with P_{beam}~27%

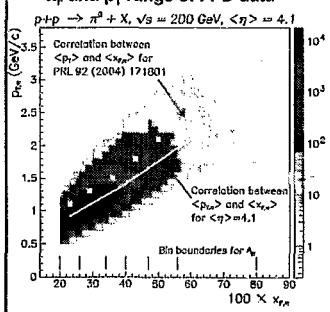
Run 3 Preliminary Backward Angle Data.
- -No significant Asymmetry seen.

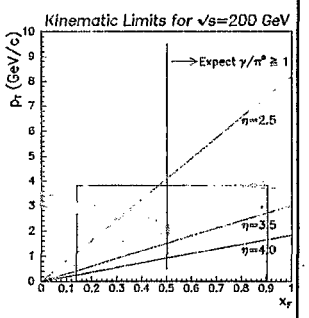
(Presented at Spin 2004: hep-ex/0502040)



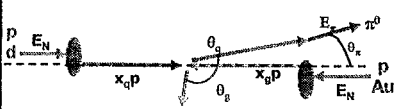
STAR

x_F and p_T range of FPD data





Forward π^0 production in hadron collider



$Q^2 \sim p_T^2$ $\quad x_F \approx \frac{2E_\pi}{\sqrt{s}}$

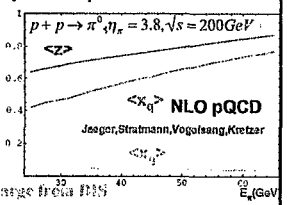
$\sqrt{s} = 2E_N$

$\eta = -\ln(\tan(\frac{\theta}{2}))$ $\quad z = \frac{E_\pi}{E_q}$

$x_q \approx x_F/\langle z \rangle$ $\quad x_g \approx \frac{p_T}{\sqrt{s}} e^{-\eta_\pi}$

(collinear approx.)

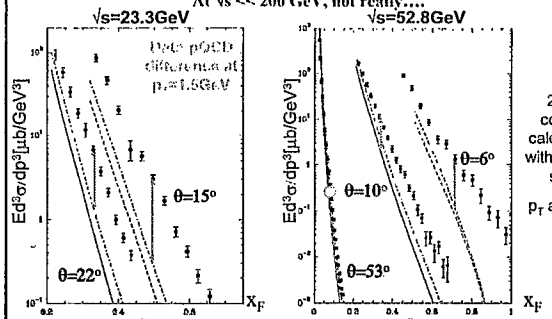
- **Large rapidity π production (η_π~4) probes asymmetric partonic collisions**
- Mostly high-x valence quark + low-x gluon
  - $0.3 < x_q < 0.7$
  - $0.001 < x_g < 0.1$
- <z> nearly constant and high 0.7 ~ 0.8



- Large-x quark polarization is known to be large from DIS
- Directly couple to gluons → A probe of low-x gluons

But, do we understand forward π^0 production in p + p?

At $\sqrt{s}$ << 200 GeV, not really....



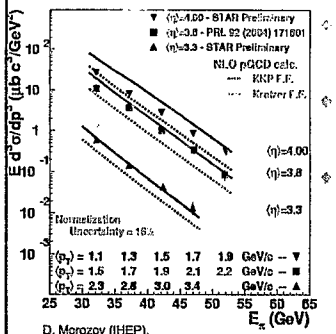
2 NLO collinear calculations with different scale: p_T and $p_T/2$

Bourrely and Soffer, EPJ C36 (2004) 371 [hep-ph/0311110]; Data references therein:

NLO pQCD calculations underpredict the data at low $\sqrt{s}$ from ISR

$\sigma_{data}/\sigma_{pQCD}$ appears to be function of θ, $\sqrt{s}$ in addition to p_T

pp→π^0X cross sections at 200 GeV

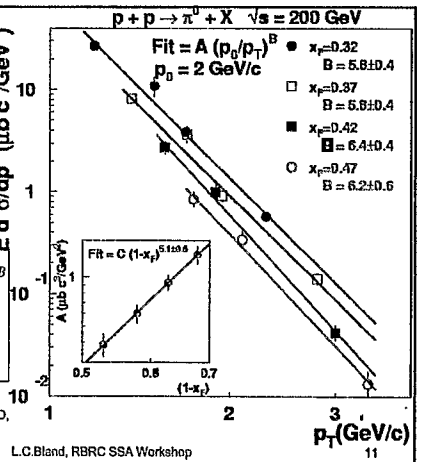


- The inclusive differential cross section for π^0 production is consistent with NLO pQCD calculations at $3.3 < \eta < 4.0$
- The data at low p_T are more consistent with the Kretzer set of fragmentation functions, similar to what was observed by PHENIX for π^0 production at midrapidity.

D. Morozov (IHEP), XXXXth Rencontres de Moriond - QCD, [hep-ex/0505024]

NLO pQCD calculations by Vogelsang, et al.

STAR -FPD Preliminary Cross Sections



Similar to ISR analysis J. Singh, et al Nucl. Phys. B140 (1978) 189.

$$E\frac{d^3\sigma}{dp^3} \propto (1-x_F)^N p_T^{-B}$$

$N \approx 5$

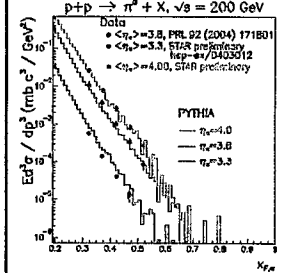
$B \approx 6$

D. Morozov (IHEP), XXXXth Rencontres de Moriond - QCD, [hep-ex/0505024]

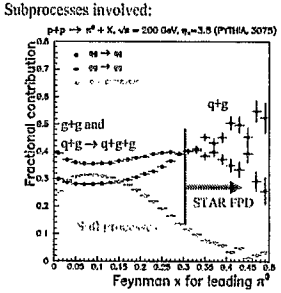
PYTHIA: a guide to the physics

Forward Inclusive π^0 Cross-Section:

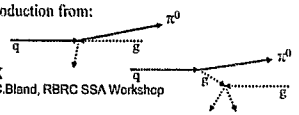
p+p → π^0 + X, $\sqrt{s}$ = 200 GeV



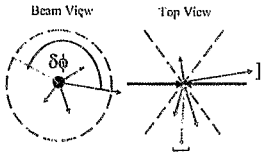
Subprocesses involved:



- PYTHIA *prediction* agrees well with the inclusive π^0 cross section at $\eta \sim 3$-4
- Dominant sources of large x_F π^0 production from:
  - $q + g \rightarrow q + g$ (2→2) $\rightarrow \pi^0 + X$
  - $q + g \rightarrow q + g + g$ (2→3) $\rightarrow \pi^0 + X$



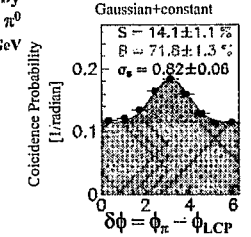
Back-to-back Azimuthal Correlations
with large $\Delta\eta$



Trigger by forward π^0

- $E_\pi > 25$ GeV
- $\langle\eta_\pi\rangle \sim 4$

Fit $\delta\phi = \phi_\pi - \phi_{LCP}$ normalized distributions and with Gaussian+constant



Midrapidity $h^\pm$ tracks in TPC

- $-0.75 < \eta < +0.75$

Leading Charged Particle (η ?)

- $p_T > 0.5$ GeV/c

S = Probability of "correlated" event under Gaussian

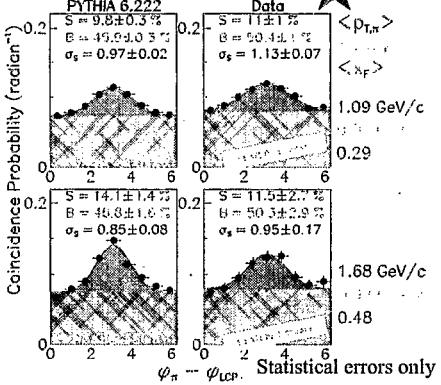
B = Probability of "un-correlated" event under constant

σ_s = Width of Gaussian

$p + p \rightarrow \pi^0 + h^\pm$, $\sqrt{s}$ = 200 GeV

$|\langle\eta_\pi\rangle| = 4.0$, $|\eta_h| < 0.75$

STAR



$\langle p_{T,\pi}\rangle$

$\langle x_F\rangle$

1.09 GeV/c

0.29

1.68 GeV/c

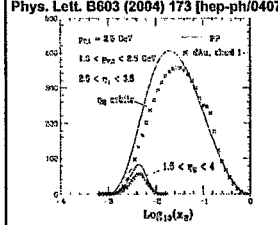
0.48

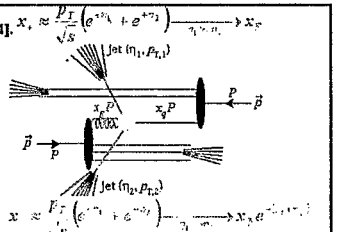
- "S" grows with $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$
- "σ_s" decrease with $\langle x_F\rangle$ and $\langle p_{T,\pi}\rangle$

PYTHIA prediction agrees with p+p data

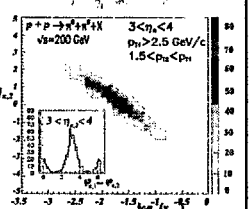
Statistical errors only

Guzey, Strikman and Vogelsang
Phys. Lett. B603 (2004) 173 [hep-ph/0407201].





- constrain x value of gluon probed by high-x quark by *detection of second hadron* serving as jet surrogate
- span broad pseudorapidity range (-1<η<+4) for second hadron ⇒ span broad range of x_{gluon}
- provide sensitivity to higher p_T for forward π^0 ⇒ reduce 2→3 (inelastic) parton process contributions thereby reducing uncorrelated background in $\Delta\phi$ correlation.

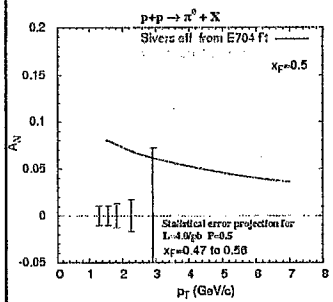


Pythia Simulation

Summary / Outlook

- Large transverse single spin asymmetries are observed for large rapidity π^0 production for polarized p+p collisions at $\sqrt{s}$ = 200 GeV
  - A_N grows with increasing x_F for x_F>0.35
  - A_N is zero for negative x_F
- Large rapidity π^0 cross sections for p+p collisions at $\sqrt{s}$ = 200 GeV is in agreement with NLO pQCD, unlike at lower $\sqrt{s}$. Particle correlations are consistent with expectations of LO pQCD (+ parton showers).
- Large rapidity π^0 cross sections and particle correlations are suppressed in d+Au collisions at $\sqrt{s_{NN}}$=200 GeV, qualitatively consistent with parton saturation models.
- Plan partial mapping of A_N in x_F–p_T plane in RHIC run-5 and first measurements of spin-dependence of two-particle correlations.
- Propose increase in forward calorimetry in STAR to probe low-x gluon densities and establish dynamical origin of A_N (complete upgrade by 10/06). Discussing enhancement of forward calorimeter for RHIC run-6.

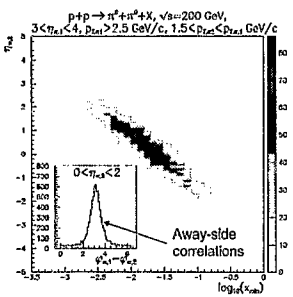
Separating x_F and p_T dependence



- 1 week of transverse polarization running at STAR in present run is expected to yield $\int \mathcal{L}\, dt \approx 1\text{pb}^{-1}$ with ≥50% beam polarization ⇒ reduce statistical errors δA_N by >4 compared to run-3 data
- enables measurement of $A_N(p_T)$ at fixed x_F

Calculations of fixed-x_F $A_N(p_T)$ by U.d'Alesio and F. Murgia (private communication) based on work described in PRD **70** (2004) 074009

Spin dependence of two-particle correlations

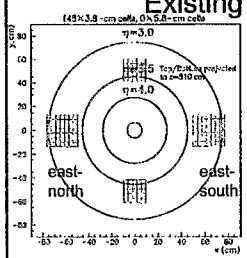


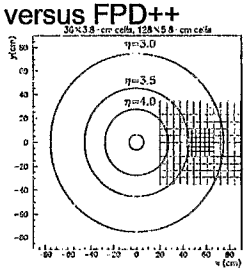
For $p_{T,\pi}$>2.5 GeV/c, expect dominance of 2→2 partonic processes ⇒

- π^0–$h^\pm$ near-side correlations between FPD and FTPC to probe Collins contribution.
- π^0–π^0 away-side correlations to probe for Sivers contribution.

Possible to embark on these measurements in run-5.

Existing FPD versus FPD++





Existing N/S/T/B FPD detectors are well suited to large rapidity inclusive π^0 reconstruction

Exploring possibility to implement interim forward calorimeter (FPD++) for RHIC run 6 designed for single γ detection as a step towards a Forward Meson Spectrometer at STAR.

Features of FPD++...

- Inner matrix of 3.8cm×3.8cm×45cm lead-glass (IHEP) to resolve γ/π^0 up to ~60 GeV
- outer matrix of 5.8cm×5.8cm×60cm lead-glass (E-831) for isolation over broad $\Delta\eta,\Delta\phi$ range.

Single transverse spin asymmetries

Jianwei Qiu

Department of Physics and Astronomy, Iowa State University
Ames, Iowa 50011, U.S.A.

With the RHIC spin program, for the first time, we are able to study single transverse-spin asymmetries (STSA) at collider energies [1]. In this talk, I will concentrate on collinear factorization approach to STSA and its connection to other approaches.

One main advantage of this approach is that we can systematically quantify high order corrections because of the extension of factorization theorem to power corrections in hadronic collisions [2]. Within the collinear factorization formalism, STSA are consequences of coherent multiparton interactions characterized by high twist matrix elements, which are as fundamental as better-known parton distributions [3, 4]. The observed rising x_F dependence of the asymmetries is a natural result of the short distance dynamics at twist-3 level.

A key difference between collinear factorization approach and the k_T-factorization approach [5, 6] to STSA is the treatment of parton's transverse motion, or the k_T information. In collinear factorization approach, parton's k_T-dependence is integrated into the nonperturbative multiparton correlation functions, while it is directly given by the k_T-dependent parton distribution in the other approach. Since k_T-dependent parton distributions at low k_T are nonperturbative, an additional large momentum scale $Q \gg \langle k_T \rangle$ is required for the k_T-factorization to work. It is the combination of collinear factorization approach, which is proportional to the "moments" of k_T, and k_T-factorization approach, which is sensitive to direct k_T information for some k_T, that will give us a more complete picture of parton's transverse motion inside a hadron.

References

[1] C. Aidala *et al.* *Research Plan for Spin Physics at RHIC*, "http://spin.riken.bnl.gov/rsc", and reference therein.

[2] J. W. Qiu and G. Sterman, AIP Conf. Proc. **223**, 249 (1991).

[3] J. W. Qiu and G. Sterman, Phys. Rev. D59, 014004 (1999).

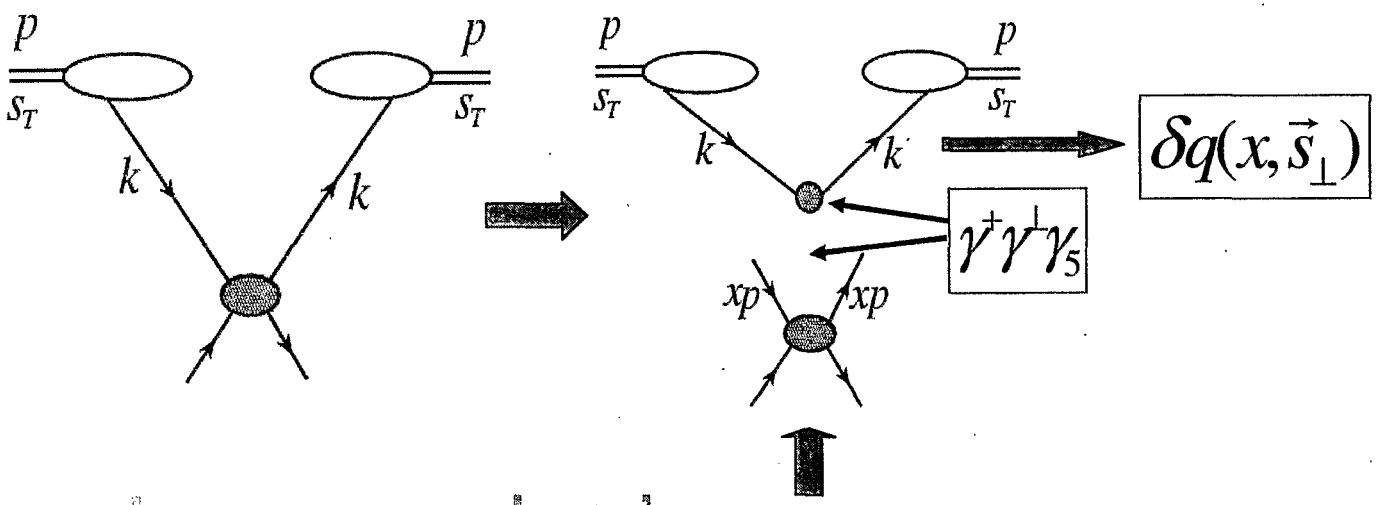
[4] Y. Koike, AIP Conf. Proc. **675**, 449 (2003).

[5] D. W. Sivers, Phys. Rev. **D41** 83 (1990).

[6] J. C. Collins, Nucl. Phys. **B396** 161 (1993); J. C. Collins, S. F. Heppelmann, G. A. Ladinsky, Nucl. Phys. **B420** 565 (1994).

Single transverse spin asymmetry – A_N
in collinear factorization approach

- Leading twist PDF with transverse hadron spin:



- need an even number γ's:

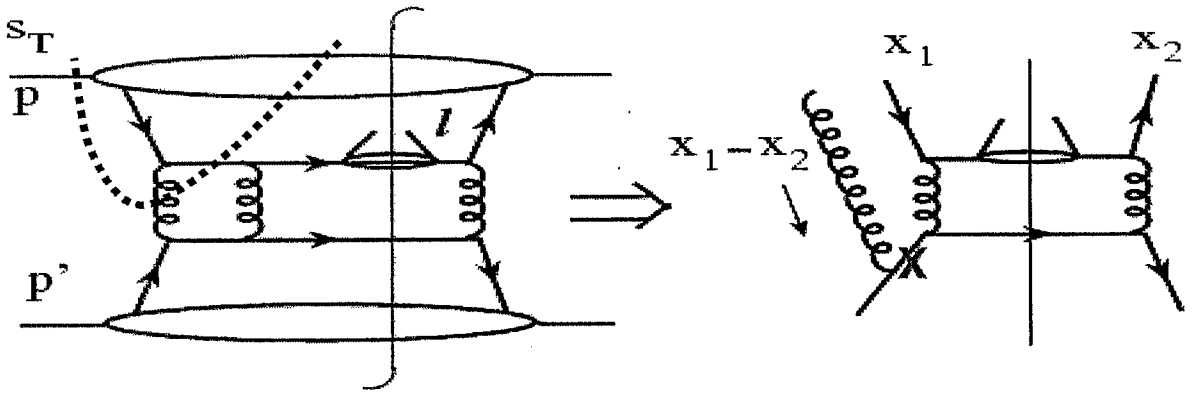
$\Gamma_i = I, \quad i\gamma_5$ ➡ **Twist-3 matrix elements**

$\sigma^{\mu\nu}(i\gamma_5)$ ➡ **An extra transverse index**

extra gluon (its polarization)

extra vector direction

High twist contribution to A_N



- Unpinched pole to give the phase: $i\delta(x_1 - x_2)$
- **Spin flip from interference between a quark state and a quark-gluon composite state**
- Observed hadron momentum provides the **3rd vector**

$$A_N \propto i\,\vec{s}_\perp \cdot (\vec{p} \times \vec{\ell})$$

Q: pQCD factorization beyond leading twist?

Single spin asymmetry within the collinear factorization

❖ **Generic twist-3 factorized contributions**

$$\Delta\sigma_{AB\to h}(\vec{s}_T) = \sum_{abc} \boxed{T^{(3)}_{a/A}(x_1, x_2, \vec{s}_T)} \otimes f_{b/B}(x') \otimes \hat{\sigma}_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z)$$

Provides hadron spin dependence

$$+ \sum_{abc} \boxed{\delta q^{(2)}_{a/A}(x, \vec{s}_T)} \otimes \left\{ f_{b/B}(x') \otimes \hat{\sigma}'_{ab\to c}(\vec{s}_T) \otimes D^{(3)}_{c\to h}(z_1, z_2) \right\}$$

transversity

Even γ's !

$$\left\{ + f^{(3)}_{b/B}(x'_1, x'_2) \otimes \hat{\sigma}''_{ab\to c}(\vec{s}_T) \otimes D_{c\to h}(z) \right\}$$

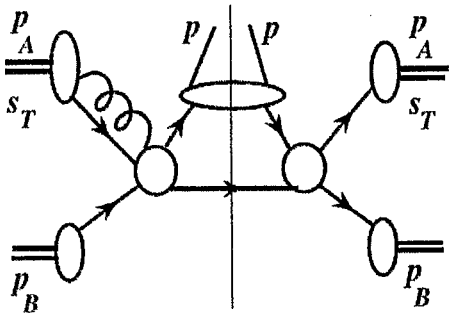
Even γ's !

(1) Calculated by Qiu and Sterman, Phys. Rev. D, 1999

(2) Calculated by Kanazawa and Koike, Phys. Lett. B, 2000

Twist-3 vs K_T approach

- Twist-3 contribution in collinear factorization
  - leading corrections from parton correlation (a minimal approach)



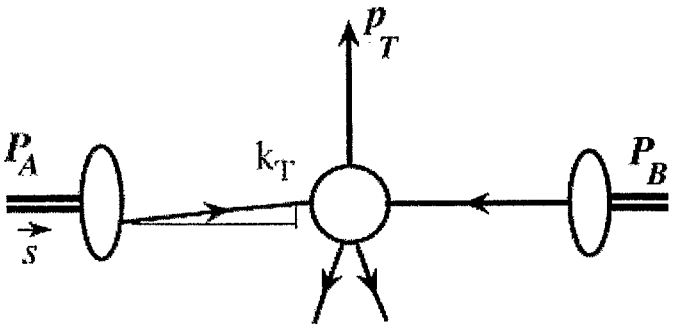
$+$ *c.c.*

$$A_N \propto \frac{1}{S}\varepsilon^{p_A p_B s_T p_T}\frac{1}{T}\frac{-x\frac{\partial}{\partial x}T^{(3)}(x)}{\phi(x)}$$

$$\Rightarrow \left(\frac{1}{p_T}\right)\left(-x\frac{\partial}{\partial x}T^{(3)}(x)\right)$$

$$\frac{d\Delta\sigma}{dy\,dp_T^2} = \sum_{abc} T^{(3)}_{a/A}(x_1)\otimes\phi_{b/B}(x_2)\otimes H_{abc}\otimes D_c(z)+\ldots$$

- Effect of non-vanish parton k_T (when $k_T \sim p_T$):



$$A_N \propto \frac{1}{S}\varepsilon^{p_A p_B s_T p_T}\frac{1}{M}f^{\perp}(x) \Rightarrow \frac{p_T}{M}$$

M = **Non-perturbative scale, e.g., di-quark mass, …**

Open questions

- How much overlap between k_T-approach at low p_T and twist expansion at high p_T?
- What these nonperturbative functions try to tell us? "direct k_T" vs "k_T – moments"
- If there is no K_T – factorization, how universal are Sivers and Collins functions?
- Although there is k_T-factorization in SIDIS, Drell-Yan and the others, how to separate dynamical k_T from intrinsic k_T ?
- How Sivers and Collins functions are affected by the process dependent gluon shower (resummation)?
- ...

Spin and Azimuthal Asymmetries at JLAB

H. Avakian *)

Jefferson Lab

Single-Spin Asymmetries Workshop, BNL June 1-3, 2005

- Introduction
- SSA in target fragmentation
- Transverse momentum of quarks in SIDIS
  - azimuthal asymmetries
- Double spin asymmetries
- SSA in SIDIS
  - beam single-spin asymmetries
  - target single-spin asymmetries
- SSA in hard exclusive processes
  - DVCS
  - DVMP
- Summary

*) in collaboration with P.Bosted, V. Burkert and L. Elouadrhiri

We present recent progress on spin and azimuthal asymmetry studies in Semi-Inclusive DIS (SIDIS) and hard exclusive processes at JLab, using the CLAS detector. Some near term future plans with 6 GeV measurements are discussed as well.
Variety of processes with hard scattering are presented,including different kinematic regions, most of them probing correlations between the quark the transverse momentum of quarks and their polarization.
Wide kinematic coverage of CLAS allows studies of both, current and target fragmentation regions in SIDIS.
One specific example of target fragmentation studies is the Lambda polarization measurement, which could be sensitive to the the strange sea in the nucleon.
In the current fragmentation region different measurements were performed, including azimuthal asymmetries with unpolarized target, spin asymmetries and spin-azimuthal asymmetries with polarized and unpolarized targets in SIDIS.

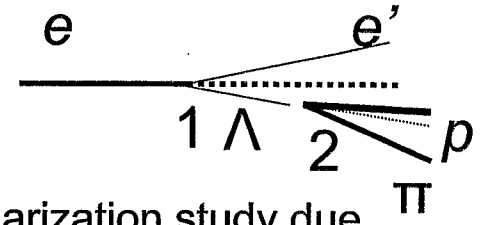
Different studies performed to demonstrate that observed picture already at 5GeV beam energy, both in unpolarized and polarized SIDIS is consistent with factorization.
No significant z-dependence of A1 in the range 0.4<z<0.7 (p+p0) and the CLAS asymmetry was observed, which is consistent with HERMES data and also LUND MC.
A very good agreement between pion and inclusive double spin asymmetries is observed.

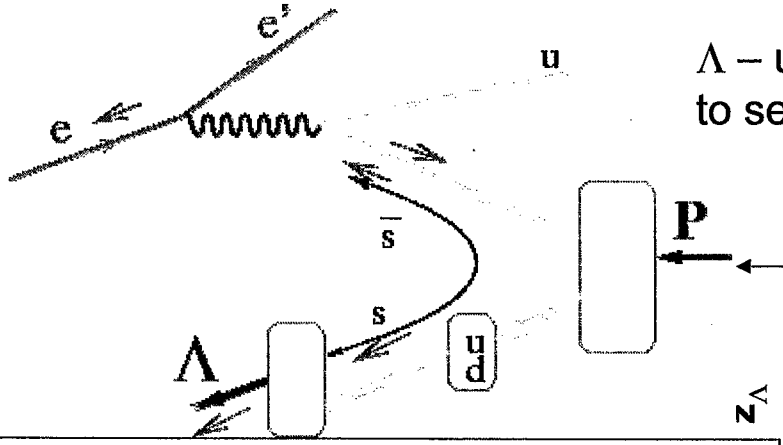
It was shown that the P_T dependence of the double spin asymmetry is flat, while P_T dependences of different SSA are all consistent with increase with P_T at small P_T.

A significant sin2\phi SSA for the longitudinally polarized target (Kotzinian-Mulders asymmetry) is measured for he first time,
The Mulders distribution related to the interference of wave functions with L=0 and L=1 is extracted for the first time.
indicating that there is a non-zero effect.

The advantages of pi0 SIDIS are discussed and future measurement with polarized target and inner calorimeter, which is significantly increasing the acceptance for photon detection at CLAS, proposed.
Studies of hard exclusive processes performed at JLAB, include measurements of DVCS with polarized and unpolarized targets and measurements of rho-0 and rho+ distributions and beam asymmetries.

Λ in target fragmentation



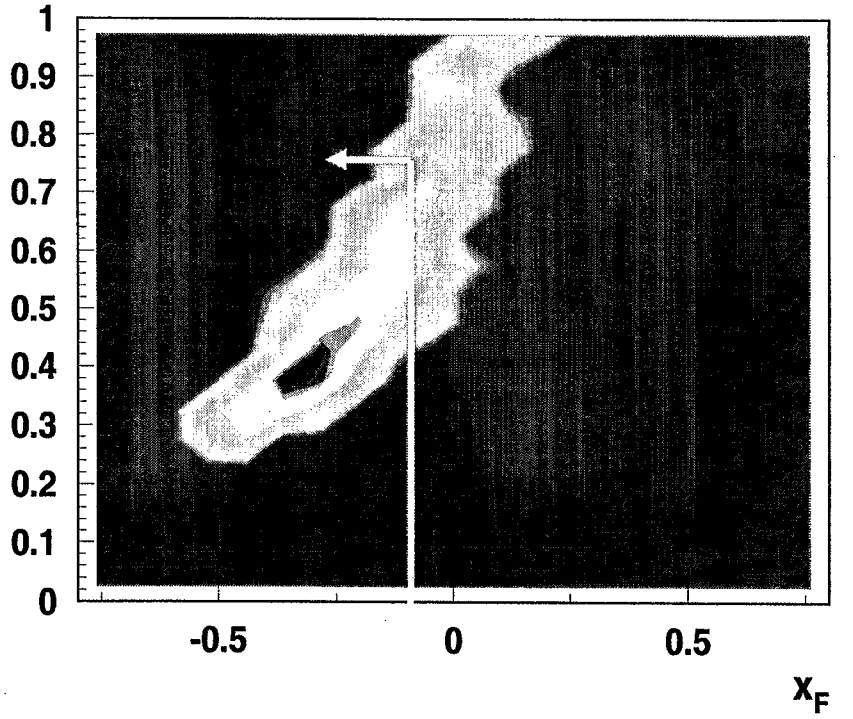


Λ – unique tool for polarization study due to self-analyzing parity violating decay

Accessing polarized PDFs with unpolarized target!

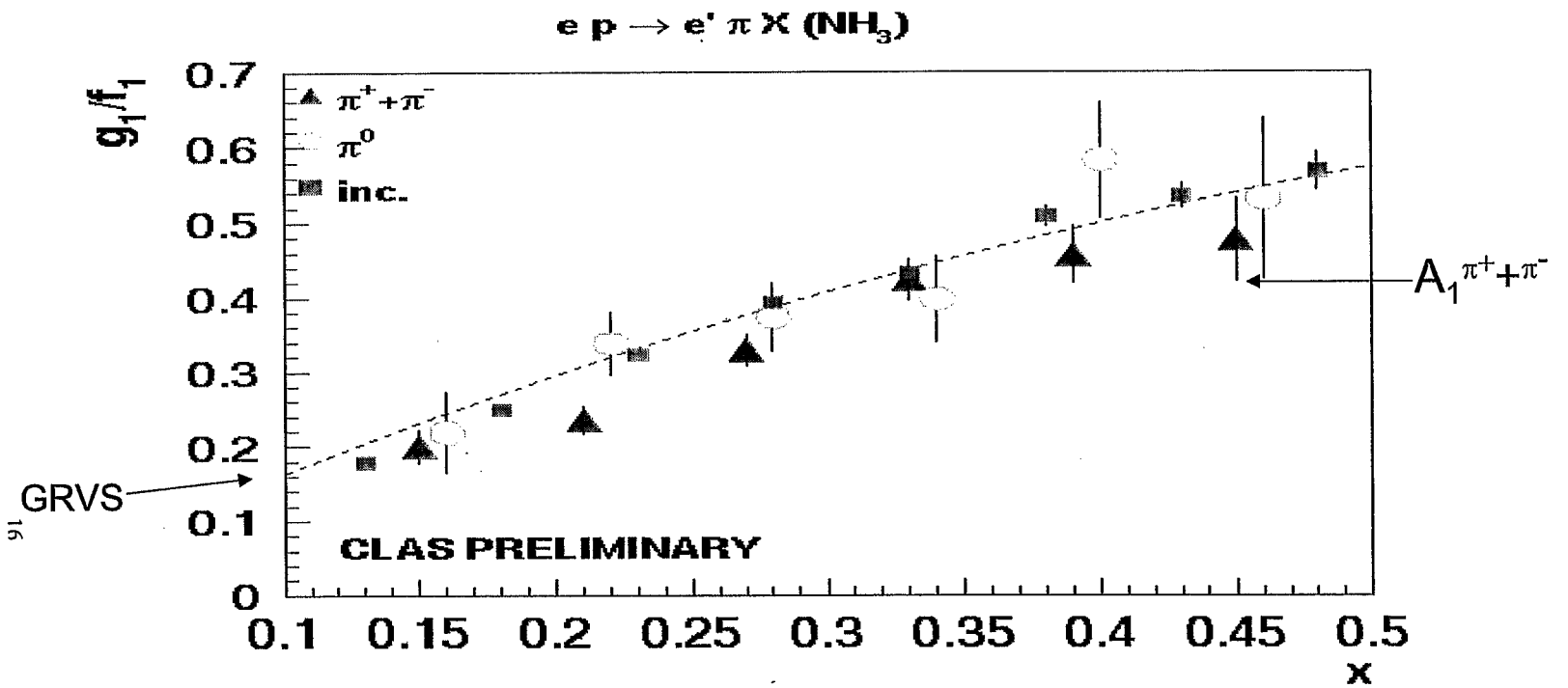
(ud)-diquark is a spin and isospin singlet
s-quark carries whole spin of Λ $|\Lambda\rangle = |uds\rangle$

Λs accessible in CLAS (even at large **z**) are mainly in the TFR region and can provide information on contribution of strange sea to proton spin



W.Melnitchouk and A.W.Thomas '96
J.Ellis, D.Kharzeev, A. Kotzinian '96

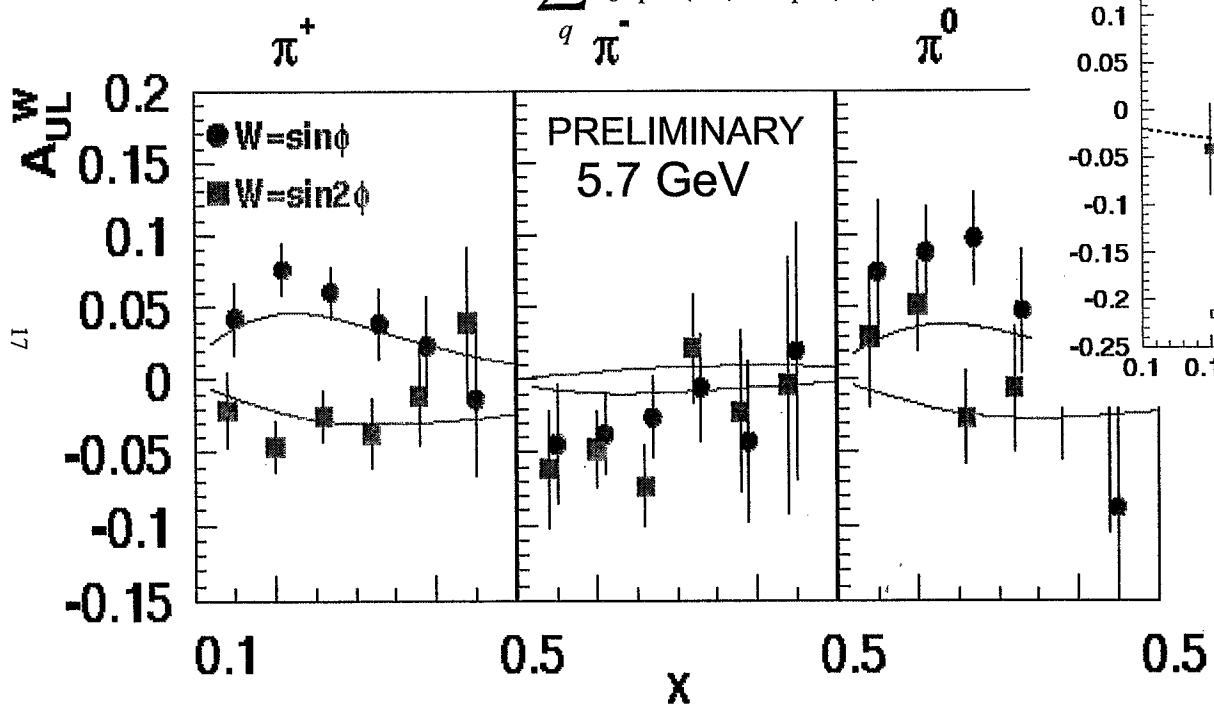
SIDIS: factorization studies

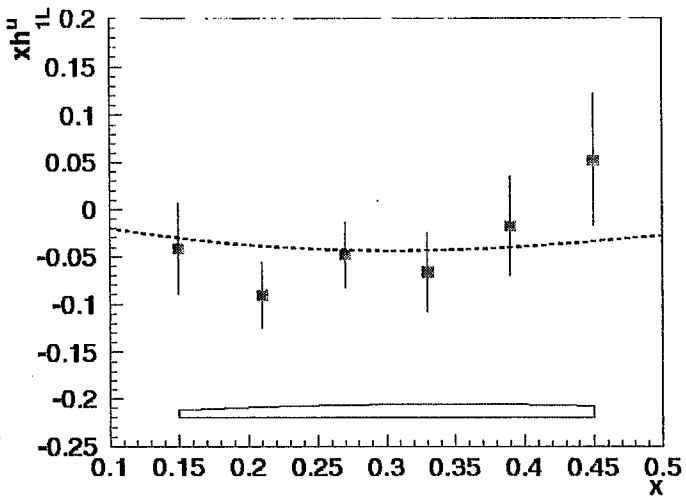


- A_1 inclusive, from $\pi^+\pi^-$ sum and π^0 are consistent (in range 0.4<z<0.7)
- A_1^p dependence can serve an important check of HT effects and applicability of simple partonic description.
- There is an indication that A_1^p of $\pi^+ + \pi^-$ is lower than inclusive at large z.

SSA: x-dependence

$$A_{UL}^{\sin 2\phi} = P_T D_{UL} \frac{\sum_q h_{1L}^{q\perp}(x) H_1^{q\perp}(z)}{\sum_q f_1^q(x) D_1^q(z)}$$



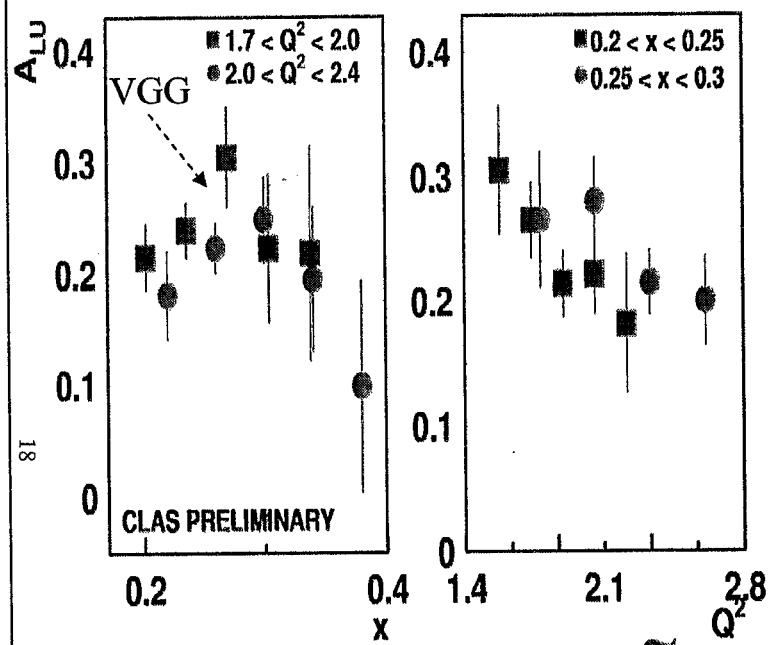


First glimpse of Twist-2 Mulders TMD $h_{1L}^{\perp}$

- Study the Collins fragmentation mechanism with long. polarized target
- For π^- and π^0 SSA is sensitive to unfavored fragmentation

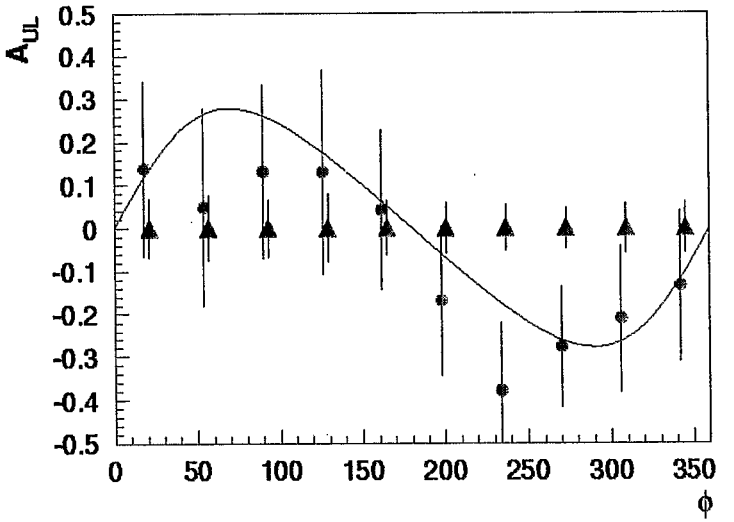
CLAS/DVCS ($ep \rightarrow epX$) at 5.75 GeV

polarized beam



$$\Delta\sigma_{LU} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)\tilde{H} + kF_2 E\}$$

polarized target



$$\Delta\sigma_{UL} \sim \sin\phi \, \mathrm{Im}\{F_1 H + \xi(F_1+F_2)(H + .. \}$$

Kinematic dependences of DVCS beam SSA consistent with GPD based predictions (same pdfs)

Summary

Spin and azimuthal asymmetries measured at 5.7 GeV with polarized beam and longitudinally polarized target at JLab.

•SIDIS multiplicities and double spin asymmetries of pions are consistent with factorization and partonic picture: may be used in future NLO QCD fits.

• $\sin\phi$ and $\sin 2\phi$ beam and target SSA measured, providing access to the twist-2 and twist-3 TMD distributions and testing the Collins fragmentation function

•Studies of hard exclusive photon and vector meson production underway, allowing access to GPDs and also providing important info for the interpretation of SIDIS SSAs.

•Ongoing and future measurements with CLAS at 6GeV, will greatly improve $\pi^{0/+/-}$, ρ and DVCS data, allowing extraction of underlying TMDs and GPDs.

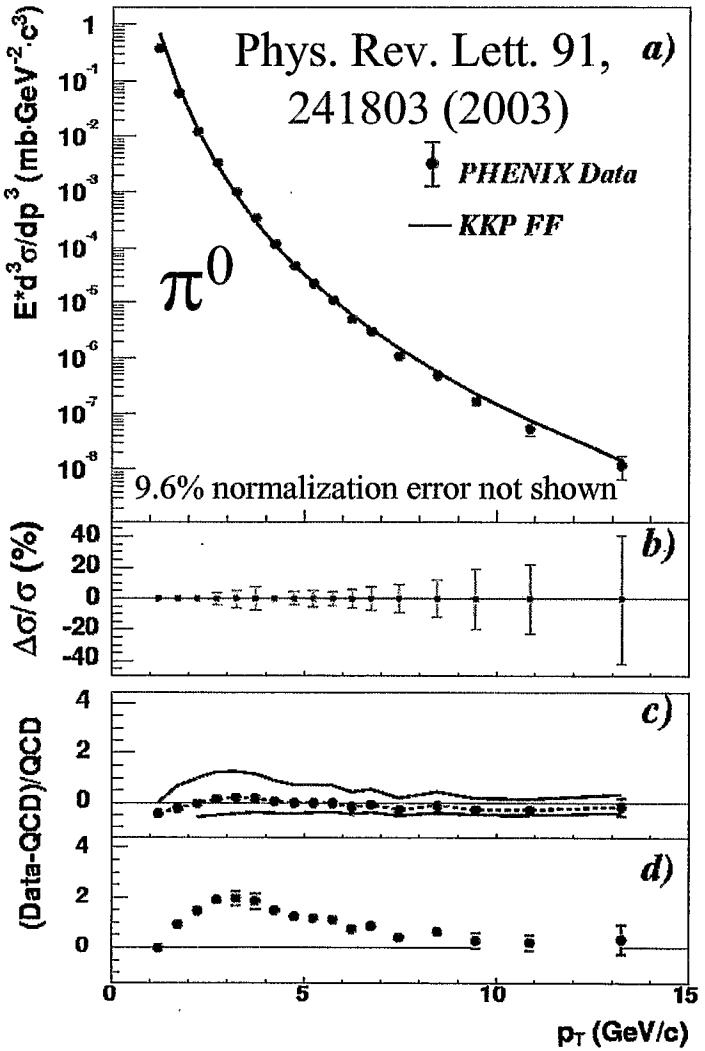
SSA's of Mid-rapidity Neutral Pions and Charged Hadrons at PHENIX

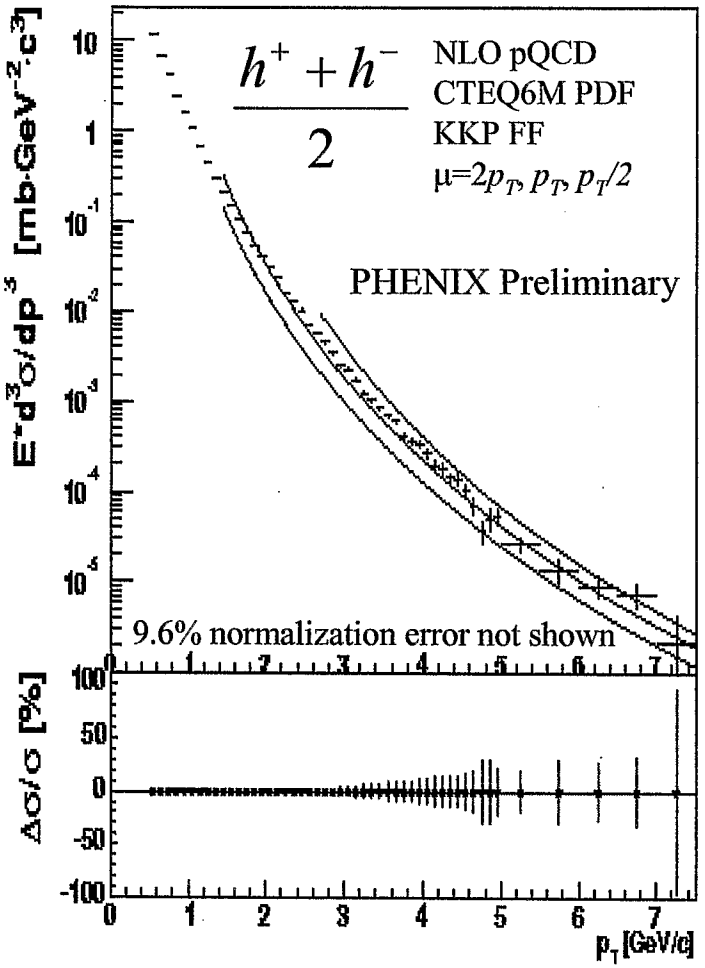
Christine Aidala, Columbia University

The transverse single-spin asymmetries, A_N, of neutral pions and charged hadrons have been measured at mid-rapidity up to a transverse momentum of 5 GeV/c. Results are consistent with zero within a few percent.

PHENIX

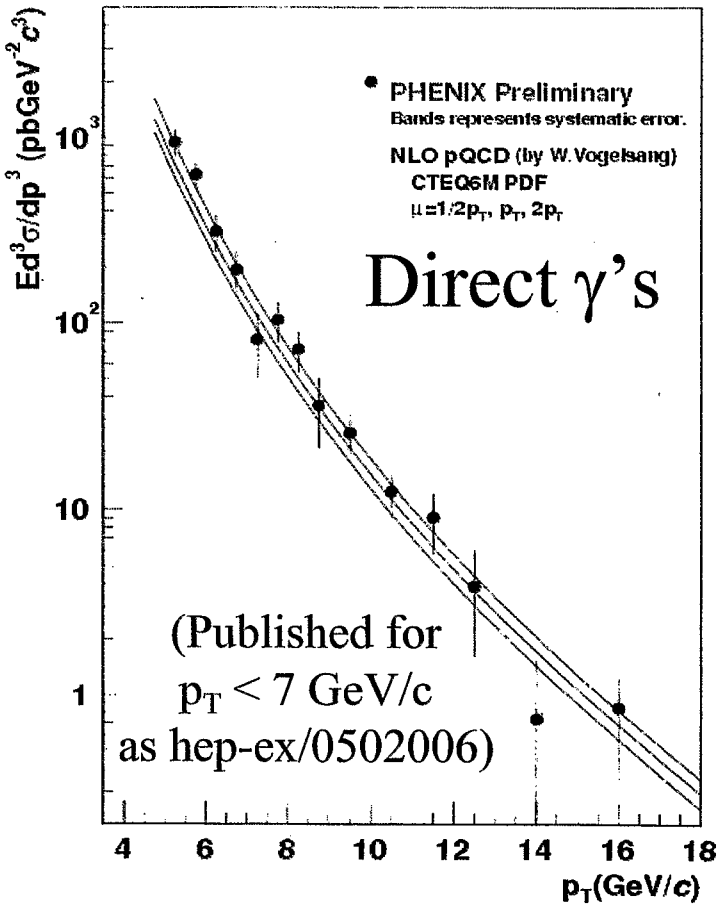
Cross Section Measurements





PHENIX

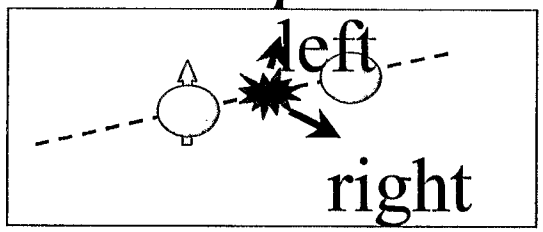
Cross Section Measurements (cont.)



- Cross sections have been measured by PHENIX for mid-rapidity π^0's, charged hadrons, and direct photons
- Good agreement with pQCD calculations for $p_T > \sim 2$ GeV/c
- Important confirmation of theoretical foundation of RHIC spin program
  - Will be able to use NLO pQCD to extract *polarized* pdf's

PHENIX

Why Measure A_N of Different Particle Species at Mid-rapidity in PHENIX?

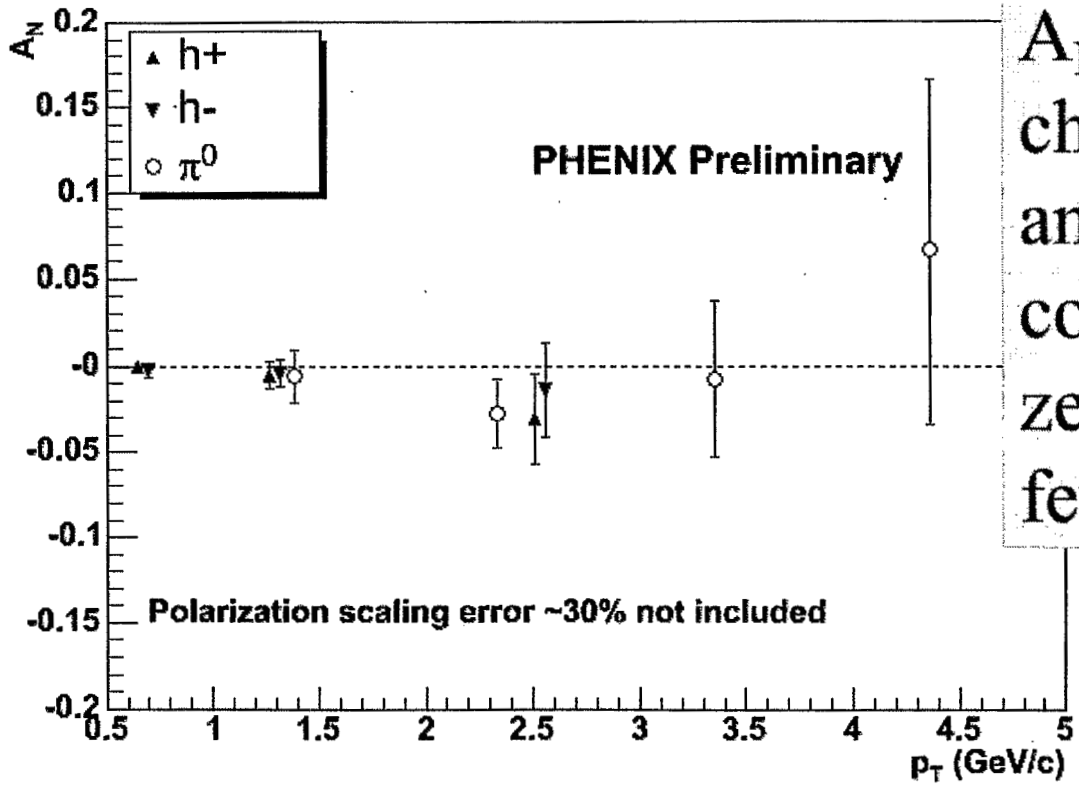


- Significant asymmetry observed by STAR for forward π^0's with x_{quark}
- Significant asymmetry observed at RHIC in forward neutron production (see M. Togawa's talk)
- A_N measurements presented here explore a different kinematic region: mid-rapidity, $x_{quark} \sim 0.1$
- Cross sections at 200 GeV described by pQCD

➢ Measuring A_N at RHIC for different particle species in different kinematic regions will help to separate contributions from transversity and Sivers
➢ PHENIX central arm spectrometers designed to measure a variety of particle species at mid-rapidity

PHENIX

A_N of Neutral Pions and Non-Identified Charged Hadrons: Results



A_N for both charged hadrons and neutral pions consistent with zero to within a few percent.

PHENIX

Summary

- A_N of neutral pions and charged hadrons measured for $0.5 < p_T < 5$ GeV/c and $|\eta| < 0.35$
- Asymmetries consistent with zero to within a few percent
- Results may provide information on gluon-Sivers
- Expect an improved measurement from data to be taken this month
  - High-statistics data will eventually allow measurement of A_N for a variety of other particle species at mid-rapidity
- Check the preprint server for final 2002 results in a couple weeks!

PHENIX

Single Spin Asymmetries in BRAHMS
F.Videbaek, BNL

The BRAHMS experiment at RHIC is primarily designed and operated to make measurements of semi-inclusive spectra of identified hadrons over a wide range in rapidity and pt. The PID coverage for pions up to 40 GeV/c and the possibility to measure at 2.3degrees (η~4) makes it well suited to study Single Spin Asymmetries for identified pions at moderate x_F.

The first data were obtained in the RHIC run-4 and shows a finite An for pi+ and pi- with sign ordering as observed previously in E704 at FNAL. Data from the ongoing RHIC run-5 will give an order of magnitude better statistics and should enable BRAHMS to make comparisons to several theoretical models.

The SSA are defined by $A_n = (\sigma^+ - \sigma^-) / (\sigma^+ + \sigma^-)$

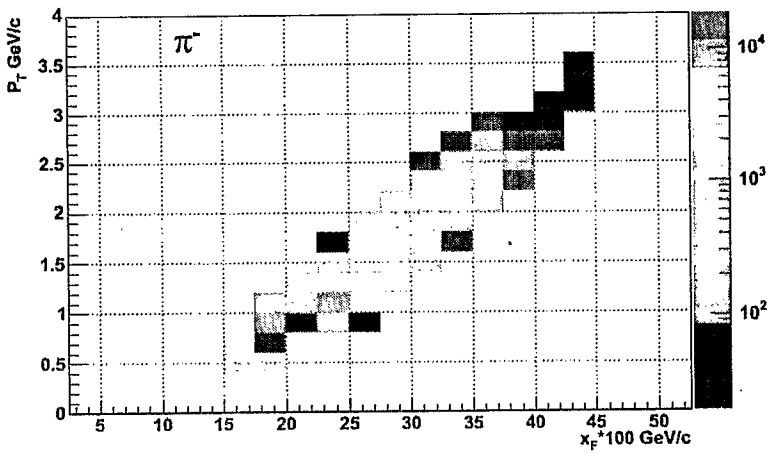
Where the spin cross section is determined with the spin direction defined by $k_b \times k_{pi}$

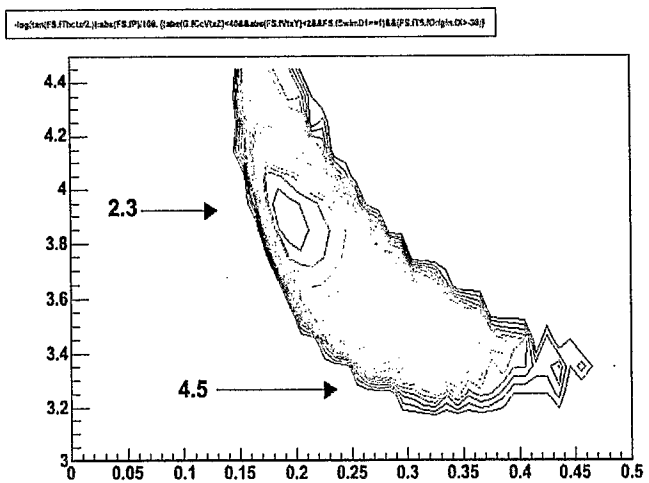
- Early (naive) QCD predicted this effect to be small.
- Non-zero Single Transverse Spin Asymmetry (SSA/ A_n) requires Spin Flip Amplitude and phase difference in intrinsic states.
- Such studies may clarify properties of transverse quark structure of the nucleon.
- Large An was observed in previous experiments

  D.L.Adams (E704) Phys.Lett B264,462(1991); Phys.ReV D53, 4747 (1996).

  Recent STAR results on π^0 also shows a significant SSA/ A_n at RHIC energies.
- The kinematic variables of interest are Feynman x (x_F) and p_T.
- Shown is the BRAHMS acceptance for the data taken at $\theta = 2.3$ deg and the maximum field setting (7.2 Tm).Note the correlation between x_F and p_T as characteristic for a fixed angle spectrometer.

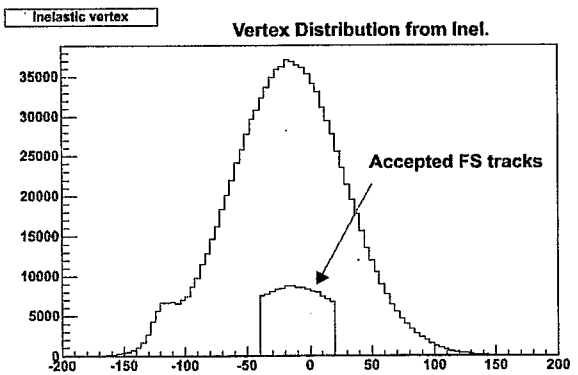
The momentum resolution is $\delta p/p \sim 1\%$ at 22 GeV/c.

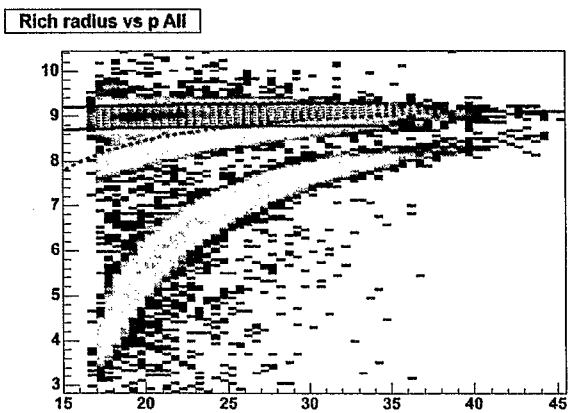




Event Selection Criteria

- Clean track through spectrometer and in time with the RHIC 108 nsec clock.
- Momentum determined from 3 measurements.
- -40< Z_Vertex <30 (Vertex from collision) determined from global detectors (INL, BB, ZDC)
- Track points to collision vertex (in Z and Y)
- Good Bunches Only (selected per store)
- Select pions using RICH for particle identification.
- Vertex Calculated from timing measurements in sets of counters INEL position on each side of IP covering roughly $2 < |\eta| < 5.2$.
- Z-resolution is ~ 10 cm in Run-4
- The spectrometer accepts track weighted towards negative Z
- Mass determined from momentum and Radius measured in a Ring Imaging Cherenkov Counter.
- The pion identification is clean up to 35 GeV.

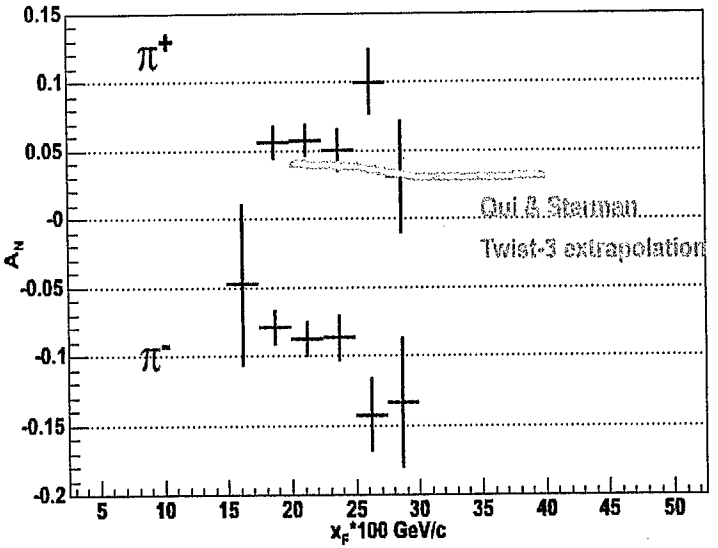




Data & Comparison

Polarization was ~42% for π^+ measurements and ~38% for π^-.

Systematic scale error on P ~ 20%. Will improve final final analysis of CNI and Gas Jet data.



Twist 3 (initial state) calculations by J.Qiu and G.Sterman, Phys.ReV.D59,014004(98)

Extrapolated to lower p_T

Conclusions

- BRAHMS has obtained the first preliminary result for single spin asymmetries for π^+ and π^- in 200 GeV pp collisions at RHIC in the x_F range of 0.17 to 0.32.
- The A_N value for π^+ and π^- are significantly different with opposite sign, and the $\pi^- < 0$ at ~ 3 sigma level and $\pi^+ > 0$ at ~ 1.5 sigma level
- The sign of A_n is consistent with behavior from lower energy.
- A_n at negative x_F for π^+ and π^- are consistent with 0 (as also found by STAR for π^0)
- The protons are found to have A_N ~0
- The ongoing Run-5 should enable BRAHMS to extend the measurements to x_F ~ 0.45 and to get some information on p_T-dependence at x_F~0.25
- The RICH operating mode can be changed to get K+ and K- out to about 40 GeV/c (x_F ~ 0.4)

Twist-3 Mechanism for Single Spin Asymmetries

YUJI KOIKE

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We study the single spin asymmetry (SSA) for the inclusive pion production in pp collision, $pp^\uparrow \to \pi X$ and SIDIS, $ep^\uparrow \to e\pi X$. SSA is a "naively T-odd" observable which appears as an interference effect between the amplitudes with different phases in the T-invariant theory. In the literature, there have been two systematic approaches to SSA. One is based on the so-called "T-odd" distribution/ fragmentation functions of quarks with intrinsic transverse momentum (k_T). The other is based on the twist-3 distribution/fragmentation functions in the framework of the collinear factorization. In this approach p_T of the final pion is generated from the partonic hard cross section and thus is suited for the describtion of SSA for the large-p_T pion production.

In this talk we present the analysis following the second approach. Given that unpolarized $pp \to \pi X$ can be well described by the NLO QCD for p_T as low as 1 GeV at RHIC energy, our LO twist-3 analysis for the above processes provides a useful reference to interpret the RHIC data and also for the future EIC experiment.

For $p + p^\uparrow \to \pi + X$, we have three contributions:

$$\text{(A)} \quad G_F(x_1, x_2) \otimes q(x') \otimes \hat{q}(z) \otimes \sigma_A,$$

$$\text{(B)} \quad \delta q(x) \otimes q(x') \otimes \hat{E}_F(z_1, z_2) \otimes \sigma_B,$$

$$\text{(C)} \quad \delta q(x) \otimes E_F(x'_1, x'_2) \otimes \hat{q}(z) \otimes \sigma_C,$$

and for $e + p^\uparrow \to e + \pi(p_T) + X$ we have two contributions:

$$\text{(A}'\text{)} \quad G_F(x_1, x_2) \otimes \hat{q}(z) \otimes \sigma'_A,$$

$$\text{(B}'\text{)} \quad \delta q(x) \otimes \hat{E}_F(z_1, z_2) \otimes \sigma'_B,$$

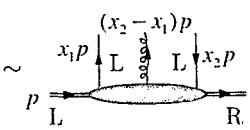
where $\delta q(x)$ is the transversity distribution. In SIDIS, (A′) and (B′) appear as an $O(\alpha_s)$ effect, while well-known Sivers and Collins effects appear at $O(\alpha_s^0)$. In this talk, I first presented the relevant twist-3 distribution and fragmentation functions and discussed the relations among different representations for those functions. Then I reviewd my analysis of A_N in pp collision: (A) and (B) can be equally important sources for A_N, while (C) is negligible. By fixing G_F and $\hat{E}_F$ so that each of (A) and (B) reproduce A_N at RHIC-STAR, we studied their effects on the SSA in $e + p^\uparrow \to e + \pi(p_T) + X$. We showed that the polarized cross section has additional components in the azimuthal-angle dependence which are absent in the LO Sivers and Collins effects. We also argued that the magnitude of SSA from (A′) is much larger than that from (B′) even if G_F and $\hat{E}_F$ are determined to reproduce independently A_N in pp collisions.

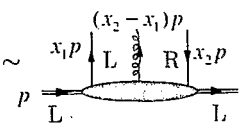
- Twist-3 distribtions: $\qquad p^2 = n^2 = 0,\ p\cdot n = 1$

$$\int \frac{d\lambda}{2\pi}\int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2-x_1)} \langle PS|\bar{\psi}_j(0) g F^{\alpha\beta}(\mu n) n_\beta \psi_i(\lambda n)|PS\rangle$$
$$= \frac{M_N}{4}(\not{p})_{ij}\, \epsilon^{\alpha p n S_\perp} G_F(x_1,x_2) + i\frac{M_N}{4}(\gamma_5 \not{p})_{ij}\, S_\perp^\alpha G_F^5(x_1,x_2) +$$
$$+ \frac{M_N}{4}(\gamma_5 \not{p}\gamma_\nu)_{ij}\, \epsilon^{\nu\alpha n p} E_F(x_1,x_2) + \cdots$$

Unpol. $\qquad$ $\perp$-pol.

M_N: chiral symmetry breaking scale.

$G_F^{(5)}(x_1,x_2) \sim$ 

$E_F(x_1,x_2) \sim$ 

* By parity and T-inv., G_F and E_F are symmetric under $x_1 \longleftrightarrow x_2$, while G_F^5 is anti-symmetric.

* $gF^{\alpha\beta}n_\beta \to D^\alpha = \partial^\alpha - igA^\alpha$ defines another set of twist-3 distributions: $G_D(x_1,x_2)$, $G_D^5(x_1,x_2)$, $E_D(x_1,x_2)$ etc.

- Relation between D-type and F-type distributions.

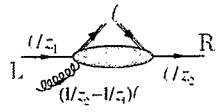
$$G_D(x_1,x_2) = P\frac{1}{x_1-x_2}G_F(x_1,x_2),$$
$$E_D(x_1,x_2) = P\frac{1}{x_1-x_2}E_F(x_1,x_2),$$
$$G_D^5(x_1,x_2) = \delta(x_1-x_2)g_5(x_1) + P\frac{1}{x_1-x_2}G_F^5(x_1,x_2)$$
$$g_5(x) = \int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS|\bar{\psi}(0)\gamma_5\not{n}S_\perp\cdot D(\lambda n)\psi(\lambda n)|PS\rangle$$
$$+ \frac{1}{2}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS|\bar{\psi}(0)\gamma_5\not{n}\int_\lambda^\infty d\mu\, igF^{S_\perp n}(\mu n)\psi(\lambda n)|PS\rangle$$
$$- \frac{1}{2}\int\frac{d\lambda}{2\pi}e^{i\lambda x}\langle PS|\bar{\psi}(0)\gamma_5\not{n}\int_{-\infty}^\lambda d\mu\, igF^{S_\perp n}(\mu n)\psi(\lambda n)|PS\rangle.$$

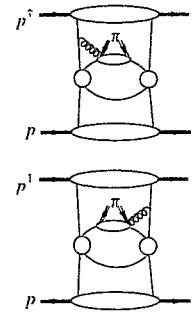
We assume there is no singularity in F-type functions at $x_1 = x_2$.

- Twist-3 fragmentation function $\qquad \ell^2 = w^2 = 0,\ \ell \cdot w = 1$

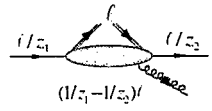
$$\frac{1}{N_c}\sum_X \int \frac{d\lambda}{2\pi}\int \frac{d\mu}{2\pi} e^{-i\frac{\lambda}{z_1}} e^{-i\mu(\frac{1}{z_2}-\frac{1}{z_1})} \langle 0|\psi_j(0)|\pi(\ell)X\rangle\langle\pi(\ell)X|gF^{\alpha,j}(\mu n)w_\lambda\bar{\psi}_j(\lambda n)|0\rangle$$

$$= \frac{M_N}{2z_2}(\gamma_5 \not{\ell}\not{\gamma}_w)_{ij}\,\epsilon^{\nu\alpha w\ell}\,\widehat{E}_F(z_1, z_2) + \cdots$$

$\widehat{E}_F(z_1, z_2) \sim$ 



M_N: Scale for the chiral symmetry breaking.

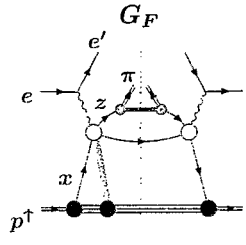
* We also have $\widehat{E}_{FR}(z_1, z_2) \sim$ 

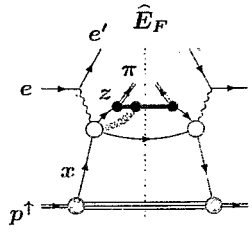
* From hermiticity, $\widehat{E}_F(z_1, z_2) = \widehat{E}^*_{FR}(z_2, z_1)$, but no constraint from T-invariance.
* $gF^{\alpha,j}n_\lambda \to D^\alpha$ defines another set of twist-3 fragmentation functions; $E_D(x_1, x_2)$ etc.

- **SSA for $e + p^\uparrow \to e' + \pi(p_T) + X$**

(H. Eguchi and YK in preparation.)

$$d\sigma^N \sim G_F(x_1, x_2) \otimes \hat{q}(z) \otimes \hat{\sigma}_A + \delta q(x) \otimes \widehat{E}_F(z_1, z_2) \otimes \hat{\sigma}_B$$



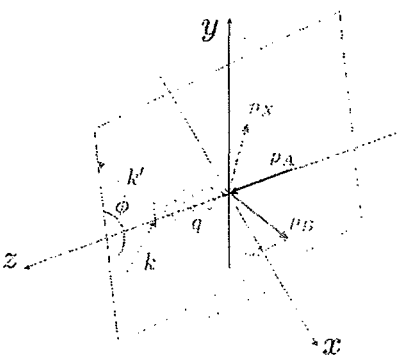


Question:
How does SSA for $ep^\uparrow \to e\pi X$ behave if one determine G_F and $\widehat{E}_F$ to reproduce A_N for $p^\uparrow p \to \pi X$?

N.B. Our formalism is suited for large-p_T production at EIC energy.

- Hadron frame for $e(k)+p^{\uparrow}(p_A,S_A)\rightarrow e(k')+\pi(p_B)+X$

(Meng, Olness, Soper('91)) photon-proton Breit frame



$q=k-k'=(0,0,0,-Q)$

$p_A=(\frac{Q}{2x_{bj}},0,0,\frac{Q}{2x_{bj}})$

$p_B=\frac{z_f}{2}(1+\frac{q_T^2}{Q^2},\frac{2q_T}{Q},0,\frac{q_T^2}{Q^2}-1)$

$p_T=z_f q_T$: $\perp$ mom. of hadron B

$k=\frac{Q}{2}(\cosh\psi,\sinh\psi\cos\phi,\sinh\psi\sin\phi,-1)$

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

ϕ: Azymuthal angle between lepton and hadron plane

Φ_A: Azimuthal angle of S_A measured from hadron plane.

Azimuth. dep. of SSA for $ep^{\uparrow}\rightarrow e\pi X$

- G_F contribution

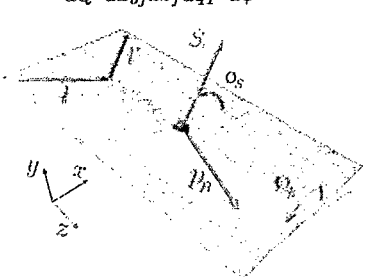
$$\frac{d^5\sigma^N}{dQ^2dx_{bj}dz_fdq_T{}^2d\phi}=\sin\Phi_A(\sigma_0^N+\sigma_1^N\cos(\phi)+\sigma_2^N\cos(2\phi))$$

Same as Sivers effect: $\Phi_A=\phi_h-\phi_S$, $\phi=\phi_h$

- $\widehat{E}_F$ contribution

$$\frac{d^5\sigma'^N}{dQ^2dx_{bj}dz_fdq_T{}^2d\phi}=\sigma'^N_0\sin\Phi_A+\sigma'^N_1\sin(\Phi_A-\phi)+\sigma'^N_2\sin(\Phi_A-2\phi)$$

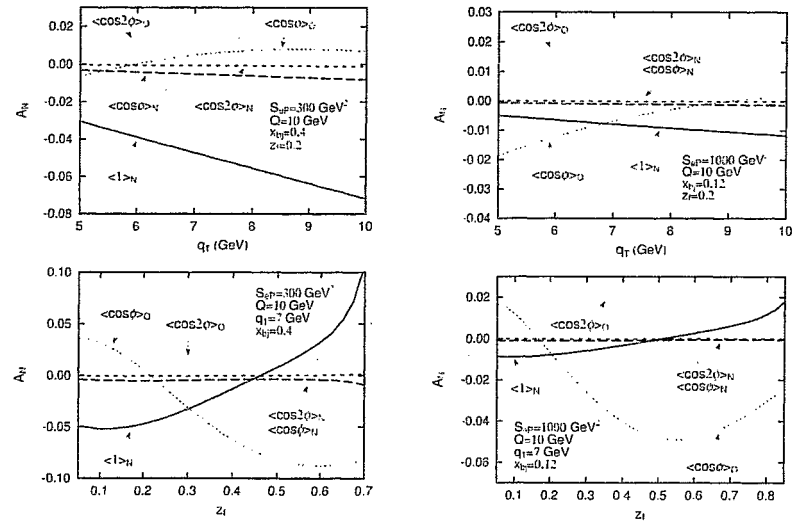
Same as Collins effect.



- Unpol. cross section

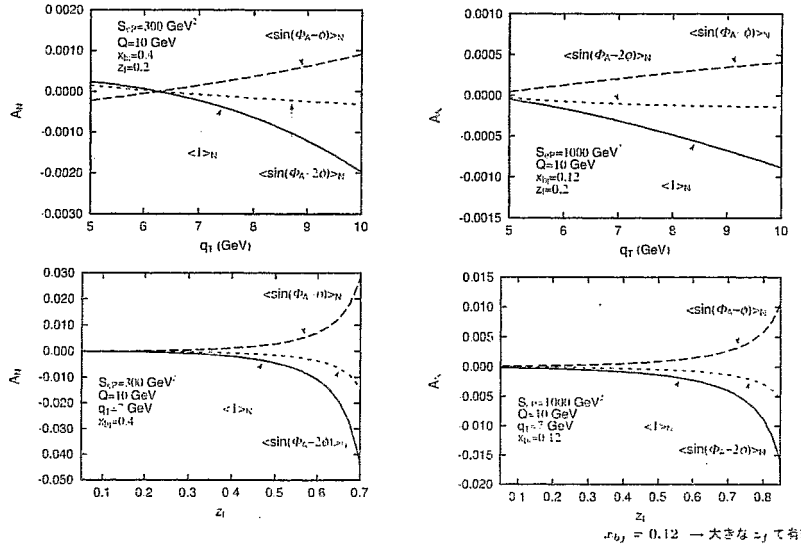
$$\frac{d^5\sigma^O}{dQ^2dx_{bj}dz_fdq_T{}^2d\phi}=\sigma_0^O+\sigma_1^O\cos(\phi)+\sigma_2^O\cos(2\phi)$$

SSA for $ep^{\uparrow} \to e'\pi^0 X$ from G_F.



$x_{bj} = 0.12$ → 大きな z_f で有効

SSA for $ep^{\uparrow} \to e'\pi^0 X$ from $\widehat{E}_F$.



$x_{bj} = 0.12$ → 大きな z_f で有効

Cahracteristics of $ep^{\uparrow} \to e\pi X$

- **Contribution from G_F**
  - $\langle 1 \rangle_N \simeq O(5\%)$ at $x_{bj} \simeq 0.4$.
  - $\langle \cos n\phi \rangle_N (n = 1, 2) < 1\%$.
- **Contribution from $\widehat{E}_F$**
  - $\langle \sin(\Phi_A - 2\phi) \rangle_N < \langle \sin(\Phi_A - \phi) \rangle_N < \langle 1 \rangle_N$
  - Smaller than 1 % at $z_f < 0.5$.
- **Divergence at $z_f \to 1$ is due to our model.**
- **Complete calculation with non-derivative terms is ongoing.**

⋆ Summary

- Derivative of SGP $\frac{d}{dx} G_F(x, x)$ could explain naturally the rising behavior of A_N of $p^{\uparrow} p \to \pi X$ at large x_F.
- Re $\left[\frac{\partial}{\partial z_1} \widehat{E}_F(z_1, z) \right]_{z_1 = z}$ could also be parametrized to explain A_N in $p^{\uparrow} p \to \pi X$.
- Twist-3 $O(\alpha_s)$ contribution to $ep^{\uparrow} \to e\pi X$ gives rise to additional azimuth. dep. components in SSA different from LO Sivers and Collins asymmetries.
- If one determines G_F and $\widehat{E}_F$ to parametrize A_N in $p^{\uparrow} p \to \pi X$, $\widehat{E}_F$ gives rise to much smaller SSA in $ep^{\uparrow} \to e\pi X$ than G_F, due to the smallness of the corresponding hard cross section.
- Complete calculation with SFP and nonderivative SGP is ongoing for $p^{\uparrow} p \to \pi X$ and $ep^{\uparrow} \to e\pi X$.

SSA and parton intrinsic motion

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We consider a general formalism to compute inclusive polarized and unpolarized cross sections within pQCD and the factorization scheme, taking into account parton intrinsic motion in distribution and fragmentation functions, as well as in the elementary dynamics.

We focus mainly on SSA in $pp \to hX$ processes where different mechanisms may be at work at the same time and discuss, by considering different kinematical configurations, the role of the correct azimuthal angular dependences in the partonic subprocesses.

In particular from a detailed numerical analysis of $pp \to \pi X$ we show that

1) a good description of E704 A_N data at $\sqrt{s} = 20$ GeV for neutral and charged pions can be obtained by a suitable parameterization of the valence quark Sivers functions. Former results on the Sivers effect therefore are essentially confirmed. Predictions and comparisons to high-energy data (BRAHMS, PHENIX and STAR at RHIC) as well as for intermediate-energy experiments (PAX at GSI) are given.

2) the intrinsic partonic motion produces a strong suppression of the transverse single spin asymmetry arising from the Collins mechanism. As a consequence, and in contradiction with earlier claims, the Collins mechanism is unable to explain the large asymmetries found in $p^\uparrow p \to \pi X$ at moderate to large Feynman x_F.

3) all other mechanisms give a negligible contribution to A_N.

An equally interesting and potential source of information on TMD PDF is the study of SSA in hadronic processes in the negative x_F region. A case of study for E704 kinematics extrapolated to the $x_F < 0$ region shows how, even if partially suppressed, only the Sivers mechanism from sea quarks and gluons can play a role. The last ones, in particular, giving values up to 10% for A_N. On the other hand analogous estimates for the backward pion production at STAR, $\eta = -4.1$, give much smaller values, reaching at most 2%, and prevent a clear constraint on the gluon Sivers function. Indeed, the recent STAR data for A_N at $x_F < 0$ can be well described by the quark Sivers functions as extracted from E704 data.

At moderate energies (PAX, $\sqrt{s} = 14$ GeV) the study of the $p^\uparrow \bar{p} \to \pi X$ process at fixed p_T could be a complementary tool: in this case a sizeable A_N in the negative x_F region would be a clear evidence of a non zero gluon Sivers function. The main differences between STAR and PAX configurations can be understood in terms of the role played by the partonic azimuthal phases in the extreme backward direction (STAR) with respect to the not so large scattering angle that can be explored at PAX (at $p_T \simeq 1 - 2$ GeV/c).

Preliminary data for $A_N(pp \to \pi X)$ at $\sqrt{s} = 200$ GeV and $x_F \simeq 0$ for $1 < p_T < 5$ GeV (PHENIX) are compatible with zero and can be described in terms of valence-like Sivers functions. It is worth to notice that due to the small values of x_{Bj} covered at these energies, the dominant partonic channel are $gg \to q\bar{q}$ and $gq \to gq$. This could give a clear constraint on the gluon Sivers function since all other mechanisms give a vanishing contribution to A_N.

As an alternative tool to extract the gluon Sivers function we consider the study of A_N in $pp \to DX$ at RHIC energies. D production at intermediate rapidity values is dominated by the elementary $gg \to c\bar{c}$ channel; contributions from $q\bar{q} \to c\bar{c}$ s-channel become important only at very large values of x_F. In both processes there is no sizeable single spin transfer, so that the final c or $\bar{c}$ quarks are not polarized. Therefore, any transverse single spin asymmetry observed for D's produced in $p^\uparrow p$ interactions cannot originate from the Collins fragmentation mechanism, but only from the Sivers effect in the distribution functions. In particular, any sizeable spin asymmetry measured in $p^\uparrow p \to D\,X$ at mid-rapidity values will be a direct indication of a non zero gluon Sivers distribution function. On the other hand, the same study at lower energies (PAX) offers a clear opportunity to gain information on the quark Sivers PDF. In this case, the large values of x_{Bj} explored select the partonic subprocess is $q\bar{q} \to c\bar{c}$. Preliminary estimates are given.

Finally we discuss how a detailed analysis of SSA in Drell-Yan processes, by suitably integrating out the angular dependence of the lepton pair, can give a direct access to the Sivers effect. In this case the competing effect to A_N coming from the Boer-Mulders mechanism ($h_1^\perp$), which enters with the double spin partonic asymmetry, is integrated to zero and only the Sivers effect can be active. This, together with the extraction of the Sivers function from the azimuthal asymmetries observed in Semi-Inclusive DIS could allow a clear test of the universality of TMD PDF.

This analysis is based on a series of papers in collaboration with M. Anselmino, M. Boglione, E. Leader, S. Melis and F. Murgia.

Polarized cross sections: Helicity formalism

◇ **Helicity density matrices** within a $\boldsymbol{k}_\perp$-factorization scheme to describe parton spin states for a polarized cross section:

$$d\sigma^{A,S_A+B,S_B\to C+X} = \sum_{a,b,c,d,\{\lambda\}} \rho^{a/A,S_A}_{\lambda_a,\lambda'_a}\, \hat{f}_{a/A,S_A}(x_a,\boldsymbol{k}_{\perp a}) \otimes \rho^{b/B,S_B}_{\lambda_b,\lambda'_b}\, \hat{f}_{b/B,S_B}(x_b,\boldsymbol{k}_{\perp b})$$

$$\otimes\ \hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}\, \hat{M}^*_{\lambda'_c,\lambda_d;\lambda'_a,\lambda'_b} \otimes \hat{D}^{\lambda_C,\lambda_C}_{\lambda_c,\lambda'_c}(z,\boldsymbol{k}_{\perp C})$$

- $\rho^{a/A,S_A}_{\lambda_a,\lambda'_a}$: helicity density matrix of parton a inside hadron A with spin S_A
- $\frac{d\hat{\sigma}^{ab\to cd}}{d\hat{t}} \simeq \sum_{\lambda_a,\lambda_b,\lambda_c,\lambda_d} |\hat{M}_{\lambda_c,\lambda_d;\lambda_a,\lambda_b}|^2$ (scattering amplitudes)
- $\hat{D}^{\lambda_C,\lambda'_C}_{\lambda_c,\lambda'_c} \equiv \sum\!\!\!\!\!\!\int_{X,\lambda_X} \hat{\mathcal{D}}_{\lambda_C,\lambda_X;\lambda_c}\, \hat{\mathcal{D}}^*_{\lambda'_C,\lambda_X;\lambda'_c}$

  i.e. the product of *fragmentation amplitudes* for $c \to C + X$

by including proper phases + numerical (8-dim., VEGAS) integration:

$$d\sigma^{\rm unp} \simeq f_{a/p} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c}$$

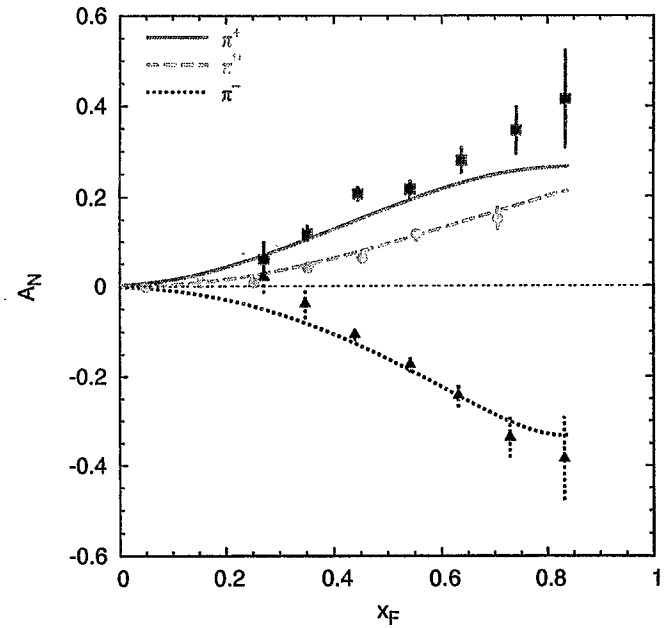
$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \simeq \Delta^N f_{a/p^\uparrow} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \qquad \text{“Sivers effect”}$$
$$+ \; h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^\uparrow} \qquad \text{“Collins effect”}$$

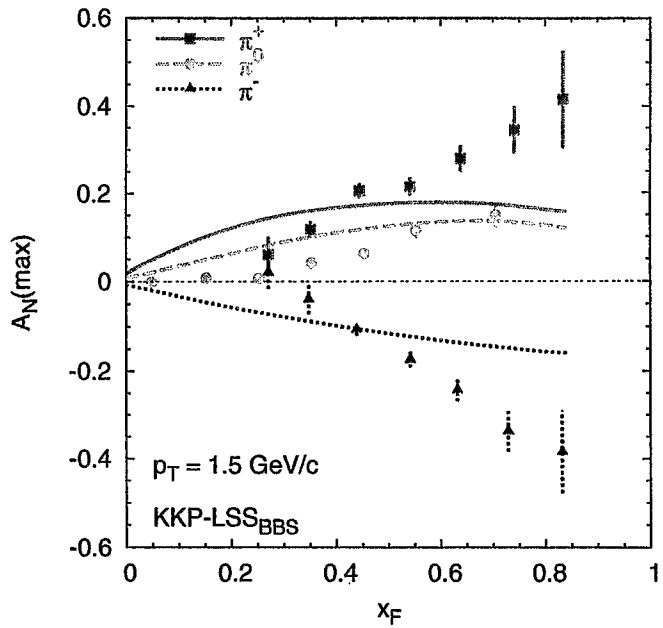
Notice: the explicit phases entering the convolutions are

$$\Delta^N f_{a/p^\uparrow} \otimes f_{b/p} \otimes d\hat{\sigma} \otimes D_{\pi/c} \to \sin(\phi_{S_A} - \phi_a) \equiv \cos\phi_a$$

$$h_{1a} \otimes f_{b/p} \otimes d\Delta\hat{\sigma} \otimes \Delta^N D_{\pi/c^\uparrow} \to \sin[\phi_{S_A} - (\phi_a + \phi_c'' - \xi_a - \tilde{\xi}_a + \xi_c + \tilde{\xi}_c + \phi_\pi^H)]$$

M. Anselmino, M. Boglione, U.D., E. Leader, F. Murgia PRD71 (05)





A_N at $E = 200$ GeV vs. x_F at $p_T = 1.5$ GeV/c. Data are from [E704] PLB261-264 (1991).

Sivers effect [left] (valence-like).

Collins effect [right](full saturated).

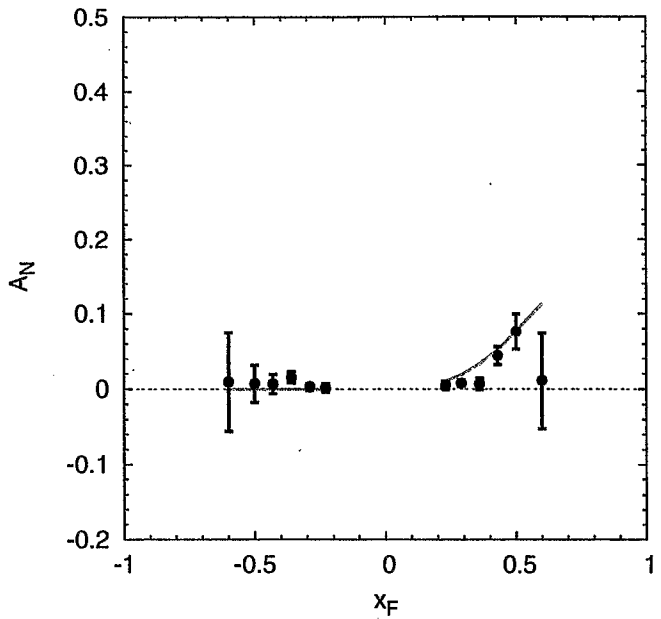
$N_u = +0.40 \; a_u = 2.0 \; b_u = 0.3$

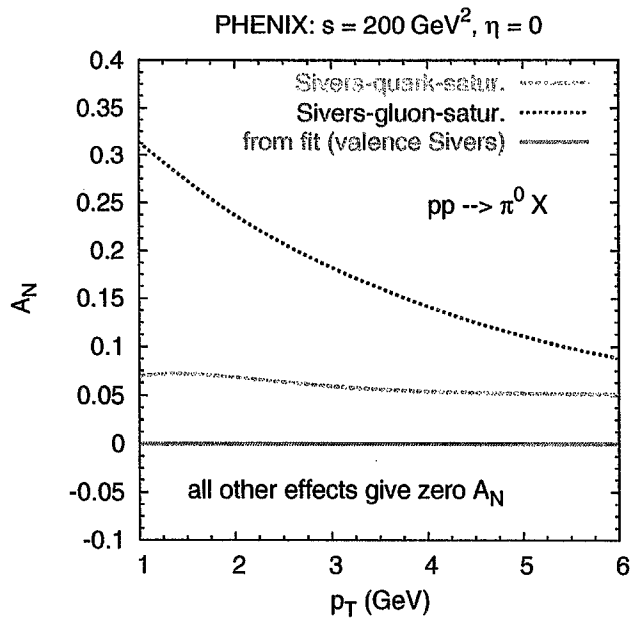
$N_d = -0.90 \; a_d = 2.0 \; b_d = 0.2$

$\simeq$ CONSISTENCY with SIDIS

Transversity funct. and

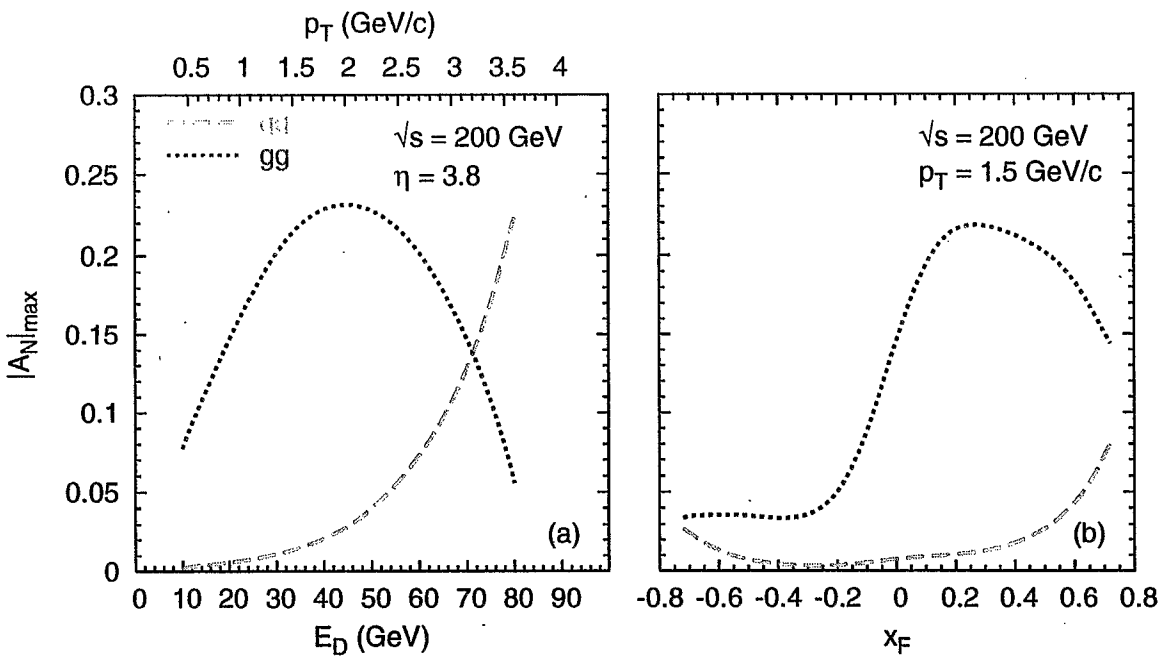
Collins funct. full saturated





Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone [U.D. and F. Murgia PRD70 (05)] at $\sqrt{s}$ = 200 GeV and $\eta = 3.8$ vs. x_F Data are from [STAR] PRL92 (04).

Predictions of $A_N(pp \to \pi^0 X)$ in terms of Sivers effect alone at $\sqrt{s}$ = 200 GeV and $\eta = 0$ vs. p_T [PHENIX kinematics]. Consistent with preliminary data.
Maximized effects are also shown.
Collins effect suppressed!



Estimates for $A_N(pp \to DX)$ in terms of Sivers effect, $x-$ saturated from quarks or gluons at $\sqrt{s}$ = 200 GeV vs. x_F at fixed $\eta = 3.8$ (left) and at fixed p_T = 1.5 GeV/c (right). FF set: Cacciari *et al.* PRD55 (1997).

Sudakov suppression of asymmetries involving TMDs

Daniël Boer

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In processes such as Drell-Yan one can probe the transverse momentum $\boldsymbol{q}_T$ of the lepton pair w.r.t. the two colliding hadrons. Depending on the magnitude Q_T of this transverse momentum, different factorization theorems apply. When Q_T is of the order of the invariant mass Q of the lepton pair, collinear factorization applies. In the limit of small Q_T in this formula, large logarithms arise that need to be resummed. This results in the factorization formula referred to as the Collins-Soper-Sterman (CSS) formalism [1]. It involves collinear parton densities and applies to the situation that $Q_T^2 \ll Q^2$. If Q_T is so small that it is a nonperturbative scale (of the order of Λ_{QCD}, then a nonperturbative Sudakov factor needs to be introduced. Such a factor has been fitted [2] from data on $pp/\bar{p} \to V\,X$ that includes both the low energy data (Drell-Yan scattering where $V = \gamma^*$) and high energy Tevatron data ($V = Z$). A crucial observation is that such a nonperturbative Sudakov factor is necessary to describe the data and moreover, it is Q dependent (!).

When one considers the cross section as a function of the *direction* of $\boldsymbol{q}_T$ as well, then angular asymmetries appear. At large Q_T the fixed order perturbative result in collinear factorization is still appropriate, but at small Q_T another factorization applies (despite the fact that the small Q_T limit of the fixed order large Q_T result is not singular for these angular asymmetries), here referred to as the Collins-Soper '81 (CS-81) formalism [3] (see also Ref. [4] for a closely related study for SIDIS and DY). It involves parton densities, TMDs, that have transverse momentum dependence. In this talk I discuss the consequences of this type of factorization on azimuthal asymmetries in leading logarithmic approximation. I focus especially on the effect of the Sudakov factors on the Q^2 dependence of the Q_T dependence, which is discussed for several examples. To be specific, for an asymmetry involving a product of two k_T-odd TMDs (the $\cos 2\phi$ asymmetry in Drell-Yan, the data of which cannot be explained by NLO pQCD in collinear factorization) and one involving only one k_T-odd TMD (the Collins asymmetry in SIDIS, but the analysis applies equally to the Sivers asymmetry). The first type of asymmetry was found to be approximately power suppressed as $1/Q$ and the second type as $1/\sqrt{Q}$ [5].

At larger Q_T the small Q_T result from the CS-81 formalism should be matched to the large Q_T fixed order result, which for the $\cos 2\phi$ behaves as Q_T^2/Q^2, whereas for the Collins and Sivers asymmetries it is $1/Q_T$ suppressed (cf. forthcoming work by Ji, Ma, Yuan and Eguchi, Koike). Stated differently, at low Q_T the nontrivial (quark or hadron) spin dependent TMDs leads to azimuthal asymmetries that do not occur at leading twist in collinear factorization. If one includes only the spin independent TMD, then the CS-81 factorization theorem generates the CSS factorization at higher Q_T, upon expansion of the TMD in $1/k_T^2$. If one includes the spin-dependent TMDs, such an expansion is not possible, since it will become proportional to next-to-leading twist, collinear distributions. As explained in the talk, particular transverse momentum weighted moments of the asymmetries can be defined that are insensitive to Sudakov factors and suppression, but the large Q_T tails may dominate these moments if not cut-off or subtracted.

[1] Collins, Soper & Sterman, NPB 250 ('85) 199
[2] Landry, Brock, Nadolsky, Yuan, PRD 67 ('03) 073016
[3] Collins & Soper, NPB 193 ('81) 381
[4] Ji, Ma, Yuan, PRD 71 ('05) 034005 & PLB 597 ('04) 299
[5] Boer, NPB 603 ('01) 195

Numerical study of Sudakov suppression

$$\frac{d\sigma}{dQ^2 dy d^2\boldsymbol{q}_T d\Omega} = \int d^2b\, e^{-i\boldsymbol{b}\cdot\boldsymbol{q}_T}\tilde{W}(\boldsymbol{b}, Q; x_A, x_B) + Y(\boldsymbol{q}_T, Q; x_A, x_B)$$

with $\tilde{f} \to \tilde{\Phi}$

$$\begin{aligned}\tilde{W}(\boldsymbol{b}, Q; x_A, x_B) &= \sum_a \tilde{\Phi}_{a/A}(x_A, \boldsymbol{b}; 1/b, \alpha_s(1/b)) \sum_b \tilde{\Phi}_{b/B}(x_B, \boldsymbol{b}; 1/b, \alpha_s(1/b)) \\ &\quad \times e^{-S(b,Q)}\, H_{ab}\,(x_A, x_B, Q; \alpha_s(Q))\; \tilde{U}(\boldsymbol{b}; 1/b, \alpha_s(1/b))\end{aligned}$$

Scale choice is such that b dependence of soft factor $\tilde{U}$ appears only at NLLA

$$\tilde{\Phi}(x, \boldsymbol{b}) = \frac{M}{2}\left\{\tilde{f}_1(x, \boldsymbol{b}^2)\frac{\not{P}}{M} + \left(\frac{\partial}{\partial b^2}\tilde{h}_1^{\perp}(x, \boldsymbol{b}^2)\right)\frac{2\not{b}\not{P}}{M^2}\right\}$$

Furthermore, assume Gaussian k_T dependence for f_1 (with Gaussian width R_u^2) and $h_1^{\perp}$ (with Gaussian width $R^2 > R_u^2$)

Example 1: $\cos 2\phi$ in DY

$$\frac{d\sigma}{dQ^2 dy d^2\boldsymbol{q}_T d\Omega} \propto \left\{1 + \ldots + \frac{\nu(Q_T)}{2}\sin^2\theta\,\cos 2\phi\right\}$$

The asymmetry arising at large Q_T (associated to the Y term) to first order in α_s is

$$\nu_Y(Q_T) = \frac{Q_T^2}{Q^2 + 3Q_T^2/2}$$

The tree level expression at small Q_T due to $h_1^\perp$ is

$$\nu^{(0)}(Q_T) = \frac{h_1^\perp(x_1)\,\overline{h}_1^\perp(x_2)}{f_1(x_1)\,\overline{f}_1(x_2)}\,\frac{Q_T^2 R^2}{2M^2 R_u^2}\exp\left(-\left[R^2 - R_u^2\right]\frac{Q_T^2}{2}\right)$$

Including Sudakov factors:

$$\nu(Q_T) = \frac{h_1^\perp(x_1)\,\overline{h}_1^\perp(x_2)}{f_1(x_1)\,\overline{f}_1(x_2)}\,\frac{\mathcal{A}(Q_T)}{2M^4 R^4}$$

Numerical estimates

$$\nu(Q_T) = \frac{h_1^\perp(x_1)\,\overline{h}_1^\perp(x_2)}{f_1(x_1)\,\overline{f}_1(x_2)}\,\frac{\mathcal{A}(Q_T)}{2M^4R^4}$$

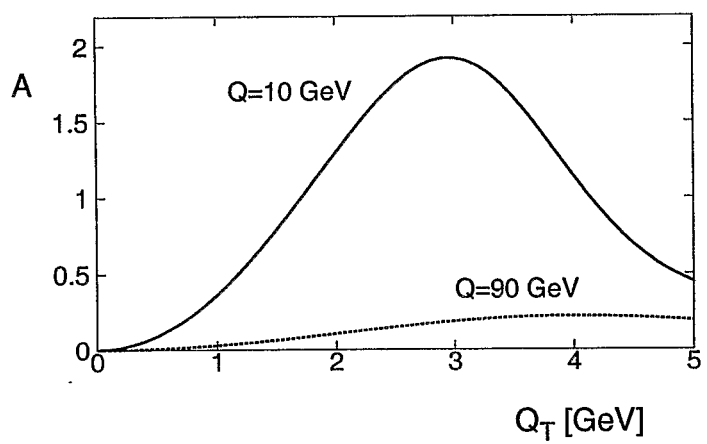
$$\mathcal{A}(Q_T) \equiv M^2\,\frac{\int_0^\infty db\,b^3\,J_2(bQ_T)\,\exp\left(-S(b_*)-S_{NP}(b)\right)}{\int_0^\infty db\,b\,J_0(bQ_T)\,\exp\left(-S(b_*)-S_{NP}^u(b)\right)}$$

Using a generic S_{NP}^u

Ladinsky & Yuan, PRD 50 ('94) R4239

Results in a considerable Sudakov suppression with increasing Q: $\sim 1/Q$

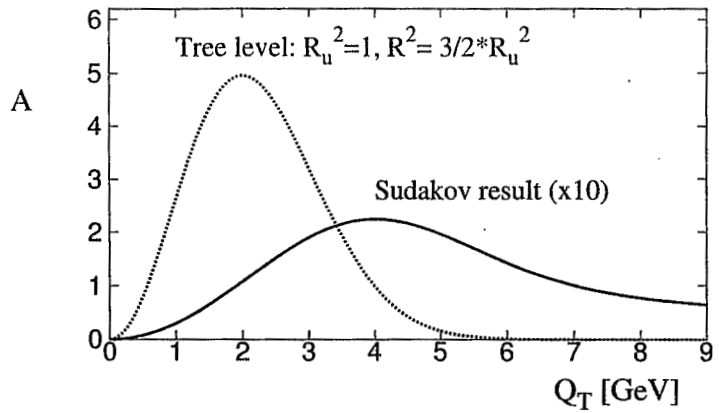
D.B., NPB 603 ('01) 195



Numerical estimates

Comparison of tree level and Sudakov results at $Q = 90$ GeV

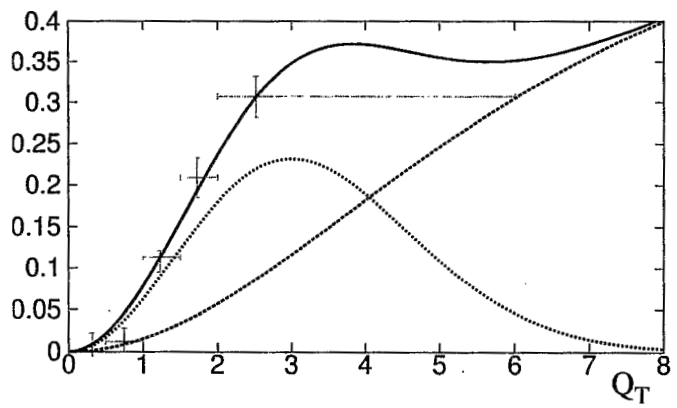
Latter is much smaller and broader



Data for $\pi^- N \to \mu^+\mu^- X$, with $N = D, W$, from NA10 Collab. ('86/'88) & E615 Collab. ('89) with π^--beams of 140-286 GeV and lepton pair invariant mass $Q \sim 4 - 12$ GeV

Impression of small and large Q_T contributions (at $Q = 8$ GeV) compared to DY data of NA10 ('88)

$h_1^\perp$ can be used to describe the data
D.B., PRD 60 ('99) 014012



Transverse moments

If one doesn't want to assume Gaussians, then one can consider taking Q_T moments

This leads to expressions involving $h_1^{\perp(1)}$

$$h_1^{\perp(1)}(x) \equiv \int d^2\boldsymbol{k}_T \frac{\boldsymbol{k}_T^2}{2M^2} h_1^{\perp}(x, \boldsymbol{k}_T^2)$$

It turns out that in the particular case of the $\cos 2\phi$ asymmetry

$$\int dQ_T^2 \, Q_T^2 \frac{d\sigma}{dQ_T^2}$$

is insensitive to the Sudakov factors

However, the Q_T^2 weight emphasizes the Y term

It is mostly sensitive to the high $Q_T^2 \sim Q^2$ hard gluon radiation

Solution: introduce an upper Q_T cut-off or subtract the calculable pQCD contribution

Single Transverse Spin Asymmetry & QCD Factorization

Xiangdong Ji
University of Maryland

I start my talk with some general remarks, in particular, emphasizing perturbative QCD mechanisms may allow us to learn something simple about the underlying spin structure of the nucleon from single transverse spin asymmetry.

I then consider transverse-momentum-dependent (TMD) QCD factorization for DIS and Drell-Yan processes. Along the way, I introduce the TMD parton distributions. Particularly interesting are these odd under time-reversal symmetry, which are non-vanishing due to initial and/or final state intereactions reflected through gauge links. The factorization is valid in the region where the observed hadron transverse momentum is much smaller than the virtual photon mass. If the transverse-momentum is hard, it is possible to show that the factorization leads to twist-3 effects after collinear expansion. Finally, I comment that in pp to pi+X process, the transverse-momentum of the pion must be large to admit a perturbative description, in which case, the twist-3 calculation of Qiu and Sterman is sufficient. It is unclear at the moment if one has a TMD factorization theorem for this later process, and it would be interesting to find this out soon.

Perturbative & Nonperturbative Mechanisms

- In general, however, the physics mechanism for SSA in strong interactions can be either be perturbative & non-perturbative,
  - pp↑ to pp at low energy: non-perturbative
  - What one would like to understand is the SSA in perturbative region=> we hope to learn something simple, maybe!

    There must be some hard momentum:

    Perturbative description of the cross section must be valid →

    - Factorization
    - A good description of spin-averaged cross sections

SSA & processes

	DIS & Drell-Yan	$p\uparrow p \to \pi X$ & friends
Hard scale	Q^2	P_T
Small $P_T \sim \Lambda_{QCD}$	QCD factorization In TMD's	**Non-perturbative**
$Q^2, s \gg P_T \gg \Lambda_{QCD}$	QCD factorization In TMD's Twist-3 effects	QCD factorization In TMD's ? Twist-3 effects

Factorization for SIDIS with $P_\perp$

- Must consider generic Feynman diagrams with partons having transverse momentum, and gluon loops.
- We have two observable scales, Q and $P_\perp$ (soft). We consider leading order effects in $P_\perp/Q$.
- The gluons can be hard, soft and collinear. Can one absorb these contributions into different factors in the cross sections.
  - X. Ji, F. Yuan, and J. P. Ma, **PRD71:034005,2005**

Factorization theorem

- For semi-inclusive DIS with small p_T

$$\frac{d\sigma}{dx_B dy dz d^2P_{h\perp}} \sim \int d^2\vec{k}_\perp d^2\vec{p}_\perp d^2\vec{\ell}_\perp \int_{x_B}^1 \frac{dx}{x} \int_{z_h}^1 \frac{dz}{z}$$
$$\times q\left(\frac{x_B}{x}, k_\perp, \mu, \zeta\right) \hat{q}\left(\frac{z_h}{z}, p_\perp, \mu, \hat{\zeta}\right) S(\vec{\ell}_\perp)$$
$$\times H\left(x, z, Q^2, \mu^2, \zeta, \hat{\zeta}\right) \delta^2(z\vec{k}_\perp + \vec{p}_\perp + \ell_\perp - \vec{P}_{h\perp})$$

  - Hadron transverse-momentum is generated from multiple sources.
  - The soft factor is universal matrix elements of Wilson lines and *spin-independent*.
  - One-loop corrections to the hard-factor has been calculated

Relation between TMDs & Twist-3?

- The TMD approach for DIS/DY works for both small and perturbative, but moderate P_T.
  - At small P_T, it is a twist-two effect
  - At moderate P_T, it is a twist-three effect.
- The TMD approach is more general, but not necessary at moderate P_T
- The twist-3 approach works only at large P_T, but is the most economical there!

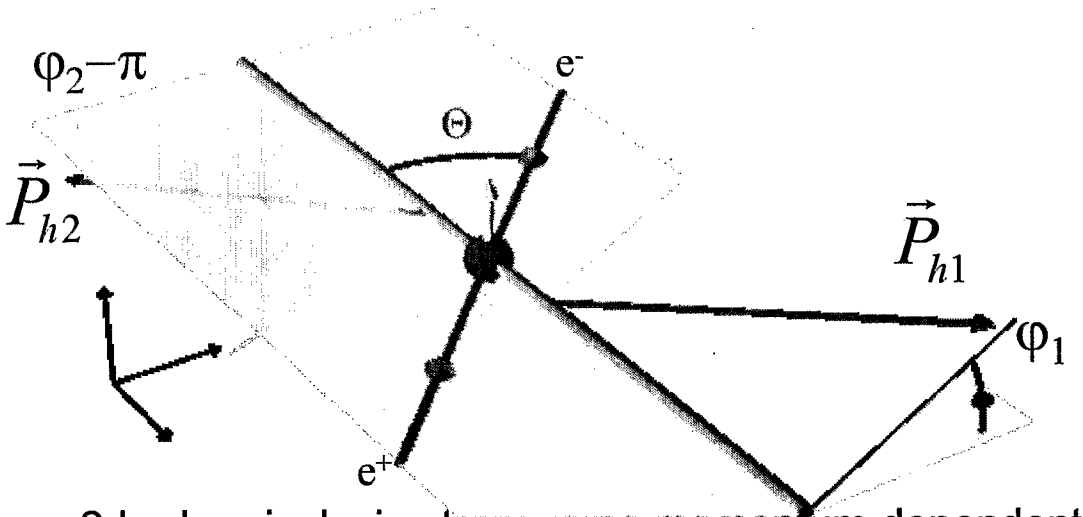
Measurements of chiral-odd fragmentation functions at Belle

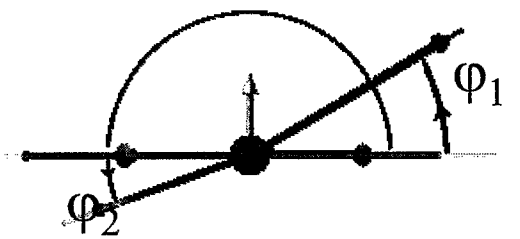
D. Gabbert (University of Illinois and RBRC)
M. Grosse Perdekamp (University of Illinois and RBRC)
K. Hasuko (RIKEN/RBRC)
S. Lange (Frankfurt University)
A. Ogawa (BNL/RBRC)
R. Seidl (University of Illinois and RBRC)
V. Siegle (RBRC)
for the Belle Collaboration

The Collins fragmentation function can be used as probe to transverse quark spin. It measures azimuthal asymmetries around the quark's momentum in the fragmentation of a transversely polarized quark into a pseudoscalar hadron. While the measurements in semi-inclusive DIS contain a convolution with the yet unknown quark transversity distribution one can directly access the Collins function in e^+e^- annihilation, since here one measures the product of a quark and an antiquark fragmentation function.
We report the measurements of azimuthal asymmetries in dihadron production. In order to reduce systematic errors double ratios of unlike sign pion pairs over like sign pion pairs have been formed. The corresponding $\cos(2\phi_0)$ and $\cos(\phi_1+\phi_2)$ are significantly nonzero and contain a rising behavior with increasing fractional pion energy z.

Collins fragmentation: Angles and Cross section $\cos(\phi_1+\phi_2)$ method

e^+e^- CMS frame:





2-hadron inclusive transverse momentum dependent cross section:

$$\frac{d\sigma(e^+e^- \to h_1 h_2 X)}{d\Omega dz_1 dz_2 d^2 \boldsymbol{q}_T} = \cdots B(y) \cos(\varphi_1 + \varphi_2) H_1^{\perp[1]}(z_1) \overline{H}_1^{\perp[1]}(z_2)$$

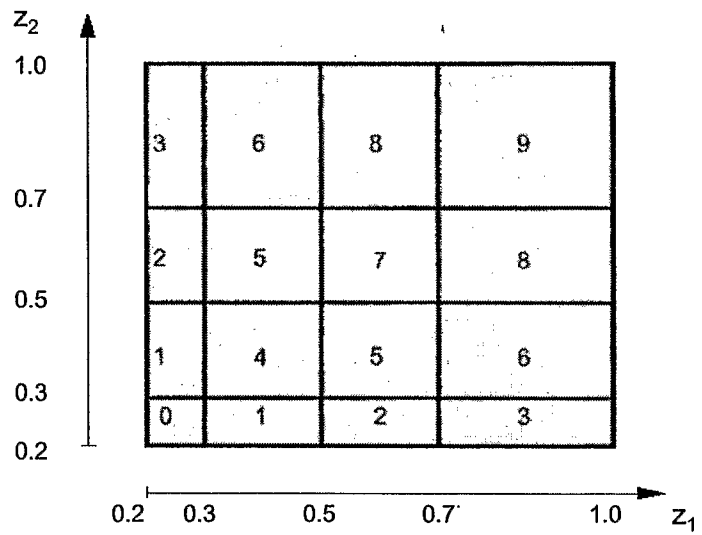
$$B(y) = y(1-y) \overset{cm}{=} \frac{1}{4} \sin^2 \Theta$$

Net anti-alignment of transverse quark spins

Applied cuts, binning

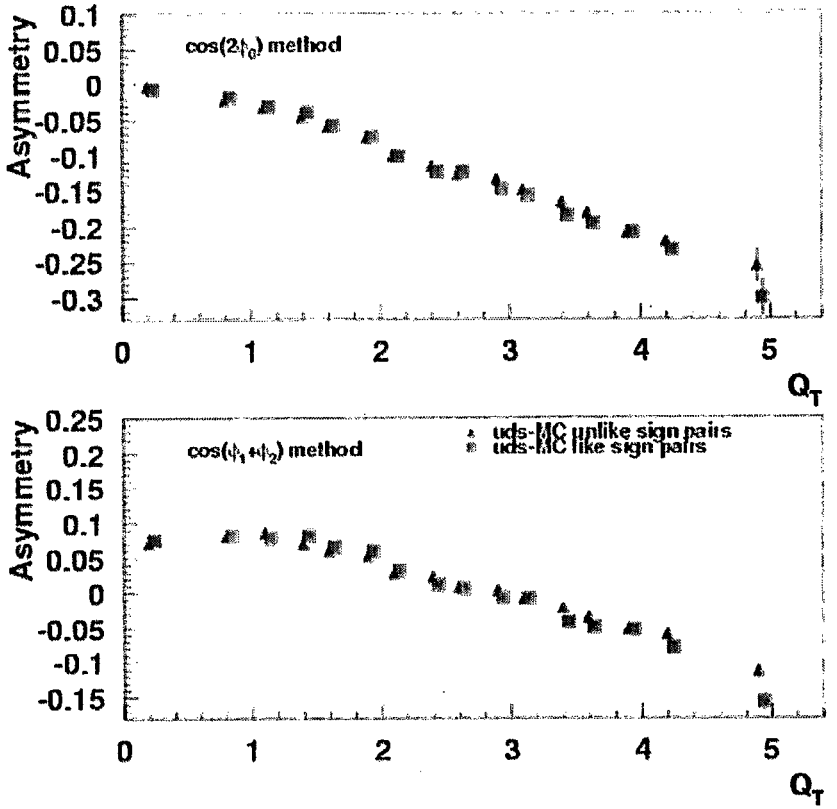
- Off-resonance data (in the future also resonance)
- Track selection:
  - pT > 0.1GeV
  - vertex cut: dr<2cm, |dz|<4cm
- Acceptance cut
  - $-0.6 < \cos\theta_l < 0.9$
- Event selection:
  - Ntrack ≥ 3
  - Thrust > 0.8
  - $Z_1, Z_2 > 0.2$

- Light quark selection
- Hemisphere cut
  $(P_{h_2} \cdot n)\, n \cdot (P_{h_1} \cdot n)\, n < 0$
- Opening angule cuts:
  - $\cos(2\phi_0)$ method: $\psi > 120°$
  - $\cos(\phi_1+\phi_2)$ method: $\psi_1 < 60°, \psi_2 > 120°$



z-binning: 0.2 0.3 0.5 0.7 1.0

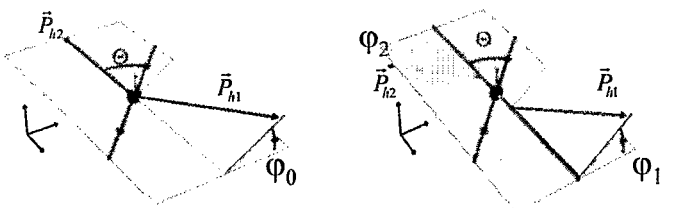
Raw asymmetries vs Q_T



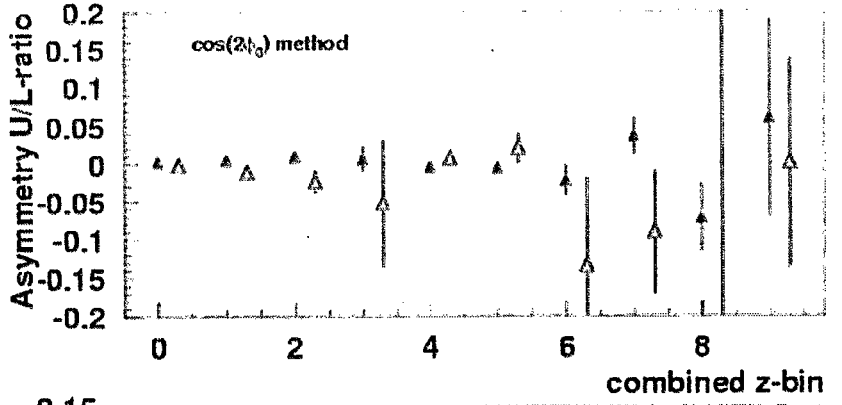
- Q_T describes transverse momentum of virtual photon in $\pi\pi$ CMS system
- Significant nonzero Asymmetries visible in MC (w/o Collins)
- Acceptance, radiative and momentum correlation effects similar for like and unlike sign pairs

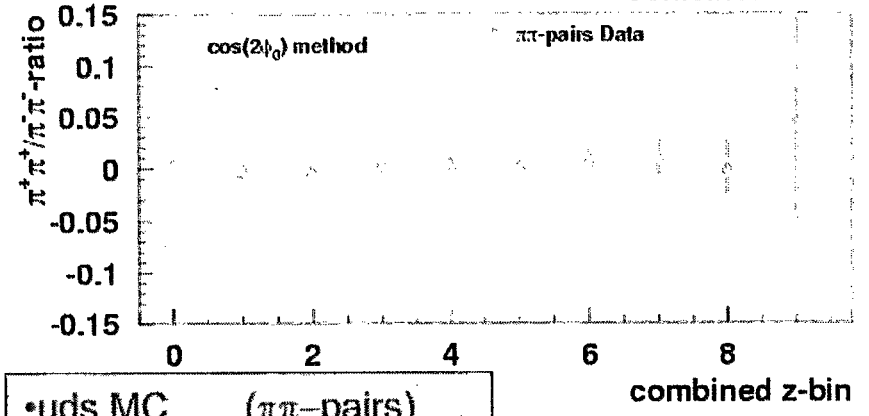
$$\frac{dN}{d\Omega} \propto \sin^2\theta \cos(2\phi_0) \frac{Q_T^2}{Q^2 + Q_T^2}$$

- uds MC ($\pi\pi$) Unlike sign pairs
- uds MC ($\pi\pi$) Like sign pairs



Testing the double ratios with MC





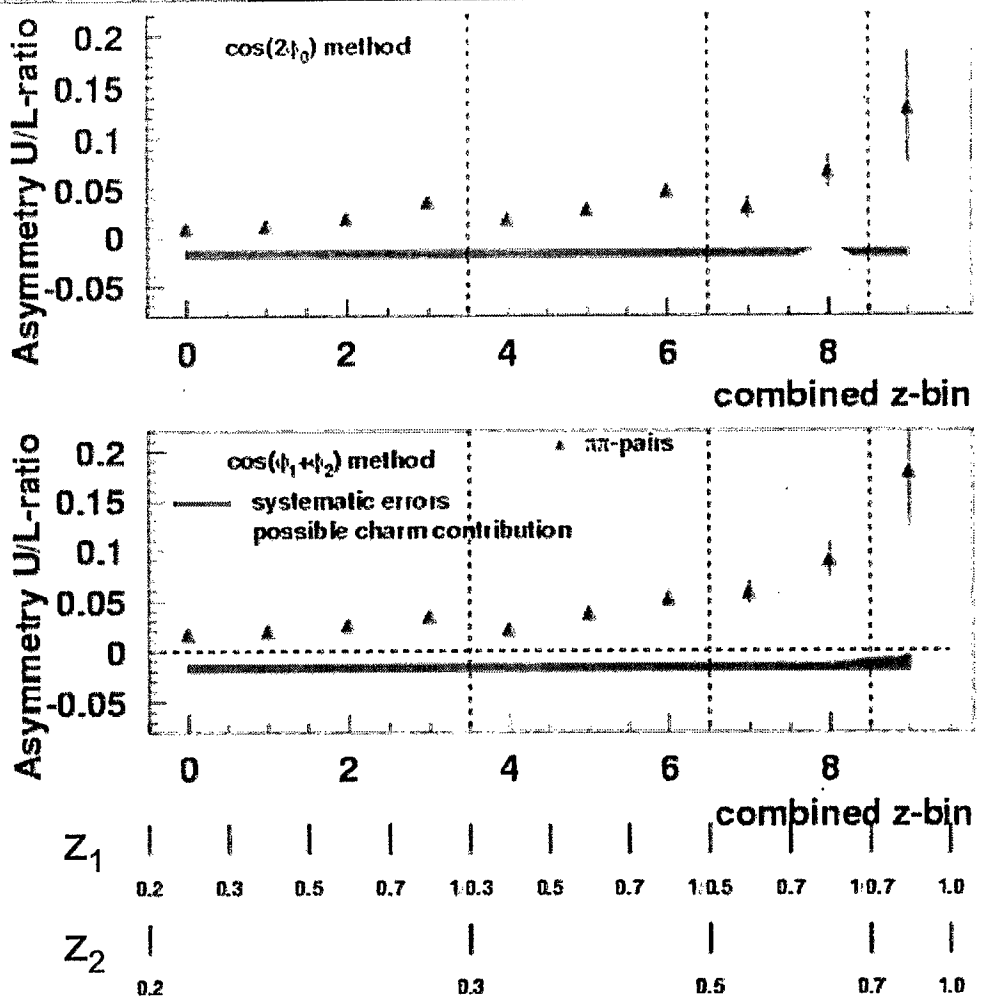
- uds MC ($\pi\pi$–pairs)
- charm MC ($\pi\pi$–pairs)
- Data ($\pi^+\pi^+/\pi^-\pi^-$)

- Asymmetries do cancel out for MC
- Double ratios of $\pi^+\pi^+/\pi^-\pi^-$ compatible to zero
- Mixed events also show zero result
- Asymmetry reconstruction works well for τ MC (weak decays)
- Single hemisphere analysis yields zero

➔ Double ratios are safe to use

	$\pi\pi$ uds	$\pi\pi$ charm	$\pi\pi$ mixed	kk mixed
constant	0.26%±0.19%	-0.45%±0.33%	0.06%±0.09%	0.01%±0.16%
reduced χ^2	1.17	1.35	1.14	1.2

Results for π-pairs for $30fb^{-1}$



- Significant non-zero asymmetries
- Rising behaviour vs. z
- $\cos(\phi_1+\phi_2)$ double ratios only marginally larger
- First direct measurement of the Collins function

Single spin asymmetry of forward neutron at PHENIX.

Manabu Togawa*†, for the PHENIX collaboration.

IP12 experiment

A. Bazilevsky**, L. Bland**, A. Bogdanov‡, G. Bunce§**, A. Deshpande¶§, H. En'yo§†, B. Fox§, Y. Fukao§*, Y. Goto§†, J. Haggerty**, K. Imai*, W. Lenz**, D. von Lintig**, M. Liu‖, Y. Makdisi**, R. Muto†*, S. Nurushev††, E. Pascuzzi§, M. L. Purschke**, N. Saito*§, F. Sakuma†*, S. Stoll**, K. Tanida†, M. Togawa*†, J. Tojo†, Y. Watanabe§† and C. Woody**

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†RIKEN, Wako, Saitama 351-0198, Japan
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The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) was commissioned for polarized proton-proton collisions at the center of mass energy $\sqrt{s}$ =200GeV during the run in 2001-2002. We have measured the single transverse-spin asymmetry A_N for production of photons, neutral pions, and neutrons at the very forward angle (±2.8mrad). The asymmetries for the photon and neutral pion sample were consistent with zero within the experimental uncertainties. In contrast, the neutron sample exhibited an unexpectedly large asymmetry ($A_N \sim$ -10%).

From RUN3 (2003~), longitudinal spin scattering program has begun. In the RHIC rings, the protons are stored with transverse vertical polarization. The polarization vector gets rotated to longitudinal at the entrance of the interaction region, and back to vertical at the exit using the spin rotator magnets.

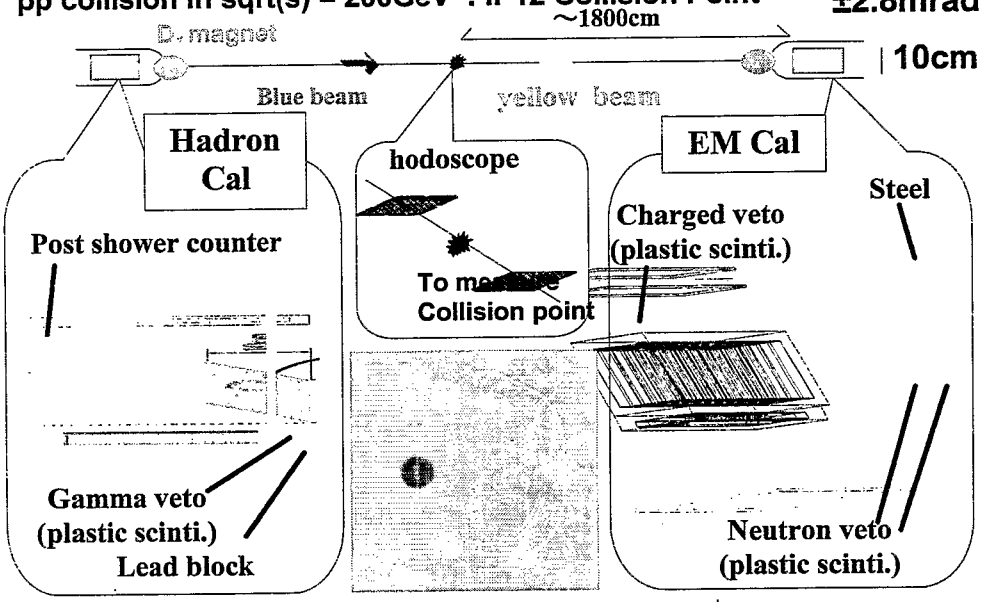
At PHENIX experiment, longitudinal of protons can be confirmed by measuring $A_N \sim 0$ of the forward neutron. We measured longitudinal component, p_L/p, $\sim$ 99% through the RUN3 and RUN4.

To understand the neutron asymmetry mechanism, we studied the single spin asymmetry of charged particles associated with the forward neutron production. Charged particles are detected by BBCs(Beam Beam Counter) which are covered with $3.0 < |\eta| < 3.9$ and 2ϕ angle. We measured negative and positive A_N of charged particles for forward and backward correlation respectively. The neutron production asymmetry could be described by diffraction-like process .

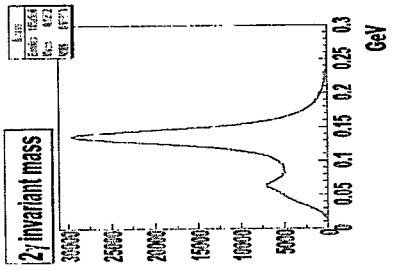
In RUN5(2005), a short $\sqrt{s}$=410GeV run is scheduled. We will explore the existence of the analyzing power at this high energy.

IP12 experiment.

pp collision in sqrt(s) = 200GeV : IP12 Collision Point ±2.8mrad



EMCal based results

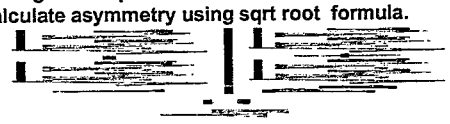


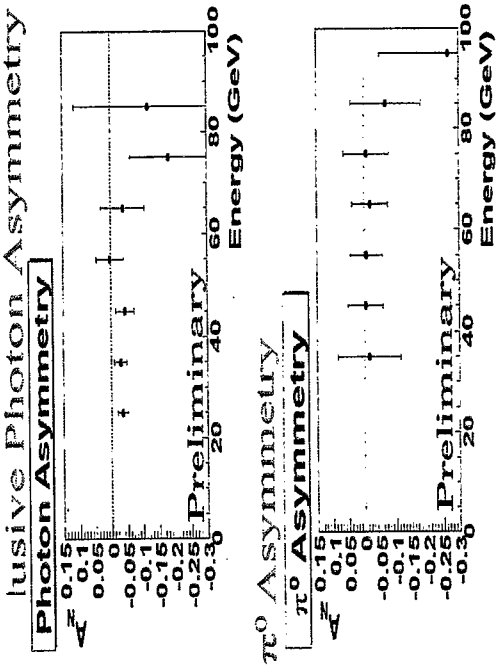
Succeed in π^0 reconstruction

$\Delta M/M \sim 9.3\%$

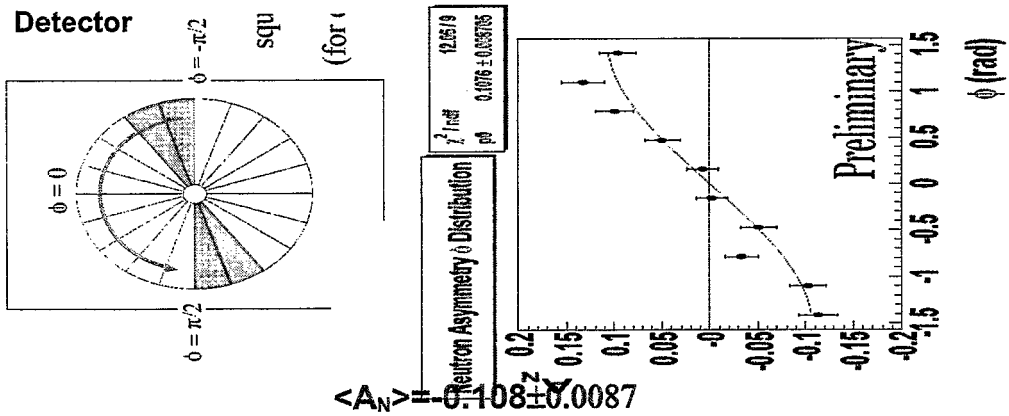
Average beam pol. ~ 11%

Calculate asymmetry using sqrt root formula.





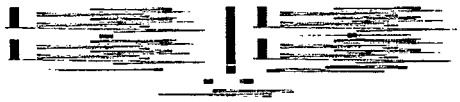
Neutron asymmetry ϕ distribution



$\langle A_N \rangle = -0.108 \pm 0.0087$

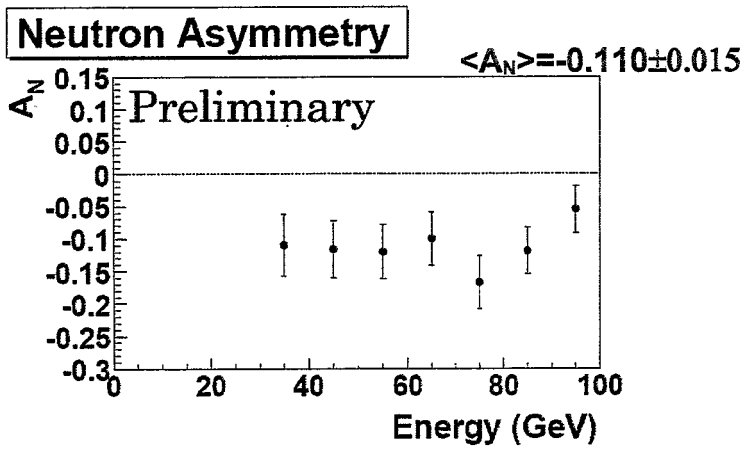
ϕ dependence is consistent with sinϕ

Average beam pol. ~ 11%
Calculate asymmetry using sqrt root formula.

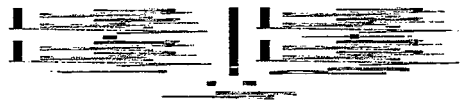


We measured ~10% level neutron L-R asymmetry.
To confirm this, we installed one more detector.

Hadron Cal-based result



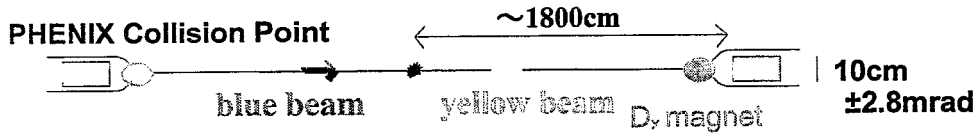
Average beam pol. ~ 18%
Calculate asymmetry using sqrt root formula.

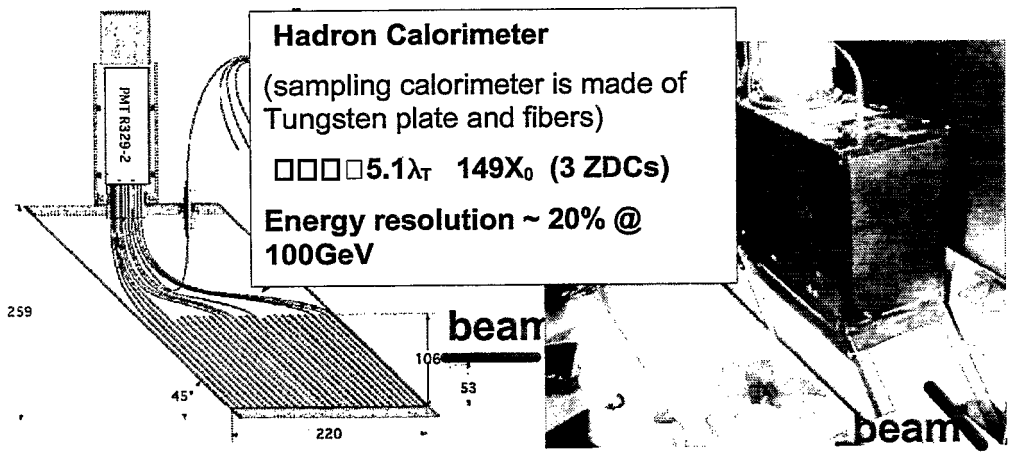


We also measured ~10% level neutron L-R asymmetry in hadron based calorimeter.

PHENIX experiment.

ZDC(Zero Degree Calorimeter)

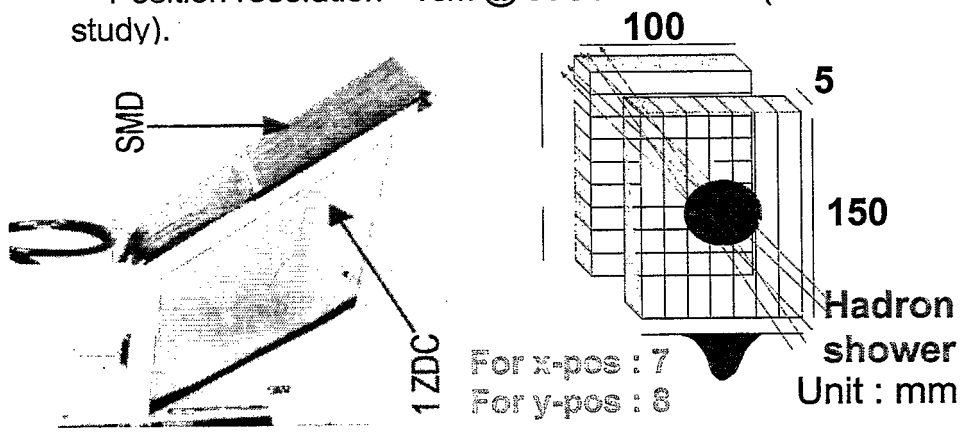


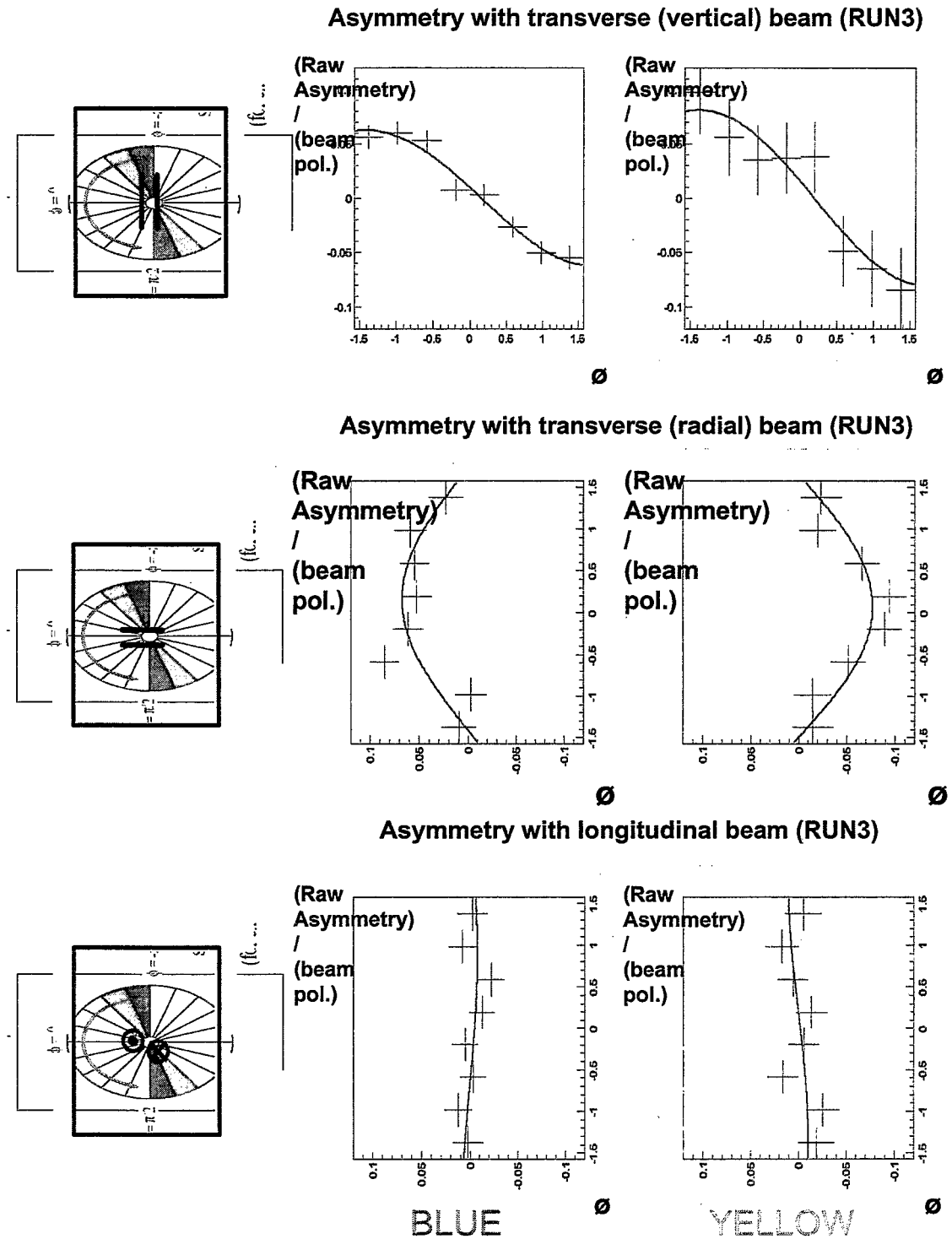


Shower MAX Detector

For measuring neutron position, SMD (Shower Max Detector) was installed btw ZDC1 and ZDC2.

- -Arrays of plastic scintillators
- -Obtain the position by calculating the center of gravity of shower generating in first ZDC.
- -Position resolution ~1cm @ 50GeV neutron (simulation study).



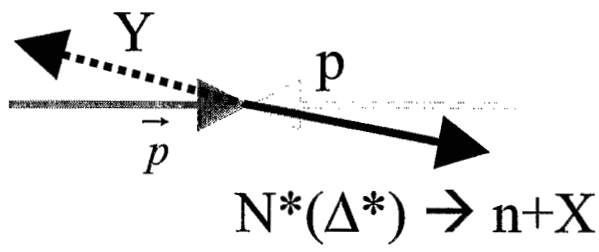

Asymmetry with transverse (vertical) beam (RUN3)
(Raw Asymmetry) / (beam pol.)
(Raw Asymmetry) / (beam pol.)
Asymmetry with transverse (radial) beam (RUN3)
(Raw Asymmetry) / (beam pol.)
(Raw Asymmetry) / (beam pol.)
Asymmetry with longitudinal beam (RUN3)
(Raw Asymmetry) / (beam pol.)
(Raw Asymmetry) / (beam pol.)
BLUE
YELLOW

BBC Asymmetry

K.Tanida et al.

- Forward neutron, forward BBC, left-right
  - $(-4.50 \pm 0.50 \pm 0.22) \times 10^{-2} \rightarrow 9\sigma!$
- Forward neutron, backward BBC, left-right
  - $(2.28 \pm 0.55 \pm 0.10) \times 10^{-2}$
    - ✓ No significant asymmetry in backward ZDC tagged data or in top-bottom asymmetry.
    - ✓ Systematic error doesn't include A_N^{CNI} error.

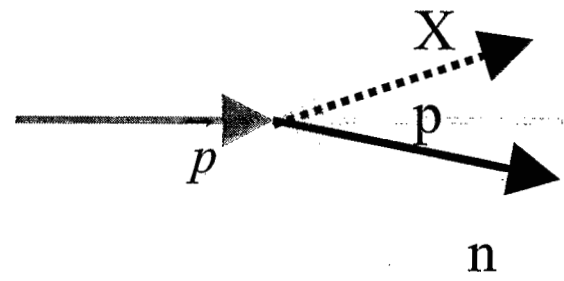
- Diffractive-like process



$N^*(\Delta^*) \rightarrow n+X$

$A_N(X) < 0,\ A_N(Y) > 0$

- kick-out/recoil picture



$A_N(X) > 0,\ A_N(Y)??$

BNL Single-Spin Asymmetry Workshop, June 2005.

Plans of Transverse Target SSA Measurements in SIDIS at Jefferson Lab Hall A and Hall C

Xiaodong Jiang (Rutgers University), June 2nd, 2005.

With a relatively high luminosity available for fixed target experiments at Jefferson Lab's Hall A and Hall C, transversely polarized target single-spin asymmetry measurements in SIDIS reactions will become a reality in the next few years. These experiments include:

- Neutron SSA measurements at Hall A on a transversely polarized ^{3}He target in $n^{\uparrow}(e, e'\pi^{\pm})$ reactions.
- Proton SSA measurements at Hall C in $p^{\uparrow}(e, e'\pi^{\pm})$ reactions.
- Proton SSA measurements at Hall C in $p^{\uparrow}(e, e'\pi^{0})$ reaction.

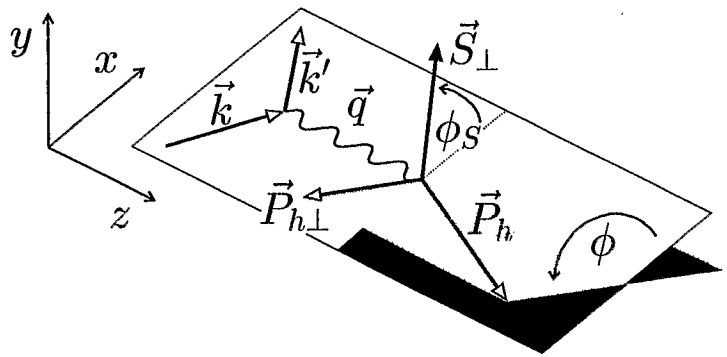
Neutron Transversity: Jefferson Lab Experiment E03-004

Spokespersons: J.-P. Chen (JLab), X. Jiang (Rutgers), J.-C. Peng (UIUC)

Argonne, CalState-LA, Duke, E. Kentucky, FIU, UIUC, JLab, Kentucky, Maryland, UMass,

MIT, ODU, Rutgers, Temple, UVa, W&M, USTC-China, CIAE-China, Glasgow-UK, INFN-Italy,

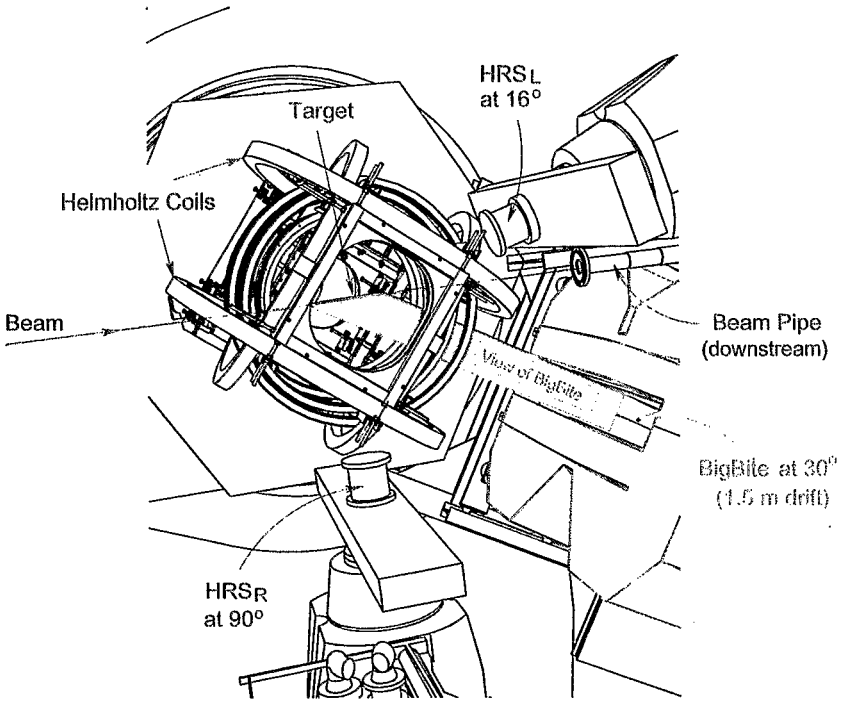
U. Ljubljana-Slovenia, St. Mary's-Canada, Tel Aviv-Israel, St. Petersburg-Russia.



$$A_{UT}(\phi_h^l, \phi_S^l) = \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

$$\begin{aligned}\sigma_{UT} \quad \propto \quad & S_T(1-y)\frac{P_{h\perp}}{zM_h}\,\sin(\phi_h^\ell + \phi_S^\ell)\cdot\sum e_q^2\, h_1^q(x)\otimes H_{1q}^{\perp h}(z, P_{h\perp}^2) \\ + \quad & S_T(1-y+\frac{y^2}{2})\frac{P_{h\perp}}{zM_N}\,\sin(\phi_h^\ell - \phi_S^\ell)\cdot\sum e_q^2\, f_{1T}^{\perp q}(x)\otimes D_{1q}^h(z_h, P_{h\perp}^2)\end{aligned}$$

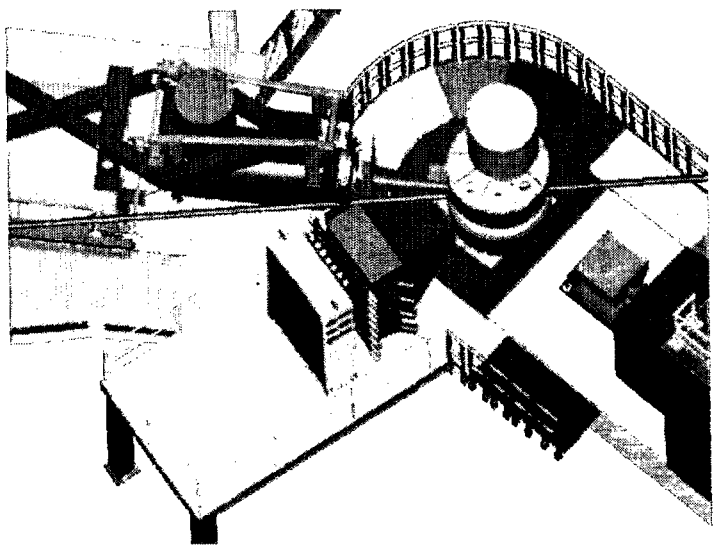
JLab E03-004: $n^{\uparrow}(e, e'\pi^-)X$ with a 6 GeV Beam



- A magnetic spectrometer BigBite as e-arm: at $30°$.
- One existing high resolution spectrometer as h-arm: at $16°$, $p_h = 2.4$ GeV/c.
- Hall A polarized ^{3}He$^{\uparrow}$ target. Rotate ϕ_S to cover $\phi_{Collins}$ and ϕ_{Sivers}.

A Letter-of-Intent to Measure SSA in $p^{\uparrow}(e, e'h)X$

A LOI has been submitted to Jefferson Lab PAC25 (LOI04-003).



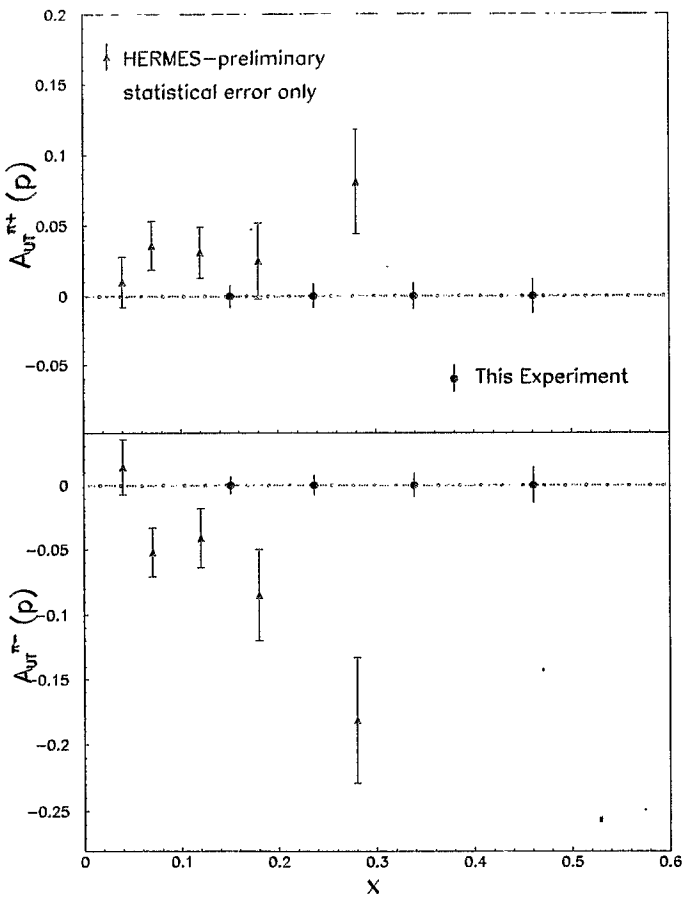
A Hall C experiment with 6 GeV beam.

A large calorimeter array as e-arm, $\Delta\Omega_e = 300$ msr.

Existing spectrometer HMS as h-arm.

Run for 45 days.

The Expected Statistical Uncertainties $p^{\uparrow}(e, e'h)X$



E_0=6 GeV, run for 45 days total. For both π^+ and π^- production.

Summary

After the HERMES transverse target data collection ends, transverse target SSA physics will be continued at Jefferson Lab for 6 GeV now and 12 GeV in the future. This includes:

- Neutron transversity measurement in $n^{\uparrow}(e, e'\pi^{-})$. Approved for 24 days of beam in Hall A, waiting for the beam time schedule.
- Neutron transversity in $n^{\uparrow}(e, e'\pi^{+})$ (a new Hall A proposal).
- Proton transverse SSA in $p^{\uparrow}(e, e'\pi^{\pm})$ (LOI in Hall C), pending on target magnet design.
- To be expanded to $p^{\uparrow}(e, e'\pi^{0})$ (Hall C).

When these measurements finish:

- Asymmetry and relative cross section from many channels will be available at the same kinematics.
- Data can be combined to form ratios.

T-odd effects in hadronic scattering processes

Cedran Bomhof

Department of Physics and Astronomy, Vrije Universiteit Amsterdam, NL-1081 HV Amsterdam, the Netherlands

Single spin asymmetries, in which one hadron is polarized, can be explained by T-odd effects. In hard processes such effects show up when the transverse momentum of the partons is taken into account. An example is the Sivers effect, that explains the single spin asymmetries as a consequence of a correlation between the transverse spin of the hadron and the intrinsic transverse momentum of an unpolarized parton. Distribution and fragmentation functions are described as hadronic matrix elements of bilocal products of quark/gluon fields. In transverse momentum dependent distribution functions the T-odd behavior comes from the presence of gauge-links, path-ordered exponentials with process-dependent integration paths, which are needed to render the bilocal products of fields color gauge invariant. Other examples are the Boer-Mulders distribution function or the Collins fragmentation function.

To get access to T-odd effects in inclusive pion production (perpendicularly back-to-back) in hadron-hadron collisions, one can look at azimuthal asymmetries, which are sensitive to the intrinsic transverse momenta of the partons. One can, for example, weigh the scattering cross section by the difference angle of the two produced pions from perfect 'back-to-back'-ness. To get nonvanishing T-odd effects in this process, the gauge-links have to be taken into account. An important complication is that the gauge-links are process dependent, depending specifically on the hard part of the process. This is best illustrated by considering the Sivers effect in identical quark scattering. In this case both direct and interference diagrams contribute. As a consequence of the dependence of the gauge-links on these processes, the Sivers effect of the direct contributions is given by $\frac{1}{2}f_{1T}^{\perp(1)}$, while the Sivers effect of the interference contributions is given by $-\frac{3}{2}f_{1T}^{\perp(1)}$, where $f_{1T}^{\perp(1)}$ is the T-odd distribution function describing the Sivers effect in semi-inclusive deep inelastic scattering. Due to the different prefactors in front of the Sivers function, the different contributions to identical quark scattering can no longer simply be added to give a folding of universal distribution and fragmentation functions with the identical quark partonic scattering cross section. However, one can obtain a folding expression of the Sivers contribution in terms of universal distribution and fragmentation functions and a hard part, by absorbing the process-dependent prefactors into modified hard parts. Consequently, these hard parts are no longer exactly equal to the partonic scattering cross sections. Similar conclusions hold for the Boer-Mulders effect and the Collins effect. That is, the expression for azimuthal asymmetries in inclusive back-to-back pion production in hadron-hadron collisions can be recast in the form of a folding of a universal T-odd function describing the T-odd effect with T-even distribution and fragmentation functions and a 'modified' or *gluonic pole scattering cross section.* The gluonic pole cross sections are often simply proportional to the true partonic cross sections, but in case of identical flavor qq, $q\bar{q}$ or $\bar{q}\bar{q}$ scattering, the difference between the partonic and the gluonic pole cross sections can be more profound.

single spin asymmetries

One possible explanation for SSA is partonic intrinsic transverse momentum.

Examples:

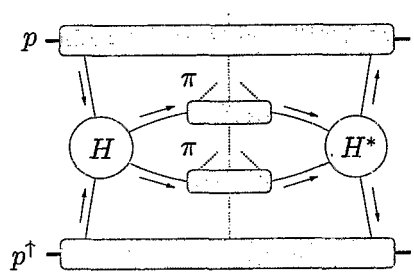
- Sivers effect $f_{1T}^{\perp(1)}$
- Collins effect $H_1^{\perp(1)}$
- Boer-Mulders effect $h_1^{\perp(1)}$

These effects are described by T-odd functions

$$f^{(T\text{-odd})}(x)$$

$$\propto \int \mathrm{d}k^- \mathrm{d}^2k_T \; k_T \; \mathcal{FT}\langle \overline{\psi}(0)\mathcal{U}(0,\xi)\Gamma\psi(\xi)\rangle$$

$p^\uparrow p \to \pi\pi X$ scattering

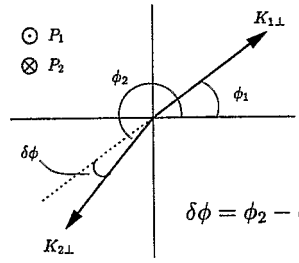


Complications

- Partonic scattering through strong interaction.
- Many different partonic scattering channels that contribute.

example of azimuthal asymmetry

Transverse plane:



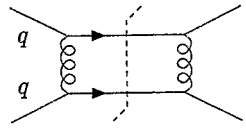
$$\delta\phi = \phi_2 - \phi_1 - \pi$$

The weighed cross section

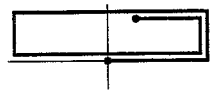
$$\langle \sin(\delta\phi)\, \mathrm{d}\sigma \rangle = \int \frac{\mathrm{d}\phi_2}{2\pi}\, \sin(\delta\phi)\, \mathrm{d}\sigma$$

is sensitive to intrinsic transverse momenta.

example of gauge-link in qq-scattering

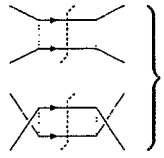


tt^*-diagram

$\frac{5}{4} \times$ $-\frac{1}{4} \times$ 

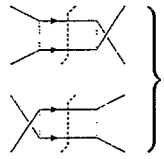
$= \frac{5}{4} \times \quad \mathrm{Tr}(\mathcal{U}^{[\square]})\mathcal{U}^{[+]}/3 \qquad -\frac{1}{4} \times \quad \mathcal{U}^{[\square]}\mathcal{U}^{[+]}$

Sivers effects in identical-quark scattering



$$\mathcal{U} = \tfrac{5}{4}\,\mathrm{Tr}(\mathcal{U}^{[\square]})\mathcal{U}^{[+]}/3 - \tfrac{1}{4}\,\mathcal{U}^{[\square]}\mathcal{U}^{[-]}$$

$$\Rightarrow \quad f_{1T}^{\perp(1)}(tt^*) = f_{1T}^{\perp(1)}(uu^*) = \tfrac{1}{2}\, f_{1T}^{\perp(1)}$$

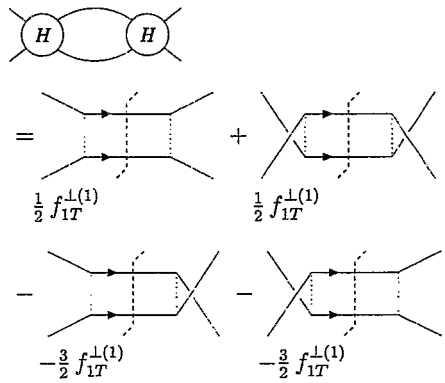


$$\mathcal{U} = \tfrac{9}{4}\,\mathrm{Tr}(\mathcal{U}^{[\square]})\mathcal{U}^{[+]}/3 - \tfrac{5}{4}\,\mathcal{U}^{[\square]}\mathcal{U}^{[-]}$$

$$\Rightarrow \quad f_{1T}^{\perp(1)}(tu^*) = f_{1T}^{\perp(1)}(ut^*) = -\tfrac{3}{2}\, f_{1T}^{\perp(1)}$$

Sivers effect in identical-quark contribution to hadronic scattering

using the 'universal' Sivers function:



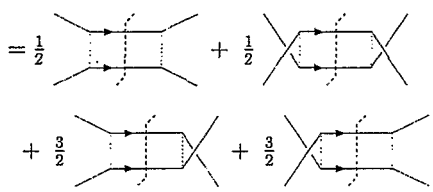
Sivers effect in identical-quark contribution to hadronic scattering

$\mathrm{d}\sigma^{\mathrm{HADRON}}$

$\propto f_{1T}^{\perp(1)}(x_1)\, f_1(x_2)\, \mathrm{d}S^{uu\to uu}\, D_1(z_1)\, D_1(z_2)$

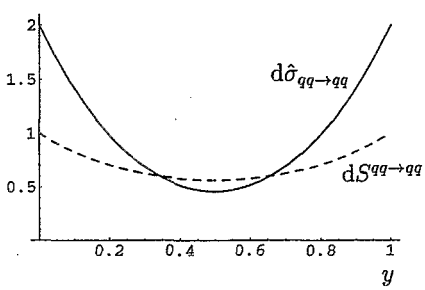
with 'modified' or
gluonic pole cross section

$\mathrm{d}S^{uu\to uu}$



$\neq \mathrm{d}\hat{\sigma}(uu\to uu)$

comparison of 'true' and gluonic pole cross section



$y = \cos^2(\frac{1}{2}\theta)$

θ : polar angle of outgoing pion in c.o.m.

weighed scattering cross section

[hep-ph/0505268]

$$\langle \sin(\delta\phi)\, \mathrm{d}\sigma \rangle$$

$$\propto M_1 \sum\nolimits_{q_i} f_{1T}^{\perp(1)}(x_1) f_1(x_2) \frac{\mathrm{d}S^{\text{SIVERS}}}{\mathrm{d}\hat{t}} D_1(z_1) D_1(z_2)$$

$$+ M_2 \sum\nolimits_{q_i} h_1(x_1) h_1^{\perp(1)}(x_2) \frac{\mathrm{d}S^{\text{BOER-MULDERS}}}{\mathrm{d}\hat{t}} D_1(z_1) D_1(z_2)$$

+ Collins effect contributions

+ Gluon scattering contributions

summary

- Gauge-links are needed for a gauge-invariant description of PDFs/FFs.
- Gauge-links can be calculated by resumming all initial and/or final state interactions of collinear gluons.
- Consequence of the gauge-links is that T-odd functions appear with different calculable strengths in the different scattering channels.
- Total cross section in $p^{\uparrow}p \to \pi\pi X$ can be written as a convolution of *universal* PDFs, FFs and process-dependent hard parts.
- These hard parts are, in general, different from the 'true' partonic cross sections.

Single Target Spin Asymmetry and GPDs

Jian-ping Chen, *Jefferson Lab, Virginia, USA*

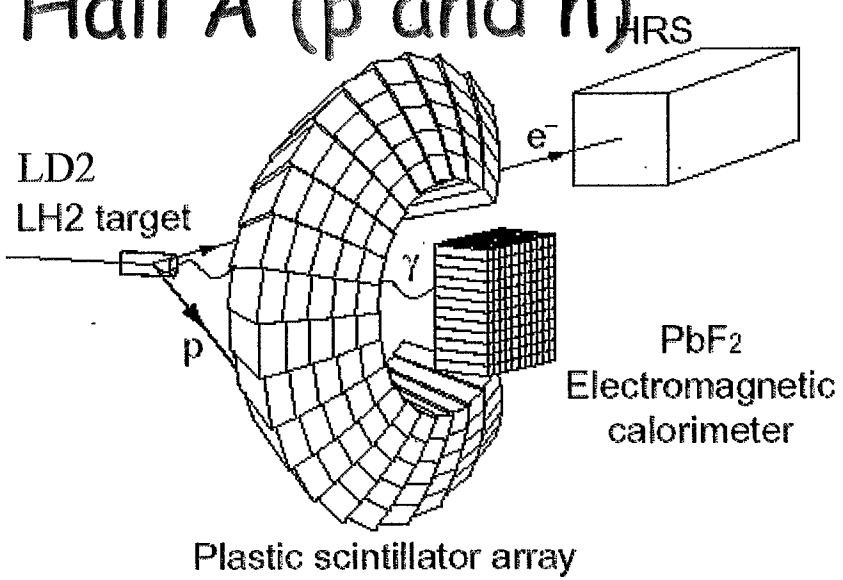
SSA Workshop, BNL, June 1-3, 2005

- Nucleon structure and GPDs
- DVCS and Wide Angle Compton Scattering
- Target SSA with 2γ exchange to probe GPDs
- JLab E05-015: neutron SSA with vertically polarized ^{3}He
- Summary

First Dedicated DVCS Experiments at JLab

=> Full reconstruction of all final state particles e, p, γ
=> High luminosity 10^{37}

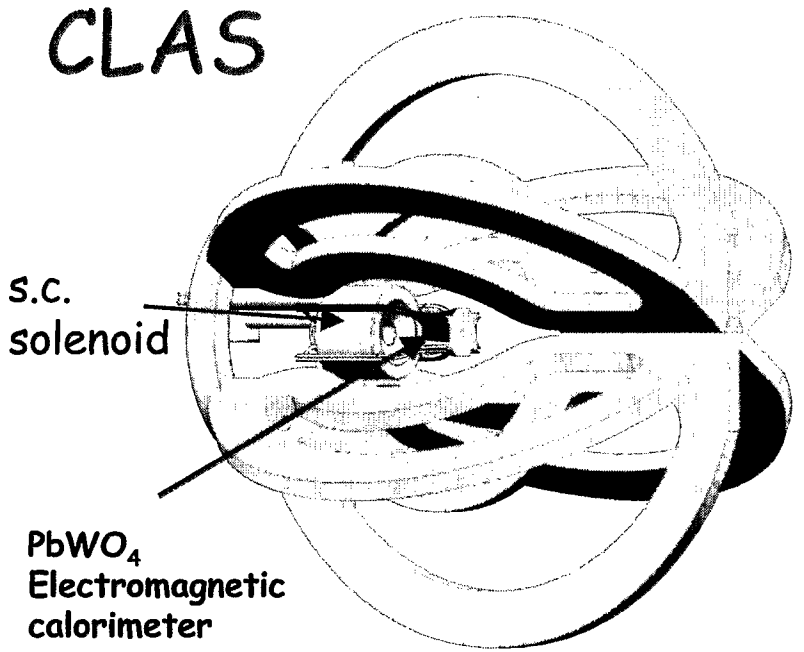
Hall A (p and n)



Azimuthal and Q^2 dependence of Im(DVCS) at fixed ξ.
Test Bjorken scaling.

Data taking completed

CLAS

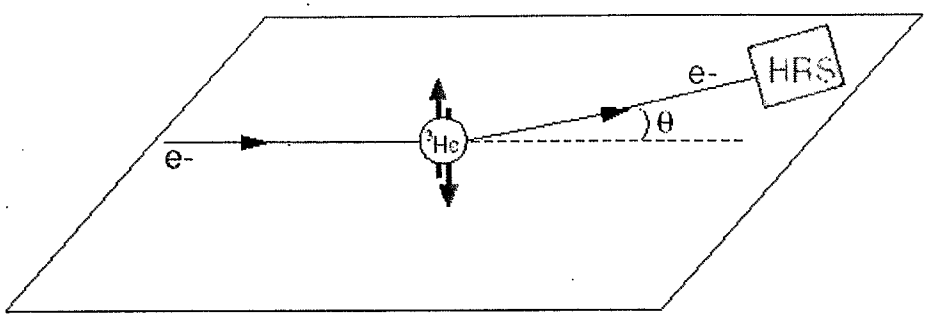


ξ, t, Q^2 - dependence of Im(DVCS) in wide kinematics. Constrain GPD models.

Currently taking data

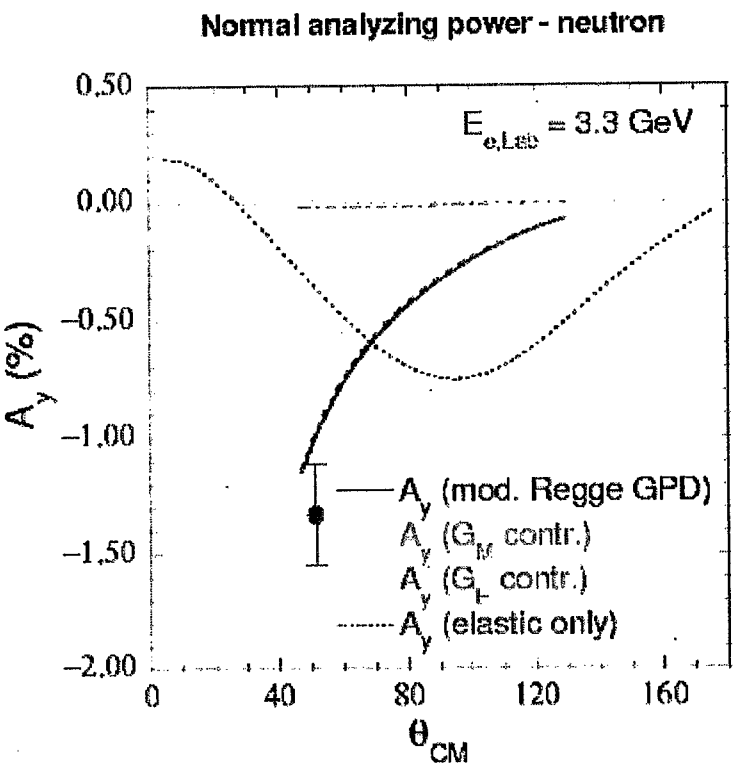
JLab E05-015: GPD moment with target SSA with 2γ eff

Overview



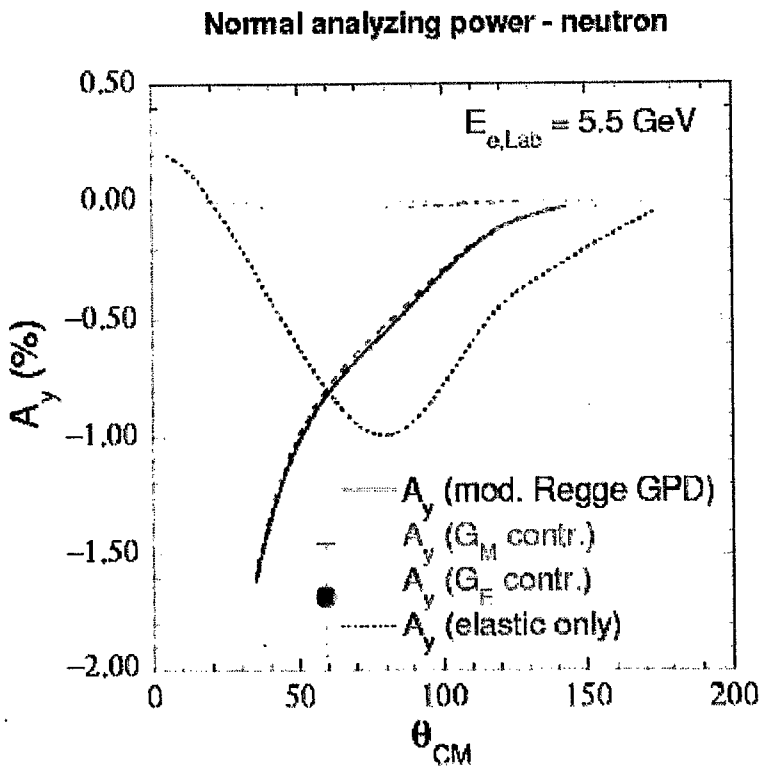
- Inclusive quasi-elastic scattering, unpolarized beam, vertically polarized ^{3}He.
- Measure single-spin asymmetry (SSA) $A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$ from target spin flip.
- $A_y \neq 0$ arises only when 2γ-exchange is included.
- 2γ exchange contains entire nucleon response $\Leftrightarrow$ Generalized Parton Distributions (GPD's).
- A non-zero A_y has never been established experimentally.

Expected Results



Neutron, $E_0 = 3.3$ GeV

$Q^2 = 1.0$ GeV^2



Neutron, $E_0 = 5.5$ GeV

$Q^2 = 2.3$ GeV^2

- Systematic error $\delta A_y / A_y \simeq 8 - 12\%$
- Measurement at GPD prediction gives $> 6\sigma$ measure of non-zero A_y

Summary

- GPD provides a unified framework
- DVCS SSA direct access GDPs
  - Results from JLab, HERMES and other labs
  - Dedicated experiments and JLab upgrade
- Wide Angle Compton Scatting access GPD moments
  - Recent results on K_{LL} and K_{LS}.
- New way to measure GPD moments: STSA with 2γ
- JLab E05-015: neutron→ one moment of GPD constraints on E GPD.

Transversity Correlations in Single Spin and Azimuthal Asymmetries

Leonard P. Gamberg

Division of Science, Penn State-Berks, Reading, PA 19610, USA *

Abstract

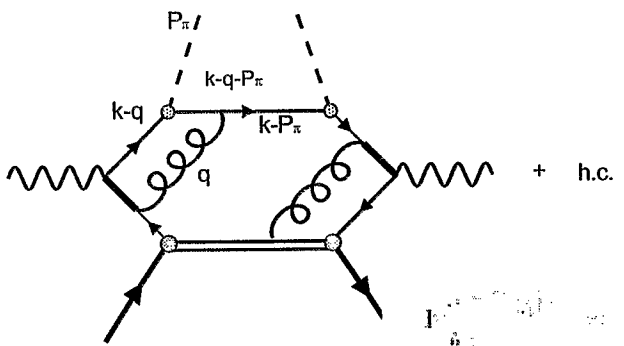
One of the persistent challenges confronting the QCD improved parton model is to account for the large azimuthal and single spin asymmetries that emerge in semi-inclusive electro-production, and di-lepton production in Drell Yan scattering. Going beyond the collinear approximation in PQCD recent progress has been achieved in characterizing these asymmetries in terms of absorptive scattering. Central to this understanding are the correlations between transverse momentum and transverse spin in QCD hard scattering. These asymmetries provide a window to explore novel quark distribution and fragmentation functions which constitute essential information about the spin, transversity and generalized momentum structure of hadrons. Along with the chiral odd transversity time-reversal even (*T-even*) distribution function, existence of the time reversal odd (*T-odd*) distribution and fragmentation functions can provide an explanation for the substantial asymmetries that have been observed in these scattering processes.

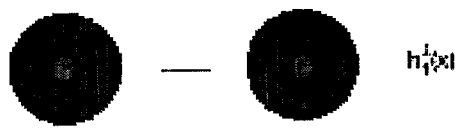
Here we consider the leading twist T-odd contributions as the dominant source of the $\cos 2\phi$ azimuthal asymmetry and $\sin(\phi \pm \phi_s)$ SSAs in SIDIS and $p\bar{p} \to \mu\mu^+ X$ dilepton production in Drell-Yan Scattering. These asymmetries contain information on the distribution of quark transverse spin in an unpolarized proton, $h_1^\perp(x, k_\perp)$. In a parton-spectator framework we estimate these asymmetries at HERMES kinematics and for Drell-Yan scattering at 50 GeV center of mass energy. The latter azimuthal asymmetry is interesting in light of proposed experiments at GSI, where an anti-proton beam is ideal for studying the transversity properties of quarks due to the dominance of *valence* quark effects.

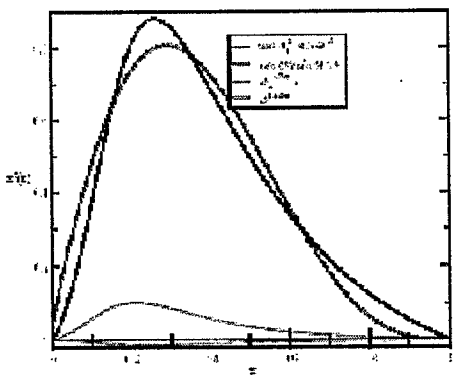
*Electronic address: lpg10@psu.edu

$\cos 2\phi$ Asymmetry Generated by ISI & FSI thru Gauge link

Goldstein, Gamberg–ICHEP-Amsterdam: 2002, hep-ph/0209085, G,G, & Oganessyan PRD:2003







$$A_{UU}^{\cos(2\phi)} = \langle \frac{|P_{h\perp}^2|}{M M_h} \cos 2\phi \rangle_{UU}$$

$$= \frac{8(1-y)\sum_q e_q^2 h_1^{\perp(1)}(x,Q^2) z^2 H_1^{\perp(1)q}(z,Q^2)}{(1+(1-y)^2)\sum_q e_q^2 f_1^q(x,Q^2) D_1^q(z,Q^2)}$$

$$\frac{d\sigma}{dx dy dz d^2P_\perp} \propto f_1 \otimes D_1 + \frac{k_T}{Q} f_1 \otimes D_1 \cdot \cos\phi + \left[\frac{k_T^2}{Q^2} f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp\right] \cdot \cos 2\phi$$

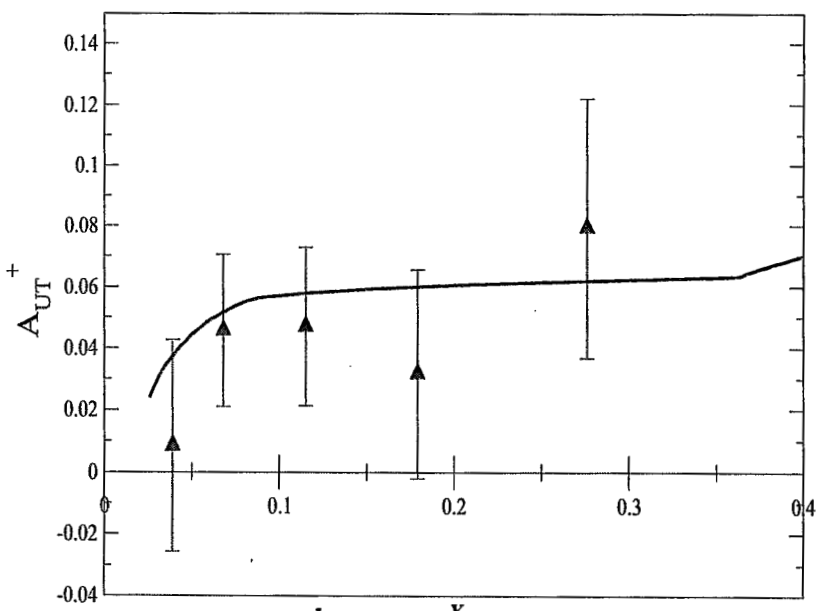
D. Boer, P. Mulders, PRD: 1998

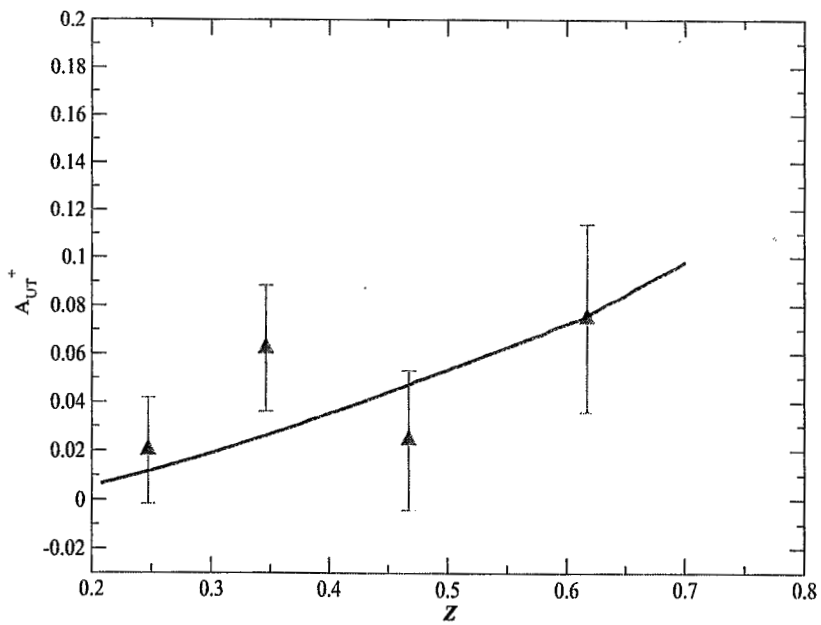
Collins Asymmetry

Gamberg, Goldstein, Oganessyan PRD 2003: updated For the HERMES kinematics
$1\ \text{GeV}^2 \leq Q^2 \leq 15\ \text{GeV}^2$, $4.5\ \text{GeV} \leq E_\pi \leq 13.5\ \text{GeV}$, $0.2 \leq x \leq 0.41$, $0.2 \leq z \leq 0.7$, $0.2 \leq y \leq 0.8$, $< P_{h\perp}^2 >= 0.25\ \text{GeV}^2$

$$\langle \frac{P_{h\perp}}{M_\pi} \sin(\phi + \phi_s) \rangle_{UT} = |S_T| \frac{2(1-y)\sum_q e_q^2 h_1(x) z H_1^{\perp(1)}(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x) D_1(z)}.$$

Data from A. Airapetian et al. PRL94,2005



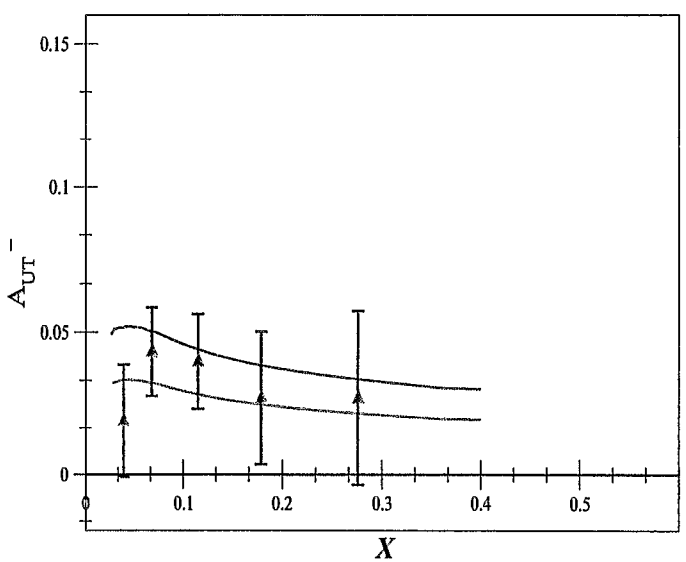


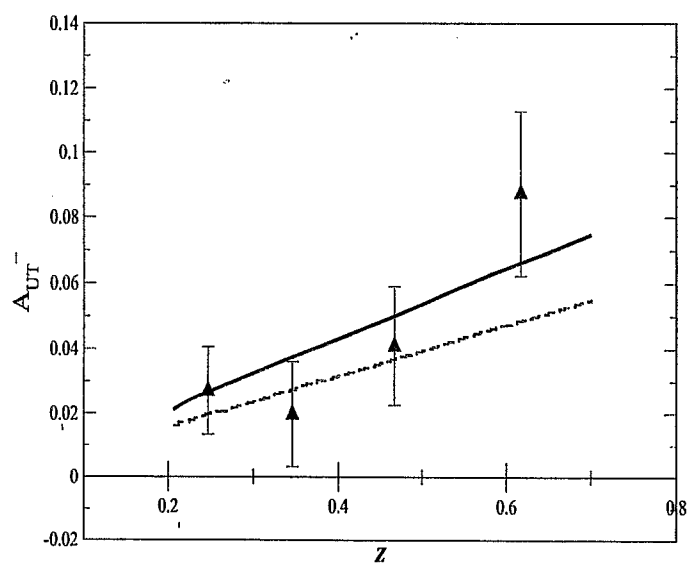
Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

$$\langle \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S) \rangle_{UT} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}|}{M} \sin(\phi - \phi_S)\, d\sigma}{\int d^2 P_{h\perp}\, d\sigma}$$

$$= \frac{(1 + (1-y)^2) \sum_q e_q^2 f_{1T}^{\perp(1)}(x) z D_1^q(z)}{(1 + (1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)},$$

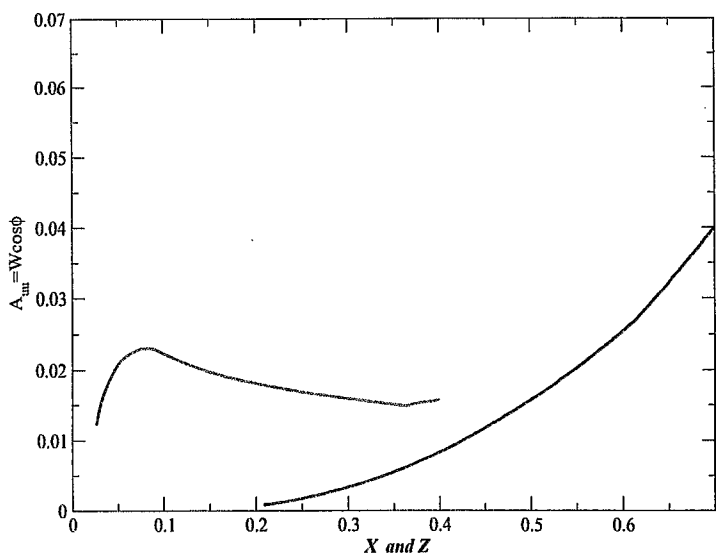


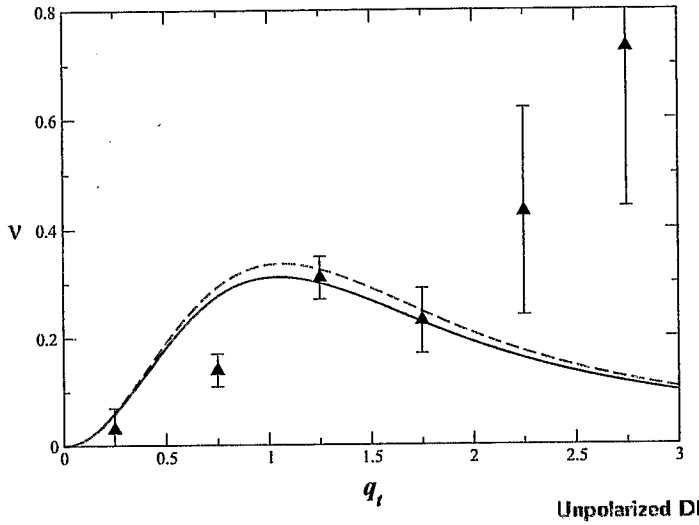


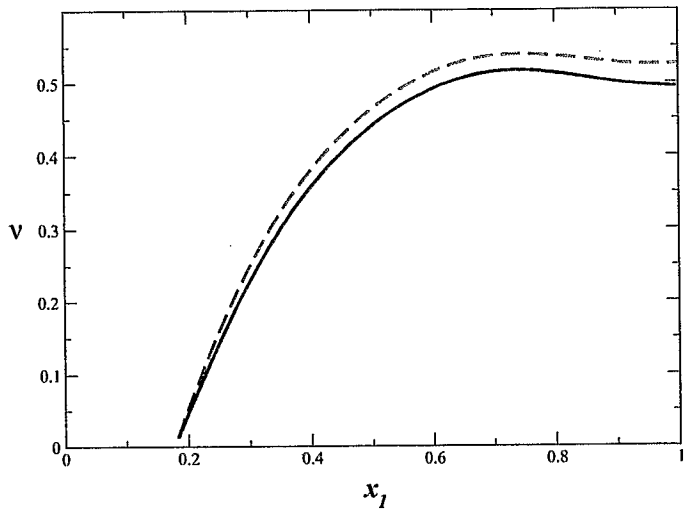
Double T-odd $\cos 2\phi$ asymmetry

Transversity of quarks inside an unpolarized hadron, and $\cos 2\phi$ asymmetries in unpolarized semi-inclusive DIS

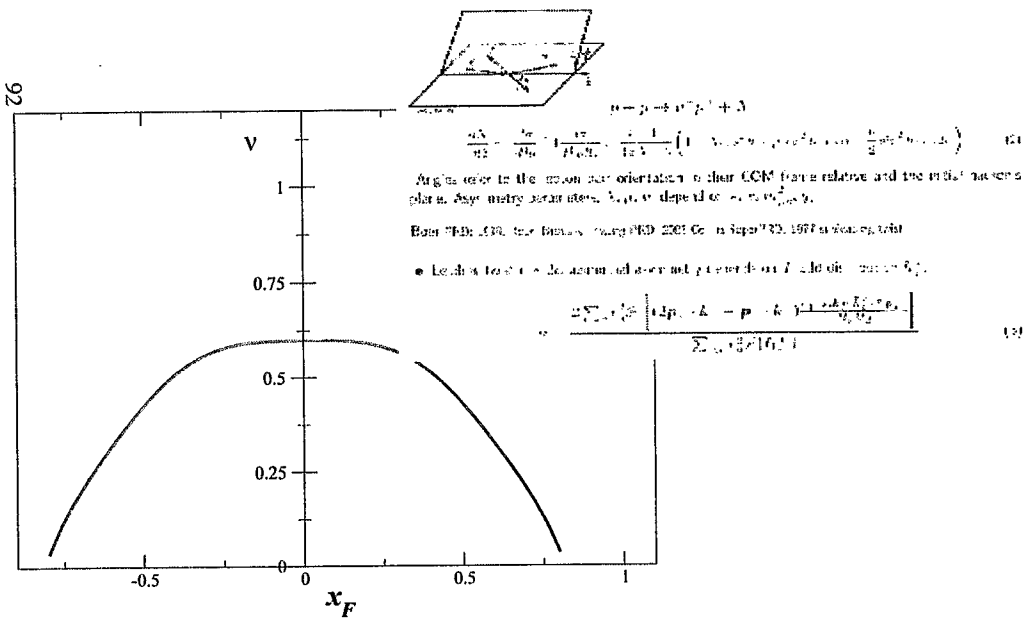
$$\langle \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \rangle_{UU} = \frac{\int d^2 P_{h\perp} \frac{|P_{h\perp}^2|}{MM_h} \cos 2\phi \, d\sigma}{\int d^2 P_{h\perp} \, d\sigma} = \frac{8(1-y) \sum_q e_q^2 h_1^{\perp(1)}(x) z^2 H_1^{\perp(1)}(z)}{(1+(1-y)^2) \sum_q e_q^2 f_1(x) D_1(z)}$$

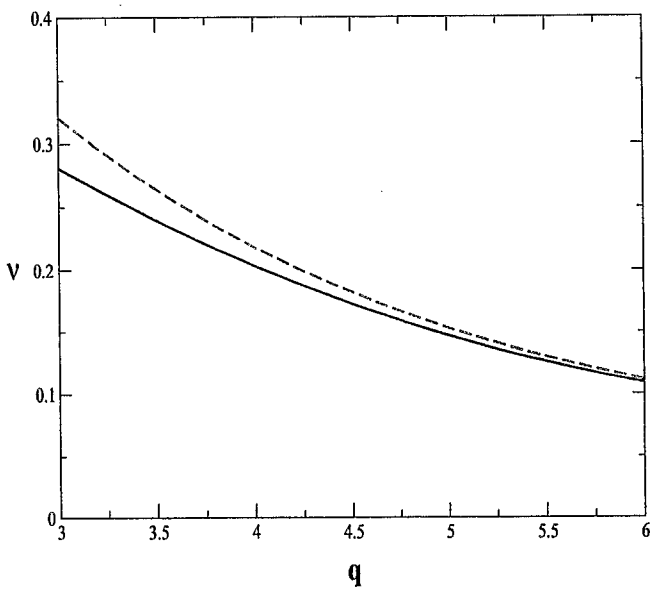






Unpolarized DRELL YAN





Gamberg Goldstein,.. In prep $s = 50GeV^2$, $x = 0.2 - 1.0$, and $q = 3.0 - 6.0\ GeV$ and $q_T = 0 - 3.0\,GeV$: DATA from E615 Conway *et al.*PRD:1989

Measuring Orbital Angular Momentum with Jet k_T

Douglas E. Fields

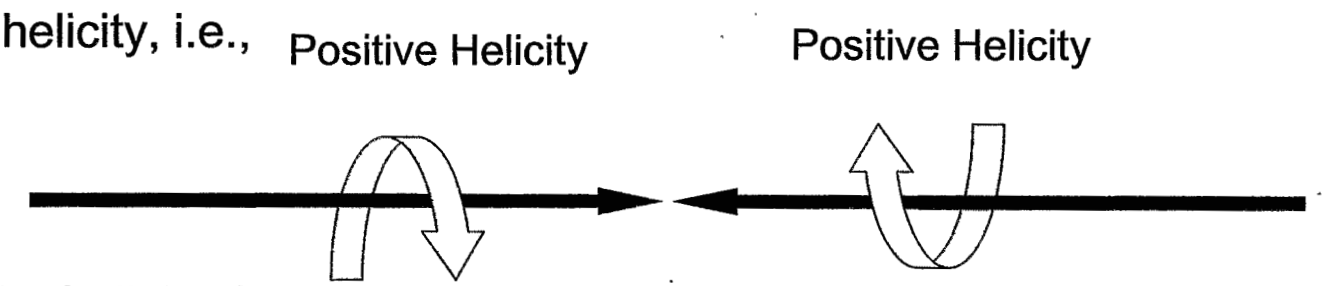
University of New Mexico/RIKEN/BNL Research Center

By looking at the proton as a collection of rotating constituents, and considering the case of longitudinally polarized collisions, we examine the possibility of measuring the orbital angular momentum of the constituents by measuring the asymmetry in jet intrinsic transverse momentum k_T. A purely classical picture given in slide 2 shows the net transverse momentum for the colliding pair can be a function of the impact parameter of the collision, and is different for different helicity combinations, like and unlike. Even after integrating over the impact parameter, one would likely be left with different pair transverse momentum for the different helicity combinations[1]. We propose to use the method of di-hadron azimuthal correlations[2] to measure this spin-correlated jet transverse momentum.

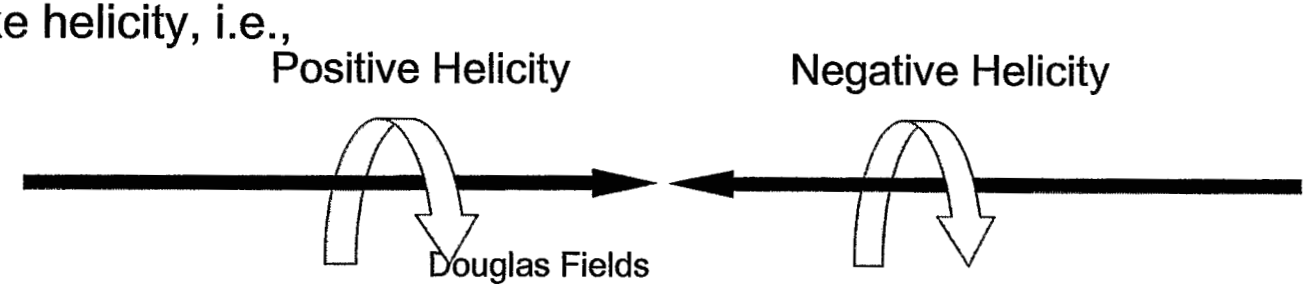
[1] Meng Ta-chung et al., Phys. Rev. D40 p769 (1989).
[2] PHENIX, to be submitted to PRD.

Basic Picture

- Idea came from me trying to understand Siver's effect
  - Quantum Fan Level Description
  - This is a double spin asymmetry
  - This is for longitudinally polarized protons
- Rotating partons around spin direction
- Two classes of collisions:
  - Like helicity, i.e.,

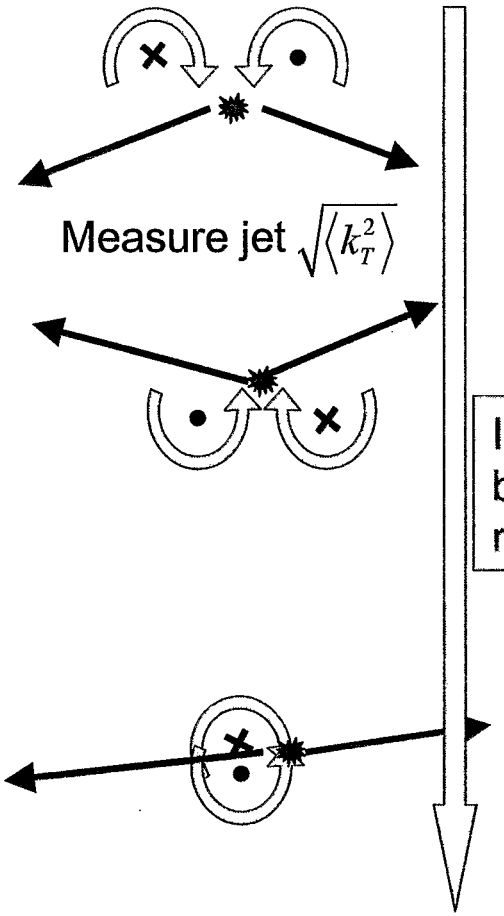


  - Un-like helicity, i.e.,



Like Helicity

(Positive on Positive Helicity)



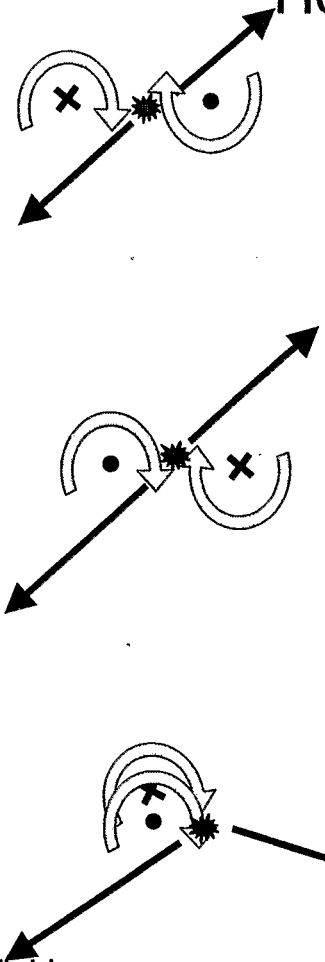
Peripheral Collisions
↓
Larger $\sqrt{\langle k_T^2 \rangle}$

Integrate over b, left with some residual k_T

Central Collisions
↓
Smaller $\sqrt{\langle k_T^2 \rangle}$

Un-like Helicity

(Positive On Negative Helicity)



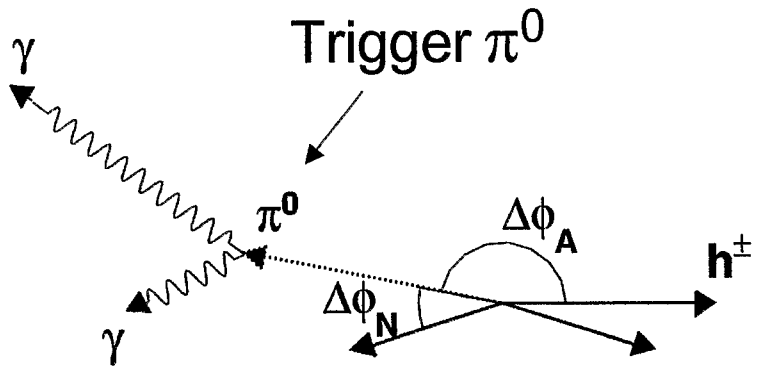
Peripheral Collisions
↓
Smaller $\sqrt{\langle k_T^2 \rangle}$

Integrate over b, left with some *different* residual k_T

Central Collisions
↓
Larger $\sqrt{\langle k_T^2 \rangle}$

How do we measure k_t?

- π^0 - $h^{\pm}$ azimuthal correlation functions



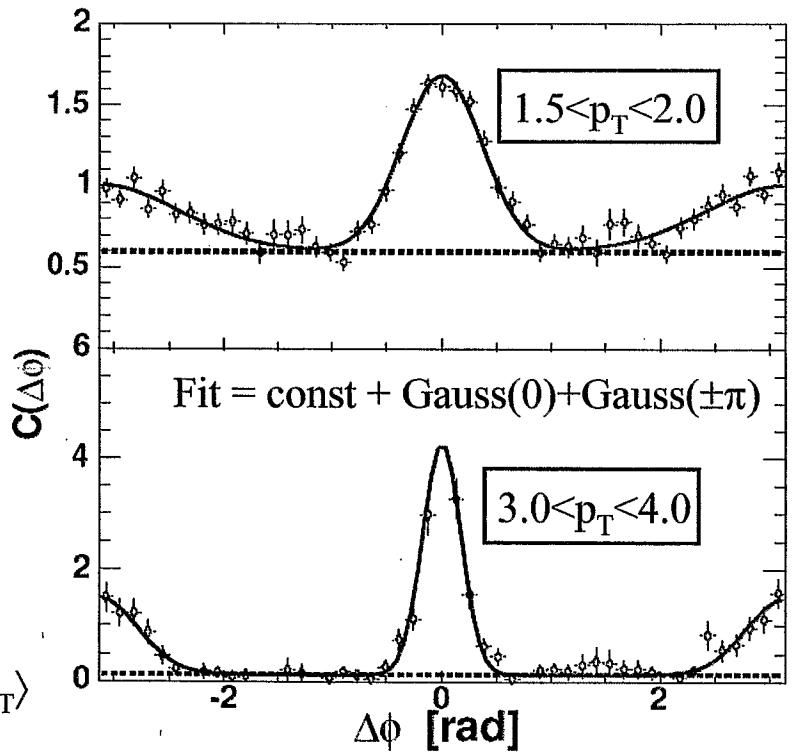
Intra-jet pairs angular width : $\sigma_N \rightarrow \langle j_T \rangle$

Inter-jet pairs angular width : $\sigma_A \rightarrow \langle j_T \rangle \oplus \langle k_T \rangle$

Correlation Functions

- dN^{real} $\Delta\varphi$ distribution from particles in the same event
- dN^{mixed} $\Delta\varphi$ distribution from particles in different events with similar vertex position
- Norm = $\sum N^{mixed} / \sum N^{real}$
- Fit to two gaussians plus a constant term

$$C_{ij}(\Delta\phi) = norm \cdot \frac{dN^{real}_{ij}}{d\Delta\phi_{ij}} \Big/ \frac{dN^{mixed}_{ij}}{d\Delta\phi_{ij}}$$



Intra-jet pairs angular width : $\sigma_N \rightarrow \langle j_T \rangle$

Inter-jet pairs angular width : $\sigma_A \rightarrow \langle j_T \rangle \oplus \langle k_T \rangle$

Summary

- We can, and are currently, making a measurement of the double-longitudinal spin dependence of jet $<k_T>$.
- This may be sensitive to orbital angular momentum.
- These effects (if really there) may also influence the double-longitudinal cross-section asymmetry.
- Need theoretical guidance…

SSA in the target fragmentation region of SIDIS

Aram Kotzinian

Torino University & INFN

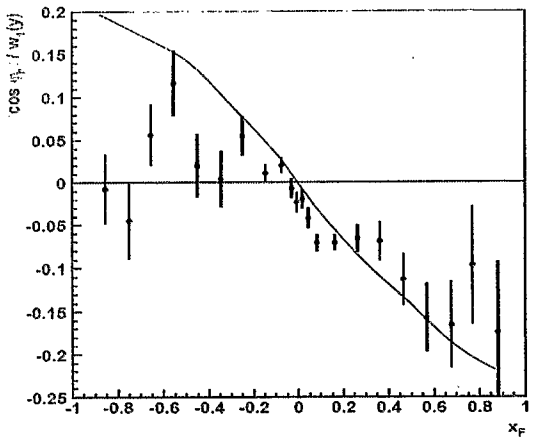
On leave in absence from YerPhI, Armenia and JINR, Russia

M.Anselmino, M.Boglione, U.D'Alesio, A.K., F.Murgia and A.Prokudin: **PRD 71, 074006 (2005)**

A.K.: **arXiv:hep-ph/0504081**

- Introduction
- Cahn and Sivers effects
- Phenomenology & Data in the CFR
- Intrinsic transverse momentum of partons in LEPTO
- Results for TFR
- Discussion & Conclusions

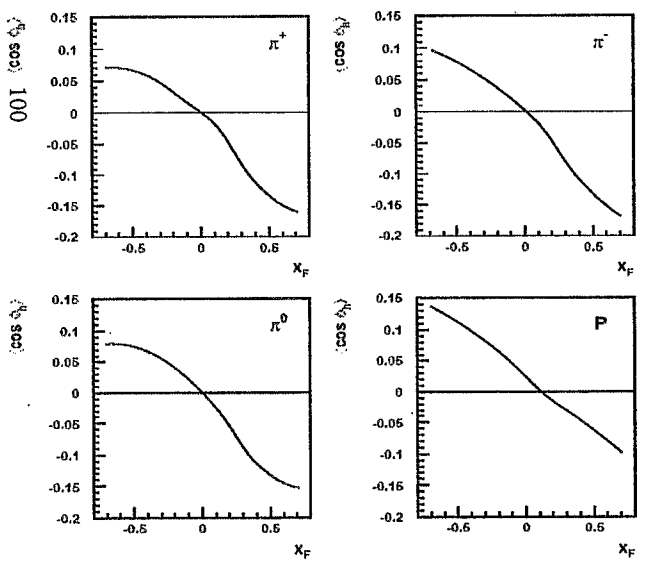
Results: Cahn



$w_1(y) = (2-y)\sqrt{1-y}/\,(1+(1-y)^2)$

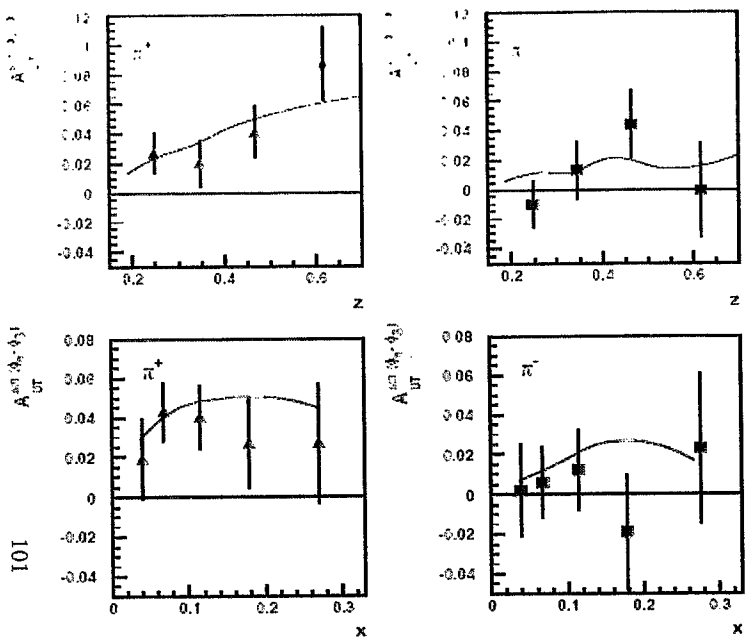
EMC Collaboration
for a beam energy of 280 GeV

Imbalance of measured $\langle \cos\phi_h \rangle$
in TFR and CFR: neutrals?



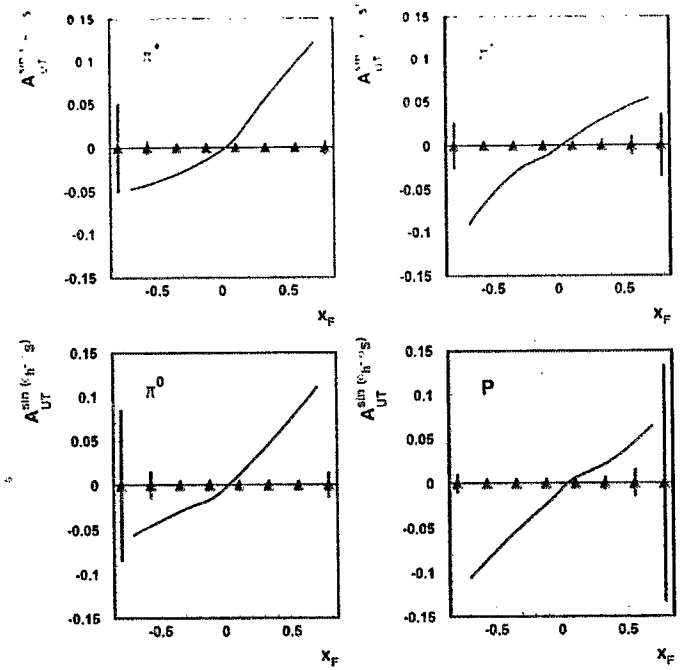
Predictions of modified LEPTO for x_F dependence of $\langle \cos\phi_h \rangle$ for different hadrons produced in 12 GeV unpolarized SIDIS process

Results: Sivers



HERMES data on $A_{UT}^{\sin(\phi_\pi-\phi_S)}$

z and x_{Bj}-dependences

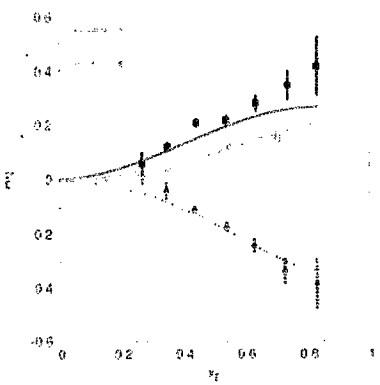


Predictions for JLab 12 GeV x_F-dependence

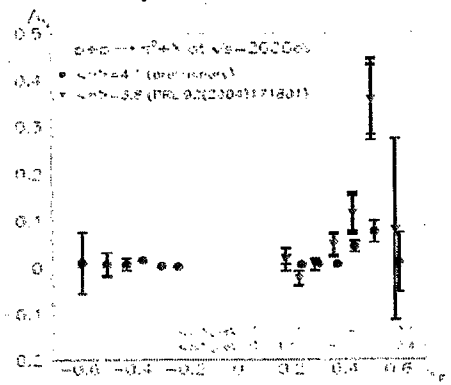
Red triangles with error bars – projected statistical accuracy for 1000h data taking (H.Avagyan).

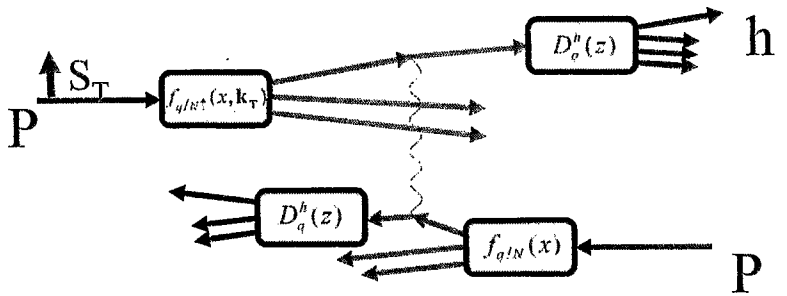
SSA in PP-interactions

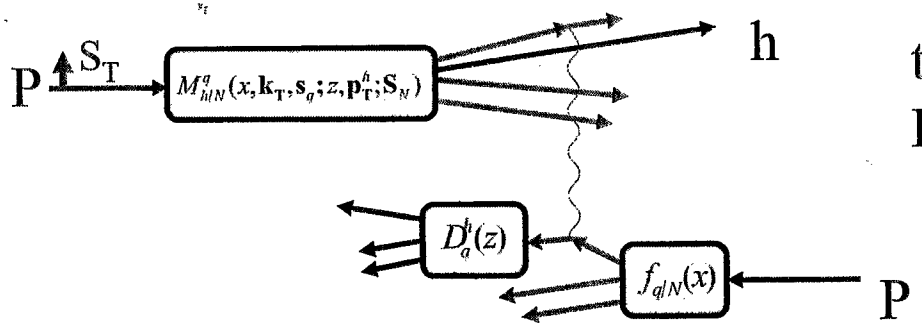
E704. Curves:
by Anselmino *et al,*



STAR
hep-ex/0505024







Which final hadrons provide transverse momentum balance? Look at forward baryons

More complicated string (color) configurations in the final state. Both the active quark and the polarized proton remnant are flying in forward direction. Which picture gives dominant contribution?

Discussion & Conclusions

- Both Cahn and Sivers effects are implemented in LEPTO. Possible effects of polarized hadronization were neglected.
  - Existing data in CFR are well described by modified LEPTO
  - The measured Cahn effect in the TFR is not well described
- Is there an universal mechanism describing SSA in SIDIS and PP interactions?
  - It will be interesting to implement Cahn and Sivers effects in PHYTIA
- It is important to perform new measurements of both effects in the TFR (JLab, HERMES, Electron Ion Colliders)
  - This will help better understand hadronization mechanism
    - Do the neutral hadrons compensate Cahn effect in CFR?
    - Multihadron final states distributions can enhance effects
    - Is there a similarity with PP-reaction?
- Fracture Function
  - Classification of spin and TMD dependent correlations in Fracture Functions
  - "Global" analysis

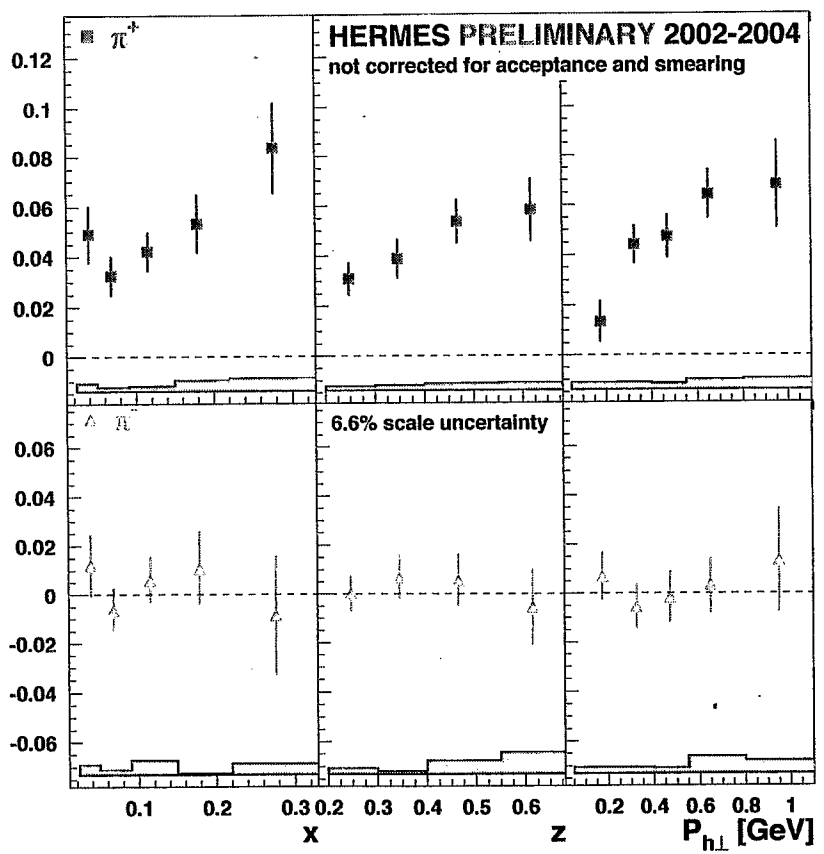
Single-Spin Asymmetries at HERMES

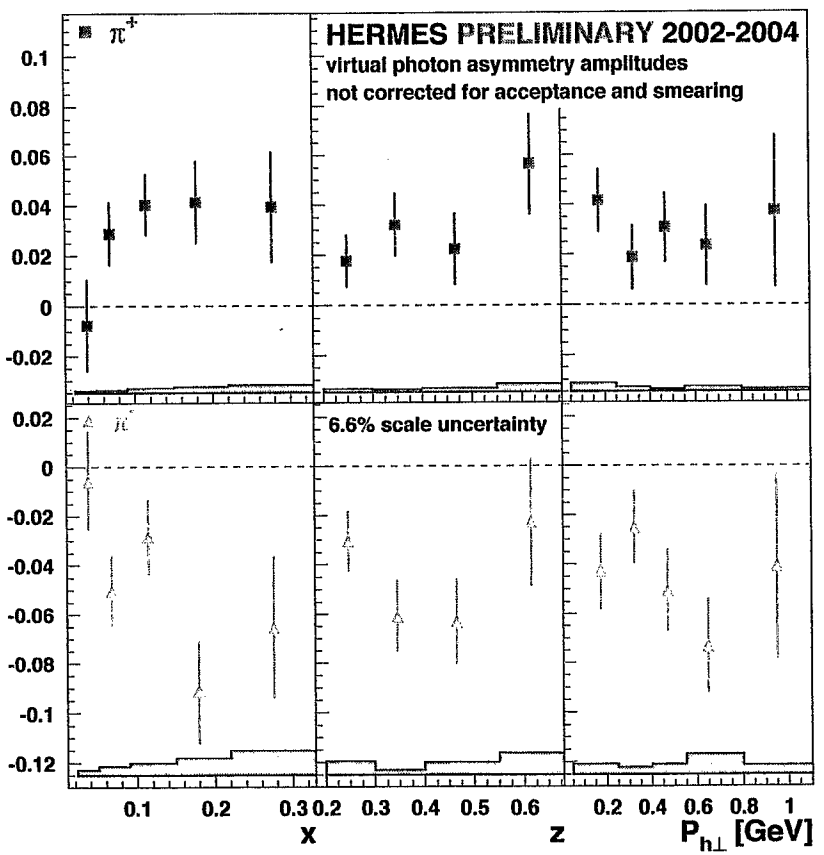
Naomi C.R. Makins
University of Illinois at Urbana-Champaign

The HERMES experiment began a second period of data taking in 2002, employing a transversely-polarized target for the first time. This new experimental configuration has enabled the study of single-spin asymmetries (SSAs) with a cleanliness of interpretation that was not available with the previous, longitudinally-polarized targets. The data collected in 2002 and the first months of 2003 we have already yielded a publication of the first clear separation of the so-called 'Collins' and 'Sivers' effects. The former is sensitive to the unknown transversity structure function of the proton, and to the novel 'Collins fragmentation function' which describes spin-orbit correlations in the fragmentation process. The Sivers effect, by comparison, is sensitive to a novel T-odd structure function within the proton itself, one which is related to the unknown orbital angular momentum of the quarks. In this talk, new results from the 2003-2004 data set will be presented, representing an increase in statistics of a factor of 4 as compared with the published measurement. Clear evidence of both the Collins and Sivers effects is observed. The measurements will be confronted with a variety of phenomenological models. They will be shown in particular to support a model of the Collins effect developed by Artru, and based on the Lund string-model of fragmentation. Two additional results from the new data will also be presented. One is a reanalysis of the previously-measured SSAs with longitudinal target polarization where the higher-twist component is isolated and shown to be dominant. The second is the first clear observation of the so-called interference fragmentation-function for pion pair production. The effect is shown to be of substantial size, but does not display the anticipated change of sign on either side of the rho mass.

New Results from 2002–2004: $H^{\uparrow}$ Target

π^+ π^+



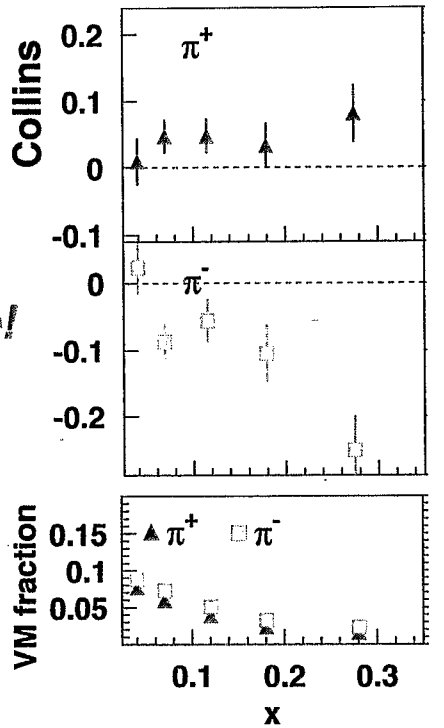


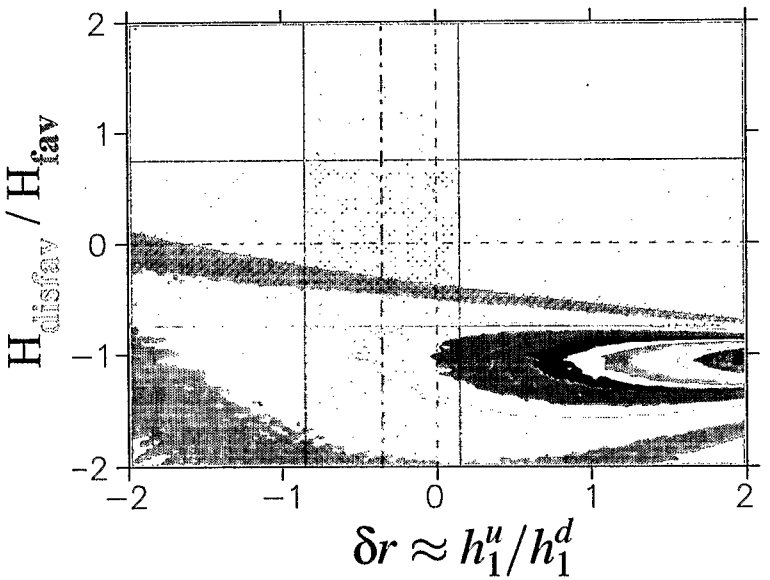
Why are the Collins π^- asymmetries so large?

DIS on proton target always dominated by ***u-quark scattering***

- $A_{\mathrm{Col}}^{\pi^+} \sim h_1^u \, H_{1,\mathrm{favored}}^{\perp}$ ... expect: **positive**
- $A_{\mathrm{Col}}^{\pi^-} \sim h_1^u \, H_{1,\mathrm{disfavored}}^{\perp}$ ... expect: ~ zero

Data indicate ***disfavored*** CollinsFF is ***large & negative!***



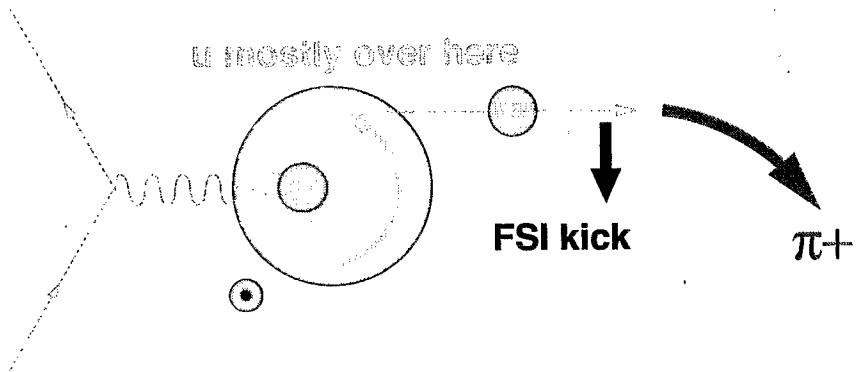


Map out solution space ...
find $H_{disfav} \approx -H_{fav}$

Dynamical Models for Sivers Mechanism

- M. Burkardt: Chromodynamic lensing

Electromagnetic coupling $\sim (J_0 + J_3)$ ***stronger for oncoming quarks***



We observe $\langle \sin(\phi_h^l - \phi_S^l) \rangle_{\mathrm{UT}}^{\pi^+} > 0$

(and opposite for π^-)

$\therefore$ for $\phi_S^l = \pi/2$, $\phi_h^l = \pi$ preferred...

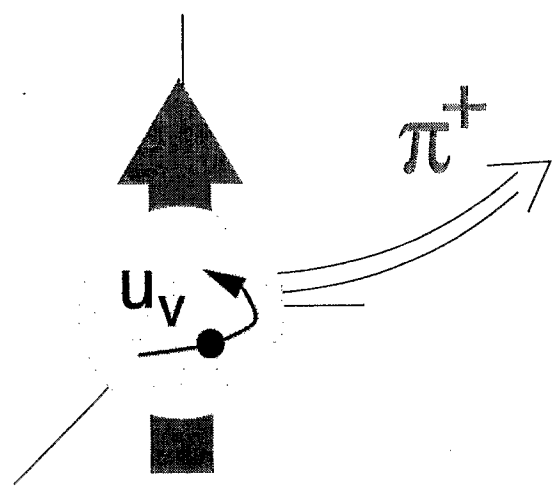
Model agrees!

- D. Sivers: Jet Shadowing

Parton energy loss considerations suggest
quenching of jets from
"near" surface of target

➡ quarks from "far" surface should dominate

Opposite sign to data ...

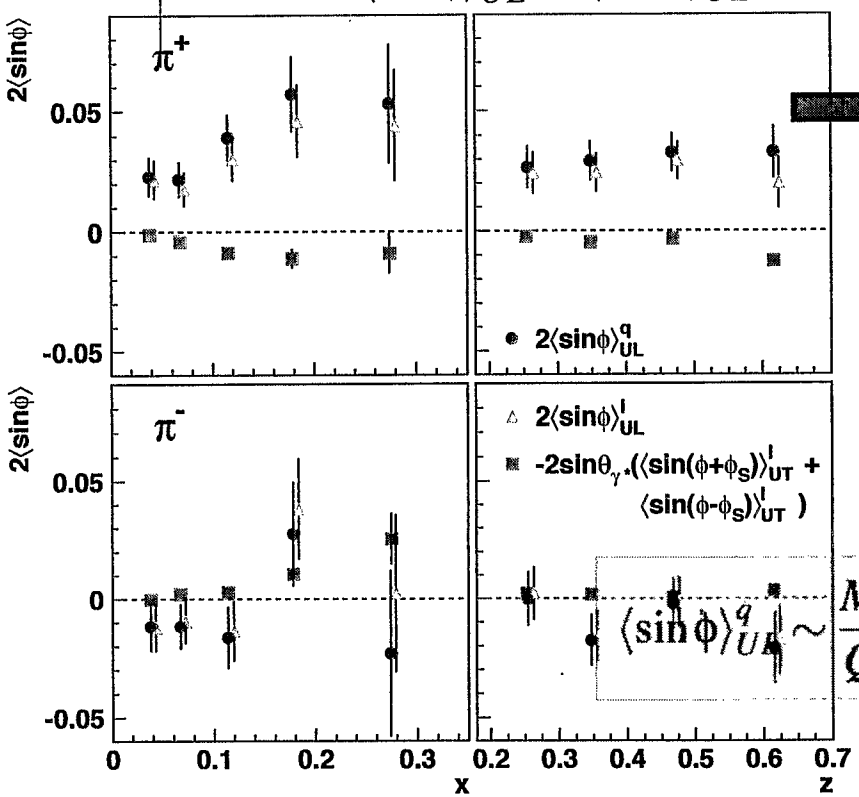


Revisiting the Longitudinal Target SSA's

Experiment: "longitudinal target" polarized // **lepton beam *l***
Theory: "longitudinal target" polarized // **virtual photon *q***

With both targets measured, can now extract pure *UL* moments

$$\langle \sin\phi \rangle^q_{UL} = \langle \sin\phi \rangle^l_{UL} + \sin\theta_{\gamma*}[\langle \sin(\phi+\phi_S)\rangle^l_{UT} + \langle \sin(\phi-\phi_S)\rangle^l_{UT}]$$



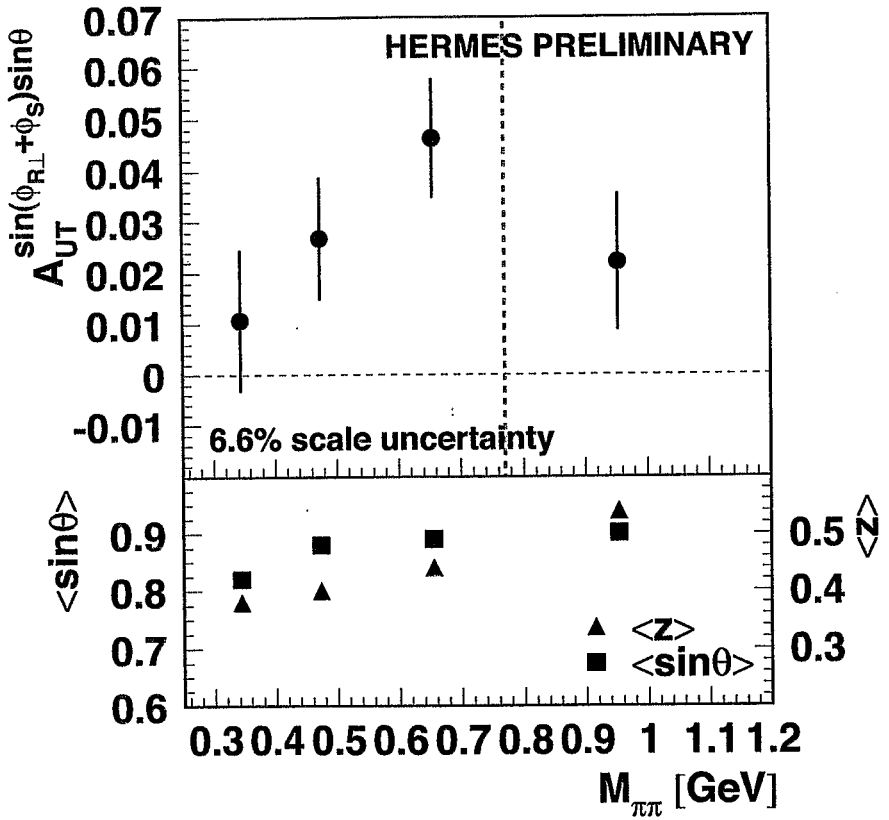
Correction is **small**: as anticipated earlier, A_{UL} ***is*** almost-entirely longitudinal (i.e. **twist-3)** in origin

Recent, more complete theoretical analysis of **sub-leading** $A_{UL}(\Phi)$ includes contribution from **twist-3 Sivers function $f_L^\perp$**

$$\langle \sin\phi \rangle^q_{UL} \sim \frac{M}{Q}\,\frac{I[g_{1L}G^\perp \oplus h_L H_1^\perp \oplus h_{1L}^\perp \tilde{H} \oplus f_L^\perp D_1]}{f_1 D_1}$$

Theoretical revisit needed ...

Invariant Mass Dependence



- positive asymmetry moment for all invariant mass bins
- result rules out predicted sign change at the ρ^0 mass (Jaffe et al.)

Where the following binning was used: 0.25 - 0.40 - 0.55 - 0.77 - 2.0

Slide from Paul van der Nat, DIS 2005

h_1

New Prospects for SSA in PHENIX

- It could already be that transversity and Collins are not important in p+p, and that gluon Sivers = 0.
  - Would be important to verify this independently with techniques that are a priori theoretically unambiguous

Sivers

- Given 0.35/pb of data, we should be able to get 1% statistical significance in A_N using gamma-charged measurements of jet $\Delta\phi$
- Expected raw A_N could be 3.5%
  - Could also be as low as 0.5%, or as large as 10%
- Effects from P=0.5, jet angle not aligned with transverse polarization, and fragmentation to dihadrons reduces raw A_N to ~1.0%

Collins

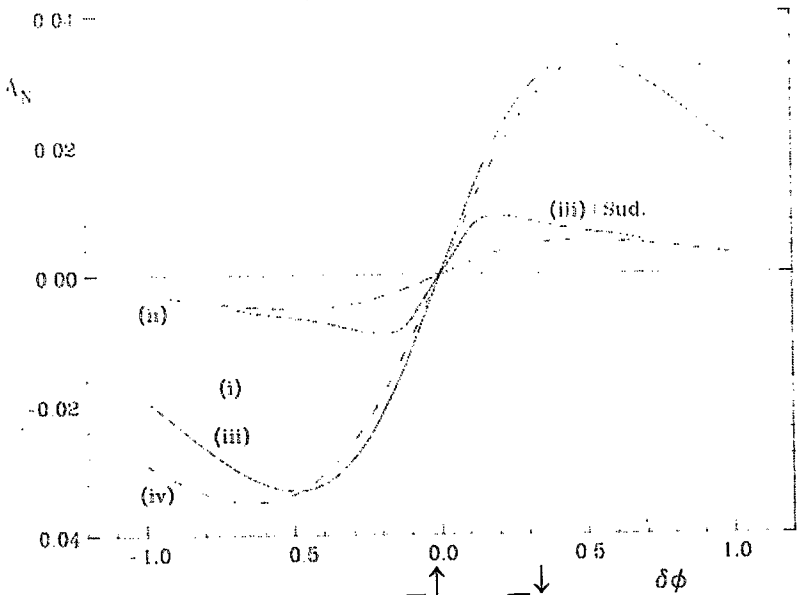
- Can Collins be directly measured at RHIC, ala Seidl?

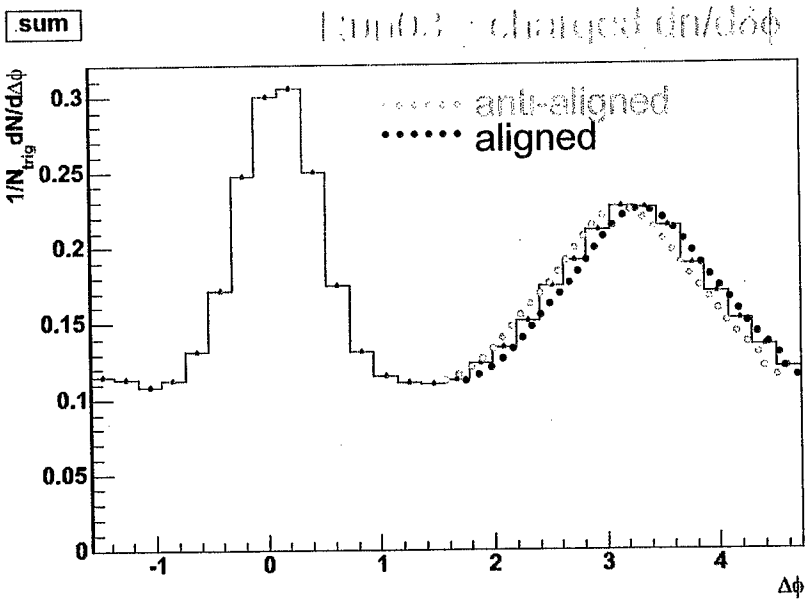
Higher Twist

- Contribution is whatever remains?

Mickey Chiu

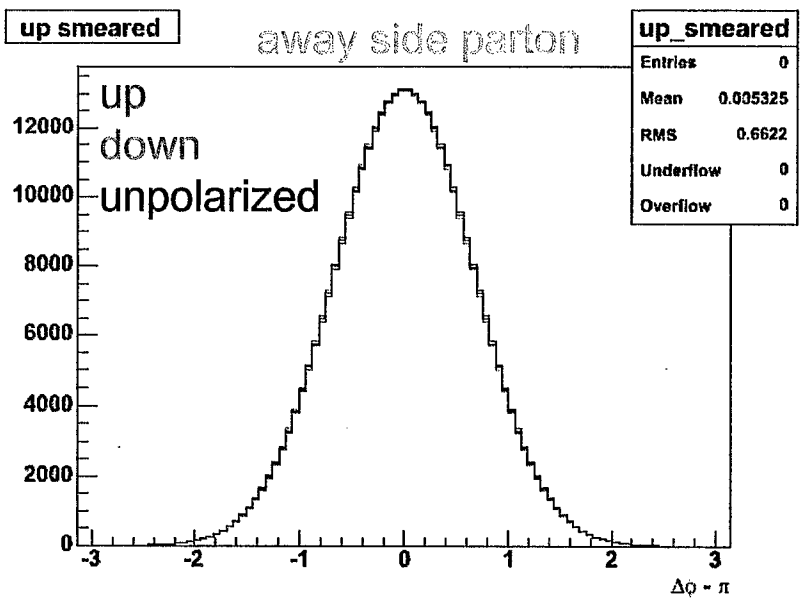
University of Illinois at Urbana-Champaign

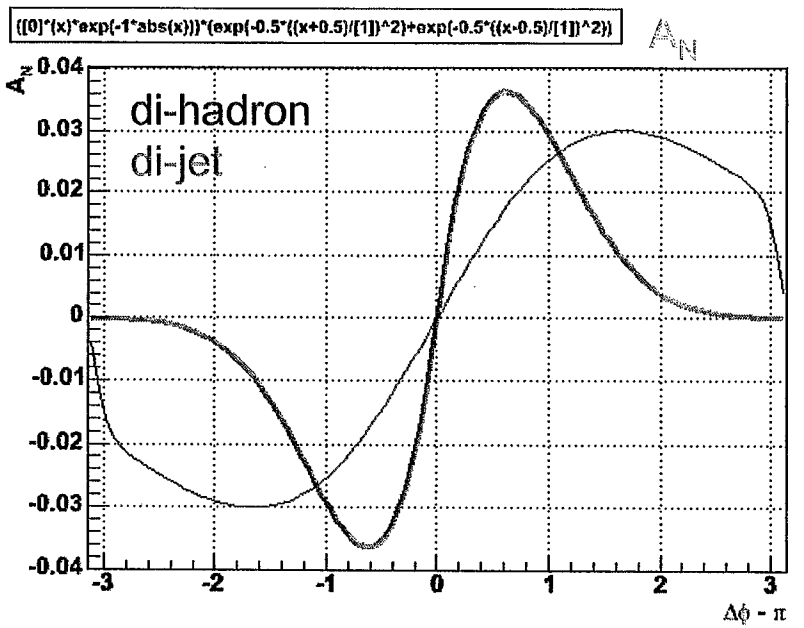




- Asymmetry $A_N \equiv \dfrac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$
  - numerator is difference between aligned and anti-aligned $\delta\phi$ dist's, where aligned means trigger jet and spin in same direction
  - denominator is simply unpolarized $\delta\phi$ distribution
- On left are some theoretical guesses on expected magnitude of AN from Siver's
- On right are gamma-charged hadron $\delta\phi$ dist's from Run03 p+p
  - 2.25 GeV gamma's as jet trigger, 0.6-4.0 GeV charged hadrons to map out jet shape
  - Dotted lines are schematic effect on away side $\delta\phi$ dist due to Siver's Fn (not to scale)

A_N Reduction: Di-Hadron vs. Di-Jets



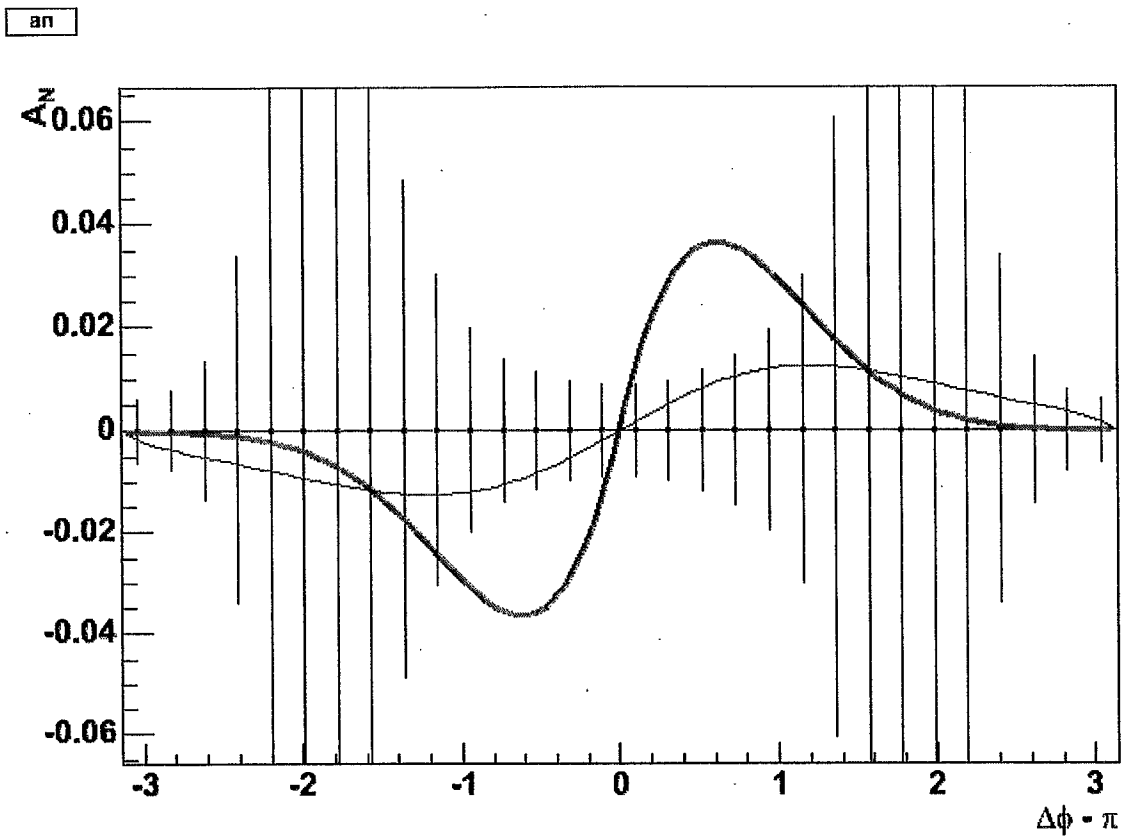


- Since we don't reconstruct jets fully, we have to use di-hadron correlations to measure jet $\delta\phi$. This smears out the di-hadron A_N relative to the di-jet A_N, with smearing function g (assumed here to be a gaussian, with σ_{jT}=0.35).

$$A_N^{dihad}(\Delta\phi) = \frac{\iint (N_{dijet}^{\uparrow}(x) + N_{dijet}^{\downarrow}(x)) A_N^{dijet}(x) g(x') \delta(x' - (\Delta\phi - x)) dx dx'}{\iint (N_{dijet}^{\uparrow}(x) + N_{dijet}^{\downarrow}(x)) g(x') \delta(x' - (\Delta\phi - x)) dx dx'}$$

- The effect broadens and lowers (by just a little bit) the asymmetry

Combined Effects

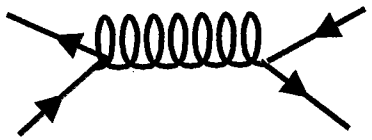


Full di-jet Sivers
Reduced by lower <P>, di-hadron smearing
Run03 p+p gamma-charged, 0.35/pb

[illegible] Collins in p+p?

e+e-

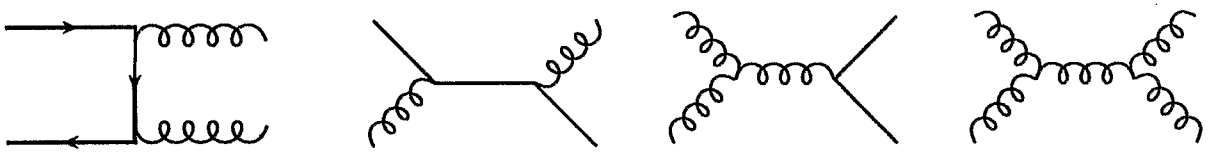
~



p+p

Belle
$\cos(2\phi_h)$ method
Seidl

- Important test of Universality and Scale Evolution
  - Collins needs to be known in p+p to get transversity from SSA
- p+p is much more complicated
  - Intrinsic k_T as well as radiative effects
  - Many other diagrams



- t-channel "dominates" over s-channel
  - At LO, this is a dilution of 10^{-3}
  - ~5% $\cos(2\phi_h)$ modulation at Belle becomes 0.5×10^{-4} modulation at RHIC
  - unpolarized beam required: ~ 300/pb (200 GeV), 980/pb (500 GeV)

Single-Spin Beam Asymmetries in QED and QCD

Andrei Afanasev

Jefferson Lab

RIKEN BNL Workshop on Single-Spin Asymmetries

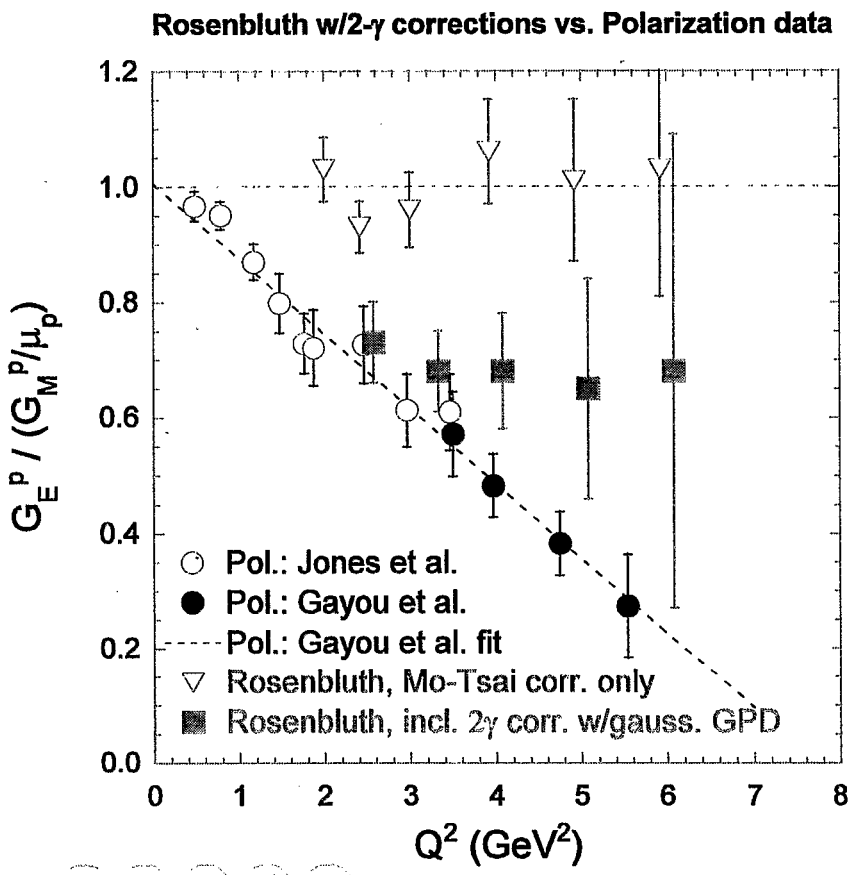
June 3, 2005, BNL

Jefferson Lab

Office of Science
U.S. DEPARTMENT OF ENERGY

Updated Ge/Gm plot due to 2-photon correction

AA, Brodsky, Carlson, Chen, Vanderhaeghen,
Phys.Rev.Lett.93:122301,2004; **hep-ph/0502013**



2-photon exchange correction
Computed using GPDs
Δs in parity-violation affected
At 10% level,
AA & Carlson, ***PRL 94, 212301 (2005):***

Special property of normal beam asymmetry

AA, Merenkov, Phys.Lett.B599:48,2004, Phys.Rev.D70:073002,2004; +Erratum (2005)

- Reason for the unexpected behavior: hard collinear quasi-real photons
  - Intermediate photon is collinear to the parent electron
  - It generates a dynamical pole and logarithmic enhancement of inelastic excitations of the intermediate hadronic state
  - For s>>-t and above the resonance region, the asymmetry is given by:

$$A_n^e = \sigma_{\gamma p} \frac{(-m_e)\sqrt{Q^2}}{8\pi^2} \cdot \frac{F_1 - \tau F_2}{F_1^2 + \tau F_2^2} (\log \frac{Q^2}{m_e^2} - 2)$$

Also suppressed by a standard diffractive factor exp(-BQ^2), where B=3.5-4 GeV^{-2}
Compare with no-structure asymmetry at small θ:

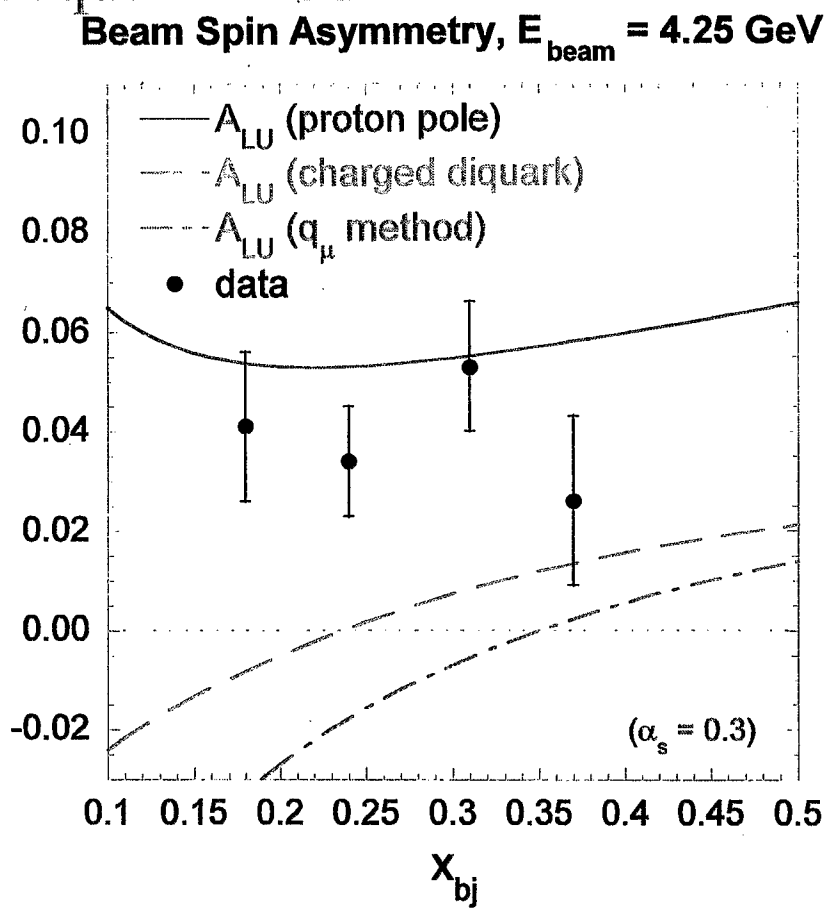
$$A_n^e \propto \alpha \frac{m_e}{\sqrt{s}} \theta^3$$

Mott Asymmetry Promoted to High Energies

- Excitation of inelastic hadronic intermediate states by the consecutive exchange of two photons leads to logarithmic and double logarithmic enhancement due to contributions of hard collinear quasi-real photons for the beam normal asymmetry
- The strongest enhancement has a form: $\log^2(Q^2/m_e^2)$ => two orders of magnitude+unsuppressed angular dependence
  - Can be generalized to transverse asymmetries in light spin-1/2 particle scattering via massless gauge boson exchange
  - Beam asymmetry at high energies is strongly affected by effects beyond pure Coulomb distortion
  - Supports Qiu-Sterman twist-3 picture of SSA
- What else can we learn from elastic beam SSA?
  - Check implications of elastic hadron scattering in QCD

    (Can large $A_{n,t}$ in pp elastic be due to onset of collinear multi-gluon exchange + inelastic excitations?)
  - Large SSA in deep-inelastic collisions due to hard collinear gluon exchange; in pQCD need NNLO to obtain unsupressed collinear gluons

Calculations vs CLAS'02 Data
Quark-Diquark Model *a la* BHS



Summary on beam SSA in SIDIS

- BSSA is due to the correlation, $\vec{S}_\gamma \cdot \vec{q} \times \vec{p}_h$
- Target SSA is due to $\vec{S}_p \cdot \vec{q} \times \vec{p}_h$
- Since no `artificially T-odd' fragmentatrion, named `photon Sivers effect' in AA, Carlson, **hep-ph/0308163**
- Beam SSA is suppressed by an extra power of 1/Q compared to target SSA, since it is due to LT (photon) interference
- Predictions for beam SSA do not depend on the assumptions of orbital angular momentum contribution to the nucleon light-cone wave function, while the remaining assumption (gluon exchange in the final state) is the same
- Result very sensitive to the method of restoring electromagnetic gauge invariance through adding *non-partonic* contributions

Azimuthal Asymmetry in Unpolarized Drell-Yan

Lingyan Zhu

University of Illinois at Urbana Champaign

SSA Workshop at BNL, Jun 1-3, 2005

- Large cos2ϕ azimuthal asymmetry has been observed in unpolarized pion-induced Drell-Yan.
- The are a few possible explanations including the non-zero Boer-Mulders function $h_1^{\perp}$, which may be related to Sivers function $f_{1T}^{\perp}$.
- The unpolarized proton-induced Drell-Yan may provide some useful information.

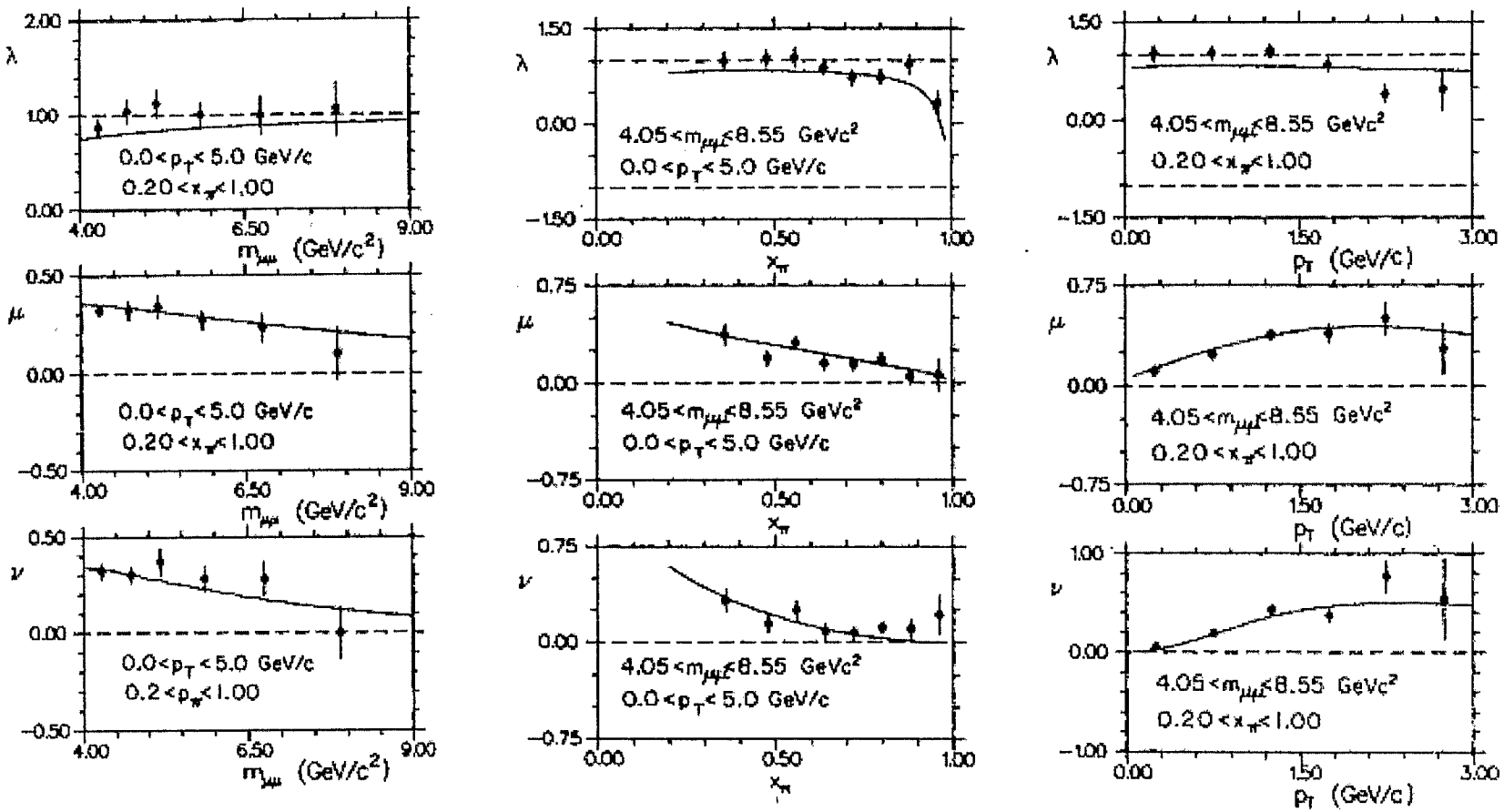
Referring to:

D. Boer's talk, G. Goldstein's talk and A. Bacchetta's talk at SIR2005

J.C. Peng's talk at E866 collaboration meeting in Oct 2004.

Angular Distribution in the πN Drell-Yan Process

E615 at Fermilab: 252 GeV π^- + W Conway et al., PRD39,92(1989)



Also see NA10 results: 140/194 GeV π- + W, 286 GeV π- + W/d

Z. Phys. C31, 513 (1986); Z. Phys. C37, 545 (1988)

What did we Learn from Data?

- There is a sizable $\cos 2\phi$ asymmetry (ν up to 0.3) in the unpolarized pion-induced Drell-Yan. The Lam-Tung sum rule is violated beyond the QCD-improved parton model.

- The asymmetry is not sensitive to the nuclear correction for nuclei.

- The asymmetry increases as P_T increases.

- The asymmetry remains flat (at 140,194 GeV) or decreases (at 252, 286 GeV) as dimuon mass increases. The dependence of the asymmetry on x_π also changes with beam energy.

- $\lambda \sim 1$ and $\mu \sim 0$ but with some deviation for a few cases.

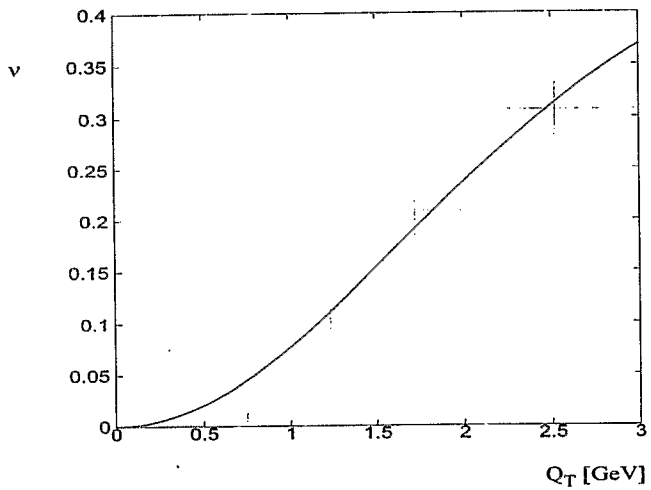
Boer-Mulders Function $h_1^{\perp}$

Boer, PRD60,014012(1999)

•An spin-correlation approach in terms of $h_1^{\perp}$ can fit the NA10 data at 194 GeV.

$$2\nu = 4\kappa = 8\kappa_1 \frac{Q_T^2 M_C^2}{(Q_T^2 + 4M_C^2)^2}; \lambda = 1; \mu = 0$$

•It can also account for the single spin asymmetry in pp"! π X.



$$\nu \propto h_1^{\perp} \bar{h}_1^{\perp}$$

$$h_1^{\perp}(x, k_T^2) = \frac{\alpha_T}{\pi} c_H \frac{M_C M_H}{k_T^2 + M_C^2} e^{-\alpha_T k_T^2} f_1(x)$$

κ_1=0.5

m_C=2.3

α_T=C_H=1

•On the base of quite general arguments, for $|q_T|$<<Q(=mμμ),

$$\nu \propto |q_T|^2/Q^2$$

Salvo,hep-ph/0407208.

What did we Learn from Models?

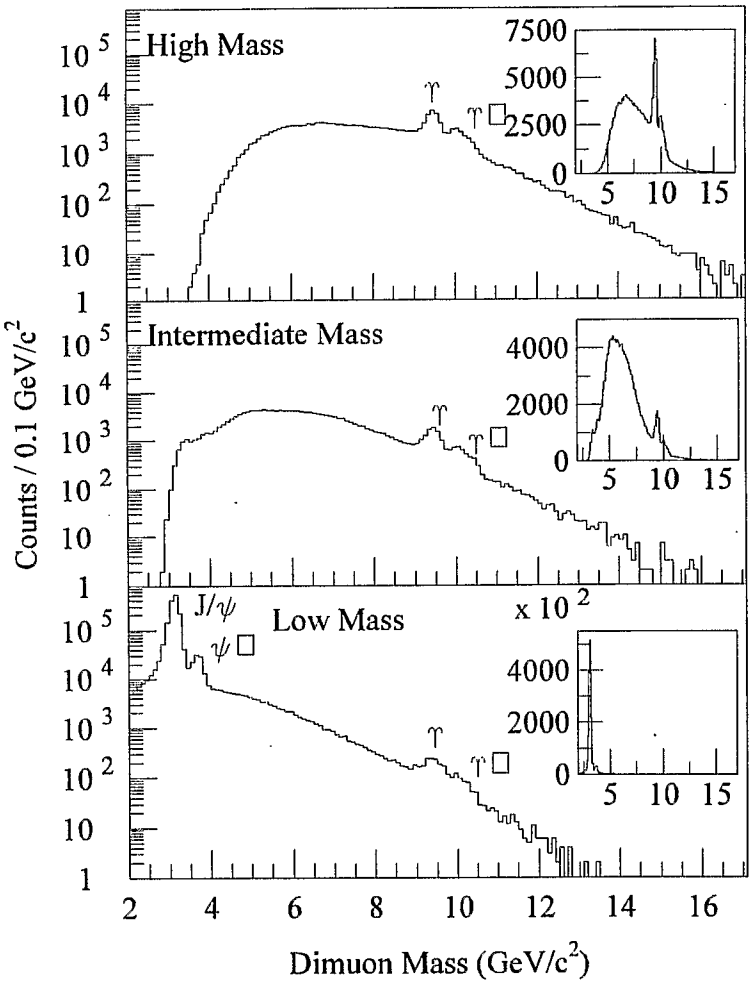
- The high twist effect in terms of pion bound state effect is not enough to explain the large $\cos 2\phi$ asymmetry and the violation of Lam-Tung sum rule. In this model, λ and μ also changes with P_T.

- The spin correlation due to nontrival QCD vacuum may cause $\cos 2\phi$ asymmetry. In instanton model, it relates to the helicity flip of one quark/antiquark in the initial state.

- The non-zero chiral-odd distribution function $h_1^{\perp}$ may cause $\cos 2\phi$ asymmetry, which can be realized in spectator model and MIT bag model with initial/final-state interaction.

  It is equal to Sivers function $f_{1T}^{\perp}$ in the quark-diquark spectator model, which can be fitted from transverse SIDIS data with a negative sign. The sign of $h_1^{\perp}$ for d quark is different in spectator model and in MIT bag model, while it is the same for u quark.

Dimuon Mass Distribution



$\sqrt{s} = 38.8\text{GeV}$

Proton and Deuterium Target

Sea asymmetry with Drell-Yan

High: 4.5<M<9.0, M>10.7; 141k

Intermediate: 4.3<M<8.8, M>10.8; 128k

Low: 4.0<M<8.8; 89k

Towell et al., Phys.Rev. D64 (2001) 052002

Single Spin Asymmetries: from JLab12 to EIC

*Harut Avakian *)*
Jefferson Lab

- Introduction
- Semi-Inclusive processes and TMD distributions
- Hard exclusive processes and GPDs
- Summary

Single-Spin Asymmetries Workshop, BNL June 1-3, 2005

*) In collaboration with V. Burkert and L. Elouadrhiri

We present future measurements of Single Spin Asymmetries (SSAs)
in semi-inclusive and hard exclusive processes
proposed for the upgraded to 12 GeV JLab,
and their possible extension to higher energies of
the Electron Ion Collider (EIC).

In the semi-inclusive processes measure the
momentum transfer to quarks,
giving access to their transverse momentum distributions (TMDs).
In exclusive processes
we measure momentum transfer to target and probe
spatial distributions, described by Generalized Parton Distributions (GPDs).
These two sets of nonperturbative functions are complimentary and together
provide a complete description of the nucleon structure.

Significant gain in acceptance of the upgraded CLAS detector at JLab,
provided by both energy and luminosity upgrade will allow measurements
of Q2-dependences and P_T dependences of different
observables to probe the transition to perturbative limit and study
different partonic distributions in a wide kinematic range.

Higher Q2 and lower x coverage of EIC will allow Q2 dependence studies
in a wide range and may be crucial for
certain processes, in particular involving vector mesons.

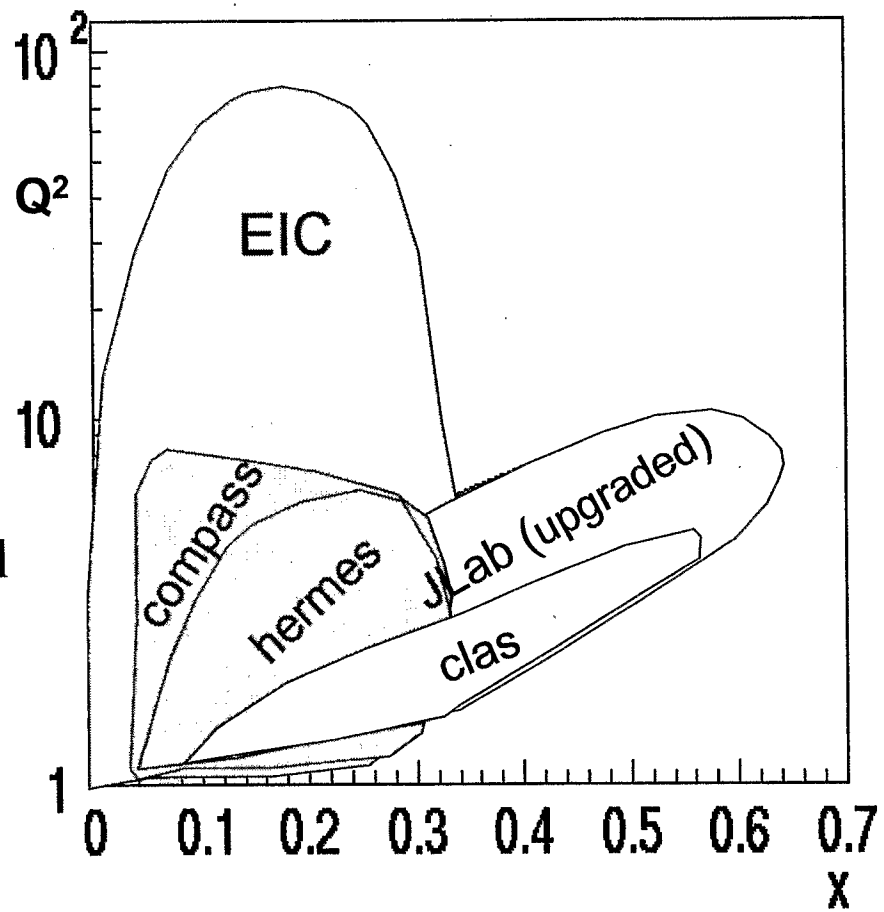
Projections for CLAS12, shown for ~1000h running, are presented
for different observables including Collins, Kotzinian-Mulders,Sivers
asymmetries for SIDIS and DVCS and rho
asymmetries for hard exclusive processes, with different target polarizations.

Kinematic coverage provided by EIC is discussed for all relevant
observables. Processes accessible at higher energies of EIC are also discussed.

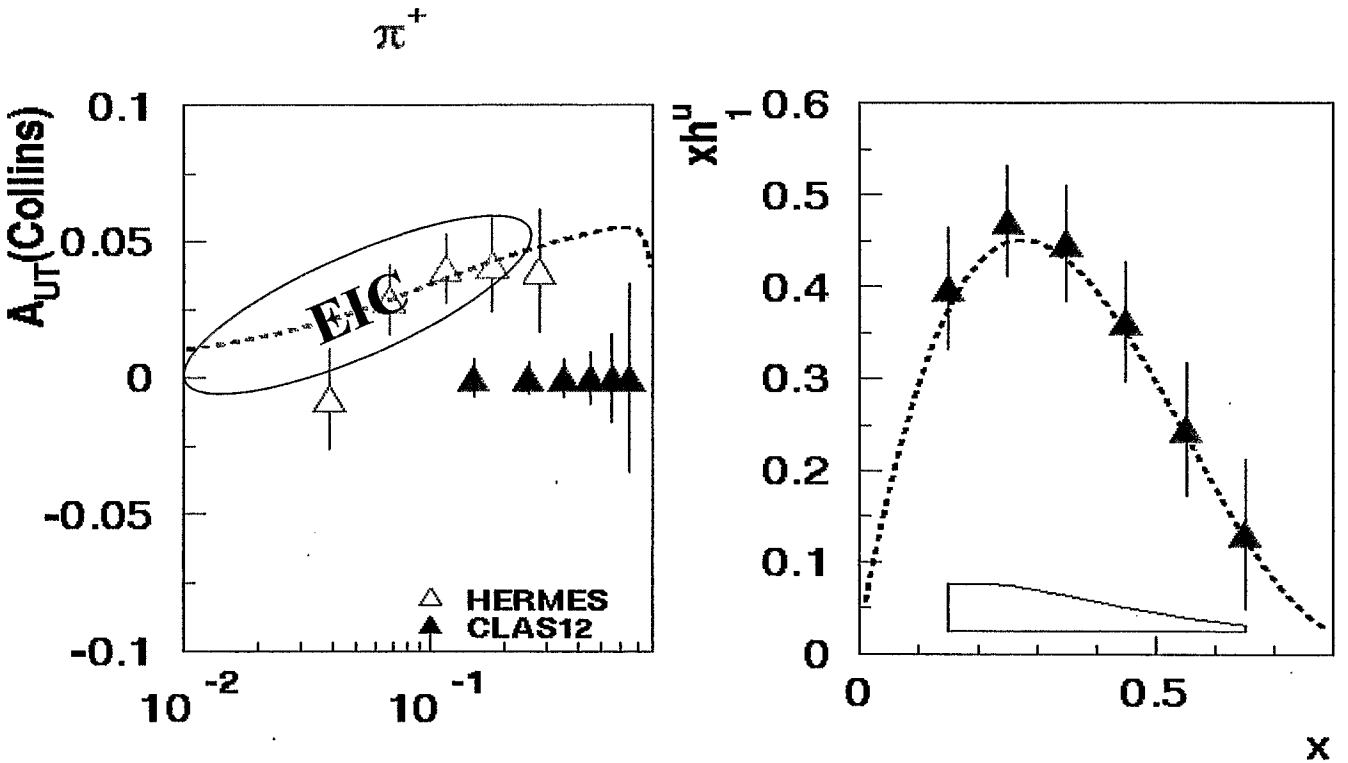
EIC

– Collider measurements, requiring high luminosity ($L \sim 10^{35} cm^{-2} sec^{-1}$), and wide coverage, will vastly increase the kinematics and the scope of observables.

–Large Q^2 may be crucial for precision studies of hard exclusive meson production.



From CLAS12 to EIC: Transversity projections



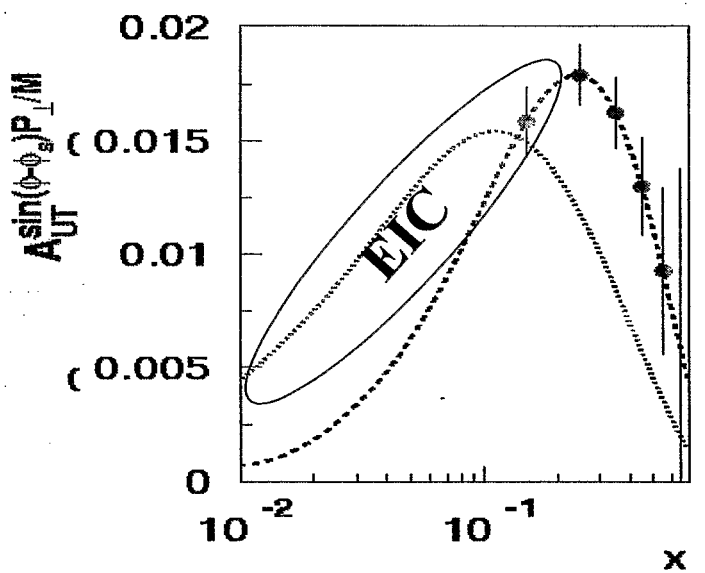
Simultaneous measurement of, exclusive ρ,ρ+,ω with a transversely polarized target
The background from vector mesons very different for CLAS12 and EIC.

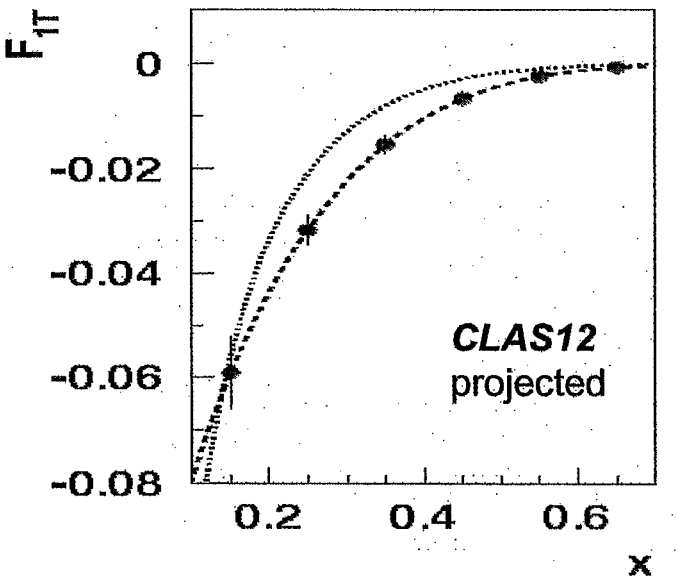
From CLAS12 to EIC: Sivers effect projections

In large Nc limit:
$f_{1T}^{u} = -f_{1T}^{d}$

$F_{1T} = \sum_q e_q^2 f_{1T}^{\perp q}$

Efremov et al
(large x_B behavior of
f_{1T} from GPD E)





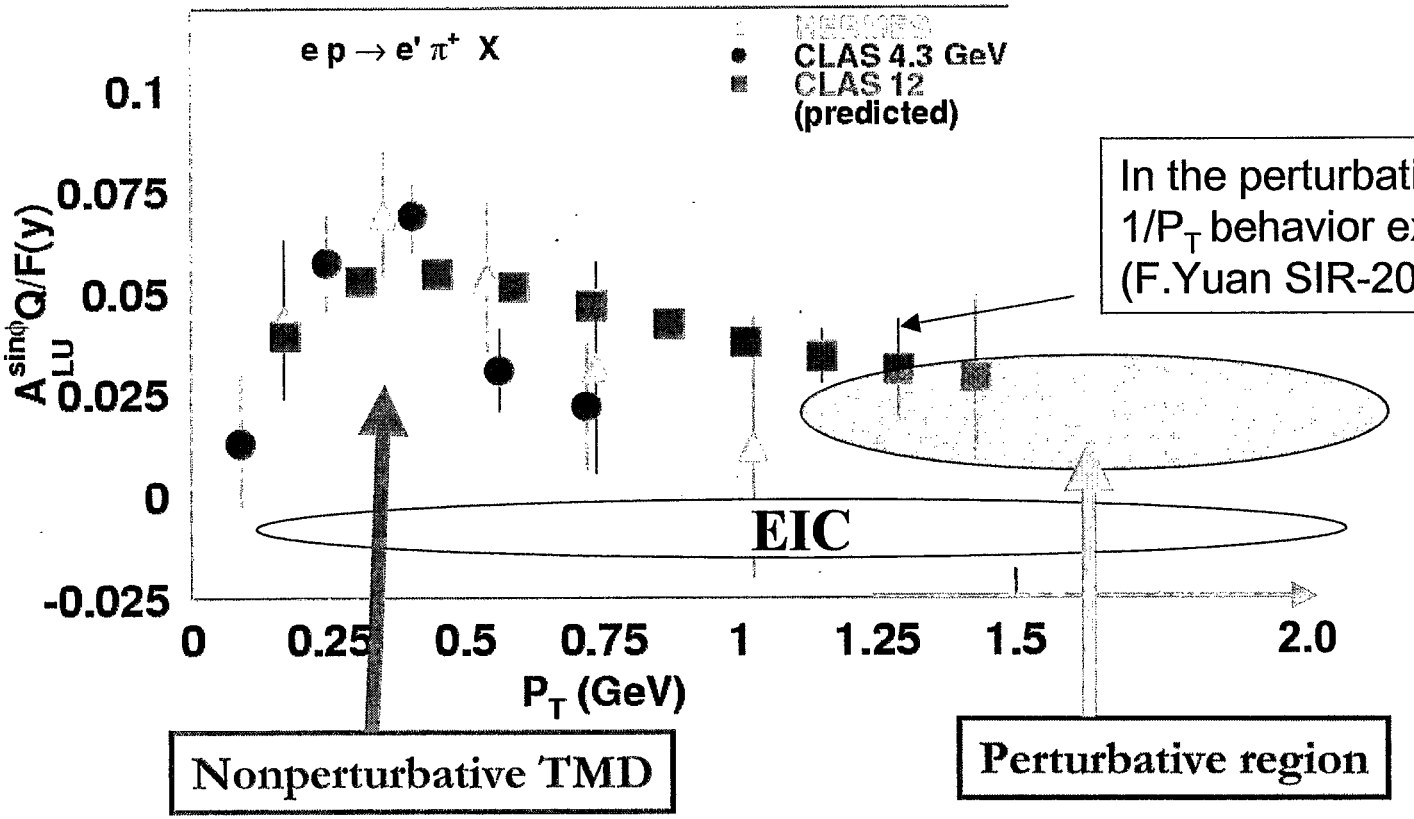
Sivers function extraction from A_{UT} (π^0) does not require information on fragmentation function. It is free of HT and diffractive contributions.

A_{UT} (π^0) on proton and neutron will allow flavor decomposition w/o info on FF.

P_T-dependence of beam SSA

$\sigma^{\sin\phi}_{LU(UL)} \sim F_{LU(UL)} \sim 1/Q$ (Twist-3)

$$A_{LU} \propto g^{\perp(1)}(x) D_1(z)$$



In the perturbative limit $1/P_T$ behavior expected (F.Yuan SIR-2005)

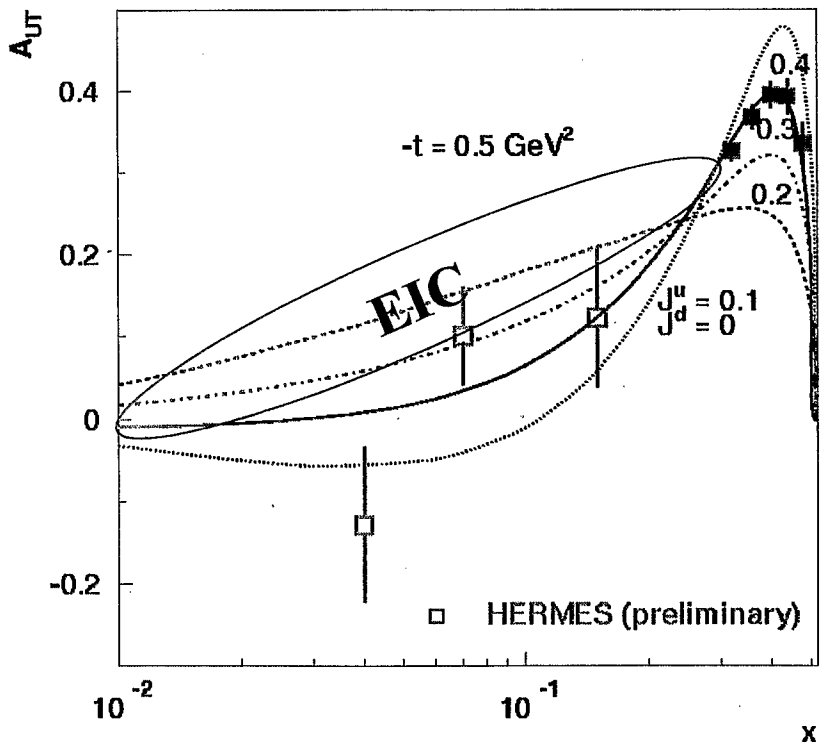
Nonperturbative TMD

Perturbative region

Asymmetries from k_T-odd and k_T-even (g_1) distribution functions are expected to have a very different behavior (**flat $A_1^p(P_T)$ observed at 5.7 GeV**).

Exclusive $\rho^{()}$ production on transverse target

$$A_{UT} = -\frac{2\Delta_\perp(\mathrm{Im}(AB^*))/\pi}{|A|^2(1-\xi^2) - |B|^2(\xi^2+t/4m^2) - \mathrm{Re}(AB^*)2\xi^2}$$



ρ^0

$A \sim 2H^u + H^d$
$B \sim 2E^u + E^d$

ρ^+

$A \sim H^u - H^d$
$B \sim E^u - E^d$

E^u, E^d needed for angular momentum sum rule.

K. Goeke, M.V. Polyakov, M. Vanderhaeghen, 2001

Summary

- *CLAS12* will be full acceptance, general purpose detector for high luminosity electron scattering experiments, and is essential for the GPD/TMD program.
  - Provide new insight into
    - quark orbital angular momentum contributions to the nucleon spin
    - 3D structure of the nucleon's interior and correlations
    - quark flavor polarization

- *EIC* will extend studies of nucleon structure performed by JLAB12 with high precision in the valence region, to low x and high Q^2, including
    - deeply virtual exclusive processes (DVCS, DVMP)
    - semi-inclusive meson production with polarized beam and polarized targets

Traverse Spin Physics at RHIC II

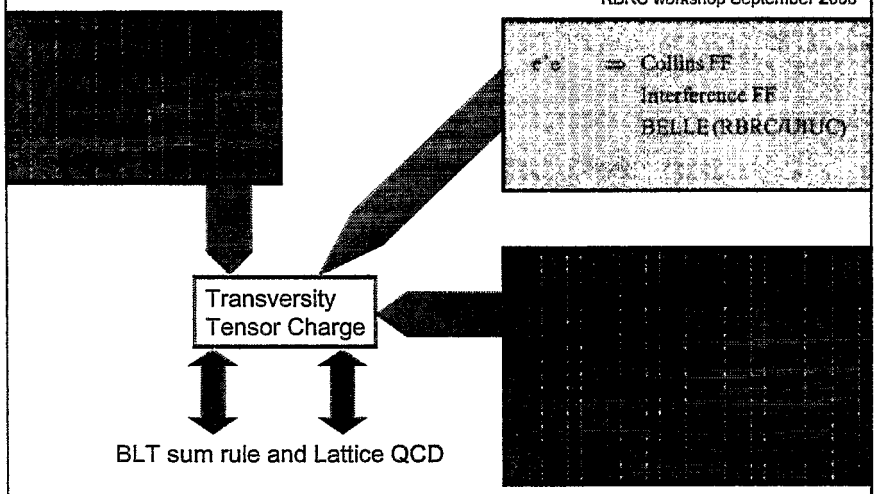
Matthias Perdekamp
University of Illinois at Urbana-Champaign and
RIKEN BNL Research Center

Transverse Spin Physics at RHIC II

- Motivation
  - Reconcile QCD with SSA observed in pp
  - Map out transverse proton spin structure (global QCD analysis of pp, SIDIS and e+e-)
  - Fundamental tests of QCD:
    - → Tensor Charge: Lattice QCD vs experiment
    - → Sivers sign in Drell Yan vs SIDIS
  - Prerequisites for a transverse spin program
- Transverse spin physics at RHIC
  - Polarized collider + experiments
  - Overview of available measurements vs luminosity
- RHIC II
  - Luminosity
  - Detector upgrades
  - A dedicated Drell Yan experiment for transverse spin physics?
  - Tensor charge at e-RHIC?
- Summary

Motivation: Global Transversity Analysis

RBRC workshop September 2000



Transverse Spin Physics at RHIC II

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Motivation: Global Transversity Analysis

RBRC workshop September 2000

e^+e^- ⇒ Collins FF
Interference FF
BELLE (RBRC/UIUC)

Transversity
Tensor Charge

BLT sum rule and Lattice QCD

Transverse spin program at RHIC is luminosity limited

	luminosity sufficient?
A_N	yes, very good
A_N(back-to-back)	good (Sivers signature!)
A_T (Collins FF)	ok
A_T (Interference FF)	poor
A_{TT} (Jets)	not studied experimentally
A_T (Drell Yan)	—
A_{TT}(Drell Yan)	—
Direct photons (A_N,A_T(CFF, IFF))	—

RHIC by 2009 at 200 GeV

$\int$Ldt ~275pb^{-1} delivered

$\int$Ldt ~100pb^{-1} accepted (eg. PHENIX: vertex cut, trigger efficiencies, duty factor)

→ $\int$Ldt ~25 pb^{-1} transverse

RHIC II

Dedicated Experiment for Drell Yan

Idea: Large acceptance calorimeter experiment at PHOBOS interaction point (10 o'clock)

Physics: A_{TT}(DY) → transversity
A_{UT} (DY) → Sivers
A_{TT} (Jets) → transversity, correlations
unpolarized DY?

Exp. Param.: Re-use existing EMC + HCAL elements, pad-chamber layer for charged particle tagging, BBC, ZDC (exists), utilize PHENIX FEE, DAQ and trigger for dead time free read out
→ $-3<\eta<3$, sample all verticies.

Low cost?

Advantages:
- 100% transverse spin
- take advantage of luminosity upgrades, large acceptance, wide vertex cuts and dead time free read out for maximum $\int$Ldt

Expected effective Luminosity in 10 weeks

100% transverse running

➔125pb^{-1} delivered in 10 weeks (projected 2008 number)

x 0.6 (vertex, trigger efficiency, DAQ dead time, up-time

x 2.5 (e-cooling)

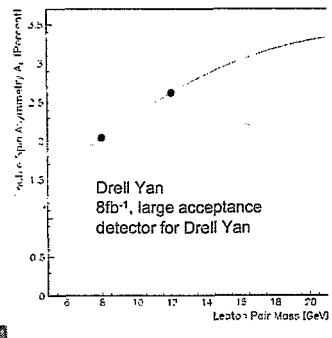
x 4 (mini quads)

x 8 (acceptance)

= 6000 pb^{-1}

Projections for pp at 200 GeV and 8000 pb^{-1}

A_{TT} for Drell Yan with PHENIX



projections for 10 weeks of running, 5-10% higher polarization, with RHIC II luminosities and large acceptance

This measurement appears to be also possible at 500 GeV

Projections for A_{UT} in Drell Yan

Ongoing work by M. Anselmino, U. D'Alesio and J. Collins, K. Goeke, S. Menzel, A. Metz and P. Schweitzer

$$A_{UT}^{\sin(\phi-\phi_S)\frac{q_T}{M}} \propto \frac{\sum_{flavors} x_1 \cdot \text{Sivers-df} \cdot x_2 \cdot \text{a-quark-df}}{\sum_{flavors} x_1 \cdot \text{quark-df} \cdot x_2 \cdot \text{a-quark-df}}$$

Using parametrizations of the Sivers function first estimates of the asymmetry at 200 GeV and Q~5 to 20 GeV give about 5%. The statistical error in two invariant mass bins will be less than 0.3%.

Comments

Pending careful evaluation of the experimental resolution, it appears that a dedicated Drell Yan experiment taking advantage of RHIC II luminosity upgrades and large acceptance will be able to carry out clean transversity and Sivers function measurements with good statistical resolution.

Possible measurements in un-polarized DY need to be evaluated.

The experiment could be based on existing detector hardware and utilize front end-, DAQ and trigger electronic designs developed for RHIC experiments. This will keep the cost low.

Running could start well before RHIC II upgrades are completed. From 2012 full RHIC II luminosity should be available.

The experiment offers interesting physics during the transition between the present Hermes and COMPASS experiments and future efforts: e-RHIC and GSI.

Single Spin Asymmetries
June 1-3, 2005
List of Registered Participants
(as of May 31, 2005)

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" Single-Spin Asymmetries "

(All talks will be in the Large Seminar Room of the Physics Department, Bldg. 510)

Wednesday, June 1 :

Morning session: (Chair: Xiangdong Ji)

8:30 - 9:00		*Registration*
9:00		*Welcome*
9:05 - 9:50	Les Bland	*Results and Plans for Transverse Spin Effects at STAR*
9:50 - 10:30	Jianwei Qiu	*Single Transverse Spin Asymmetries*
10:30 - 11:00		*Coffee Break*
11:00 - 11:45	Harut Avagyan	*Spin and Azimuthal Asymmetries at JLab*
11:45 - 12:30	Christine Aidala	*SSA of Mid-rapidity Pi0 and Charged Hadrons at PHENIX*

Afternoon session: (Chair: Yuji Goto)

14:00 - 14:45	Flemming Videbaek	*Single-Spin Asymmetries at BRAHMS*
14:45 - 15:25	Yuji Koike	*Twist-3 Mechanism for Single Spin Asymmetries*
15:25 - 16:05	Umberto D'Alesio	*SSA and Partonic Intrinsic Motion*
16:05 - 16:30		*Coffee Break*
16:30 - 17:10	Daniel Boer	*Sudakov suppression of asymmetries involving TMDs*
17:10 - 17:50	Dennis Sivers	*Orbital Structures in Hadronic Distributions*

Thursday, June 2 :

Morning session: (Chair: Daniel Boer)

9:00 - 9:40	Xiangdong Ji	*QCD Factorization for the semi-inclusive processes*
9:40 - 10:20	Ralf Seidl	*Measurements of Chiral-Odd Fragmentation Functions at Belle*
10:20 - 11:00	Manabu Togawa	*SSA of forward neutron at PHENIX*

11:00 - 11:20		*Coffee Break*
11:20 - 12:00	Xiaodong Jiang	*The Program of Transversity Experiments at Jefferson Lab*
12:00 - 12:40	Cedran Bomhof	*T-odd Effects in Hadronic Scattering Processes*

Afternoon session: (Chair: Dennis Sivers)

14:00 - 14:40	Jian-Ping Chen	*Single Target Spin Asymmetry and GPD's*
14:40 - 15:20	Leonard Gamberg	*Transversity in Azimuthal and Single Spin Asymmetries*
15:20 - 16:00	Douglas Fields	*Measuring Orbital Angular Momentum through Jet k_T*
16:00 - 16:30		*Coffee Break*
16:30 - 17:10	Aram Kotzinian	*Cahn and Sivers effects in the target fragmentation region of SIDIS*
17:10 - 17:50	Dmitry Ostrovsky	*Single-Spin Asymmetries in DIS: An Instanton Approach*

18:00 - 20:00 Workshop Dinner at Brookhaven Center

Friday, June 3 :

Morning session: (Chair: Werner Vogelsang)

9:00 - 9:40	Naomi Makins	*HERMES Results*
9:40 - 10:20	Mickey Chiu	*New Prospects for SSA Measurements with PHENIX*
10:20 - 11:00	Steve Heppelmann	*Forward Neutral Mesons at STAR*
11:00 - 11:20		*Coffee Break*
11:20 - 12:00	Andrei Afanasev	*Single-Spin Beam Asymmetries in QCD and QED*
12:00 - 12:40	Lingyan Zhu	*Azimuthal asymmetry in unpolarized Drell-Yan?*

Afternoon session: **Jointly with Spin Working Group of RHIC-II Workshop**
(Conveners: Matthias Grosse-Perdekamp, Ernst Sichtermann, Marco Stratmann)

14:00 - 14:40	Harut Avagyan	*Single Spin Asymmetries: from JLAB12 to EIC (eRHIC)*
14:40 - 15:20	Matthias Perdekamp	*Transverse Spin Physics at RHIC II*
15:20 - 15:50		*Coffee Break*
15:50 - 17:00		*(Dedicated Presentations)*
17:00 - 18:00		*(Discussion)*

Additional RIKEN BNL Research Center Proceedings:

Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-

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

Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005

Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005

Volume 69 – Review Committee – BNL-73546-2004

Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004

Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-

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), XXX (December 6, 2004) - BNL-73506-2004

Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004

Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – 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

Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004

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

Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003

Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003

Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003

Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003

Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679

Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003

Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003

Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678

Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035

Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003

Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672

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Volume 42 – Baryon Dynamics at RHIC – BNL-52669
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Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574
Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560
Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299
Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559
Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116
Volume 10 – Physics of Polarimetry at RHIC – BNL-65926

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Volume 9 – High Density Matter in AGS, SPS and RHIC Collisions – BNL-65762

Volume 8 – Fermion Frontiers in Vector Lattice Gauge Theories – BNL-65634

Volume 7 – RHIC Spin Physics – BNL-65615

Volume 6 – Quarks and Gluons in the Nucleon – BNL-65234

Volume 5 – Color Superconductivity, Instantons and Parity (Non?)-Conservation at High Baryon Density – BNL-65105

Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912

Volume 3 – Hadron Spin-Flip at RHIC Energies – BNL-64724

Volume 2 – Perturbative QCD as a Probe of Hadron Structure – BNL-64723

Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

Single Spin Asymmetri

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June 1-3, 2005

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

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Speakers:

Andrei Afanasev
Daniel Boer
Umberto D'Alesio
Xiaodong Jiang
Matthias Grosse Perdekamp
Flemming Videbaek
Christine Aidala
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