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Brookhaven Summer Program on Nucleon Spin Physics

July 14-27, 2010

Organizers: Elke Aschenauer, Jianwei Qiu, Werner Vogelsang and Feng Yuan

RIKEN BNL Research Center

Building 510A, Brookhaven National Laboratory, Upton, NY 11973-5000, USA

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Preface to the Series

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

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

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

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

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. QCDSP, a 0.6 teraflops parallel processor, dedicated to lattice QCD, was begun at the Center on February 19, 1998, was completed on August 28, 1998, and was decommissioned in 2006. It was awarded the Gordon Bell Prize for price performance in 1998. The next generation computer in this sequence, QCDCQ (400 Teraflops), will become operational in the summer of 2011.

N. P. Samios, Director
July 2010

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

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Introduction

Understanding the structure of the nucleon is of fundamental importance in sub-atomic physics. Already the experimental studies on the electro-magnetic form factors in the 1950s showed that the nucleon has a nontrivial internal structure, and the deep inelastic scattering experiments in the 1970s revealed the partonic substructure of the nucleon. Modern research focuses in particular on the spin and the gluonic structure of the nucleon. Experiments using deep inelastic scattering or polarized p-p collisions are carried out in the US at the CEBAF and RHIC facilities, respectively, and there are other experimental facilities around the world.

More than twenty years ago, the European Muon Collaboration published their first experimental results on the proton spin structure as revealed in polarized deep inelastic lepton-nucleon scattering, and concluded that quarks contribute very little to the proton's spin. With additional experimental and theoretical investigations and progress in the following years, it is now established that, contrary to naive quark model expectations, quarks and anti-quarks carry only about 30% of the total spin of the proton.

Twenty years later, the discovery from the polarized hadron collider at RHIC was equally surprising. For the phase space probed by existing RHIC experiments, gluons do not seem to contribute any to the proton's spin.

To find out what carries the remaining part of proton's spin is a key focus in current hadronic physics and also a major driving force for the new generation of spin experiments at RHIC and Jefferson Lab and at a future Electron Ion Collider. It is therefore very important and timely to organize a series of annual spin physics meetings to summarize the status of proton spin physics, to focus the effort, and to lay out the future perspectives.

This summer program on "Nucleon Spin Physics" held at Brookhaven National Laboratory (BNL) on July 14-27, 2010 [http://www.bnl.gov/spnsp/] is the second one following the Berkeley Summer Program taken place in June of 2009. This program at BNL focused on theory and had many presentations on a wide range of theoretical aspects on nucleon spin, from perturbative-QCD calculations to models, and to the first principle lattice calculation. It also had a good number of summary talks from all major experimental collaborations on spin physics. The program facilitated many discussions between theorists as well as experimentalists. With five transparencies from each presentation at the Summer Program, this proceedings provides a valuable summary on the status and progress, as well as the future prospects of spin physics.

The organizers:

- Elke-Caroline Aschenauer (BNL)
- Jianwei Qiu (BNL)
- Ernst Sichtermann (LBNL)
- Werner Vogelsang (Univ. of Tuebingen, Germany)
- Feng Yuan (LBNL/RIKEN BNL Research Center)

Brookhaven Nucleon Spin Summer Program
BNL, July 14-27, 2010

Overview of TMD factorization in high energy scattering processes

Piet Mulders

mulders@few.vu.nl

vrije Universiteit amsterdam

Abstract

Overview of TMD factorization in high energy scattering processes
P.J. Mulders, NIKHEF & VU University, Amsterdam

The basic idea of PDFs is achieving a factorized description with soft and hard parts, soft parts being portable and hard parts being calculable. At high energies interference disappears and PDFs are interpreted as probabilities. We aim to go beyond the collinear situation. We thus consider besides the dependence on partonic momentum fractions x also the dependence on the transverse momentum p_T of the partons. Experimentally that dependence on transverse momenta shows up in azimuthal asymmetries for produced hadrons or jet-jet asymmetries. In combination with polarization one can explain single spin asymmetries or look at production of polarized Lambdas.

Single spin asymmetries are examples of time-reversal odd (T-odd) observables, which rely on phases in a scattering process. In a gauge theory one naturally expects phases, but these need to be detected through interference or, as it turns out in high-energy scattering processes, by considering transverse momenta ($p_T = iD_T - gA_T$) in a proper color gaug-invariant theoretical description. The relevant transverse momentum dependent (TMD) distribution functions in the partonic correlators can be interpreted as 'single spin correlations' describing transverse spin distributions in an unpolarized hadron or unpolarized quarks in a (transversely) polarized hadron. For gluons similar correlations can be considered. The TMD correlators emerge with specific future or past-pointing gauge links as well as more complex gauge link structures, that depend on the color flow in the hard subprocess, complicating the universality of PDFs. To compare with collinear treatments, one can consider specific p_T-weighted cross sections and recover the Qiu-Sterman description of e.g. single spin asymmetries in terms of gluonic pole matrix elements.

The study of TMD correlators thus breaks the simple universality of quark and gluon distributions multiplying a hard cross section, but the resulting description offers various new possibilities to employ particular spin-momentum correlations of partons in high energy processes, while such correlations of course also offer new insight into hadron structure.

Issues

- Basic goals
  - Try to incorporate small p_T (second scale) extending f(x) to $f(x,p_T^2)$
  - Reduce effects of NLO/NNLO/...
- (Theoretical) complications
  - Operator structure (gauge links) and twist expansion
  - Gluonic interactions essential (Brodsky, Hwang, Schmidt, ...)
  - Effects from soft gluon limit (Qiu, Sterman, Koike, ...)
  - Universality and factorization (Qiu, Yuan, Vogelsang, Collins, ...)
- Opportunities/Applications
  - Explanation of T-odd effects (Sivers, Collins, Boer-M)
  - Combination with (transverse) polarization is extremely useful, but also jet effects/broadening/Lambda production (polarimetry)

INTRODUCTION

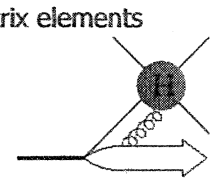
Gauge-invariant definition of TMDs: which gauge links?

$$\boxed{\Phi_{ij}^{q[C]}(x,p_T;n)=\int\frac{d(\xi.P)d^2\xi_T}{(2\pi)^3}e^{ip.\xi}\left\langle P\middle|\overline{\psi}_j(0)U_{[0,\xi]}^{[C]}\psi_i(\xi)\middle|P\right\rangle_{\xi.n=0}}$$ TMD

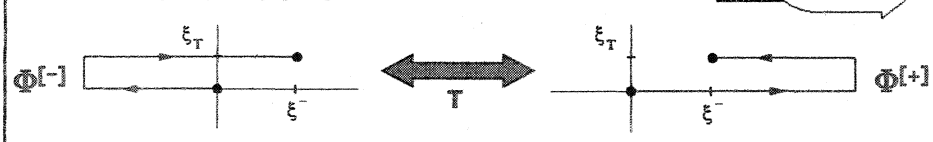
$$\Phi_{ij}^{q}(x;n)=\int\frac{d(\xi.P)}{(2\pi)}e^{ip.\xi}\left\langle P\middle|\overline{\psi}_j(0)U_{[0,\xi]}^{[n]}\psi_i(\xi)\middle|P\right\rangle_{\xi.n=\xi_T=0}$$ collinear

- Gauge links follow from inclusion of quark-gluon matrix elements

$$U_{[0,\xi]}^{[C]}=\mathcal{P}\exp\left(-ig\int_0^{\xi}ds^{\mu}A_{\mu}\right)$$



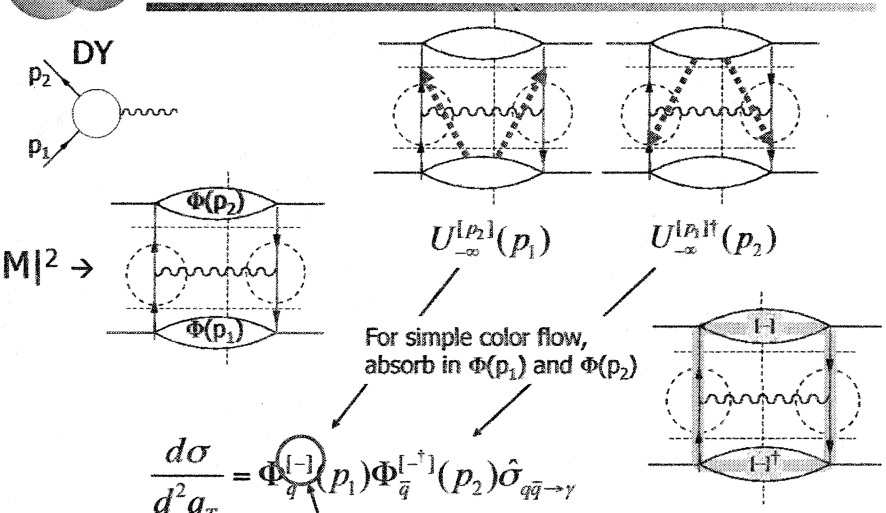
- Basic (simplest) gauge links for TMD correlators:



These become a unique 'simple' Wilson line upon p_T-integration

NON-COLLINEARITY

Gauge link calculation for DY



$U_{-\infty}^{[p_2]}(p_1)$ $U_{-\infty}^{[p_1]\dagger}(p_2)$

For simple color flow, absorb in $\Phi(p_1)$ and $\Phi(p_2)$

$$\frac{d\sigma}{d^2 q_T} = \Phi_q^{[-]}(p_1)\Phi_{\bar{q}}^{[-^\dagger]}(p_2)\hat{\sigma}_{q\bar{q}\to\gamma}$$

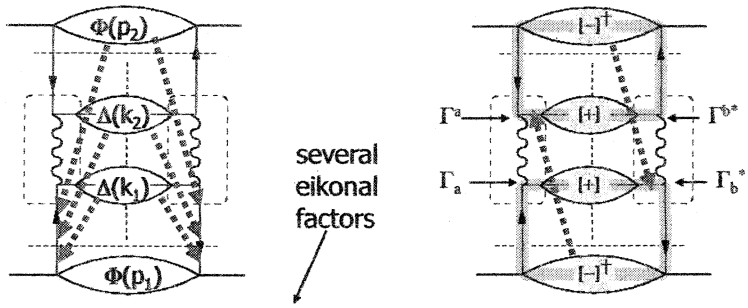
Gauge link differs from the SIDIS one!

GAUGE LINK

T.C. Rogers, PJM, PR D81:094006,2010/hep-ph 1001.2977

Color entanglement

- Illustrated in quark-quark scattering (even without color exchange)



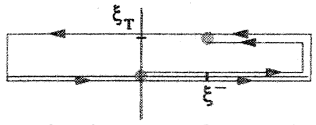
$$\sigma \sim [\Phi(p_1)U_-^{[p_1]\dagger}(p_2,k_1,k_2)\Gamma_b^*\Delta(k_1)U_+^{[k_1]}(p_1,p_2,k_2)\Gamma_a]$$
$$\times[\Phi(p_2)U_-^{[p_2]\dagger}(p_1,k_1,k_2)\Gamma^{b*}\Delta(k_2)U_+^{[k_2]}(p_1,p_2,k_1)\Gamma^a]$$

kinematically decoupled, but color entangled!

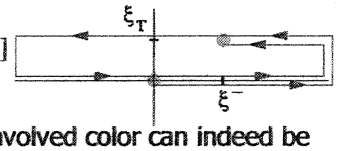
COLOR ENTANGLEMENT

Color disentanglement

- We need correlators with more complex gaugelinks, such as



$\Phi^{[(W)+]}$



$\Phi^{[W+]}$

- If only a TMD for *one* hadron is involved color can indeed be disentangled in this way (conjecture)

$$\int d^2 p_T \ldots W^{[n]}(p) \ldots = \int d^2 p_T \ldots U_{-\infty}^{[n]\dagger}(p) U_{+\infty}^{[n]}(p) \ldots = 1$$

- This can be used to simplify the integrated cross sections and to study single weighted azimuthal asymmetries

$$\int d^2 q_T \, q_T^\alpha \ldots \int d^2 k_{1T} \int d^2 k_{2T} \ldots \delta^2(q_T - k_{1T} - k_{2T})$$
$$= \int d^2 k_{1T} \, k_{1T}^\alpha \int d^2 k_{2T} \ldots + \int d^2 k_{1T} \int d^2 k_{2T} \, k_{2T}^\alpha \ldots$$

Drell-Yan and photon-jet production

- Weighted Drell-Yan

$$\left\langle q_T^\alpha \, \sigma^{H_1 H_2 \to \gamma} \right\rangle = \Phi_{\partial q}^{\alpha[-]} \Phi_{\bar{q}} \hat{\sigma}_{q\bar{q} \to \gamma} + \ldots$$

- Weighted photon-jet production in hadron-hadron scattering

$$\left\langle q_T^\alpha \, \sigma^{H_1 H_2 \to JJ} \right\rangle = \frac{N^2-1}{N} \Big[\frac{N^2}{N^2-1} \Phi_{\partial q}^{\alpha[+(W)]} \Phi_{\bar{q}} \hat{\sigma}_{q\bar{q} \to \gamma g} \Delta_g - \frac{1}{N^2-1} \Phi_{\partial q}^{\alpha[-]} \Phi_{\bar{q}} \hat{\sigma}_{q\bar{q} \to \gamma g} \Delta_g \Big] + \ldots$$

Drell-Yan and photon-jet production

- Weighted Drell-Yan

$$\Phi^{\alpha[-]}_{\partial q} = \Phi^{\alpha}_{\partial q} - \pi\Phi^{\alpha}_{Gq}$$

$$\left\langle q_T^{\alpha}\, \sigma^{H_1H_2\to\gamma}\right\rangle = \Phi^{\alpha[-]}_{\partial q}\Phi_{\bar q}\hat\sigma_{q\bar q\to\gamma} + \ldots$$

- Weighted photon-jet production in hadron-hadron scattering

$$\Phi^{\alpha[+(W)]}_{\partial q} = \Phi^{\alpha}_{\partial q} + \pi\Phi^{\alpha}_{Gq}$$

$$\left\langle q_T^{\alpha}\, \sigma^{H_1H_2\to JJ}\right\rangle = \frac{N^2-1}{N}\Big[\frac{N^2}{N^2-1}\Phi^{\alpha[+(W)]}_{\partial q}\Phi_{\bar q}\hat\sigma_{q\bar q\to\gamma g}\Delta_g - \frac{1}{N^2-1}\Phi^{\alpha[-]}_{\partial q}\Phi_{\bar q}\hat\sigma_{q\bar q\to\gamma g}\Delta_g\Big] + \ldots$$

$$\Phi^{\alpha[-]}_{\partial q} = \Phi^{\alpha}_{\partial q} - \pi\Phi^{\alpha}_{Gq}$$

APPLICATIONS

Drell-Yan and photon-jet production

- Weighted Drell-Yan

$$\hat\sigma_{[q]\bar q\to\gamma}$$

$$\left\langle q_T^{\alpha}\, \sigma^{H_1H_2\to\gamma}\right\rangle = \Phi^{\alpha}_{\partial q}\Phi_{\bar q}\hat\sigma_{q\bar q\to\gamma} + \pi\Phi^{\alpha}_{Gq}\Phi_{\bar q}\left(-\hat\sigma_{q\bar q\to\gamma}\right) + \ldots$$

- Weighted photon-jet production in hadron-hadron scattering

Gluonic pole cross sections

$$\left\langle q_T^{\alpha}\, \sigma^{H_1H_2\to JJ}\right\rangle = \Big[\Phi^{\alpha}_{\partial q}\Phi_{\bar q}\hat\sigma_{q\bar q\to\gamma g}\Delta_g + \pi\Phi^{\alpha}_{Gq}\Phi_{\bar q}\left(\frac{N^2+1}{N^2-1}\hat\sigma_{q\bar q\to\gamma g}\right)\Delta_g\Big] + \ldots$$

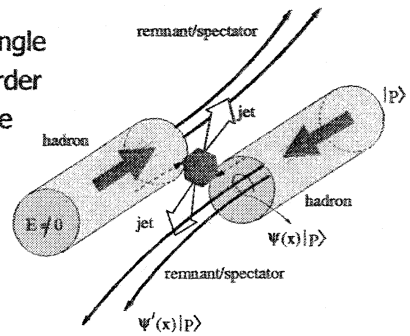
$$\hat\sigma_{[q]\bar q\to\gamma g}$$

Note: color-flow in this case is more SIDIS like than DY

APPLICATIONS

Outlook (work in progress)

- A possible way out to include the color entanglement of different hadrons is to include all (or more) hadrons in *one* soft part
- In p_T-averaged situation it reduces to a product of single-hadron collinear soft parts, for single-weighted case to two single-hadron collinear soft parts, ...
- This may have advantages that a single treatment of factorization (higher order QCD contributions) becomes feasible
- The multi-hadron soft part will most likely involve novel multi-hadron correlations (through color entanglement)



OUTLOOK

Conclusions

- Transverse momentum dependence, experimentally important for single spin and azimuthal asymmetries, theoretically challenging (consistency, gauges and gauge links, universality, factorization)
- For leading integrated and single-weighted functions factorization is possible, but it requires besides the normal 'partonic cross sections' use of 'gluonic pole cross sections' and it is important to realize that q_T-effects generally come from all partons
- It is still an open issue how to achieve factorization into hard partonic part including its colorflow and a set of (gauge-link dependent, possibly multi-hadron correlating) TMDs (ongoing work with a.o. Ted Rogers, Mert Aybat).

Relevant for past, present and future experiments
(RHIC, COMPASS, JLAB, JPARC, GSI, LHC)

CONCLUSIONS

GPD phenomenology of hard exclusive processes

Dieter Müller

Ruhr-Universität Bochum

K. Kumerički, DM, K. Passek-Kumerički (KMP-K), hep-ph/0703179
GPD fits at NLO and NNLO of H1/ZEUS data

KMP-K, 0805.0152 [hep-ph]
constructive critics on ad hoc GPD model approach [lot of good news]
first applications of dispersion integral approach

KMP-K, 0807.0159 [hep-ph]; KM 0904.0458 [hep-ph]
flexible GPD model for small x and fits of H1/ZEUS data
dispersion integral fits of HERMES and JLAB data

C. Bechler, DM 0906.2571 [hep-ph]
a GPD LO-look at π^+ production

M. Meskauskas, DM *(in preparation)*
a GPD LO-look at *vector meson* production

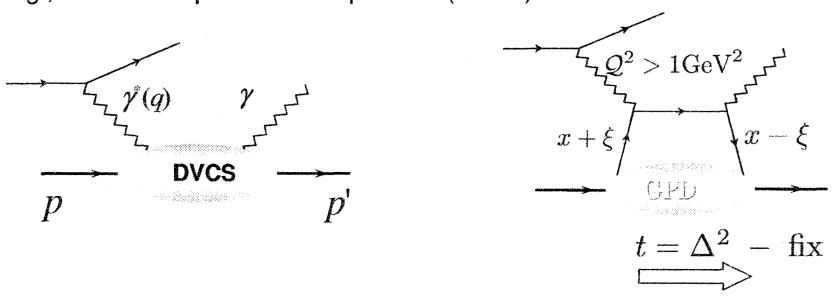
1

GPDs embed non-perturbative physics

GPDs appear in various hard exclusive processes,

**[DM et. al (90/94)
Radyushkin (96)
Ji (96)]**

e.g., hard electroproduction of photons (DVCS)

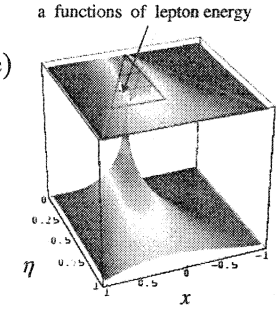


$$\mathcal{F}(\xi, Q^2, t) = \int_{-1}^{1} dx\, C(x, \xi, \alpha_s(\mu), Q/\mu) F(x, \xi, t, \mu) + O(\tfrac{1}{Q^2})$$

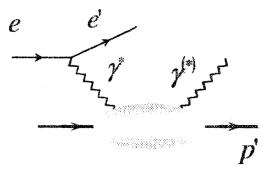
CFF	hard scattering part	**GPD**	**higher twist**
Compton form factor observable	perturbation theory (our conventions/microscope)	universal (conventional)	depends on approximation

GPD related hard exclusive processes

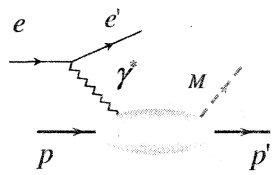
scanned area of the surface as a functions of lepton energy



- Deeply virtual Compton scattering (clean probe)



- Hard exclusive meson production (flavor filter)



- etc.

3

GPD Properties

GPDs are intricate functions: $H(x, \eta = \xi, t, \mu^2 = Q^2)$

a non-trivial interplay of variable dependence

- *t*-dependence dies out at large *x* (spectator models, indicated by lattice & *X*QS-model)
- effective Regge behavior (from phenomenology) at small *x*; unknown η-dependence
- evolution depends on the GPD shape

at least four phenomenological important GPDs for each parton

GPD-constraints:

- reduction to PDFs: $q(x, \mu^2) = \lim_{\Delta \to 0} H(x, \eta, t, \mu^2)$
- generalized form factor sum rules, e.g.: (polynomiality, GPD support property) $F_1(t) = \int_{-1}^{1} dx\, H(x, \eta, t, \mu^2)$
- Ji's sum rule $\frac{1}{2} = \frac{1}{2} \int_{-1}^{1} dx\, x(H + E)(x, \eta, t = 0, \mu^2)$
- positivity constraints (**valid at LO**) **[P. Pobylitsa 02]**

  (strongly constraining variable interplay in the outer region)

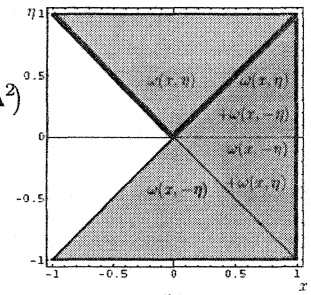
4

A partonic duality interpretation

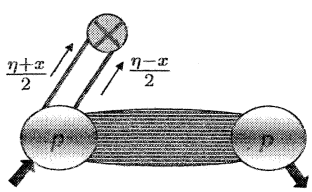
quark GPD (anti-quark $x \to -x$):

$$F = \theta(-\eta \le x \le 1)\,\omega(x,\eta,\Delta^2) + \theta(\eta \le x \le 1)\,\omega(x,-\eta,\Delta^2)$$

$$\omega\left(x,\eta,\Delta^2\right) = \frac{1}{\eta}\int_0^{\frac{x+\eta}{1+\eta}} dy\, x^p f(y,(x-y)/\eta,\Delta^2)$$

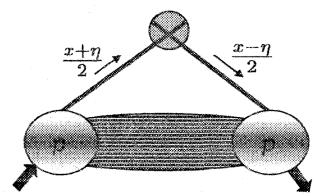


dual interpretation on partonic level:



support extension is unique [DM et al. 92]

ambiguous (*D*-term) [DM, A. Schäfer (05) KMP-K (07)]



central region $-\eta < x < \eta$
mesonic exchange in *t*-channel

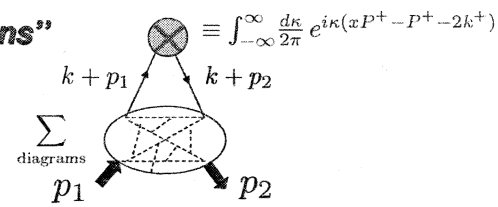
outer region $\eta < x$
partonic exchange in *s*-channel

5

Overview: GPD representations

``light-ray spectral functions"
diagrammatic α-representation
DM, Robaschik, Geyer, Dittes, Hořejši (88 (92) 94)

called ***double distributions***
A. Radyushkin (96)



light cone wave function overlap
(Hamiltonian approach in light-cone quantization)

Diehl, Feldmann, Jakob, Kroll (98,00)
Diehl, Brodsky, Hwang (00)

SL(2,R) (conformal) expansion
(series of local operators)

one version is called Shuvaev transformation, used in `dual' (*t*-channel) GPD parameterization

Radyushkin (97); Belitsky, Geyer, DM, Schäfer (97); DM, Schäfer (05); ....

Shuvaev (99,02); Noritzsch (00) Polyakov (02,07)

➡ each representation has its own ***advantages***, however, they are ***equivalent*** **(clearly spelled out in [Hwang, DM 07])**

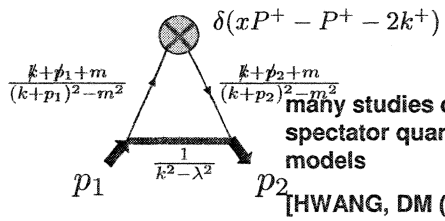
6

Towards realistic GPD (TMD) models

$$\mathcal{L} = \bar{\psi}\left(i\partial\!\!\!/ - m\right)\psi - \frac{1}{2}\phi\left(\partial^2 + \lambda^2\right)\phi + g\bar{\psi}\psi\phi$$

struck spin-*1/2* quark — collective scalar diquark spectator — coupling knows about spin

Diagrammatic approach:
via covariant time ordered perturbation theory



many studies of spectator quark models

LC- Hamiltonian approach

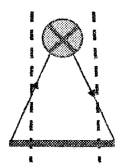
[HWANG, DM (07)]

$$k^\mu \to (k^+, k^-, \mathbf{k}_\perp),\ k^\pm = k^0 \pm k^3,\ \mathbf{k}_\perp = (k^1, k^2).$$

integrate out minus component to find LCWF

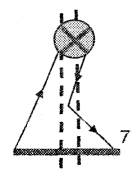
parton number conserved LCWF

(outer region)



parton number violating LCWF

(central region)



7

SL(2,R) representations for GPDs

- support is a consequence of Poincaré invariance (polynomiality)

$$H_j(\eta, t, \mu^2) = \int_{-1}^{1} dx\, c_j(x,\eta) H(x,\eta,t,\mu^2)\,, \qquad c_j(x,\eta) = \eta^j C_j^{3/2}(x/\eta)$$

- conformal moments evolve autonomous (to LO and beyond in a special scheme)

$$\mu\frac{d}{d\mu}H_j(\eta,t,\mu^2) = -\frac{\alpha_s(\mu)}{2\pi}\gamma_j^{(0)} H_j(\eta,t,\mu^2)$$

- inverse relation is given as series of mathematical distributions:

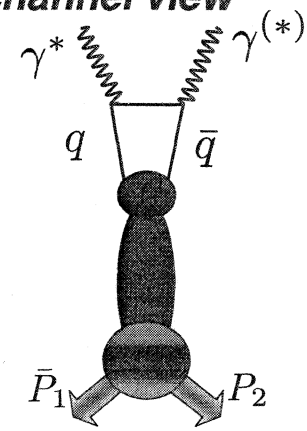
$$H(x,\eta,t) = \sum_{j=0}^{\infty}(-1)^j p_j(x,\eta) H_j(\eta,t)\,,\ p_j(x,\eta) \propto \theta(|x| \le \eta)\frac{\eta^2 - x^2}{\eta^{j+3}} C_j^{3/2}(-x/\eta)$$

- various ways of resummation were proposed:

smearing method [Radyushkin (97); Geyer, Belitsky, DM., Niedermeier, Schäfer (97/99)]
mapping to a kind of forward PDFs [A. Shuvaev (99), J. Noritzsch (00)]
dual parameterization (a mixture of both) [M. Polyakov, A. Shuvaev (02)]
based on conformal light-ray operators [Balitsky, Braun (89); Kivel, Mankewicz (99)]
Mellin-Barnes integral [DM, Schäfer (05); A. Manashov, M. Kirch, A. Schäfer (05)]

8

GPD ansatz at small x from t-channel view

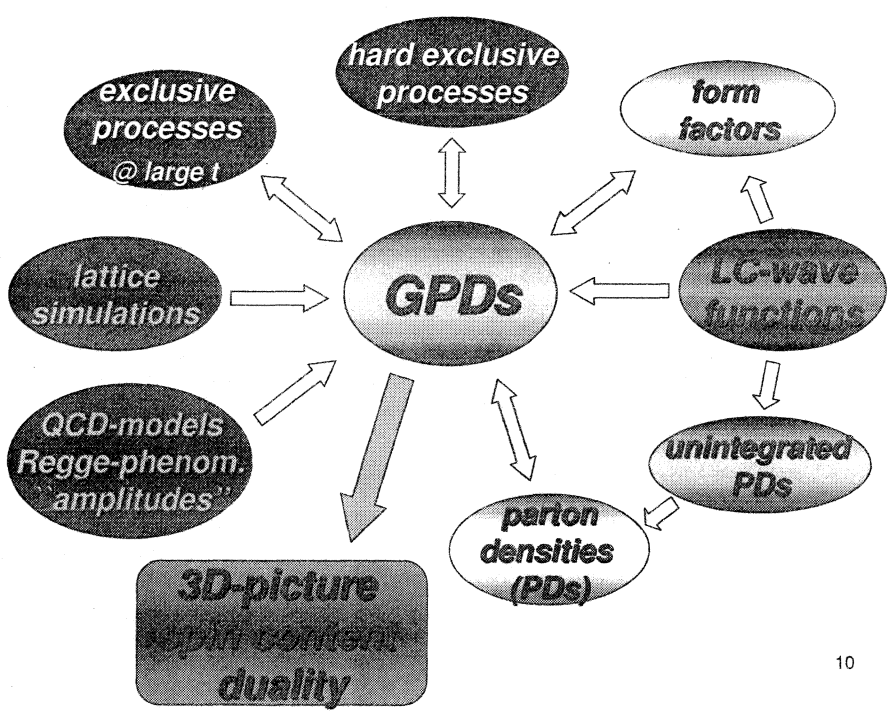


- at short distance a quark/anti-quark state is produced, labeled by ***conformal spin j+2***
- they form an intermediate mesonic state with total angular momentum ***J***
  strength of ***coupling*** is $f_j^J,\ J \leq j+1$
- mesons propagate with $\frac{1}{m^2(J)-t} \propto \frac{1}{J-\alpha(t)}$
- decaying into a nucleon anti-nucleon pair with given angular momentum *J*, described by an *impact form factor*

$$F_j^J(t) = \frac{f_j^J}{J-\alpha(t)} \frac{1}{(1-\frac{t}{M^2(J)})^p}$$

! GPD *E* is zero if chiral symmetry holds
(partial waves are Gegenbauer polynomials with index 3/2)
D-term arises from the SO(3) partial wave *J=j+1* *(j → -1)*

9



10

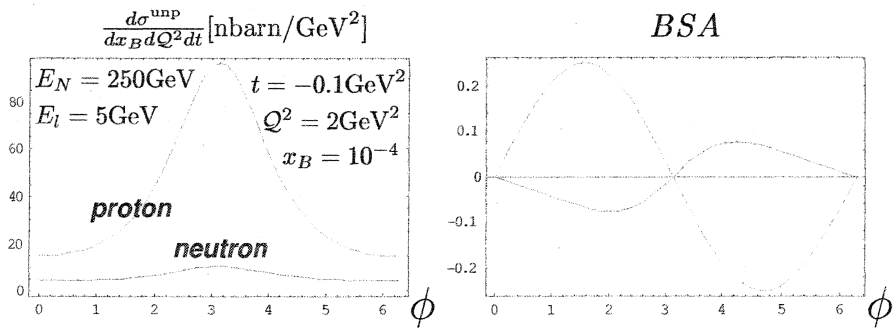
EIC potential for DVCS studies:

DVCS: cross section, beam spin, target spin, and double spin flip experiments
(disentangling CFF at small x)

$$BSA \propto y\left\{F_1(t)H(\xi,\xi,t,\mathcal{Q}^2) - \frac{t}{4M^2}F_2E(\xi,\xi,t,\mathcal{Q}^2)\right\}$$

$$TSA \propto \left\{F_1(t)\widetilde{H}(\xi,\xi,t,\mathcal{Q}^2) + \xi(F_1+F_2)(t)H(\xi,\xi,t,\mathcal{Q}^2)\right\}$$

off neutron another possibility to access GPD E
time-like region (a new field to study)
off nuclei (has its own interest)



Summary

GPDs are intricate and (thus) a promising tool

- to reveal the transverse distribution of partons
- to address the spin content of the nucleon
- providing a bridge to non-perturbative methods (e.g., lattice)

hard exclusive leptoproduction

- possesses a rich structure, allowing to access various CFFs/GPDs
- it is elaborated in NLO and offers a new insight in QCD
- DVCS is widely considered as a theoretical clean process
- covering the kinematical region between HERA/HERMES/COMPASS and JLAB and future experiments (high luminosity and dedicated detectors) is needed to quantify exclusive and inclusive QCD phenomena

"next generation" tools/technology for global fits are desired:

to quantify the partonic picture and to get a better QCD understanding

Measurements of the Neutron Single Spin Asymmetries Using a Polarized ^{3}He Target

Jian-ping Chen, Jefferson Lab *

On behalf of the Jefferson Lab Hall A and polarized ^{3}He collaborations

Summer Spin Program at BNL, July 13, 2010

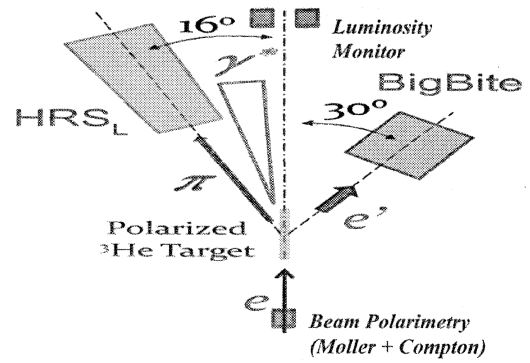
Semi-Inclusive deep-inelastic scattering (SIDIS) is a powerful tool to study transverse spin and transverse structure of the nucleon.

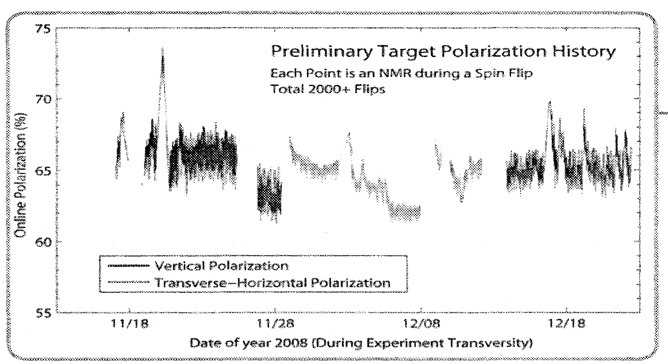
First neutron single target spin asymmetry measurement in SIDIS using a polarized ^{3}He target was performed in Hall A at Jefferson Lab. Preliminary results on the Collins, Sivers and A_{LT} asymmetries are presented. Plan for future precision measurements of the single spin asymmetry in SIDIS with 12 GeV energy upgraded Jefferson Lab is discussed. Possible longer term measurements with an electron ion collider (EIC) are shown.

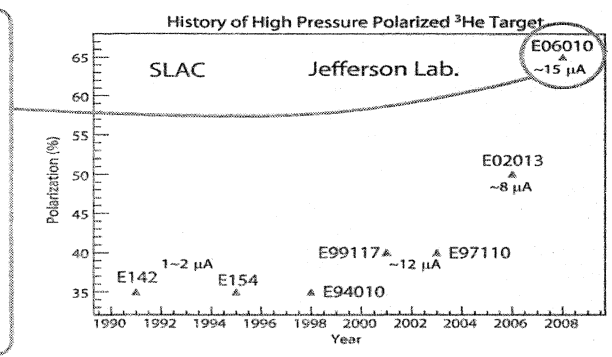
*Authored by Jefferson Science Associates, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

E06-010 Experiment: $^3He^{\uparrow}(\vec{e},e'\pi^{\pm})X$

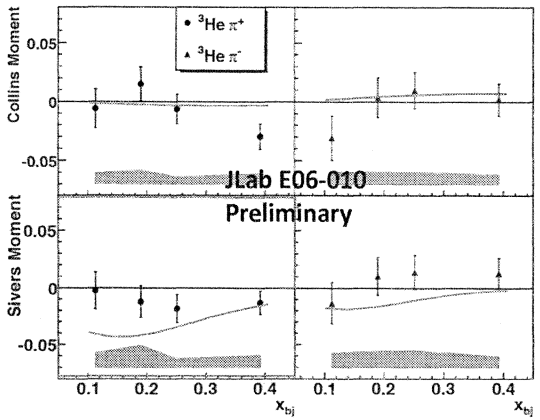
- First measurement **of the SSA and DSA in SIDIS**
- **Upgraded** Polarized ^{3}He Target
- BigBite at 30º as Electron Arm
  - P_e = 0.7 ~ 2.2 GeV/c
- HRS_L at 16º as Hadron Arm with a new RICH Detector
  - P_h = 2.35 GeV/c



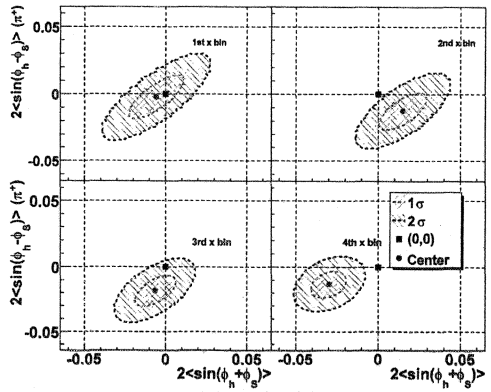


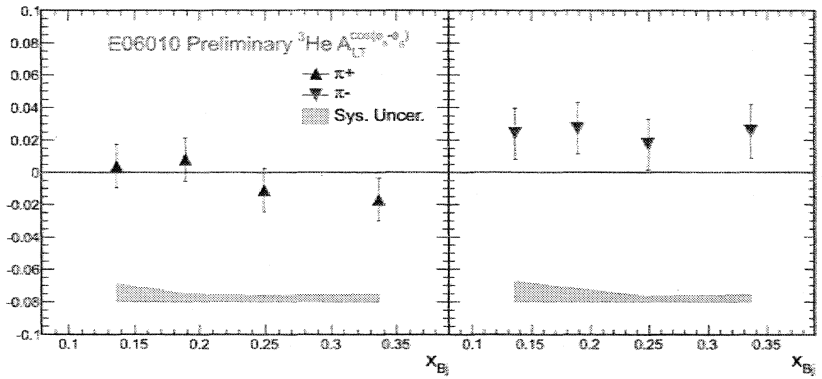


^{3}He Target Single-Spin Asymmetry in SIDIS: JLab E06-010

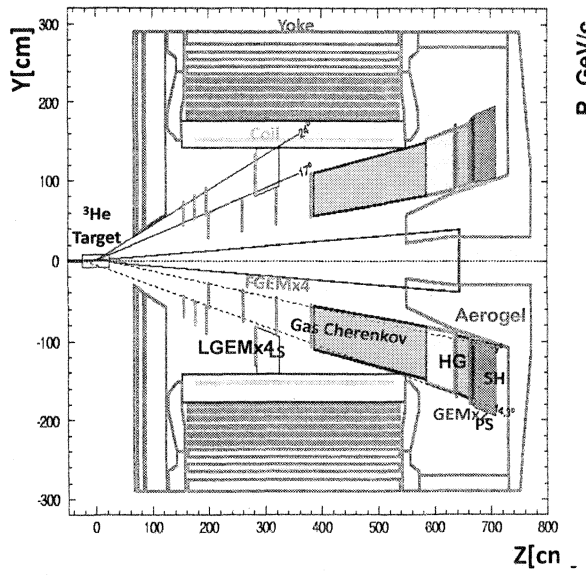


Statistical uncertainties are correlated between Collins and Sivers asymmetries on ^{3}He (π^+)

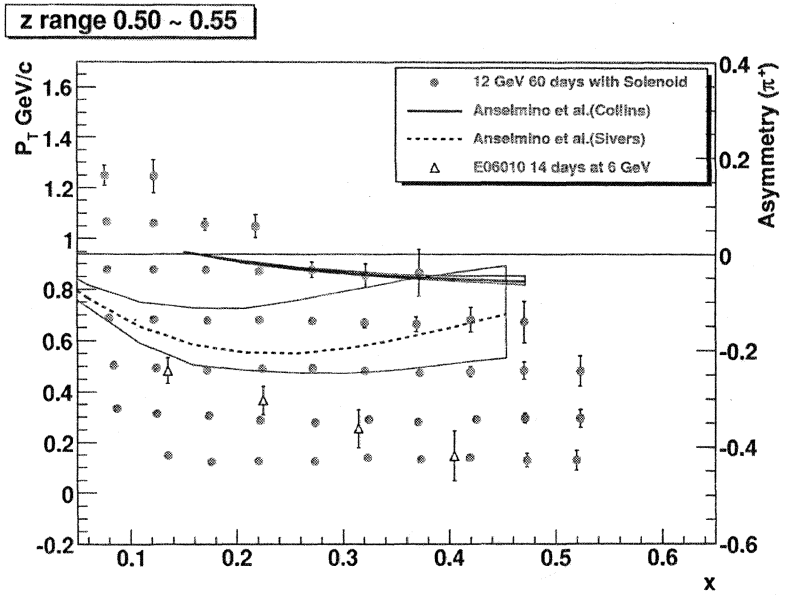




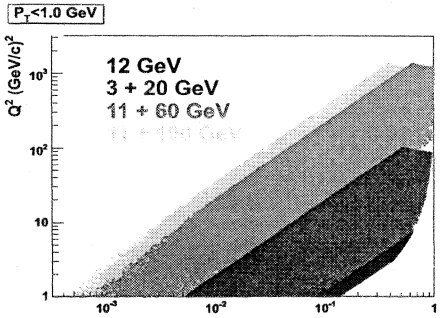
Solenoid detector for SIDIS at 11 GeV



4-d Mapping of Collins/Sivers Asymmetries
12 GeV With SOLID (L=10^{36})

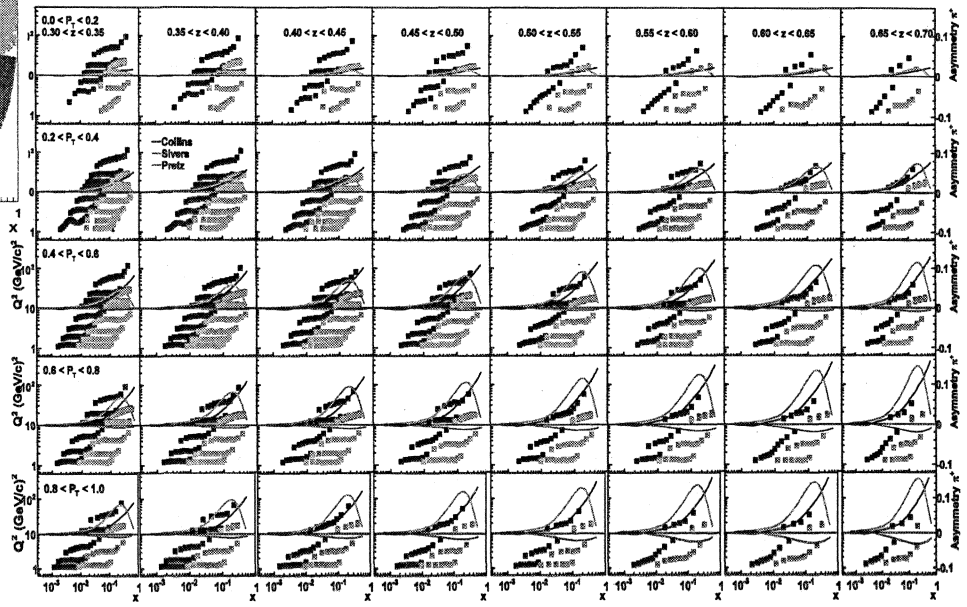


- Will obtain 8 z bins (0.3-0.7)
- Both π+ and π-



EIC phase space

EIC projection: Proton π^+ (z = 0.3-0.7)



JLab 12 GeV upgrade and spin physics

H.Avakian Jefferson Lab.

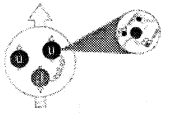
A measurement of transverse momenta (P_T) of final-state hadrons in semi-inclusive deep inelastic scattering (SIDIS) $\vec{e}\vec{p} \rightarrow e'hX$, for which a hadron is detected in coincidence with the scattered lepton, gives access to the transverse momentum distributions (TMDs) of partons, which are not accessible in inclusive scattering. QCD factorization for SIDIS, established at low transverse momentum in the current-fragmentation region at higher energies, provides a rigorous starting point for the study of partonic TMDs from SIDIS data using different spin-dependent and spin-independent observables.

Measurements of the P_T-dependences of spin asymmetries (for P_T comparable to the proton mass M_p and Λ_{QCD}), in particular, allow studies of transverse momentum (k_T) widths of different TMDs, providing quantitative information on how quarks are confined in hadrons. The P_T-dependence of the double-spin asymmetry also probes the transition from a non-perturbative to a perturbative description. At large P_T ($\Lambda_{QCD} << P_T << Q$), the double spin asymmetry is expected to be independent of P_T.

Azimuthal distributions of final state particles in SIDIS, containing information on both magnitude and direction of the hadronic transverse momentum, are sensitive to the orbital motion of quarks and play an important role in the study of transverse momentum distributions of quarks in the nucleon. Large Single Spin Asymmetries (SSAs), appearing as azimuthal moments of the cross section, have been observed for decades in hadronic reactions. Since at relatively low P_T non perturbative effects are expected to dominate, SSAs have been among the most difficult phenomena to understand from first principles in QCD. Two fundamental mechanisms have been identified that lead to SSAs in hard processes; the Sivers mechanism, which generates an asymmetry in the distribution of quarks due to orbital motion of partons, and the Collins mechanism, which generates an asymmetry during the hadronization of quarks.

Measurement of the P_T dependence of SSAs will also allow for checking of the predictions of a unified description of SSA by Ji and collaborators and for study of the transition from a non-perturbative to a perturbative description at large P_T. Higher-twist observables, such as longitudinally polarized beam or target SSAs, are important for understanding long-range quark-gluon dynamics. Recently, higher-twist effects in SIDIS were interpreted in terms of an average transverse force acting on the active quarks in the instant after being struck by the virtual photon.

Measurements of semi-inclusive processes combined with inclusive and exclusive measurements with upgraded JLab will allow to study the quark structure of the nucleon with unprecedented detail. Significantly higher statistics from `CLAS12` data, especially in the large x region, will also enable the extraction of the x and Q^2 dependencies for different azimuthal moments in a wide kinematic range allowing extraction of the underlying distribution functions.



Transverse structure of the nucleon and partonic correlations

What is the shape of k_T-distributions?
Can k_T-distributions be flavor dependent?
Are k_T-distributions the same for different spin orientations?
How spin-orbit correlations change the momentum distributions?
How big are quark-gluon correlations?
How nuclear medium changes k_T-distributions?
What is the fraction of k_T-generated in FSI?
How gluons and sea are distributed in k_T

How spin-orbit correlations are related to the longitudinal structure and nuclear effects?

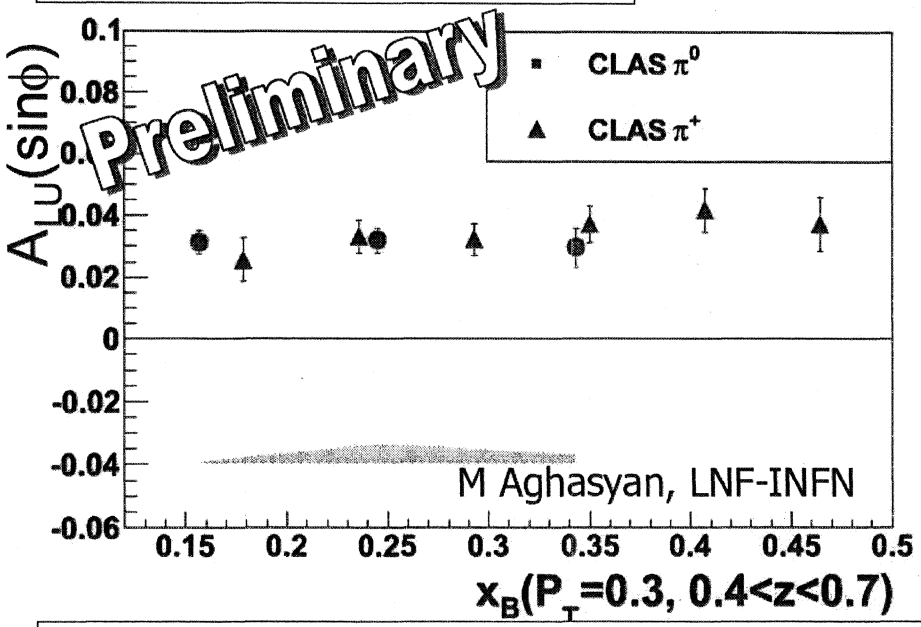
Beam SSA: A_{LU} from CLAS @ JLab

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

Photon Sivers Effect Afanasev & Carlson, Metz & Schlegel

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

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



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

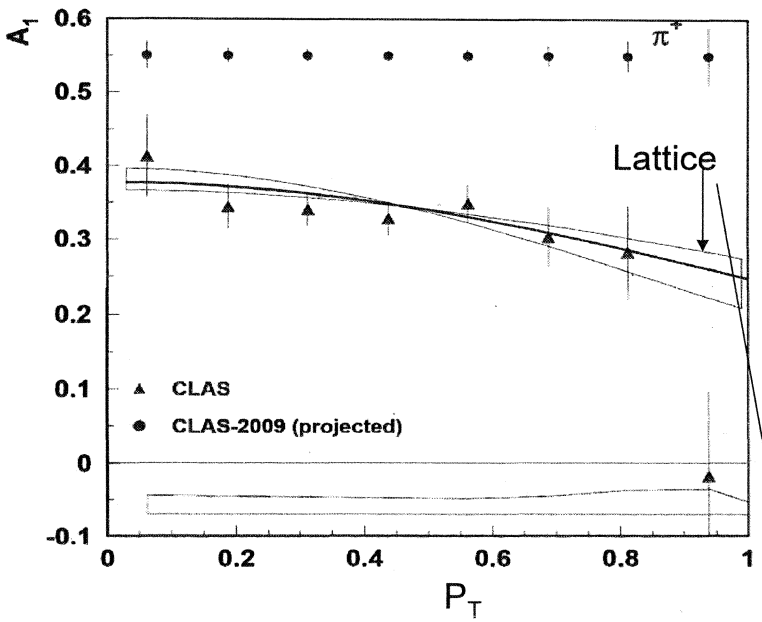
Beam SSA from hadronization (Collins effect) by Schweitzer et al.

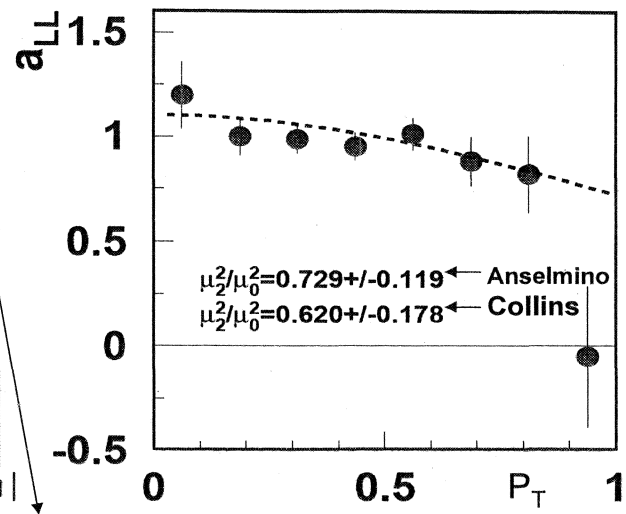
Collins contribution should be suppressed → $g^{\perp}$ wanted !!!

A_1 P_T-dependence

arXiv:1003.4549

$$A_1(\pi) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^{q\to\pi}(z)}{\sum_q e_q^2 f_1^q(x) D_1^{q\to\pi}(z)} \longrightarrow A_1(x,z,P_T) = A_1(x,z)\underbrace{\frac{\langle P_T^{2,unp}\rangle}{\langle P_T^{2,pol}\rangle}\exp(-P_T^2/\langle P_T^{2,pol}\rangle - P_T^2/\langle P_T^{2,unp}\rangle)}_{a_{LL}}$$





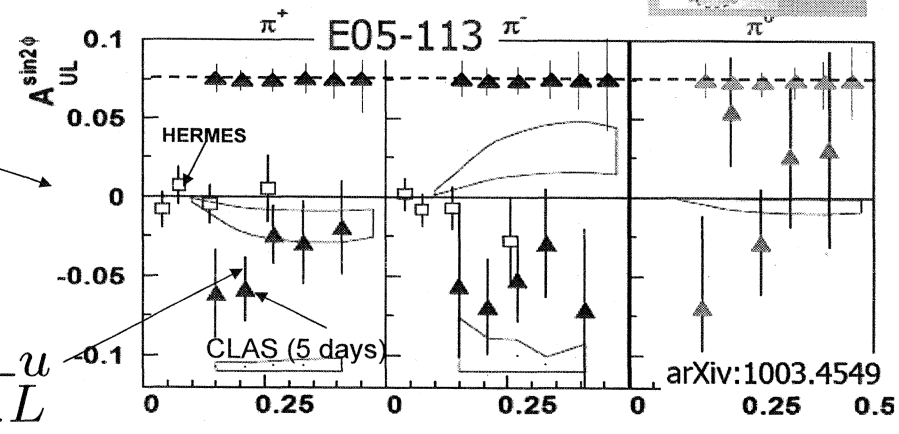
$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$

CLAS data suggests that width of g_1 is less than the width of f_1

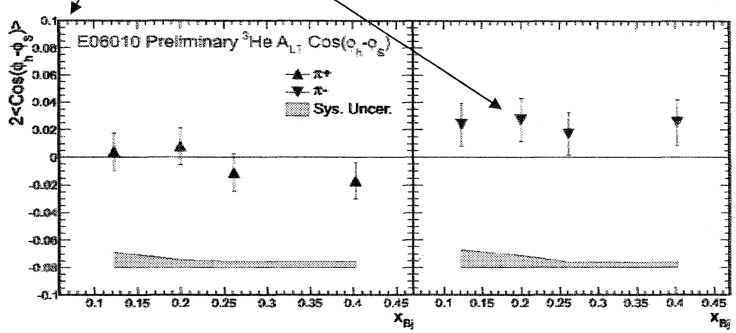
New CLAS data would allow multidimensional binning to study k_T-dependence for fixed x

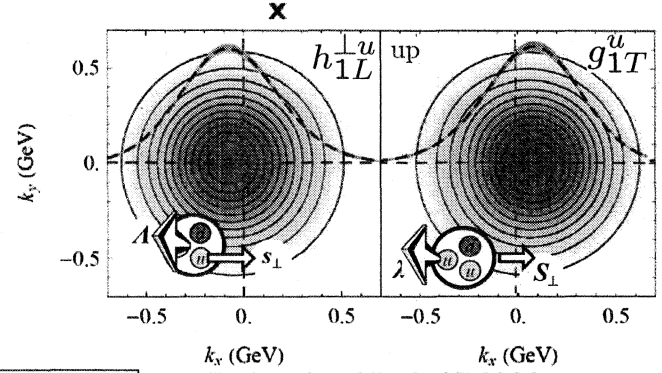
Kotzinian-Mulders Asymmetries

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



$$g_{1T}^u \approx -h_{1L}^{\perp u}$$





Worm gear TMDs are unique (no analog in GPDs)

B.Musch arXiv:0907.2381
B.Pasquini et al, arXiv:0910.1677

TMDs program @ 12 GeV in Hall B

PAC approved experiments & LoI

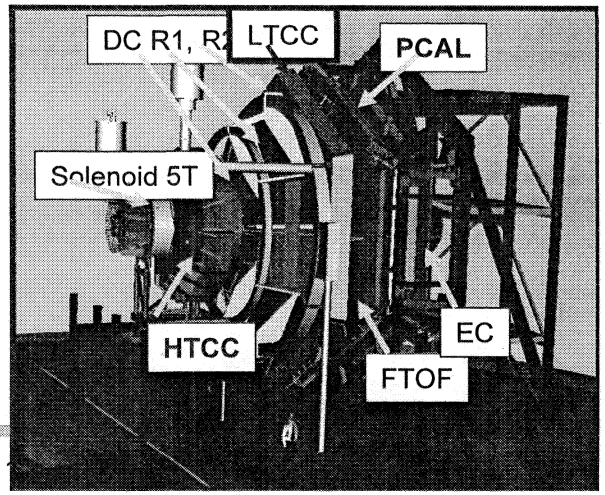
E12-06-112: **Pion** SIDIS
E12-09-008: **Kaon** SIDIS

E12-07-107: **Pion** SIDIS
E12-09-009: **Kaon** SIDIS

LOI12-06-108: **Pion** SIDIS
LOI12-09-004: **Kaon** SIDIS

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

- Complete program of TMDs studies for pions and kaons
- Kaon measurements crucial for a better understanding of the TMDs "kaon puzzle"
- Kaon SIDIS program requires an upgrade of the CLAS12 detector PID ⇒ RICH detector to replace LTCC
  Project under development



Summary

•CLAS longitudinally polarized NH3 and ND3 target data provides superior sample of events allowing detailed studies of single and double spin asymmetries using multidimensional bins

Measurements of spin and azimuthal asymmetries with unpolarized, longitudinally polarized and transversely polarized targets in semi-inclusive processes at Hall-A/B :

•Measure TMDs of partons in the valence region
•Provide detailed info on partonic spin-orbit correlations
•Study quark-gluon correlations (HT)
•Study nuclear modification of 3D PDFs

JLab12 will significantly increase the luminosity, kinematical coverage and particle identification capabilities of Hall-A/B

Spin Observables in hadronic collisions

Marc Schlegel

Institute for Theoretical Physics
University of Tuebingen

in collaboration with Werner Vogelsang

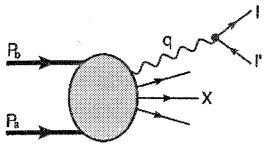
Nuclear Spin Physics Summer Program, BNL, July 15

Plan of the talk

- Drell-Yan lepton pair production and photon pair production
- The Sivers effect:
  Fit to data, Models, Prediction for photon pairs
- Drell-Yan and Diphoton production at high q_T
- The double spin asymmetry A_{TT}

The Drell-Yan process

Kinematics (lepton pair produced by one decaying gauge boson):



$$\frac{d\sigma}{d^4l\,d^4l'} = \frac{d\sigma}{d^4q\,d^4l} \propto \frac{\delta^+(l^2)\delta^+((q-l)^2)}{4F}\sum_X |M|^2\delta^{(4)}(P_a+P_b-q-P_X)$$

Disentangling the δ-functions → Dilepton rest frame

Gottfried-Jackson frame and Collins-Soper frame:

Gottfried-Jackson frame

Collins-Soper frame

Lepton angles:

$$d^4l \to d\Omega = d\phi\, d\cos\theta$$

Diff. CS including angular dependences: $\dfrac{d^6\sigma}{d^4q\,d\Omega} = 2\dfrac{d^6\sigma}{dy\,dQ^2\,d^2\vec{q}_T\,d\Omega}$

Angular structure functions

Separation of the leptonic part (generated by one photon):

$$\frac{d\sigma}{d^4q\,d\Omega} \propto L_{\mu\nu}W^{\mu\nu}$$

with: $L_{\mu\nu} = 4\left(l_\mu l'_\nu + l_\nu l'_\mu - \frac{Q^2}{2}g_{\mu\nu}\right)$ ⟶ **Limited number of structure function**

Hadronic Tensor: $$W^{\mu\nu}(P_a,S_a;P_b,S_b;q) = \int \frac{d^4x}{(2\pi)^4}\,\mathrm{e}^{iq\cdot x}\langle a,b|J^\mu(0)J^\nu(x)|a,b\rangle$$

Parameterization constraint by current conservation, hermiticity and parity

Decomposition into 4 + 8 +8 + 28 = 48 structure functions $F(x_a,x_b,q_T^2,Q^2)$

[Arnold, Metz, M.S., PRD 79, 034005] **e.g. unpolarized Drell-Yan**

$$\frac{d\sigma_{UU}}{dx_a\,dx_b\,d^2q_T\,d\Omega} = \frac{\alpha^2 s}{2Q^2F}\left((1+\cos^2\Theta)F_{UU}^1 + (1-\cos^2\Theta)F_{UU}^2 + \sin 2\Theta\cos\phi F_{UU}^{\cos\phi} + \sin^2\Theta\cos 2\phi F_{UU}^{\cos 2\phi}\right)$$

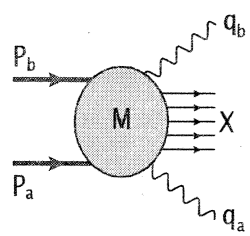
Classification of structure functions helpful for data analysis
→ *Parton model*: 24 leading twist structure functions

$$
\begin{aligned}
\frac{d\sigma}{d^4q\,d\Omega} = \frac{\alpha_{em}^2}{Fq^2}\{&((1+\cos^2\theta)F_{UU}^1 + (1-\cos^2\theta)F_{UU}^2 + \sin2\theta\cos\phi F_{UU}^{\cos\phi} + \sin^2\theta\cos2\phi F_{UU}^{\cos2\phi}) \\
&+ S_{aL}(\sin2\theta\sin\phi F_{LU}^{\sin\phi} + \sin^2\theta\sin2\phi F_{LU}^{\sin2\phi}) + S_{bL}(\sin2\theta\sin\phi F_{UL}^{\sin\phi} + \sin^2\theta\sin2\phi F_{UL}^{\sin2\phi}) \\
&+ |\vec{S}_{aT}|[\sin\phi_a((1+\cos^2\theta)F_{TU}^1 + (1-\cos^2\theta)F_{TU}^2 + \sin2\theta\cos\phi F_{TU}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TU}^{\cos2\phi}) \\
&+ \cos\phi_a(\sin2\theta\sin\phi F_{TU}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TU}^{\sin2\phi})] + |\vec{S}_{bT}|[\sin\phi_b((1+\cos^2\theta)F_{UT}^1 + (1-\cos^2\theta)F_{UT}^2 \\
&+ \sin2\theta\cos\phi F_{UT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{UT}^{\cos2\phi}) + \cos\phi_b(\sin2\theta\sin\phi F_{UT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{UT}^{\sin2\phi})] \\
&+ S_{aL}S_{bL}((1+\cos^2\theta)F_{LL}^1 + (1-\cos^2\theta)F_{LL}^2 + \sin2\theta\cos\phi F_{LL}^{\cos\phi} + \sin^2\theta\cos2\phi F_{LL}^{\cos2\phi}) \\
&+ S_{aL}|\vec{S}_{bT}|[\cos\phi_b((1+\cos^2\theta)F_{LT}^1 + (1-\cos^2\theta)F_{LT}^2 + \sin2\theta\cos\phi F_{LT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{LT}^{\cos2\phi}) \\
&+ \sin\phi_b(\sin2\theta\sin\phi F_{LT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{LT}^{\sin2\phi})] + |\vec{S}_{aT}|S_{bL}[\cos\phi_a((1+\cos^2\theta)F_{TL}^1 + (1-\cos^2\theta)F_{TL}^2 \\
&+ \sin2\theta\cos\phi F_{TL}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TL}^{\cos2\phi}) + \sin\phi_a(\sin2\theta\sin\phi F_{TL}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TL}^{\sin2\phi})] \\
&+ |\vec{S}_{aT}||\vec{S}_{bT}|[\cos(\phi_a+\phi_b)((1+\cos^2\theta)F_{TT}^1 + (1-\cos^2\theta)F_{TT}^2 + \sin2\theta\cos\phi F_{TT}^{\cos\phi} + \sin^2\theta\cos2\phi F_{TT}^{\cos2\phi}) \\
&+ \cos(\phi_a-\phi_b)((1+\cos^2\theta)\bar{F}_{TT}^1 + (1-\cos^2\theta)\bar{F}_{TT}^2 + \sin2\theta\cos\phi\bar{F}_{TT}^{\cos\phi} + \sin^2\theta\cos2\phi\bar{F}_{TT}^{\cos2\phi}) \\
&+ \sin(\phi_a+\phi_b)(\sin2\theta\sin\phi F_{TT}^{\sin\phi} + \sin^2\theta\sin2\phi F_{TT}^{\sin2\phi}) \\
&+ \sin(\phi_a-\phi_b)(\sin2\theta\sin\phi\bar{F}_{TT}^{\sin\phi} + \sin^2\theta\sin2\phi\bar{F}_{TT}^{\sin2\phi})]\}.
\end{aligned}
$$

: *Leading twist in TMD – parton model* $F = F(y, Q^2, q_T^2)$

- p – p scattering: relations between structure functions, e.g. $A_{UT} = -A_{TU}$
- p – _ scattering: no double polarization
- Integration over CS-angles: 8 structure functions survive

Diphoton production



Two highly energetic real photons produced with

$$q \equiv q_a + q_b$$

$$\frac{d\sigma}{d^4q_a\,d^4q_b} = \frac{d\sigma}{d^4q\,d^4q_a} \propto \frac{\delta^+(q_a^2)\delta^+((q-q_a)^2)}{2\times 4F}\sum_X |M|^2\delta^{(4)}(P_a+P_b-q-P_X)$$

Convenient choice: Diphoton rest frame → **Collins-Soper frame** $\dfrac{d^6\sigma}{dy\,dQ^2\,d^2\vec{q}_T\,d\Omega_a}$

Unfortunately: No separation into ***hadronic – photonic*** parts possible!
→ *all* angular modulations are allowed, in principle.

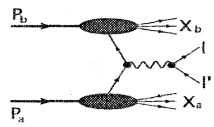
$$\frac{d^6\sigma}{dy\,dQ^2\,d^2\vec{q}_T\,d\Omega_a} = \sum_{l=0}^{\infty}\sum_{m=-l}^{l} C_{lm}(y, Q^2, q_T^2)\,Y_{lm}(\Omega_a) \qquad C_{00} = \frac{d^4\sigma}{dy\,dQ^2\,d^2q_T}, \ldots$$

However, we can calculate the cross section in the parton model.

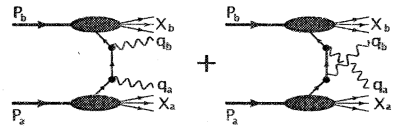
TMD tree-level formalism

Parton model tree-level at $O(\alpha_s^0)$:

Drell-Yan dilepton production:



Diphoton production:



Only relevant at very small q_T: $\Lambda_{QCD} \sim q_T \ll Q$

$$\left(\frac{d\sigma}{d^4q\, d\Omega}\right) \propto \int d^2k_{aT} \int d^2k_{bT}\, \delta^{(2)}(\vec{k}_{aT} + \vec{k}_{bT} - \vec{q}_T)\, \mathrm{Tr}\Big[\Phi(x_a, \vec{k}_{aT})\, H(x_a, x_b, q_a, q_b)\, \bar{\Phi}(x_b, \vec{k}_{bT})\, H^\dagger\Big] + \mathcal{O}\left(\frac{M}{Q}\right)$$

k_T - correlator: $$\Phi_{ij}(x, \vec{k}_T) = \int \frac{dz^- d^2z_T}{(2\pi)^2}\, e^{ik\cdot z} \langle P, S|\, \bar{q}_j(0)\, \mathcal{W}^{?/DY}[0\,;\, z]\, q_j(z)\, |P, S\rangle\Big|_{z^+=0}$$

→ can be parameterized in terms of TMDs according to quark / nucleon spin

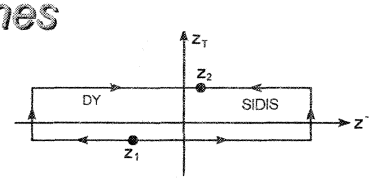
Main result of the TMD tree-level formalism:

$$\left(\frac{d^6\sigma^{hh\to\gamma\gamma X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q) = \frac{2}{\sin^2\theta}\left(\frac{d\sigma^{hh\to l^+l^-X}}{dy\, dQ^2\, d^2q_T\, d\Omega}\right)(\Lambda \sim q_T \ll Q\,|\, e_q \to e_q^2)$$

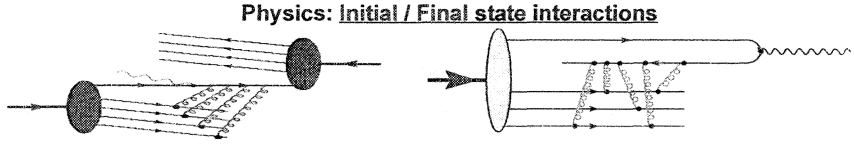
Wilson lines

Wilson line process-dependent in DY/SIDIS:

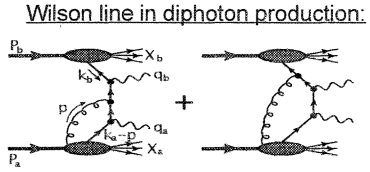
$$\mathcal{W}[z_1; z_2] = \mathcal{P} e^{-ig\int_{z_1}^{z_2} ds\cdot A(s)}$$



Physics: Initial / Final state interactions



Wilson line in diphoton production:



+crossed

Check for A^+, $A_T^i(z^- = -\infty)$

Diagrams topologically different to DY, *but* cancellations between diagrams

$$\mathcal{W}^{\gamma\gamma}[0; z]\Big|_{z^+=0} = 1 - ig\int_0^{-\infty} d\lambda\, A^+(\lambda n) - ig\int_{0_T}^{z_T} d\vec{y}_T \cdot \vec{A}_T(-\infty, 0, \vec{y}_T) - ig\int_{-\infty}^{0} d\lambda\, A^+(\lambda n + z_T) + \mathcal{O}(g^2) = \mathcal{W}^{DY}[0; z]\Big|_{z^+=0}$$

The Sivers effect

k_T – correlator for unpolarized quarks: $\frac{1}{2}\mathrm{Tr}[\Phi(x,\vec{k}_T)\gamma^+] = f_1(x,\vec{k}_T^2) - \frac{\epsilon_T^{ij} k_T^i S_T^j}{M} f_{1T}^{\perp}(x,\vec{k}_T^2)$

Sivers function → time-reversal odd → sign switch: $f_{1T}^{\perp}\Big|_{DIS} = -f_{1T}^{\perp}\Big|_{DY}$

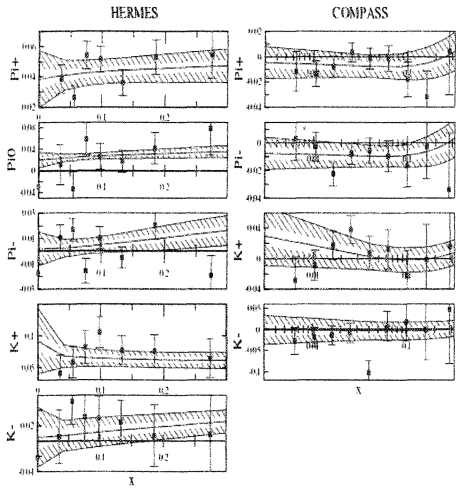
Can be determined from SIDIS data of a transverse target SSA (HERMES, COMPASS): $A_{UT}^{Siv} \sim \frac{f_{1T}^{\perp} \otimes D_1}{f_1 \otimes D_1}$

k_T – deconvolution through Gaussian ansatz $f(x,\vec{k}_T^2) = f(x)\exp\left[-\vec{k}_T^2/\langle k_T^2\rangle\right]$

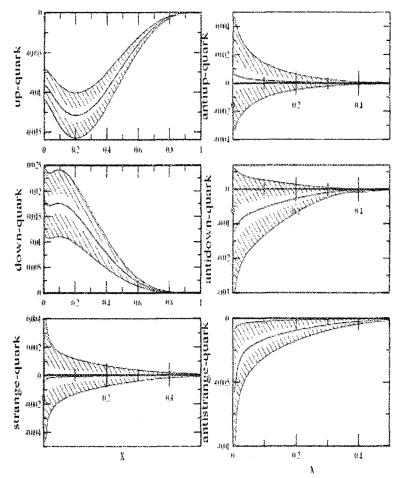
Fit of the Sivers function to data: $f_{1T}^{\perp,q}(x) = A^q f_1^q(x)$
[Anselmino et al., EPJA 39, 89],
[Schweitzer, M.S., 0805.2137 and in prep.]

- non-zero sea-quark Sivers functions.
- Take into account finalized HERMES proton data and COMPASS deuteron data
- small statistical errors, χ^2 / d.o.f. ~ 1.07
- u- and d-Sivers roughly equal, but opposite sign
- Fits not constraint for x > 0.4...
  → (future) Jlab data, also COMPASS proton data

The Sivers Asymmetry plotted vs. x



First transverse Moment of Sivers functions

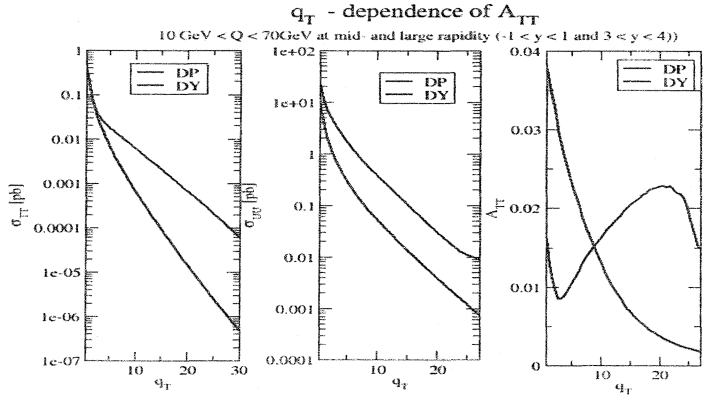


A_{TT} in diphoton production

$$A_{TT} \sim \frac{\int h_1^q(x_1)\, h_1^{\bar{q}}(x_2) d\hat{\sigma}_{TT}}{\int f_1^q(x_1)\, f_1^{\bar{q}}(x_2)\, d\hat{\sigma}_{UU}}$$

q_T - dependence of A_{TT}

10 GeV < Q < 70GeV at mid- and large rapidity (-1 < y < 1 and 3 < y < 4))



- Saturation of Soffer bound assumed
  → implementation of transversity extraction in progress...
- Asymmetry is of the same size as for Drell-Yan (1 - 2 %)
- Event rate is larger at higher q_T

Summary:

- Drell-Yan cross section can be decomposed model-independently into angular structure function, not possible for photon pair production
- TMD-factorization at low q_T: Photon pair production similar to Drell-Yan
- Sivers effect similar in Photon pair production, but higher production rate
  → simultaneous measurement
- Collinear factorization at larger q_T: all azimuthal modulations possible for photon pair production in contrast to lepton pair production
- Expansion to smaller q_T: Azimuthal behaviour partly recovered
  → photon fragmentation or isolation needed.
- Double Transverse Spin Asymmetry A_{TT} revisited: also higher production rate for the diphoton production

Spin physics with unpolarized protons

Spin and other effects in multiple parton interactions

M. Diehl

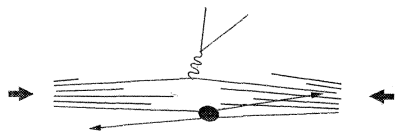
Deutsches Elektronen-Synchroton DESY, 22603 Hamburg, Germany

Abstract

In proton-proton collisions at high energies, more than one parton in one proton can undergo a hard scattering with a parton in the other proton. Such multiple parton interactions have been seen at the Tevatron and are expected to play an important role for many final states at the LHC. Their current phenomenological description is based on simple and rather intuitive assumptions. The present talk reports on an effort to identify to which extent this simple picture can be derived from QCD and where it needs to be extended.
It turns out that multiple interactions involve interesting aspects of spin physics. Even in an unpolarized proton, the polarizations of two partons (each entering its own hard scattering process) can be correlated, and such correlations can have significant effects both on the rate and final-state distributions of double scattering events. Specific angular distributions, e.g. in double Drell-Yan production, may offer a way to study this phenomenon experimentally.

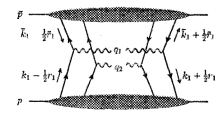
Multi-parton interactions

- generically take place in hadron-hadron collisions
  at high c.m. energy several interactions can be hard
- effects average out in sufficiently inclusive quantities
  but do affect final state properties



- estimated to be important for many processes at LHC
  see e.g. Procs. of the Workshop on HERA and the LHC, 2005 and 2008
- many studies:
  theory: Treleani et al; Artru, Mekhfi; Frankfurt, Strikman, Weiss; ...
  experiment: Tevatron, ...
  Monte Carlo generators: Sjostrand et al; Gieseke et al

Basic structure: cross section



- get cross section formula

$$\frac{d\sigma}{dx_1\, d\bar{x}_1\, d^2\boldsymbol{q}_1\; dx_2\, d\bar{x}_2\, d^2\boldsymbol{q}_2} = \left[\prod_{i=1}^{2} \hat{\sigma}_i\big(q_i^2 = x_i \bar{x}_i s\big)\right]$$

$$\times \left[\prod_{i=1}^{2} \int d^2\boldsymbol{k}_i\, d^2\bar{\boldsymbol{k}}_i\, \delta(\boldsymbol{q}_i - \boldsymbol{k}_i - \bar{\boldsymbol{k}}_i)\right] \int d^2\boldsymbol{y}_1\, F(x_i, \boldsymbol{k}_i, \boldsymbol{y}_1)\, \bar{F}(\bar{x}_i, \bar{\boldsymbol{k}}_i, \boldsymbol{y}_1)$$

$\hat{\sigma}_i =$ parton-level cross section

$F(x_i, \boldsymbol{k}_i, \boldsymbol{y}_1) = k_T$ dependent two-parton distribution

- result follows from Feynman graphs and hard-scattering approximation
  no semi-classical approximation involved
- $\int d^2\boldsymbol{q}_1 \int d^2\boldsymbol{q}_2$ in cross sect. $\longrightarrow$ collinear distributions

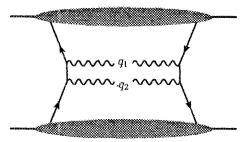
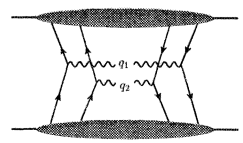
$$F(x_i, \boldsymbol{y}_1) = \int d^2\boldsymbol{k}_1 \int d^2\boldsymbol{k}_2\, F(x_i, \boldsymbol{k}_i, \boldsymbol{y}_1)$$

spin and color neglected so far $\longrightarrow$ later

Power behavior: single versus double hard scattering

- from scattering formulae readily find

$$s\,\frac{d\sigma}{dx_1\,d\bar{x}_1\,d^2\boldsymbol{q}_1\,dx_2\,d\bar{x}_2\,d^2\boldsymbol{q}_2} \sim \frac{1}{Q^2\Lambda^2} \qquad Q^2 \sim q_i^2,\ \Lambda^2 \sim \mathrm{GeV}^2$$

for both  and 

$\Rightarrow$ double scattering not power suppressed

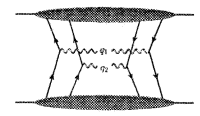
- but if integrate over $\boldsymbol{q}_1$ and $\boldsymbol{q}_2$ then

single: $$s\,\frac{d\sigma}{dx_1\,d\bar{x}_1\,dx_2\,d\bar{x}_2} \sim 1 \quad \text{since} \quad \int d^2(\boldsymbol{q}_1+\boldsymbol{q}_2) \sim \Lambda^2 \quad \text{and} \quad \int d^2(\boldsymbol{q}_1-\boldsymbol{q}_2) \sim Q^2$$

double: $$s\,\frac{d\sigma}{dx_1\,d\bar{x}_1\,dx_2\,d\bar{x}_2} \sim \frac{\Lambda^2}{Q^2} \quad \text{since} \quad \int d^2\boldsymbol{q}_1 \int d^2\boldsymbol{q}_2 \sim \Lambda^4$$

i.e. single hard scattering has larger phase space in transv. momenta

More spin structure



$$F(x_i, \boldsymbol{k}_i, y_1) = \int \frac{dz_2^-\, d^2\boldsymbol{z}_2}{(2\pi)^3}\, e^{ix_2 z_2^- p^+ - i\boldsymbol{z}_2\boldsymbol{k}_2} \int \frac{dz_1^-\, d^2\boldsymbol{z}_1}{(2\pi)^3}\, e^{ix_1 z_1^- p^+ - i\boldsymbol{z}_1\boldsymbol{k}_1}$$
$$\times\, 2p^+ \int dy_1^-\, \langle p|\bar{q}(-\tfrac{1}{2}z_2)\Gamma_2\, q(\tfrac{1}{2}z_2)\, \bar{q}(y_1 - \tfrac{1}{2}z_1)\Gamma_1\, q(y_1 + \tfrac{1}{2}z_1)|p\rangle$$

- transverse spin correlations from $\Gamma_1 = \Gamma_2 = \frac{1}{2} i\sigma^{+j}\gamma_5$
- in gauge boson pair production:
  $\rightsquigarrow$ interference of bosons with opposite helicities
  $\rightsquigarrow$ $\cos 2\phi$ modulation between decay planes of the two bosons
  at low $\boldsymbol{q}_1, \boldsymbol{q}_2$ single hard scattering does not give $\cos 2\phi$ term
- in general: correlation between planes of the two hard scatters
- may naively expect spin effects to decrease for small x_1, x_2, but
  - will see counter-example on slide 19
  - for $x_1 \sim x_2 \ll 1$ spin correlations may be
    weak a parton and the proton (far away in rapidity)
    important between two partons (close in rapidity)

Summary

- multiple hard interactions not power suppressed
  for cross section differential in $|\boldsymbol{q}_i| \ll Q$
- nontrivial spin and color structure
  interference in fermion number and quark flavor
  can affect rates and distributions, size of effects unknown
- some simplification for transv. mom. $|\boldsymbol{q}_i| \gg \Lambda$
  - collinear distributions as input
  - enhancement of color singlet combinations

  further studies needed, techniques from spin physics very useful
- multi-parton distr's depend on transverse distance between partons
- under assumptions can relate multi-parton distr's to generalized parton distributions, which may help estimate
  - transv. distr'n of partons and its correlation with long. momenta
  - size of interference-type multi-parton distr's

Overview of single-transverse-spin asymmetry: Twist-3 mechanism

YUJI KOIKE

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

Abstract

After a brief theory overview on the single-transverse-spin asymmetry, I discussed the following two topics based on our recent works.

(1) New Analysis of the Single Transverse-Spin Asymmetry for Hadron Production at RHIC [1].

We analyze the single transverse-spin asymmetry (SSAs) for inclusive hadron production in the pp collision at RHIC based on the twist-3 machanism in QCD. As an origin of SSAs, we take into account of all kinds of pole contributions associated with the twist-3 quark-gluon correlation functions in the polarized proton. By the inclusion of the soft-fermion-pole contribution [2] in addition to the soft-gluon-pole contribution, we find SSAs observed at RHIC are better described for all kinds of mesons. P_T-dependence of the asymmetry and the comparison with the FNAL data are also presented.

(2) Contribution of Twist-3 Multi-Gluon Correlation Functions to Single Spin Asymmetry in Semi-Inclusive Deep Inelastic Scattering [3].

As a possible source of the single transverse spin asymmetry, we study the contribution from purely gluonic correlation represented by the twist-3 "three-gluon correlation" functions in the transversely polarized nucleon. We first define a complete set of the relevant three-gluon correlation functions, and then derive its contribution to the twist-3 single-spin-dependent cross section for the D-meson production in semi-inclusive deep inelastic scattering, which is relevant to determine the three-gluon correlations. Our cross-section formula differs from the corresponding result in the literature [4, 5], and the origin of the discrepancy is clarified.

References

[1] K. Kanazawa and Y. Koike, Phys. Rev. D **82**, 034009 (2010).

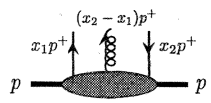
[2] Y. Koike and T. Tomita, Phys. Lett. **B675**, 181 (2009).

[3] H. Beppu, Y. Koike, K. Tanaka and S. Yoshida, Phys. Rev. D **82**, 054005 (2010).

[4] Z. B. Kang and J. W. Qiu, Phys. Rev. **D78**, 034005 (2008).

[5] Z. B. Kang, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. **D78**, 114013 (2008).

⋆ A_N for $p^\uparrow p \to hX$ $(h = \pi,\ K)$



$\sim \langle \bar{\psi} g F^{+\alpha} \psi \rangle \ \to G_F(x_1, x_2),\ \widetilde{G}_F(x_1, x_2)$

Two twist-3 quark-gluon correlation funcitons

$$\Delta\sigma \sim \left\{ \underbrace{\hat{\sigma}_{\rm SGP} \otimes \left(G_F(x,x) - x\frac{dG_F(x,x)}{dx} \right)}_{\text{SGP (soft-gluon-pole)}} + \underbrace{\hat{\sigma}_{\rm SFP} \otimes \left(G_F(0,x) + \widetilde{G}_F(0,x) \right)}_{\text{SFP (soft-fermion-pole)}} \right\} \otimes f(x') \otimes D(z)$$

⋆ Kouvaris *et al.* (Phys.Rev.D74:114013,2006.)

-Calculation of $\hat{\sigma}_{\rm SGP}$ and phenomenology for E704 and RHIC data.

Good description of A_N data, except for BRAHMS K^- data and P_T-dependence.

⋆ YK-Tomita (PLB675(2009)181, arXiv:0903.1923 [hep-ph])

- Calculation of $\hat{\sigma}_{\rm SFP}$ and study its impact compared to SGP contribution.
- Appears in combination of $G_F(0,x) + \widetilde{G}_F(0,x)$.

⋆ Data included in the fitting

61 data points in total

· RHIC-STAR, PRL 92(2004)171801, PRL101(2008)222001, $\sqrt{S} = 200$ GeV.

All data for $A_N^{\pi^0}$ have $P_T \geq 1$ GeV.

· RHIC-BRAHMS, PRL 101(2008)042001, $\sqrt{S} = 62.4$ GeV.

A_N data for π and K with $P_T \geq 0.7$ GeV have been included.

-Use correct values of P_T at each x_F.

· We did not include the FNAL-E704 data at $\sqrt{S} = 20$ GeV.

-NLO QCD can not reproduce the unpolarized cross section.

-P_T-values at each x_F are unknown.

- DSS fragmentation function (PRD75)

  - Can describe greater variety of data compared with the older ones.

  - Large gluon fragmentation functions.

    $\longrightarrow$ Sensitive to the SFP contribution; e.g. $\hat{\sigma}^F_{ag\to g} \gg \hat{\sigma}^G_{ag\to g}$.

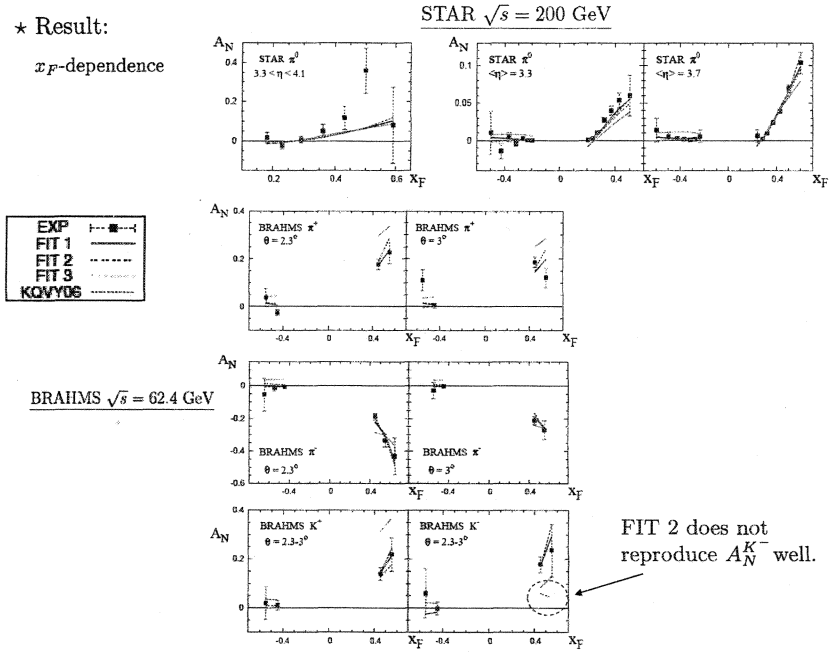
  - Larger strangeness contribution to $K^{\pm}$.

We could not get good fit by Kretzer's fragmentation fuctions.

⋆ Result:

x_F-dependence

STAR $\sqrt{s} = 200$ GeV



BRAHMS $\sqrt{s} = 62.4$ GeV

FIT 2 does not reproduce $A_N^{K^-}$ well.

⋆ Summary of the analysis of A_N.

· Better description of the RHIC A_N data for π and K was obtained by the inclusion of the SFP contribution as well as the SGP contribution.

· The SGP provides a main contribution to A_N, and the SFP provides a smaller (partly because of cancelation) but nonnegligible contribution.

· It is difficult to substitute the role of the SFP by the SGP contribution.

⋆ Twist-3 "three-gluon" correlation functions (cont'd)

- Hermiticity, PT-invariance, Permutation symmetry
- Only two independent scalar functions due to the different color structures:

$$O^{\alpha\beta\gamma}(x_1,x_2) = 2iM_N\left[O(x_1,x_2)g^{\alpha\beta}\epsilon^{\gamma pnS} + O(x_2,x_2-x_1)g^{\beta\gamma}\epsilon^{\alpha pnS} + O(x_1,x_1-x_2)g^{\gamma\alpha}\epsilon^{\beta pnS}\right]$$

$$N^{\alpha\beta\gamma}(x_1,x_2) = 2iM_N\left[N(x_1,x_2)g^{\alpha\beta}\epsilon^{\gamma pnS} - N(x_2,x_2-x_1)g^{\beta\gamma}\epsilon^{\alpha pnS} - N(x_1,x_1-x_2)g^{\gamma\alpha}\epsilon^{\beta pnS}\right].$$

$$\epsilon^{\gamma pnS} \equiv \epsilon^{\gamma\mu\nu\lambda}p_\mu n_\nu S_\lambda \text{ etc.}$$

$$O(x_1,x_2) = O(x_2,x_1), \qquad O(x_1,x_2) = O(-x_1,-x_2),$$

$$N(x_1,x_2) = N(x_2,x_1), \qquad N(x_1,x_2) = -N(-x_1,-x_2).$$

- All three terms with the above coefficient tensors are required due to the Bose statistics of the gluon fields.

- Contribution to SSA is from $x_1 = x_2 \equiv x$ (soft-gluon-pole (SGP)):

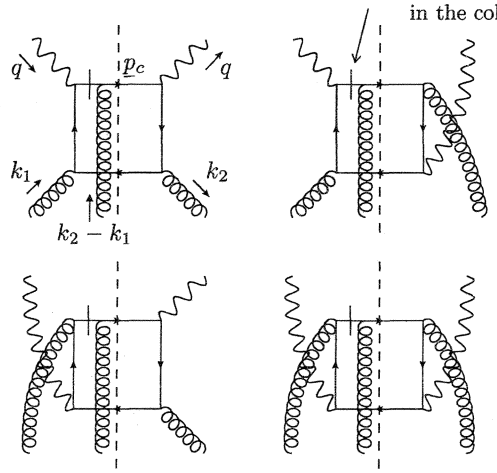
$$O^{\alpha\beta\gamma}(x,x) = 2iM_N\left[O(x,x)g^{\alpha\beta}\epsilon^{\gamma pnS} + O(x,0)\left(g^{\beta\gamma}\epsilon^{\alpha pnS} + g^{\gamma\alpha}\epsilon^{\beta pnS}\right)\right]$$

→ Different partonic cross sections for the different tensor structures.

↔ Kang-Qiu (PRD 78('08)034005), Kang-Qiu-Vogelsang-Yuan (PRD 78('08)114013)

⋆ Leading order diagrams for the SGPs

SGP: $\delta\left((p_c - k_2 + k_1)^2\right) \to\propto \delta(x_1 - x_2)$
in the collinear limit ($k_i \to x_i p$)



+ mirrors

Other pole contributions cancel among them!

Eventually, we obtain

$$\boxed{w(p,q,p_c) = \int \frac{dx_1}{x_1} \int \frac{dx_2}{x_2} \left.\frac{\partial S^{abc}_{\mu\nu\lambda}(k_1,k_2,q,p_c)p^\lambda}{\partial k_2^\sigma}\right|_{k_i = x_i p} \omega^\mu{}_\alpha\, \omega^\nu{}_\beta\, \omega^\sigma{}_\gamma\, \mathcal{M}^{\alpha\beta\gamma}_{F,abc}(x_1,x_2),}$$

where

$$\omega^\mu{}_\alpha = g^\mu{}_\alpha - p^\mu n_\alpha$$

$$\begin{aligned}\mathcal{M}^{\alpha\beta\gamma}_{F,abc}(x_1,x_2) &= -gi^3 \int \frac{d\lambda}{2\pi} \int \frac{d\mu}{2\pi} e^{i\lambda x_1} e^{i\mu(x_2 - x_1)} \langle pS | F_b^{\beta n}(0) F_c^{\gamma n}(\mu n) F_a^{\alpha n}(\lambda n) | pS \rangle \\ &= \frac{3}{40} d^{abc} O^{\alpha\beta\gamma}(x_1,x_2) - \frac{i}{24} f^{abc} N^{\alpha\beta\gamma}(x_1,x_2),\end{aligned}$$

· $\frac{\partial}{\partial k_2^\sigma}$ hits δ-functions in the hard part (on-shell condition and the SGP).

· $\left.\frac{\partial S^{abc}_{\mu\nu\lambda}(k_1,k_2,q,p_c)p^\lambda}{\partial k_2^\sigma}\right|_{k_i = x_i p}$ produces $\delta(x_1 - x_2)$ and $\delta'(x_1 - x_2)$.

$$\longrightarrow \quad \begin{aligned} O^{\alpha\beta\gamma}(x,x) &= 2iM_N \left[O(x,x) g^{\alpha\beta} \epsilon^{\gamma pnS} + O(x,0)\left(g^{\beta\gamma}\epsilon^{\alpha pnS} + g^{\gamma\alpha}\epsilon^{\beta pnS}\right)\right] \\ N^{\alpha\beta\gamma}(x,x) &= 2iM_N \left[N(x,x) g^{\alpha\beta} \epsilon^{\gamma pnS} - N(x,0)\left(g^{\beta\gamma}\epsilon^{\alpha pnS} + g^{\gamma\alpha}\epsilon^{\beta pnS}\right)\right]\end{aligned}$$

⋆ Final cross section formula for $ep^\uparrow \to eDX$ generated from three-gluon correlation functions

$$\frac{d^5\Delta\sigma}{dx_{bj}dQ^2dz_f dq_T^2 d\phi}$$

$$= \frac{\alpha_{em}^2\alpha_s e_c^2 M_N}{8\pi x_{bj}^2 S_{ep}^2 Q^2}\left(\frac{-\pi}{2}\right)\sum_{k=1,\cdots,4,8,9}\mathcal{A}_k\mathcal{S}_k\int\frac{dx}{x}\int\frac{dz}{z}\delta\left(\frac{q_T^2}{Q^2}-\left(1-\frac{1}{\hat{x}}\right)\left(1-\frac{1}{\hat{z}}\right)+\frac{m_c^2}{\hat{z}^2Q^2}\right)$$

$$\times\sum_{a=c,\bar{c}}D_a(z)\left[\delta_a\left\{\left(\frac{d}{dx}O(x,x)-\frac{2O(x,x)}{x}\right)\Delta\hat{\sigma}_k^1+\left(\frac{d}{dx}O(x,0)-\frac{2O(x,0)}{x}\right)\Delta\hat{\sigma}_k^2+\frac{O(x,x)}{x}\Delta\hat{\sigma}_k^3+\frac{O(x,0)}{x}\Delta\hat{\sigma}_k^4\right\}\right.$$

$$\left.+\left\{\left(\frac{d}{dx}N(x,x)-\frac{2N(x,x)}{x}\right)\Delta\hat{\sigma}_k^1-\left(\frac{d}{dx}N(x,0)-\frac{2N(x,0)}{x}\right)\Delta\hat{\sigma}_k^2+\frac{N(x,x)}{x}\Delta\hat{\sigma}_k^3-\frac{N(x,0)}{x}\Delta\hat{\sigma}_k^4\right\}\right],$$

$\delta_c = 1,\ \delta_{\bar{c}} = -1$ $\quad\mathcal{A}_1 = 1+\cosh^2\psi,\quad \mathcal{A}_2=-2,\quad \mathcal{A}_3=-\cos\phi\sinh 2\psi,\quad \mathcal{A}_4=\cos 2\phi\sinh^2\psi,$
$\mathcal{A}_8=-\sin\phi\sinh 2\psi,\quad \mathcal{A}_9=\sin 2\phi\sinh^2\psi.$

$\cosh\psi = \frac{2x_{bj}S_{ep}}{Q^2}-1$ $\quad\mathcal{S}_k=\sin\Phi_S\ \ (k=1,2,3,4),\qquad \mathcal{S}_k=\cos\Phi_S\ \ (k=8,9)$

$$\Phi_S\equiv\phi_h-\phi_S\qquad \phi\equiv\phi_h$$

- Receives contribution from 4 functions $O(x,x)$, $O(x,0)$, $N(x,x)$ and $N(x,0)$, and all of them contribute both as derivative and nonderivative forms.

-5 structure functions with different azimuthal dependence

$$=\sin\Phi_S\left(\mathcal{F}_1+\mathcal{F}_2\cos\phi+\mathcal{F}_3\cos 2\phi\right)+\cos\Phi_S\left(\mathcal{F}_4\sin\phi+\mathcal{F}_5\sin 2\phi\right).$$

$$=\sin(\phi_h-\phi_S)\,F^{\sin(\phi_h-\phi_S)}+\sin(2\phi_h-\phi_S)\,F^{\sin(2\phi_h-\phi_S)}+\sin\phi_S\,F^{\sin\phi_S}$$
$$+\sin(3\phi_h-\phi_S)\,F^{\sin(3\phi_h-\phi_S)}+\sin(\phi_h+\phi_S)\,F^{\sin(\phi_h+\phi_S)},$$

The same as TMD factorization approach.

⋆ Comparison with the previous works

Kang-Qiu (PRD 78('08)034005), Kang-Qiu-Vogelsang-Yuan (PRD 78('08)114013)

These authors defined a particular projection

$$T_G^{(\pm)}(x,x)=\int\frac{dy_1^-dy_2^-}{2\pi}e^{ixp^+y_1^-}\frac{1}{xp^+}g_{\beta\alpha}\epsilon_{S\gamma np}\langle pS|C_\pm^{bca}F_b^{\beta+}(0)F_c^{\gamma+}(y_2^-)F_a^{\alpha+}(y_1^-)|pS\rangle.$$

which are related to our functions as

$$\frac{xg}{2\pi}T_G^{(+)}(x,x)=-4M_N\left(N(x,x)-N(x,0)\right),$$
$$\frac{xg}{2\pi}T_G^{(-)}(x,x)=-4M_N\left(O(x,x)+O(x,0)\right).$$

- Formula by Kang-Qiu:

$$w\left(p,q,p_c\right)|^{KQ}=\int\frac{dx_1}{x_1}\int\frac{dx_2}{x_2}\left.\frac{\partial S_{\mu\nu\lambda}^{abc}(k_1,k_2,q,p_c)p^\lambda g_\perp^{\mu\nu}}{\partial k_{2\perp}^\gamma}\right|_{k_i=x_ip}\underbrace{g_{\alpha\beta}^\perp}_{\text{additional projections}}\overbrace{\mathcal{M}_{F,abc}^{\alpha\beta\gamma}(x_1,x_2)}^{T_G^{(\pm)}(x,x)},$$

⇕

- Our formula:

$$w\left(p,q,p_c\right)=\int\frac{dx_1}{x_1}\int\frac{dx_2}{x_2}\left.\frac{\partial S_{\mu\nu\lambda}^{abc}(k_1,k_2,q,p_c)p^\lambda}{\partial k_2^\sigma}\right|_{k_i=x_ip}\omega^\mu{}_\alpha\,\omega^\nu{}_\beta\,\omega^\sigma{}_\gamma\,\mathcal{M}_{F,abc}^{\alpha\beta\gamma}(x_1,x_2),$$

-If $O(x,0)\equiv 0$ and $N(x,0)\equiv 0$, two formulas are identical!

Single transverse-spin asymmetry in inclusive hadron production

Zhong-Bo Kang
RIKEN BNL Research Center
Brookhaven National Laboratory

Brookhaven Summer Program on Nucleon Spin Physics
Upton, NY, July 14-27, 2010

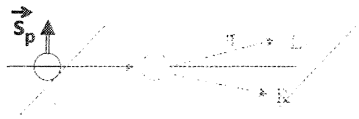
based on work with Gamberg ,Qiu, Vogelsang, Yuan, Zhou

Outline

- Introduction
- Collinear factorization approach:
  - Basic formalism
  - Quark and gluon contributions
  - pT behavior
  - Global analysis
  - Twist-3 fragmentation function contribution
- TMD approach:
  - Generalized Parton Model (GPM)
  - Process-dependent Sivers function
- Summary

A_N Definition: Single Transverse Spin Asymmetry (SSA)

- Consider the scattering of a transversely polarized nucleon with another nucleon, observe a particle going left or right: left-right asymmetry



$$A_N = \frac{N_L - N_R}{N_L + N_R}$$

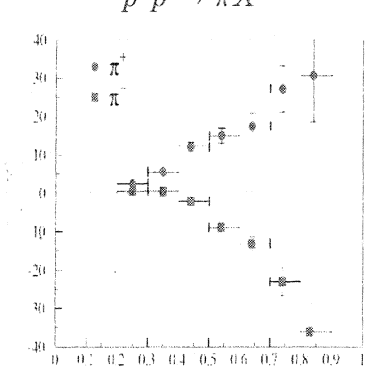
- Because of rotational symmetry, this corresponds to an asymmetry relate to the difference of the cross section when the spin of the incoming nucleon is flipped
  - Spin-averaged cross section: $\sigma(\ell) = \frac{1}{2}\left[\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})\right]$
  - Spin-dependent cross section: $\Delta\sigma(\ell,\vec{s}) = \frac{1}{2}\left[\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})\right]$
  - Single transverse-spin asymmetry (SSA):

$$A_N \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s}) - \sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s}) + \sigma(\ell,-\vec{s})}$$

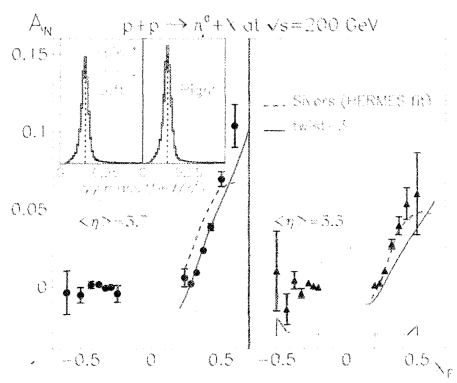
Experiment: Single Spin Asymmetries

- Fermilab E704, STAR, PHENIX, BRAHMS, COMPASS, HERMES, JLAB:

$$p^{\uparrow}p \to \pi X$$



E704



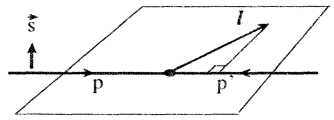
STAR

SSAs are observed in various experiments at different √s

SSA corresponds to a T-odd triplet product

- SSA measures the correlation between the hadron spin and the production plane, which corresponds to $\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$

$$p^{\uparrow} p \to \pi(\ell) X$$



- Such a product is (naive) odd under time reversal (T-odd), thus they can arise in a time-reversal invariant theory (eg, QCD) only when there is a phase between different spin amplitudes

  ➡ $A_N \propto i\vec{s}_p \cdot (\vec{p} \times \vec{\ell})$

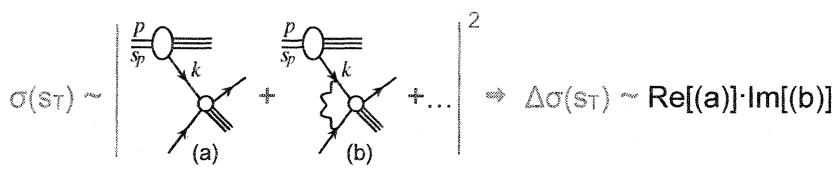
  - the phase "i" is required by time-reversal invariance
  - covariant form: $A_N \propto i\epsilon^{\mu\nu\alpha\beta} p_\mu s_\nu \ell_\alpha p'_\beta$

Nonvanishing A_N requires a phase, a helicity flip, and enough vectors to fix a scattering plane

SSA vanishes at leading twist in collinear factorization

- At leading twist formalism: partons are collinear

Kane, Pumplin, Repko, 1978



  - generate phase from loop diagrams, proportional to α_s
  - helicity is conserved for massless partons, helicity-flip is proportional to current quark mass m_q

Therefore we have

$$A_N \sim \alpha_s \frac{m_q}{\sqrt{s}} \to 0$$

- $A_N \neq 0$: result of parton's transverse motion or correlations!

Two mechanisms to generate SSA in QCD

- SSA is related to parton's transverse motion
- TMD approach: Transverse Momentum Dependent distributions probe the parton's intrinsic transverse momentum
  - Sivers function: in Parton Distribution Function (PDF)

    Sivers 90
  - Collins function: in Fragmentation Function (FF)

    Collins 93
- Collinear factorization approach:
  - Twist-3 three-parton correlation functions: Qiu-Sterman matrix element, ...

    Efremov-Teryaev 82, 84, Qiu-Sterman 91, 98, ...
  - Twist-3 three-parton fragmentation functions:

    Koike, 02, Zhou, Yuan, 09, Kang, Yuan, Zhou, 10

Relation between twist-3 and TMD approaches

- They apply in different kinematic domain:
  - TMD approach: need TMD factorization, applies for the process with two observed momentum scales: DY at small $q_\perp$

    $Q_1 \gg Q_2$ $\begin{cases} Q_1 & \text{necessary for pQCD factorization to have a chance} \\ Q_2 & \text{sensitive to parton's transverse momentum} \end{cases}$
  - Collinear factorization approach: more relevant for single scale hard process: inclusive pion production at pp collision
- They generate same results in the overlap region when they both apply:
  - Twist-3 three-parton correlation in distribution $\Longleftrightarrow$ Sivers function

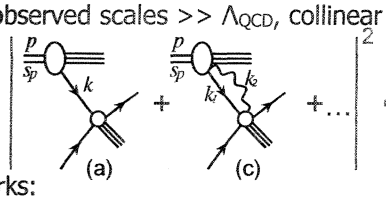
    Ji, Qiu, Vogelsang, Yuan, 06, ...
  - Twist-3 three-parton correlation in fragmentation $\Longleftrightarrow$ Collins function

    Zhou, Yuan, 09, Kang, Yuan, Zhou, 10

SSA in collinear factorization approach

Efremov-Teryaev, 1982, Qiu-Sterman, 1991

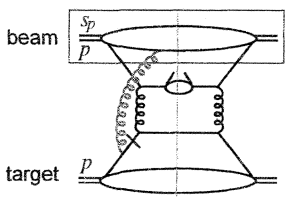
- When all observed scales >> Λ_{QCD}, collinear factorization should work:

$\sigma(s_T) \sim$ 

$\Rightarrow \Delta\sigma(s_T) \sim$ Re[(a)]·Im[(c)]

- How it works:

$T_{q,F}(x,x)$



some propagators in the tree diagrams go on-shell

$$\frac{1}{k^2-m^2+i\epsilon} = P\frac{1}{k^2-m^2} - i\pi\delta(k^2-m^2)$$

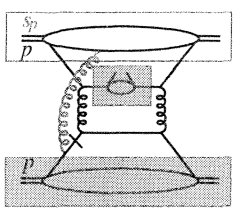
- phase: from hard scattering amplitudes (unpinched pole)
- spin flip: from interference between a quark state and a quark-gluon composite state

- Twist-3 quark-gluon correlation function $T_{q,F}(x,x)$:

$$T_{q,F}(x,x) = \int \frac{dy_1^- dy_2^-}{4\pi} e^{ixP^+y_1^-} \langle P, s_T|\bar{\psi}_q(0)\gamma^+ \boxed{[e^{s_T\sigma n\bar{n}} F_\sigma{}^+(y_2^-)]} \psi_q(y_1^-)|P, s_T\rangle$$

The sources of the twist-3 effects

- Three places where the twist-3 effects could come from:



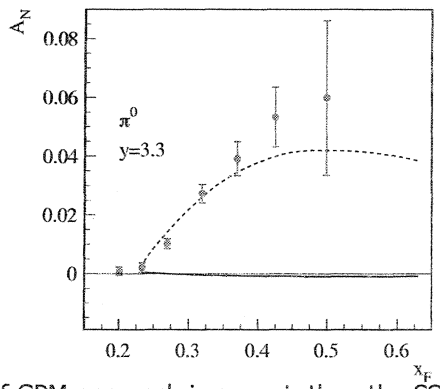
- From polarized hadron
- **From unpolarized hadron**
- From fragmentation function

$$\Delta\sigma_{A+B\to hX}(\ell_\perp, \vec{s}_T) = \boxed{\sum_{abc} \phi^{(3)}_{a/A}(x_1, x_2, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes H_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D_{c\to h}(z)}$$
$$+ \boxed{\sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \otimes \phi^{(3)}_{b/B}(x_1', x_2') \otimes H'_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D_{c\to h}(z)}$$
$$+ \boxed{\sum_{abc} \delta q_{a/A}(x, \vec{s}_T) \otimes \phi_{b/B}(x') \otimes H''_{ab\to c}(\ell_\perp, \vec{s}_T) \otimes D^{(3)}_{c\to h}(z_1, z_2)}$$

- Within each term, there could be several twist-3 correlation functions

Predictions with process-dependent Sivers function

- Do the calculation more consistently: take into account the process-dependence of the Sivers function



Kang, Gamberg, 2010

Red solid: with process dependence in Sivers function

Blue dashed: without

- If GPM approach is correct, then the SSA for inclusive pion probably does not come from Sivers effect

Summary

- Single transverse-spin asymmetry is directly connected to the parton's transverse motion
  - an excellent probe for the parton's transverse motion
- More correlation functions (than spin-avg case) are involved, much theoretical progress made for PDF side
  - A better way to describe pT behavior is provided
  - Three-gluon correlation functions are extracted from pion data
- For FF side, a sizable asymmetry could also be generated.
  - Need more data to constrain the relevant twist-3 fragmentation correlation
- With process-dependence included in the description of the GPM approach for inclusive pion, we typically have very small asymmetry

Transverse Spin Physics Current & Future with PHENIX

M. Grosse Perdekamp, Illinois

- The PHENIX detector, its upgrades and assumptions on future running
- Inclusive A_N
- Measurements constraining Sivers distributions
- Drell-Yan
- Measurements constraining quark transversity distributions

Upgrade Overview

2002	Complete	ERT	
2003		Local Pol	
2004		Aerogel	
2006		TOF-Wes	
2007		HBD	
		RXP	
	MPC		
09/10	Active Construction	μ-Trigger	W-physics
2010		VTX	c-, b-tagging, central tracking
2011		FVTX	c-, b-tagging
2014		FOCAL	γ, π^0, η
	Under Study	S-PHENIX	central: full jet capability, heavy flavor tagging; forward: full jet capability, PID, heavy flavor tagging

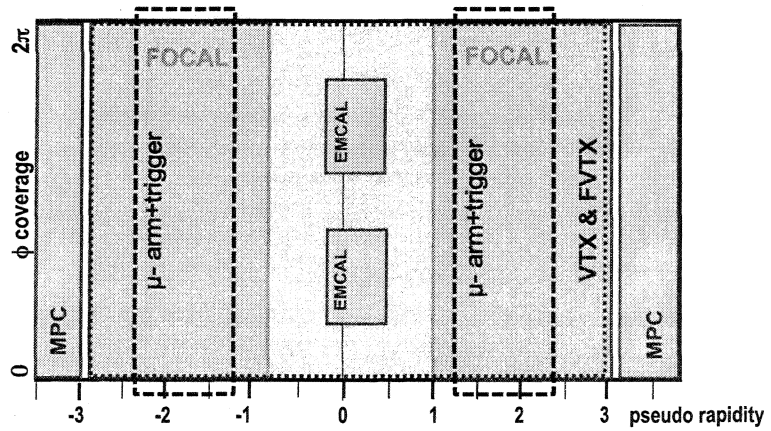
$\int Ldt \approx 10\ pb^{-1}$ by 2009 transverse
$\int Ldt \approx 40\ pb^{-1}$ by 2009 longitudinal

$\int Ldt \approx 30\ pb^{-1}$ 2011-15 $\sqrt{s}$=200 GeV
$\int Ldt \approx 300\ pb^{-1}$ 2011-15 $\sqrt{s}$=500 GeV

$\int Ldt \approx 250\ pb^{-1}$ after 2016 $\sqrt{s}$=500 GeV

→ Upgrades will be available for most of RHIC spin luminosity!

Acceptance + Experimental Capabilities with MPC, VTX, FVTX and μ-Trigger Upgrades



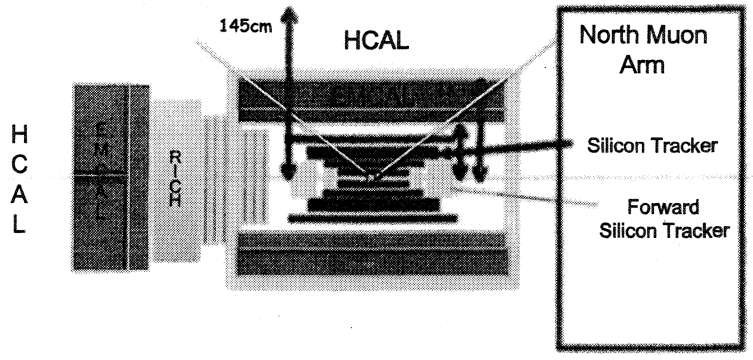
(i) π^0 and direct γ with additional electromagnetic calorimeters *(FOCAL 2014)*
(ii) Heavy flavor tagging with silicon detectors *(central from run 11, forward run 12)*
(iii) High p_T muon trigger *(from run 11)*

6

S-PHENIX Spectrometer (2016+x)

(Courtesy E. Aschenauer)

- o Acceptance: $-1 < \eta < 4$ and $-2.4 < \eta < -1.2$
- o Full jet capability: electromagnetic + hadronic calorimetery
- o Heavy flavor tagging, PID for : $1 < \eta < 4$
- o W-physics: a) reconstruct missing mass, b) access to hadronic final states
- o Opportunity to improve relative luminosity measurement → access to asymmetries $< 10^{-3}$



7

Muon Trigger Upgrade will be Installed for Run 11

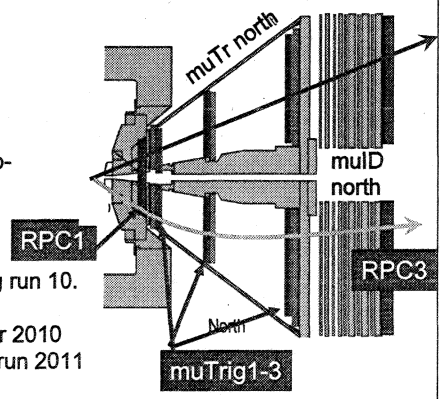
Status:

(1) muTrig electronics 1-3 for both muon spectrometers are fully installed.
(2) RPC-3 north fully installed.
(3) Trigger processor boards have been manufactured.
(4) muTrig south and two full size RPC prototypes tested sucessfully during run 9

Schedule:

(1) Full muTrig system tests with LL1 during run 10.
(2) Partial tests of RPC-3 north.
(3) RPC-3 + absorber installation in summer 2010
(4) Ready for W-physics (and Drell-Yan) in run 2011
(5) RPC-1 will be installed once the FVTX has been installed.

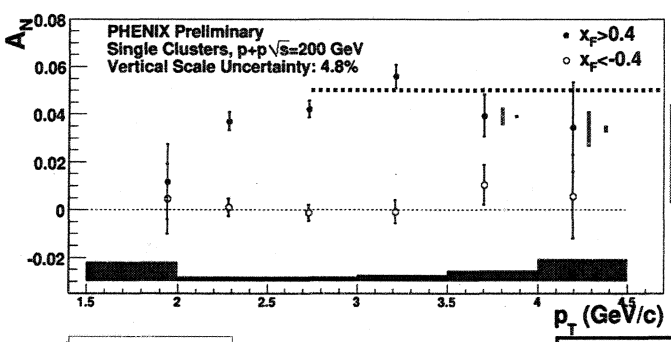
PHENIX Muon Spectrometer



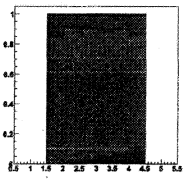
Trigger for W, Drell-Yan and heavy flavor

8

A_N for inclusive hadrons: Observation of $1/p_T$ dependence for A_N in polarized p-p?



30 pb^{-1}
250 pb^{-1}



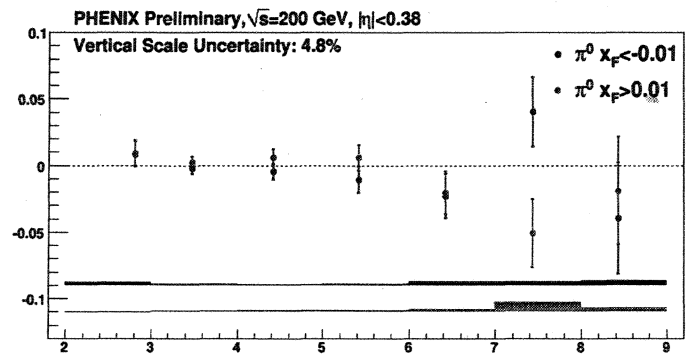
Decay photon
π^0
Direct photon

FOCAL:
removes dependence on cluster decomposition
cluster -> π^0

19

2008 Central arm π^0 A_N $|x_F|>0.01$

(from J. Koster, Illinois)

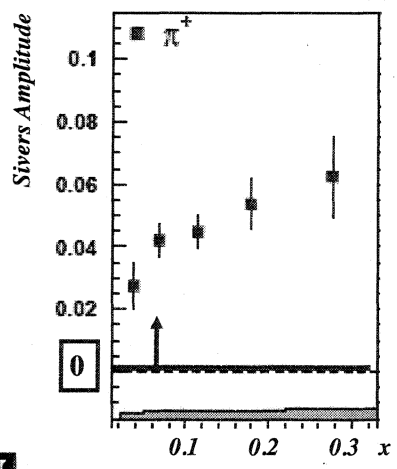


- A_N consistent with zero

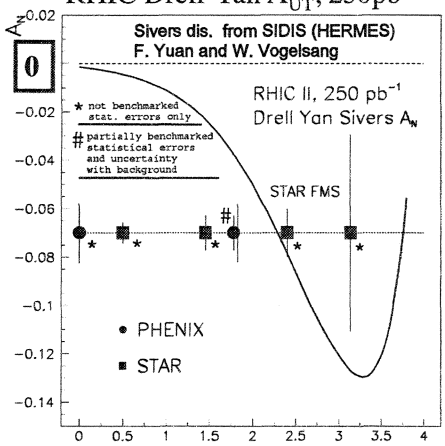
24

Sivers Asymmetries in Drell-Yan
(II) SIDIS in HERMES vs Drell-Yan at RHIC

HERMES Sivers Results



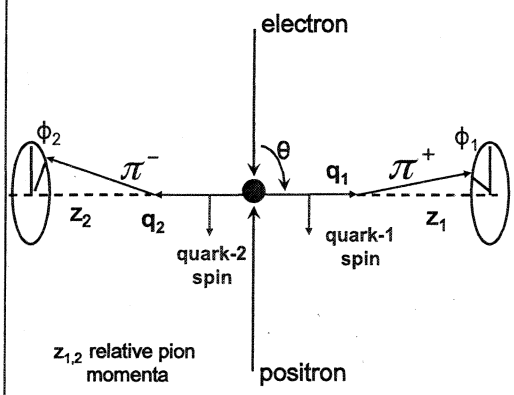
RHIC Drell-Yan A_{UT}, 250pb^{-1}



RHIC projections: Beau Meredith and MGP

31

e^+e^- Annihilation into Quarks is sensitive to [Collins FF, *CFF* (z_1)] x [Collins FF, *CFF* (z_2)]



Collins effect in e^+e^- quark fragmentation will lead to azimuthal asymmetries in di-hadron correlation measurements:

$e^+ + e^- \rightarrow \pi^+ + \pi^- + X$

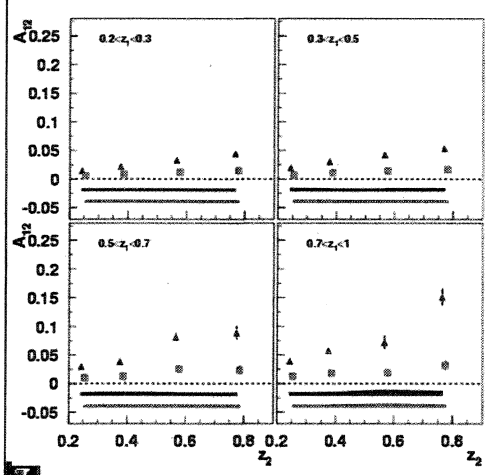
$N_{\pi_1,\pi_2}(\phi_1+\phi_2) \sim a_{12}\cos(\phi_1+\phi_2)$

$a_{12} \sim$ *Collins*(z_1) x *Collins* (z_2)

39

e^+e^- Annihilation into Quarks is sensitive to [Collins FF, *CFF* (z_1)] x [Collins FF, *CFF* (z_2)]

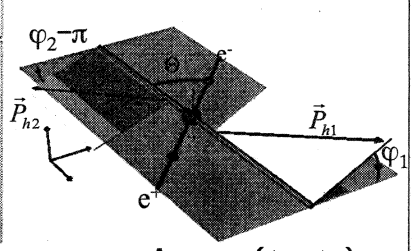
R. Seidl, K. Hasuko, A. Ogawa, S. Lange, M. Grosse Perdekamp et al.
Phys. Rev. Lett. 96 232002 2006 and Phys. Rev. D 78 032011, 2008



Collins Asymmetries in e^+e^- annihilation into hadrons

$e^+ + e^- \rightarrow \pi^+ + \pi^- + X$

~ *Collins*(z_1) x *Collins* (z_2)



$A_{12}\cos(\phi_1+\phi_2)$

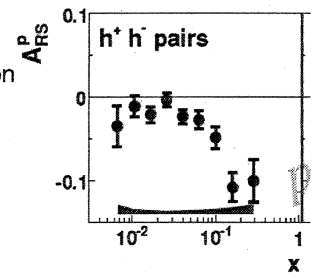
40

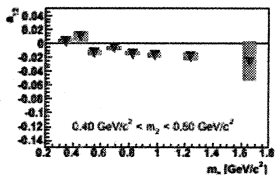
Solution III: Use A_{UT} in IFF

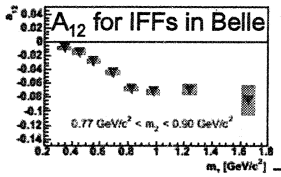
Alternative Approach:

Spin-Dependent di-Hadron Fragmentation:
Interference Fragmentation ➔ transverse single spin asymmetries "survive" k_T integration

IFF in COMPASS







Need measurements of asymmetries & yields in SIDIS and e+e-!

Charm contribution in e+e- may be Difficult to quantify.

Flavor separation non trivial!

46

Summary

Broad range of unexplored options to measure transverse spin asymmetries in PHENIX.

At mid-rapdity precision measurements of A_N and IFF asymmetries remain interesting. However, larger analyzing powers are expected in the forward direction.

A set of di-hadron measurements (Sivers, Collins, IFF, A_{TT}) may become possible should the FOCAL upgrade go forward.

A S-PHENIX forward spectrometer upgrade would cover the same physics channels but with di-jets instead of di-hadrons and likely with superior ability to measure TMDs as function of their kinematics.

Observation of the sign change requires large data samples (~250pb^{-1})

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Transverse Spin Physics

OUTLINE

- Brief motivations
- Reminders from the past (fixed target experiments)
- Review of the present
- Plans for the future

L.C. Bland
Summer Program on Nucleon Spin
Brookhaven, 16 July 2010

BROOKHAVEN NATIONAL LABORATORY

1

RHIC Spin Goals

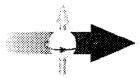
Understanding the Origin of Proton Spin

Spin Sum Rules

Longitudinal Spin

$$S_z = \tfrac{1}{2} = \tfrac{1}{2}\,\Delta\Sigma + \Delta G + L_{z,q} + L_{z,g}$$

ΔG is found small in measured region. Low x? Large L?

Transverse Spin  PRD 70 (2004) 114001

$$S_y = \tfrac{1}{2} = \tfrac{1}{2}\,\delta\Sigma + L_{y,q} + L_{y,g}$$

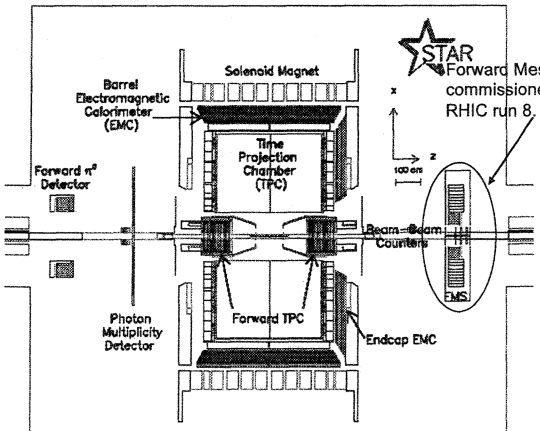
Ongoing debates... (see E.Leader talk on 21 July)

Understanding the origin of proton spin helps to understand its structure

Summer Program on Nucleon Spin, BNL 2010

2

STAR Detector

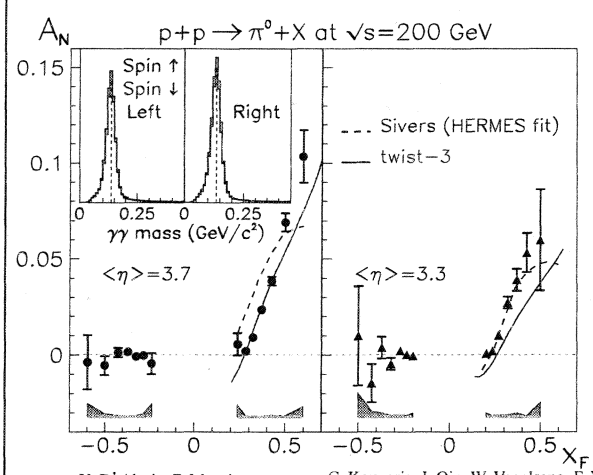


Forward Meson Spectrometer commissioned/operated in RHIC run 8.

- STAR and PHENIX are primarily instrumented near mid-rapidity
- Forward direction can be viewed at STAR, but present instrumentation is limited and not completely compatible with high luminosity polarized p+p collisions

x_F Dependence of Inclusive π^0 A_N

RHIC Runs 3,5,6 with FPD



PRL 101, 222001 (2008)
arXiv:0801.2990v1 [hep-ex]

Fit to SIDIS is consistent with data

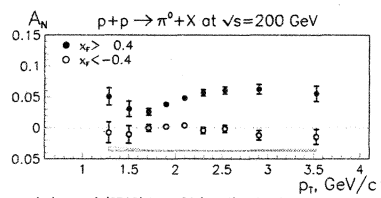
A_N at positive x_F grows with increasing x_F

U. D'Alesio, F. Murgia
Phys. Rev. D 70, 074009 (2004)
arXiv:hep-ph/0712.4240

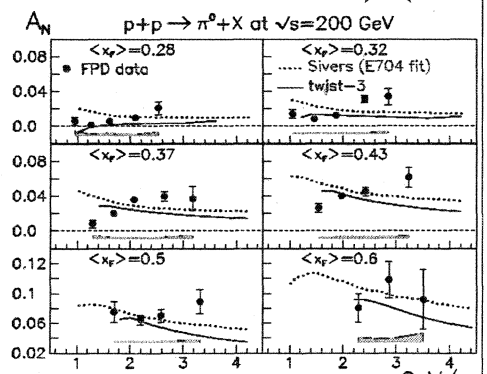
C. Kouvaris, J. Qiu, W. Vogelsang, F. Yuan,
Phys. Rev. D 74, 114013 (2006).

p_T Dependence of Inclusive π^0 A_N

RHIC Runs 3,5,6 with FPD



B.I. Abelev et al. (STAR) PRL **101** (2008) 222001



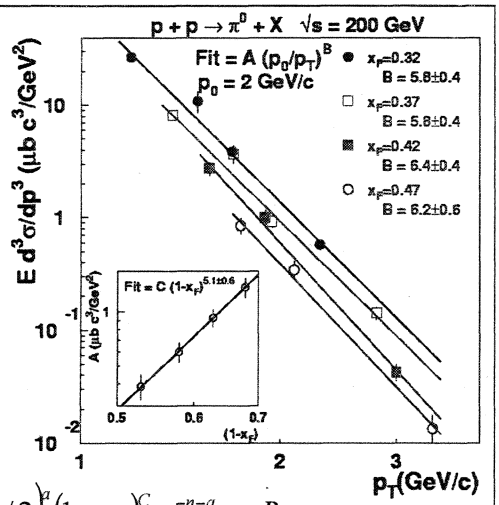
STAR, PRL 101 (2008) 222001

- x_F dependence is consistent with Sivers model
- Rising p_T dependence is not explained

STAR-Forward Cross Sections

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

$$E\frac{d^3\sigma}{dp^3} \propto (1-x_F)^C p_T^{-B}$$
$$C \approx 5$$
$$B \approx 6$$



Expect QCD scaling of form:

$$E\frac{d^3\sigma}{dp^3} \propto x_T^{-a}(1-x_F)^C p_T^{-n} = \left(\sqrt{s}/2\right)^a (1-x_F)^C p_T^{-n-a} \Rightarrow B = n + a$$

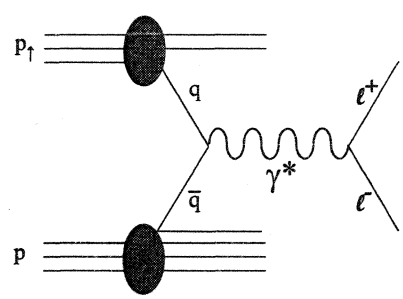
⇒ Require $\sqrt{s}$ dependence (e.g., measure π^0 cross sections at $\sqrt{s}$ = 500 GeV) to disentangle p_T and x_T dependence

Conclusions

Summary of Results

- Transverse spin asymmetries are present at RHIC energies
- Transverse spin asymmetries are present at large rapidity (η)
- Particle production cross sections and correlations are consistent with pQCD expectations at large η where transverse spin effects are observed
- Essential to go beyond inclusive meson production to disentangle dynamical origins

Future Plans

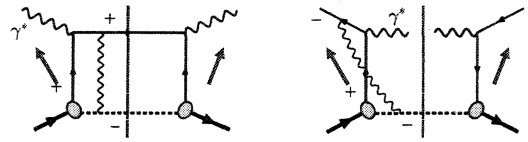


Status of Letter of Intent to 2010 BNL program advisory committee for transverse spin Drell Yan production

Attractive vs Repulsive Sivers Effects

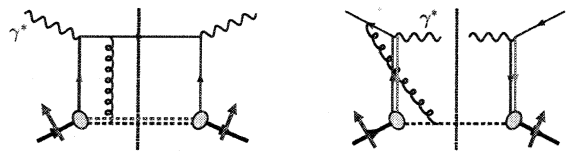
Unique Prediction of Gauge Theory !

Simple QED example:



DIS: attractive | **Drell-Yan: repulsive**

Same in QCD:



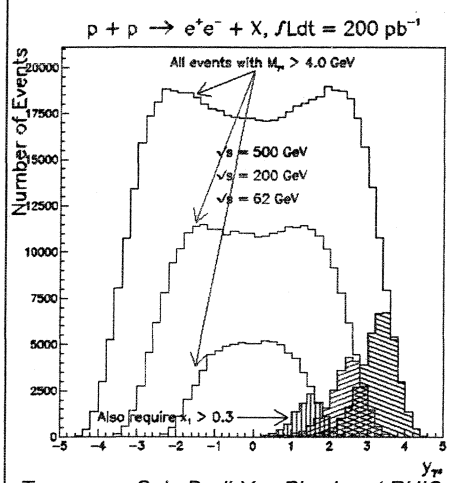
As a result:

$$\text{Sivers}|_{\text{DIS}} = -\text{Sivers}|_{\text{DY}}$$

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Collision Energy Dependence of Drell Yan Production



Comments...

- partonic luminosities increase with √s
- net result is that DY grows with √s
- in any case, largest √s probes lowest x

⇒ Consider large-x_F DY at √s=500 GeV

$$x_F = x_1 - x_2$$

$$x_F >> 0 \Rightarrow x_1 \approx x_F \text{ and } x_2 \approx \frac{M^2}{x_F s}$$

Transverse Spin Drell-Yan Physics at RHIC (2007)

http://spin.riken.bnl.gov/rsc/write-up/dy_final.pdf

Motivations for DY Feasibility at IP2

2015	HP13 (new)	Test unique QCD predictions for relations between single-transverse spin phenomena in p-p scattering and those observed in deep-inelastic lepton scattering

Report to NSAC from the Subcommittee on Performance Measures (August, 2008)
http://www.sc.doe.gov/np/nsac/docs/PerfMeasEvalFinal.pdf

- **Timeliness** – HP13 milestone completion by 2015. This could be accomplished during W program if 3IR impact is acceptable.
- **Acceptance/background rejection** – severe space constraints at STAR and PHENIX require major changes in the forward direction. Space constraints are not present at IP2.
- **Is charge sign a requirement?**

Objective of DY feasibility test is to establish the **requirements for future major forward upgrades at STAR and PHENIX** that would be used in a future p+Au or d+Au run that would emphasize Drell Yan production to probe low-x through scaling violations or virtual photon p_T dependence.

Status

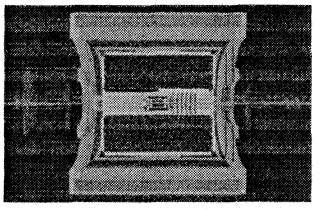
- Luminosity gains projected for $\sqrt{s}$=200 GeV polarized proton collisons were not realized in run 9, so L_{int}=30 pb^{-1} and P_{beam}=65% required for transverse spin direct photon would be challenging.
- Theory community has revisited whether color-charge interactions are robustly calculable [arXiv:1001.2977] for transverse single-spin asymmetries for processes *other than Drell Yan production*
- Low-x/saturation physics looks to be very interesting at RHIC collision energies. Non-universality of k_T dependent distribution functions for di-jets may impact small-x as well as transverse spin [arXiv:1003.0482]. This should not be the case for *low-x probed by Drell-Yan production*

⇒ establishing the requirements for a large-x_F Drell Yan production experiment will provide the most robust test of theory for transverse spin, and lead to future avenues that provide the most robust interconnections between low-x probed at RHIC and low-x probed at eRHIC.

The STAR W Physics Program - Status and Future Plans -

Bernd Surrow

Massachusetts Institute of Technology



Outline

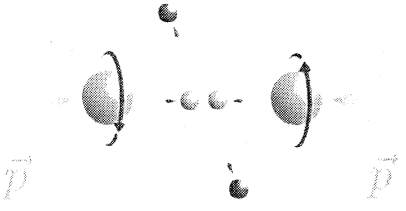
- W production - Recent Results

  First W^+/W^- Cross-section and A_L Measurement at STAR

- Future Plans - STAR W Program
  - Plans
  - Projections of future mid-rapidity measurements
  - Projections of future forward/ backward rapidity measurements

- Experimental aspects: STAR

- Introduction



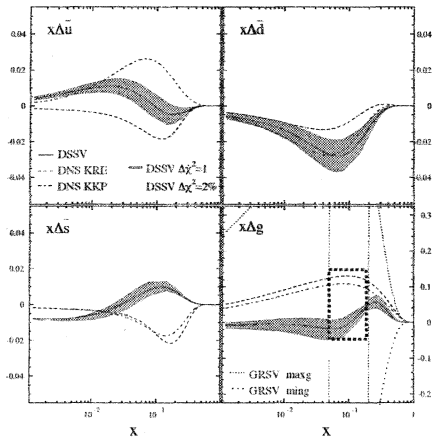
- Summary and Outlook

Introduction

- What do we know about the polarized quark and gluon distributions?
  - Spin carried by quarks is very small ($\Delta\Sigma \sim 0.3$)!

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma}_{} + \underbrace{\langle S_g \rangle + \langle L_q \rangle + \langle L_g \rangle}_{\Delta G}$$

$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}$$



u/d sea-quarks large uncertainties!

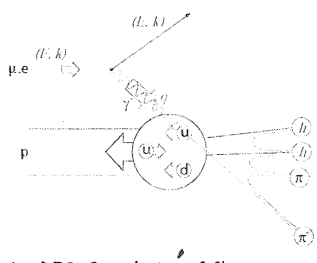
Substantial improvement for 0.05<x<0.2 Large uncertainties at low x

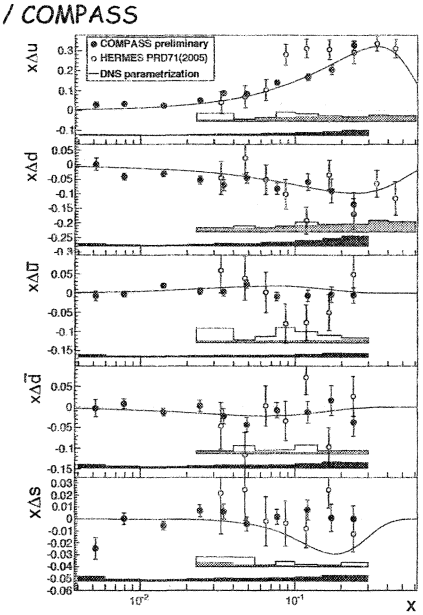
D. de Florian et al., Phys. Rev. Lett. 101 (2008) 072001

$$\Delta q_i(Q^2) = \int_0^1 \Delta q_i(x, Q^2)dx \qquad \Delta G(Q^2) = \int_0^1 \Delta g(x, Q^2)dx$$

Introduction

- Polarized semi-inclusive DIS results: HERMES / COMPASS

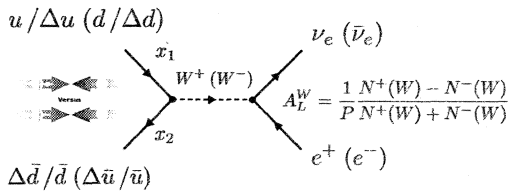




- Semi-inclusive DIS: Correlation of flavor content of hadron with flavor of quark / antiquark probed
- Good agreement of COMPASS and HERMES LO analysis
- Good agreement with global fit analysis / Sea quark distributions compatible with zero
- Great value of independent probe at large momentum scales (sub-leading twist effects unimportant) without hadronic fragmentation

Introduction

- STAR W program in e-decay mode at mid-rapidity and forward/backward rapidity



$$A_L^W = \frac{1}{P}\frac{N^+(W) - N^-(W)}{N^+(W) + N^-(W)}$$

$$y_l = y_W + \underbrace{\frac{1}{2}\ln\frac{1+\cos\theta^*}{1-\cos\theta^*}}_{y_l^*}$$

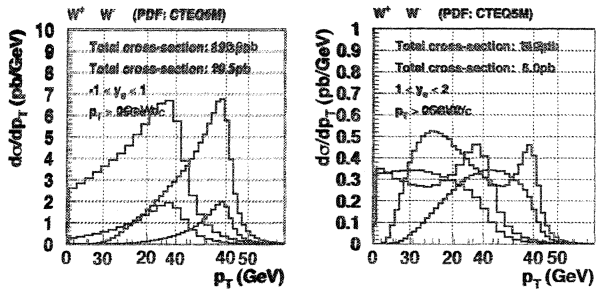
$$p_T = p_T^* = \frac{M_W}{2}\sin\theta^*$$

$$x_1 = \frac{M_W}{\sqrt{s}}e^{y_W}$$

$$x_2 = \frac{M_W}{\sqrt{s}}e^{-y_W}$$

$$\frac{M_W}{\sqrt{s}} = 0.16$$

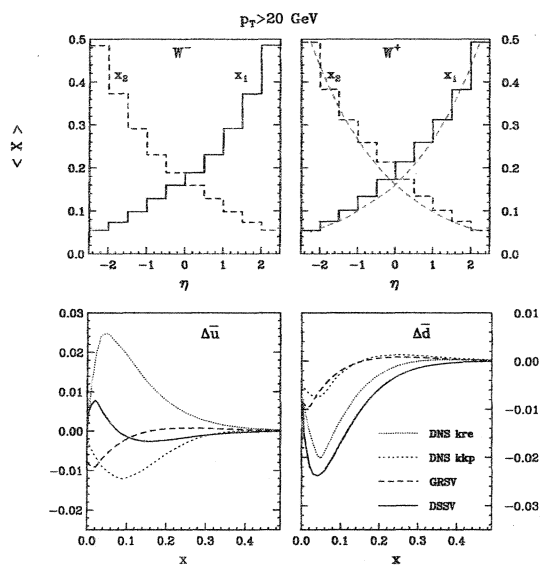
- Key signature: High p_T lepton (e^-/e^+)(Max. $M_W/2$) - Selection of W^+/W^-: Charge sign discrimination of high p_T lepton
- Required: Lepton/Hadron discrimination



Total ($\sqrt{s}$=500GeV) $\sigma(W^+)$=135pb and $\sigma(W^-)$=42pb

Introduction

- W boson kinematics relevant for STAR rapidity acceptance
  - Leptonic rapidity inherits relation to mean x
  - Forward rapidity:
    - $\eta > 0$
    - $\langle x_1 \rangle$ larger than $\langle x_2 \rangle$
  - Backward rapidity:
    - $\eta < 0$
    - $\langle x_1 \rangle$ less than $\langle x_2 \rangle$
  - Mid-rapidity:
    - $\eta \sim 0$
    - $\langle x_1 \rangle$ similar to $\langle x_2 \rangle$



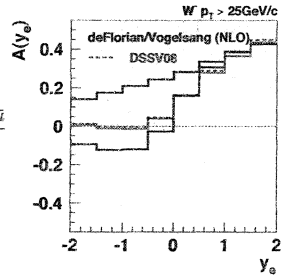
$$< X_{1,2} > \simeq \frac{M_W}{\sqrt{S}}e^{[\pm\eta/2]}$$

D. deFlorian and W. Vogelsang, hep-ph/1003.4533

Introduction

- A_L behavior for STAR mid-rapidity and forward/backward rapidity region

$$A_L^{W^-} = \frac{\Delta\bar{u}}{\bar{u}} \qquad x_1 \ll x_2$$



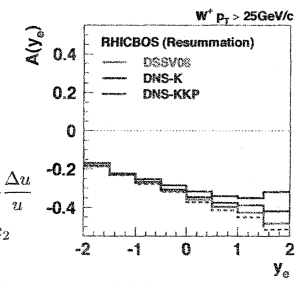
$$A_L^{W^-} = -\frac{\Delta d}{d} \qquad x_1 \gg x_2$$

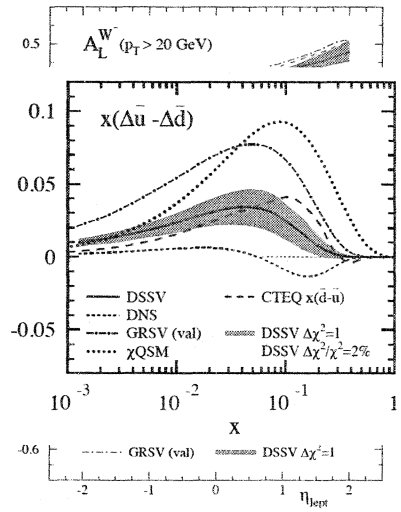
$$A_L^{W^-} = \frac{1}{2}\left(\frac{\Delta\bar{u}}{\bar{u}} - \frac{\Delta d}{d}\right) \qquad x_1 = x_2$$

$$A_L^{W^+} = \frac{1}{2}\left(\frac{\Delta\bar{d}}{\bar{d}} - \frac{\Delta u}{u}\right)$$

$$A_L^{W^+} = \frac{\Delta\bar{d}}{\bar{d}} \qquad x_1 \gg x_2$$

$$A_L^{W^+} = -\frac{\Delta u}{u} \qquad x_1 \ll x_2$$





Calculations:

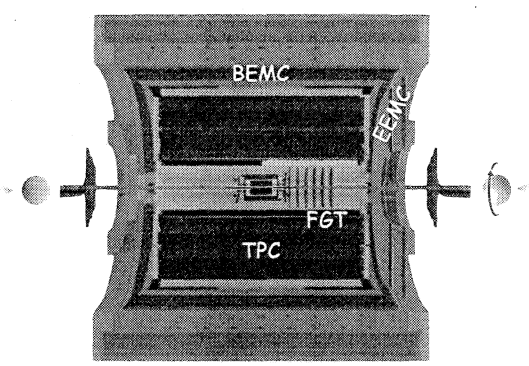
1) RHICBOS: P.M. Nadolsky and C.-P. Yuan, Nucl. Phys. B666 (2003) 31.

2) deFlorian / Vogelsang: D. deFlorian, private communications.

The STAR Experiment at RHIC

- Overview
  - Calorimetry system with 2π coverage: BEMC ($-1<\eta<1$) and EEMC ($1<\eta<2$)
  - TPC: Tracking and particle ID
  - ZDC: Relative luminosity and local polarimetry
  - BBC: Relative luminosity and Minimum bias trigger

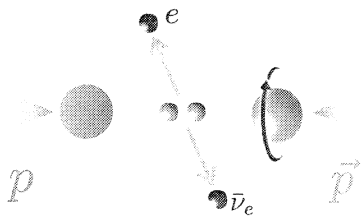
First collisions of polarized proton beams at STAR at $\sqrt{s}$ = 500GeV: Run 9 (P~40% / L~14pb^{-1})



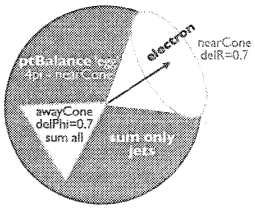
- STAR Mid-rapidity W program ($-1<\eta<1$): BEMC and TPC
- STAR Forward/Backward W program ($1<\eta<2$): EEMC and TPC / FGT (Installation in summer 2011)

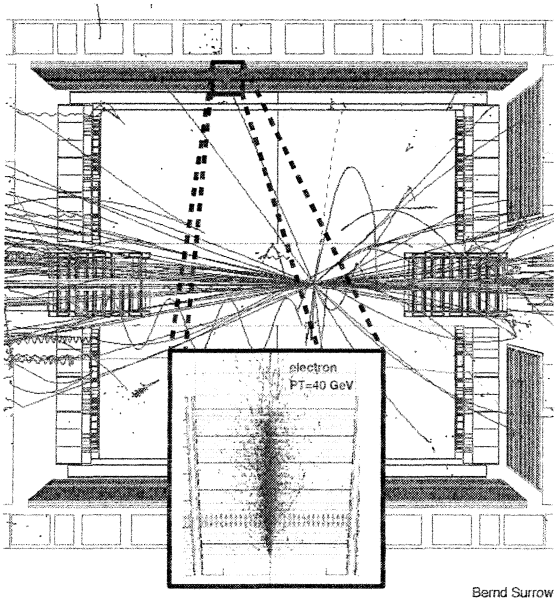
W production results: Algorithm

- W reconstruction - Algorithm : Idea



Transverse plane view

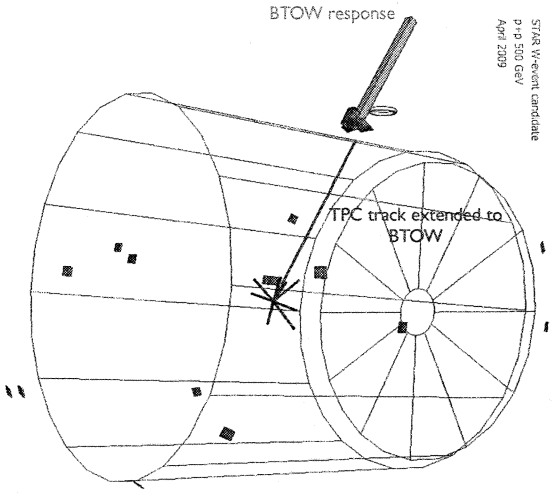




W production results: W event

- Event display (W event candidate) and detector signature

We found ~600 of those kinds of events!



Summary

- STAR W program
  - First Run 9 STAR W result (Cross-section and A_L for W^+/W^- at mid-rapidity) important milestone!
  - Mid-rapidity:
    - Charge sign discrimination: Demonstrated at high-p_T (~50GeV/c)
    - Signal (S) / Background (B): S/B = 6 for W^- and S/B = 11 for W^+ (Integrated for E_T>25GeV)
  - Forward rapidity: Complete FGT construction by the end of 2010 followed by full system test and subsequent full installation in ~summer 2011
    ⇒ Ready for anticipated long 500GeV polarized pp run in FY12 (Run 12)
  - Critical: Design polarization performance of 70% with ~5% absolute polarization uncertainty (⇒ Required by eRHIC program!) to collect at least 300pb^{-1}!
  - Future measurements of A_L at STAR at mid-rapidity and forward rapidity (Wide rapidity coverage!) are expected to play an important role in our understanding of the polarized QCD sea!

Outlook

- Outlook - RHIC SPIN
  - Three key elements:
    - Gluon polarization
    - Quark / Anti-Quark Polarization
    - Transverse spin dynamics
  - Critical:
    - Beam polarization: 70% / Narrow vertex region / Spin flipper
    - Sufficient running time!

Recorded Luminosity	Main physics Objective	Remarks
~50pb^{-1}	Gluon polarization using di-jets and precision inclusive measurements	200 GeV
~100pb^{-1}	W production (Important consistency check to DIS results - Phase I) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~300pb^{-1}	W production (Constrain antiquark polarization - Phase II) Gluon polarization (Di-Jets / Photon-Jets)	500 GeV
~30pb^{-1}	Transverse spin gamma-jet	200 GeV
~250pb^{-1}	Transverse spin Drell-Yan (Long term)	200 GeV

Status of Collinear PDFs and FFs

(bread & butter physics)

Marco Stratmann

Regensburg / Wűrzburg

Abstract:
We review the status of collinear unpolarized and polarized parton densities and fragmentation functions as obtained in recent global QCD analyses. Open questions and opportunities for studies of PDFs and FFs at a future electron-ion collider are pointed out.

Refs:
[1] D. de Florian, R. Sassot, and M. Stratmann, PR D75 (2007) 114010; D76 (2007) 074033
[2] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, PRL 101 (2008) 072001; PR D80 (2009) 034030

prerequisite: a reliable theoretical framework

guiding principle: factorization

long-distance physics
μ-dep. predicted by pQCD

$$\frac{d\sigma^{pp\to\pi X}}{dp_T d\eta} = \sum_{abc}\int dx_a\, dx_b\, dz_c\, f_a(x_a,\mu_f)\, f_b(x_b,\mu_f)\, D_c^{\pi}(z_c,\mu_f')$$
$$\times \frac{d\hat{\sigma}^{ab\to cX'}}{dp_T d\eta}(x_a P_a, x_b P_b, P^{\pi}/z_c, \mu_f, \mu_f', \mu_r) + \mathcal{O}(\frac{\lambda}{p_T})^n$$

short-distance physics
calculable in pQCD as series in α_s

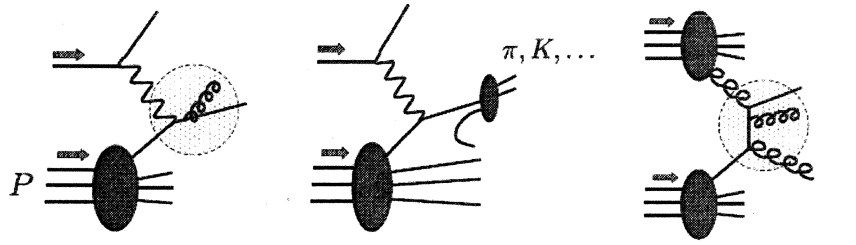
power corrections
usually safely neglected

factorization ...

- ... separates physics happening at different time/distance scales
- ... introduces unphysical scales $\mu_{f,r}$ (leads to powerful RGE like DGLAP)
- ... requires presence of a hard scale (like Q in DIS or p_T in pp collisions)
- ... is an approximation – corrections are power suppressed
- ... leads to a successful quantitative description of many hard scattering proc's

how to determine PDFs (and FFs) from data?

information on nucleon (spin) structure available from



DIS SIDIS hadron-hadron

task: extract reliable pdfs not just compare some curves to data

- all processes tied together: universality of pdfs & Q^2 - evolution
- each reaction provides insights into *different* aspects and kinematics
- need at least NLO for quantitative analyses; PDFs are not observables!
- information on PDFs "hidden" inside complicated (multi-)convolutions

a **"global QCD analysis"** is required

opportunities for PDF studies at an EIC

HERA has provided a lot of data & unpol. PDFs are rather well known

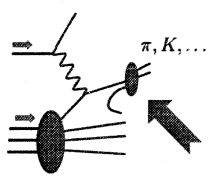
some "weak spots" though: (improvements require an EIC or the LHeC)

- F_L : needs variable beam energy **gluon density**
- $F_2^{c,b}$ & semi-inclusive processes : need excellent particle ID
  flavor separation incl. strangeness, charm, bottom
- electro-weak precision tests: need luminosity [beam polarization; positrons (?)]

beyond that:

- hadronization **flavor separation of fragmentation fcts**
- unintegrated k_T dependent PDFs **largely unknown**
- repeat HERA program in eN scattering at large $\sqrt{S}$ **terra incognita**

fragmentation functions: overview

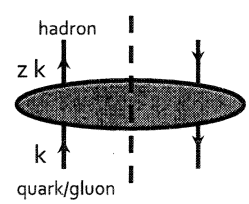


crucial for pQCD interpretation (factorization)
of all data with detected (identified) hadrons, e.g.,
SIDIS (HERMES, COMPASS), $pp \to \pi X$ (PHENIX, ALICE, ...)

observation: all FFs based only on e^+e^- (LEP) data do a bad job here

some properties of $D_i^h(z,\mu)$ [very similar to PDFs]:

- non-perturbative but universal; pQCD predicts μ-dep.
- describe the *collinear* transition of a parton "i" into a massless hadron "h" carrying fractional momentum z

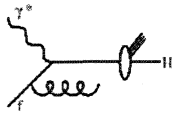


recent progress: global NLO QCD analysis of $\pi^\pm$, $K^\pm$ yields in e^+e^- and ep, pp

DSS analysis (de Florian, Sassot, MS) **Phys. Rev. D75 (2007) 114010; D76 (2007) 074033**

describes all relevant data; **crucial impact on extraction of helicity PDFs**

good description of SIDIS multiplicities

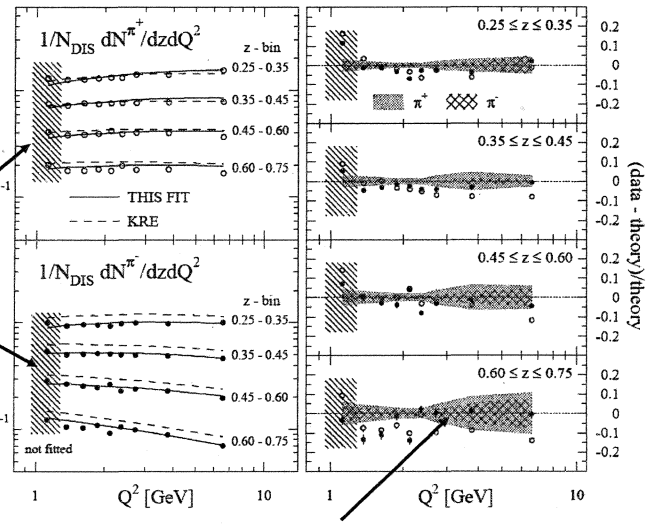


HERMES data (not yet final)
A. Hillenbrand (thesis)

π^+

π^-

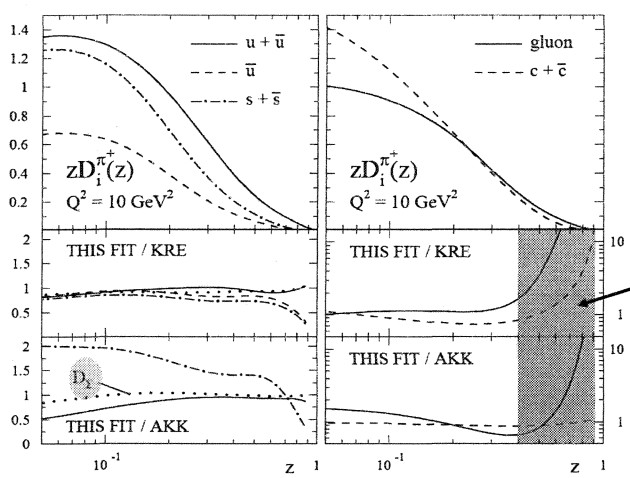
Kretzer's assumption
$D_d^{\pi^+} \simeq (1-z) D_u^{\pi^+}$
works for π^+
but not for π^-



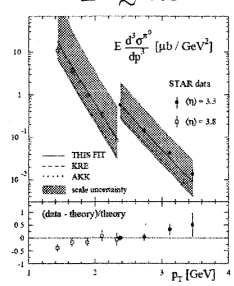
x, Q^2 range can be significantly extended at an EIC

shaded bands:
our estimate of
"Q^2-binning effects"

meet the $D_i(z)$'s for pions



$\langle z \rangle \gtrsim 0.6$

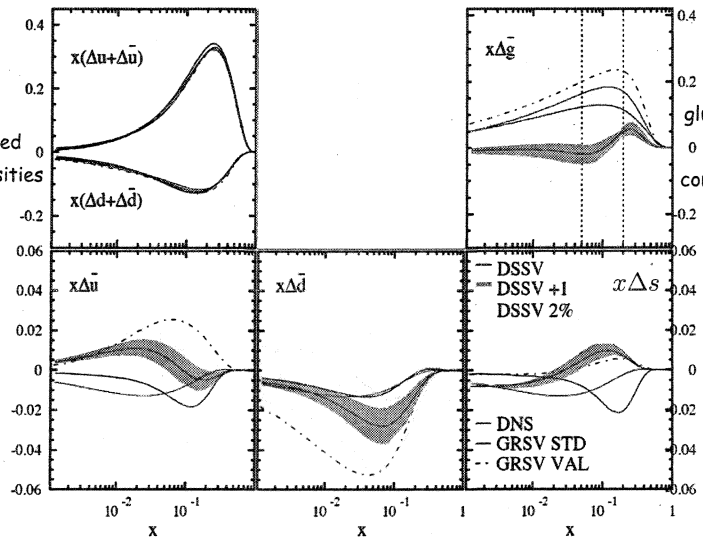


z-range of RHIC pp data explains differences in D_g

- singlet fragmentation D_Σ very similar (fixed by SIA at M_Z)
- u-frag. smaller than in AKK (due to SIDIS) ; compensated by larger D_s in SIA
- find: SU(2) violation < 10%; SU(3) violation $\simeq$ 17%

DSSV analysis - emerging picture

well determined total quark densities



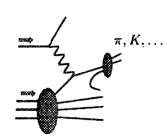
gluon small (node?) in x-region constrained by data

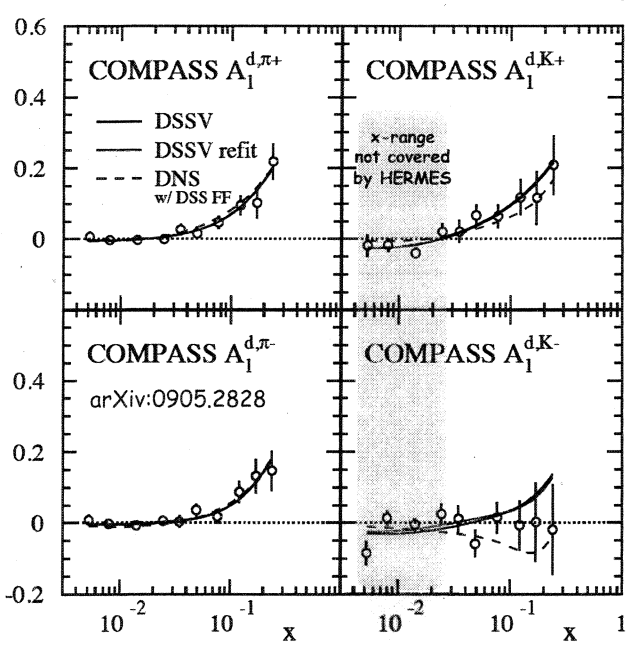
indications for non-trivial sea quark polarizations $\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

surprising strangeness polarization (also found in lattice QCD; sizable SU(3) breaking?)
Bali et al., 0811.0807; 0911.2407

flavor separation only from SIDIS; depends on fragmentation functions (global NLO fit by DSS)
de Florian, Sassot, MS

coping with new data: SIDIS $A_1^{d,\pi,K}$





✓ DSSV works well:
no surprises at small x

χ^2 numerology:

	DSSV 08 data sets	with $A_1^{d,\pi,K}$
DSSV 08	392.5	420.8
refit		418.9

✓ **no refit required**
(recall: $\Delta\chi^2=1$ does not reflect faithful PDF uncertainties)

DSSV - readiness for new observables

- **general policy:** NLO must be known for an observable to be included in fit
- use of **improved Mellin technique** allows us to included *any* observable consistently at NLO accuracy without the usual cheating ("K-factors", etc)

most promising future avenues to further our knowledge of pol. PDFs

	focus on
▪ particle correlations, like di-jets better control on probed x-range; expect data soon (STAR)	Δg
▪ rare probes (prompt photons, heavy flavors) probe different aspects of hard scattering dynamics (test of factorization)	Δg
▪ W boson parity-violating single spin asymmetries A_L neat handle on flavor separation; large asymmetries	$\Delta\bar{u}, \Delta\bar{d}$ $\Delta u, \Delta d$

opportunities for spin physics studies at an EIC

so far, our knowledge on polarized (SI)DIS is based on fixed target experiments

many "weak spots" & room for new "spin surprises":

▪ small x region: crucial for all sum rules ("proton spin", "Bjorken", ...)	**unknown**
▪ flavor separation: SU(2) breaking, strangeness	**largely unknown**
▪ electro-weak effects/structure fcts.	**never measured**
▪ full understanding of transverse spin phenomena	**still in early stages**
▪ issues with factorization for Sivers fct.	**intriguing**
▪ role of orbital angular momentum	**largely unknown**

▪ plus: spin phenomena in diffraction, photoproduction, hadronization, ...

repeat full HERA program in polarized high energy ep scattering with good particle ID & ability to measure exclusive processes

New Results on SSAs in Collinear Factorization

Jian Zhou
Temple University

ABSTRACT

Recent developments in both theory and experiment have demonstrated that transverse spin physics offers a new window into central aspects of QCD. Theoretically, it is well known that SSAs can be described in both TMD factorization and collinear factorization, which both have been well established. Transverse spin physics also gives us a unique chance to study the universality of TMD distributions and to test the factorization. The relation between large k_T TMDs and collinear functions has been thoroughly investigated. With this relation, one can show the consistency between the TMD approach and the collinear approach in the overlap region where they both apply. The scale evolution equation of the moment of TMDs have been derived as well. Moreover, transverse spin physics is interesting because of its potential to access the parton OAM and parton distributions in 2D.

There are still a few remaining theoretical issues which motivated our work. The first one: the sign change of the Sivers effect between DIS and DY scattering is a very firm theoretical prediction, while an experimental test for the sign change is still missing. Since the measurements of the polarized DY process will be not available in the near future, we looked for an alternative way to check the sign change. The second issue addresses the Qiu-Sterman function T_F, which is closely related to the transverse SSAs in the collinear approach and is not well constrained so far. Finally, we consider the correlation between transverse spin and relative final state particle transverse momentum. To address these issues, we computed SSAs in three processes using collinear approach: (1) inclusive lepton production from the decay of W bosons in pp scattering, (2) jet production in ep scattering, (3) SSA in Drell-Yan lepton pair angular distribution.

New results on SSAs in collinear factorization

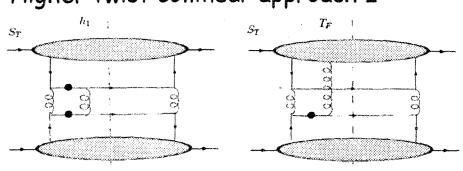
Jian Zhou
Temple University

July 19 2010, BNL

Outline:

- Brief review on single spin Asymmetries (SSAs)
- SSA in lp-->jet X
- SSA in pp-->W bosons-->l X
- SSA in Drell-Yan process
- Summary

Higher twist collinear approach I



$A_N \propto \alpha_s\, m_q/Q \ll 1$
Kane, Pumplin, Repko
quark mass → helicity flip

$A_N \propto T_F/Q \propto m_N/Q$
Efremov, Teryaev; Qiu, Sterman; kouvaris, Qiu, Vogelsang, Yuan.
qgq correlation → helicity flip

imaginary phase is generated in the hard scattering.

⟹ qgq correlation $T_F(x,x)$:

fragmentation effect $H_F(x,x1)$... **Koike; Feng, JZ; Kang, Feng, JZ.**

Higher twist collinear approach II

In general, twist-3 polarized cross section takes form ($Q, l_T \gg \Lambda_{QCD}$),

$$d\sigma(S_T) \propto H(Q, l_T) \otimes \underbrace{f_3(x_1,x_2) \otimes f_2(x')}_{,\tilde{T}_F(x_1,x_2),\, T_F^{(\sigma)}(x_1,x_2),\, \tilde{T}_F^{(\sigma)}(x_1,x_2),\, \tilde{g}(x),\, \tilde{h}(x)}$$

complete set of twist-3 functions

Ellis, Furmanski, Petronzio; Eguchi, Koike, Tanaka

plays a central role in the study of SSAs.

$$T_F(x,x) = -\int \frac{d^2\vec{k}_\perp}{2\pi}\frac{\vec{k}_\perp^2}{M^2} f_{1T}^{\perp}|_{DIS}(x,k_\perp) \cdot \quad \tilde{g}(x) = \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M^2} g_{1T}(x,k_\perp)$$

$$T_F^{(\sigma)}(x,x) = -\int \frac{d^2\vec{k}_\perp}{2\pi}\frac{\vec{k}_\perp^2}{M^2} h_1^{\perp}|_{DIS}(x,k_\perp) \quad \tilde{h}(x) = \int d^2\vec{k}_\perp \frac{\vec{k}_\perp^2}{2M^2} h_{1L}(x,k_\perp)$$

Boer, Mulders, Pijlman

The relation between TMDs and collinear functions

when $k_T \gg \Lambda_{QCD}$, TMDs can be calculated in perturbative QCD and expressed in terms of twist-3 functions.

$$f_{1T}^{\perp}|_{\rm DIS}(x_B, k_\perp) = \frac{-\alpha_s}{\pi}\frac{M^2}{(\vec{k}_\perp^2)^2}\int\frac{dx}{x}\left[A_{f_{1T}} + C_F T_F(x,x)\delta(1-\xi)\left(\ln\frac{x_B^2\zeta^2}{\vec{k}_\perp^2} - 1\right)\right]$$

$$A_{f_{1T}} = \frac{1}{2N_c}T_F(x,x)\frac{1+\xi^2}{(1-\xi)_+} + \frac{C_A}{2}T_F(x,x_B)\frac{1+\xi}{(1-\xi)_+} + \frac{C_A}{2}\tilde{T}_F(x_B,x)$$

Ji, Qiu, Vogelsang, Yuan

$$h_1^{\perp} \sim T_F^{(\sigma)} \qquad g_{1T} \sim T_F, \tilde{T}_F, \tilde{g}$$

$$h_{1L}^{\perp} \sim T_F^{(\sigma)}, \tilde{T}_F^{(\sigma)}, \tilde{h}$$

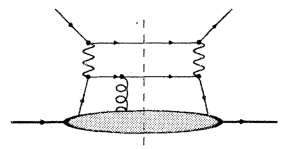
JZ, Yuan, Liang

Notice $k_T \ll Q$, in order to justify describing SSAs using TMD distributions

With these expressions of large k_T TMDs, one may show the consistence between TMD approach and collinear approach in the overlap region.

SSA in lp-->jet X

Collaborators: Z. B. Kang, A. Metz, J. W. Qiu



Motivations:

- The kinematics of this process is rather simple.
- No uncertainties from parton fragmentation are involved.
- The source contributing to SSA is limited.

SSA in this process has been calculated in terms of TMD distributions

M. Anselmino *et al.*, Eur. Phys. J. A **39**, 89 (2009)

Analytical result

$$A_{UT}\quad E_J\frac{d^3\sigma}{d^3P_J} = \frac{\alpha_{em}^2}{S}\sum_a e_a^2\frac{1}{S+T}\epsilon^{S_T P_J P P}\frac{1}{x}\left[T_F(x,x) - x\frac{d}{dx}T_F(x,x)\right]\frac{\hat{s}}{\hat{u}\hat{t}}H_{Born}$$

where, $H_{Born} = \frac{2(\hat{s}^2+\hat{u}^2)}{\hat{t}^2}$

$$A_{LL}\quad E_J\frac{d^3\sigma}{d^3P_J} = \lambda_e\lambda_p\frac{\alpha_{em}^2}{S}\sum_a e_a^2\frac{1}{S+T}\frac{1}{x}g_1(x)H_{Born}^{LL}$$

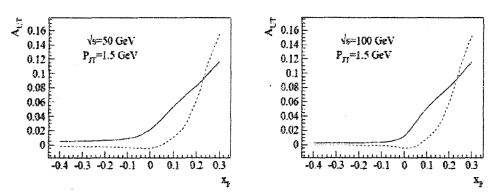
where, $H_{Born}^{LL} = -\frac{2(\hat{s}-\hat{u})}{\hat{t}}$

$$A_{LT}\quad E_J\frac{d^3\sigma}{d^3P_J} = \lambda 2M\frac{\alpha_{em}^2}{S}\sum_a e_a^2\frac{1}{S+T}S_T\cdot P_J\left\{\frac{1}{x}\left[\tilde{g}(x) - x\frac{d}{dx}\tilde{g}(x)\right]\frac{\hat{s}}{\hat{u}\hat{t}}H_{Born}^{LL} + g_T(x)\frac{2}{\hat{t}}\right\}$$

$$\tilde{g}(x) = \int\frac{dy^-}{4\pi M}e^{-ixP^+y^-}\langle P,S|\bar{\psi}_\beta(y^-)\gamma_5\not{S}_{\perp P}\left(iD_\perp^\alpha - ig\int_0^\infty d\zeta^- F^{+\perp}(\zeta^-)\right)\psi_\alpha(0)|P,S\rangle$$

It can be related to the moment of corresponding TMD. $\tilde{g}(x) = \int d^2\vec{k}_\perp\frac{\vec{k}_\perp^2}{2M^2}g_{1T}(x,k_\perp)$

Numerical result: A_{UT}



A_{UT} as a function of X_F for √s=50GeV(left) and √s=100GeV(right). The solid line is for T_F from the fit of the Sivers function in Ref.II, while the dashed line is computed with T_F from Ref. I

I. C. Kouvaris, J. W. Qiu, W. Vogelsang and F. Yuan, Phys. Rev. D **74**, 114013 (2006)

II. M. Anselmino *et al.*, Eur. Phys. J. A **39**, 89 (2009)

$$T_F(x,x) = \int d^2\vec{k}_\perp\frac{\vec{k}_\perp^2}{M}f_{1T}^{\perp}|_{DY}(x,k_\perp)$$

Conclusion:

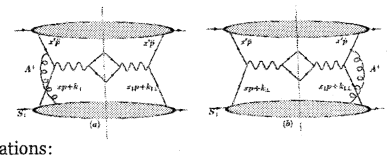
- The numerical result for A_{LL} A_{LT} is small(tiny), while A_{UT} is of the order 10% in the forward region.
- Our prediction for A_{UT} is close to that from TMD factorization.

Outlook:

- Extend our analysis to the 1-loop level.

SSA in pp-->W bosons-->l X

Based on the paper: arXiv:1006.3097 A. Metz, JZ



Motivations:

- the detectors at RHIC can not reconstruct the W's;
- it can be considered as the alternative way to check the sign-change of the Sivers effect between semi-inclusive DIS scattering and Drell-Yan process;
- provides an excellent flavor separation of the Sivers effect.

The SSA in this process has been calculated based on TMD factorization. Kang, Qiu

Analytical result

$$E\frac{d^3\Delta\sigma(S_\perp)}{d^3l} = \frac{1}{3S}\sum_q \int \frac{dx'}{xx'}\frac{1}{\tilde{u}}\frac{1}{x'S+T}H^W_{Born}$$

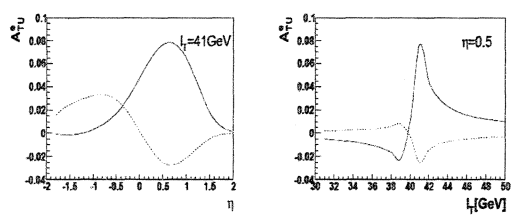
$$\times\left\{ -\left[\left(T_F(x,x) - x\frac{d}{dx}T_F(x,x)\right) + \frac{2M_W^2(\tilde{s}-M_W^2-\Gamma_W^2)}{(M_W^2-\tilde{s})^2+M_W^2\Gamma_W^2}T_F(x,x)\right]\tilde{f}(x') \right.$$

$$\left. + 2M\left[\left(\tilde{g}(x) - x\frac{d}{dx}\tilde{g}(x)\right) + \frac{2M_W^2(\tilde{s}-M_W^2-\Gamma_W^2)}{(M_W^2-\tilde{s})^2+M_W^2\Gamma_W^2}\tilde{g}(x) + 2xg_T(x)\right]\tilde{f}(x')\right\}$$

Where, $H^W_{Born} = \frac{g^4}{64\pi^2}\frac{\tilde{u}^2}{(\tilde{s}-M_W^2)^2+M_W^2\Gamma_W^2}$

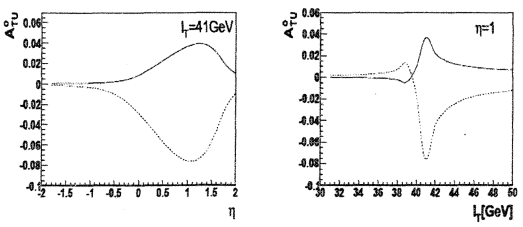
Chiral odd contribution is absent (no Boer-Mulders effect) because of the same reason why A_{TT} asymmetry vanishes in W production process.

Numerical result: $S_T \times L_T$



A_N ($S_T \times L_T$) as a function of η(left) and l_T(right) for √S=500GeV
Solid line is l^- production, dashed line is for l^+ production.

Numerical result: $S_T \cdot L_T$



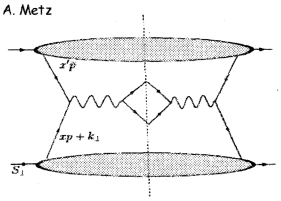
A_N ($S_T \cdot L_T$) as a function of η(left) and l_T(right) for √S=500GeV
Solid line is for l^- production and dashed line is for l^+ production.

Conclusion:

- Our prediction for parity-even A_{UT} is very close to that from TMD factorization.
- It can be considered as the alternative way to check the sign-change of the Sivers effect.
- Parity-odd A_{UT} is measurable. It gives rather clean access to the TMD g_{1T}.
- T-odd A_{LT} asymmetry is too small to check sign change (1%).

SSA in Drell-Yan lepton pair angular distribution

Collaborator: A. Metz



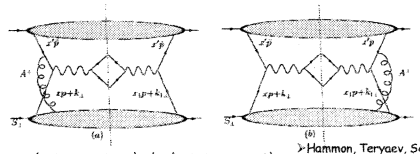
integrating over total transverse momentum $d\sigma(s_T)/dQ^2 d\Omega$

The correlation between the spin and relative transverse momentum

$S_T \times (P_{e1} - P_{e2})_T$

$$A_N = \left(\frac{d\sigma(S_T)}{d\Omega dQ^2} - \frac{d\sigma(-S_T)}{d\Omega dQ^2}\right) \Big/ \left(\frac{d\sigma(S_T)}{d\Omega dQ^2} + \frac{d\sigma(-S_T)}{d\Omega dQ^2}\right)$$

Revisit the SSA in the Drell-Yan Process



$$A_N \equiv \frac{1}{2}\left(\frac{d\sigma(s_T)}{dQ^2 d\Omega} - \frac{d\sigma(-s_T)}{dQ^2 d\Omega}\right) \Big/ \frac{1}{2}\left(\frac{d\sigma(s_T)}{dQ^2 d\Omega} + \frac{d\sigma(-s_T)}{dQ^2 d\Omega}\right)$$

- Hammon, Teryaev, Schafer
- Boer, Mulders, Teryaev
- Boer, Qiu
- J.P. Ma, Wang
- Anikin, Teryaev

To isolate the twist-3 effect, we have to make k_T expansion and keep the liner term.

Virtual photon momentum q=xp+x'\bar{p}+k_T lepton tensor is also k_T dependent

$$\frac{d\sigma(S_T)}{dQ^2 d\Omega} = \frac{4\pi\alpha_{em}^2}{9Q^2} \sum_{i,j} e_q^2 \int dx dx' \left[T_{F,i}(x,x)\bar{f}_j(x') + h_{1,i}(x)\bar{\tilde{T}}_{F,j}^{(\sigma)}(x,x)\right] \times \frac{1}{Q}\left[\frac{1}{4\pi}\frac{3}{8}\{-g\sin 2\theta \sin\phi\}\delta\left(Q^2 - xx'S\right)\right]$$

Our result is

- EM gauge invariant
- Color gauge invariant
- Frame independent(CS,GJ)

$$\frac{d\sigma(S_T)}{dQ^2 d\Omega} = \frac{4\pi\alpha_{em}^2}{9Q^2}\sum_{i,j} e_q^2 \int dx dx' \left[T_{F,i}(x,x)\bar{f}_j(x') + h_{1,i}(x)\bar{T}_{F,j}^{(\sigma)}(x,x)\right] \times \frac{1}{Q}\left[\frac{1}{4\pi}\frac{3}{8}[-g\sin 2\theta \sin\phi]\delta\left(Q^2 - xx'S\right)\right]$$

One more cross check(NLO real correction)

take leading logarithm approximation to identify collinear divergence.

$$\frac{d\sigma(S_T)}{dQ^2 d\Omega} = \sigma_0(S_T)\sum_{i,j} e_q^2 \int dx dx' \left[T_{F,q}(x,x)\bar{f}(x')\right]\delta\left(Q^2 - xx'S\right) + \sigma_0(S_T)\frac{\alpha_s}{2\pi}\int \frac{dq_T^2}{q_T^2}\int dx dx' \bar{f}(x')\{A+B\}$$

where (for q \bar q channel),

$$A = \frac{1}{2N_c}[x\frac{d}{dx}T_F(x,x)(1-\xi^2) + T_F(x,x)\frac{-2\xi^3+\xi^2-1}{(1-\xi)_+}] + \frac{C_A}{2}T_F(x,x\xi)\frac{1+\xi}{(1-\xi)_+}$$

$$B = C_F T_F(x,x)[\frac{1+\hat{\xi}^2}{(1-\hat{\xi})_+} + 2\delta(\hat{\xi}-1)\ln\frac{Q^2}{q_T^2}] \qquad \xi = z/x, \hat{\xi} = z/x' \text{ with } z = Q/\sqrt{s}$$

After performing partial integration, A term can be re-organized as,

$$A = \frac{1}{2N_c}[T_F(x,x)\frac{-\xi^2-1}{(1-\xi)_+}] + \frac{C_A}{2}T_F(x,x\xi)\frac{1+\xi}{(1-\xi)_+}$$

which is the splitting kernel of evolution equation for $T_F(x,x)$

Conclusion:

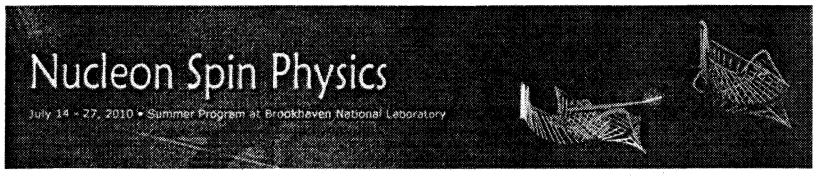
- This is new type of the correlation $S_T X(P_{T1}\text{-}P_{T1})$, requires the further technique development.

Outlook:

- It may be promising to have a complete NLO analysis.
- Extend to study the same type observables: IFF(di-hadron fragmentation functions) when $M_{hh} \gg \Lambda_{QCD}$.
  1) address its invariant mass M_{hh} dependent behavior,
  2) and its delicate relation to Collins function.

Summary

- ep DIS with an unidentified final state lepton may constitute an interesting part of the physics program at a future electron-ion collider (for instance, better pin down T_F).
- Lepton asymmetry from the decay of W bosons may allow us to address the sign-change of Sivers effect between semi-inclusive DIS scattering and Drell-Yan process.
- We re-examine the single spin asymmetry in Drell-Yan lepton pair angular distribution. The technique developed can be applied to other cases.



Gluon Polarization Measurements with STAR

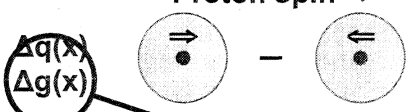
Carl A. Gagliardi
Texas A&M University

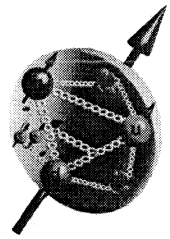
for the STAR Collaboration

What contributes to the proton spin?

Consider a proton moving toward the right

Proton spin ⇒





$\Delta q(x)$
$\Delta g(x)$

Polarized DIS: ~ 0.3

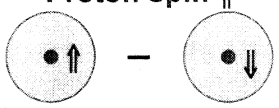
Both are poorly constrained

Spin sum rule: $\langle S_z^p \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_z \rangle$

This talk

Proton spin ⇑

$\delta q(x)$

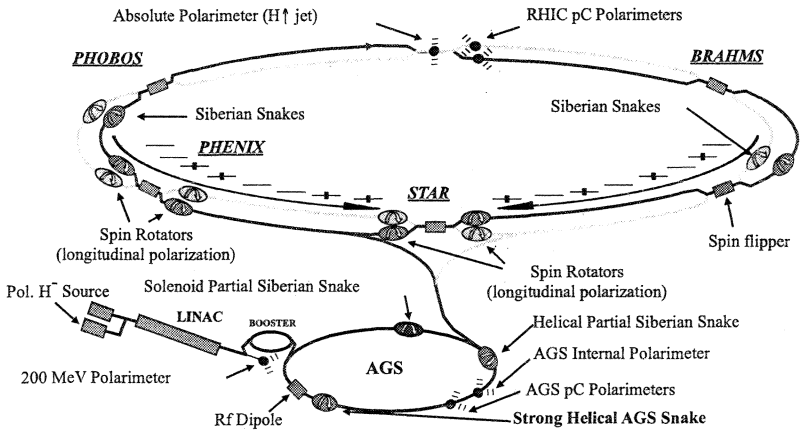


Transversity – very little data

***STAR* spin program:**

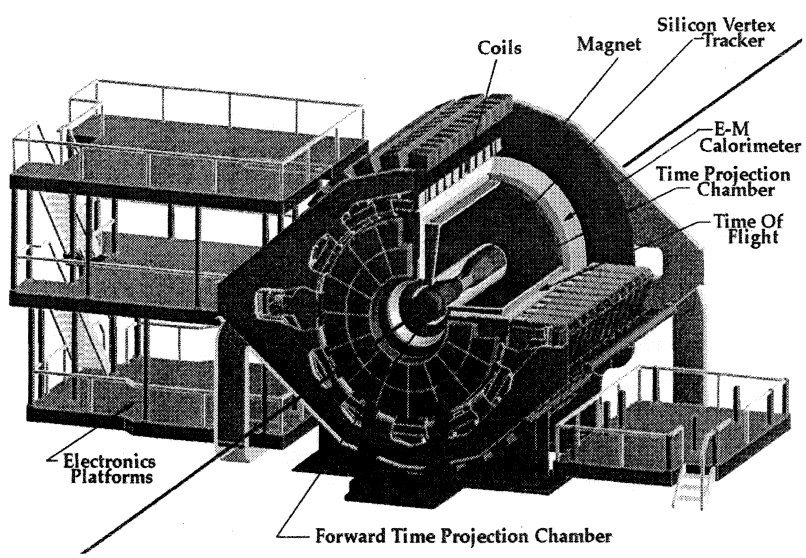
Exploring poorly determined components of the proton

RHIC: the world's first polarized hadron collider



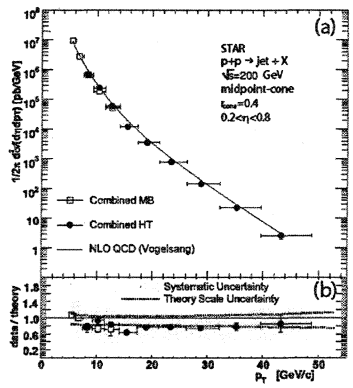
- Spin varies from rf bucket to rf bucket (9.4 MHz)
- Spin pattern changes from fill to fill
- Spin rotators provide choice of spin orientation
- "Billions" of spin reversals during a fill with little if any depolarization

STAR detector

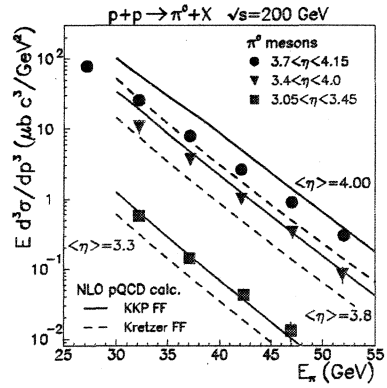


Essential benchmark – unpolarized cross sections

STAR PRL 97, 252001

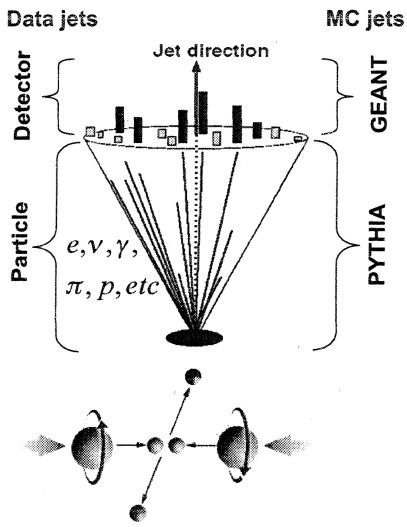


STAR PRL 97, 152302



- Mid-rapidity jet cross section is consistent with NLO pQCD over 7 orders of magnitude
- Forward rapidity π^0 cross section also consistent with NLO pQCD
- Many other examples
- **pQCD works over a very broad kinematic range at RHIC energies**

Jet reconstruction in *STAR*

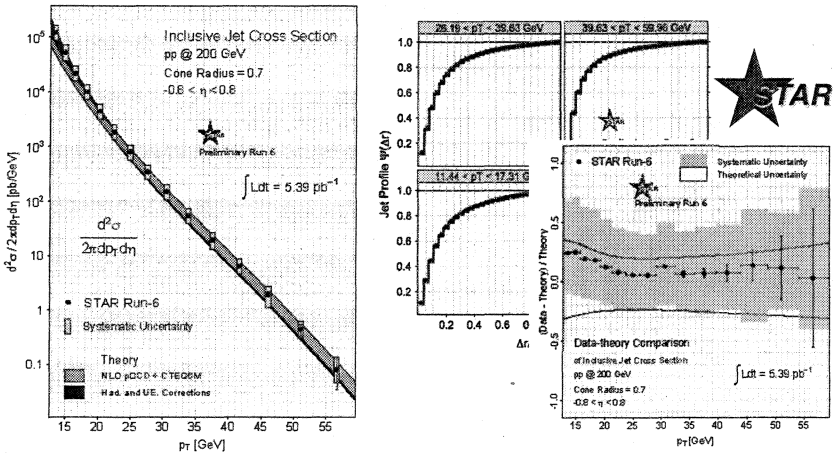


Midpoint cone algorithm
(Adapted from Tevatron II - hep-ex/0005012)

- Seed energy = 0.5 GeV
- Cone radius in η-φ
  - R=0.4 with $0.2 < \eta < 0.8$ (till 2005)
  - R=0.7 with $-0.7 < \eta < 0.9$ (since '06)
- Splitting/merging fraction f=0.5

Use **PYTHIA** + **GEANT** to quantify detector response

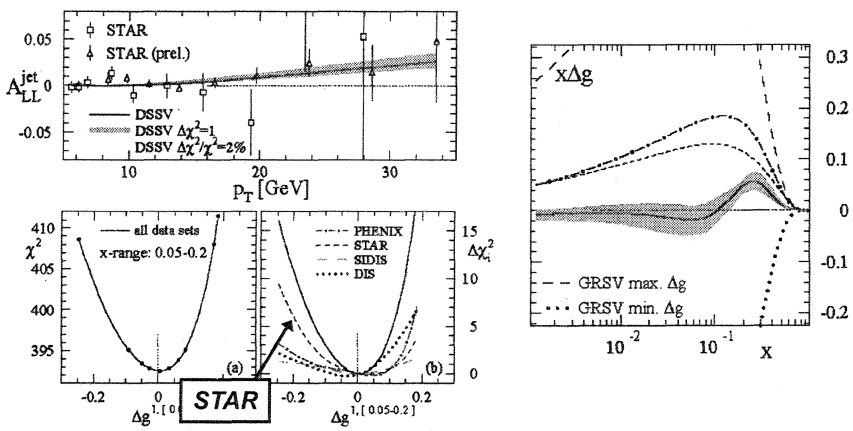
Jet cross section from 2006 data



- Good agreement between data and simulation
- Good agreement with NLO pQCD calculation after hadronization and underlying event correction is applied
- Jet production is well understood at 200 GeV

DSSV – first global analysis with polarized jets

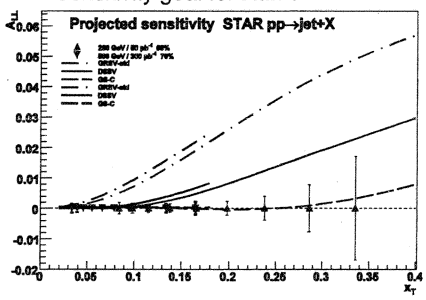
de Florian et al., PRL 101, 072001



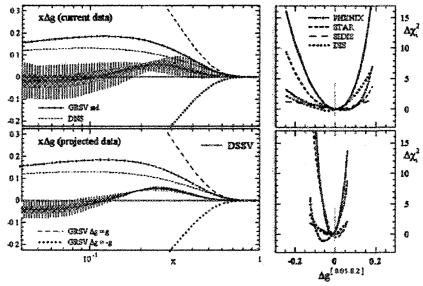
- The first global NLO analysis to include inclusive DIS, SIDIS, and RHIC pp data on an equal footing
- Finds a node in the gluon distribution near $x \sim 0.1$, but with the opposite phase from GS-C

Anticipated Run 9 inclusive jet A_{LL} sensitivity

Sensitivity goal for **Run 9**



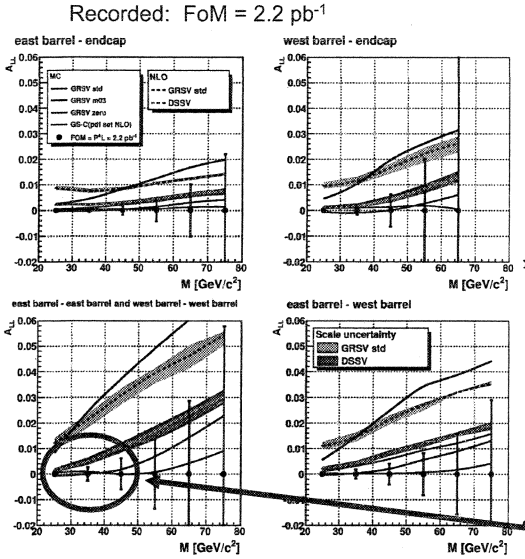
Projected improvement in xΔg from **Run 9** had we achieved the goal



- Original ***STAR*** goal for the 200 GeV run:
  - 50 pb^{-1} @ 60% pol – reduce A_{LL} uncertainties a factor of ~4
  - Would provide very strong constraints on gluon polarization
- Only sampled ~1/3 of the desired figure-of-merit
- Will still yield quite significant results

Di-jets and $\Delta g(x)$: projected sensitivity for Run 9

Recorded: FoM = 2.2 pb^{-1}



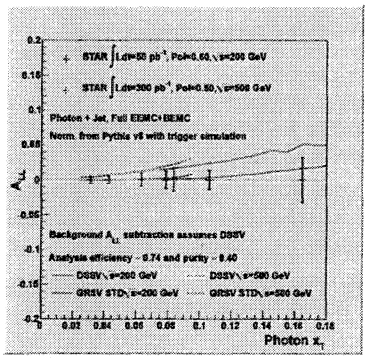
$$x_1, x_2 = \frac{M}{\sqrt{s}} \exp\left(\pm \frac{\eta_3 + \eta_4}{2}\right)$$

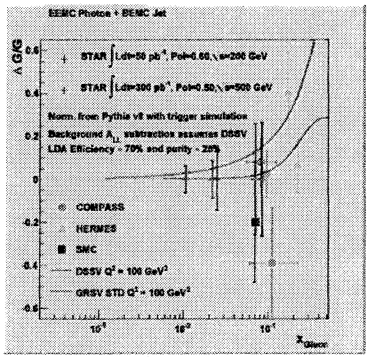
- Di-jets provide **direct access to initial parton kinematics** at LO
- Di-jets in different regions of the ***STAR*** detector
  - Sample different mixtures of *qq*, *qg*, *gg*
  - Sample different ranges of x_g

$\Delta g(x)/g(x)$ to ± 0.04 ~ 0.05 for x_g = 0.075 ~ 0.13

Would have been ± 0.02 ~ 0.03 with FoM = 6.5 pb^{-1}

Gluon polarization with gamma+jet





- Now have sensitivity estimates including realistic photon efficiencies and purities, benchmarked with real data
  - Still a work in progress
  - Hope for higher sensitivity after analysis of new high-statistics Monte Carlo events with improved simulation of the EEMC SMD
  - Maybe higher purity with future isolation cuts using FGT

Conclusions

- ***STAR*** results have provided important new information about gluon polarization
- First global analysis including RHIC jet data indicates the gluon polarization is small in the range $0.05 < x < 0.2$
- Expect substantially improved precision from 2009 data
- Di-jet and gamma+jet measurements will **constrain the functional form of $\Delta g(x)$**
- The large acceptance of ***STAR*** combined with 500 GeV collisions will **extend the measured region to lower x_g**

Quark and Gluon Polarization Measurements with PHENIX

Kieran Boyle (RBRC)

Outline

- Introduction
- Experiment as of 2009
- Gluon Polarization
  - Results
  - Limitations
  - Future plans and measurements
- Sea Quark Polarization
  - A first result
  - Muon trigger upgrade
  - Expectations
- Conclusion

Proton Helicity Structure

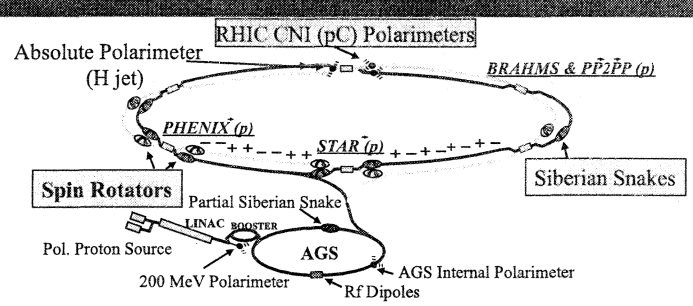
- Helicity Sum Rule:

$$S_p = \frac{1}{2} = \boxed{\frac{1}{2}\Delta\Sigma} + \boxed{\Delta G} + \boxed{L_{z,q} + L_{g,z}}$$

- $\Delta\Sigma$: Quark spin contribution. Well determined by DIS. Found to be ~25-30% [DSSV].
  - Flavor separated quark distributions not as well know for sea quarks
- $L_{z,q}$ and $L_{z,g}$: Quark and gluon orbital angular momentum. Unclear how to measure
- ΔG: Gluon spin contribution. Not well determined from DIS due to small Q^2 coverage of fixed target experiments

  → Go to p+p for "direct" access to the gluon via A_{LL}

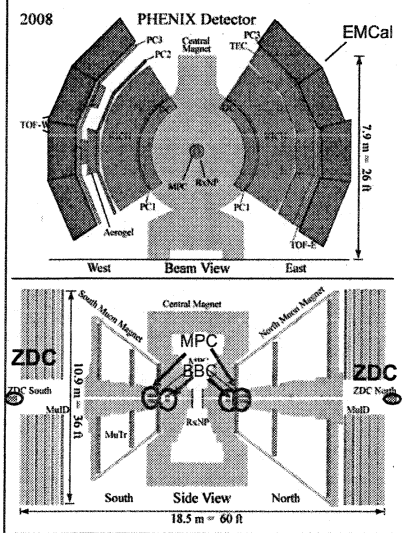
RHIC



Longitudinally Polarized RHIC Runs

Year	√s [GeV]	L [pb^{-1}]	P [%]	A_{LL} FoM (P^4L)	A_L FoM (P^2L)
2003	200	0.35	27	0.0019	
2004	200	0.12	40	0.0031	
2005	200	3.4	49	0.20	
2006	200	7.5	57	0.79	
2006	62.4	0.08	48	0.0042	
2009	500	10	40	0.26	1.6
2009	200	14	55	1.3	

PHENIX Detector in 2009



π^0, η, γ detection
- Electromagnetic Calorimeter (PbSc/PbGl):
  - High p_T photon trigger to collect trigger to collect π^0's, η's, γ's
  - Acceptance: $|\eta|<0.35$, $\phi = 2 \times \pi/2$
  - High granularity (~10*10mrad^2)

π^+/π^-
- Drift Chamber (DC) for Charged Tracks
- Ring Imaging Cherenkov Detector (RICH)
  - High p_T charged pions (p_T>4.7 GeV).

$W^\pm$ from $e^\pm$
- EMCal: triggering and energy determination
- DC\PC: Sign determination

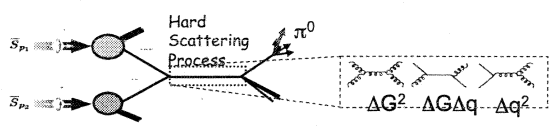
$W^\pm$ from $\mu^\pm$ (background studies)
- Tracking (MuTR)
- RPC prototype
- MuTrig Partially installed

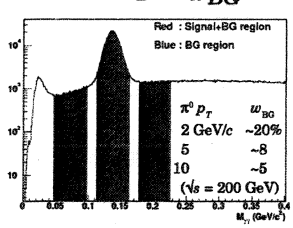
Forward "π^0" and eta (MPC)
- Acceptance: 3.1< η<3.9

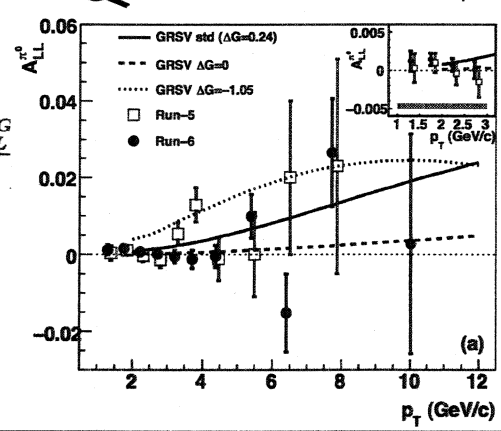
Neutral Pion A_{LL}

- Large cross section + finely segmented EMCal + high p_T photon trigger → large statistics
- $|\eta|<0.35$
- 2005: PRD 76, 051106
- 2006: PRL 103, 012003

$$A_{LL}^{\pi 0} = \frac{A_{LL}^{\pi 0+BG} - w_{BG} A_{LL}^{BG}}{1 - w_{BG}}$$

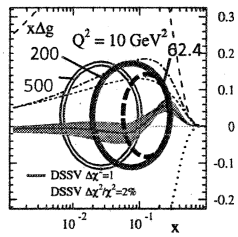


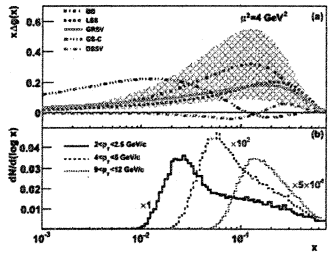




Limitations of Current Data

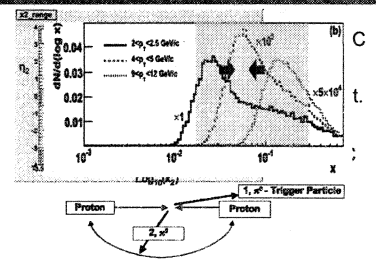
- Currently cover 0.02<x<0.3
  - Two ways to extend x range:
    - Change √s, such as 500 GeV (Run9, Run11)
    - Forward (MPC)
    - Analyses underway for both
  - 500 GeV only effective if polarization is high
    - At P=40% (50%), need 5 (2) times more data to reach same figure of merit as if had P=60%
    - Run9 will have limited value for A_{LL}.
- Wide distributions in x
  - Look at correlations
    - Central-Central → $x_1 \sim x_2$
    - Central-Forward → $x_1 > x_2$
    - Forward-Forward → $x_1 >> x_2$

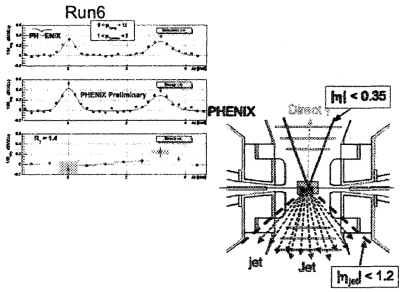




Narrowing sensitivity in x

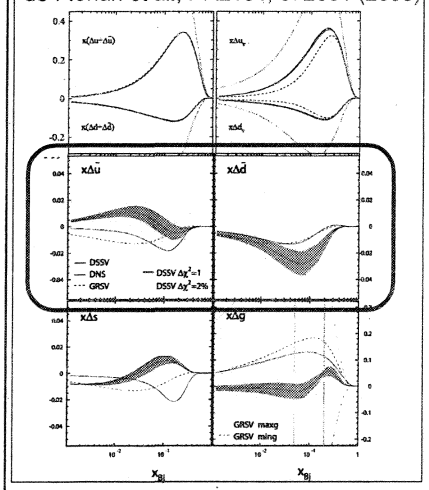
- Present results integrate ΔG over wide x range.
- Correlation measurements allow for a more constrained x range, though with less statistical precision.
- Analysis in Run 9 underway:
  - Trigger particle: π^0, $\pi^\pm$ or direct γ
  - Associated: π^0, $h^\pm$
  - Either trigger or associated in either central detector (|η|<0.35) or in MPC (3.1<|η|<3.9)
  - Different combinations sensitive to different x ranges
- Run 11 and beyond:
  - New detector: VTX/FVTX
    - Significantly increase η coverage
    - Can reconstruct jet axis for awayside





Quark Helicity Distributions

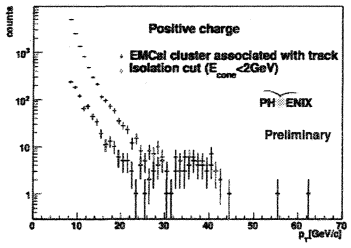
de Florian et al., PRL101, 072001 (2008)

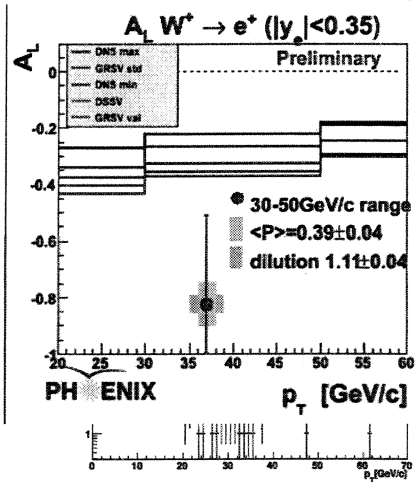


- DIS:
  - Valence quark distributions well determined
  - Flavor separated sea quark distributions are not accessible
- SIDIS:
  - Can access in semi-inclusive DIS
  - Rely on fragmentation functions
- p+p:
  - Accessible through parity violating W production

Measuring A_L

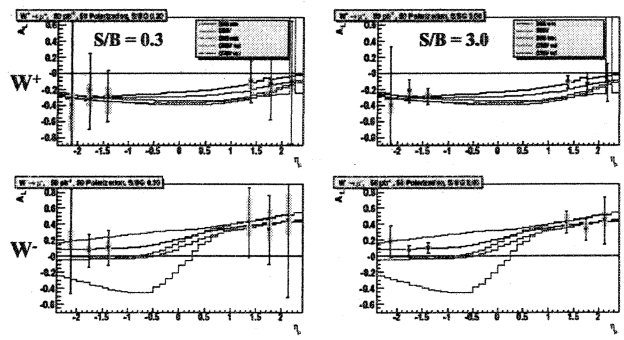
- For asymmetry, use additional isolation cut
  - Background reduced
- Non-zero asymmetry found
- Agrees within large statistical uncertainty
- Not corrected for Z, DY
- In future, VTX will allow better background determination





Run11 Expectations

- With a 10 week 500 GeV run next year, expect a cross section and first look at A_L in the forward region
  - Can make significant measurement if polarization is ~50%
  - Main analysis hurdle is increasing S/B



Conclusions

- Cross section measurements from $\sqrt{s}$=62.4 - 500 GeV are described by pQCD
- A number of channels have been measured which can constrain ΔG
  - 200 and 62.4 GeV π^0 data have been used in DSSV, and significantly constrain ΔG in the x range 0.02-0.3
  - We will extend the covered x range with measurements at 500 GeV and at larger η.
  - Correlation measurements will allow better determination of ΔG as a function of x
  - VTX and FVTX will extend η coverage greatly
- With the first 500 GeV run, parity violating W production asymmetry has been measured
- Upgrades for W→μ will be ready for Run11
  - Additional upgrades will help increase S/B

Thank you

Aurore Courtoy -INFN Pavia
with
Alessandro Bacchetta
Marco Radici

Dihadron Fragmentation Functions

Nucleon Spin Summer Program
BNL
20th of July 2010

Tuesday, 20 July 2010

Aurore Courtoy -INFN Pavia
with
Alessandro Bacchetta
Marco Radici

Dihadron Fragmentation Functions

PRELIMINARY

Nucleon Spin Summer Program
BNL
20th of July 2010

Tuesday, 20 July 2010

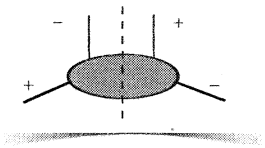
- Motivations
  - Transverse Spin from Fragmentation Functions
- From Theory to Data
  - Framework for DiFF
    - electron-positron annihilation
    - SIDIS
  - The Physics
    - Invariant Mass Spectrum
    - ... some model approach
- From Data to Theory
  - Extraction from BELLE
    - Unpolarized cross section
    - Polarized cross section
  - Back to the motivations ⟶ SIDIS

OUTLINE

Tuesday, 20 July 2010

Transverse Spin & TMDs

From DIS to Semi-Inclusive DIS



- *Transversity* not accessible through inclusive DIS
- we go to SIDIS
  - one more variable $\mathbf{k}_\perp$
  - Lorentz expansion of all the possible functions
  - birth of TMDs

TMD factorization

- Convolution
- Soft factors
- Evolution and Sudakov form factors
- Complex universality

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Transverse Spin from Fragmentation Functions

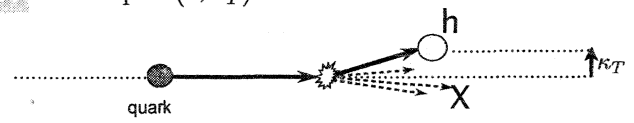
Distribution of hadrons inside the jet

⟶ Direction of the transverse polarization of the fragmenting quarks

also unpolarized

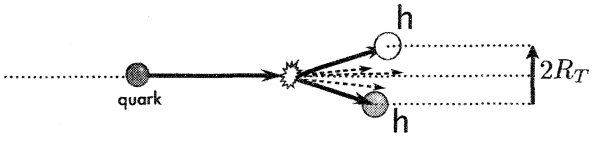
1 TMD FF

$$D_1^{q\to h}\left(z,\kappa_T^2\right)$$



2 DiFF

$$D_1^{q\to h_1h_2}\left(z_1,z_2,R_T^2\right)$$



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Transverse Spin from Fragmentation Functions

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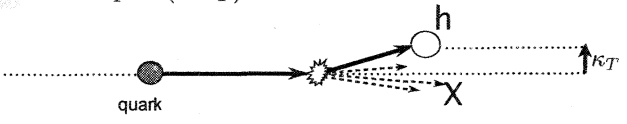
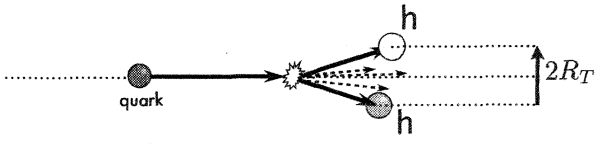


2 DiFF

$$D_1^{q\to h_1h_2}\left(z_1,z_2,R_T^2\right)$$



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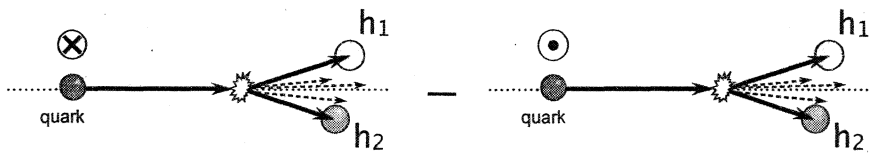
Transverse Spin from Fragmentation Functions

Interference Fragmentation Functions



$H^{\sphericalangle}_{1,q\to h_1 h_2}(z_1, z_2, R_T^2)$

relates transverse polarization of the fragmenting quark to angular distribution of the hadron pairs in the transverse plane

Collins, Heppelman, Ladinsky, NPB420 (94)

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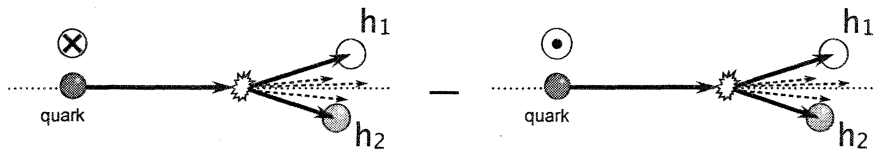
Transverse Spin from Fragmentation Functions

Interference Fragmentation Functions



$H^{\sphericalangle}_{1,q\to h_1 h_2}(z_1, z_2, R_T^2)$

relates transverse polarization of the fragmenting quark to angular distribution of the hadron pairs in the transverse plane

- ✓ Naive T-odd ; chiral-odd
- ✓ Does not vanish if integrated over transverse momentum
- ✓ The two hadrons must be distinguishable

Collins, Heppelman, Ladinsky, NPB420 (94)

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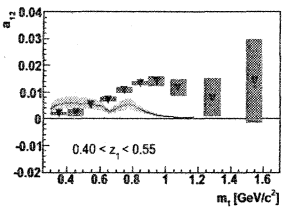
From theory to data



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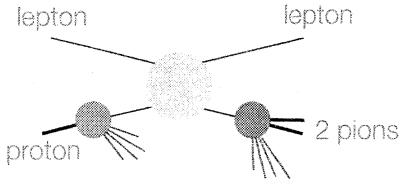
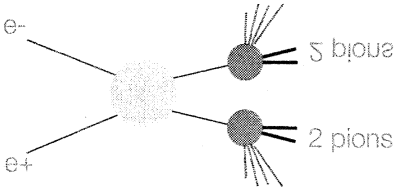
Framework for DiFF

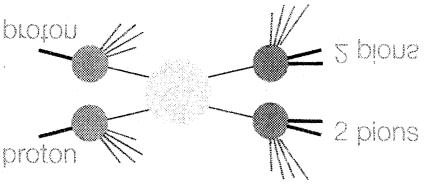
SIDIS on pp↑



e+e- to pions



pp↑ to pions



- Collinear factorization
- Universality
- No convolution
- Evolution understood (see after)

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Prediction for SIDIS using our fit for the DiFF

?

As for a 0th step,

What we already know

- assumptions on flavor separation
  - Issue: role of charm in the asymmetry
  - favored vs. unfavored
- evolution not needed for the ratio
- then we are left with a **one variable** fit

Tuesday, 20 July 2010

Di-hadron Fragmentation Functions

probability for (un-)polarized quarks to fragment into the hadron pair (h1 h2)

In particular, IFF

relates transverse polarization of the fragmenting quark to angular distribution of the hadron pairs in the transverse plane

- Collinear factorization
- Universality
- No convolution
- Evolution understood

- We have fitted the D1 DiFF from the BELLE experiment
- We have almost extracted H1< from the BELLE data
- Next step: Go down to SIDIS

CONCLUSIONS

Tuesday, 20 July 2010

Fragmentation function measurements at Belle

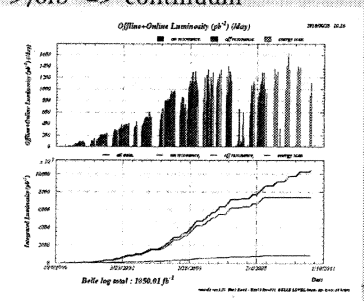
Summer program on Nuclear spin physics,
BNL, July 20

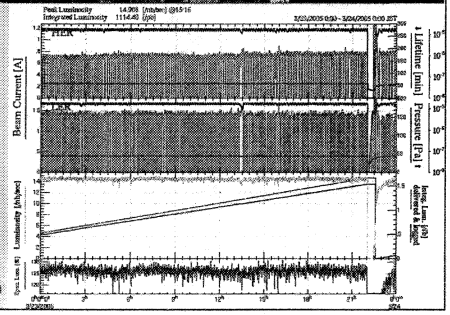
Ralf Seidl (RIKEN)
Anselm Vossen (University of Illinois)
Matthias Grosse Perdekamp (University of Illinois)
Martin Leitgab (University of Illinois)
Akio Ogawa (BNL/RBRC)
Kieran Boyle (RBRC)

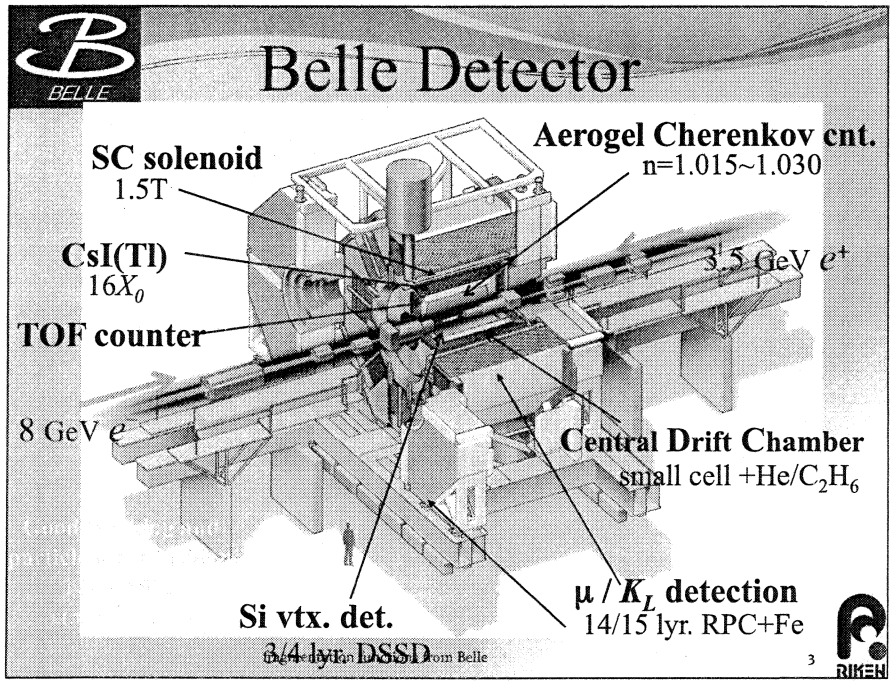
KEKB: $L>2.1\times10^{34}cm^{-2}s^{-1}$!!

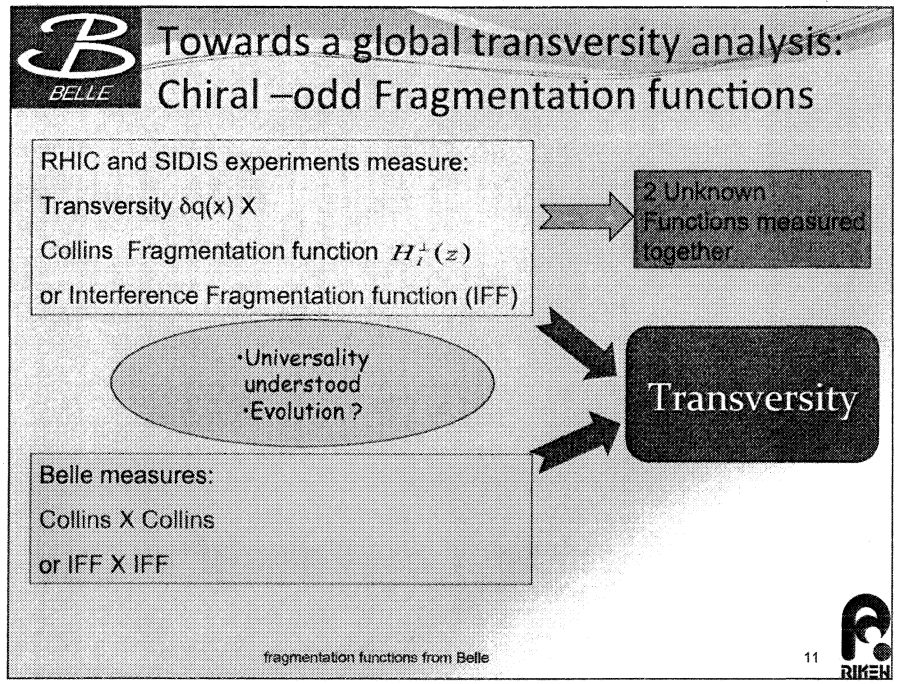
- Asymmetric collider
- 8GeV e^- + 3.5GeV e^+
- $\sqrt{s}$ = 10.58GeV (Y(4S))
- $e^+e^- \rightarrow Y(4S) \rightarrow B\bar{B}$
- Continuum production: 10.52 GeV
- $e^+e^- \rightarrow q\bar{q}$ (u,d,s,c)
- Integrated Luminosity: >1000 fb^{-1}
- >70fb^{-1} => continuum

Main research at Belle:
CP violation and determination of Cabbibo Kobayashi Masukawa (CKM) matrix



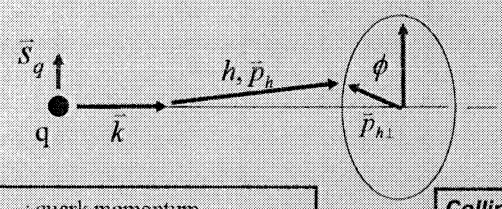



Belle Detector
SC solenoid
1.5T
CsI(Tl)
16X_0
TOF counter
8 GeV e^-
Aerogel Cherenkov cnt.
n=1.015~1.030
3.5 GeV e^+
Central Drift Chamber
small cell +He/C_2H_6
μ / K_L detection
14/15 lyr. RPC+Fe
Si vtx. det.
3/4 lyr. DSSD
fragmentation functions from Belle
3
RIKEN


Towards a global transversity analysis:
Chiral –odd Fragmentation functions
RHIC and SIDIS experiments measure:
Transversity δq(x) X
Collins Fragmentation function $H_1^\perp(z)$
or Interference Fragmentation function (IFF)
2 Unknown Functions measured together
•Universality understood
•Evolution ?
Transversity
Belle measures:
Collins X Collins
or IFF X IFF
fragmentation functions from Belle
11
RIKEN

Collins effect in quark fragmentation

J.C. Collins, Nucl. Phys. B396, 161(1993)



$\vec{k}$	: quark momentum
$\vec{s}_q$	: quark spin
$\vec{p}_h$	: hadron momentum
$\vec{p}_{h\perp}$	: transverse hadron momentum
$z_h = E_h/E_q$	
$= 2E_h/\sqrt{s}$	: relative hadron momentum

Collins Effect:
Fragmentation with of a quark q with spin s_q into a spinless hadron h carries an azimuthal dependence:

$$\propto \left(\vec{k} \times \vec{p}_{h\perp}\right) \cdot \vec{s}_q$$

$$\propto \sin\phi$$

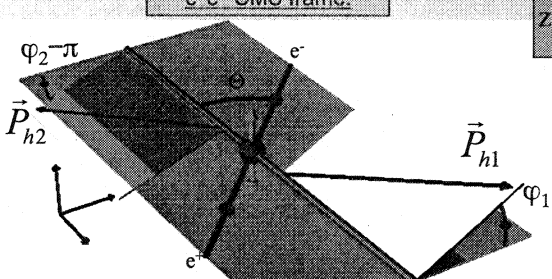
fragmentation functions from Belle

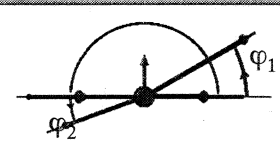
12

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

e^+e^- CMS frame:

$$z = \frac{2E_h}{\sqrt{s}}, \quad \sqrt{s} = 10.52\ GeV$$





[D.Boer: **PhD thesis(1998)**]

2-hadron inclusive transverse momentum dependent cross section:

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

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

Net (anti-)alignment of transverse quark spins

fragmentation functions from Belle

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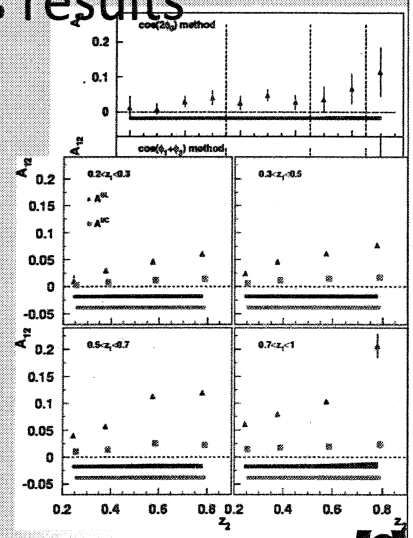
Final Collins results

- First direct measurement of the Collins effect: (PRL96: 232002)
- Nonzero asymmetries
- Belle 547 fb^{-1} data set (PRD78:032011)



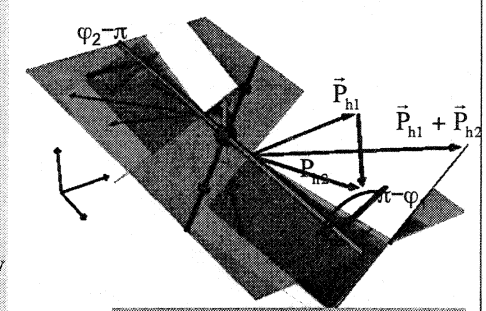
fragmentation functions from Belle

15

Interference Fragmentation – thrust method (Anselm, RS)

- $e^+e^- \rightarrow (\pi^+\pi^-)_{jet1}(\pi^+\pi^-)_{jet2}X$
- Stay in the mass region around ρ-mass
- Find pion pairs in opposite hemispheres
- Observe angles $\varphi_1+\varphi_2$ between the event-plane (beam, jet-axis) and the two two-pion planes.
- Transverse momentum is integrated (universal function, evolution easy → directly applicable to semi-inclusive DIS and pp)
- Theoretical guidance by papers of Boer,Jakob,Radici[PRD 67,(2003)] and Artru,Collins[ZPhysC69(1996)]
- Early work by Collins, Heppelmann, Ladinsky [NPB420 (1994)]

$$A_{12} \propto H_1^{\sphericalangle}(z_1, m_1) H_1^{\sphericalangle}(z_2, m_2) \cos(\varphi_1 + \varphi_2)$$



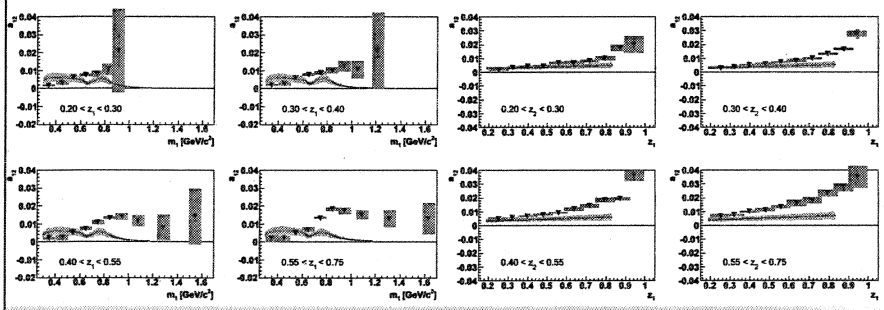
Model predictions by:

- Jaffe et al. [PRL 80,(1998)]
- Radici et al. [PRD 65,(2002)]

fragmentation functions from Belle

17

Comparison to theory predictions



Red line: theory prediction + uncertainties
Blue points: data (after sign change and cos moment, decay angular moments adjustment)

- Mass dependence : Magnitude at low masses comparable, high masses significantly larger (some contribution possibly from charm)
- Z dependence : Rising behavior steeper

However: Theory contains parameters based on HERMES data which already fail to explain COMPASS well

BELLE

Summary and outlook

- First direct measurement of the interference fragmentation function
  - Large asymmetries seen, rising with z and invariant mass
  - No sign change at ρ mass
  - No double reatios make interpretation simple
- Significant, nonzero Collins asymmetries, long paper published
- Data used already in Global analysis
- Measure precise unpolarized fragmentation functions of many final states

→ Important input for general QCD physics and helicity structure measurements

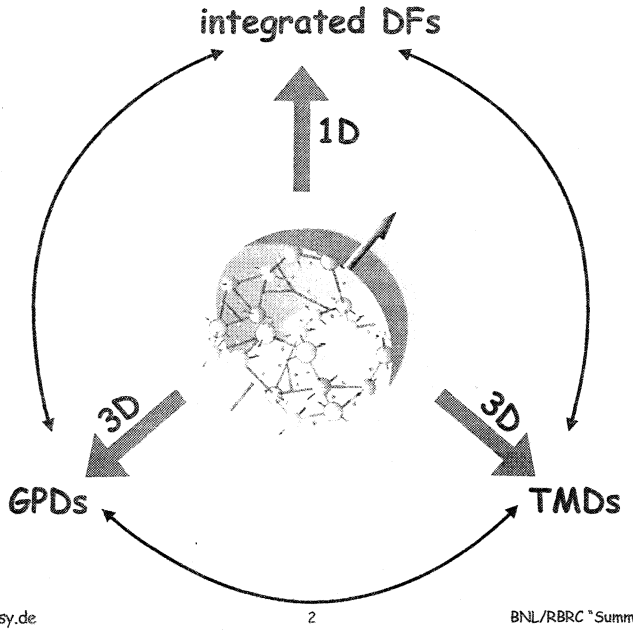
- Analysis progressing:
  - PID studies finished
  - Acceptance correction
- Many more types of analysis on the shopping list

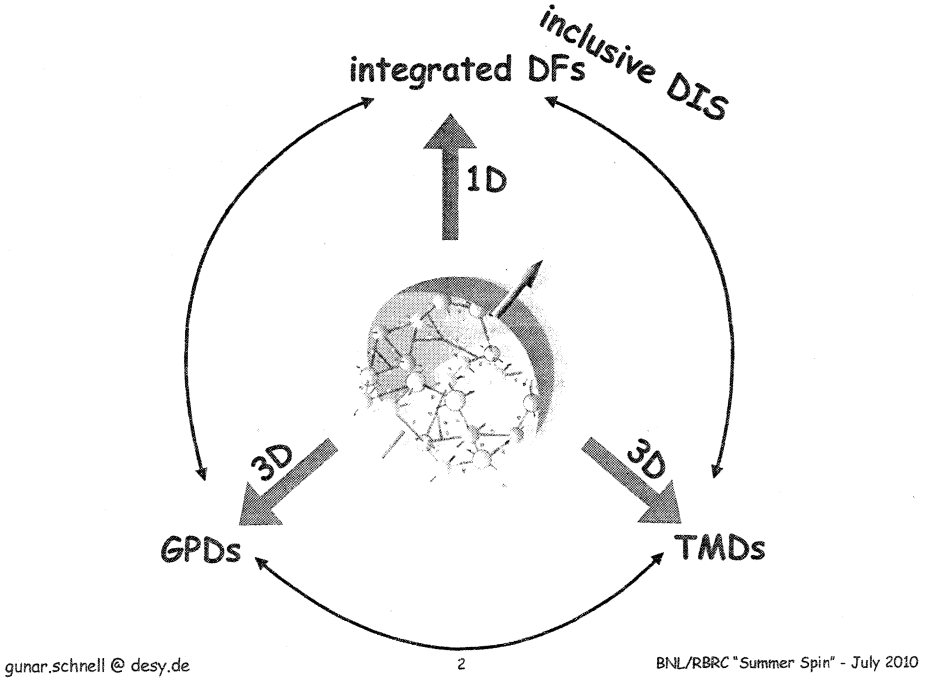
BNL/RBRC Summer Program on Nucleon Spin
July 14-27, 2010

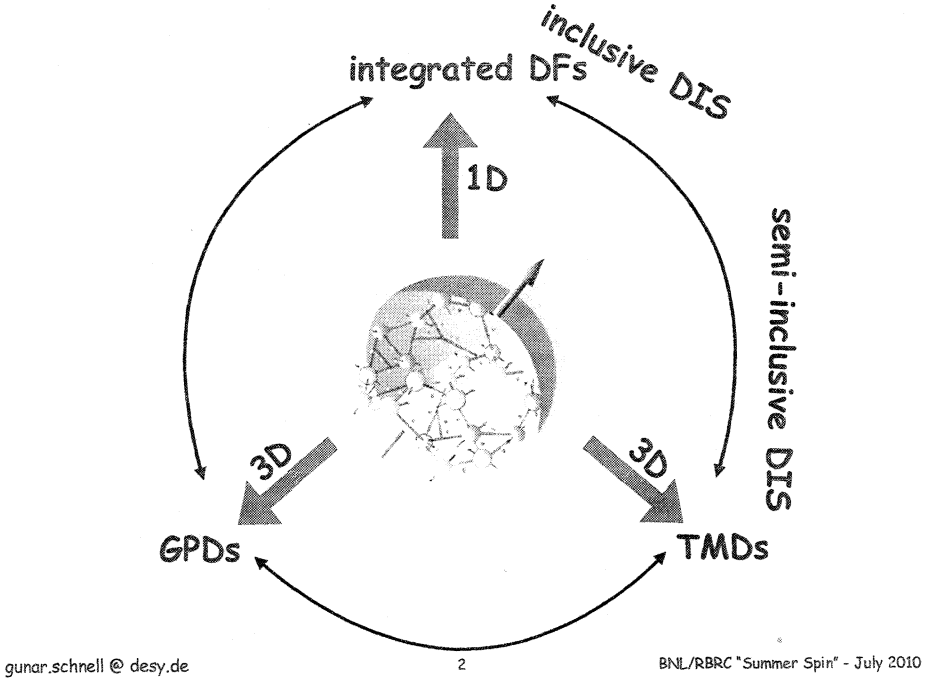
The structure of the nucleon

--the hermes perspective--

Gunar.Schnell @ desy.de




integrated DFs
inclusive DIS
1D
3D
3D
GPDs
TMDs
gunar.schnell @ desy.de
2
BNL/RBRC "Summer Spin" - July 2010


integrated DFs
inclusive DIS
1D
semi-inclusive DIS
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3D
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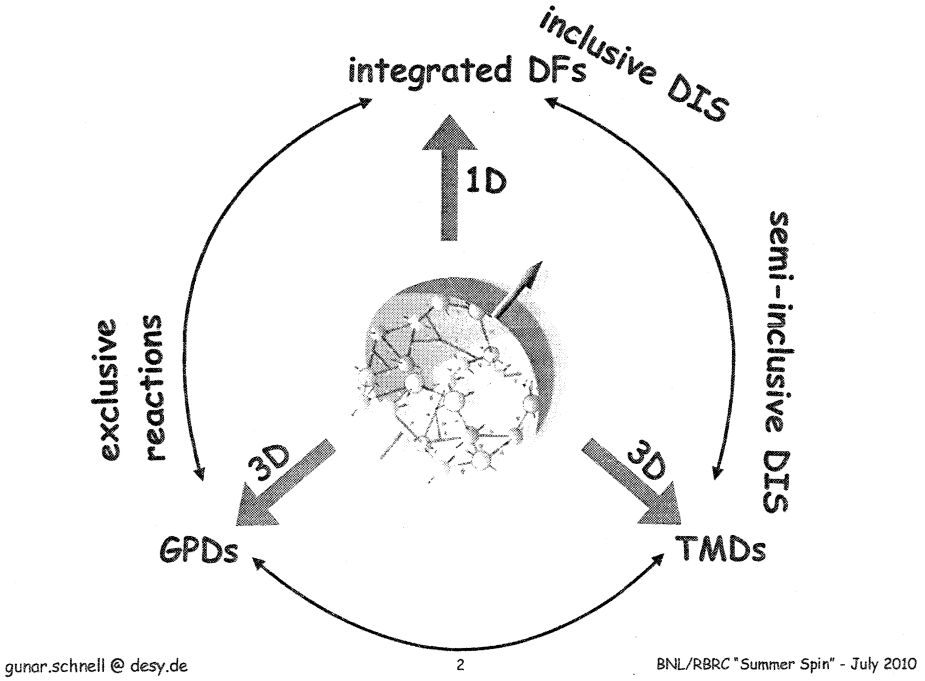
integrated DFs
inclusive DIS
1D
semi-inclusive DIS
exclusive reactions
3D
3D
GPDs
TMDs
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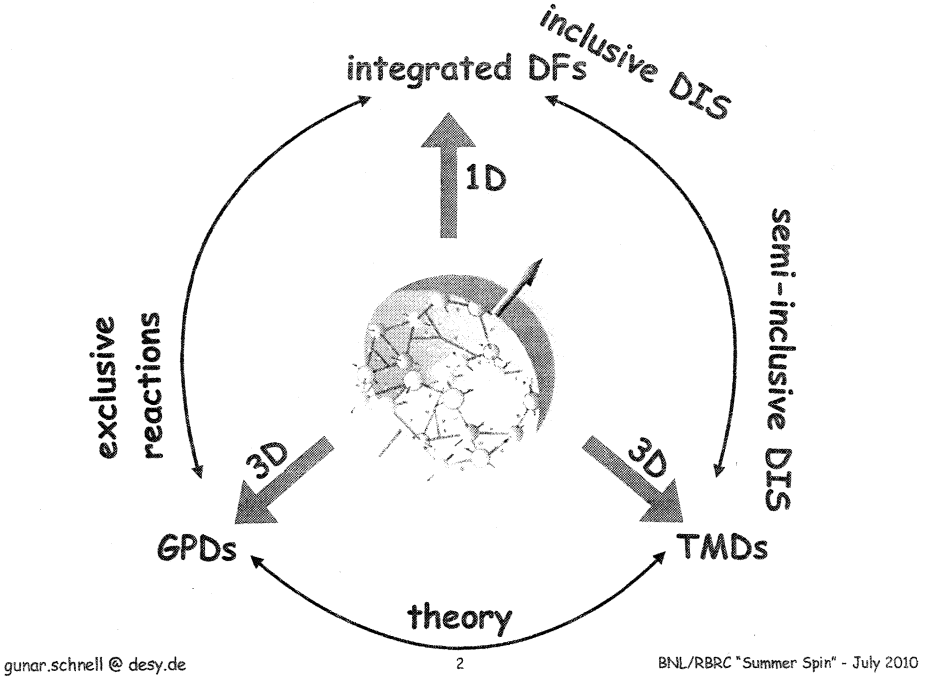
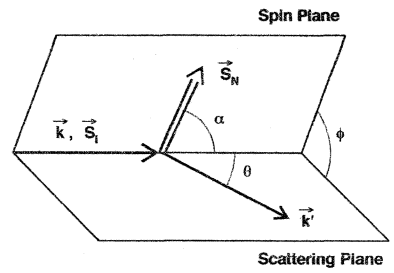
2
BNL/RBRC "Summer Spin" - July 2010


integrated DFs
inclusive DIS
1D
semi-inclusive DIS
exclusive reactions
3D
3D
GPDs
TMDs
theory
gunar.schnell @ desy.de
2
BNL/RBRC "Summer Spin" - July 2010

Inclusive DIS

$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

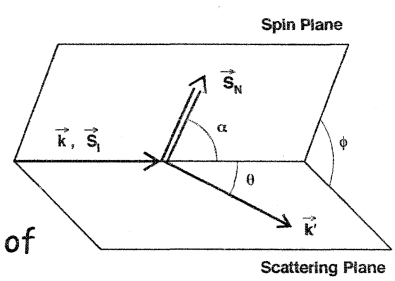


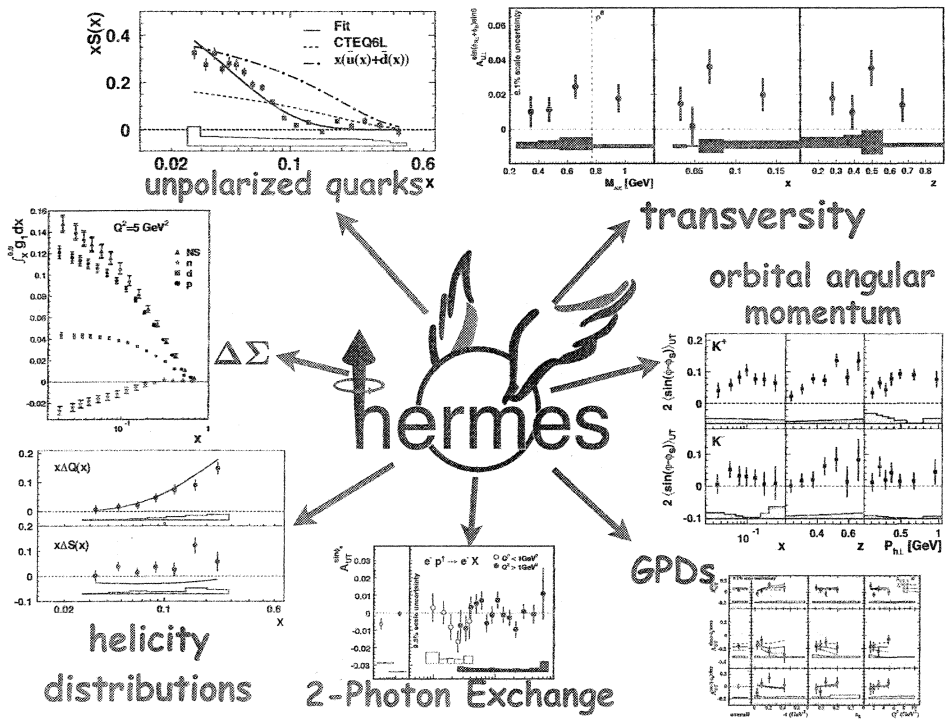
Inclusive DIS

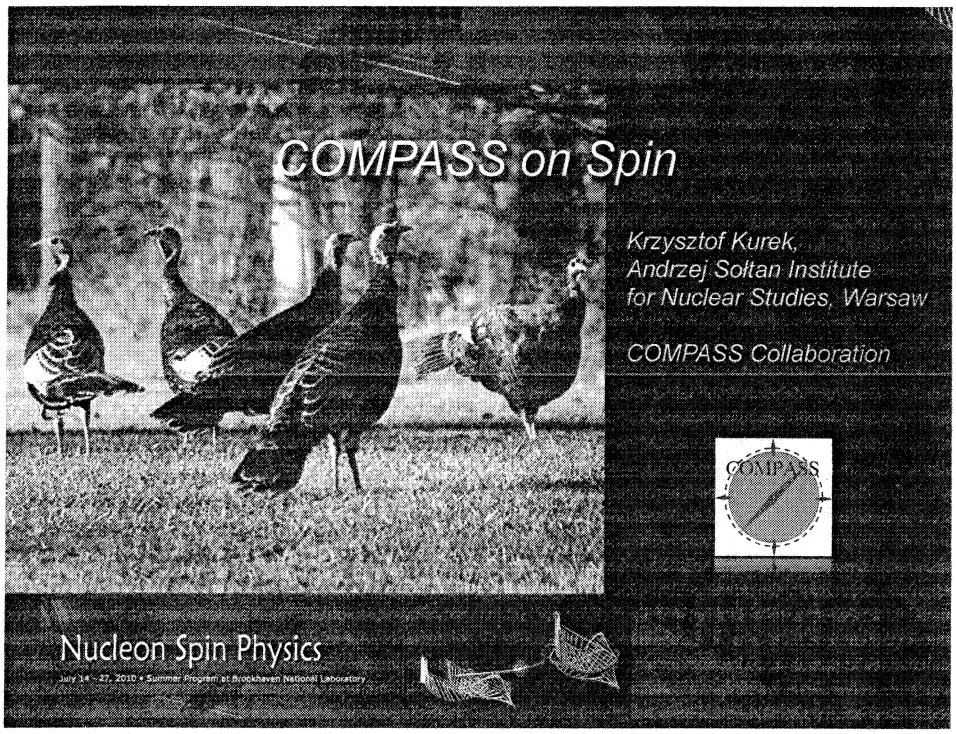
$$\frac{\mathrm{d}^2\sigma(s,S)}{\mathrm{d}x\ \mathrm{d}Q^2} = \frac{2\pi\alpha^2 y^2}{Q^6}\mathbf{L}_{\mu\nu}(s)\mathbf{W}^{\mu\nu}(S)$$

Lepton Tensor

Hadron Tensor parametrized in terms of Structure Functions




xS(x)
Fit
CTEQ6L
x(u(x)+d(x))
unpolarized quarks
transversity
orbital angular momentum
ΔΣ
helicity distributions
2-Photon Exchange
GPDs



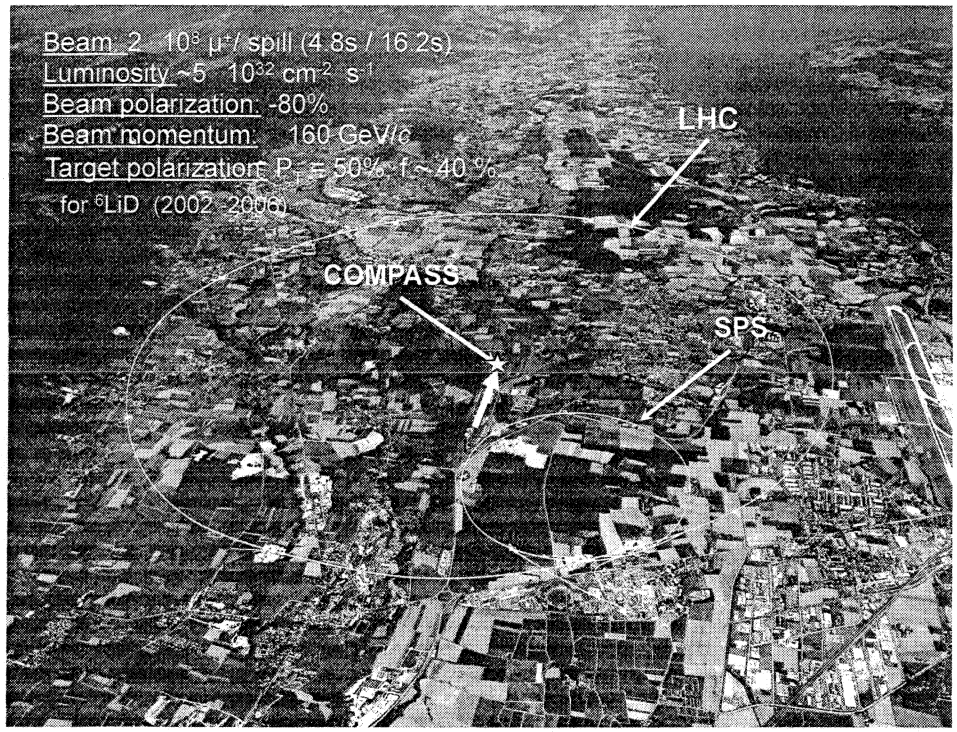
COMPASS Collaboration at CERN

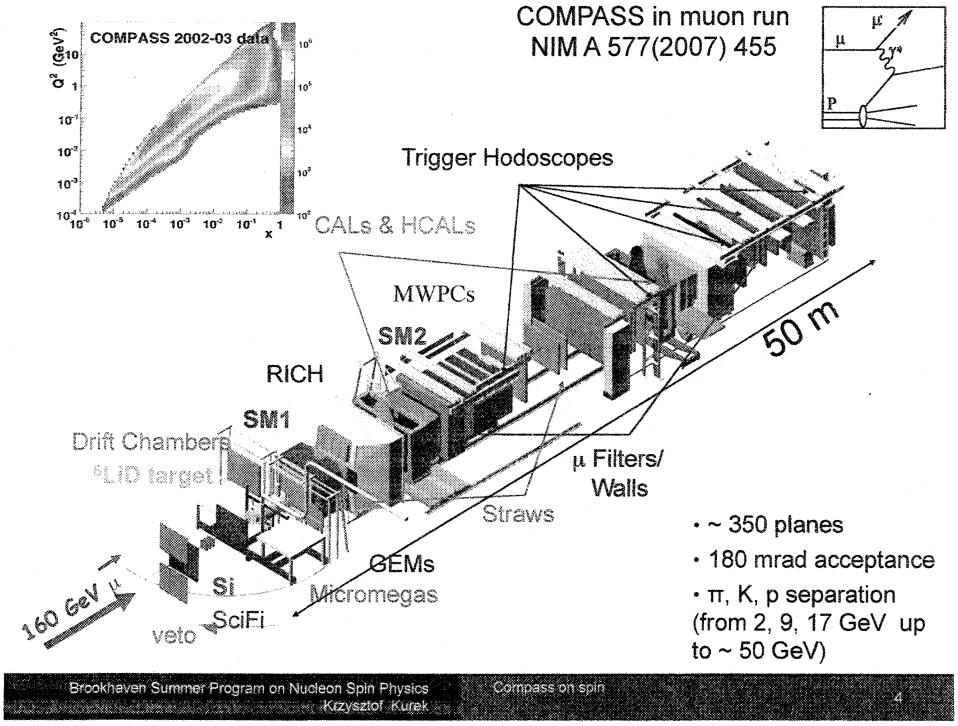
Common Muon and Proton Apparatus
for Structure and Spectroscopy

Czech Rep., France, Germany, India, Israel, Italy, Japan, Poland, Portugal, Russia and CERN

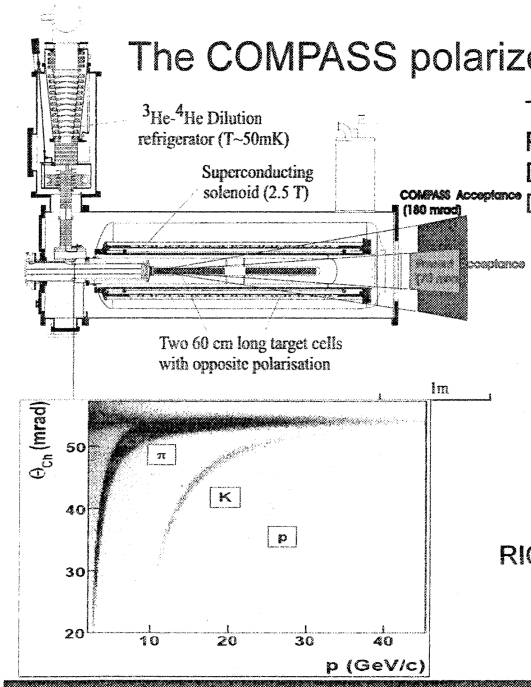
Bielefeld, Bochum, Bonn, Burdwan and Calcutta, CERN, Dubna, Erlangen, Freiburg, Lisbon, Mainz, Moscow, Munich, Prague, Protvino, Saclay, Tel Aviv, Torino, Trieste, Warsaw, Yamagata

~240 physicists, 30 institutes


Beam: 2 10^8 μ^+/ spill (4.8s / 16.2s)
Luminosity ~5 10^{32} cm^{-2} s^{-1}
Beam polarization: -80%
Beam momentum: 160 GeV/c
Target polarization: P_T = 50%, f ~ 40 %
for ^{6}LiD (2002-2006)
LHC
COMPASS
SPS

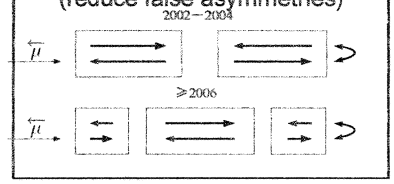

COMPASS 2002-03 data
Q^2 (GeV^2)
x
COMPASS in muon run
NIM A 577(2007) 455
μ
μ
γ*
P
Trigger Hodoscopes
CALs & HCALs
MWPCs
SM2
RICH
SM1
Drift Chambers
^{6}LiD target
μ Filters/
Walls
Straws
50 m
GEMs
Micromegas
Si
SciFi
veto
160 GeV μ
• ~ 350 planes
• 180 mrad acceptance
• π, K, p separation
(from 2, 9, 17 GeV up
to ~ 50 GeV)
Brookhaven Summer Program on Nucleon Spin Physics
Krzysztof Kurek
Compass on spin
4

The COMPASS polarized target



Target material: ^{6}LiD
Polarisation: >50%
Dilution factor: ~0.4
Dynamic Nuclear Polarization

2006 - new solenoid
with acceptance 180 mrad
3 target cells
(reduce false asymmetries)

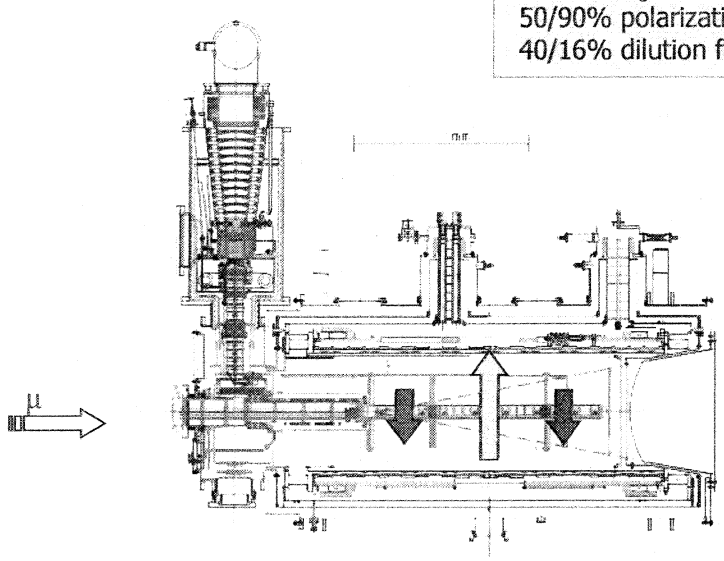


RICH 2006 upgrade : better PID

MAPMTs in central region

APV electronics in periphery

^{6}LiD or NH_3
50/90% polarization
40/16% dilution factor



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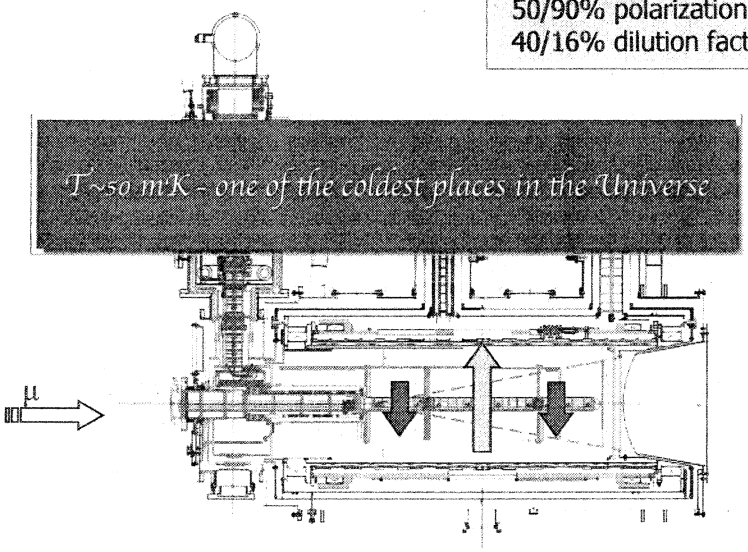
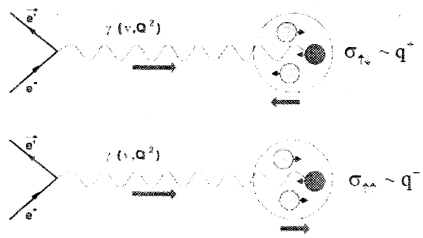


Contents

- Introduction
- DIS and SIDIS results; quark helicity distributions
- Gluon polarization: results from high-p_T hadron pairs
- Gluon polarization: result from open-charm measurement
- Transverse Spin Physics@COMPASS
- Future plans
- Summary

Polarized Deep Inelastic scattering



$$\Delta q(x) = q(x)^{+} - q(x)^{-}$$

$$q(x) = q(x)^{+} + q(x)^{-}$$

+ quark ↑↑ nucleon

− quark ↑↓ nucleon

Inclusive asymmetry:

$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2\, \Delta q(x,Q^2)}{\sum_q e_q^2\, q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

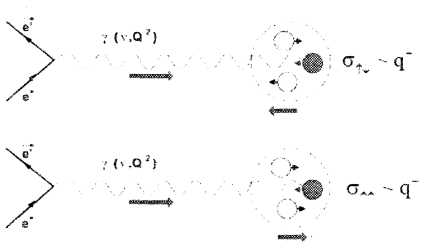
Semi-inclusive asymmetry:

$$A_1^h(x,z,Q^2) = \frac{\sigma^h_{\uparrow\downarrow} - \sigma^h_{\uparrow\uparrow}}{\sigma^h_{\uparrow\downarrow} + \sigma^h_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2\, \Delta q(x,Q^2) D_q^h(z,Q^2)}{\sum_q e_q^2\, q(x,Q^2) D_q^h(z,Q^2)}$$

2002-2006 deuteron data taking in COMPASS:

2007: proton data; DIS events - Q^2 >1 $(GeV/c)^2$

Polarized Deep Inelastic scattering



Total sample, [$\times 10^6$ evts]

	target	
	deuteron	proton
incl.	135.1	85.3
π^+	22.8	12.3
π^-	20.5	10.9
K^+	4.8	3.6
K^-	3.3	2.3

Inclusive asymmetry:

$$A_1(x,Q^2) = \frac{\sigma_{\uparrow\downarrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\uparrow\downarrow} + \sigma_{\uparrow\uparrow}} \approx \frac{\sum_q e_q^2\, \Delta q(x,Q^2)}{\sum_q e_q^2\, q(x,Q^2)} = \frac{g_1(x,Q^2)}{F_1(x,Q^2)}$$

Semi-inclusive asymmetry:

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2002-2006 deuteron data taking in COMPASS:

2007: proton data; DIS events - Q^2 >1 $(GeV/c)^2$

Phys. Lett. B 647 (2007) 8
Phys. Lett. B 690 (2010) 466–472

Hadron spin structure from lattice QCD

Philipp Hägler

TECHNISCHE UNIVERSITÄT MÜNCHEN

Topics:

- axial vector coupling constant, quark spin fraction, tensor charge
- n=2 moments of GPDs – generalized form factors incl. form factors of the energy momentum tensor
- decomposition of the nucleon spin
- TMDs and correlations between momenta, positions and spins

[for an overview, see e.g. Ph.H. Phys.Rep. 2010 (0912.5483)]

supported by

Emmy Noether-Programm DFG

TUM LMU excellence cluster universe

EM-tensor form factors of the nucleon and fundamental sum rules

$n = 2$

$$\langle P'|\bar{q}\gamma^{\{\mu} iD^{\nu\}} q|P\rangle = \langle P'|T_q^{\mu\nu}|P\rangle$$

gravitational spin-2 coupling

$$\langle P'|T^{\mu\nu}|P\rangle = \overline{U}(P')\Big\{\gamma^\mu \overline{P}^\mu \underline{A_{20}(\Delta^2)} + \frac{i\sigma^{\mu\rho}\Delta_\rho \overline{P}^\nu}{2m_N}\underline{B_{20}(\Delta^2)} + \frac{\Delta^\mu\Delta^\nu}{m_N}C_{20}(\Delta^2)\Big\}U(P)$$

translation invariance

rotational symmetry

conservation of momentum

conservation of angular momentum

momentum sumrule

$$\begin{aligned} 1 &= \sum_q A_{20}^q(0) + A_{20}^g(0) \\ &= \sum_q \langle x\rangle_q + \langle x\rangle_g \end{aligned}$$

vanishing of the anomalous gravitomagnetic moment

$$0 = \sum_q B_{20}^q(0) + B_{20}^g(0)$$

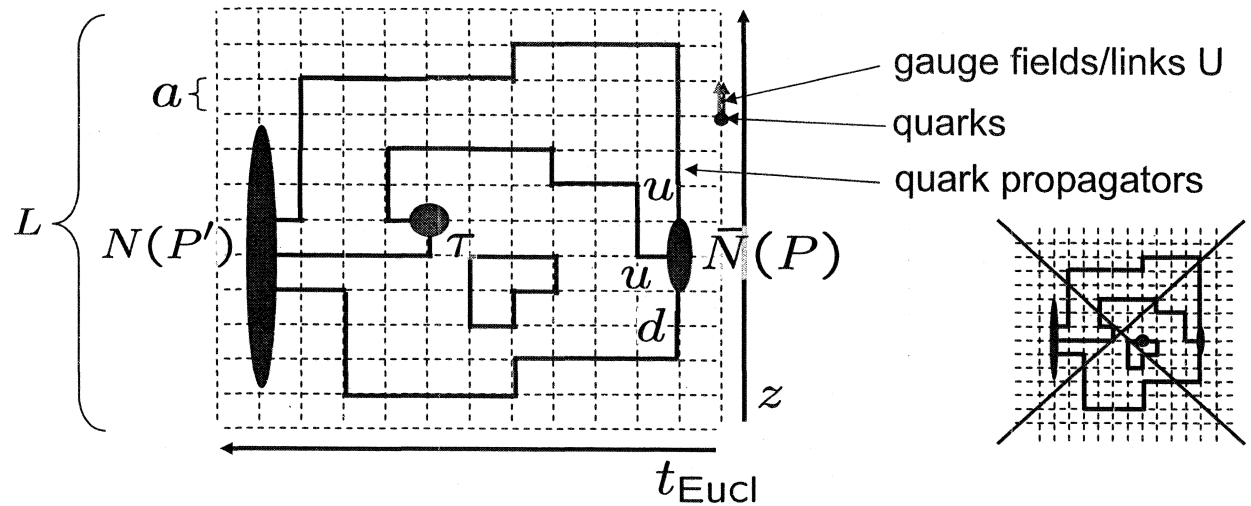
Ji's nucleon spin sum rule (X. Ji, PRL 1997)

$$\begin{aligned} \frac{1}{2} = S_z &= \frac{1}{2}\Big(\sum_q A_{20}^q(0) + A_{20}^g(0) + \sum_q B_{20}^q(0) + B_{20}^g(0)\Big) \\ &= \sum_q J_q + J_g = \sum_q \frac{1}{2}\Delta\Sigma_q + \sum_q L_q + J_g \end{aligned}$$

$$\begin{aligned} L_q &\equiv J_q - \frac{1}{2}\Delta\Sigma_q \\ (L_g &\equiv J_g - \Delta G) \end{aligned}$$

everything is: -gauge-invariant
-scale and scheme dependent
-measurable

Lattice QCD calculations of hadron structure



● = vector-, axialvector-, *quark spin flip-,* (spin-2) *graviton-, „spin-n"* coupling

$$C_{3pt}(P',P,\tau) \leftrightarrow e^{-E'(T-\tau)-E\tau}\langle P',\Lambda'|\underbrace{\mathcal{O}}_{\bullet}|P,\Lambda\rangle \propto g_A, \Delta\Sigma, F_1(t), F_2(t), \langle x\rangle, A_{20}(t), ..$$

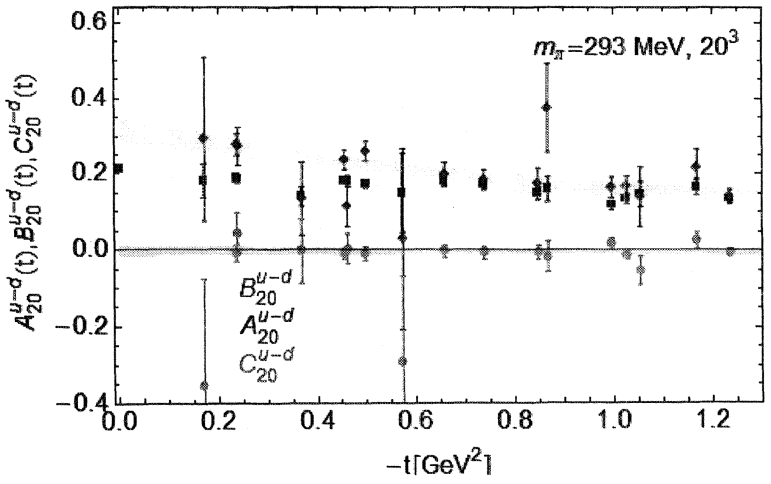
$t = \Delta^2 (\hat{=} q^2)$

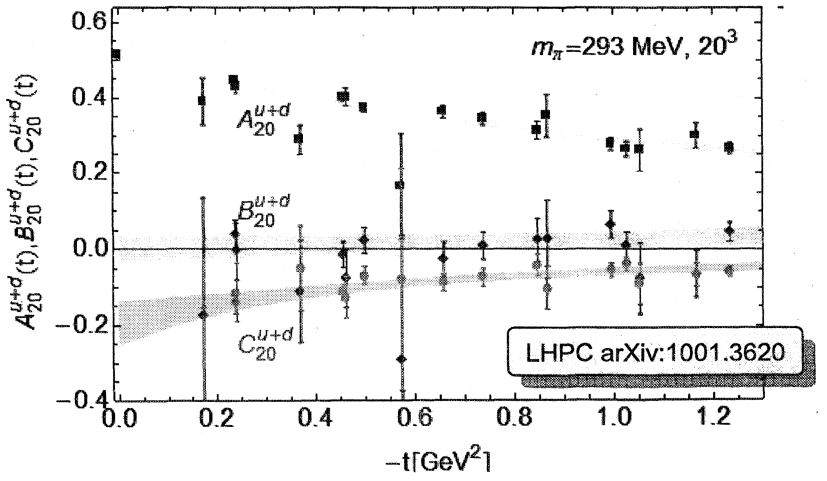
$$\langle q_2\bar{q}_1\rangle \propto \int DADqd\bar{q}e^{iS[q,\bar{q},A]} \rightarrow \left[\int DUe^{-S[U]}\det D[U]\right] D^{-1}_{1\rightarrow 2}[U] \approx \frac{1}{N}\sum_{i=1}^{N} D^{-1}_{1\rightarrow 2}[U_i]$$

compute the path-integral numerically

A, B, C - Form factors of the energy momentum tensor

$$\langle P'|T_q^{\mu\nu}|P\rangle = \langle P'|\bar{q}\gamma^{\{\mu}iD^{\nu\}}q|P\rangle = \overline{U}(P')\Big\{\gamma^{\{\mu}\overline{P}^{\nu\}}A_{20}(t) - \frac{i\Delta_\rho\sigma^{\rho\{\mu}\overline{P}^{\nu\}}}{2m_N}B_{20}(t) + \frac{\Delta^\mu\Delta^\nu}{m_N}C_{20}(t)\Big\}U(P)$$





$B_{20}^{u-d} > A_{20}^{u-d}$
$C_{20}^{u-d} \approx 0$

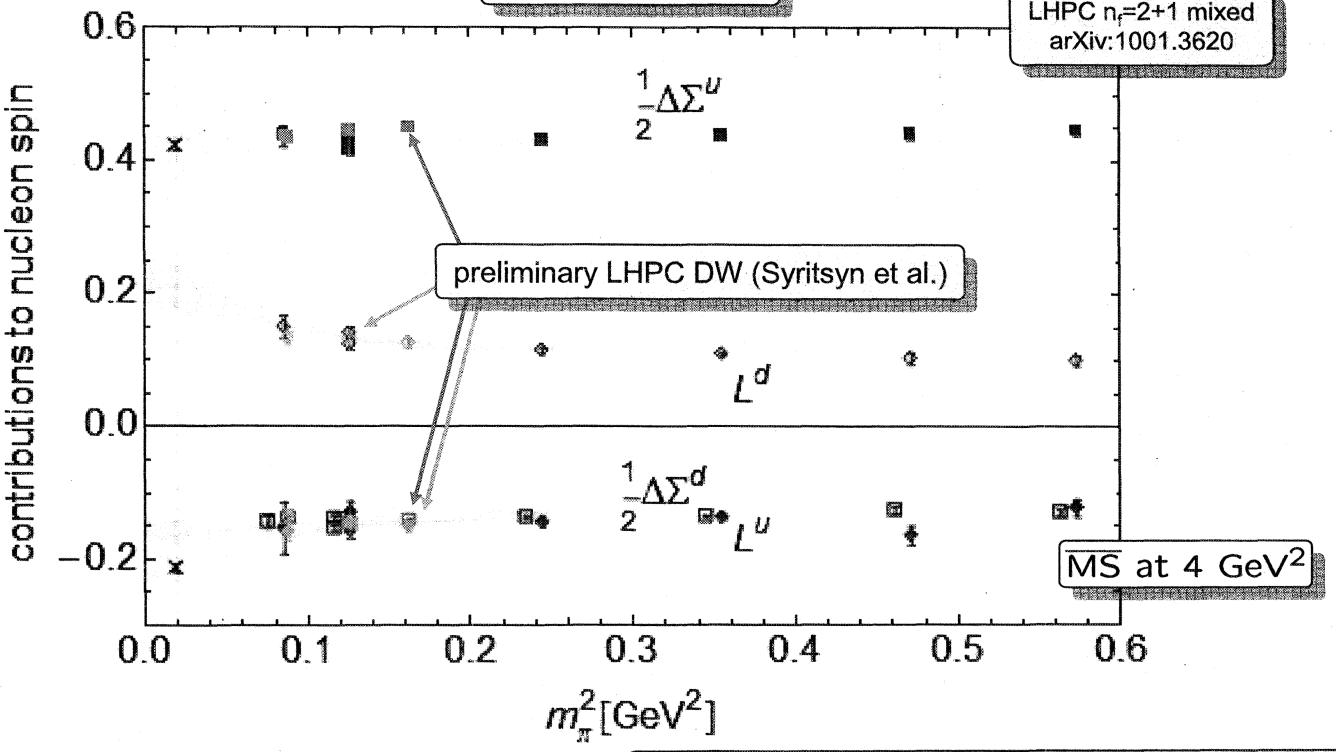
$A_{20}^{u+d} > B_{20}^{u+d}$
$C_{20}^{u+d} < 0$

disconnected contributions are not included↔ only u-d is „exact"

seems to be compatible with large N_c limit
– see e.g. Goeke, Polyakov, et al. PiPaNP 2001

Quark spin and orbital angular momentum

$L_q = J_q - \Delta\Sigma_q/2$



$J^u \approx 0.236 \pm 0.006 \hat{=} 48\%$ of $1/2$
$J^d \approx 0.002 \pm 0.004$

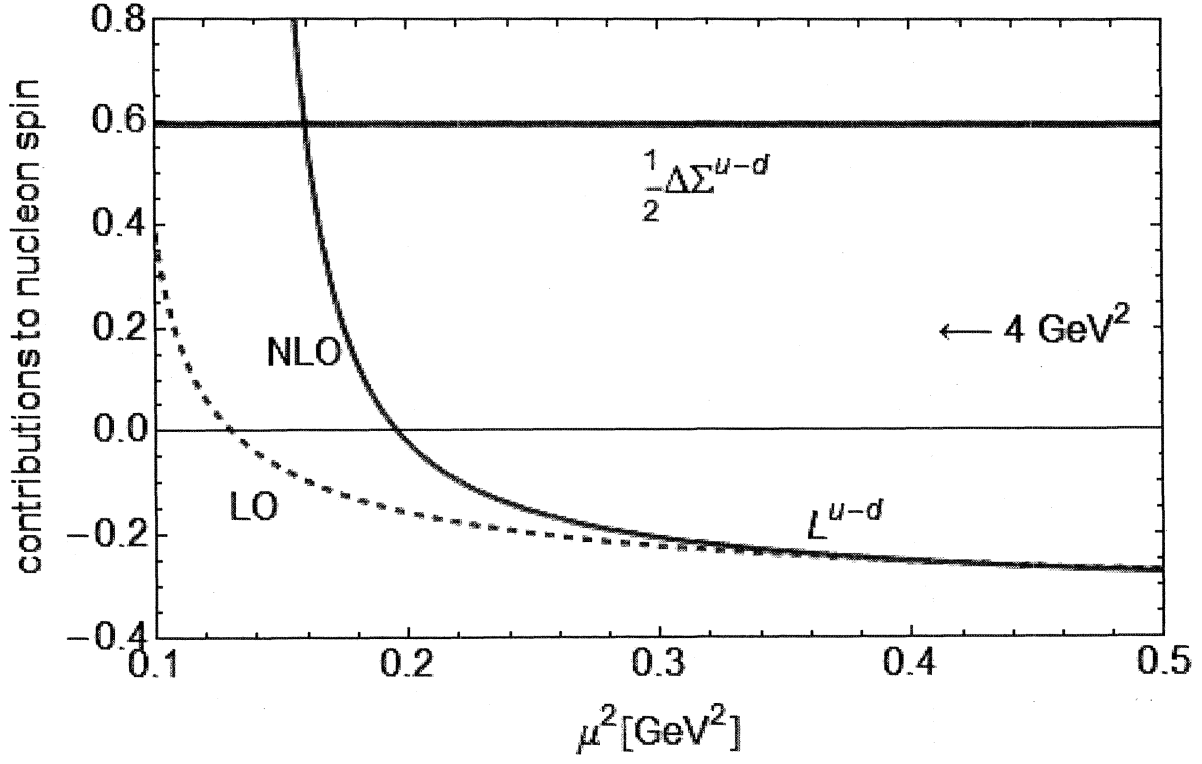
$L^d \approx -L^u \approx 0.185 \pm 0.06 \approx 36\%$ of $1/2$
$L^{u+d} \approx 0.030 \pm 0.012 \approx 6\%$ of $1/2$

$\kappa^{u+d} = 3\kappa^{p+n} = -0.36$

Lattice QCD vs relativistic quark models – QCD evolution

Wakamatsu 2005; Thomas, PRL 2008; M.Altenbuchinger, Ph.H., W.Weise, 2010 (tbp)

$$L^{u-d}(t) = \left(\frac{t}{t_0}\right)^{\frac{2}{\beta_0}\left(\frac{-16}{9}\right)} \left\{ L^{u-d}(t_0) + \frac{1}{2}\Delta\Sigma^{u-d} \right\} - \frac{1}{2}\Delta\Sigma^{u-d}$$



Ph. Hägler, Spin Summer@BNL, 07/10

Some comments on the controversy concerning the definition of quark and gluon angular momentum

work in progress

Elliot Leader

Imperial College London

Background

• Controversy in QCD : how to split the total angular momentum into separate quark and gluon components • Ji vs Chen, Lu, Sun, Wang and Goldman (Chen etal) • Ji stresses: gauge invariant operators; covariance; local operators • Chen at al: don't like Ji; don't like any previous theory; claim even in QED the traditional, decades-old identification of electron and photon angular momentum is incorrect • Different results for momentum and angular momentum carried by quarks and gluons e.g. as $\mu^2 \to \infty$

There are three versions of $\boldsymbol{J}$

Canonical (can), Bellinfante (bel)= Ji, Chen at al (chen)

$$\begin{aligned} \boldsymbol{J}_{can} &= \int d^3x\, \psi^\dagger \boldsymbol{\gamma}\gamma_5 \psi + \int d^3x\, \psi^\dagger [\boldsymbol{x} \times (-i\boldsymbol{\nabla})]\psi \\ &+ \int d^3x\, (\boldsymbol{E} \times \boldsymbol{A}) + \int d^3x\, E^i [\boldsymbol{x} \times \boldsymbol{\nabla} A^i] \\ &= \boldsymbol{S}_{can}(el) + \boldsymbol{L}_{can}(el) + \boldsymbol{S}_{can}(\gamma) + \boldsymbol{L}_{can}(\gamma) \end{aligned} \tag{1}$$

$$\begin{aligned} \boldsymbol{J}_{bel} &= \int d^3x\, \psi^\dagger \boldsymbol{\gamma}\gamma_5 \psi + \int d^3x\, \psi^\dagger [\boldsymbol{x} \times (-i\boldsymbol{D})]\psi \\ &+ \int d^3x\, \boldsymbol{x} \times (\boldsymbol{E} \times \boldsymbol{B}) \\ &= \boldsymbol{S}_{bel}(el) + \boldsymbol{L}_{bel}(el) + \boldsymbol{J}_{bel}(\gamma) \end{aligned} \tag{2}$$

$$\begin{aligned} \boldsymbol{J}_{chen} &= \int d^3x\, \psi^\dagger \boldsymbol{\gamma}\gamma_5 \psi + \int d^3x\, \psi^\dagger [\boldsymbol{x} \times (-i\boldsymbol{D}_{pure})]\psi \\ &+ \int d^3x\, (\boldsymbol{E} \times \boldsymbol{A}_{phys}) + \int d^3x\, E^i [\boldsymbol{x} \times \boldsymbol{\nabla} A^i_{phys}] \\ &= \boldsymbol{S}_{ch}(el) + \boldsymbol{L}_{ch}(el) + \boldsymbol{S}_{ch}(\gamma) + \boldsymbol{L}_{ch}(\gamma) \end{aligned} \tag{3}$$

Some consequences:
1) Note: Ji = Belinfante = bel : Burkhardt and Hikmat, quark-scalar diquark model:

$$L^z_{can}(quark) - L^z_{Ji}(quark) = \frac{\alpha_s}{4\pi} \tag{4}$$

$$J^z_{Ji}(gluon) - \frac{1}{2}\Delta G = L^z_{can}(gluon) + \frac{\alpha_s}{4\pi} \tag{5}$$

2) Similar differences in definitions of linear momentum.
Asymptotically what fraction of total momentum is carried by gluons?

Ji: $\frac{16}{16+3n_f} \simeq 1/2$ for $n_f = 5$

Chen et al: $\frac{8}{8+6n_f} \simeq 1/5$ for $n_f = 5$!

General thesis: not enough attention paid to difference between CLASSICAL and QUANTUM field theory.

Examples
• "Measurable operators must be gauge invariant"
No: physical matrix elements of measurable operators must be gauge invariant
• "A^μ should transform as a 4-vector"
Beware quantization conditions! Bellinfante, as used, does not correspond to covariant quantization.
• "OK to use non-local field operators"
Not OK if they are dynamical variables. In Coulomb gauge A^0 is not an independent dynamical variable.
• "If E and F are interacting particles, definition of e.g. $\boldsymbol{J}(E)$ should satisfy $[J^i(E), J^j(E)] = i\,\epsilon^{ijk} J^k(E)$"
Impossible. Cannot be checked!

The momentum operator in gauge-invariant theories

Theory invariant under translations; Noether construction, from classical Lagrangian; canonical e-m density $t^{\mu\nu}_{can}(x)$. A conserved density, generally not symmetric under $\mu \leftrightarrow \nu$.

$$\partial_\mu t^{\mu\nu}_{can}(x) = 0$$

Canonical total linear momentum operator P^j_C

$$P^j_C = \int d^3x\; t^{0j}_{can}(x)$$

independent of time.

Canonical momentum operator as generator of translations

Classically : P_C^j generates spatial translations. Quantum theory: check correct commutation relations with fields i.e. for any field $\phi(x)$

$$i\,[P_C^j,\,\phi(x)] = \partial^j\,\phi(x) \qquad (7)$$

Interacting theory: cannot calculate arbitrary commutation relation between the fields. But Equal Time Commutators (ETC) fixed in quantizing theory. Thus can check (7) because P_C^j independent of time. Take time variable of fields in P_C^j to coincide with time variable in $\phi(x) \equiv \phi(t, \boldsymbol{x})$. Crucial when discussing division of total momentum into contributions from different fields .

An example of the confusion: Non-gauge invariance of the QED momentum operator

Can prove the following Theorem: Consider a theory which is invariant under local c-number gauge transformations. Let P^μ be the total momentum operator, defined as the generator of space-time translations. Then P^μ cannot be a gauge invariant operator.
But, lack of gauge invariance of no physical significance. Example, covariantly quantized QED: can show that the matrix element of P_C^j between any normalizable physical states, unaffected by gauge changes in the operator.

Relativistic covariance

Non-trivial to quantize theory covariantly. Lautrup-Nakanishi Lagrangian density: combination of the Classical Lagrangian ($Clas$) and a Gauge Fixing part (Gf)

$$\mathcal{L} = \mathcal{L}_{Clas} + \mathcal{L}_{Gf}$$

where

$$\mathcal{L}_{Clas} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\,[\bar{\psi}(i\,\not{\partial} - m + e\,\not{A})\psi + \text{h.c.}]$$

and

$$\mathcal{L}_{Gf} = B(x)\,\partial_\mu A^\mu(x) + \frac{\mathsf{a}}{2}B^2(x)$$

$B(x)$: gauge-fixing field. Parameter a determines structure of photon propagator; irrelevant for present discussion .
Ji rightly argues that Chen et al vector potential does not transform as a 4-vector under Lorentz transformations, and implies that his does.
If so then Ji's expressions for momentum is incomplete. The point is that the gauge-fixing field $B(x)$ in the covariant quantization appears in the expressions for the momentum .
One finds for the canonical e-m density,

$$t_{can}^{\mu\nu} = \frac{i}{2}\,\bar{\psi}\gamma^\mu \overleftrightarrow{\partial}^\nu\,\psi - F^{\mu\beta}\partial^\nu A_\beta + B\partial^\nu A^\mu - g^{\mu\nu}\mathcal{L}$$

where $\overleftrightarrow{\partial}^{\nu} \equiv \overrightarrow{\partial}^{\nu} - \overleftarrow{\partial}^{\nu}$.
For the Bellinfante density one finds,

$$t^{\mu\nu}_{bel} = \theta^{\mu\nu} + t^{\mu\nu}_{Gf}$$

where $\theta^{\mu\nu}$, the classical e-m density, is

$$\theta^{\mu\nu} = \frac{i}{4}\,\bar{\psi}(\gamma^{\mu}\overleftrightarrow{D}^{\nu} + \gamma^{\nu}\overleftrightarrow{D}^{\mu})\,\psi - F^{\mu\beta}F^{\nu}{}_{\beta} - g^{\mu\nu}\mathcal{L}_{Clas}$$

where $\overleftrightarrow{D}^{\nu} = \overleftrightarrow{\partial}^{\nu} - 2ieA^{\nu}$, and

$$t^{\mu\nu}_{Gf} = -(\partial^{\mu}B)\,A^{\nu} - (\partial^{\nu}B)\,A^{\mu} - g^{\mu\nu}\mathcal{L}_{Gf}$$

The conservation of an e-m tensor depends on the equations of motion, which are a consequence of the Lagrangian. Thus $t^{\mu\nu}_{bel}$ is conserved, but $\theta^{\mu\nu}$ is not, when the Lagrangian is $\mathcal{L}_{Clas} + \mathcal{L}_{Gf}$.
On the other hand $\theta^{\mu\nu}$ would be conserved *if* the Lagrangian were $\mathcal{L}_{Clas}$.

Now Ji and Chen at al utilize $\theta^{\mu\nu}$ and treat it as if it were conserved i.e. they take the momentum operator based on it to be independent of time (equivalently: to remain unrenormalized), which implies that the Lagrangian is just $\mathcal{L}_{Clas}$.

But it is well known that one cannot quantize QED *covariantly* using $\mathcal{L} = \mathcal{L}_{Clas}$. Nonetheless Ji insists that his A_{μ} transforms covariantly, which is thus a contradiction.

The problem of defining separate quark and gluon moment

Heart of the controversy between Ji and Chen at al: how to define the separate contributions of quarks and gluons to the momentum and angular momentum of a nucleon.
Two separate issues:
(1) General how to define the separate momenta for a system of interacting particles.
(2) Specific to gauge theories, including the issue of splitting the angular momentum of a gauge particle into a spin and orbital part. Here we only comment on (1).
System of interacting particles E and F. Split the total momentum into two pieces

$$P^{j} = P^{j}_{E} + P^{j}_{F} \qquad (13)$$

associated with momentum carried by the individual particles E and F respectively.

Crucial: Eq. (13), as it stands, is *totally misleading*, and should be written

$$P^{j} = P^{j}_{E}(t) + P^{j}_{F}(t)$$

to reflect the fact that the particles exchange momentum as a result of their interaction.

Criterion for identifying $P_{E,F}$ as the momentum associated with particles E, F respectively?????
Seductively obvious answer would be to demand that

$$i[P_E^j, \phi_E(x)] = \partial^j \phi_E(x) \qquad (14)$$

but no way we can check this, since $P_E^j(t)$ depends on t and, without solving the theory, can only compute equal time commutators
.
Suggest: *minimal requirement for identifying an operator P_E^j with the momentum carried by E , is to demand that* at equal times *the analogue of Eq. (14) holds*

$$i[P_E^j(t)\,, \phi_E(t, \boldsymbol{x})] = \partial^j \phi_E(t, \boldsymbol{x}).$$

For the total momentum P_C and P_B are equivalent, since their integrands differ by the spatial divergence of a local operator.
But if split P_C into $P_{CE} + P_{CF}$ and P_B into $P_{BE} + P_{BF}$, then the integrands of P_{CE} and P_{BE} do *not* differ by a spatial divergence, and hence P_{CE} and P_{BE} do not generate the same transformation on $\phi_E(x)$.
Example: Could identify

$$t_{can}^{0j}(\text{electron}) = \frac{i}{2}\,\bar{\psi}\gamma^0 \overleftrightarrow{\partial}^j \psi \qquad (6)$$

and

$$t_{bel}^{0j}(\text{electron}) = \frac{i}{4}\,\bar{\psi}(\gamma^0 \overleftrightarrow{D}^j + \gamma^j \overleftrightarrow{D}^0)\,\psi \qquad (7)$$

and these do not differ by a spatial divergence.
By construction, P_{CE} and P_{CF} generate the correct transformations on $\phi_E(x)$ and $\phi_F(x)$ respectively.

We conclude that with the above minimal requirement we are forced to associate the momentum of E and F with the *canonical version* of the relevant operators.

This disagrees with both Ji and Chen et al.

Similar arguments suggest thst the correct identification of the angular momentum operators for E and F are the *canonical* versions.

The gauge theory aspect will be discussed elsewhere.

Drell-Yan with an internal target at RHIC

Jen-Chieh Peng

University of Illinois at Urbana-Champaign

Abstract

After a brief historical review of the Drell-Yan Process (which was discovered at BNL 40 years ago), we present highlights of several dimuon experiments at Fermilab. The complementarity of the Drell-Yan process and the DIS as clean tools to probe parton distributions in nucleon and nuclei is emphasized. Recent results on the azimuthal angular distributions in p+p and p+d unpolarized Drell-Yan process have provided unique information on the size of the sea-quark Boer-Mulders functions. Dedicated polarized Drell-Yan experiments are being considered at RHIC, and we discuss the recent LOI proposing the use of internal gas target. The prospect of polarized Drell-Yan experiments in addressing some crucial unresolved issues in spin physics is also presented.

Physics results from Fermilab dimuon experiments

1) Drell - Yan process :

- Antiquarks in nuclei and nucleons
- Quark energy loss in nuclear medium
- Drell-Yan angular distributions

2) Quarkonium production :

- Pronounced nuclear dependence
- Production mechnism and polarizations
- Gluon distributions in the nucleons

3) Heavy quark production :

- Open charm production
- B-meson production

Transversity and Transverse Momentum Dependent PDFs are also probed in Drell-Yan

) Boer-Mulders functions:

- Unpolarized Drell-Yan: $d\sigma_{DY} \propto h_1^{\perp}(x_q) h_1^{\perp}(x_{\bar{q}}) \cos(2\phi)$

) Sivers functions:

- Single transverse spin asymmetry in polarized Drell-Yan:

$A_N^{DY} \propto f_{1T}^{\perp}(x_q) f_{\bar{q}}(x_{\bar{q}})$

) Transversity distributions:

- Double transverse spin asymmetry in polarized Drell-Yan:

$A_{TT}^{DY} \propto h_1(x_q) h_1(x_{\bar{q}})$

Drell-Yan does not require knowledge of the fragmentation functions

T-odd TMDs are predicted to change sign from DIS to DY

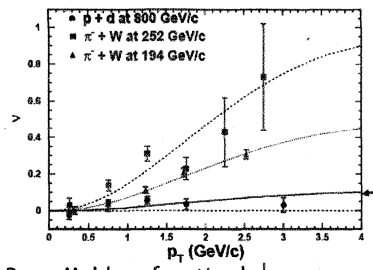
(Boer-Mulders and Sivers functions)

Remains to be tested experimentally!

18

Azimuthal cos2Φ Distribution in p+p and p+d Drell-Yan

E866 Collab., Lingyan Zhu et al.,
PRL 99 (2007) 082301; PRL 102 (2009) 182001



Small ν is observed for p+d and p+p D-Y

With Boer-Mulders function $h_1^{\perp}$:

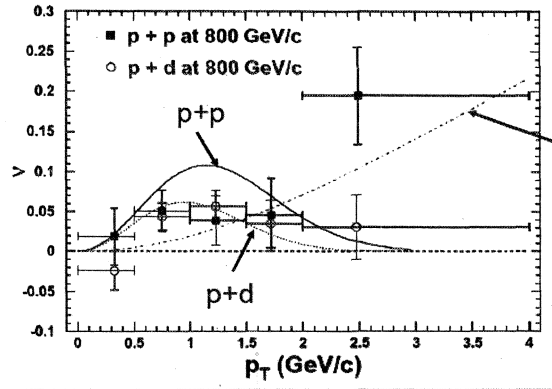
$\nu(\pi^- W \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(\pi)$] * [valence $h_1^{\perp}(p)$]

$\nu(pd \to \mu^+\mu^- X) \sim$ [valence $h_1^{\perp}(p)$] * [sea $h_1^{\perp}(p)$]

Sea-quark BM functions are much smaller than valence quarks

Results on cos2Φ Distribution in p+p Drell-Yan

L. Zhu, J.C. Peng, et al., PRL 102 (2009) 182001

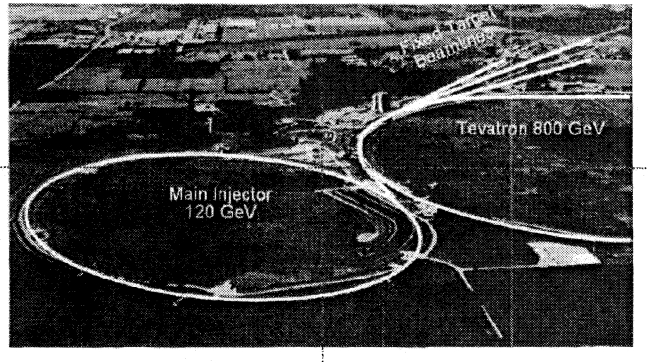


QCD
(Boer, Vogelsang; Berger, Qiu, Rodriguez-Pedraza)

Combined analysis of SIDIS and D-Y by Melis et al.

More data are anticipated from Fermilab E906

Fermilab E906 dimuon experiment (Geesaman, Reimer et
expected to run ~2010-2013)



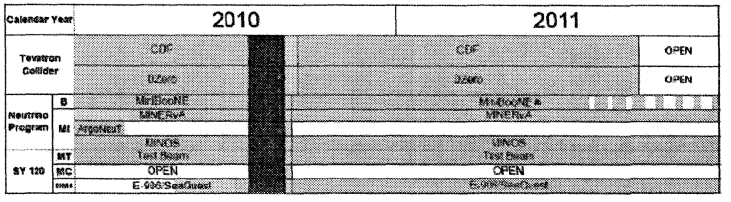
- Main goal is to measure the flavor asymmetry for the sea
- Boer-Mulders can also be studied

Experiment Schedule

http://www.fnal.gov/directorate/program_planning/schedule/index.html

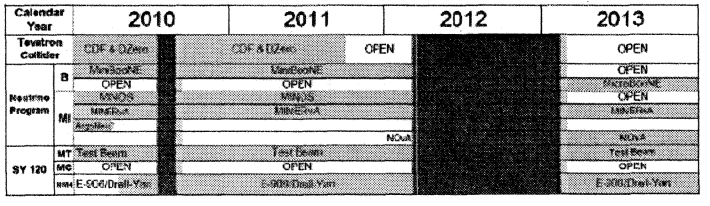
2010-2011 Fermilab Accelerator Experiments Schedule

This schedule will be updated regularly, as plans change.



Draft 2010-13 Fermilab Accelerator Experiments' Run Schedule

Typically Revised Annually - This Version from October, 2009



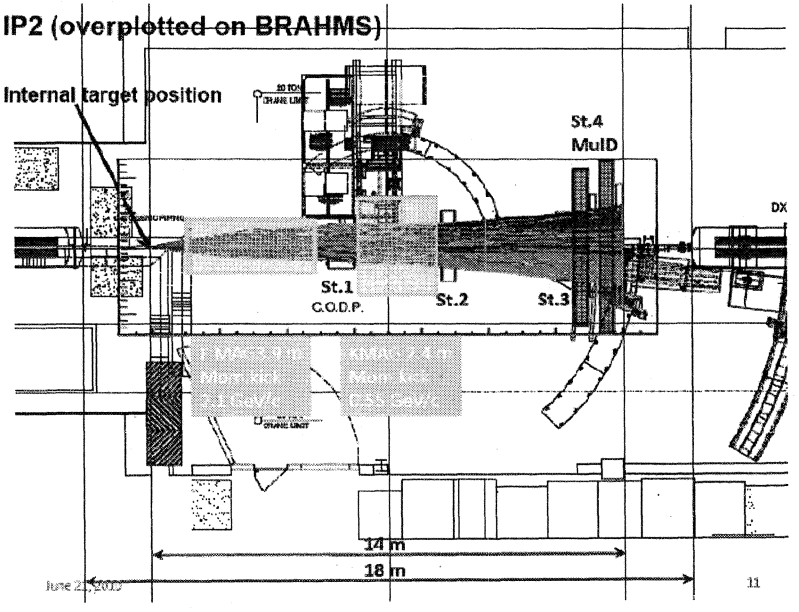
Letter of Intent

Measurement of Dimuons from Drell-Yan Process with Polarized Proton Beams and an Internal Target at RHIC

May 21, 2010

M. Brooks[4], A. Deshpande[6,7], N. Doshita[9], Y. Fukao[5], D. F. Geesaman[1], Y. Goto[5,6], M. Grosse Perdekamp[2], T. Iwata[9], X. Jiang[4], K. Kondo[9], G. Kunde[4], M. J. Leitch[4], M. X. Liu[4], P. L. McGaughey[4], Y. Miyachi[8,9], I. Nakagawa[5,6], K. Nakano[5,8], K. Okada[6], J.-C. Peng[2], P. E. Reimer[1], J. Rubin[1], N. Saito[3], S. Sawada[3], R. Seidl[6], T.-A. Shibata[8], and A. Taketani[5,6]

[1] *Argonne National Laboratory, Argonne, Illinois 60439, USA*
[2] *University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[3] *KEK, High Energy Accelerator Research Organization, Tsukuba, Ibaraki 305-0801, Japan*
[4] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[5] *RIKEN, Institute of Physical and Chemical Research, Wako, Saitama 351-0198, Japan*
[6] *RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[7] *Stony Brook University, SUNY, Stony Brook, New York 11794, USA*
[8] *Tokyo Institute of Technology, Tokyo 152-8551, Japan*
[9] *Yamagata University, Yamagata 990-8560, Japan*



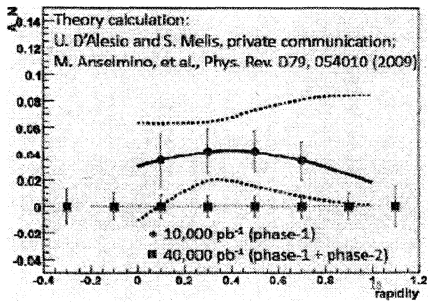
From Y. Goto

Experimental sensitivities

- Phase-1 (parasitic operation)
  - $L = 2 \times 10^{33}$ cm^{-2}s^{-1}
  - 10,000 pb^{-1} with 5×10^6 s ~ 8 weeks, or 3 years (10 weeks × 3) of beam time by considering efficiency and live time
- Phase-2 (dedicated operation)
  - $L = 3 \times 10^{34}$ cm^{-2}s^{-1}
  - 30,000 pb^{-1} with 10^6 s ~ 2 weeks, or 8 weeks of beam time by considering efficiency and live time

Measure not only the sign of the Sivers function but also the shape of the funcion

From Y. Goto

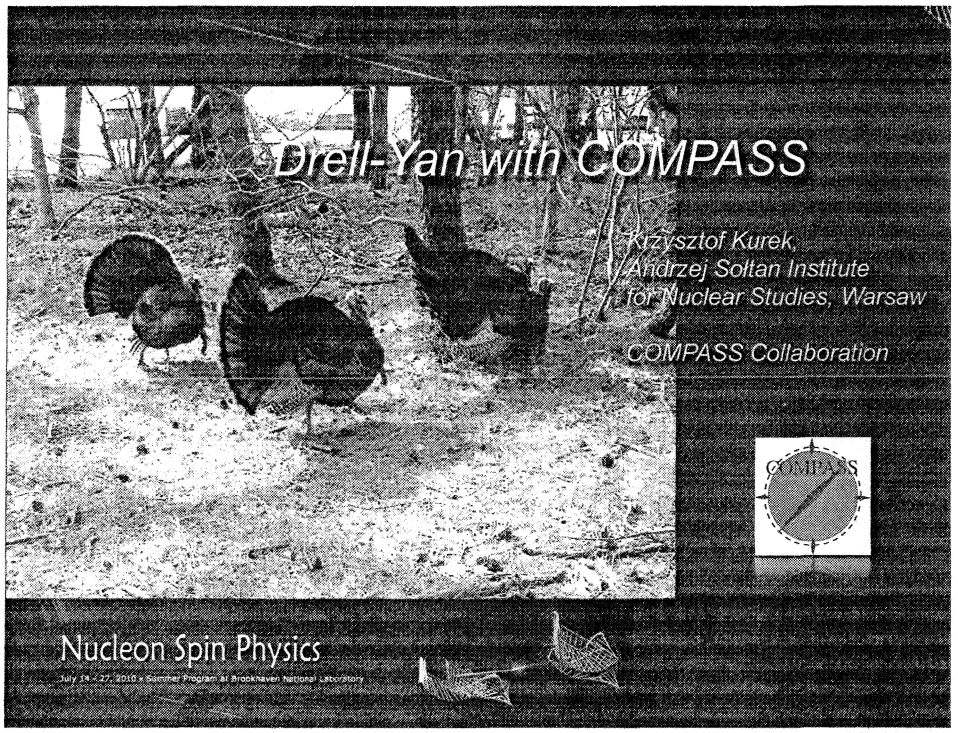


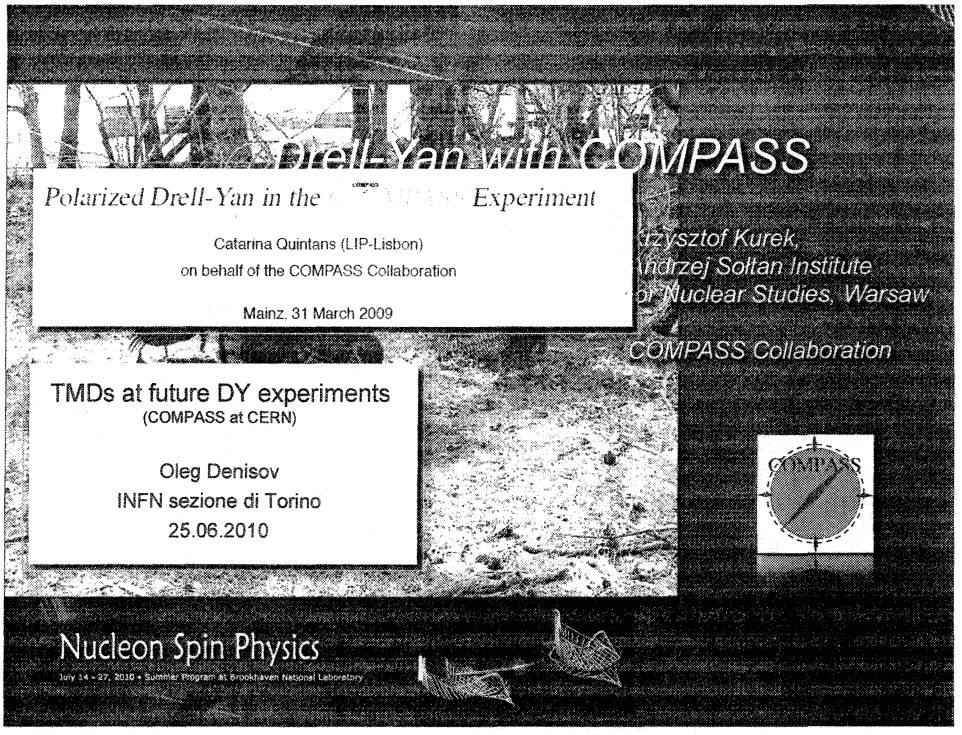
June 21, 2010

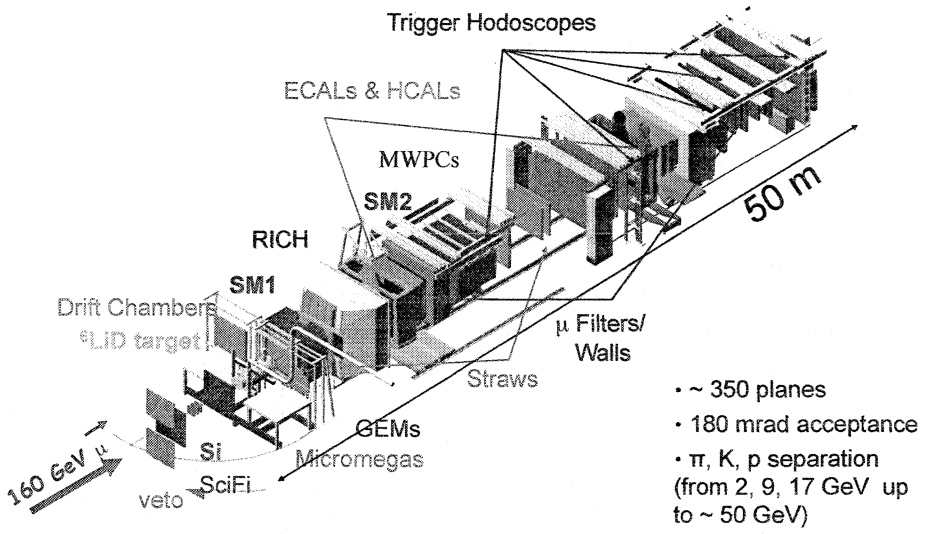
PAC recommends preparation of full proposal

Future prospect for Drell-Yan experiments

- Fermilab p+p, p+d, p+A
  - Unpolarized beam and target
- RHIC
  - Doubly and singly polarized p+p collision
- COMPASS
  - π-p and π-d with polarized targets
- FAIR
  - Polarized antiproton-proton collision
- J-PARC
  - Possibly polarized proton beam and target
- JINR
  - NICA with polarized target
- IHEP
  - SPASCHARM with polarized target p-p and π-p

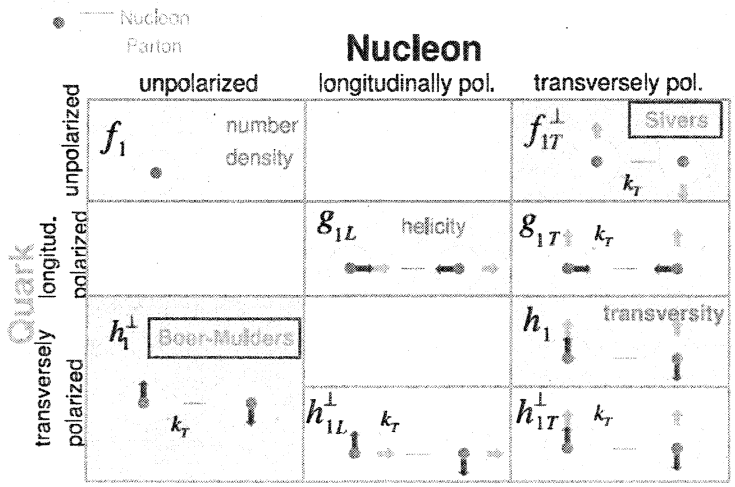

Drell-Yan with COMPASS
Krzysztof Kurek,
Andrzej Sołtan Institute
for Nuclear Studies, Warsaw
COMPASS Collaboration
COMPASS
Nucleon Spin Physics


Drell-Yan with COMPASS
Polarized Drell-Yan in the COMPASS Experiment
Catarina Quintans (LIP-Lisbon)
on behalf of the COMPASS Collaboration
Mainz, 31 March 2009
Krzysztof Kurek,
Andrzej Sołtan Institute
for Nuclear Studies, Warsaw
COMPASS Collaboration
TMDs at future DY experiments
(COMPASS at CERN)
Oleg Denisov
INFN sezione di Torino
25.06.2010
COMPASS
Nucleon Spin Physics



Contents

- Introduction - motivation
- Why DY@COMPASS?
- Beam test 2009
- Projections
- Summary



- $f_1(x, k_T^2)$: unpolarized. Integrated in k_T^2 gives the usual $f_1(x)$.
- $g_{1L}(x, k_T^2)$: longitudinally polarized. When integrated over k_T^2 it is the helicity function $g_1(x)$. From its 1st moment one can obtain $\Delta\Sigma = \Delta u + \Delta d + \Delta s$

  ↪COMPASS DIS and SIDIS results:
  PLB647(2007)8-17;
  PLB647(2007)330-340;
  PLB660(2008)458-465.
- $h_1(x, k_T^2)$: transversely polarized. When integrated over k_T^2 it survives, giving the transversity function $h_1(x)$.

  ↪COMPASS SIDIS results:
  PRL94(2005)202002;
  NPB765(2007)31-70;
  PLB673(2009)127-135.

Catalog of PDFs

- $f_{1T}^{\perp}(x, k_T^2)$: Sivers function. It describes the distortion of the probability distribution of a non-polarized quark when it is inside a transversely polarized nucleon.

  ↪COMPASS DIS results:
  PRL94(2005)202002;
  NPB765(2007)31-70;
  PLB673(2009)127-135.

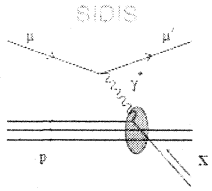
- $h_1^{\perp}(x, k_T^2)$: Boer-Mulders function. It describes the correlation between the transverse spin and the transverse momentum of a quark inside the unpolarized hadron.

- $h_{1T}^{\perp}(x, k_T^2)$: Pretzelosity function. It describes the transverse polarization of a quark, along its intrinsic k_T direction. It allows to access the orbital angular momentum information.

SIDIS versus DY

COMPASS accesses the Sivers PDF from semi-inclusive DIS (SIDIS). Another possible way to do it is via the Drell-Yan process (DY)

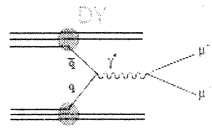
SIDIS



The physics asymmetry is given by the convolution of structure functions with fragmentation functions:

$$A_{Sivers} \propto \frac{\sum_q e_q^2 f_{1T}^{\perp(1)}(x) D_q^h(z)}{\sum_q e_q^2 f_1(x) D_q^h(z)}$$

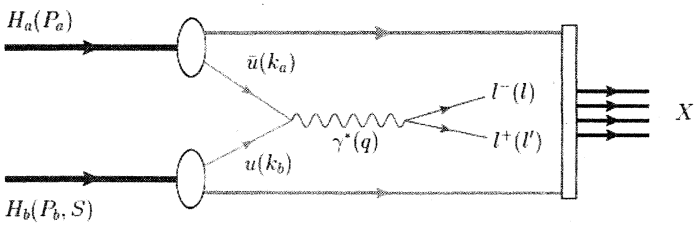
DY



The spin asymmetry is proportional to a product of structure functions. If unpolarized beam and transversely polarized target:

$$A_{Sivers} \propto 2\frac{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1T_q}^{\perp(1)}(x_2)}{\sum_q e_q^2 \bar{f}_{1q}(x_1) f_{1q}(x_2)}$$

DY kinematics



$P_{a(b)}$	the momentum of the beam (target) hadron.
$s = (P_a + P_b)^2$,	the total centre-of-mass energy squared.
$x_{a(b)} = q^2/(2P_{a(b)} \cdot q)$,	the momentum fraction carried by a parton from $H_{a(b)}$.
$x_F = x_a - x_b$,	the Feynman variable.
$M^2_{\mu\mu} = Q^2 = q^2 = s\ x_a\ x_b$,	the invariant mass squared of the dimuon.
$\mathbf{k}_{Ta(b)}$	the transverse component of the quark momentum.
$\mathbf{q}_T = \mathbf{P}_T = \mathbf{k}_{Ta} + \mathbf{k}_{Tb}$	the transverse component of the momentum of the virtual photon.

DY kinematics - transverse motion

- If we consider the transverse motion of partons then:

$$p_a = \frac{\sqrt{s}}{2} x_a \left(1 + \frac{k^2_{\perp a}}{x_a^2 s}, \frac{2k_{\perp a}}{x_a\sqrt{s}}, 1 + \frac{k^2_{\perp a}}{x_a^2 s}\right)$$

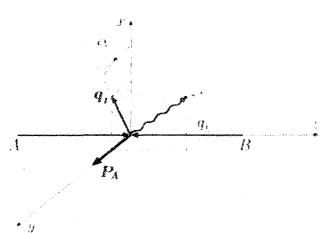
$$p_b = \frac{\sqrt{s}}{2} x_b \left(1 - \frac{k^2_{\perp b}}{x_b^2 s}, \frac{2k_{\perp b}}{x_b\sqrt{s}}, -1 + \frac{k^2_{\perp b}}{x_b^2 s}\right)$$

- ... and the γ^* (dilepton) momentum has a transverse component in the h.c.m. frame

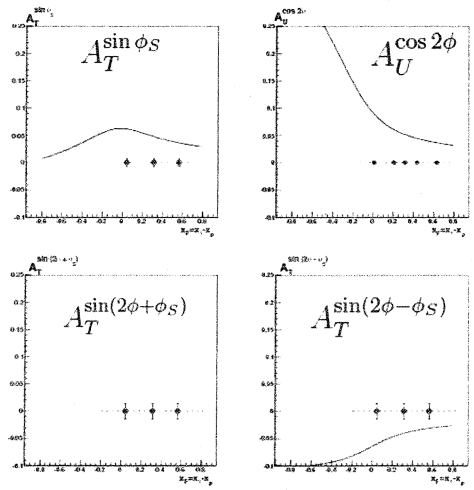
$$q = p_a + p_b = (q_0, \boldsymbol{q}_T, q_L)$$

$$\boldsymbol{q}_T = \boldsymbol{k}_{\perp a} + \boldsymbol{k}_{\perp b}$$

Only low q_T ($q_T^2 \ll q^2$)
have a non-perturbative origins



J/ψ region: $2.9 \leq M_{\mu\mu} \leq 3.2$ GeV/c^2

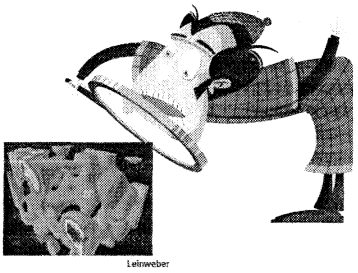


Summary

- Pion and, later, antiproton beams (50-200 GeV), Drell-Yan process dominated by the contribution from the valence quarks (both beam and target), $\tau = x_1 x_2 = Q^2/s \approx 0.05 \div 0.3$
- Solid state polarised targets, NH_3 and ^{6}LD, in case of hydrogen target – pure u-dominance
- Statistical error on single spin asymmetries is on the level 1÷2%
- Proposal has been submitted to the committee on May 17th

- Start date ≥ 2013

The Science of the Electron Ion Collider
(It's the *Glue* Stupid!)
& status, hopes and possible timelines....



BNL, July 2010
Spin Theory WS & Spin Fest

Abhay Deshpande
Stony Brook University

STONY BROOK UNIVERSITY

QCD

"Folks, we need to stop "testing" QCD and start <u>understanding</u> it"

Yuri Dokshitzer

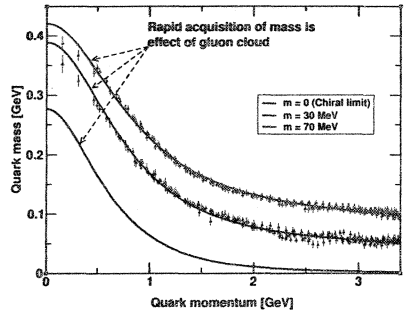
1998, ICHEP Vancouver, CA in his Summary Talk

2004 For the discovery of asymptotic freedom in QCD

Origin of Mass – Gluons in QCD

- Protons and neutrons form most of the mass of the visible universe
- 99% of the nucleon mass is due to self generated gluon fields
  - Similarity between p, n mass is a testimony to the fact that gluon dynamics is identical & overwhelmingly important
- Lattice QCD supports this

Higgs Mechanism, often credited with mass generation, is of no consequence



Many body dynamics of QCD

While there is no reason to doubt QCD, our level of understanding of QCD remains extremely unsatisfactory: both at low & high energy

- Do we understand the basic properties of hadrons such as mass and spin from the QCD degrees of freedom?
- What are the effective degrees of freedom at high energy?
- How do these degrees of freedom interact with each other and with other hard probes?
- What can we learn from them about confinement & universal features of the theory of QCD?

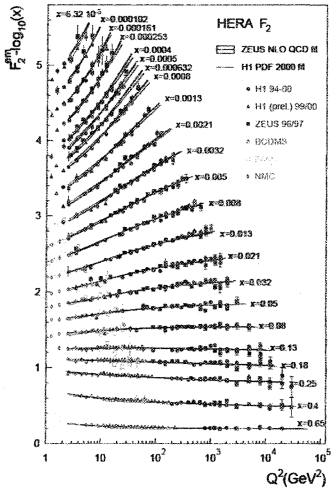
We are only beginning to explore the high energy many body dynamics of QCD

Overarching questions in QCD

- What are the phases of strongly interacting matter?
  - What roles do they play in the cosmos?
- What is the internal landscape of the nucleon?
- What does QCD predict for the properties of strongly interacting matter?
- What governs the transition from quarks & gluons in to meson & hadrons?
- What is the role of gluons and gluon self interactions in nucleons and nuclei?
- What determines the key features of QCD and what is their relation to the nature of gravity and space-time?

Gluons manifestly important in answering most of these questions!

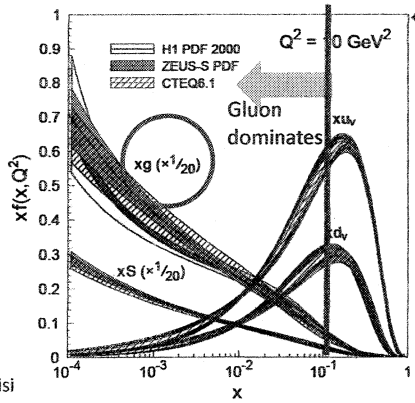
Measurement of Glue at HERA



- Scaling violations of $F_2(x,Q^2)$

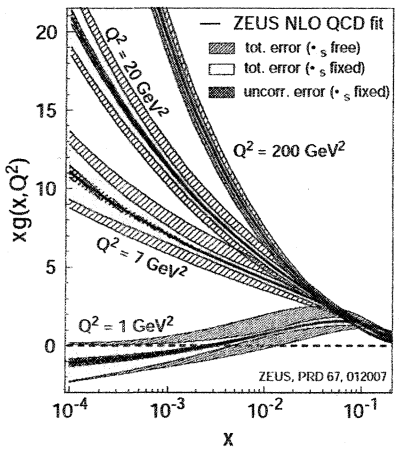
$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

- NLO pQCD analyses: fits with linear DGLAP* equations



*Dokshitzer, Gribov, Lipatov, Altarelli, Parisi

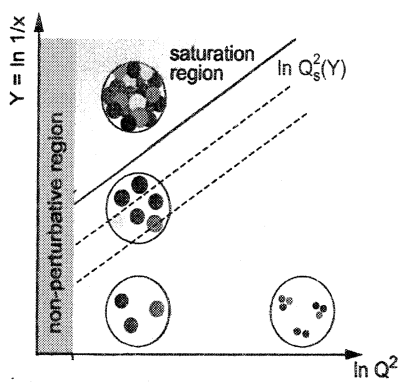
Gluon behavior at low x is it correct?



- **Indefinite rise: Infinite hadron-hadron cross section?**
  - Could this be an **artifact** of using of **linear** DGLAP in gluon extraction?
- **Negative g(x) at low Q^2 !**
- **Different from Sea quark distribution (g → q+qbar) !**
- **How would we find out?**
  - **Need theoretical development**
  - **Need experimental measurements at lower x!**

Low-x, higher twist & Color Glass Condensate

McLerran, Venugopalan... See Review: F. Gelis et al., , arXiv:1002.0333)



What is the effect of including **non-linear effects in DGLAP equation?** ➔
Small coupling, high gluon densities
→ **Color Glass Condensate**

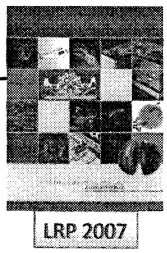
Saturation Scale $Q_s(x,Q^2,A)$

$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

No unambiguous experimental evidence yet, but many smoking guns

No higher energy e-p collider than HERA!
→ Nuclei, naturally enhance the densities of partonic matter
Why not use Nuclear DIS at high energy?

Spin of the Nucleon

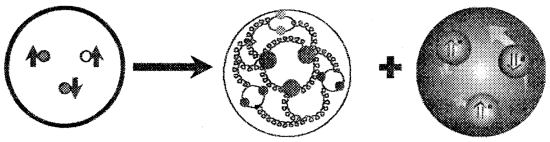


- Protons and neutrons are complex, dynamics objects composed of quarks and gluons: tightly bound by Strong Interactions. In spite of the complexity (& richness) spin of the nucleon is precisely ½ (in units of h/2π)

- Are we able to identify how this value arises from its constituents: quarks, gluons, their angular momenta?

- Can we reconstruct a 3D picture of a proton from the spin information we have?

Evolution of understanding of "Nucleon Spin"



1980s 1990/2000s

$$\frac{1}{2}\Delta\Sigma = \frac{1}{2}$$

$$J_G \neq \Delta G + L_G \qquad \frac{1}{2}\Delta\Sigma + \Delta G = \frac{1}{2}$$

$$\frac{1}{2}\Delta\Sigma + \Delta G + L_Q + L_G = \frac{1}{2}$$

$$J_Q + J_G = \frac{1}{2}\Delta\Sigma + L_Q + \Delta G + L_G = \frac{1}{2}$$

Hope: Towards the Next Long Range Plan

- **Focused workshops during FY10 establish and articulate the EIC science along with the facility design (around INT2010 Workshop)**
- After INT2010, a small steering committee oversees writing of a single, community wide White Paper laying out the full EIC science in broad compelling strokes followed by sufficient details of "golden experiments" –establish credibility. Complete White Paper Draft by FY11. Describe science program for full-energy and full-luminosity EIC, but with clear science deliverables for the Stage 1
- Spring 2011: **JLAB, BNL, EIC Collaboration, EICAC & DOE define a facility design down-select criteria and review mechanism.**
- Spring 2012: Down-select review, informed by latest R&D results on critical technologies and a fair bottoms-up cost estimate comparison for the designs
- Fall 2012: **Update White Paper with realizable EIC design, cost range, performance goals, science deliverables, upgrade paths, and prepare for the LRP 2013**

Summary

- A Strong Science Case for EIC:
  - Investigation of low-x (gluons in nuclei), and spin longitudinal and spatial distributions (3D tomography) of nucleons
  - Opportunities in EW and Beyond SM under investigation
- **The Collaboration & the Labs are moving towards realization:**
  - Machine R&D, detector design discussions, simulation studies
  - Physics case consistent with the technical design
  - Realistic cost estimation
- **Seek NSAC 2013 approval/recommendation for construction:** A unified QCD-community request for an EIC essential
- Any one of you interested in helping, contributing to the science or any other aspect of the project, is always welcome!

A DEDICATED DETECTOR FOR AN ELECTRON-ION COLLIDER

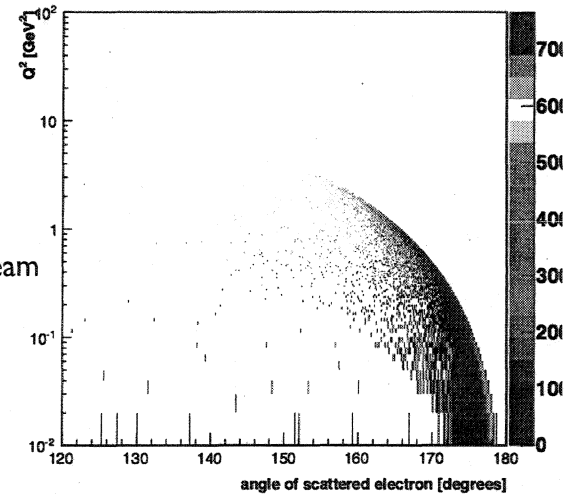
THOMAS BURTON

Plans for a future electron-ion collider (EIC) are underway at Brookhaven National Laboratory (BNL) in the form of the addition of an electron ring to the existing Relativistic Heavy Ion Collider (RHIC), termed eRHIC. An EIC would address wide-ranging physics questions in the fields of nucleon and nuclear structure and nucleon spin. A dedicated EIC detector would have to deliver the detection capabilities required to meet such diverse goals. This would involve measurments of inclusive, semi-inclusive and exclusive interactions covering a large span in Bjorken-x and Q^2. The detector must be capable of measuring such interactions over the wide range of beam energies proposed (electrons from 5 to 30 GeV, protons from 50 to 325 GeV, gold nuclei up to 130 GeV). Important features include electron detection at very forward angles to provide access to low Q^2, hadron identification over a wide range in momentum and detection of scattered protons and nuclear fragments close to the beam line. Beam luminosity monitors and polarimeters for spin measurements will also be required.

The BNL EIC taskforce is developing a design for such a dedicated detector. The design accommodates the requirements of the measurements outlined above, while paying close attention to issues of integration into the interaction point and the requirements of the accelerator. The current design includes tracking detectors close to the beams, nearly hermetic coverage with electromagnetic calorimetry and Cherenkov detectors for hadron identification and triggering on the scattered beam electron. The interaction point is offset from the centre of the detector due to the asymmetric momenta of the electron and hadron beams. A model of the detector has been implemented Geant 3 as part of ongoing studies into optimisation of its design. Monte Carlo simulations of some of the processes of interest used to guide design choices, and the current status of the detector design are presented.

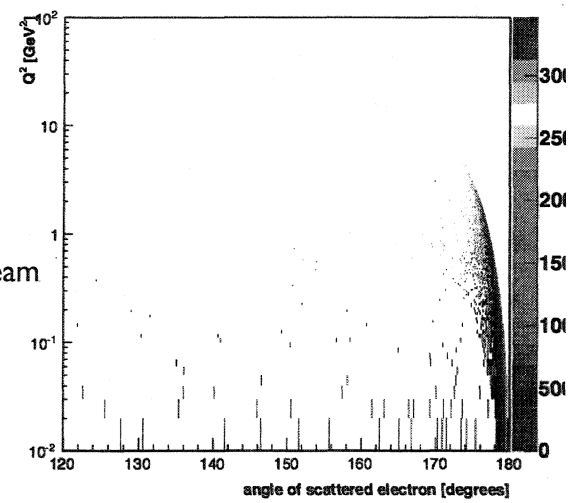
Q^2 reach : electron detection

- Independent of hadron beam energy
- **4 GeV** electron
- Electrons up to **~2°**



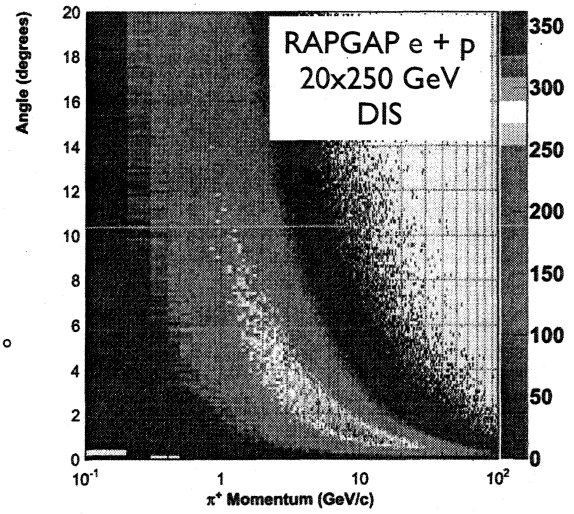
Q^2 reach : electron detection

- Independent of hadron beam energy
- **20 GeV** electron
- Electrons at **<1°**



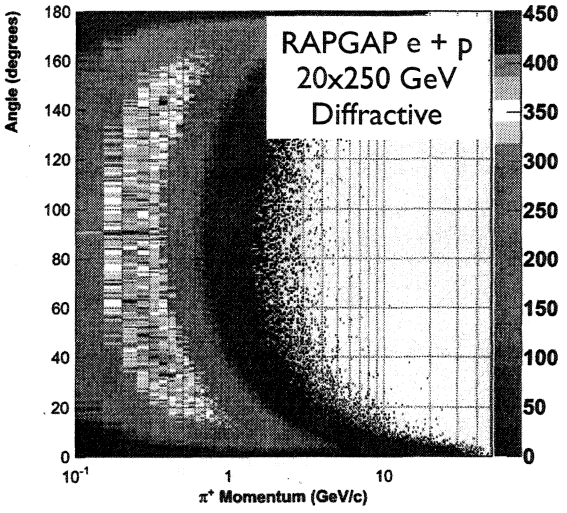
Hadron detection: DIS

- **Strongly** dependent on hadron beam energy:
  - **50 GeV:** π at several °
  - **250 GeV:** π < 4°
- **High** momentum

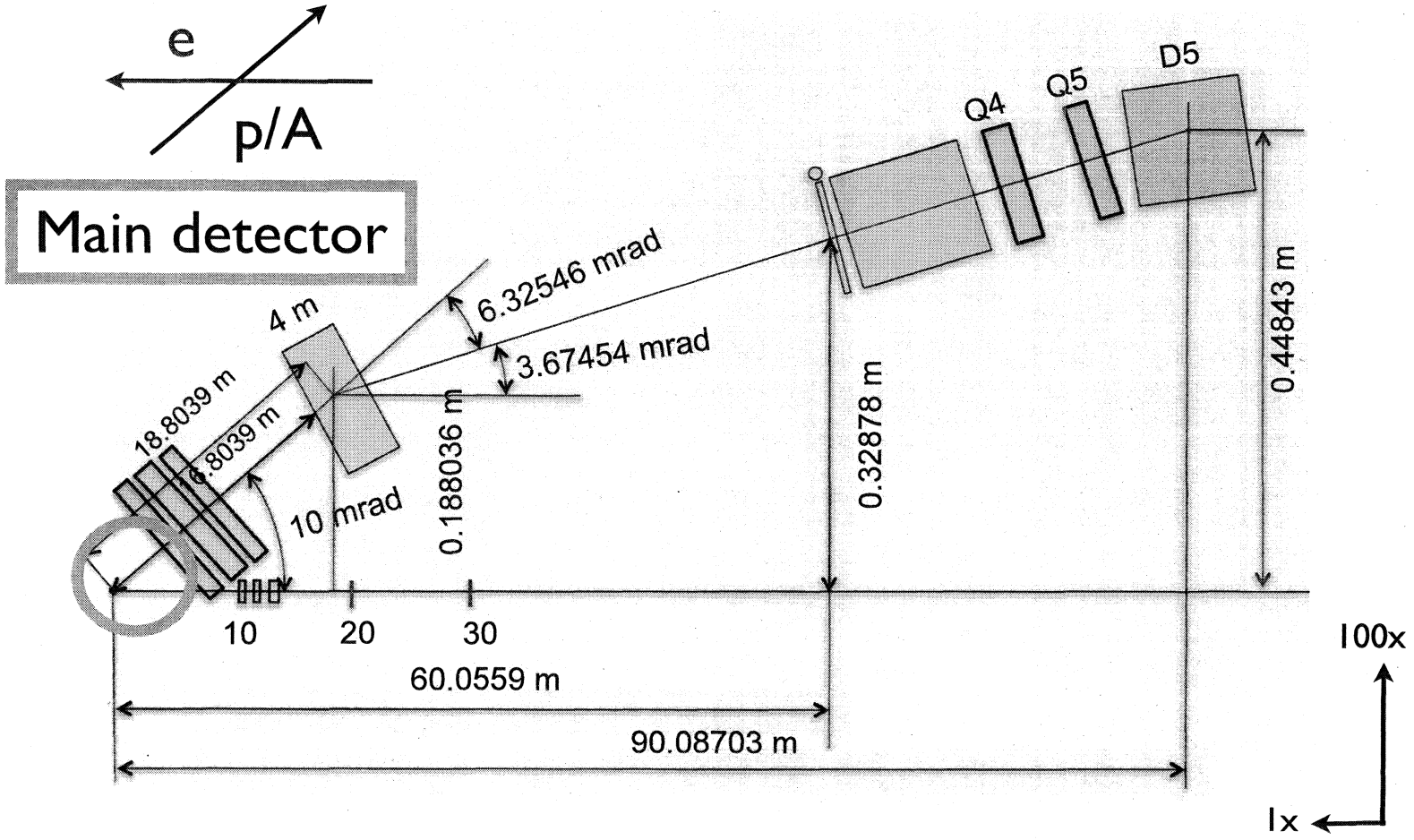


Hadron detection: diffractive

- **Little** energy-dependence
- Easy-to-detect angles
- Very **wide** angular range
- **Low** momentum



Interaction point layout



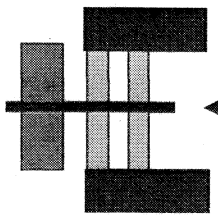
Detector design

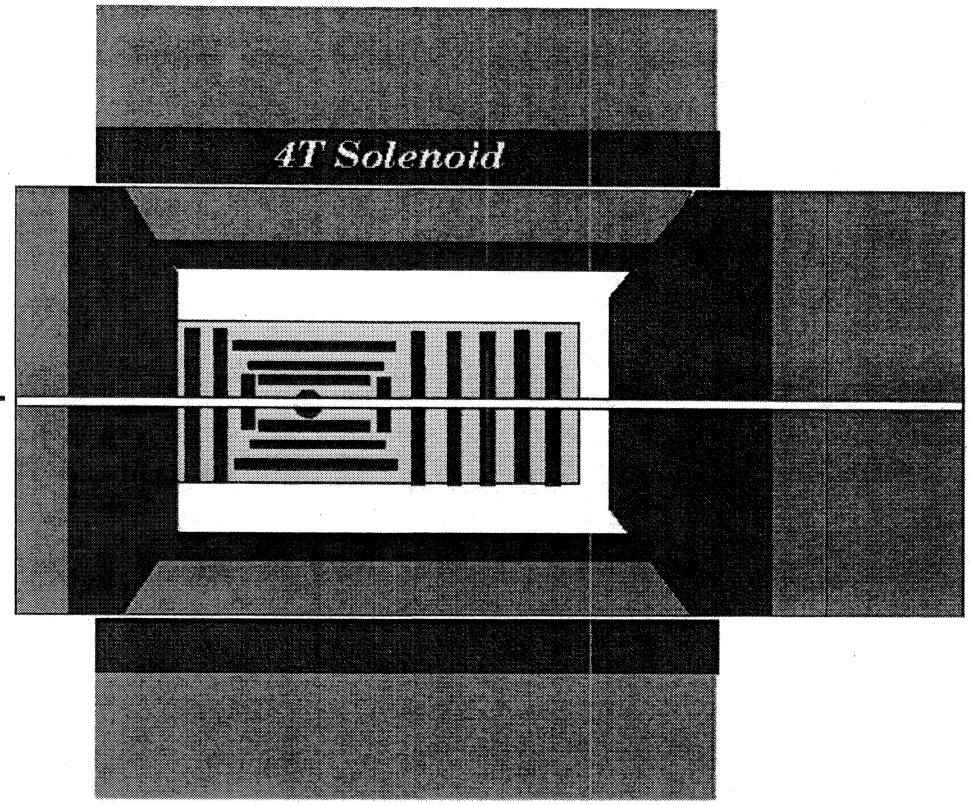
Energy:

e 5-30 GeV,

p 50-250(325) GeV

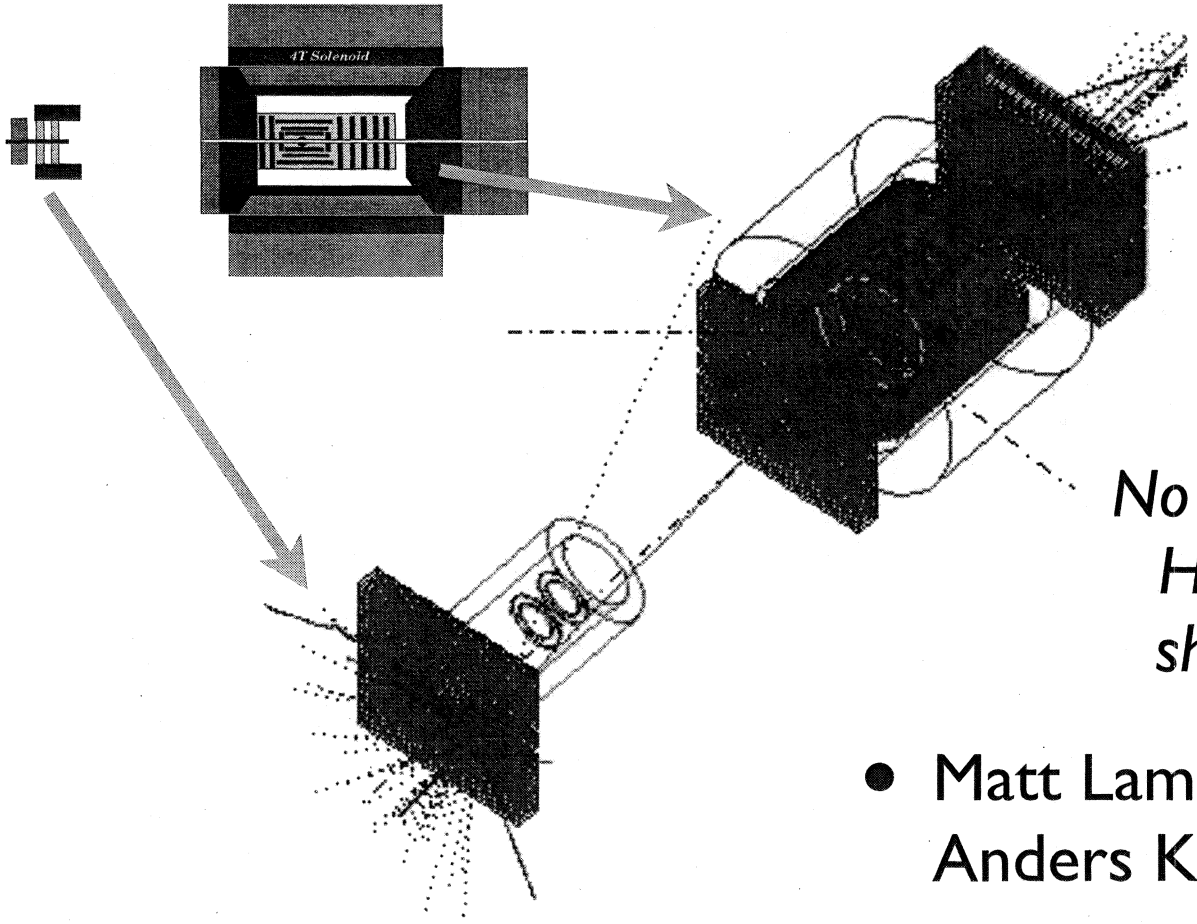
Au 100(130) GeV.





- Solenoid
- Hadronic Calorimeter
- EM–Calorimeter
- RICH
- High Threshold Cerenkov
- DIRC
- Tracking

First GEANT model



No barrel HCAL shown

- Matt Lamont and Anders Kirleis

Gauge- and frame-independent decomposition of nucleon spin

M. Wakamatsu

Department of Physics, Faculty of Science, Osaka University, Toyonaka, Osaka 560-0043, JAPAN

When discussing the spin structure of the nucleon, color gauge invariance is sometimes a nuisance. For instance, it is known that the polarized gluon distribution in the nucleon can be defined in terms of a nucleon matrix element of gauge invariant correlation function. On the other hand, one is also aware of the fact that there is no gauge-invariant local operator corresponding to the 1st moment of the polarized gluon distribution in the standard operator-product expansion. Undoubtedly, this seemingly conflicting observation has the common root as the familiar statement that there is no gauge-invariant decomposition of the gluon total angular momentum into its spin and orbital parts. Inspired by the recent proposal by Chen et al., we find it possible to make a gauge-invariant decomposition of covariant angular-momentum tensor of QCD in an arbitrary Lorentz frame. Making use of this fact, we could show that our decomposition of the nucleon spin is not only gauge-invariant but also practically frame-independent. We have also succeeded to convince that each piece of our nucleon spin decomposition just corresponds to the observable extracted through combined analyses of the GPD measurements and the polarized DIS measurements. (This is not true for our another gauge-invariant decomposition, which is shown to reduce to any of the Chen decomposition, the Bashinsky-Jaffe one, and the Jaffe-Manohar one, after an appropriate gauge-fixing.) In particular, the gluon spin part of our decomposition precisely coincides with the 1st moment of the polarized gluon distribution function. In our theoretical framework, this gluon spin part of the decomposition is given as a nucleon matrix element of gauge-invariant operator. However, since this operator is generally nonlocal, there is no conflict with the knowledge of the standard operator-product expansion. In this way, we now have a completely satisfactory theoretical basis for the gauge- and frame-independent decomposition of the nucleon spin.

From a practical viewpoint, an important lesson to be learned from our present theoretical consideration is that the quark orbital angular momentum extracted from the combined analysis of GPDs and polarized PDFs is the *dynamical* quark orbital angular momentum $\langle \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A}) \rangle$ not the *canonical* one $\langle \boldsymbol{x} \times \boldsymbol{p} \rangle$ or its non-trivial *gauge-invariant generalization* $\langle \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A}_{pure}) \rangle$. Even though the latter does not correspond to any directly measurable quantity, one should keep in mind the existence of two kinds of quark orbital angular momentum, which also means the existence of two kinds of gluon orbital angular momentum.

References

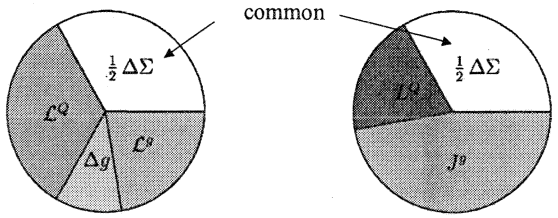
[1] M. Wakamatsu, Phys. Rev. D **81**, 114010 (2010).

[2] M. Wakamatsu, arXiv : 1007.5355 [hep-ph].

Two popular decompositions of the nucleon spin

Jaffe-Manohar | **Ji**

common



$$\begin{aligned} \boldsymbol{J}_{QCD} &= \int \psi^\dagger \frac{1}{2}\boldsymbol{\Sigma}\,\psi\, d^3x \\ &+ \int \psi^\dagger\, \boldsymbol{x} \times \frac{1}{i}\nabla\,\psi\, d^3x \\ &+ \int \boldsymbol{E}^a \times \boldsymbol{A}^a\, d^3x \\ &+ \int E^{ai}\, \boldsymbol{x} \times \nabla A^{ai}\, d^3x \end{aligned}$$

$$\begin{aligned} \boldsymbol{J}_{QCD} &= \int \psi^\dagger \frac{1}{2}\boldsymbol{\Sigma}\,\psi\, d^3x \\ &+ \int \psi^\dagger\, \boldsymbol{x} \times \frac{1}{i}\boldsymbol{D}\,\psi\, d^3x \\ &+ \int \boldsymbol{x} \times (\boldsymbol{E}^a \times \boldsymbol{B}^a)\, d^3x \end{aligned}$$

Each term is not separately gauge-invariant ! No further decomposition of $\boldsymbol{J}^g$!

In a recent paper (M.W., Phys. Rev. D81 (2010) 114010), we have shown that the way of gauge-invariant decomposition of nucleon spin is not necessarily unique, and proposed another gauge-invariant decomposition :

$$\boldsymbol{J}_{QCD} = \boldsymbol{S}^q + \boldsymbol{L}^q + \boldsymbol{S}^g + \boldsymbol{L}^g$$

where

$$\begin{aligned} \boldsymbol{S}^q &= \int \psi^\dagger \frac{1}{2}\boldsymbol{\Sigma}\,\psi\, d^3x \\ \boldsymbol{L}^q &= \int \psi\, \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A})\,\psi\, d^3x \\ \boldsymbol{S}^g &= \int \boldsymbol{E}^a \times \boldsymbol{A}^a_{phys}\, d^3x \\ \boldsymbol{L}^g &= \int E^{aj}\,(\boldsymbol{x} \times \nabla)\, A^{aj}_{phys}\, d^3x + \boxed{\int \rho^a\,(\boldsymbol{x} \times \boldsymbol{A}^a_{phys})\, d^3x} \end{aligned}$$

- The quark part of our decomposition is common with the Ji decomposition.
- The quark and gluon intrinsic spin parts are common with the Chen decomp.
- A crucial difference with the Chen decomp. appears in the orbital parts

$$\boldsymbol{L}^g - \boldsymbol{L}''^g = -(\boldsymbol{L}^q - \boldsymbol{L}''^q) = \int \rho^a\,(\boldsymbol{x} \times \boldsymbol{A}^a_{phys})\, d^3x$$

$$\equiv \text{"potential angular momentum"}$$

The QED correspondent of this term is the orbital angular momentum carried by electromagnetic field, appearing in the famous Feynman paradox in his textbook.

Using solely gauge-invariant nature of the potential angular momentum term

$$\int \rho^a \, \boldsymbol{x} \times \boldsymbol{A}^a_{phys} \, d^3x \;=\; g \int \psi^\dagger \, \boldsymbol{x} \times \boldsymbol{A}_{phys} \, \psi \, d^3x$$

one is free to include it into the quark OAM part, which leads to the Chen decomp.

$$\begin{aligned} & \boldsymbol{L}^q\,(\text{Ours}) \;+\; \text{potential angular momentum} \\ = & \int \psi^\dagger \, \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A}) \, \psi \, d^3x \;+\; g \int \psi^\dagger \, \boldsymbol{x} \times \boldsymbol{A}_{phys} \, \psi \, d^3x \\ = & \int \psi^\dagger \, \boldsymbol{x} \times (\boldsymbol{p} - g\,\boldsymbol{A}_{pure}) \, \psi \, d^3x \qquad = \quad \boldsymbol{L}''^q\,(\text{Chen}) \end{aligned}$$

We do not recommend Chen's decomposition, because the knowledge of standard electrodynamics tells us that the momentum appearing in the equation of motion with the Lorentz force is the so-called "dynamical momentum" $\boldsymbol{\Pi}$

$$\boldsymbol{\Pi} \;=\; \boldsymbol{p} - e\,\boldsymbol{A}, \qquad m\frac{d^2\boldsymbol{x}}{dt^2} \;=\; \frac{d\boldsymbol{\Pi}}{dt} \;=\; \boldsymbol{F}_{\text{Lorentz}}$$

with the full gauge field, not the "canonical momentum"

$$\boldsymbol{p}$$

or its nontrivial generalization

$$\boldsymbol{p} - e\,\boldsymbol{A}_{pure}$$

Because of the limitation of time, I skip here tedious intermediate steps and write down the final answer. We can show that (M.W., arXiv : 1007.5355 [hep-ph])

$$\begin{aligned} M^{\mu\nu\lambda} \;=\; & M^{\mu\nu\lambda}_{q-spin} \;+\; M^{\mu\nu\lambda}_{q-OAM} \;+\; M^{\mu\nu\lambda}_{g-spin} \;+\; M^{\mu\nu\lambda}_{g-OAM} \\ & +\; M^{\mu\nu\lambda}_{boost} \;+\; \text{total divergence} \end{aligned}$$

where

$$\begin{aligned} M^{\mu\nu\lambda}_{q-spin} \;&=\; \frac{1}{2}\epsilon^{\mu\nu\lambda\sigma}\,\bar{\psi}\,\gamma_\sigma\,\gamma_5\,\psi, \\ M^{\mu\nu\lambda}_{q-OAM} \;&=\; \bar{\psi}\,\gamma^\mu\,(\,x^\nu\,i\,D^\lambda \;-\; x^\lambda\,i\,D^\nu\,)\,\psi \end{aligned}$$

$$\begin{aligned} M^{\mu\nu\lambda}_{g-spin} \;&=\; 2\,\mathrm{Tr}\,[\,F^{\mu\lambda}\,A^\nu_{phys} \;-\; F^{\mu\nu}\,A^\lambda_{phys}\,], \\ M^{\mu\nu\lambda}_{g-OAM} \;&=\; -\,2\,\mathrm{Tr}\,[\,F^{\mu\alpha}\,(\,x^\nu\,D^\lambda_{pure} \;-\; x^\lambda\,D^\nu_{pure}\,)\,A^{phys}_\alpha\,], \\ & \quad +\,2\,\mathrm{Tr}\,[\,(\,D_\alpha\,F^{\alpha\mu}\,)\,(\,x^\nu\,A^\lambda_{phys} \;-\; x^\lambda\,A^\nu_{phys}\,)\,], \end{aligned}$$

$$M^{\mu\nu\lambda}_{boost} \;=\; -\frac{1}{2}\,\mathrm{Tr}\,F^2\,(\,x^\nu\,g^{\mu\lambda} \;-\; x^\lambda\,g^{\mu\nu}\,)$$

3. Frame-independence of our nucleon spin decomposition

nucleon spin sum rule

$$\langle P,s\,|\,M^{012}\,|\,P,s\rangle\,/\,\langle P,s\,|\,P,s\rangle \;=\; \frac{1}{2} \quad : \quad \text{equal-time quantization}$$

$$\langle P,s\,|\,M^{+12}\,|\,P,s\rangle\,/\,\langle P,s\,|\,P,s\rangle \;=\; \frac{1}{2} \quad : \quad \text{light-cone quantization}$$

or, alternatively

$$\langle P,s\,|\,W^{\mu}s_{\mu}\,|\,P,s\rangle\,/\,\langle P,s\,|\,P,s\rangle \;=\; \frac{1}{2}$$

where

$$W^{\mu} \;=\; -\frac{1}{2\sqrt{P^2}}\,\epsilon^{\mu\alpha\beta\gamma}\,J_{\alpha\beta}\,P_{\gamma} \quad \text{with} \quad J^{\alpha\beta} \;=\; M^{0\alpha\beta}$$

is the Pauli-Lubansky vector such that

$$W^{\mu}s_{\mu} \;=\; \boldsymbol{J}\cdot\hat{\boldsymbol{P}} \;=\; \boldsymbol{J}\cdot\boldsymbol{P}\,/|\boldsymbol{P}| \quad : \quad \text{helicity operator}$$

We need nucleon forward matrix element of $M^{\mu\nu\lambda}$

(D) gluon OAM part : $M^{\mu\nu\lambda}_{g-OAM}$

Although we shall omit the detail, the forward matrix element of this part can be obtained just in the same way as the quark-OAM part.

$$\langle P,s\,|\,M^{\mu\nu\lambda}_{g-OAM}(0)\,|\,P,s\rangle \;=\; \frac{B_g(0)}{2\,M}\,P^{\{\mu}\,\epsilon^{\lambda\}\nu\alpha\beta}\,s_{\alpha}\,P_{\beta} \;-\; (\,\nu\leftrightarrow\lambda\,)$$
$$-\;\; 2\,M\,\Delta g\;\epsilon^{\mu\nu\lambda\sigma}\,s_{\sigma}$$

The key identity for obtaining this result is

$$M^{\mu\nu\lambda}_{g} \;-\; \text{boost} \;=\; M^{\mu\nu\lambda}_{g-spin} \;+\; M^{\mu\nu\lambda}_{g-OAM}$$
$$+\;\; \text{total divergence}$$

To sum up, we arrive at the following answer for nucleon spin decomposition

$$M^{\mu\nu\lambda} = M^{\mu\nu\lambda}_{q-spin} + M^{\mu\nu\lambda}_{q-OAM} + M^{\mu\nu\lambda}_{g-spin} + M^{\mu\nu\lambda}_{g-OAM} + M^{\mu\nu\lambda}_{boost}$$

with

$$\begin{aligned}
\langle P,s\,|\,M^{\mu\nu\lambda}_{q-spin}(0)\,|\,P,s\rangle &= M\,\Delta q\;\epsilon^{\mu\nu\lambda\sigma}\,s_\sigma, \\
\langle P,s\,|\,M^{\mu\nu\lambda}_{q-OAM}(0)\,|\,P,s\rangle &= \frac{B_q(0)}{2\,M}\,P^{\{\mu}\,\epsilon^{\lambda\}\nu\alpha\beta}\,s_\alpha\,P_\beta \;-\; (\nu\leftrightarrow\lambda) \\
&\quad -\; M\,\Delta q\;\epsilon^{\mu\nu\lambda\sigma}\,s_\sigma,
\end{aligned}$$

$$\begin{aligned}
\langle P,s\,|\,M^{\mu\nu\lambda}_{g-spin}(0)\,|\,P,s\rangle &= 2\,M\,\Delta g\;\epsilon^{\mu\nu\lambda\sigma}\,s_\sigma, \\
\langle P,s\,|\,M^{\mu\nu\lambda}_{g-OAM}(0)\,|\,P,s\rangle &= \frac{B_g(0)}{2\,M}\,P^{\{\mu}\,\epsilon^{\lambda\}\nu\alpha\beta}\,s_\alpha\,P_\beta \;-\; (\nu\leftrightarrow\lambda) \\
&\quad -\; 2\,M\,\Delta g\;\epsilon^{\mu\nu\lambda\sigma}\,s_\sigma
\end{aligned}$$

- gauge-invariant and Lorentz-covariant decomposition of QCD AM tensor -

One sees that this precisely takes the same form as our Δg term

$$\begin{aligned}
\Delta g &= \langle P,s\,|\,M^{+12}_{g-spin}(0)\,|\,P,s\rangle\,/\,2\,P^+ \\
&= \langle P,s\,|\,2\,\mathrm{Tr}\,[\,F^{+\lambda}\,\epsilon^{+-}{}_{\lambda}{}^{\chi}\,A^{phys}_{\lambda}\,]\,|\,P,s\rangle\,/\,2\,P^+
\end{aligned}$$

- That is, the gluon spin part in our gauge-invariant decomposition precisely reduces to the 1st moment of polarized gluon distribution accessed by high-energy DIS measurement.
- We have pointed out that there is no gauge-invariant local operator corresponding to the 1st moment of the polarized gluon distribution in the standard OPE.
- However, it should be clear by now that there is no conflict between this statement and our finding.
- The decomposition of the gauge field A_χ into its physical and pure-gauge part is generally a nonlocal operation so that A^{phys}_χ is not a local operator.

- Inspired by the recent proposal by Chen et al., we find it possible to make a gauge-invariant decomposition of covariant angular-momentum tensor of QCD in an arbitrary Lorentz frame.

- Making use of this fact, we could show that our decomposition of nucleon spin is not only gauge-invariant but also practically frame-independent.

- We have also succeeded to convince that each piece of our nucleon spin decomposition precisely corresponds to the observables that can be extracted through combined analysis of the GPD measurements and the polarized DIS measurement, thereby supporting the standardly-accepted experimental project aiming at complete decomposition of the nucleon spin.

See, for the detail

- M. Wakamatsu, arXiv : 1007.5355 [hep-ph]

- A practically very important lesson learned from our theoretical consideration is that the quark OAM extracted from the combined analysis of GPD and polarized PDF is the "dynamical OAM (or mechanical OAM)"

$$\langle \boldsymbol{x} \times (\boldsymbol{p} - g\boldsymbol{A}) \rangle$$

not the "canonical OAM"

$$\langle \boldsymbol{x} \times \boldsymbol{p} \rangle$$

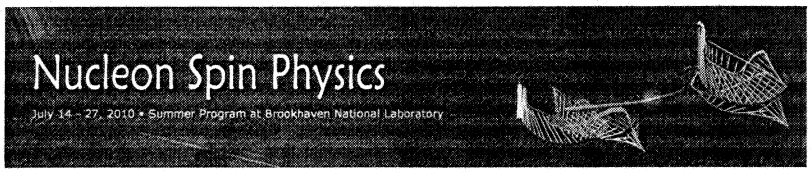
- At the moment, we do not know any means, with which we can extract the canonical OAM purely experimentally, i.e. model independently.

$$\Downarrow$$

Still, one should keep in mind the existence of 2 kinds of quark OAM !

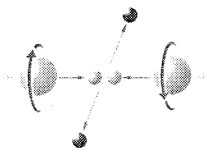
[Naturally, this also means the existence of 2 kinds of gluon OAM !]

Transverse spin and momentum correlation in QCD



23 July 2010

Brookhaven National Lab



Leonard Gamberg
Penn State University

w/ Marc Schlegel, Zhongbo Kang,
Piet Mulders, Asmita Mukherjee

Outline

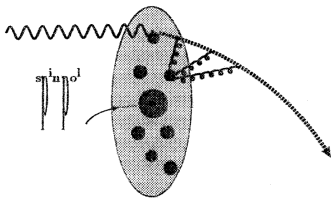
- **Transverse structure spin Effects in TSSAs**
- **Gauge links-Color Gauge Inv.-"T-odd" TMDs**
- **T-odd PDFs via FSIs Summing the gauge link**

"QCD calc " FSIs Gauge Links-Color Gauge Inv. "T-odd" TMDs

"Pheno" -Transverse Structure TMDs and TSSAs-**b** and **k** asymm

An improved dynamical approach for FSIs & model building

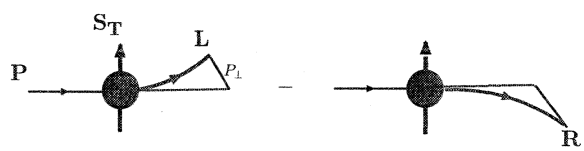
$f_{1T}^{\perp}(x, \mathbf{k}_{\perp}^2)$



- Generalizing the Generalized Parton Model through color gauge invariance, with Zhongo Kang
- Universality proof for Collins Fragmentation function w/ Piet Mulders, Asmita Mukherjee ...

Transverse SPIN Observables SSA (TSSA) $P^{\uparrow}P \to \pi X$

- **Single Spin Asymmetry**

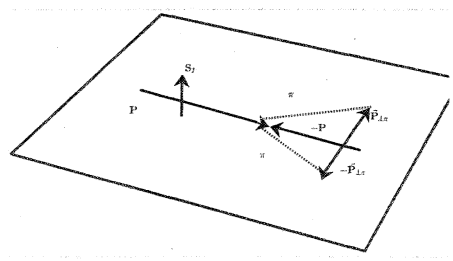


Parity Conserving interactions: SSAs Transverse Scattering plane

$$\Delta\sigma \sim iS_T \cdot (\mathbf{P} \times P_\perp^\pi)$$

- **Rotational invariance** $\sigma^{\downarrow}(x_F, p_\perp) = \sigma^{\uparrow}(x_F, -p_\perp)$
  $\Rightarrow$ ***Left-Right Asymmetry***

$$A_N = \frac{\sigma^{\uparrow}(x_F,p_\perp)-\sigma^{\uparrow}(x_F,-p_\perp)}{\sigma^{\uparrow}(x_F,p_\perp)+\sigma^{\uparrow}(x_F,-p_\perp)} \equiv \Delta\sigma$$

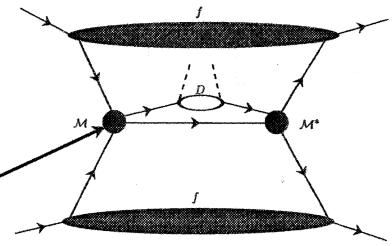


Transverse Polarization in Inclusive Reactions $P^{\uparrow}P \to \pi X$

e.g. Goldstein & Owens NPB 76

Transv. polarization cross section "interference" of helicity flip and non-flip amps.

quark-quark scattering



Elastic scattering of 2 quarks of different flavor

6 independent helicity Amps $M_{\lambda'_{q_1},\lambda'_{q_2};\lambda_{q_1},\lambda_{q_2}}$

$$M_{++,++} \equiv \Phi_1 \quad M_{--,++} \equiv \Phi_2 \quad M_{+-,+-} \equiv \Phi_3$$

$$M_{-+,+-} \equiv \Phi_4 \quad M_{-+,++} \equiv \Phi_5 \quad M_{++,+-} \equiv \Phi_6$$

$$A_N = \frac{\hat{\sigma}^{\uparrow} - \hat{\sigma}^{\downarrow}}{\hat{\sigma}^{\uparrow} + \hat{\sigma}^{\downarrow}} \sim \mathrm{Im}\left[\Phi_6(\Phi_1 + \Phi_3)^* - \Phi_5(\Phi_2 - \Phi_4)^*\right]$$

Interference of helicity flip and non-flip amps

1) requires breaking of chiral symmetry m_q/E

2) phases require higher order corrections

Reaction Mechanism

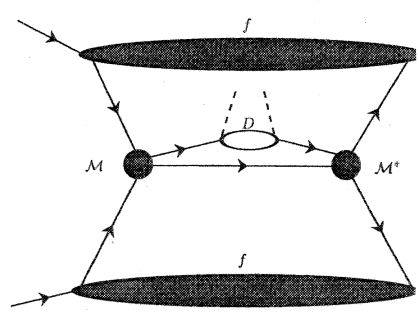
Collinear factorized QCD parton dynamics

$$\Delta\sigma^{pp^{\uparrow}\to\pi X} \sim f_a \otimes f_b \otimes \Delta\hat{\sigma} \otimes D^{q\to\pi}$$

$$\Delta\hat{\sigma} \equiv \hat{\sigma}^{\uparrow} - \hat{\sigma}^{\downarrow}$$

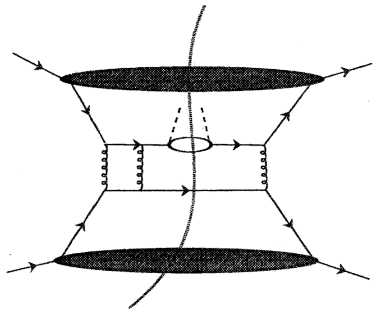
$$|\uparrow / \downarrow\rangle = (|+\rangle \pm i|-\rangle)$$

$$\hat{a}_N = \frac{\hat{\sigma}^{\uparrow} - \hat{\sigma}^{\downarrow}}{\hat{\sigma}^{\uparrow} + \hat{\sigma}^{\downarrow}} \sim \frac{\mathrm{Im}\left(\mathcal{M}^{+*}\mathcal{M}^{-}\right)}{|\mathcal{M}^{+}|^2 + |\mathcal{M}^{-}|^2}$$

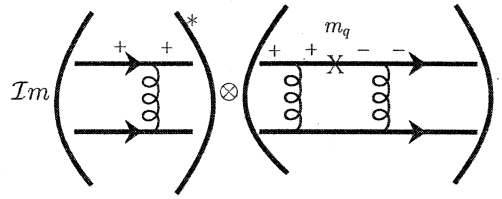


⋆ **TSSA requires relative phase btwn *different* helicity amps**

Factorization Theorem & SSAs at Partonic level



$\Delta\hat{\sigma} \sim \mathcal{I}m[M^*{}_+ M_-]$



- **Born amps are real -- need "loops"----> phases**
- **QCD interactions conserve helicity up to corrections** $\mathcal{O}\left(\frac{m_q}{E_q}\right)$

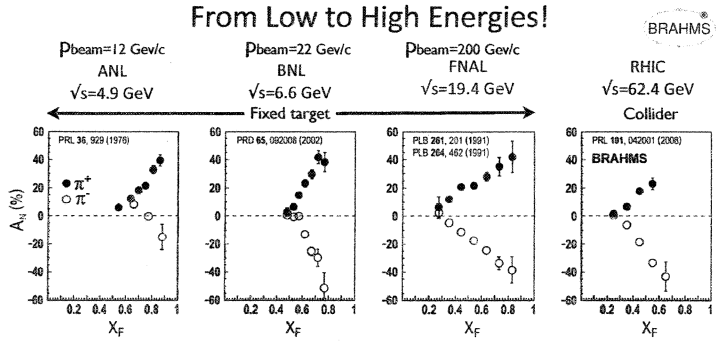
Twist three and trivial in chiral limit

$A_N \propto \frac{m_q}{E}\alpha_s$ at the partonic level

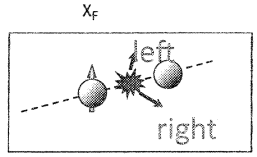
Kane & Repko, PRL: 1978

Large Transverse Polarization in Inclusive Reactions

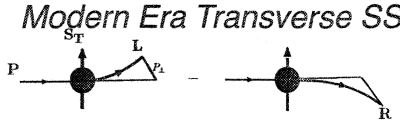
Transverse Single-Spin Asymmetries:
From Low to High Energies!

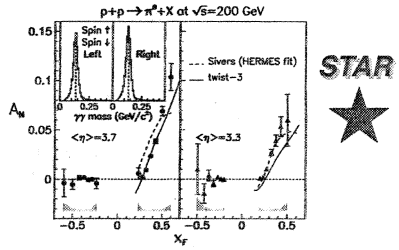


$x_F = 2p_{long}/\sqrt{s}$

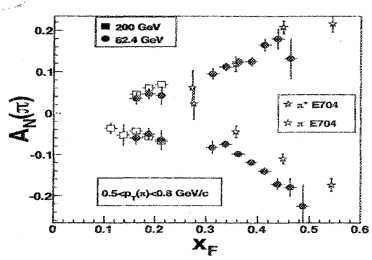


Modern Era Transverse SSA's at $\sqrt{s}$ = 62.4 & 200 GeV at RHIC

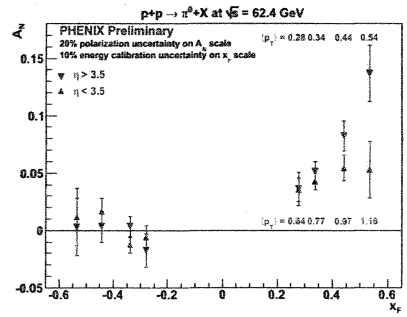




BRAHMS PRL101, 042001 (2008)



PHENIX



Talks of Les Bland and Matthias Perdekamp

QCD test-Λ Production $pp \to \Lambda^\uparrow X$

Partonic Model Test.....

$$P_\Lambda = \frac{\sigma^{pp\to\Lambda^\uparrow X} - \sigma^{pp\to\Lambda^\downarrow X}}{\sigma^{pp\to\Lambda^\uparrow X} + \sigma^{pp\to\Lambda^\downarrow X}}$$

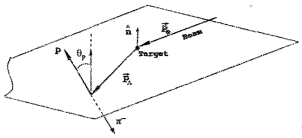


FIG. 1: Schematic diagram of inclusive Λ production and decay. The angle θ_p of the decay proton with respect to the normal $\hat{n}$ to the production plane is defined in the Λ rest frame.

Interference of loops and tree level Phases in *hard part* $\Delta\hat{\sigma}$

- **Need strange quark to polarize a Λ**

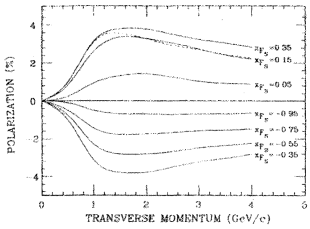


FIG. 4. Strange-quark polarization in the proton c.m. frame, $P_{c.m.}$ = 14 GeV/c(400-GeV beam), after the convolution for the initial state gluons. x_{F_s} is the Feynman x for the strange quark. Dashed curve corresponds to $P_{c.m.}$ = 30.6 GeV/c.

Dharmartna & Goldstein PRD 1990

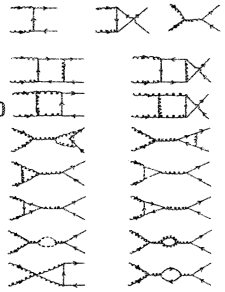


FIG. 1. Feynman diagrams for gluon fusion, $g+g\to s+\bar{s}$. In the second order, only the diagrams which contribute to the imaginary amplitude are shown.

Conclusions

- **Going beyond one loop in spectator framework transverse distortion of T-odd TMDs from FSIs as path ordered Gauge link, factorize into Lensing function times transverse distortion**
- *Approximate dynamical relation good for phenomenological approach for model builders*
- **Pheno-Transverse Structure TMDs and TSSAs *b* and *k* asymm. An improved dynamical approach for FSI & model building**

"QCD calc" FSIs Gauge Links-Color Gauge Inv. "T-odd" TMDs

- Generalize GPM?? w/ color
- Pink Elephant in the room is factorization and let alone universality
- Twist 3 and twist 2 approach connection...

RECENT ADVANCES IN THE STATISTICAL PARTON DISTRIBUTIONS

Jacques Soffer

Department of Physics, Temple University
Philadelphia, Pennsylvania 19122-6082, USA
E-mail: jacques.soffer@gmail.com

Abstract

A new set of parton distribution functions (PDF) was constructed in the framework of a statistical approach of the nucleon which has some characteristic features. For quarks (antiquarks), the building blocks are the helicity dependent distributions $q_\pm(x)$ ($\bar{q}_\pm(x)$) and we define $q(x) = q_+(x) + q_-(x)$ and $\Delta q(x) = q_+(x) - q_-(x)$ (similarly for antiquarks). At the initial energy scale taken at $Q_0^2 = 4\text{GeV}^2$, these distributions are given by the sum of two terms, a quasi Fermi-Dirac function and a helicity independent diffractive contribution, which leads to a universal behavior at very low x for all flavors. The flavor asymmetry for the light sea, *i.e.* $\bar{d}(x) > \bar{u}(x)$, observed in the data is built in. This is clearly understood in terms of the Pauli exclusion principle, based on the fact that the proton contains two u quarks and only one d quark. The chiral properties of QCD lead to strong relations between $q(x)$ and $\bar{q}(x)$. For example, it is found that the well estalished result $\Delta u(x) > 0$ implies $\Delta\bar{u}(x) > 0$ and similarly, $\Delta d(x) < 0$ leads to $\Delta\bar{d}(x) < 0$. Concerning the gluon, the unpolarized distribution $G(x, Q_0^2)$ is given in terms of a quasi Bose-Einstein function, with only *one free parameter*, and for simplicity, one assumes zero gluon polarization, *i.e.* $\Delta G(x, Q_0^2) = 0$, at the initial energy scale Q_0^2. All unpolarized and polarized light quark distributions depend upon *eight* free parameters, which were determined in 2002, from an NLO fit of a selected set of accurate DIS data. More recently, new tests against experimental (unpolarized and polarized) data turned out to be very satisfactory, in particular in hadronic reactions. The statistical approach has been extended to the interesting situation where the PDF have, in addition to the usual Bjorken x dependence, an explicit k_T transverse momentum dependence (TMD), assuming no x, k_T factorization and taking into account Melosh-Wigner effects. This is a very important topic, with a growing interest because it is now clear that several new phenomena are sensitive to TMD PDF.

References

C. Bourrely, F. Buccella, J. Soffer, Euro. Phys. J. **C23** (2002) 487.

C. Bourrely, F. Buccella, J. Soffer, Mod. Phys. Letters **A18** (2003) 771.

C. Bourrely, F. Buccella, J. Soffer, Euro. Phys. J. **C41** (2005) 327.

C. Bourrely, F. Buccella, J. Soffer, Mod. Phys. Letters **A21** (2006) 143.

C. Bourrely, F. Buccella, J. Soffer, Phys. Lett. **B648** (2007) 39.

C. Bourrely, F. Buccella, J. Soffer, Mod. Phys. Letters **A24** (2009) 1889.

C. Bourrely, F. Buccella, J. Soffer, (arXiv:1008.5322).

Nine free parameters

By performing a NLO QCD evolution of these PDF, we were able to obtain a good description of a large set of very precise data on $F_2^p(x,Q^2)$, $F_2^n(x,Q^2)$, $xF_3^{\nu N}(x,Q^2)$ and $g_1^{p,d,n}(x,Q^2)$, in correspondance with nine free parameters with some physical significance:

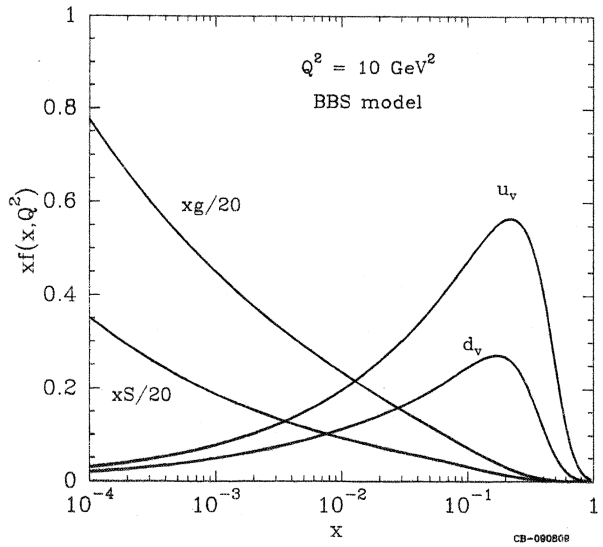
* the four potentials X_{0u}^+, X_{0u}^-, X_{0d}^-, X_{0d}^+,
* the universal temperature $\bar{x}$,
* and b, $\tilde{b}$, b_G, $\tilde{A}$.

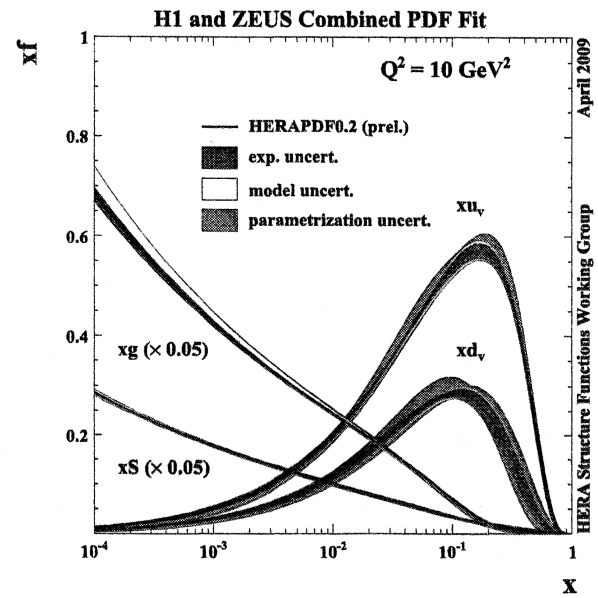
We also have three additional parameters, A, $\bar{A}$, A_G, which are fixed by 3 normalization conditions .

$$u - \bar{u} = 2, \quad d - \bar{d} = 1$$

and the momentum sum rule.

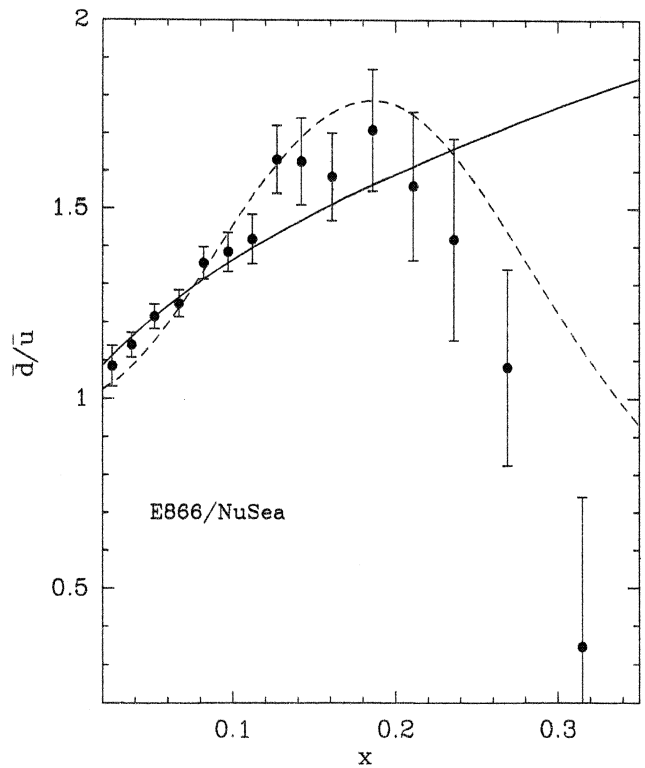
A global view of the unpolarized parton distributions



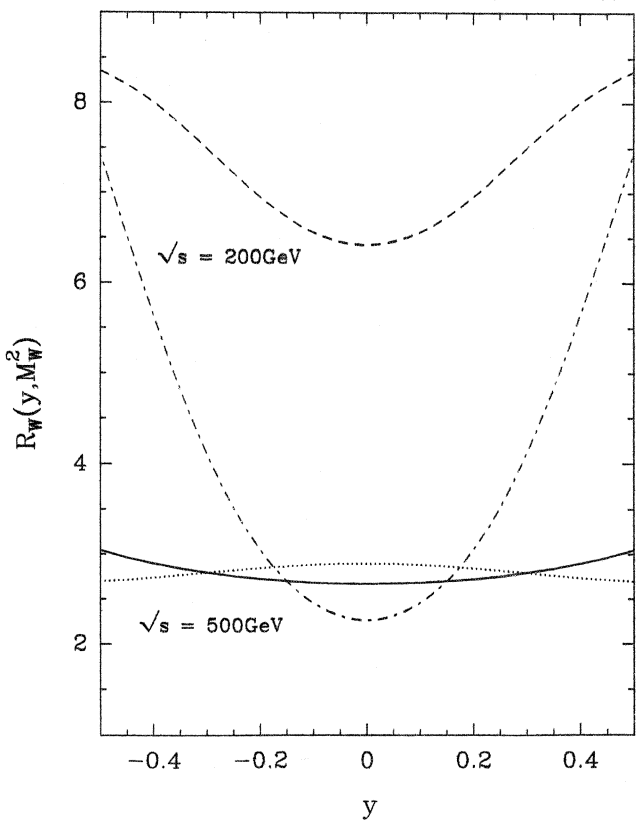


The important issue of $\bar{d}/\bar{u}$ at large x

$Q^2 = 54\text{GeV}^2$

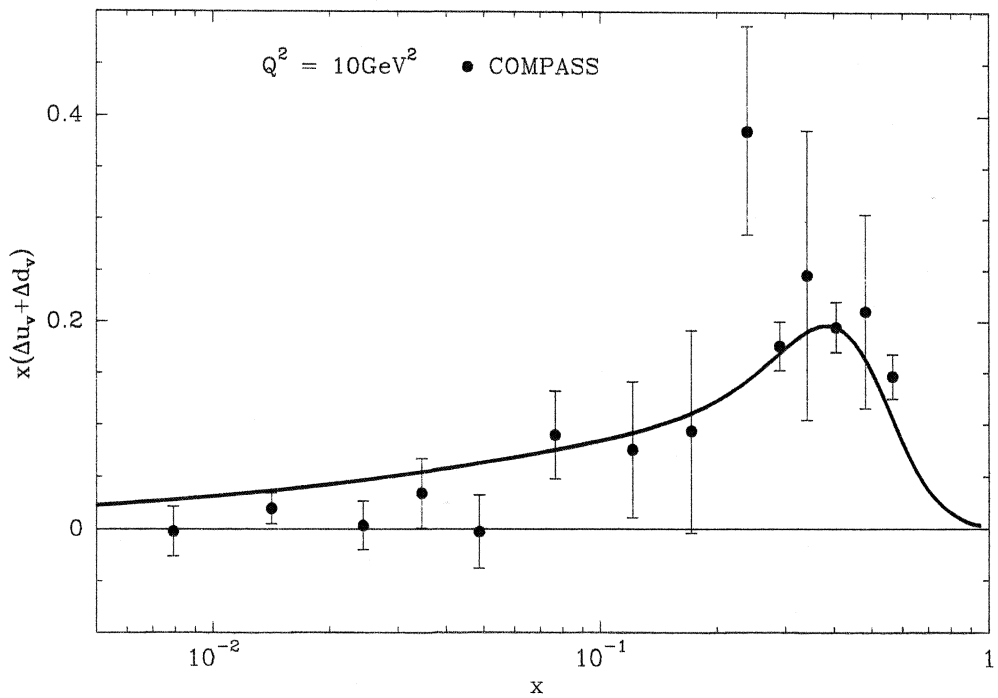


$R_W = (d\sigma_W^+/dy)/(d\sigma_W^-/dy) \quad Q^2 = M_W^2$



The valence quark helicity distributions versus x

From semi-inclusive DIS $\mu p \to \mu h^{\pm} X$ can determine the valence quark helicity distributions
Combined with g_1^d it leads to $\Delta\bar{u} + \Delta\bar{d} = 0.0 \pm 0.04 \pm 0.03$, *i.e.* non-symmetric polarized sea



– p. 28/44

(TMD) in the statistical approach

The quantum statistics distributions for quarks and antiquarks read in this case

$$xq^h(x,k_T^2) = \frac{F(x)}{\exp(x - X_{0q}^h)/\bar{x} + 1}\frac{1}{\exp(k_T^2/x\mu^2 - Y_{0q}^h) + 1},$$

$$x\bar{q}^h(x,k_T^2) = \frac{\bar{F}(x)}{\exp(x + X_{0q}^{-h})/\bar{x} + 1}\frac{1}{\exp(k_T^2/x\mu^2 + Y_{0q}^{-h}) + 1}, \qquad (1)$$

where

$$F(x) = \frac{Ax^{b-1}X_{0q}^h}{\ln(1+\exp Y_{0q}^h)\mu^2} = \frac{Ax^{b-1}}{k\mu^2},$$

because Y_{0q}^h are the thermodynamical potentials chosen such that $\ln(1+\exp Y_{0q}^h) = kX_{0q}^h$, in order to recover the factors X_{0q}^h, introduced earlier.
Similarly for $\bar{q}$ we have $\bar{F}(x) = \bar{A}x^{2b-1}/k\mu^2$. This determination of the 4 potentials Y_{0q}^h can be achieved with the choice $k = 3.05$ and they have the following values

$$Y_{0u}^+ = 1.122,\ Y_{0u}^- = 0.388,\ Y_{0d}^- = 0.409,\ Y_{0d}^+ = 0.010\,.$$

Finally μ^2 will be determined by the transverse energy sum rule and one finds $\mu^2 = 0.198\text{GeV}^2$.

Melosh-Wigner effects

The basic effect in a situation where $k_T \neq 0$ is the Melosh-Wigner rotation which mixes the components $q^{\pm}$ in the following way

$$q^{+\prime} = \cos^2\theta\, q^+ + \sin^2\theta\, q^- \quad \text{and} \quad q^{-\prime} = \cos^2\theta\, q^- + \sin^2\theta\, q^+$$

where $2\theta = \mathrm{Arctg}(\kappa k_T/xM)$ and κ is a dimensionless parameter.

Consequently $q = q^+ + q^-$ remains unchanged $q' = q$, whereas we have

$$\Delta q' = (\cos^2\theta - \sin^2\theta)\, \Delta q = \cos 2\theta\, \Delta q = \cos\, \mathrm{Arctg}(\kappa k_T/xM)\, \Delta q$$

So we finally get

$$\Delta q' = \frac{1}{\sqrt{1 + (\kappa k_T/xM)^2}}\, \Delta q$$

This effect which clearly vanishes at $k_T = 0$, was taken into account with $\kappa = 1.35$.

Conclusions

- A new set of PDF is constructed in the framework of a statistical approach of the nucleon.
- All unpolarized and polarized distributions depend upon nine free parameters, with some physical meaning.
- New tests against experimental (unpolarized and polarized) data on DIS, Semi-inclusive DIS and hadronic processes are very satisfactory.
- Good predictive power but some special features remain to be verified, specially in the high x region.
- Extension to TMD successful for SIDIS and must be tested, for example, in the p_T dependence of the DY cross section.

For practical use of our PDF see www.cpt.univ-mrs.fr/$\sim$ bourrely/research/bbs-dir/bbs.html

TMD Factorization and Small-x physics

Bo-Wen Xiao

Lawrence Berkeley National Laboratory

BNL Spin Workshop, July, 2010

Outline

K_t Factorization "expectation"

Non-Universality and k_t factorization violation
- Breaking down of the k_t factorization in di-hadron production
- Breaking down of the k_t factorization at small-x

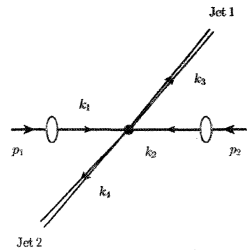
Non-Universality in CGC
- Di-hadron measurement at RHIC and theoretical interpretation
- Brief introduction to CGC
- Non-Universality in CGC

Conclusion

Di-hadron production in hadron-hadron collision

Consider the inclusive production of two high-transverse-momentum back-to-back particles in hadron-hadron collisions, i.e., in the process:

$$H_1 + H_2 \to H_3 + H_4 + X.$$



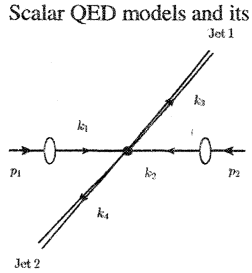
The standard k_t factorization "expectation" is:

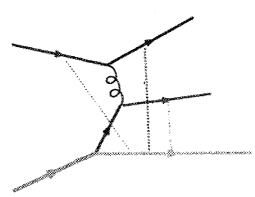
$$\boxed{E_3E_4\frac{d\sigma}{d^3p_3d^3p_4} = \sum\int d\hat{\sigma}_{i+j\to k+l+X}f_{i/1}f_{j/2}d_{3/k}d_{4/l}+\cdots}$$

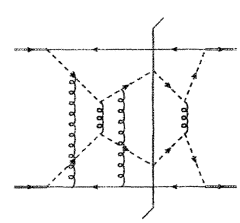
- Convolution of hard cross section $d\hat{\sigma}$ with TMD parton distribution function $f(x, k_\perp)$ and fragmentation function d.
- Only Drell-Yan process is proved for factorization in hadron-hadron collisions. *[Bodwin; 85, 86], [Collins, Soper, Sterman; 85, 88].*

Breaking down of the k_t factorization in di-hadron production

- *[Bacchetta, Bomhof, Mulders and Pijlman; 04-06]* Wilson lines approach
  Studies of Wilson-line operators show that the TMD parton distributions are not generally process-independent due to the complicated combinantion of initial and final state interactions. TMD PDFs admit process dependent Wilson lines.
- *[Collins, Qiu; 07], [Collins; 07], [Vogelsang, Yuan; 07] and [Rogers, Mulders; 10]*
  Scalar QED models and its generalization to QCD (Counterexample to Factorization)



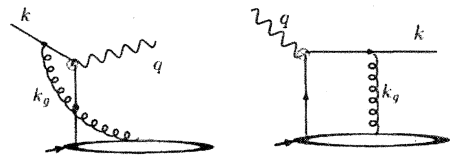




- $\mathcal{O}(g^2)$ calculation shows non-vanishing anomalous terms with respect to standard factorization.
- Remarks: TMD parton distributions are non-universal. k_t factorization is violated in di-jet production.
- Trouble? or Opportunity?
- Resummation up to all order of g including the anomalous terms*[BX, Yuan; 10]*.
- The effect of k_t factorization violation is resummable and calculable. Opportunity!

Why is the di-jet production process special?

Initial state interactions and/or final state interactions



- In Drell-Yan process, there are only initial state interactions.

$$\int_{-\infty}^{+\infty} dk_g^+ \frac{i}{-k_g^+ - i\epsilon} A^+(k_g) = \int_0^{-\infty} d\zeta^- A^+(\zeta^-)$$

  Eikonal approximation $\Longrightarrow$ gauge links.
- In DIS, there are only final state interactions.

$$\int_{-\infty}^{+\infty} dk_g^+ \frac{i}{-k_g^+ + i\epsilon} A^+(k_g) = \int_0^{+\infty} d\zeta^- A^+(\zeta^-)$$

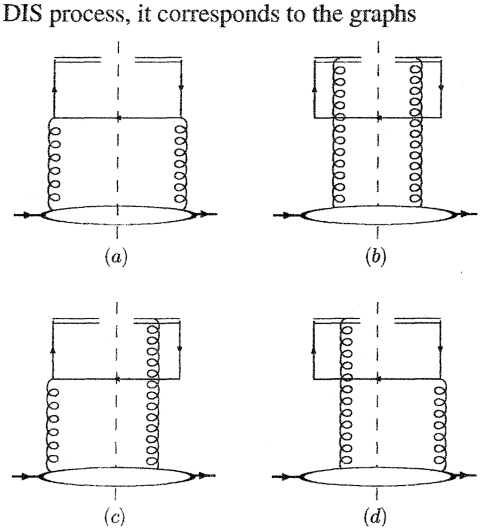
  Eikonal approximation $\Longrightarrow$ gauge links.
- However, there are both initial state interactions and final state interactions in the di-jet process.

Definition of the TMD parton distribution function

The TMD parton distribution function is defined as:*[Belitsky, Ji, Yuan; 02]*

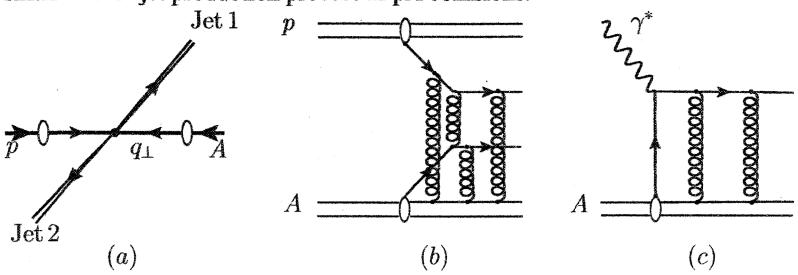
$$q(x, q_\perp) = \frac{1}{2} \int \frac{d^2\xi_\perp d\xi^-}{(2\pi)^2} e^{-ixP^+\xi^- - iq_\perp\cdot\xi_\perp} \langle P|\bar{\Psi}(\xi)\mathcal{L}_\xi\gamma^+\mathcal{L}_0\Psi(0)|P\rangle \ .$$

At lowest order in DIS process, it corresponds to the graphs



Breaking down of the k_t factorization at small-x

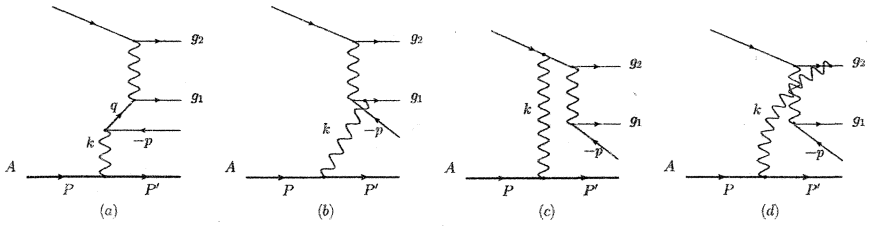
[Brodsky, et al, 02](DIS)
[Collins, Qiu; 07], [Collins; 07], [Vogelsang, Yuan; 07](di-jet)
We employ the same scalar QED model, and study the TMD parton distributions at small-x in di-jet production process in pA collisions.



- This model allows us to calculate the TMD pdfs up to all order in a few of different processes exactly in the small-x limit.
- The goal is to compute the TMD pdf in di-jet production and compare it with those calculated in DIS and Drell-Yan process.
- Look for an effective generalized TMD factorization in pA collision. For pp or AA there is no such factorization. *[Rogers, Mulders; 10]*

The lowest order amplitude

[BX, Yuan; 10] We focus on the TMD parton distributions of the nucleus target at small-x limit, namely $q^+ \ll P^+$.
$qq' \to qq'$ channel:



Remarks:

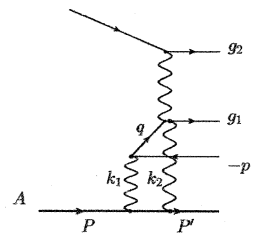
- We assign charge g_1 to the parton from the nucleus target, and g_2 to the scalar quark from the projectile proton. Also assume the nucleus has charge g.
- The lowest order amplitude is found to be

$$A^{(1)}(k,p) = gg_1 \frac{1}{k_\perp^2 + \lambda^2}\left[\frac{1}{D_1} - \frac{1}{D_2}\right], \text{Hard part factorized out.}$$

where $D(p_\perp) = 2xP^+p^- + p_\perp^2 + m^2$ and $D_1 = D(q_\perp)$ and $D_2 = D(p_\perp)$.

The second order amplitude

[BX, Yuan; 10] The second order amplitude:



(a)

- There are 20 graphs in total.
- The amplitude starts to show dependence on g_2. Similar with *[Collins; 07]*.

Remarks:

- The second order amplitude is found to be

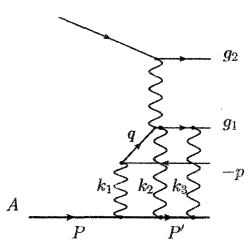
$$A^{(2)}(k,p) = \frac{i}{2}g^2 \int d[1]d[2] \left\{ g_1^2 \left[\frac{1}{D_1} + \frac{1}{D_2} - \frac{1}{D_{21}} - \frac{1}{D_{22}} \right] + g_1 g_2 \left[\frac{2}{D_2} - \frac{2}{D_{21}} \right] \right\},$$

where $D_{1i} = D(q_\perp - k_{i\perp})$, $D_{2i} = D(p_\perp - k_{i\perp})$ and

$$\int d[1]d[2] = \int \frac{d^2k_{1\perp}d^2k_{2\perp}}{(2\pi)^4} \frac{1}{k_{1\perp}^2 + \lambda^2} \frac{1}{k_{2\perp}^2 + \lambda^2} \times (2\pi)^2 \delta^{(2)}(k_\perp - k_{1\perp} - k_{2\perp})$$

The third order amplitude

[BX, Yuan; 10] The third order amplitude:



(b)

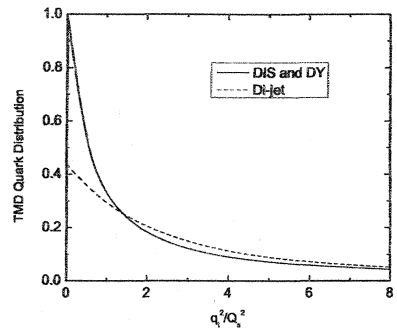
- Motivation: $|A^{(1)} + A^{(2)} + A^{(3)} + \cdots|^2$ and resummation.
- There are 120 graphs in total.
- The amplitude also contains dependence on g_2.

Remarks:

- The third order amplitude is found to be

$$A^{(3)}(k,p) = \frac{1}{3!}g^3 \int d[1]d[2]d[3] \left\{ g_1^3 \left[\frac{1}{D_2} - \frac{1}{D_1} + \frac{3}{D_{13}} - \frac{3}{D_{21}} \right] + g_1^2 g_2 \left[\frac{3}{D_2} + \frac{3}{D_{13}} - \frac{3}{D_{21}} - \frac{3}{D_{22}} \right] + g_1 g_2^2 \left[\frac{3}{D_2} - \frac{3}{D_{21}} \right] \right\}$$

Non-Universality



- Comparison of quark distributions $\frac{4\pi^4}{N_c}\frac{dx\tilde{q}_{tot}(x,q_\perp)}{d^2R_\perp}$ as functions of $\frac{q_\perp^2}{Q_s^2}$ in DIS (or Drell-Yan) and di-hadron production. The solid curve stands for the quark distribution in DIS and Drell-Yan process, and the dash curve represents the distribution involved in di-hadron production.
- Non-Universality (as a result of initial and final state interactions) and k_t factorization violation in CGC. However, they are calculable.
- Integrated quark distributions are universal.

Conclusion and Remarks

- The effect of the k_t factorization violation is calculable and resummable.
- Non-Universality in CGC. Process-dependent TMD parton distributions. However, different distributions are related.
- The Wilson line is Universal.

TSSA in Heavy Quark Production

Ming X. Liu
Los Alamos National Lab

BNL/RBRC Summer Spin Workshop 07/2010

A new Experimental Test of color dynamics in hard scattering

- Color flow, DIS and DY
- Open charm TSSA
- J/Psi TSSA
- Experimental prospects: PHENIX@RHIC and other new Exp's

An experimentalist's point of view

Charm and anti-Charm TSSA and Color Flow

- Quark and antiquark could have different color flow structure in hard scattering
- Experimentally Charm and anti-Charm can be cleanly identified,

$$A_N(c): \quad c \rightarrow \mu^+ + X$$
$$A_N(\bar{c}): \quad \bar{c} \rightarrow \mu^- + X$$

$A_N(c) \neq A_N(\bar{c})$ A new experimental test of the color coupling to quark vs antiquark in hard scatterings!

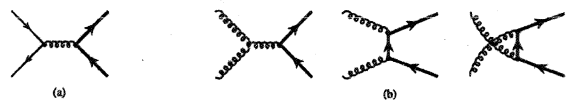
- A_N(charm) provide new insight to the underlying physics of TSSA
  - Directly test the different color coupling for quark and anti-quark

TSSA in Heavy Quark Production at LO

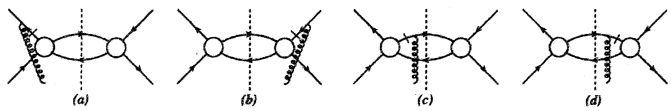
Kang, Qiu, Vogelsang, Yuan, PRD 2008

D-meson production in hadronic collisions

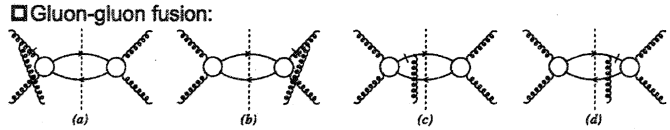
- Two partonic subprocesses:



- Quark-antiquark annihilation:



- Gluon-gluon fusion:



Charm TSSA in Twist-3 Approach

Factorized formula for D-meson production

- Same factorized formula for both subprocesses:

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{q\bar{q}\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_q \int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{\bar{q}/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\boxed{\left(T_{q,F}(x,x)-x\frac{d}{dx}T_{q,F}(x,x)\right)}H_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})+T_{q,F}(x,x)\mathcal{H}_{q\bar{q}\to c}(\tilde{s},\tilde{t},\tilde{u})\right],$$

$$E_{P_h}\frac{d\Delta\sigma}{d^3P_h}\bigg|_{gg\to c\bar{c}} = \frac{\alpha_s^2}{S}\sum_{i=f,d}\int\frac{dz}{z^2}D_{c\to h}(z)\int\frac{dx'}{x'}\phi_{g/B}(x')\int\frac{dx}{x}\sqrt{4\pi\alpha_s}\left(\frac{\epsilon^{P_h s_T n\bar{n}}}{z\tilde{u}}\right)\delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right)$$
$$\times\left[\boxed{\left(T_G^{(i)}(x,x)-x\frac{d}{dx}T_G^{(i)}(x,x)\right)}H^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})+T_G^{(i)}(x,x)\mathcal{H}^{(i)}_{gg\to c}(\tilde{s},\tilde{t},\tilde{u})\right].$$

- Hard parts:

$$H_{q\bar{q}\to c}=H^I_{q\bar{q}\to c}+H^F_{q\bar{q}\to c}\left(1+\frac{\tilde{u}}{\tilde{t}}\right)\qquad H^{(i)}_{gg\to c}=H^{I(i)}_{gg\to c}+H^{F(i)}_{gg\to c}\left(1+\frac{\tilde{u}}{\tilde{t}}\right)$$

All $\mathcal{H}_{q\bar{q}\to c}$ and $\mathcal{H}^{I(i)}_{gg\to c}$ and $\mathcal{H}^{F(i)}_{gg\to c}$ vanish as $m_c^2\to 0$

- Hard parts change sign for $T_G^{(d)}(x,x)$ when $c\to\bar{c}$

$$H^{(f)}_{gg\to\bar{c}}=H^{(f)}_{gg\to c},\qquad H^{(d)}_{gg\to\bar{c}}=-H^{(d)}_{gg\to c},$$
$$\mathcal{H}^{(f)}_{gg\to\bar{c}}=\mathcal{H}^{(f)}_{gg\to c},\qquad \mathcal{H}^{(d)}_{gg\to\bar{c}}=-\mathcal{H}^{(d)}_{gg\to c}.$$

October 3, 2008 21 Jianwei Qiu

Heavy Quark SSA (II)

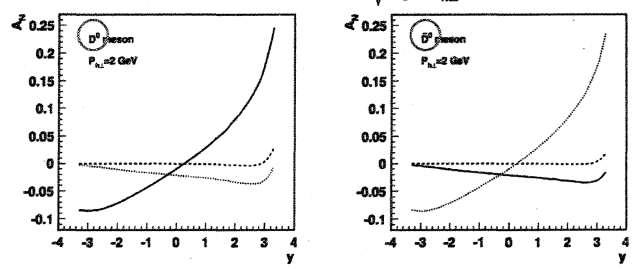
$g + g \rightarrow c + \bar{c}$

Twist-3 tri-gluon correlation

- Consequence of different color factors for charm and anti-charm

Rapidity dependence of D-meson production

SSA at RHIC: $\sqrt{s} = 200$ GeV $\quad \mu = \sqrt{m_c^2 + P_{h\perp}^2} \quad m_c = 1.3$ GeV



Kang, Spin2008

Solid: $(1)\lambda_f = \lambda_d = 0.07$ GeV $\quad T_G^{(d)} = T_G^{(f)}$

Dashed: $(2)\lambda_f = \lambda_d = 0 \quad T_G^{(d)} = T_G^{(f)} = 0$

Dotted: $(3)\lambda_f = -\lambda_d = 0.07$ GeV $\quad T_G^{(d)} = -T_G^{(f)}$

$\boxed{A_N(D) = A_N(\bar{D}) \text{ if } T_G^{(d)} = 0}$

J/Psi SSA: p+p (III)

@RHIC/PHENIX!

- Singlet vs Octet channels

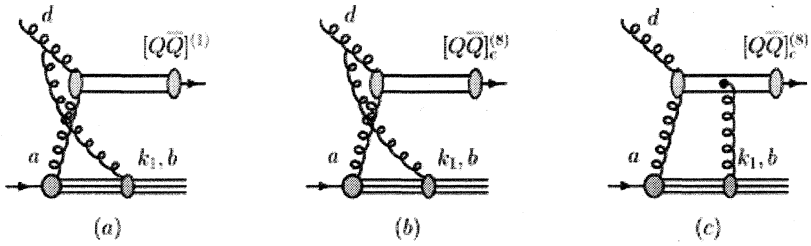
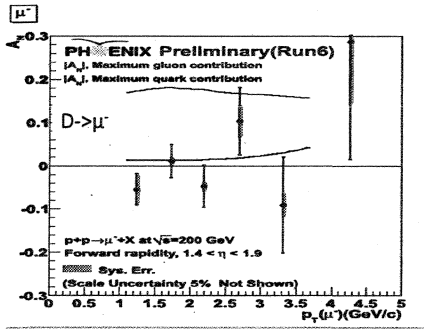
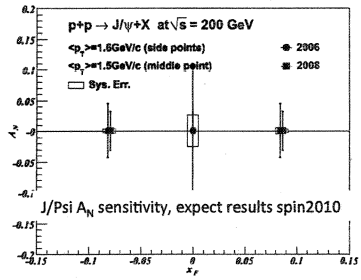


FIG. 4. Only initial state interactions contribute to the SSA in hadron-production process in the color-singlet model (a). On the other hand, the SSA vanishes in the color-octet model because of the cancellation between initial (b) and final (c) state interactions.

Latest Results of Heavy Quark SSA

Probing Gluon's Sivers Asymmetry

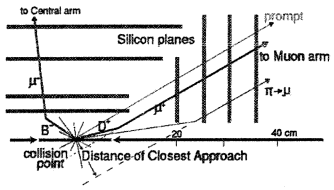


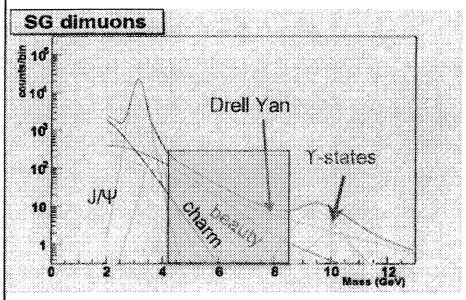


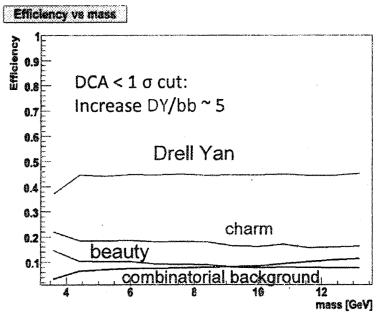
- Gluon's Sivers fun was not constrained well by DIS data
- PHENIX Charm data exclude the maximum gluon Sivers Fun (Anselmino et al, 06)
- Much improved results expected soon (Run6+Run8)

Critical Role of VTX/FVTX for Drell-Yan and Open Charm

- Tracking muons with MuTr+FVTX
  - Prompt muons from DY
  - Displaced tracks from π/K and heavy quark decays





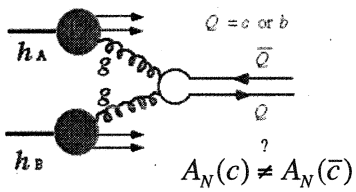


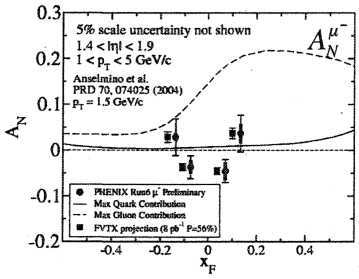
→DY: 4 GeV < M < 9 GeV; B-background: use FVTX

Charm SSA to Probe Gluon Sivers Distribution

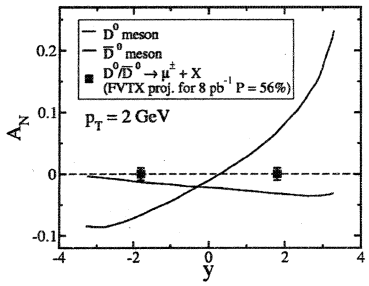
D meson Single-Spin Asymmetry:

- Production dominated by gluon-gluon fusion
- Sensitive to gluon Sivers distribution
  - PHENIX-2006 data ruled out the max. gluon Sivers
  - Much improved results expected with VTX detectors





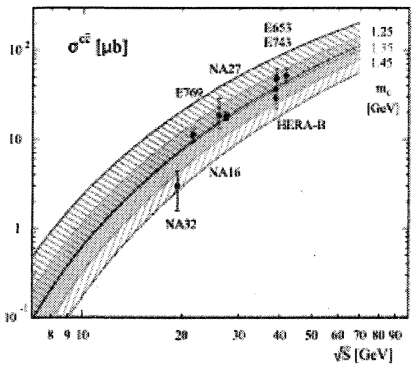
Kang, Qiu, Yuan, Vogelsang, Phys. Rev. D 78,114013(2008)



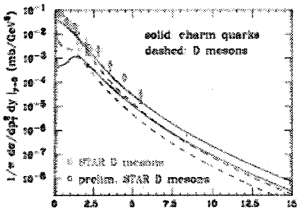
More on Open Charm Production

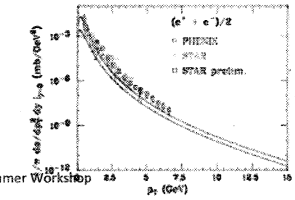
- Fixed targets
- Collider mode @RHIC

EPJ C 52, 987 (2007) J. Riedl, A. Schafer, M. Stratmann



PRL 95, 122001 (2005) M. Cacciari, P. Nason, R. Vogt





A few Observations and Comments

- Twist-3 and Generalized TMD Parton Model
  - Color gauge approach
- Quark sector: some knowledge
  - Quark Sivers and Collins functions
  - Twist-3 quark-gluon correlation functions
- Gluon sector: largely unknown
  - Gluon Sivers function(s)??
  - Twist-3 tri-gluon correlation functions
- What is the next experimental step?
  - Heavy quark probe!
  - Directly access the color charge coupling to quark and anti-quark
- It is all about the color flow in hard scattering
  - TSSA @RHIC-SPIN
  - p/d+A @RHIC Xiao @ this workshop!
  - Jlab-12, EIC...

Summary and Outlook

- Experimental confirmation (or disproval) of color flow in hard scattering is a critical step toward understanding the mechanisms of SSA
- Color charge dependence is originated from the Gauge formulism. Experimental study of SSA in charm and anti-charm is as important as the test of sign change in DY SSA.
- Future experimental prospects – exciting opportunity!
  - RHIC, high energy
  - Low energy fixed target
  - Jlab-12
  - EIC

Some comments on the derivation of the transverse angular momentum sum rule

Elliot Leader

Imperial College London

work in collaboration with Larry Trueman

(LT may disagree with some of the things I say)

Background and Outline

- Some people unhappy about our method of deriving sum rule using Instant Form quantization
- Will show equivalence to Light-Cone approach

Introduction

In this paper we shall discuss the physical interpretation of the angular momentum sum rule for a transversely polarized nucleon derived by Bakker, Leader and Trueman (BLT) [1].

The derivation of an angular momentum sum rule, relating the angular momentum of a nucleon to the angular momentum carried by its constituents, starts from an expression for the expectation value of the angular momentum operators in a state of the nucleon specified by its 4-momentum P^μ and its covariant spin vector S^μ

$$\langle P, S \,|\, J_i \,|\, P, S \rangle \qquad i = 1, 2, 3 \tag{1}$$

i.e. from an expression showing the dependence of the matrix element on the variables P^μ and S^μ.

Some time ago BLT demonstrated that the standard expression in the literature [2] for the matrix element in Eqn. (1), while correct for nucleons polarized longitudinally, was incorrect for the transversely polarized case, and this had given rise to the incorrect claim that there could not exist an angular momentum sum rule for a transversely polarized nucleon.
In deriving the correct expression for the matrix element in Eqn. (1) for a massive particle of spin-$\frac{1}{2}$ with 4-momentum P it turns out to be advantageous to utilize canonical spin states $|P, \boldsymbol{s}\rangle$ (i.e. 'boost' states of the kind generally used in textbooks on Field Theory e.g. in Bjorken and Drell [3], or in Peskin and Schroeder [4]), where the spin state is specified by $\boldsymbol{s}$, which is twice the spin eigenvector in the *rest* frame ($\boldsymbol{s}^2 = 1$). The covariant spin vector is related to this by

$$S^\mu = \left(\frac{\boldsymbol{P}\cdot\boldsymbol{s}}{M},\, \boldsymbol{s} + \frac{\boldsymbol{P}\cdot\boldsymbol{s}}{M(P_0+M)}\boldsymbol{P} \right) \tag{2}$$

The correct result for the forward matrix elements of the angular momentum turns out to be

$$\langle P', \boldsymbol{s}|J_i|P, \boldsymbol{s}\rangle = 2P^0(2\pi)^3 \left[\frac{1}{2}\, s_i + i(\boldsymbol{P}\times\boldsymbol{\nabla}_{\boldsymbol{P}})_i \right] \delta^3(\boldsymbol{P'}-\boldsymbol{P}). \tag{3}$$

and there is then no problem with the transverse case —it is quite analogous to the longitudinal case. Thus BLT were able to derive a sum rule relating the transverse spin of the nucleon to the transverse polarized quark densities $\Delta_T q(x)$ and the transverse orbital angular momentum carried by quarks and gluons, namely

$$\frac{1}{2} = \frac{1}{2} \sum_{\text{flavours } f} \{ \int dx\, [\, \Delta_T q^f(x) + \Delta_T \bar{q}^f\,] + \sum_{a=q,\,\bar{q},\,G} \langle L_{\boldsymbol{s}_T}\rangle^a \} \tag{4}$$

where $L_{\boldsymbol{s}_T}$ is the component of $\boldsymbol{L}$ along $\boldsymbol{s}_T$.

In deriving Eqn. (4) BLT, for simplicity, substituted into Eqn. (3) an equal-time or instant-form Fock expansion for the nucleon state, in terms of its quark and gluon constituents, rather than a light-cone expansion. As a consequence questions have been raised as to whether the identification of the terms on the RHS of Eqn. (4) is correct, given that the parton densities are conventionally defined using light-cone Fock expansions.

We shall show that the identification of terms on the RHS of Eqn. (4) is correct.We shall also comment upon the fact, which has caused some confusion, that for a transversely polarized nucleon what appears in the sum rule is the *sum* of quark and antiquark transversity densities, in contrast to the case of the tensor charge of the nucleon, where the difference appears.

Instant-form Fock expansion

We shall here demonstrate that the instant-form Fock expansion used by BLT in deriving the angular momentum sum rules from Eqn. (3), when applied to the expression for the quark correlator, leads to the standard connection between parton densities and the wave-functions appearing in the expansion. This vindicates the interpretation of the RHS of Eqn. (4) given by BLT. For simplicity we shall give the proof only for the unpolarized quark density $q(x)$, but the argument holds equally well for them polarized densities $\Delta q(x)$ and $\Delta_T q(x)$.

The quark correlator $\Phi_{\alpha\beta}(k; P, S)$, for a given flavour, integrated over k with the constraint $x = k^+/P^+$ yields

$$\Phi\alpha\beta(x) = P^+ \int \frac{d\xi^-}{2\pi}\, e^{ixP^+\xi^-}\, \langle P,\, S\,|\, \bar{\psi}_\beta(0)\, \psi_\alpha(0, \xi^-, \mathbf{0}_\perp)\,|\, P,\, S\rangle \tag{5}$$

where

$$P^{\pm} = \frac{1}{\sqrt{2}}\,(P_0 \pm P_z) \tag{6}$$

At leading twist $\Phi\alpha\beta(x)$ can be expressed in terms of the three leading-twist quark distribution functions, in matrix form, as

$$\Phi(x) = \frac{1}{2}\,\not{P}\{q(x) - 2\,\lambda\,\Delta q(x)\gamma_5 + \Delta_T q(x)\gamma_5\,\not{S}_\perp\} \tag{7}$$

where $\lambda = \pm 1/2$ is the nucleon helicity.

From this one obtains the standard expression

$$q(x) = \frac{1}{2\,P^+}\,Tr[\gamma^+\,\Phi(x)]. \tag{8}$$

However, we are considering a nucleon, mass m, moving fast along OZ so that

$$P^\mu = (P_0, 0, 0, P)$$

with $P \gg m$ and $P_0 \approx P$ so that

$$Tr[\gamma^+\Phi(x)] = \frac{P^+}{P_0}\,Tr[\gamma^0\Phi(x)] \approx \sqrt{2}\,Tr[\gamma^0\Phi(x)].$$

Thus we may take

$$q(x) = \frac{1}{2\,P_0}\,Tr[\gamma^0\Phi(x)], \tag{9}$$

which, via Eqn. (5), can be written

$$q(x) = \frac{\sqrt{2}}{4\pi}\sum_X \int d\xi^-\,e^{ixP^+\xi^-}\,\langle P,\,S\,|\,\psi_\alpha^\dagger(0)\,|\,X\rangle\langle X\,|\psi_\alpha(0,\xi^-,\mathbf{0}_\perp)\,|\,P,\,S\rangle. \tag{10}$$

Using translation invariance we obtain the final expression which we shall work from, namely

$$q(x) = \frac{1}{\sqrt{2}}\sum_{X,\alpha}\,|\,\langle X\,|\,\psi_\alpha(0)\,|\,P,\,S\rangle|^2\,\delta[P_X^+ - (1-x)P^+] \tag{11}$$

Since the matrix element in Eqn. (11) involves the field at only one time, and since the hadronic state is a one-particle state, we may evaluate the matrix element in the Interaction Picture i.e we may use the *free-field* expansion

$$\begin{aligned}\psi_\alpha(0) &= \sum_\lambda \int \frac{d^3\boldsymbol{p}}{(2\pi)^3\,2E_p}\,b(\boldsymbol{p},\lambda)u_\alpha(\boldsymbol{p},\lambda)\\ &+ \sum_\lambda \int \frac{d^3\bar{\boldsymbol{p}}}{(2\pi)^3\,2E_{\bar{p}}}\,d^\dagger(\bar{\boldsymbol{p}},\lambda)u_\alpha(\bar{\boldsymbol{p}},\lambda)\end{aligned} \tag{12}$$

where we have used $\bar{\boldsymbol{p}}$ just to emphasize that $d^\dagger$ creates an antiquark. Note that

$$E_p = \sqrt{\boldsymbol{p}^2 + m_q^2} \qquad \text{and} \qquad E_{\bar{p}} = \sqrt{\bar{\boldsymbol{p}}^2 + m_q^2} \tag{13}$$

The nucleon state with $\boldsymbol{P} = (0, 0, P)$ is expanded as a superposition of n-parton Fock states, wherein, for simplicity, we will not display flavour and colour labels. Rather than the commonly used "Light-Cone" form [5] we proceed as in BLT and use the "Instant" form

$$\begin{aligned} |\boldsymbol{P}, m\rangle &= [(2\pi)^3 2P_0]^{1/2} \sum_n \sum_\mu \int \frac{d^3\boldsymbol{k}_1}{\sqrt{(2\pi)^3 2k_1^0}} \cdots \frac{d^3\boldsymbol{k}_n}{\sqrt{(2\pi)^3 2k_n^0}} \\ &\quad \times \psi_{\boldsymbol{P},m}(\boldsymbol{k}_1, \mu_1, ...\boldsymbol{k}_n, \mu_n) \\ &\quad \times \delta^{(3)}(\boldsymbol{P} - \boldsymbol{k}_1 - ... - \boldsymbol{k}_n) |\boldsymbol{k}_1, \mu_1, ...\boldsymbol{k}_n, \mu_n\rangle. \end{aligned} \tag{14}$$

where μ_i denotes the helicity. $\psi_{\boldsymbol{P},m}$ is the partonic wave function of the nucleon normalized so that

$$\sum_{\{\sigma\}} \int d^3\boldsymbol{k}_1 \ldots d^3\boldsymbol{k}_n |\psi_{\boldsymbol{P},m}(\boldsymbol{k}_1, \mu_1, ...\boldsymbol{k}_n, \mu_n)|^2 \delta^{(3)}(\boldsymbol{p} - \boldsymbol{k}_1 - ... - \boldsymbol{k}_n) = \mathcal{P}_n. \tag{15}$$

with $\mathcal{P}_n$ denoting the probability of the n-parton state.

Consider now the contribution to the matrix element $\langle X | \psi_\alpha(0) | P \rangle$ when the nucleon is represented by a Fock state with n constituents

$$|\boldsymbol{k}_1, \mu_1; - - - - - \boldsymbol{k}_n, \mu_n\rangle \quad \text{with} \quad \sum_j \boldsymbol{k}_{jT} = 0 \quad \text{and} \quad \sum_j k_{j_z} = P \tag{16}$$

Now because $\psi_\alpha(0)$ contains both creation and an annihilation operators, one might , at first sight, expect to find that its modulus squared involves the modulus squared of a *sum* of two wave-functions, referring to different numbers of partons, which would imply that $q(x)$ is not given simply by the modulus squared of a wave-function, as it ought to be. Indeed it has sometimes been said that the latter form is a miracle of the Light Cone expansion. We now show that this is not quite a miracle and that there is no problem also in the Instant form.

Focus, therefore, on the $d^\dagger$ term in $\psi_\alpha(0)$

$$\langle X | d^\dagger(\bar{\boldsymbol{p}}, \lambda) | \boldsymbol{k}_1, \mu_1; - - - - - \boldsymbol{k}_n, \mu_n\rangle = \langle X | \bar{\boldsymbol{p}}, \lambda : \boldsymbol{k}_1, \mu_1; - - - - - \boldsymbol{k}_n, \mu_n\rangle \tag{17}$$

Aside from combinatoric factors this implies that one must have

$$|X\rangle = |\bar{\boldsymbol{p}}, \lambda : \boldsymbol{k}_1, \mu_1; - - - - - \boldsymbol{k}_n, \mu_n\rangle \tag{18}$$

For this state

$$P_{X_z} = \sum_j k_{j_z} + \bar{p}_z = P + \bar{p}_z \tag{19}$$

Its energy is

$$\begin{aligned} E_X &= \sum_j \sqrt{\boldsymbol{k}_j^2 + m_q^2} + E_{\bar{p}} \\ &\geq \sum_j k_{j_z} + E_{\bar{p}} \\ &\geq P + E_{\bar{p}} \qquad \text{by Eqn.(16)} \end{aligned} \tag{20}$$

Together with Eqn. (19) this implies

$$P_X^+ > P^+ + \bar{p}^+ > P^+ \tag{21}$$

so that the delta-function condition in Eqn. (11) cannot be fulfilled since $x > 0$. Thus the $d^\dagger$ term does not contribute.

The rest of the derivation is standard giving $q(x)$ as the sum of wave-functions squared for helicity $+1/2$ + helicity $-1/2$.

Thus the identification of the wave functions used by BLT with the standard parton densities is correct

References

[1] B. L. G. Bakker, E. Leader, and T. L. Trueman, Phys. Rev. **D70**, 114001 (2004), hep-ph/0406139.

[2] R. L. Jaffe and A. Manohar, Nucl. Phys. **B337**, 509 (1990).

[3] J. D. Bjorken and S. D. Drell, New York, USA: McGraw-Hill (1965) 396 p.

[4] M. E. Peskin and D. V. Schroeder, Reading, USA: Addison-Wesley (1995) 842 p.

[5] S. J. Brodsky, M. Diehl, and D. S. Hwang, Nucl. Phys. **B596**, 99 (2001), hep-ph/0009254.

Nucleon Spin Physics Summer Program

July 14 – 27, 2010

Registered Participants

Name	Affiliation
Christine Aidala	Los Alamos National Laboratory
Hussein Al-Taani	New Mexico State University
Mauro Anselmino	Torino University & INFN
Elke Aschenauer	Brookhaven National Laboratory
Harut Avagyan	Thomas Jefferson National Accelerator Facility
Kenneth Barish	UC Riverside
Mike Beaumier	University of California Riverside
Les Bland	Brookhaven National Laboratory
Kieran Boyle	RIKEN BNL Research Center
Jingyi Chao	North Carolina State University
Jian-ping Chen	Thomas Jefferson National Accelerator Facility
Mickey Chiu	Brookhaven National Laboratory
William Christie	Brookhaven National Laboratory
Aurore Courtoy	INFN-Sezione di Pavia
Amaresh Datta	UMass, Amherst
Abhay Deshpande	Stony Brook University
Markus Diehl	DESY
Pibero Djawotho	Texas A&M University
Douglas Fields	University of New Mexico
Achim Franz	Brookhaven National Laboratory
Yoshinori Fukao	RIKEN
Carl Gagliardi	Texas A&M University
Ciprian Gal	Stony Brook University
Leonard Gamberg	Penn State University
Yuji Goto	RIKEN
Matthias Grosse Perdekamp	University of Illinois
Philipp Haegler	TU Munich
John Haggerty	Brookhaven National Laboratory
Richard Hollis	University of California, Riverside
Huan Huang	University of California Los Angeles
Zhongbo Kang	RIKEN BNL Research Center
David Kawall	University of Massachusetts and RBRC
David Kleinjan	University of California, Riverside
Paul Kline	Stony Brook University

Registered Participants, continued

Yuji Koike	Niigata University
Shunzo Kumano	KEK
Krzysztof Kurek	Soltan Institute for Nuclear Studies
Elliot Leader	Imperial College London
Sookhyun Lee	Stony Brook University
Xuan Li	Brookhaven National Laboratory
Ming Liu	Los Alamos National Laboratory
Thomas Ludlam	Brookhaven National Laboratory
Andrew Manion	Stony Brook University
Dieter Mueller	Ruhr University Bochum
Piet Mulders	VU University Amsterdam
Itaru Nakagawa	RIKEN
Katsuro Nakamura	Kyoto University / RIKEN
Kensuke Okada	RIKEN BNL Research Center
Chris Perkins	UC Berkeley/Stony Brook University
Jianwei Qiu	Brookhaven National Laboratory
Marc Schlegel	Tuebingen University
Gunar Schnell	DESY
Ralf Seidl	RIKEN
Ernst Sichtermann	Lawrence Berkeley National Laboratory
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Bernd Surrow	Massachusetts Institute of Technology
Swadhin Taneja	Stony Brook University
Rusty Towell	Abilene Christian University
Larry Trueman	Brookhaven National Laboratory
Flemming Videbaek	Brookhaven National Laboratory
Werner Vogelsang	Tuebingen University
Anselm Vossen	University of Illinois
Masashi Wakamatsu	Brookhaven National Laboratory
Bowen Xiao	Lawrence Berkeley National Laboratory
Hongxi Xing	Lawrence Berkeley National Laboratory
Nu Xu	Lawrence Berkeley National Laboratory
Feng Yuan	Lawrence Berkeley National Laboratory
Hong Zhang	Iowa State University
Jian Zhou	Temple University

Brookhaven/RBRC Summer Program on Nucleon Spin Physics
July 14 – 27, 2010

Agenda

Wednesday, July 14, 2010

Large seminar room, Physics Department

9:00AM – 9:10AM	Ludlam, Thomas (BNL) Welcome
9:10AM – 10:10AM	Mulders, Piet (Amsterdam) "Overview on TMD factorization"
10:10AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Mueller, Dieter (Bochum) "GPD phenomenology of hard exclusive processes"
11:30AM – Noon	Discussion

Large seminar room, Physics Department

1:30PM – 2:30PM	Chen, Jian-Ping (JLab) "Measurements of the Neutron Single Spin Asymmetries in SIDIS on a Polarized 3He Target"
2:30PM – 3:30PM	Avakian, Harut (JLab) "JLab 12 GeV upgrade and spin physics"
3:30PM – 5:00PM	Coffee break and DISCUSSION

Thursday, July 15, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Schlegel, Marc (Tubigen) "Spin observables in hadron collisions"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Diehl, Markus (DESY) "Spin Physics with Unpolarized Protons"
11:30AM – Noon	Discussion

Friday, July 16, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Koike, Yuji (Niigata) "Overview of single transverse spin asymmetry – twist-3 mechanism"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Kang, Zhong-Bo (RBRC, BNL) "Global analysis of single transverse spin asymmetries - twist-3 distributions"
11:30AM – Noon	Discussion

Large seminar room, Physics Department

1:30PM – 2:30PM	Grosse-Perdekamp, Matthias (UIUC) "Transverse Spin Physics Current and Future with PHENIX "
2:30PM – 3:30PM	Bland, Les (BNL) "Transverse Spin Physics "
3:30PM – 4:00PM	Coffee break
4:00PM – 5:00PM	Surrow, Bernd (MIT) "W measurements with STAR"

Monday, July 19, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Stratmann, Marco (Regensburg/Wurzburg) "Global analysis of spin PDFs"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Zhou, Jian (Temple) "SSAs for a Few Processes"
11:30AM – Noon	Discussion

Large seminar room, Physics Department

1:30PM – 2:30PM	Gagliardi, Carl (Texas A&M) "Gluon Polarization measurements with STAR"
2:30PM – 3:30PM	Boyle, Kieran (RBRC/Stony Brook) "Quark and Gluon Polarization measurements with PHENIX"
3:30PM – 5:00PM	Coffee break and DISCUSSION (include higher twists etc.)

Tuesday, July 20, 2010 – no physics colloquium

Small seminar room, Physics Department

9:00AM – 10:00AM	Courtoy, Aurore (Pavia) "Di-hadron fragmentation functions"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Seidl, Ralf (RIKEN) "Polarized Fragmentation functions"
11:30AM – Noon	Discussion

Small seminar room, Physics Department

1:30PM – 2:30PM	Schnell, Gunar (DESY) "HERMES on Spin"
2:30PM – 3:30PM	Kurek, Krzysztof (Warsaw) "COMPASS on Spin"
3:30PM – 5:00PM	Coffee break and Discussions

Wednesday, July 21, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Haegler, Philip (Munich) "Spin PDFs on Lattice"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Leader, Elliot (Imperial College London) "On the Controversy in Defining Quark and Gluon Angular Momentum"
11:30AM – Noon	Discussion

Small seminar room, Physics Department

1:30PM – 2:30PM	Peng, Jen-Chieh (UIUC) "DY with an internal target at RHIC"
2:30PM – 3:10PM	Perkins, Chris (BNL) "DY with a dedicated collider experiment at RHIC"
3:10PM – 3:40PM	Kurek, Krzysztof (Warsaw) "DY with COMPASS"
3:40PM – 5:00PM	Coffee Break and Discussions
6:00OM –	Workshop dinner at Brookhaven Center

Thursday, July 22, 2010

Large seminar room, Physics Department

9:00AM – 9:45AM	Deshpande, Abhay (Stony Brook) "An EIC in the U.S., science goals, initiatives, and timelines."
9:45AM – 10:30AM	Burton, Thomas (BNL) "Dedicated EIC detector design/Semi-inclusive DIS"
10:30AM – 11:00AM	Coffee break
11:00AM – 12:00PM	Elke/Ernst " Discussions on Current Capabilities from STAR and PHENIX"
1:30PM –	More discussion if needed

Friday, July 23, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Wakamatsu, Masashi (Osaka) "Gauge- and frame-independent decomposition of nucleon spin"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Gamberg, Leonard (PSU) "Transverse spin and momentum correlation in QCD"

Monday, July 26, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Soffer, Jacques (Temple)
	"Recent advances in the statistical parton distributions"
10:00AM – 10:30AM	Coffee break
10:30AM – 11:30AM	Xiao, Bowen (LBNL)
	"TMD factorization and small-x physics"
11:30AM – Noon	Discussion

Small seminar room, Physics Department

2:00PM – 2:30PM	Liu, Ming (LANL)
	"SSA in Heavy Flavor Production"
2:30PM – 3:00PM	Leader, Elliot (Imperial College London)
	"Comments on the Transverse Anguar Momentum Sum Rule"
3:00PM – 3:30PM	Coffee break
3:30PM - 5:00PM	Short talks (20-30 min each)?

Tuesday, July 27, 2010

Small seminar room, Physics Department

9:00AM – 10:00AM	Topic discussions
10:00AM – 10:30AM	Coffee break
10:30AM – Noon	Workshop summary on various topics

Noon	Closing

Additional RIKEN BNL Research Center Proceedings:

Volume 99 – The Physics of W and Z Bosons, BNL, June 24-25, 2010 – BNL-94287-2010
Volume 98 – Saturation, the Color Glass Condensate and the Glasma: What Have we Learned from RHIC?, BNL, May 10-12, 2010 – BNL-94271-2010
Volume 97 – RBRC Scientific Review Committee Meeting, October 21-22, 2009 – BNL-90674-2009
Volume 96 – P- and CP-Odd Effects in Hot and Dense Matter, April 26-30, 2010 – BNL-94237-2010
Volume 95 – Progress in High-pT Physics at RHIC, March 17-19, 2010 – BNL-94214-2010
Volume 94 – Summer Program on Nucleon Spin Physics at LBL, June 1-12, 2009
Volume 93 – PHENIX Spinfest School 2009 at BNL - July 1-31, 2009. BNL-90343-2009
Link: PHENIXSpinfestSchool2009@BNL
Volume 92 – PKU-RBRC Workshop on Transverse Spin Physics, June 30-July 4, 2008, Beijing, China, BNL-81685-2008
Volume 91 – RBRC Scientific Review Committee Meeting, November 17-18, 2008 – BNL-81556-2008
Volume 90 – PHENIX Spinfest School 2008 at BNL, August 4-8, 2008 - BNL-81478-2008
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Volume 88 – Hydrodynamics in Heavy Ion Collisions and QCD Equation of State, April 21-22, 2008 – BNL-81307-2008
Volume 87 – RBRC Scientific Review Committee Meeting, November 5-6, 2007 – BNL-79570-2007
Volume 86 – Global Analysis of Polarized Parton Distributions in the RHIC Era, October 8, 2007 – BNL-79457-2007
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Volume 84 – Domain Wall Fermions at Ten Years, March 15-17, 2007 – BNL 77857-2007
Volume 83 – QCD in Extreme Conditions, July 31-August 2, 2006 – BNL-76933-2006
Volume 82 – RHIC Physics in the Context of the Standard Model, June 18-23, 2006 – BNL-76863-2006
Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-75937-2006
Volume 80 – Can We Discover the QCD Critical Point at RHIC?, March 9-10, 2006 – BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-79763-2008
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, Dec 12-14, 2005 – BNL-76915-2006
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649-2005
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
Volume 71 – Classical and Quantum Aspects of the Color Glass Condensate – BNL-73793-2005
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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
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

Additional RIKEN BNL Research Center Proceedings:

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
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Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
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Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
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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
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Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
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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
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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

For information please contact:

Ms. Pamela Esposito
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

Phone: (631) 344-3097
Fax: (631) 344-4067
E-Mail: pesposit@bnl.gov

Ms. Susan Foster
RIKEN BNL Research Center
Building 510A
Brookhaven National Laboratory
Upton, NY 11973-5000 USA

(631) 344-5864
(631) 344-2562
sfoster@bnl.gov

Homepage: http://www.bnl.gov/riken

RIKEN BNL RESEARCH CENTER

Brookhaven Summer Program on Nucleon Spin Physics

July 14-27, 2010

Li Keran

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

Speakers:

H. Avakian	L. Bland	K. Boyle	T. Burton	J.-P. Chen
A. Courtoy	A. Deshpande	M. Diehl	C. Gagliardi	L. Gamberg
M. Grosse-Perdekamp	P. Haegler	Z.-B. Kang	Y. Koike	K. Kurek
E. Leader	M. Liu	D. Mueller	P. Mulders	J.-C. Peng
C. Perkins	M. Schlegel	G. Schnell	R. Seidl	J. Soffer
M. Stratmann	B. Surrow	M. Wakamatsu	B. Xiao	J. Zhou

Organizers: Organizers: Elke Aschenauer, Jianwei Qiu, Werner Vogelsang and Feng Yuan