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FORMAL REPORT

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Joint RBRC-UNM Workshop

Parton Orbital Angular Momentum

February 24-26, 2006

Organizers:

Gerry Bunce, Douglas Fields and Werner Vogelsang

RIKEN BNL Research Center

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DISCLAIMER

Preface to the Series

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

The RBRC has both a theory and experimental component. The RBRC Theory Group currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~40 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

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

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are eighty proceeding volumes available.

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

N. P. Samios, Director
October 2005

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Parton Orbital Angular Momentum

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The joint UNM/RBRC "Workshop on Parton Orbital Angular Momentum" was held on February 24th through 26th at the University of New Mexico Department of Physics and Astronomy in Albuquerque, New Mexico, and was sponsored by The University of New Mexico (Physics Department, New Mexico Center for Particle Physics, Dean of Arts and Sciences, and Office of the Vice Provost for Research and Economic Development) and the RIKEN-BNL Research Center. The workshop was motivated by recent and upcoming experimental data based on methods which have been proposed to access partonic angular momenta, including Deeply Virtual Compton Scattering, measuring the Sivers functions, and measuring helicity dependent k_t in jets. Our desire was to clarify the state of the art in the theoretical understanding in this area, and to help define what might be learned about partonic orbital angular momenta from present and upcoming high precision data, particularly at RHIC, Jlab, COMPASS and HERMES.

The workshop filled two rather full days of talks from both theorists and experimentalists, with a good deal of discussion during, and in between talks focusing on the relationship between the intrinsic transverse momentum, orbital angular momentum, and observables such as the Sivers Function. These talks and discussions were particularly illuminating and the organizers wish to express their sincere thanks to everyone for contributing to this workshop.

Orbital Angular Momentum on the Light-Front and QCD Observables

Stanley J. Brodsky

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The light-front wavefunction formalism provides a physical, but rigorous, representation for angular momentum in a relativistic quantum field theory. Each n-particle LFWF $\psi_n(x_i, \vec{k}_\perp i, S_i^z)$ in the Fock state expansion of a hadron in QCD is frame-independent and satisfies angular momentum conservation $J^z = \sum_{i=1}^n S_i^z + \sum_{i=1}^{n-1} L_i^z$, summed over the $n-1$ independent intrinsic orbital angular momenta $L_i^z = -i\left[\vec{k}_i^x \frac{\partial}{\partial \vec{k}_i^y} - \vec{k}_i^y \frac{\partial}{\partial \vec{k}_i^x}\right]$. Gluons propagate with physical polarization $S_g^z = \pm 1$ in light-cone gauge $A^+ = 0$. All of these features are illustrated by the Fock state expansion of the electron in terms of its fermion-boson components.

The light-front formalism provides a representation of hadron physics at the amplitude level. Quark and gluon distributions are computed from the square of the LFWFs and obey DGLAP evolution. The gauge-independent hadron distribution amplitudes $\phi(x_i, Q)$ which control hard exclusive processes is an integral $\int d^2k_\perp \theta(Q^2 - k_\perp^2)\psi(x, \vec{k}_\perp)$ of the valence LFWF and obeys ERBL evolution. Current matrix elements, and thus all form factors, have an exact representation as overlap of the LFWFs. The Pauli form factor is the matrix element of the J^+ current with opposite J^z and thus is nonzero only between states which have $\Delta L_z = \pm 1$. In particular, the anomalous magnetic moment is the matrix element of the ladder operator $\vec{J}^\pm \cdot \vec{L}^\mp$. Thus, as shown by Drell and myself, the anomalous magnetic moment of any system is nonzero only if the LF Fock expansion contains states with nonzero orbital angular momentum. A similar result holds for the E spin-flip generalized parton distribution. The single-spin asymmetries (Sivers effect) in deep inelastic scattering (and the Drell-Yan process) depend on the same matrix element which enters the Pauli form factor as well as the difference of phases of the final- (initial-) state interactions for Fock states differing by $\Delta L_z = \pm 1$. The anomalous gravitomagnetic moment $B(0)$, the spin-flip matrix element of the energy momentum tensor, is found to be zero, Fock state by Fock state, consistent with the equivalence theorem. The electric dipole moment of a hadron is related to the anomalous moment by a factor $\tan\beta$, where β is the CP-violating phase of the LFWF.

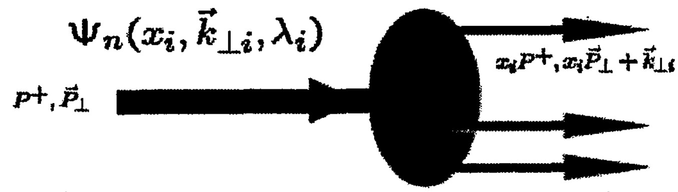
The AdS/CFT formalism provides a remarkable framework for hadron physics in which conformal symmetry is taken as an initial approximation. Color confinement is introduced by imposing Dirichlet boundary conditions $\phi(z = \frac{1}{\Lambda_{QCD}}) = 0$ for the hadron amplitude in the fifth dimension. De Teramond and I have found an exact mapping for current matrix elements in AdS space to the corresponding Drell-Yan West formula for hadron form factors in the light-front formalism. This correspondence leads in turn leads to an exact identification of the z coordinate in AdS/CFT to a variable ζ in physical space-time which represents the measure of transverse separation of the constituents within the hadrons. In addition, we have derived effective four-dimensional LF Schrödinger equations for the bound states of massless quarks and gluons which exactly reproduce the AdS/CFT results and give a realistic description of the light-quark meson and baryon spectrum for all orbital angular momentum excitations L, as well as form factors for spacelike Q^2. Only one parameter Λ_{QCD}, which sets the mass scale, is introduced.

I also discuss a number of tests of orbital angular momentum in exclusive and inclusive reactions.

This research was supported by the Department of Energy contract DE–AC02–76SF00515.

$\sum_i^n x_i = 1$ $\qquad$ $\sum_i^n \vec{k}_{\perp i} = \vec{0}_\perp$

$\sum_{i=1}^n k_i^+ = \sum_{i=1}^n x_i p^+ = p^+$ $\qquad$ $\sum_{i=1}^n (x_i \vec{P}_\perp + \vec{k}_{\perp i}) = \vec{P}_\perp$



$$\vec{\ell}_j \equiv (\vec{k}_\perp \times \vec{b}_\perp)_j = (\vec{k}_\perp \times \frac{i\partial}{\partial \vec{k}_\perp})_j$$

n-1 Intrinsic Orbital Angular Momenta

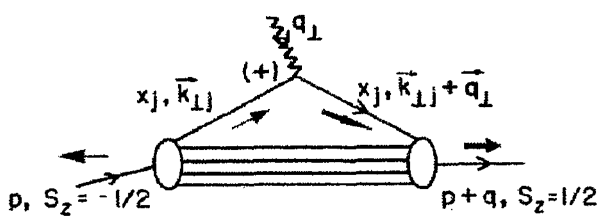
Frame Independent $\qquad j = 1, 2, \cdots (n-1)$

$$\frac{F_2(q^2)}{2M} = \sum_a \int [dx][d^2k_\perp] \sum_j e_j \frac{1}{2} \times$$

$$\left[-\frac{1}{q^L}\psi_a^{\uparrow *}(x_i, k'_{\perp i}, \lambda_i)\, \psi_a^{\downarrow}(x_i, k_{\perp i}, \lambda_i) + \frac{1}{q^R}\psi_a^{\downarrow *}(x_i, k'_{\perp i}, \lambda_i)\, \psi_a^{\uparrow}(x_i, k_{\perp i}, \lambda_i)\right]$$

$k'_{\perp i} = k_{\perp i} - x_i q_\perp$ $\qquad$ $k'_{\perp j} = k_{\perp j} + (1 - x_j) q_\perp$

Drell, sjb



Must have $\Delta \ell_z = \pm 1$ to have nonzero $F_2(q^2)$

LFWFs of Electron (n=2)

$$J_z = +\frac{1}{2}$$

Gives Schwinger Anomalous Moment $\frac{\alpha}{2\pi}$

$$\begin{cases} \psi^{\uparrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(-k^1+ik^2)}{x(1-x)}\,\varphi\,, & L_z = -1 \\ \psi^{\uparrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(+k^1+ik^2)}{1-x}\,\varphi\,, & L_z = 1 \\ \psi^{\uparrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\,, & L_z = 0 \\ \psi^{\uparrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_\perp) = 0\,, & \end{cases}$$

where

$$\varphi = \varphi(x,\vec{k}_\perp) = \frac{e/\sqrt{1-x}}{M^2 - (\vec{k}_\perp^2+m^2)/x - (\vec{k}_\perp^2+\lambda^2)/(1-x)}\,.$$

$M \to m + \lambda$

Spin-1 mass λ

Spin-1/2 mass m

$$\begin{cases} \psi^{\downarrow}_{+\frac{1}{2}\,+1}(x,\vec{k}_\perp) = 0\,, \\ \psi^{\downarrow}_{+\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}(M-\frac{m}{x})\,\varphi\,, \\ \psi^{\downarrow}_{-\frac{1}{2}\,+1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(-k^1+ik^2)}{1-x}\,\varphi\,, \\ \psi^{\downarrow}_{-\frac{1}{2}\,-1}(x,\vec{k}_\perp) = -\sqrt{2}\frac{(+k^1+ik^2)}{x(1-x)}\,\varphi\,. \end{cases}$$

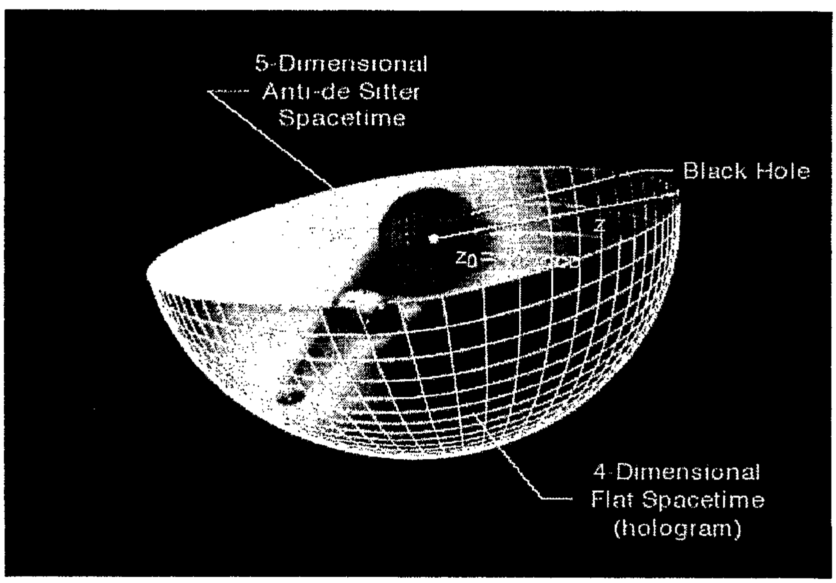
Drell, sjb
Hwang, Schmidt, sjb

Measure Orbital Angular Momentum in Diffractive Reactions

- $pA \to qqqA$ Coulomb Excitation $pe \to qqqe$
- Test Color Transparency
- Measure $\psi_p(x_i, \vec{k}_{\perp i}, \lambda_i)$
- Angular distributions reveal S vs. P waves
- Correlations with Spin of Projectile Proton
- $\gamma^* p \to q\bar{q}p$

Orbital Angular Momentum and Hard Exclusive Reactions

- LFWFs with L nonzero have faster fall-off at short distances $\psi(x, \vec{k}_\perp) \to \left[\frac{|\vec{k}_\perp|}{\sqrt{x(1-x)}}\right]^L \left[\frac{x(1-x)}{\vec{k}_\perp^2}\right]^{1+L}$,
- Faster fall-off of hard exclusive reactions
- Hadron helicity conservation violation $\frac{u_\downarrow(x)}{u_\uparrow(x)} \sim (1-x)^2$
- Spectator rule for structure functions at $x \to 1$
- Spectacular violations, spin anomalies
- Ann in p p scattering
- $J/\psi \to \rho\pi$ puzzle



- Pseudoscalar mesons: $\mathcal{O}_{3+L} = \overline{\psi}\gamma_5 D_{\{\ell_1} \dots D_{\ell_m\}}\psi$ ($\Phi_\mu = 0$ gauge).
- 4-d mass spectrum from boundary conditions on the normalizable string modes at $z = z_0$, $\Phi(x, z_o) = 0$, given by the zeros of Bessel functions $\beta_{\alpha,k}$: $\mathcal{M}_{\alpha,k} = \beta_{\alpha,k}\Lambda_{QCD}$
- Normalizable AdS modes $\Phi(z)$

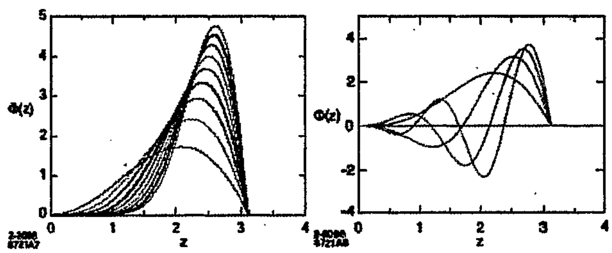
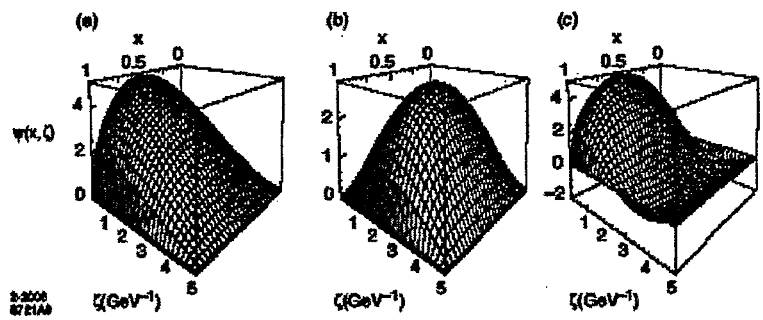


Fig: Meson orbital and radial AdS modes for $\Lambda_{QCD} = 0.32$ GeV.



Two-quark holographic LFWF in impact space $\psi(x,\zeta)$: (a) $\ell = 0$, $k = 1$; (b) $\ell = 1$, $k = 1$; c) $\ell = 0$, $k = 2$. The variable ζ is the holographic variable $z = \zeta = |b_\perp|\sqrt{x(1-x)}$.

Map AdS/CFT to 3+1 LF Theory

Effective radial equation:

$$\left[-\frac{d^2}{d\zeta^2} + V(\zeta)\right] = \mathcal{M}^2 \phi(\zeta)$$

$$\zeta^2 = x(1-x)b_\perp^2.$$

Effective conformal potential: $V(\zeta) = -\frac{1-4L^2}{4\zeta^2}.$

G. de Teramond and sjb (preliminary)

General solution:

$$\widetilde{\psi}_{L,k}(x, \vec{b}_\perp) = B_{L,k}\sqrt{x(1-x)}$$

$$J_L\left(\sqrt{x(1-x)}|\vec{b}_\perp|\beta_{L,k}\Lambda_{\rm QCD}\right)\theta\left(\vec{b}_\perp^{\,2} \le \frac{\Lambda_{\rm QCD}^{-2}}{x(1-x)}\right),$$

New Mexico 2-24-06 | Orbital Angular Momentum in QCD | Stan Brodsky, SLAC

Outlook

- Only one scale Λ_{QCD} determines hadronic spectrum (slightly different for mesons and baryons).
- Light-cone frame is the natural frame to establish the AdS/QCD holographic duality.
- Ratio of Nucleon to Delta trajectories determined by zeroes of Bessel functions.
- AdS modes dual to hadrons extrapolate to valence constituents at zero separation in the AdS boundary.
- Non-zero orbital angular momentum and higher Fock-states require introduction of quantum fluctuations.
- Initial good approximation for description of the structure of hadronic form factors and other observables.
- Use of holographic light-front wave functions to compute hadronic matrix elements.
- Dominance of quark-interchange in hard exclusive processes emerges naturally from the classical duality of the holographic model, modified by gluonic quantum fluctuations.
- Covariant version of the bag model with confinement and conformal symmetry.
- Precise mapping of string modes to partonic states. Modes inside AdS represent the probability amplitude for the distribution of quarks at a given scale.
- Exact holographic mapping for n-parton state determines effective QCD transverse charge density in terms of modes in AdS space.
- Holographic mapping allows deconstruction: express the eigenvalue problem in terms of 3+1 QCD degrees of freedom.

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Hadron Dynamics at the Amplitude Level

- LFWFS are the universal hadronic amplitudes that underlie structure functions, GPDs, exclusive processes.
- Relation of transversity and other distributions to physics of the hadron itself.
- Connections between observables
- GPDs are not densities or probability distributions
- Parton number not conserved: n=n' & n=n'+2 at nonzero skewness
- orbital angular momentum
- Role of FSI and ISIs--Sivers effect

The total intrinsic $\boldsymbol{k}_\perp$ carried by quarks

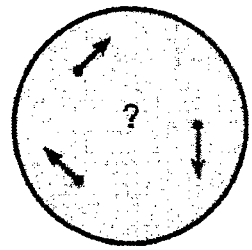
Mauro Anselmino – INFN

The issue of the total amount of intrinsic transverse momentum, $\boldsymbol{k}_\perp$, carried by quarks inside a transversely polarized proton, is addressed. In principle, the Sivers function gives the necessary amount of information: the number density of partons with longitudinal momentum fraction x and transverse momentum $\boldsymbol{k}_\perp$, inside a proton with spin $\boldsymbol{S}$. The extraction of the Sivers functions for u and d quarks, based on HERMES and COMPASS data on SIDIS azimuthal asymmetries, and performed by several groups, is reviewed. Models for such functions are given. They allow to obtain, multiplying by $\boldsymbol{k}_\perp$ and integrating over x and $\boldsymbol{k}_\perp$, the total intrinsic momentum carried by u and d quarks. Existing data do not allow any conclusion yet about the Sivers functions for sea quarks and for gluons: it is shown how indications about the gluons might be obtained by studying D and D^* production at RHIC.

The extracted Sivers functions are consistent with opposite total amounts of intrinsic motion for u and d quarks, $\boldsymbol{k}_\perp^u \simeq \boldsymbol{k}_\perp^d$, in agreement with M. Burkardt sum rule. The possible implications of such values for the orbital angular momentum carried by u and d quarks are discussed.

The total intrinsic $\mathbf{k}_\perp$ carried by quarks

- Extraction of the Sivers function
- What do we learn from it?
- $\mathbf{k}_\perp$ and orbital angular momentum
- Orbiting quarks … ?



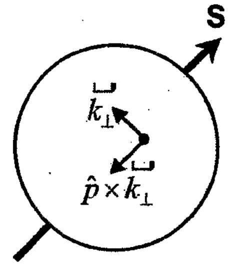
Mauro Anselmino, Parton Orbital Angular Momentum,
RBRC-UNM Workshop, Albuquerque, 24-26/02/2006

The Sivers distribution function

$$f_{a/p^\uparrow}(x,\vec{k}_\perp) = f_{a/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{a/p^\uparrow}(x,k_\perp)\, \vec{S}\cdot(\hat{p}\times\hat{k}_\perp)$$
$$= f_{a/p}(x,k_\perp) - f_{1T}^{\perp a}(x,k_\perp)\frac{\vec{S}\cdot(\hat{p}\times\vec{k}_\perp)}{M}$$

$$\left(\Delta^N f_{a/p^\uparrow} = -\frac{2k_\perp}{M} f_{1T}^{\perp a}\right)$$

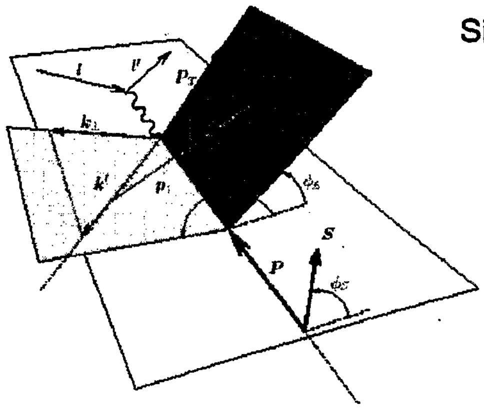
number density of partons with longitudinal momentum fraction x and transverse momentum $\mathbf{k}_\perp$, inside a proton with spin S



$$\sum_a \int dx\, d^2\vec{k}_\perp\, \vec{k}_\perp\, f_{a/p^\uparrow}(x,\vec{k}_\perp) = 0$$

M. Burkardt, PR D69, 091501 (2004)

Sivers mechanism in SIDIS



$$d\sigma = \frac{d^5\sigma}{dx\, dQ^2 dz\, d^2 P_T}$$

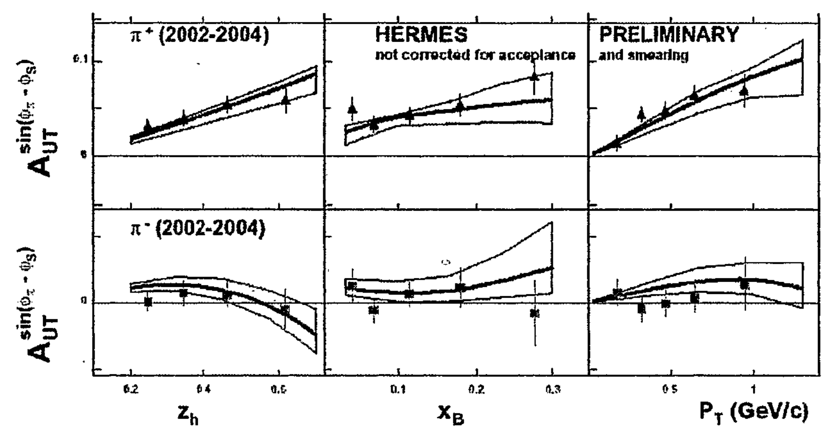
$$d\hat{\sigma} = \frac{d\hat{\sigma}^{lq\to lq}}{dQ^2}$$

$p_\perp = P_T - z\, k_\perp + O(k_\perp^2/Q^2)$

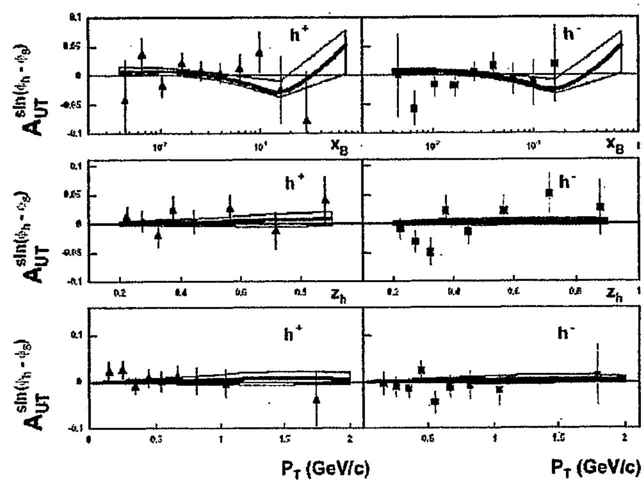
$$A_{UT}^{\sin(\Phi-\Phi_S)}(x,y,z,P_T) = \frac{\sum_q \int d\Phi_S d\Phi_h d^2k_\perp\, \Delta^N f_{q/p^\uparrow}(x,k_\perp) \sin(\varphi-\Phi_S)\, d\hat{\sigma}\, D_q^h(z,p_\perp) \sin(\Phi_h-\Phi_S)}{\sum_q \int d\Phi_S d\Phi_h d^2k_\perp\, f_{q/p}(x,k_\perp)\, d\hat{\sigma}\, D_q^h(z,p_\perp)}$$

$A_{UT}^{\sin(\Phi-\Phi_S)}$ from Sivers mechanism

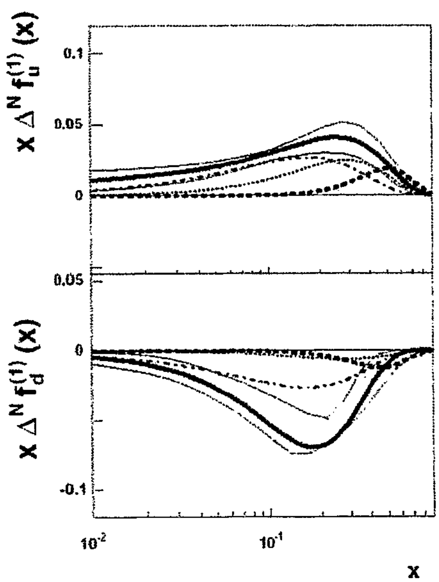
M.A., U.D'Alesio, M.Boglione, A.Kotzinian, A Prokudin



Deuteron target $A_{UT}^{\sin(\Phi_h-\Phi_S)} \propto \left(\Delta^N f_{u/p^\uparrow} + \Delta^N f_{d/p^\uparrow}\right)\left(4D_u^h + D_d^h\right)$



M.A, M. Boglione, U. D'Alesio, A. Kotzinian, F. Murgia, A. Prokudin



comparison of different extractions: hep-ph/0511017

first $p_\perp$ moments of extracted Sivers functions, compared with models

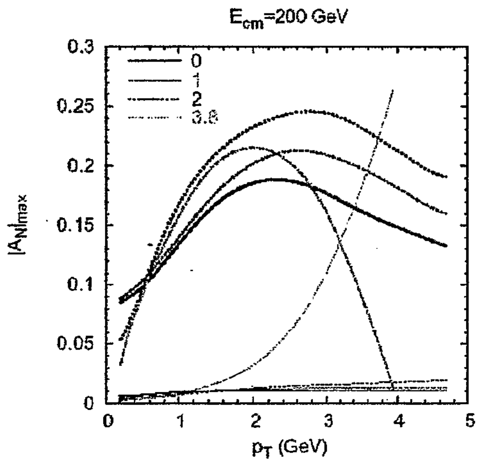
data from HERMES and COMPASS

$$\Delta^N f_q^{(1)} = -f_{1T}^{\perp(1)q} = \int d^2 k_\perp \frac{k_\perp}{4M} \Delta^N f_{q/p^\uparrow}(x, k_\perp)$$

$$\Delta^N f_{\bar{q}/p^\uparrow} = 0$$

SSA in p↑p → D X

$$d\sigma^{\uparrow} - d\sigma^{\downarrow} \propto \sum_q \Delta^N f_{q/p^{\uparrow}} \otimes f_{\bar{q}/p} \otimes d\hat{\sigma}^{q\bar{q}\to Q\overline{Q}} \otimes D_{D/Q}$$
$$+ \Delta^N f_{g/p^{\uparrow}} \otimes f_{g/p} \otimes d\hat{\sigma}^{gg\to Q\overline{Q}} \otimes D_{D/Q}$$



only Sivers effect: no transverse spin transfer in $q\bar{q} \to Q\overline{Q},\ gg \to Q\overline{Q}$

dominance of gluonic channel, access to gluon Sivers function

$|A_N|_{\max} =$ assuming saturated Sivers function

$$\Delta^N f_{a/p^{\uparrow}} = 2 f_{a/p}$$

(thick lines : $gg \to Q\overline{Q}$, thin lines : $q\bar{q} \to Q\overline{Q}$
0, 1, 2, 3.8 denote rapidities)

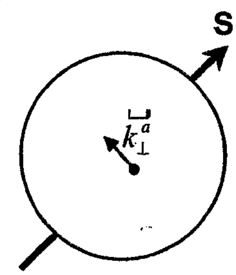
What do we learn from Sivers distribution?

total amount of intrinsic momentum carried by partons of flavour a

$$\vec{k}_{\perp}^{a} = \int dx\, d^2\vec{k}_{\perp}\, \vec{k}_{\perp} \left[\hat{f}_{a/p}(x,k_{\perp}) + \frac{1}{2} \Delta^N \hat{f}_{a/p^{\uparrow}}(x,k_{\perp})\, \vec{S}\cdot(\hat{p}\times\hat{k}_{\perp}) \right]$$
$$= \left(\sin\Phi_S\, \hat{i} - \cos\Phi_S\, \hat{j}\right) \frac{\pi}{2} \int dx\, dk_{\perp}\, k_{\perp}^2\, \Delta^N \hat{f}_{a/p^{\uparrow}}(x,k_{\perp})$$

for a proton moving along the +z-axis and polarization vector

$$\vec{S} = \left(\cos\Phi_S\, \hat{i} + \sin\Phi_S\, \hat{j}\right)$$
$$\vec{S}\cdot(\hat{p}\times\hat{k}_{\perp}) = \sin(\Phi_S - \varphi)$$



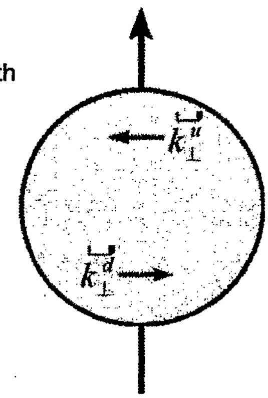
$$\vec{k}_\perp^u \cong +0.141\ (\cos\Phi_S\,\hat{\imath} + \sin\Phi_S\,\hat{\jmath}) \quad \text{GeV/c}$$

$$\vec{k}_\perp^d \cong -0.128\ (\cos\Phi_S\,\hat{\imath} + \sin\Phi_S\,\hat{\jmath}) \quad \text{GeV/c}$$

Sivers functions extracted from A_N data in $p\,p \to \pi\,X$ give also opposite results, with

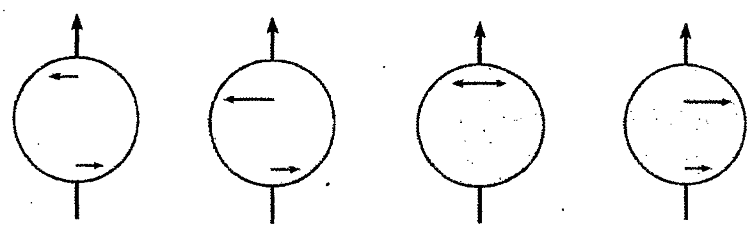
$k_\perp^u \cong 0.032 \qquad k_\perp^d \cong -0.036$

$$\boxed{\vec{k}_\perp^u + \vec{k}_\perp^d \approx 0\,?}$$



k⊥ and orbital angular momentum

(case of 2 quarks)



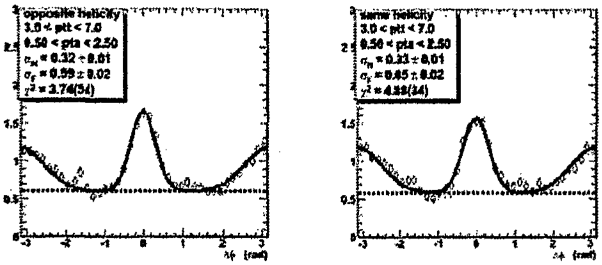
$\vec{k}_\perp^1 + \vec{k}_\perp^2 = 0$	$\vec{k}_\perp^1 + \vec{k}_\perp^2 \neq 0$	$\vec{k}_\perp^1 + \vec{k}_\perp^2 = 0$	$\vec{k}_\perp^1 + \vec{k}_\perp^2 \neq 0$
$\vec{L}^1 + \vec{L}^2 \neq 0$	$\vec{L}^1 + \vec{L}^2 \neq 0$	$\vec{L}^1 + \vec{L}^2 = 0$	$\vec{L}^1 + \vec{L}^2 = 0$

Does $\vec{k}_\perp^1 + \vec{k}_\perp^2 \neq 0$ imply $\vec{L}^1 + \vec{L}^2 \neq 0$?

It depends on space distribution …… to be continued ……

k_T Asymmetry in Longitudinally Polarized pp Collisions at PHENIX

D. E. Fields,[*1,*2] J. Rak,[*1] I. Younus,[*1] and R. Hobbs[*1]



(a) (b)

Fig. 1. Azimuthal correlation functions for opposite (a) and same (b) helicities in the ($3.0GeV/c < p_{Tt} < 7.0GeV/c$) range of triggered π^0 transverse momentum.

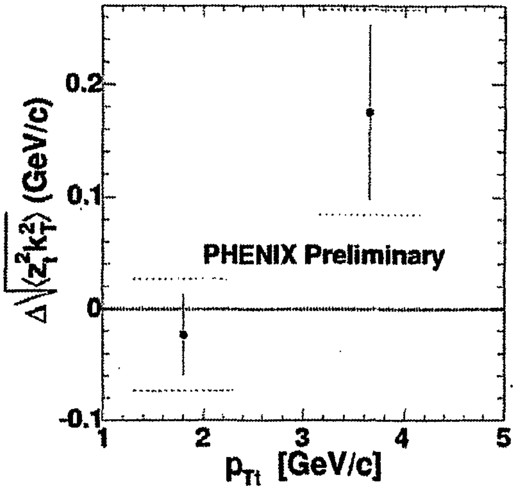


Fig. 2. Difference in $(zk_T)_{RMS}$ for the same helicity minus opposite helicity events as a function of triggered π^0 transverse momentum p_{Tt}.

Researchers in the PHENIX experiment at RHIC have developed a method for measuring the average net pair transverse momentum of hard scattered jets at central rapidity[1)]. This method utilizes the azimuthal correlation between a leading high p_T π^0 and another charged hadron. The widths of the resulting near- and far-side peaks can then be related to the fragmentation transverse momentum, j_T (the transverse momentum of the fragmented hadron relative to the hard-scattered parton) and the net pair transverse momentum, k_T in a straightforward manner. The net pair transverse momentum can be produced from parton intrinsic transverse momentum inside the proton, from soft gluon emmission, or from next-to-leading order processes of the perturbative QCD. In addition, one can consider the possibility that spin-correlated transverse momentum (orbital angular momentum) may contribute to k_T, as discussed in Ref. 2. Coherent spin-dependent parton transverse momentum adds to k_T an amount dependent upon the helicity combination of the colliding protons, and upon the impact parameter of the collision. However, an integration over impact parameter will likely leave a residual effect that is dependent only on the helicity combination, a signal that could be examined in the present data from past RHIC runs.

We have examined this k_T asymmetry in the 2003 RHIC run. Figure 1 shows the azimuthal angle distribution between triggered π^0 in the transverse momentum range of ($3.0GeV/c < p_{Tt} < 7.0GeV/c$) and an associated charged hadron in the ($0.5GeV/c < p_{Ta} < 2.5GeV/c$) range for opposite (left panel) and same (right panel) helicities for the colliding protons. From these correlation functions, the widths of the near-side peak (around $\Delta\phi = 0$) and the far-side peak (around $\Delta\phi = \pi$) are exctracted. From these, the corresponding values of fragmentation transverse momentum j_T, and root-mean-squared (RMS) transverse momentum fraction weighted by a momentum fraction (z) of the fragmented hadron to the scattered parton, $(zk_T)_{RMS}$, are determined.

The difference in the extracted $(zk_T)_{RMS}$ for the same helicity minus the opposite helicity events is shown in Fig. 2. The 2003 RHIC run data set does not show a significant effect. A bunch shuffling technique[3)] was used to test the errors on the points by randomly assigning helicity combinations to each RHIC bunch crossing and then resorting. The distribution of differences in the extracted $(zk_T)_{RMS}$ for many sets of randomized "shuffles" was centered on zero and had widths (shown as dotted lines in Fig. 2) which were consistent with the statistical uncertainties (solid lines in Fig. 2).

The PHENIX data set from polarized proton running during the 2005 RHIC run has approximately ten times higher luminosity, and has almost twice the polarization as that of the 2003 RHIC run. Analysis of this data set is on-going and should be completed soon.

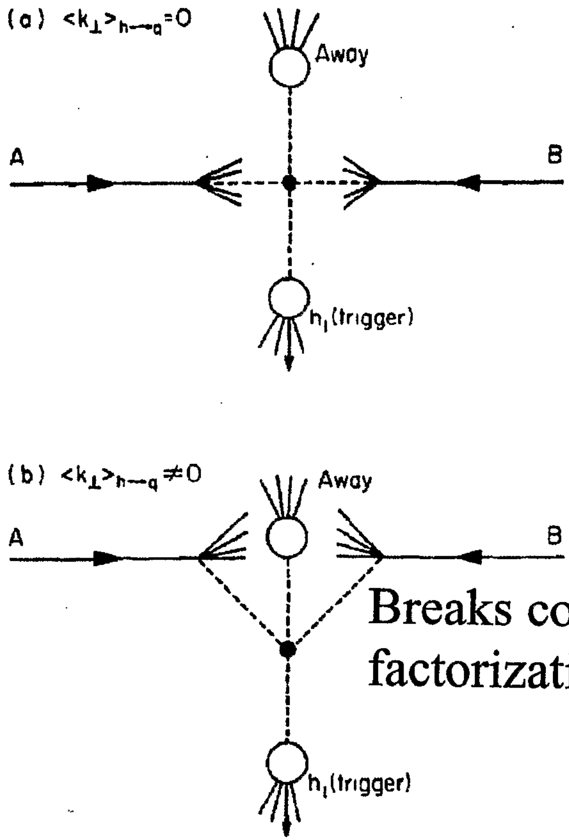
References
1) J. Rak, J. Phys. G30 (2004), S1309-S1312.
2) Meng Ta-chung et al., Phys. Rev. D 40 (1989)
3) Adler, S. S. et al., Phys. Rev. Lett. 93 (2004)

*1 University of New Mexico
*2 RIKEN-BNL Research Center

What is the origin of k_T?

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

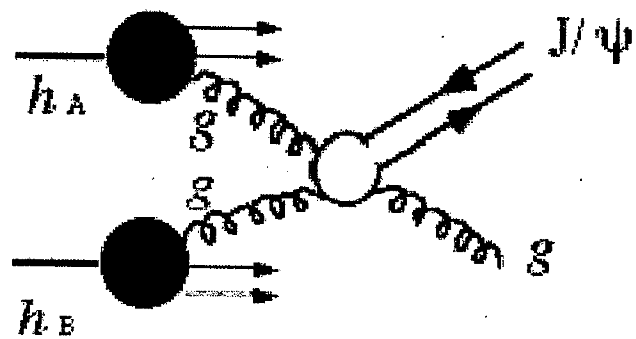
Intrinsic (Confinement) $k_T \approx 200$ MeV/c



Breaks collinear factorization

Soft QCD radiation.

An example - J/ψ production.



Extra gluon kick

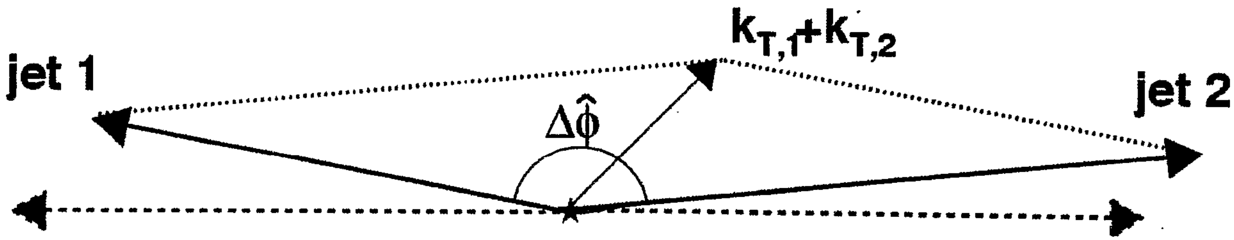
$\langle p_T \rangle_{J/\psi} = 1.8 \pm 0.23 \pm 0.16$ GeV/c

Phys. Rev. Lett. 92, 051802, (2004).

Another Possibility

- Spin-Correlated transverse momentum – Partonic orbital angular momentum
- We can perhaps measure using jet k_T
  - –Sivers Effect in single (double?) transverse spin
  - –Possible Effect in double longitudinal spin

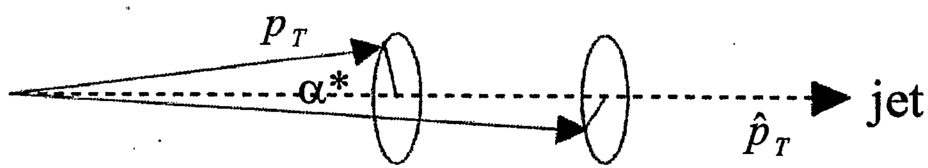
k_T, j_T "easy" measurement in $p+p$

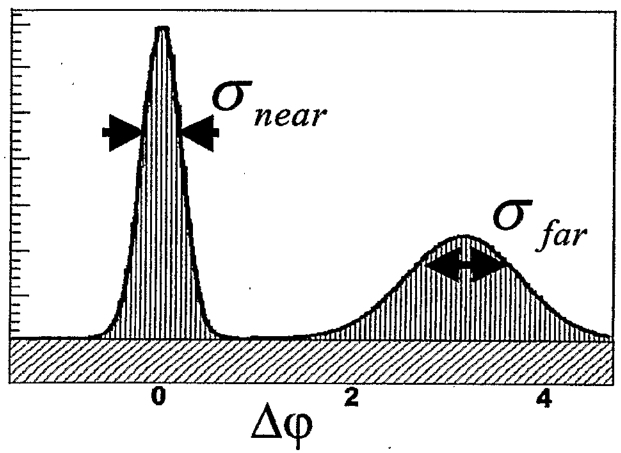


$j_T = \hat{p}_T \sin(\alpha^*)$

fragmentation

$z = \frac{p_T \cos(\alpha^*)}{\hat{p}_T}$





$\propto \sigma_N$

jet fragmentation transverse momentum, j_T-scaling.

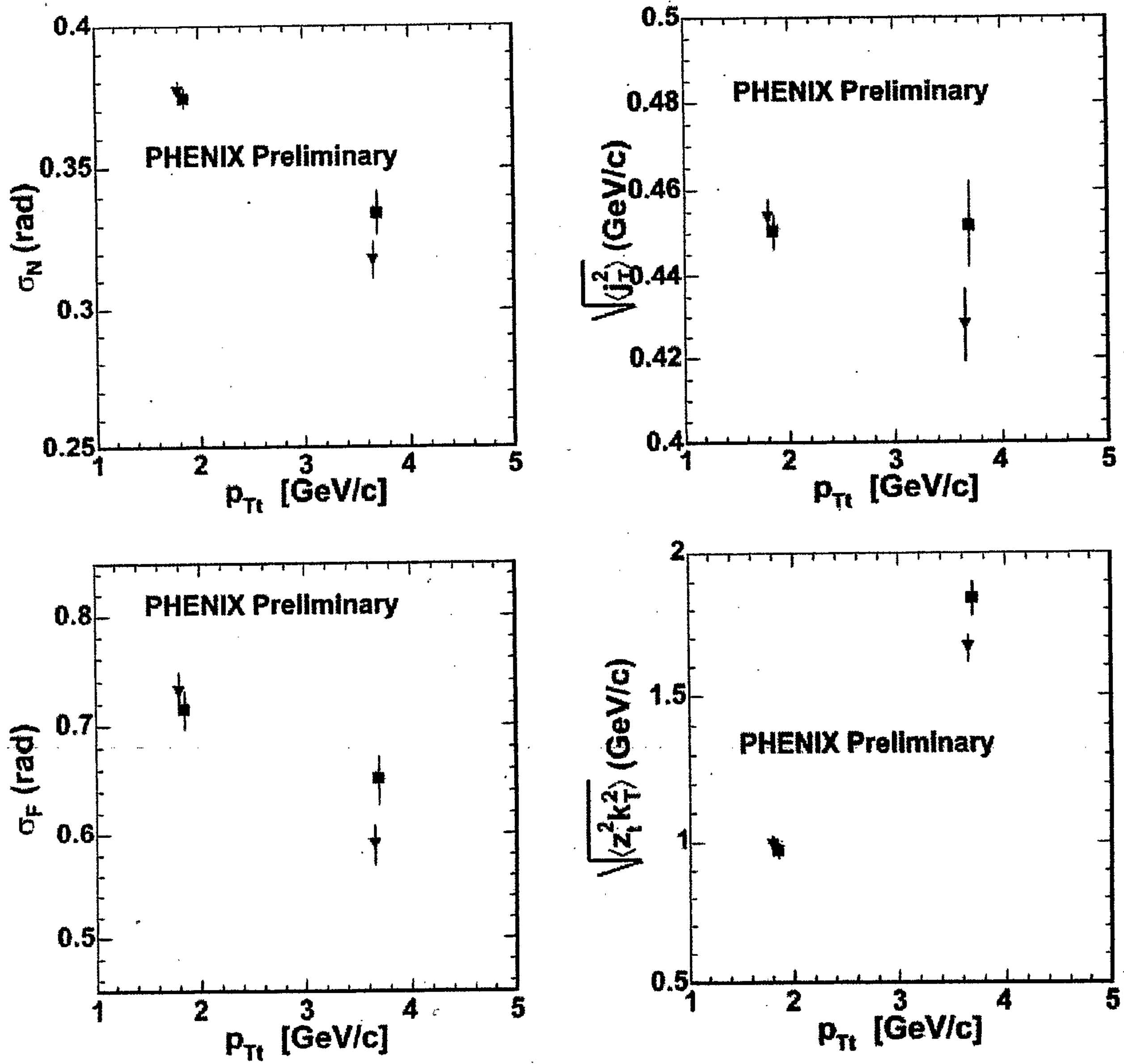
$\propto \sqrt{\sigma^2_F - \sigma^2_N}$

parton transverse momentum, intrinsic + NLO radiative corrections.

Run03 Data

Like sign

Unlike sign



trigger π^0

$1 < p_{Tt} < 3$ Gev/c

$3 < p_{Tt} < 7$ Gev/c

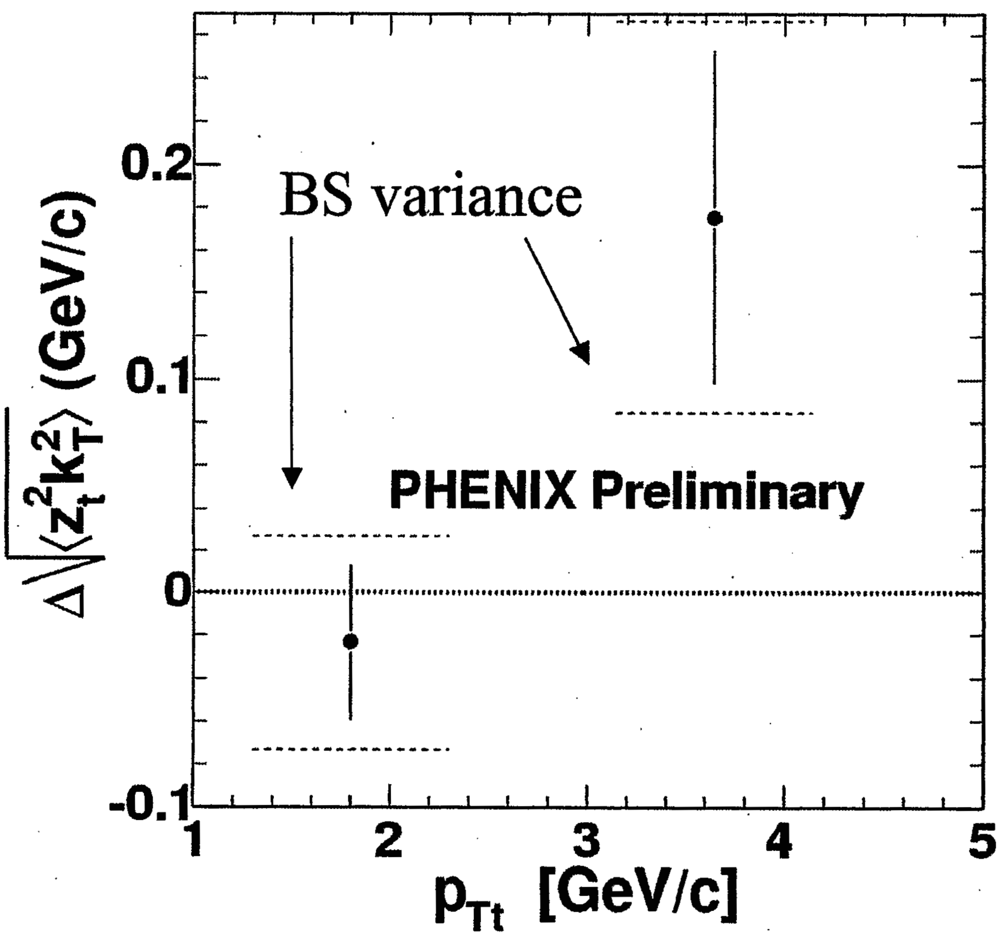
Associated $h^{\pm}$

$1 < p_{Ta} < 2.5$ Gev/c

Run03 Data

Its too early to make a definite statement about the apparent excess as the systematic uncertainties are being evaluated.

However, there is an ongoing analysis of 10x more stat. and 2x better polarization in run05 ➔ should yield a definite answer.



Summary

- Jet k_T can be extracted from di-hadron correlations using method developed by J. Rak and others.
- Jet k_T can be used to probe initial and final state contributions to transverse momentum distributions.
- We can make a measurement of the spin dependence of jet $<k_T>$ in:
  - Single transverse spin asymmetries – Sivers Function.
  - Double-longitudinal spin asymmetry – Fields Function.
- These may be sensitive to orbital angular momentum.
- Need theoretical guidance…

Some thoughts on the helicity dependence of "jet-k_T"

Werner Vogelsang

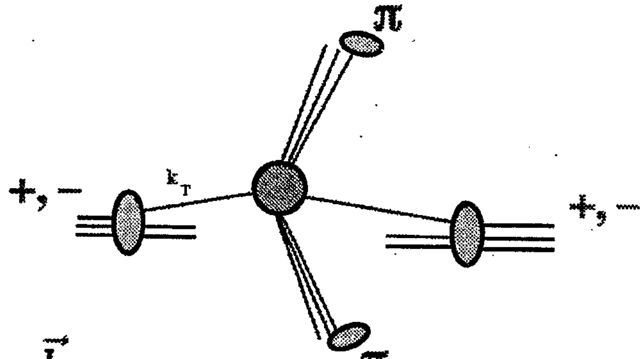
Physics Department and RIKEN-BNL Research Center,
Brookhaven National Laboratory, Upton, NY 11973, U.S.A.

The observable discussed in Doug Field's talk, and experimentally studied by Phenix, is the average pair transverse momentum $\langle K_\perp^2 \rangle$ of the two hadrons (pions) produced in $\vec{p}\vec{p} \to h_1 h_2 X$, separately for the two settings ++ or +− of the initial protons' helicities. Based on earlier work by Meng et al. (T. c. Meng, J. c. Pan, Q. b. Xie and W. Zhu, Phys. Rev. D **40**, 769 (1989)), it is hoped that any difference between $\langle K_\perp^2 \rangle_{++}$ and $\langle K_\perp^2 \rangle_{+-}$ could be an indication of the presence of partonic orbital angular momenta in the proton, through a dependence of parton motion "around" the proton momentum on helicity.

The present talk discusses the observable in perturbative QCD. It shows first that even without any intrinsic relation between proton helicity and parton transverse momenta, a non-vanishing difference between $\langle K_\perp^2 \rangle_{++}$ and $\langle K_\perp^2 \rangle_{+-}$ may be generated by the fact that several partonic channels contribute to the observable, each of which has difference spin dependence. If the widths of the quark and gluon distributions in intrinsic transverse momentum differ (which is supported by perturbation theory), then the helicity-dependence of the partonic scatterings will not cancel in the difference $\sqrt{\langle K_\perp^2 \rangle_{++}} - \sqrt{\langle K_\perp^2 \rangle_{+-}}$. This effect is estimated in a simple Gaussian model to be of the order of a few tens of MeV, with large uncertainties. The effect becomes very small whenever a single partonic process dominates. This implies that the Drell-Yan process with its single LO partonic reaction $q\bar{q} \to \gamma^*$ would be ideal for disentangling genuine effects associated with the structure of the proton from the more "mundane" ones discussed here. The Drell-Yan process was also the process discussed in the Meng et al. paper mentioned above.

In the second part of the talk, we discuss the relevance of Sudakov effects for the observable considered. Large logarithmic corrections appear in processes characterized by a large momentum scale (here, the transverse momenta of each of the produced hadrons) and a much smaller, measured, transverse momentum (here, the pair transverse momentum). These corrections may be resummed to all orders in perturbation theory. A detailed study of the difference $\sqrt{\langle K_\perp^2 \rangle_{++}} - \sqrt{\langle K_\perp^2 \rangle_{+-}}$ will need to take into account these primarily perturbative effects.

- **The observable :**



$$\vec{K}_\perp \equiv \vec{k}_{\perp,1} + \vec{k}_{\perp,2}$$

measure $\langle \mathrm{K}_\perp^2 \rangle_{++}$ **vs** $\langle \mathrm{K}_\perp^2 \rangle_{+-}$

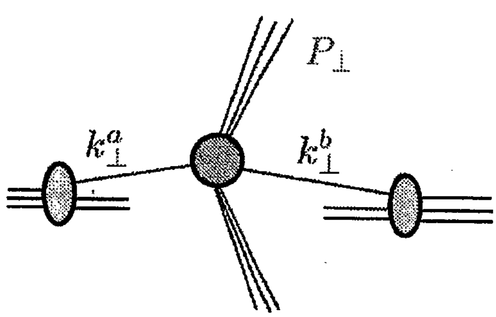
- **it is hoped that any difference has to do with OAM (won't be discussed in this talk...)** Meng et al.
- **what can we say (in pQCD) about this observable ?**

Let's assume :

(1) can describe process by partonic hard scattering (✔)

(2) can use factorization in terms of k_T-dependent parton distributions and fragmentation fcts. :

$$d\sigma = \sum_{ab} \int d^2\vec{k}_\perp^a \, dx_a \int d^2\vec{k}_\perp^b \, dx_b \; f_a(x_a, \vec{k}_\perp^a) \, f_b(x_b, \vec{k}_\perp^b) \times \delta^{(2)}\left(\vec{k}_\perp^b + \vec{k}_\perp^b - \vec{K}_\perp\right) \hat{\sigma}_{ab}\left(\vec{P}_\perp, x_a, x_b\right)$$



(?)

(3) dependence of distrib. on k_T is entirely non-perturbative, Gaussian, and factorizes from x-dependence :

$$f_i(x,\vec{k}_\perp) = f_i(x)\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_i}}{\pi\langle k_\perp^2\rangle_i}$$

(none of these will be true ...)

usual pdf

then : $$\langle K_\perp^2\rangle = \langle k_\perp^2\rangle_a + \langle k_\perp^2\rangle_b$$ **for one part. channel ab → cd**

(4) if all quarks and antiquarks have same widths, obtain after sum over all partonic channels :

$$\langle K_\perp^2\rangle = \frac{2\langle k_\perp^2\rangle_g\,S_{gg} + \left(\langle k_\perp^2\rangle_g + \langle k_\perp^2\rangle_q\right)S_{qg} + 2\langle k_\perp^2\rangle_q\,S_{qq}}{S_{gg} + S_{qg} + S_{qq}}$$

contain all partonic cross secs. pdf's & fragm. fcts.

(5) gluons are "broader" than quarks :

$$\langle k_\perp^2\rangle_g \approx 2\,\langle k_\perp^2\rangle_q$$

(has probably some truth ...)

(the "2" really is $C_A/C_F = 9/4$)

(6) now assume that k_T-widths are spin-*in*dependent:

$$\Delta f_i(x, \vec{k}_\perp) = \Delta f_i(x) \, \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle_i}}{\pi \langle k_\perp^2 \rangle_i}$$

(supported by pert. theory)

Then :

$$\langle K_\perp^2 \rangle_{++} = \frac{2\langle k_\perp^2 \rangle_g \, S_{gg}^{++} + \left(\langle k_\perp^2 \rangle_g + \langle k_\perp^2 \rangle_q \right) S_{qg}^{++} + 2 \langle k_\perp^2 \rangle_q \, S_{qq}^{++}}{S_{gg}^{++} + S_{qg}^{++} + S_{qq}^{++}}$$

$$\langle K_\perp^2 \rangle_{+-} = \frac{2\langle k_\perp^2 \rangle_g \, S_{gg}^{+-} + \left(\langle k_\perp^2 \rangle_g + \langle k_\perp^2 \rangle_q \right) S_{qg}^{+-} + 2 \langle k_\perp^2 \rangle_q \, S_{qq}^{+-}}{S_{gg}^{+-} + S_{qg}^{+-} + S_{qq}^{+-}}$$

Note :

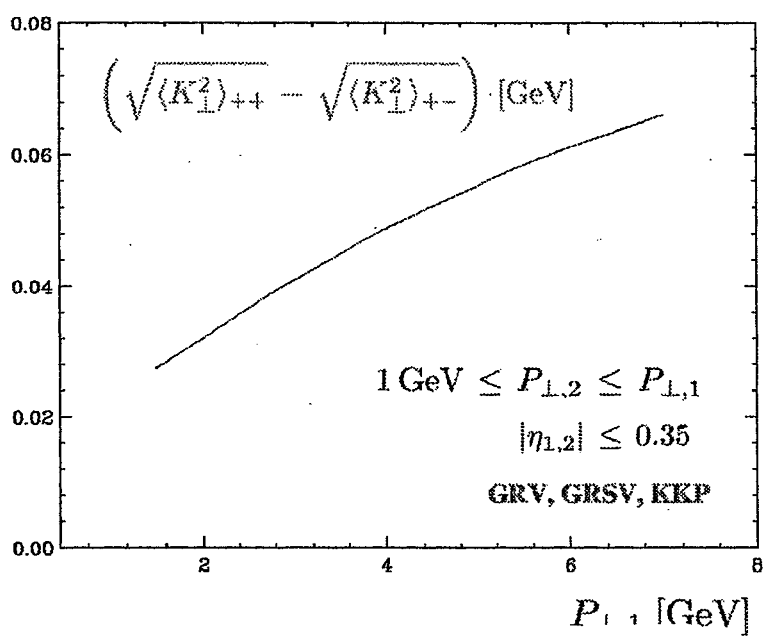
$$S_{ij}^{++} \neq S_{ij}^{+-} \quad \longrightarrow \quad \langle K_\perp^2 \rangle_{++} \neq \langle K_\perp^2 \rangle_{+-}$$

- **a relatively small effect :** $\vec{p}\vec{p} \to \pi^0 \pi^0 X$

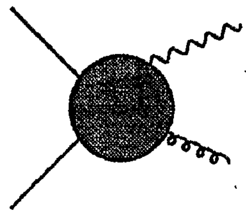
$\sqrt{\langle k_\perp^2 \rangle_g} = 2$ GeV

$$\langle k_\perp^2 \rangle_a + \langle k_\perp^2 \rangle_b + \left(1/z_c^2 + 1/z_d^2 \right) \langle k_\perp^2 \rangle_{fr}$$

fragm., 0.25 GeV²

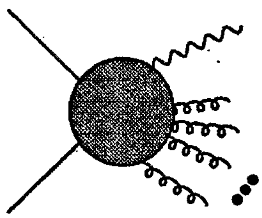


- **DY, first-order correction :**



as $q_T \rightarrow 0$ $$\frac{d^2\hat{\sigma}^{(1)}_{q\bar{q}}}{dQ^2 d^2 q_T} \sim \alpha_s \frac{\ln(q_T/Q)}{q_T^2} + \ldots$$

- **higher orders :**



$$\frac{d^2\hat{\sigma}^{(k)}_{q\bar{q}}}{dQ^2 d^2 q_T} \sim \alpha_s^k \frac{\ln^{2k-1}(q_T/Q)}{q_T^2} + \ldots$$

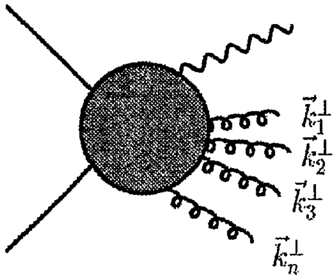
- $\alpha_s^k \, L^{2k-1}$, ... **can be taken into account to all orders**

  = **Resummation !**

- **work began in the '80s with Drell-Yan**

  * **q_T resummation** — Dokshitzer et al.; Parisi Petronzio; Collins, Soper, Sterman; ...

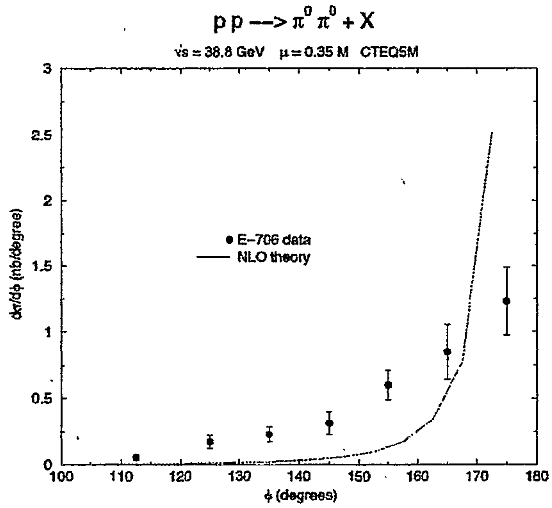
- **large log. terms exponentiate after suitable integral transform is taken :**

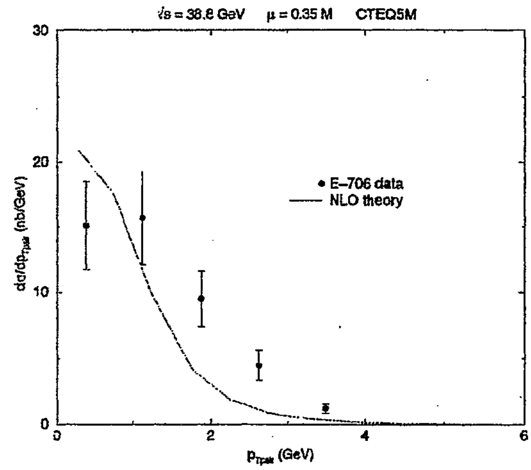


$$\delta^2\left(\vec{q}_T + \sum_i \vec{k}_T^i\right) = \frac{1}{(2\pi)^2}\int d^2b \, e^{-i\vec{b}\cdot(\vec{q}_T + \sum_i \vec{k}_T^i)}$$

$$\frac{\ln^{2k-1}(q_T/Q)}{q_T} \leftrightarrow \ln^{2k}(bQ)$$

- **same phenomenon in back-to-back hadrons :**





J. Owens

IV. Conclusions

- **one expects a difference between**

$$\langle K_\perp^2 \rangle_{++} \quad \textbf{and} \quad \langle K_\perp^2 \rangle_{+-}$$

for pp → ππX

- **not related to "intrinsic" properties**
- **on the other hand, effect is probably relatively small**
- **Refinement of observable ? Other final states?**

Aspects of Quark Orbital Angular Momentum

Matthias Burkardt (New Mexico State University)

Distributions of quarks are transversely deformed when one considers transversely polarized nucleons and/or quarks. The transverse deformation of the unpolarized quark distribution in a transversely polarized nucleon is descibed by the Fourier transform of the GPD $E(x, 0, -\mathbf{\Delta}_\perp^2)$. The transverse deformation of the transversely polarized quark distribution in an unpolarized nucleon is descibed by the Fourier transform of the GPD $\tilde{H}_T + E_T$. The physical origin of these deformations is the orbital motion of the quarks. Parton distributions have the physical interpretation as momentum distributions in the infinite momentum frame [1]. For a quark orbiting transversely to the nucleon this implies an increase of quark momentum due to the orbital motion on one side and a decrease of the other side of the nucleon. The increase/decrease of a quark's momentum implies an increase/decrease in the momentum disytribution which causes the transverse distortion. Since E enters Ji's angular momentum sum rule for the total angular momentum carried by the quarks, it is thus not surprising that $\tilde{H}_T + E_T$ enters a similar relation for the correlation between the quark spin and its total angular momentum [2]

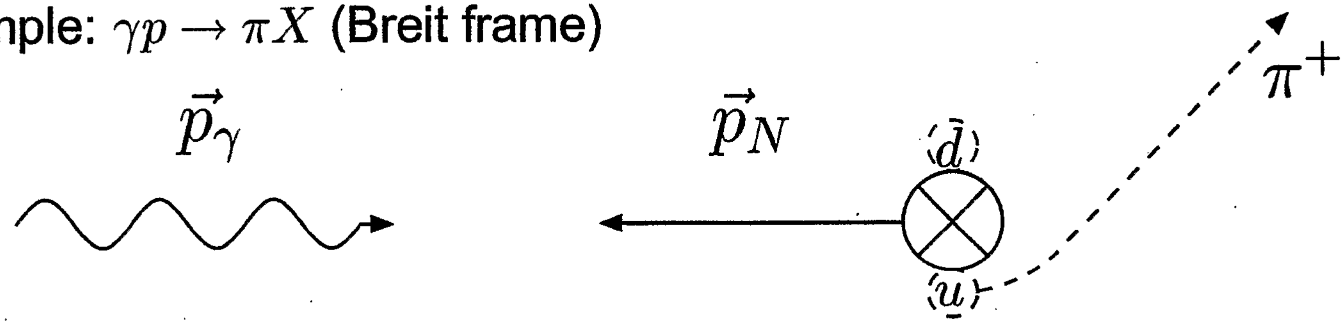
$$\langle \delta^x J_q^x \rangle = \frac{1}{2} \int_0^1 dx \left[H_T(x,0,0) + 2\tilde{H}_T(x,0,0) + E_T(x,0,0) \right] x. \qquad (1)$$

1. M. Burkardt, Int. J. Mod. Phys. **A18**, 173 (2003).

2. M. Burkardt, Phys. Rev. D **72**, 094020 (2005).

GPD $\longleftrightarrow$ SSA (Sivers)

- example: $\gamma p \rightarrow \pi X$ (Breit frame)



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

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

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

- $f_{1T}^{\perp q} \sim -\kappa_q$ consistent with HERMES & COMPASS results

Chirally Odd GPDs

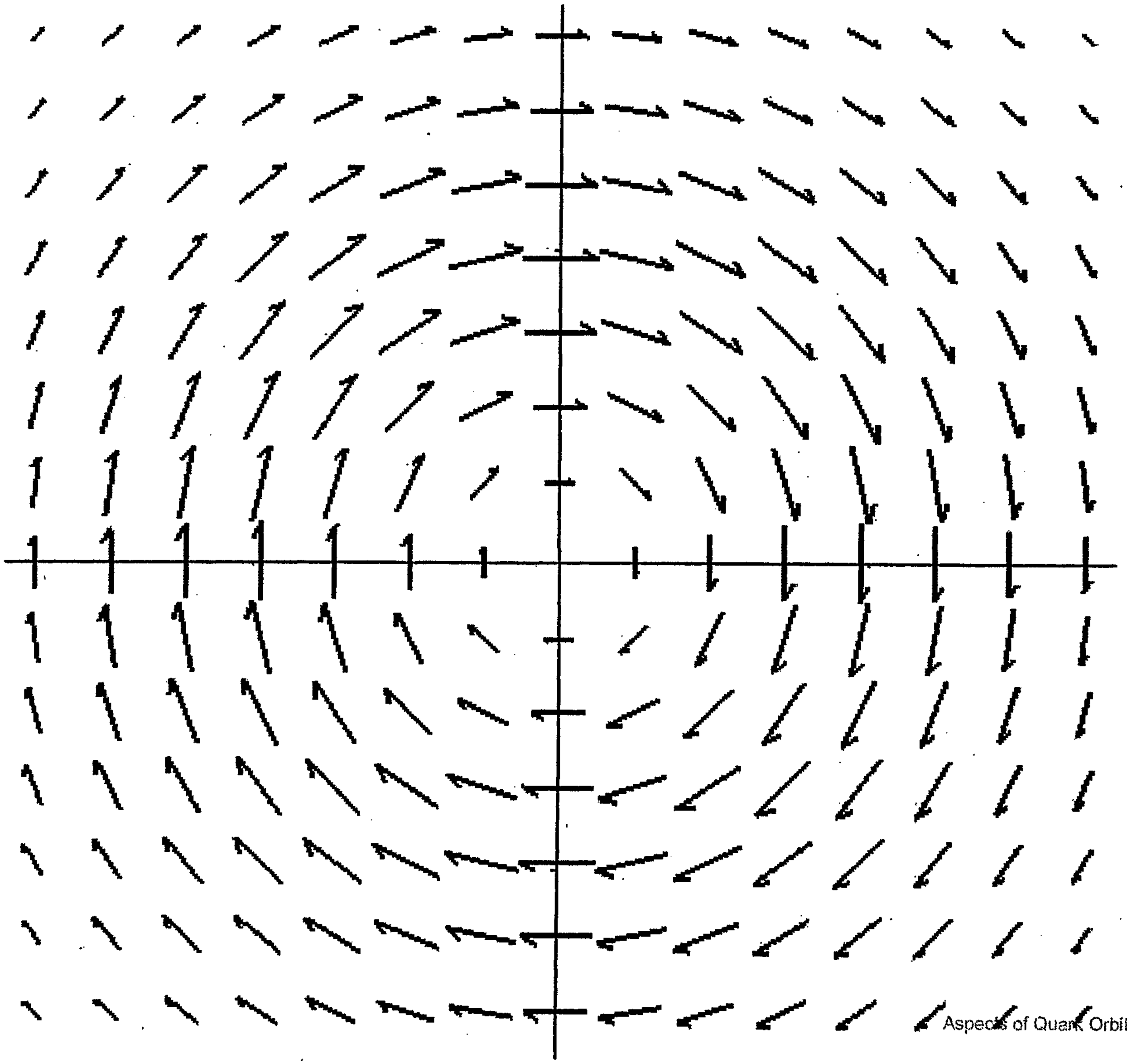
$$\int \frac{dx^-}{2\pi} e^{ixp^+x^-} \left\langle p' \left| \bar{q}\left(-\frac{x^-}{2}\right) \sigma^{+j}\gamma_5 q\left(\frac{x^-}{2}\right) \right| p \right\rangle = H_T \bar{u}\sigma^{+j}\gamma_5 u + \tilde{H}_T \bar{u}\frac{\varepsilon^{+j\alpha\beta}\Delta_\alpha P_\beta}{M^2} u$$
$$+ E_T \bar{u}\frac{\varepsilon^{+j\alpha\beta}\Delta_\alpha\gamma_\beta}{2M} u + \tilde{E}_T \bar{u}\frac{\varepsilon^{+j\alpha\beta}P_\alpha\gamma_\beta}{M} u$$

- Fourier trafo of $2\tilde{H}_T^q + E_T^q$ for $\xi = 0$ describes distribution of transversity $q^i(x, \mathbf{b}_\perp)$ for unpolarized target in $\perp$ plane: (M.Diehl+P.Hägler, hep-ph/0504175)

$$q^i(x, \mathbf{b}_\perp) = \frac{\varepsilon^{ij}}{2M}\frac{\partial}{\partial b_j}\int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{i\mathbf{b}_\perp\cdot\mathbf{\Delta}_\perp}\left[2\tilde{H}_T^q(x, 0, -\mathbf{\Delta}_\perp^2) + E_T^q(x, 0, -\mathbf{\Delta}_\perp^2)\right]$$

- origin: correlation between quark spin (i.e. transversity) and angular momentum

Transversity Distribution in Unpolarized Target



Transversity Decomposition of J_q^x

- similarily $\perp$ deformation distribution for quarks with given transversity described by $2\tilde{H}_T + E_T$

$\hookrightarrow$ new relation: transversity decomposition of $J_q^x = J_{q,+\hat{x}}^x + J_{q,-\hat{x}}^x$

$$\langle J_{q,\pm\hat{x}}^x \rangle = \frac{S^x}{2} \int dx\, x \left[H(x,0,0) + E(x,0,0)\right]$$
$$\pm \frac{1}{4} \int dx\, x \left[H_T(x,0,0) + 2\tilde{H}_T(x,0,0) + E_T(x,0,0)\right].$$

- $J_{q,\pm\hat{x}}^x$ is angular momentum carried by quarks with spin (transversity) in $\pm\hat{x}$-direction; $P_{\pm\hat{x}} = \frac{1}{2}(1 \pm \gamma^x\gamma_5)$
- Decomposition is possible since $J_q^x \sim \int d^3r \left(T_q^{0z} y - T_q^{0y} z\right)$ is diagonal in transversity!
- unpol. target: $J_{q,\pm\hat{x}}^x \pm \frac{1}{4} \int dx\, x \left[H_T + 2\tilde{H}_T + E_T\right]$
- $\int dx\, x \left[2\tilde{H}_T + E_T)\right]$ from lattice (hep-ph/0511047), or ...

Boer-Mulders function

- Boer-Mulders: distribution of $\perp$ **pol.** quarks in **unpol.** proton

$$f_{q^\uparrow/p}(x,\mathbf{k}_\perp) = \frac{1}{2}\left[f_1^q(x,\mathbf{k}_\perp^2) - h_1^{\perp q}(x,\mathbf{k}_\perp^2)\frac{(\hat{\mathbf{P}}\times\mathbf{k}_\perp)\cdot S_q}{M}\right]$$

- can be probed in Drell-Yan ($\to$ J-PARC)
- physical mechanism for BM-function: attractive FSI expected to convert position space asymmetry for $\perp$ polarized quark distributions into momentum space asymmetry

$\hookrightarrow$ e.g. quarks at negative b_x with spin in $+\hat{y}$ get deflected (due to FSI) into $+\hat{x}$ direction

$\hookrightarrow$ (qualitative) connection between Boer-Mulders function $h_1^\perp(x,\mathbf{k}_\perp)$ and the chirally odd GPD $2\tilde{H}_T + E_T$ that is similar to (qualitative) connection between Sivers function $f_{1T}^\perp(x,\mathbf{k}_\perp)$ and the GPD E.

- No sum rule for $h_1^\perp(x,\mathbf{k}_\perp)$
(even possible that $h_1^{\perp\, u}$ same sign as $h_1^{\perp\, d}$

Studies of OAM at JLab

H. Avakian for the CLAS Collaboration

Jefferson Lab

The orbital motion of quarks has been of particular interest since the EMC measurements implied that the helicity of the constituent quarks account for only a fraction of the nucleon spin. Two new sets of parton distribution functions were introduced contain information not only on the longitudinal but also on the transverse distributions of partons in a fast moving. This distributions are experimentally accessible in measurements of azimuthal distributions of final state particles in semi-inclusive and hard exclusive processes.

We present recent results from Jefferson Lab's CLAS detector on beam and target single-spin asymmetries in pion and photon electroproduction off unpolarized hydrogen and polarized NH_3 targets. A precision measurement of DVCS asymmetries was performed on the hydrogen target in a wide kinematic range , allowing a fine binning required for extraction of underlying GPDs (slides 17,19 in the talk). The DVCS asymmetry was also measured with longitudinally polarized target, which is sensitive to the polarized GPD, allowing separation of polarized and unpolarized GPDs (slide 20). Measurements of Single Spin Asymmetries (SSAs) in exclusive rho production at CLAS with a transversely polarized target will provide additional information on flavor dependence of GPDs (slide 23).

Single spin asymmetries of pions were also measured with longitudinally polarized target. The target spin dependent $\sin 2\phi$ moment of the cross section gives access to the transverse momentum dependent distribution, describing the transverse polarization of quarks in the longitudinally polarized nucleon(27). In addition the target spin dependent $\sin\phi$ moment of the cross section probes the higher twist (HT) distribution (slide 28). The JLab upgrade will allow a precise test of the factorization ansatz and the investigation of the Q^2 dependence of the $\sin\phi$ moments of unpolarized and longitudinally polarized SSAs (slide 30) to prove their HT nature.

Studies of OAM at JLAB

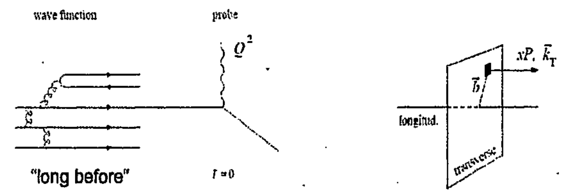
Harut Avakian
Jefferson Lab

UNM/RBRC Workshop on Parton Angular Momentum , NM, Feb 2005

- Introduction
- Exclusive processes
- Semi-Inclusive processes
- Summary

* In collaboration with V.Burkert and L.Elouadrhiri

Parton picture: Longitudinal and transverse variables



Inclusive	$f(x)$	PDF (spin/flavor)	Twist-2
Exclusive	$f(x, b, \xi)$	GPD $\leftrightarrow J_q$	Twist-2
Semi-inclusive	$f(x, k_T)$	TMD (Sivers, Boer-Mulders)	Twist-2, 3, 4 interaction-dep.

Quark Angular Momentum Sum Rule

GPDs H^u, H^d, E^u, E^d provide access to total quark contribution to proton angular momentum.

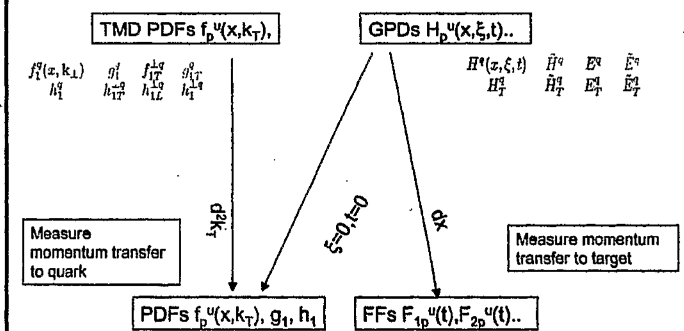
Proton's spin $\frac{1}{2} = \frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q + J_g$, where $\frac{1}{2}(\Delta u + \Delta d + \Delta s) + L_q = J_q$

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx \left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

X. Ji, Phy.Rev.Lett.78,610(1997)

Large x contributions important.

3D Parton Distributions



Analysis of SIDIS and DVMP are complementary

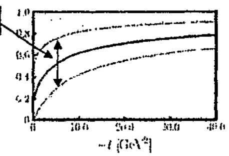
Form Factor Studies

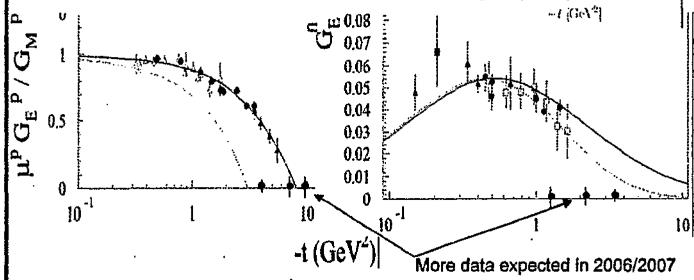
Sachs Form Factors

$G_E(t)=F_1(t)+t/4M^2*F_2(t)$
$G_M(t)=F_1(t)+F_2(t)$

$$\int_0^1 dx\, \mathcal{H}^q(x,t) = F_1^q(t)$$
$$\int_0^1 dx\, \mathcal{E}^q(x,t) = F_2^q(t)$$

~9 0%





Form Factor Studies

Use various parameterizations for GPDs to fit the existing form factor data

$$\int_0^1 dx\, \mathcal{H}^q(x,t) = F_1^q(t)$$
$$\int_0^1 dx\, \mathcal{E}^q(x,t) = F_2^q(t)$$

A.Afanasev hep-ph/9910565
Diehl et al, Eur.Phys.J c39 (2005)
M.Guidal et al PRD (2005)

Different parameterizations yield different contributions for quarks to the OAM

A)Large L_d and small L_u
B)Sum of L_u and L_d small

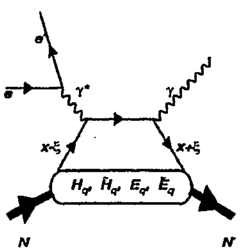
	A	B	C
$\Delta_u + L_u$	0.6	0.82	0.73
$\Delta_d + L_d$	-0.08	-0.37	-0.25
$\Delta_u + L_u + \Delta_d + L_d$	0.52	0.45	0.48

Issues: different realistic fits to FFs produce different values for Lq fits done at high t, need to be extrapolated to t→0

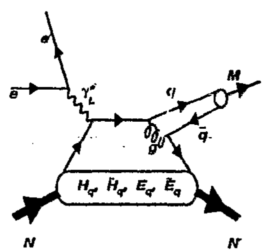
More observables needed for detailed studies of GPDs and the OAM (RCS,DVCS,DVMP)

Hard Exclusive Processes and GPDs

DVCS



DVMP



DVCS – for different polarizations of beam and target provide access to different combinations of GPDs H, $\tilde{H}$, E

DVMP for different mesons is sensitive to flavor contributions (ρ^0/ρ^+ select H, E, for u/d flavors, π, η, K select $\tilde{H}$, $\tilde{E}$)

Study the asymptotic regime and guide theory in describing HT.

Deeply Virtual Compton Scattering ep->e'p'γ

$$\frac{d^4\sigma}{dQ^2 dx_B dt d\phi} \sim |T^{DVCS} + T^{BH}|^2$$

T^{BH}: given by elastic form factors
T^{DVCS}: determined by GPDs

Polarized beam, unpolarized target:

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

Kinematically suppressed

Unpolarized beam, longitudinal target:

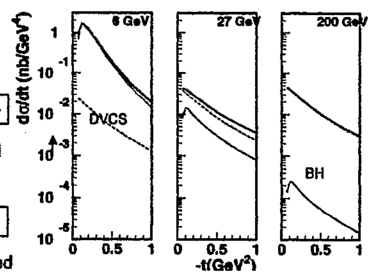
$\Delta\sigma_{UL} \sim \sin\phi \mathrm{Im}\{F_1\tilde{H} + \xi(F_1+F_2)(H + ..\}$

Kinematically suppressed

Unpolarized beam, transverse target:

$\Delta\sigma_{UT} \sim \sin\phi \mathrm{Im}\{k_1(F_2 H - F_1 E) + ..\}$

Kinematically suppressed



$\xi = x_B/(2-x_B)$, $k = t/4M^2$

•Different GPD combinations accessible as **azimuthal moments** of the total cross section.

38

Deeply Virtual Compton Scattering ep→e'p'γ

$$|\mathcal{T}_{BH}|^2 = \frac{e^6}{x_B^2 y^2 (1+\epsilon^2)^2 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{BH} + \sum_{n=1}^{2} c_n^{BH} \cos(n\phi) + s_1^{BH} \sin(\phi) \right\}$$

$$|\mathcal{T}_{DVCS}|^2 = \frac{e^6}{y^2 Q^2} \left\{ c_0^{DVCS} + \sum_{n=1}^{2} \left[c_n^{DVCS} \cos(n\phi) + s_n^{DVCS} \sin(n\phi) \right] \right\}$$

$$\mathcal{I} = \frac{\pm e^6}{x_B y^3 \Delta^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \left\{ c_0^{\mathcal{I}} + \sum_{n=1}^{3} \left[c_n^{\mathcal{I}} \cos(n\phi) + s_n^{\mathcal{I}} \sin(n\phi) \right] \right\}$$

Interference responsible for SSA, contain the same lepton propagator $P_1(\phi)$ as BH

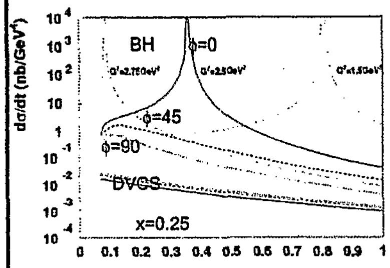
$$A_{LU} \approx \frac{x_B}{y} \frac{s_1^I}{c_0^{BH}}$$ → Way to access to GPDs

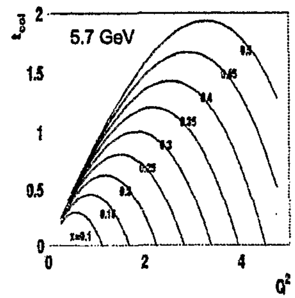
$$s_1^I = 8\lambda K y (2-y)\, \mathrm{Im}\left[F_1 H + \frac{x_B}{2-x_B}(F_1+F_2)\tilde{H} - \frac{\Delta^2}{4M^2} F_2 E \right]$$

GPD combinations accessible as azimuthal moments of the total cross section.

φ-dependent amplitude

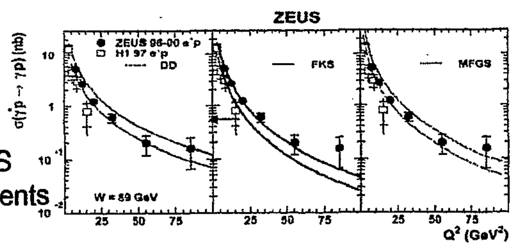
$$y_{col} = \frac{Q^2 - t}{Q^2 - xt} = y \longrightarrow t_{col} = \frac{Q^2(Q^2 - 2xME)}{(Q^2 - 2ME)x}$$

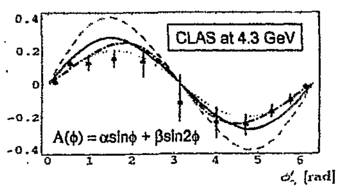


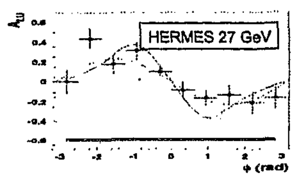


Strong dependence on kinematics of prefactor φ-dependence, at $y=y_{col}$ $P_1(\phi)=0$ Fraction of pure DVCS increases with t and φ

DVCS Experiments



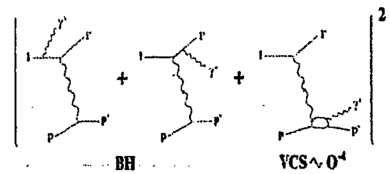




S. Stepanyan et al. Phys. Rev. Lett. **87** (2001)

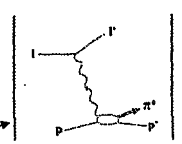
A. Airapetian et al. Phys. Rev. Lett. **87** (2001)

GPDs from ep->e'p'γ



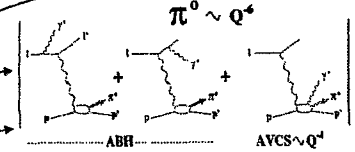
Requirements for precision (<15%) measurements of s_2^I and GPDs from DVCS SSA:

- Define relation between A_{LU} and s_2^I
  - → effect of other non-0 moments ~5-10%
  - effect of finite bins ~10%



- Define background corrections
  - → pion contamination ~10%
  - → radiative background
  - → ADVCS <3% at CLAS

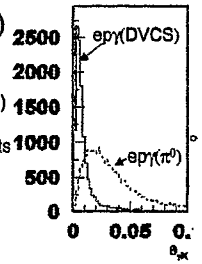
More relevant when proton is not detected

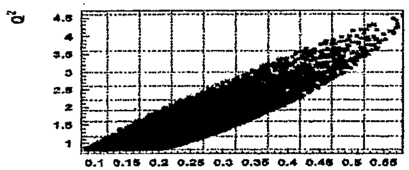


DVCS event samples

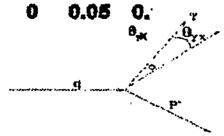
3 event samples(after data quality cuts)

1) ep 0 photons (**~2M events**)
tight cuts on PID,missing mass MX
2) epγ 1 photon in Calorimeter (**~150000 events**)
cut on the direction $\theta_{\gamma X}$<0.015,
3) epγγ 2 photon(π^0) in Calorimeter (**~70000 events**)
cut on the direction $\theta_{\pi X}$<0.02,



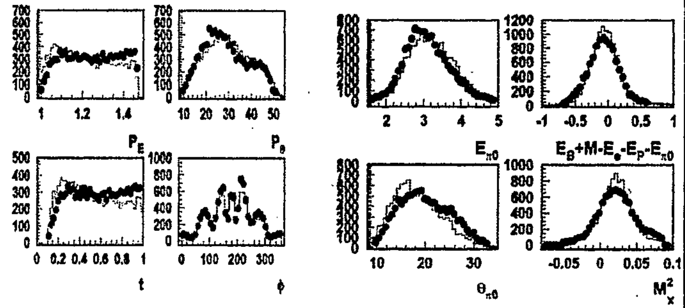


Kinematic coverage of 5.75 GeV(red) and 5.48(blue) CLAS data sets



Angular cut most efficient in separating π^0

π^0 MC vs Data

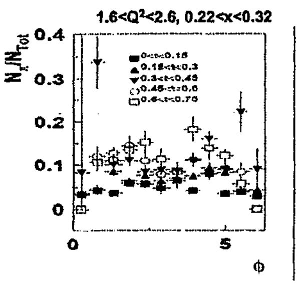


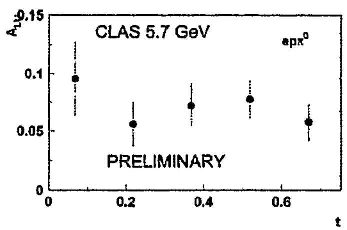
- Exclusive pi0 production simulated using a realistic MC
- Kinematic distributions in x,Q^2,t tuned to describe the CLAS data

π^0 beam SSA cross section

Main unknown in corrections of photon SSA are the π^0 contamination and its beam SSA.

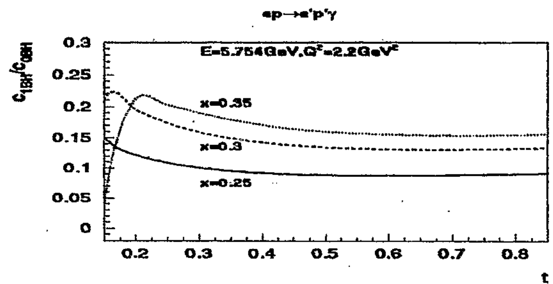
Use epγγ to estimate the contribution of π0 in the ep and epγ samples





Contamination from π^0 photons increasing at large t and x and also at large f.
Significant SSA measured for exclusive π0s also should be accounted

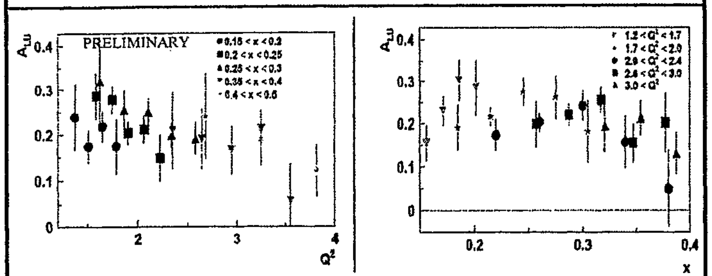
BH cosϕ moment



$$A_{LU} \propto \frac{\lambda s_2^I \sin\phi}{c_0^{BH}(1+c_1^{BH}/c_0^{BH}\cos\phi)} \approx \frac{\lambda s_2^I \sin\phi - \lambda s_2^I (c_1^{BH}/2c_0^{BH})\sin 2\phi}{c_0^{BH}}$$

BH cosϕ moment can generate ~3% sin2ϕ in the A_{LU}

DVCS SSA kinematic dependences at 5.7 GeV

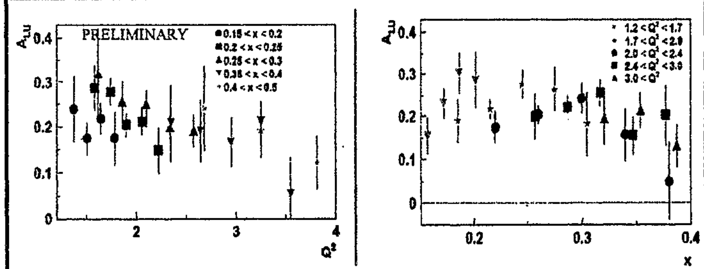


Fine binning allows to observe the x and Q^2 dependence

A_{LU} for **ep->ep[γ]** sample with **-t<0.5** GeV^2

Preliminary data for fully exclusive epγ is consistent with the ep data and consistent with GPD base predictions

DVCS SSA kinematic dependences at 5.7 GeV



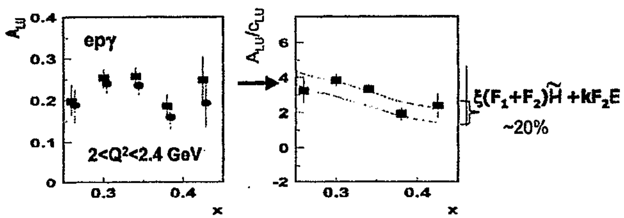
Fine binning allows to observe the x and Q^2 dependence

A_{LU} for **ep->ep[γ]** sample with **-t<0.5** GeV^2

Preliminary data for fully exclusive epγ is consistent with the ep data and consistent with GPD base predictions

Extraction of GPD H from A_{LU} moment

$$A_{LU}(\phi) \approx \frac{x}{y}\overbrace{\frac{8K(x,t,Q^2)y(2-y)F_1 sin(\phi)}{c_0^{BH}(1+c_1^{BH}/c_0^{BH}cos(\phi))}}^{c_{LU}}\{\mathcal{H}+...\},$$



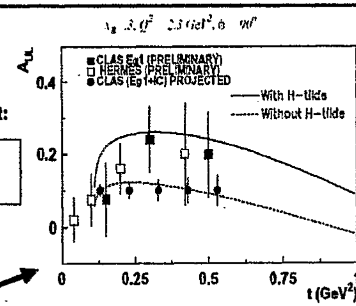
- **Red[blue] points correspond to projected A_{LU} [un]corrected for π0 (bin by bin)**
- **H stands for the ratio of the A_{LU} and prefactor calculated for all events in a bin (averaged over ϕ)**
- **Curves are for a simple model for CFF H (blue) and H+...(red)**

Target Spin Asymmetry: t- Dependence

Unpolarized beam, longitudinal target:

$\Delta\sigma_{UL} \sim \sin\phi Im\{F_1\tilde{H}+\xi(F_1+F_2)(H+..\}$
$\Delta\sigma_{LL} \sim \cos\phi Re\{F_1\tilde{H}+\xi(F_1+F_2)(H+..\}$

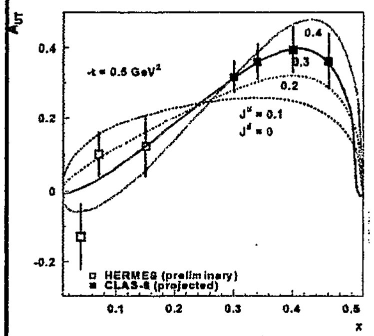
Kinematically suppressed



First data available(5 CLAS days), more(60 days) to come at 6 GeV

Measurements with polarized target will constrain the polarized GPD and combined with beam SSA measurements would allow precision measurement of unpolarized GPDs.

Exclusive ρ^0 production on transverse target



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

ρ^0: $A \sim 2H^u + H^d$, $B \sim 2E^u + E^d$

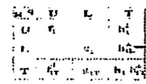
ρ^+: $A \sim H^u - H^d$, $B \sim E^u - E^d$

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

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

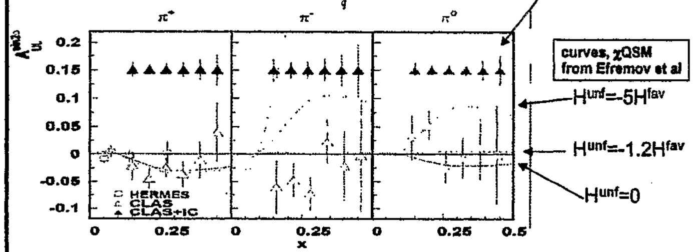
Asymmetry is a more appropriate observable for GPD studies at JLab energies as possible corrections to the cross section are expected to cancel

Polarized target SSA using CLAS at 6 GeV



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

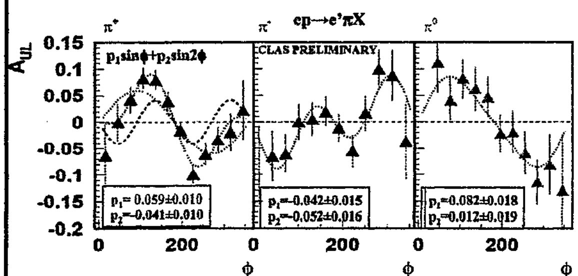
60 days of CLAS+IC ($L=1.5 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$)



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

Target SSA measurements at CLAS

$$A_{UL}(\phi) = \frac{1}{P_T}\frac{N^+ - N^-}{N^+ + N^-} \qquad \sigma_{UL}^{\sin\phi} \propto S_L \frac{M}{Q} y\sqrt{1-y} \sum_{q,\bar q} e_q^2 x f_L^{\perp q}(x) D_1^q(z)$$



W^2>4 GeV²
Q^2>1.1 GeV²
y<0.85

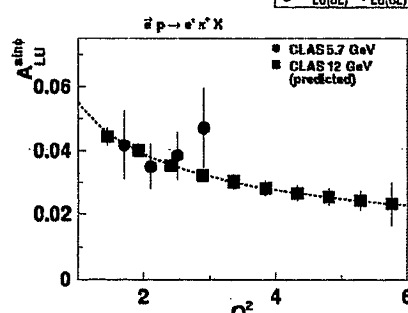
0.4<z<0.7
M_X>1.4 GeV

P_T<1 GeV
0.12<x<0.48

- Significant SSA measured for pions with longitudinally polarized target
- Complete azimuthal coverage crucial for separation of sinφ, sin2φ moments

Measuring the Q^2 dependence of SSA

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



For fixed x, 1/Q behavior expected

Wide kinematic coverage and higher statistics will allow to check the higher twist nature of beam and longitudinal target SSAs

Probes of Orbital Angular Momentum at HERMES

G. SCHNELL [on behalf of the HERMES Collaboration]

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

In spite of significant progress that has been achieved, the spin of the proton is far from being explained. Though not yet completed, the contribution $\Delta\Sigma$ to the proton spin from the spin of the quarks has been studied quite extensively. As already observed by EMC in the 1980s, $\Delta\Sigma$ is small. Hence, the quark spin does not answer the question about the origin of the proton spin.

Different decompositions of the proton spin have been discussed in the literature. Both the gauge-invariant decomposition by Ji and the light-cone decomposition by Jaffe have in common that besides the contribution from gluons the orbital angular momentum of quarks L_z^q has to be considered as well. The unfortunate situation to face is the lack of direct probes of orbital angular momenta. However, Generalized Parton Distributions (GPDs) represent powerful tools in the undertaking of extracting information on orbital angular momentum. In the Ji decomposition of the proton spin, a certain moment of two GPDs, E and H, gives the total angular momentum of quarks and/or gluons. In combination with measurements of $\Delta\Sigma$ this moment can be used to extract L_z^q.

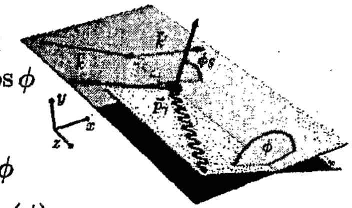
The most promising processes to measure GPDs are exclusive reactions. Among them, Deeply Virtual Compton Scattering (DVCS) has been identified as the cleanest and simpliest one. It gives access to both E and H. Exclusive Vector Meson (VM) production can also be used to extract information on E and H. Both processes have been studied extensively by the HERMES collaboration. In both cases, HERMES looks at azimuthal single-spin or beam-charge asymmetries. They are proportional to either one GPD amplitude convoluted with the well-known Dirac and Pauli form factors (DVCS) or to the product of both E and H (VM production on a transversely polarized target).

HERMES observed significantly non-zero azimuthal beam-spin and beam-charge asymmetries. They are important to constrain the GPD H. HERMES is in the fortunate and exclusive situation, that it can measure both with electrons and positrons, which at present can only be done at HERA at DESY. In order to constrain the GPD E one has to turn to a transversely polarized target and either measure azimuthal SSAs in DVCS or in exclusive VM production. HERMES has taken data on a transversely polarized proton target during 2002-2005. Preliminary results available for the 2002-2004 data set support in certain models a total angular momentum of *up* quarks at least bigger than zero (exclusive VM production) and in the order of about 0.3 (DVCS).

A completely different observable that is sensitive to L_z^q is the Sivers function. It has long been conjectured that L_z^q can lead to SSAs in inelastic reactions. A clean process to study the Sivers function is semi-inclusive deep-inelastic scattering on a transversely polarized target where it produces a peculiar azimuthal distribution of hadrons from current fragmentation. HERMES has done such a measurement with transversely polarized protons. It was found that positive pions show a strong correlation between their momenta and the target spin direction. Negative pions did not expose such a correlation. These results suggest – in a model-dependent analysis – a positive contribution of the *up* quark's orbital angular momentum to the spin of the proton.

Azimuthal Asymmetries in DVCS

Interference DVCS & BH cause azimuthal asymmetries in cross-section:



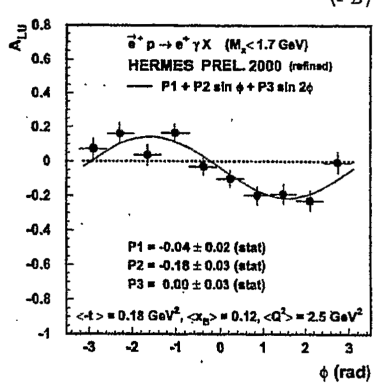
- Beam-charge asymmetry $A_C(\phi)$:
  $d\sigma(e^+,\phi) - d\sigma(e^-,\phi) \propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$
- Beam-spin asymmetry $A_{LU}(\phi)$:
  $d\sigma(\overrightarrow{e},\phi) - d\sigma(\overleftarrow{e},\phi) \propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$
- Long. target-spin asymmetry $A_{UL}(\phi)$:
  $d\sigma(\overleftarrow{P},\phi) - d\sigma(\overrightarrow{P},\phi) \propto \mathrm{Im}[F_1\widetilde{\mathcal{H}}] \cdot \sin\phi$
- Transverse target-spin asymmetry $A_{UT}(\phi,\phi_s)$ [TTSA]:

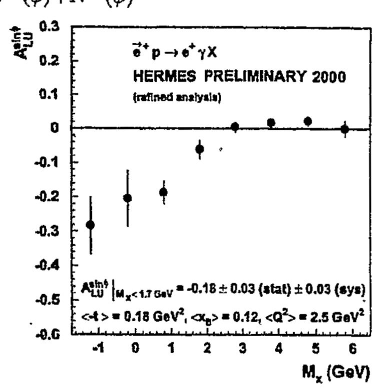
$$d\sigma(\phi,\phi_S) - d\sigma(\phi,\phi_S+\pi) \propto \mathrm{Im}[F_2\mathcal{H} - F_1\mathcal{E}] \cdot \sin(\phi-\phi_S)\cos\phi + \mathrm{Im}[F_2\widetilde{\mathcal{H}} - F_1\xi\widetilde{\mathcal{E}}] \cdot \cos(\phi-\phi_S)\sin\phi$$

(F_1, F_2 are the Dirac and Pauli form factors, calculable in QED)
($\widetilde{\mathcal{H}}, \widetilde{\mathcal{E}}, \ldots$ Compton form factors involving GPDs $H, E, \ldots$)

Constraining H – Part I
BSA $\propto \mathrm{Im}[F_1\mathcal{H}] \cdot \sin\phi$

Beam Spin Asymmetry: $\frac{1}{\langle P_B \rangle} \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$ (± ... beam helicity)



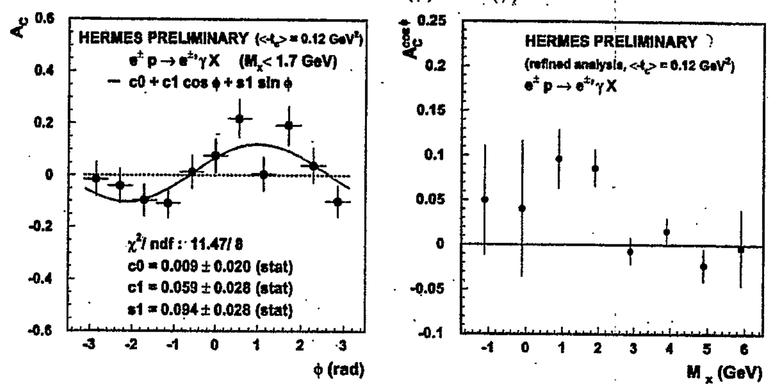


significant $\sin\phi$ modulation in exclusive region

Constraining H – Part II

BCA $\propto \mathrm{Re}[F_1\mathcal{H}] \cdot \cos\phi$

Beam Charge Asymmetry: $\frac{N^+(\phi)-N^-(\phi)}{N^+(\phi)+N^-(\phi)}$ (± ... beam charge)



significant $\cos\phi$ modulation in exclusive region

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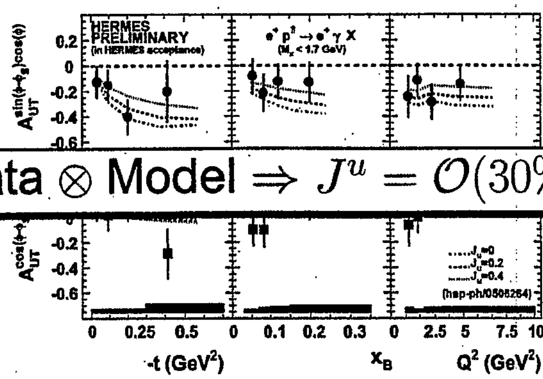
Constraining E – Transverse TSA

Target Spin Asymmetry: $\frac{1}{\langle S_T\rangle}\frac{N^\uparrow(\phi)-N^\downarrow(\phi)}{N^\uparrow(\phi)+N^\downarrow(\phi)}$ (↑↓ ... target polarization)

$\Rightarrow$ extract $\sin(\phi-\phi_S)\cos\phi$ and $\cos(\phi-\phi_S)\sin\phi$ amplitudes



Data $\otimes$ Model $\Rightarrow J^u = \mathcal{O}(30\%)$

model calculation [hep-ph/0506264]

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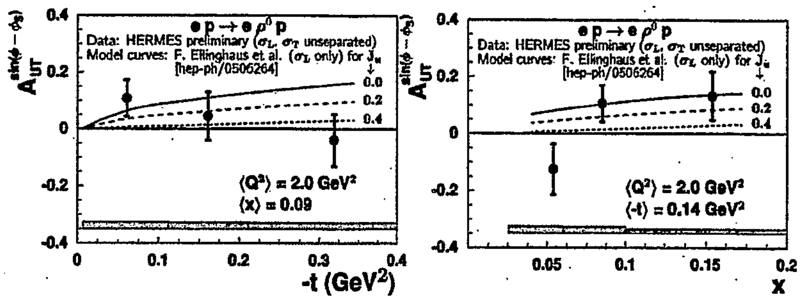
Exclusive ρ^0 Production

TTSA $\propto$ [E H] $\cdot \sin(\phi - \phi_S)$

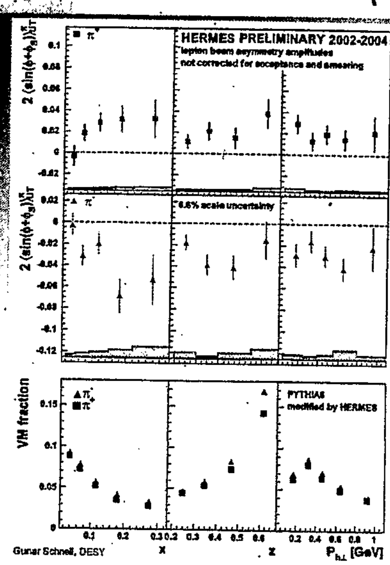
Target Spin Asymmetry: $\frac{1}{\langle S_T \rangle} \frac{N^{\uparrow}(\phi) - N^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + N^{\downarrow}(\phi)}$ ($\uparrow\downarrow$ ... target polarization)



- qualitative agreement with model prediction [hep-ph/0506264]
- model $\oplus$ HERMES data $\Rightarrow$ slight preference for $J^u > 0$

Collins Asymmetries 2002-2004

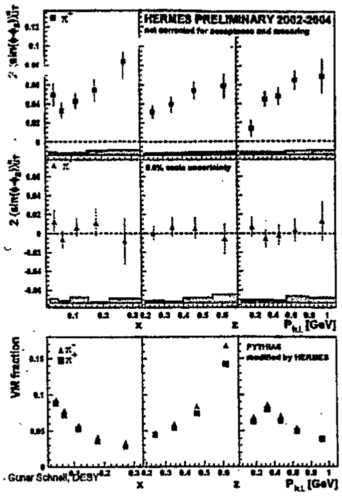
(Lepton-Beam Asymmetries)



- published results confirmed with much higher statistical precission
- lepton-beam asymmetries (vs. virtual-photon SSA in publication) $\hookrightarrow$ kin. prefactors ("depolarization factors") still included
- overall scale uncertainty of 6.6%
- positive for π^+ and negative for π^- as maybe expected ($\delta u > 0$, $\delta d < 0$)
- unexpected large π^- asymmetry $\Rightarrow$ role of disfavored Collins FF most likely: $H_1^{\perp,disf.} \approx -H_1^{\perp,fav}$
- no (new) constraint on transversity yet

Results on Sivers Moments from 2002-2004 data

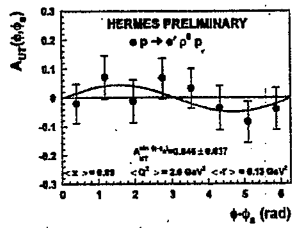
$$2\left\langle \sin(\phi-\phi_S)\right\rangle_{UT}^{q} \propto -\sum_q e_q^2\, \mathcal{I}\left[\frac{p_T \hat{P}_{h\perp}}{M}\, f_{1T}^{\perp,q}(x,p_T^2)\, D_1^q(z,K_T^2)\right]$$



- π^+: positive; π^-: consistent with zero

$\Rightarrow$ first evidence for non-zero Sivers fct.: $f_{1T}^{\perp,u} < 0$ (u-quark dominance)

- Exclusive ρ^0 asymmetry (2005 prel.):



$\Rightarrow$ small syst. error from vector mesons

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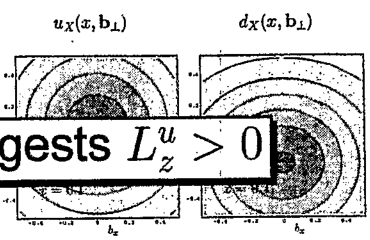
Chromodynamic Lensing
Understanding the Sivers Moments

approach by M. Burkardt:

spatial distortion of q-distribution
(obtained using anom. magn. moments
& impact parameter dependent PDFs)



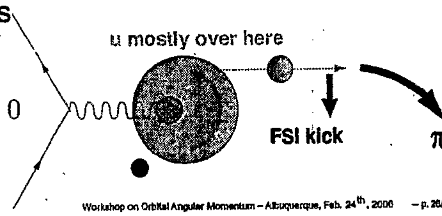
model $\otimes$ data suggests $L_z^u > 0$

\+ attractive QCD potential
(gluon exchange)

$\Rightarrow$ transverse asymmetries

$$\left.\begin{aligned}\phi_S &= \pi/2\\ \phi &= \pi\end{aligned}\right\}\sin(\phi-\phi_S) > 0$$

✓



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So much data – but what is L_z?

- have some indication that L_z^u & $J^u > 0$
- however, no model-independent extraction possible:
  - DVCS gives access to GPDs (needed for *Ji's recipe*), but can only constrain GPD models, no direct measurement of GPDs possible
  - Sivers function related to OAM, but how?
- transversity extraction requires knowledge of Collins FF
- how is "Leader's OAM" related to "Ji's OAM"?
- unpolarized-target data still under investigation

COMPASS plans to measure GPDs

Jean-Marc Le Goff,
DAPNIA CEA-Saclay
in behalf of the COMPASS collaboration

COMPASS is a fixed target experiment at the CERN SPS. It makes use of a 160 GeV polarized muon beam to study the spin structure of the nucleon and of hadron beams to study hadron spectroscopy.

The setup allows for the measurement of exclusive ρ^0 production. At high Q^2, small momentum transfer to the nucleon ($t \ll Q^2$) and for longitudinal photons, the cross-section factorizes in a hard cross-section convoluted with generalized parton distributions (GPDs). A one-dimension study of the ρ^0 angular distributions was performed. It provides several ρ^0 spin-density matrix-elements and confirms the earlier finding that s-channel helicity conservation (*i.e.* $\lambda_\rho = \lambda_\gamma$) is valid to a good approximation. In this framework the matrix element r^{04}_{00} gives $R = \sigma_L/\sigma_T$. The 2002 data provide very good statistics up to Q^2 on the order of 5 GeV^2. The 2003 and 2004 data will increase the statistics and, due to an improved trigger, cover higher Q^2. R appears to be increasing with Q^2 and is larger than 1 for $Q^2 > 2$ GeV^2, so the data will be used to measure the total cross-section and extract a reliable measurement of the longitudinal cross-section, σ_L, at large Q^2. Data with a transversely polarized target have also been recorded. The corresponding spin asymmetry is proportional to the GPD ratio E/H. This is particularly interesting because E enters the Ji sum rule (which gives the total quark spin, including orbital momentum contribution) while other observables show very little sensitivity to E. These will, however, be exploratory measurements, since the setup does not guaranty the exclusivity of the reaction and the target is a nuclear target (^{6}Lid).

In a new phase of COMPASS an upgrade of the setup is considered for a dedicated measurement of GPDs through deeply virtual Compton scattering (DVCS) and hard exclusive meson production (HEMP). This would include a 2.5 m long liquid hydrogen target, a proton recoil detector around this target and an additional electromagnetic calorimeter to cover $12 < \theta < 30^o$. A Pythia-based simulation showed that the background rate falls faster with Q^2 than the DVCS rate and that DVCS is already dominant at $Q^2 > 1$. Due to the interference with the Bethe-Heitler process, the difference of the cross section for positive muons of negative helicity and negative muons of positive helicity provides the real part of the DVCS amplitude. In 150 days of data taking the ϕ dependence could be measured in 3 bins in x_{bj} times 6 bins in Q^2. In each bin a clear difference could be seen between different models. ρ^0 production could be measured up to 20 GeV^2 and ω, π, η and ϕ production up to 7 GeV^2. The proposal for this new phase could appear in 2008 and data taking could start in 2010.

Determination of $R=\sigma_L/\sigma_T$

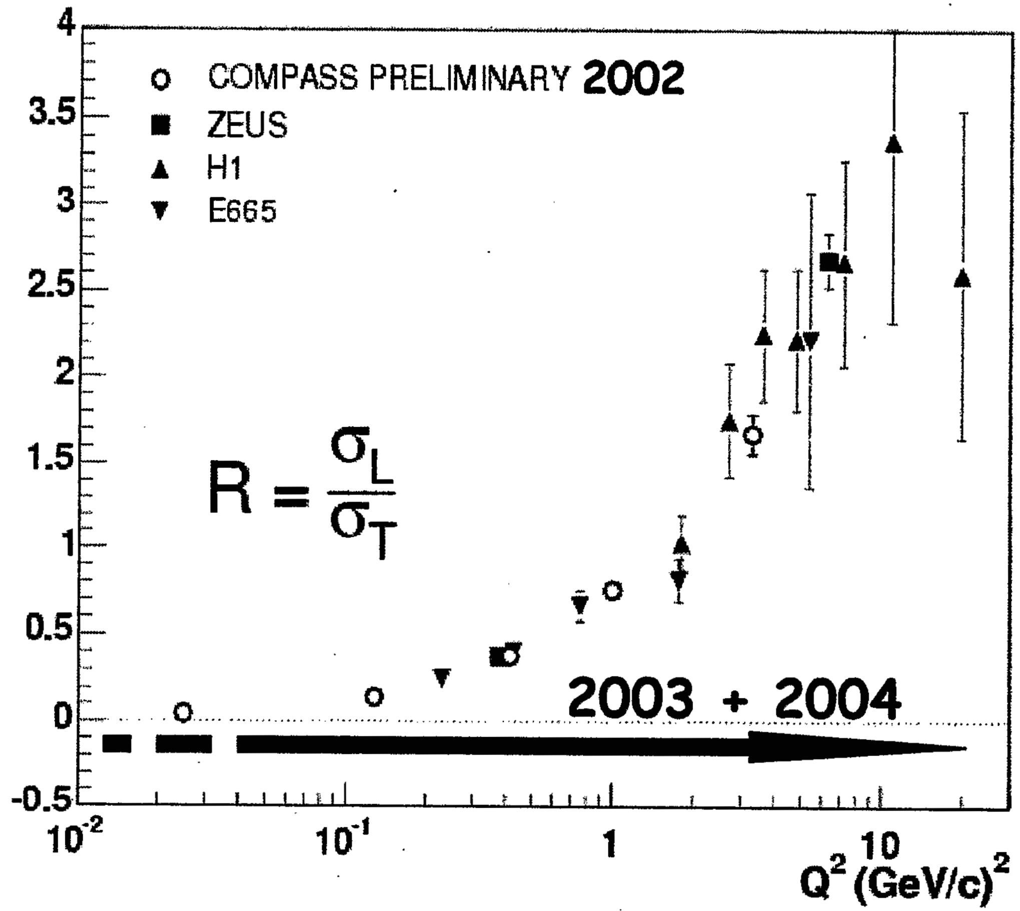
- If SCHC holds :

$$R = \frac{\sigma_L}{\sigma_T} = \frac{1}{(\epsilon+\delta)}\frac{r_{00}^{04}}{1-r_{00}^{04}}$$

- σ_L is dominant at $Q^2>2$

- 2002: high stat in large Q^2 range

- 2003 and 2004 data :
  - much more stat
  - better high Q^2 coverage



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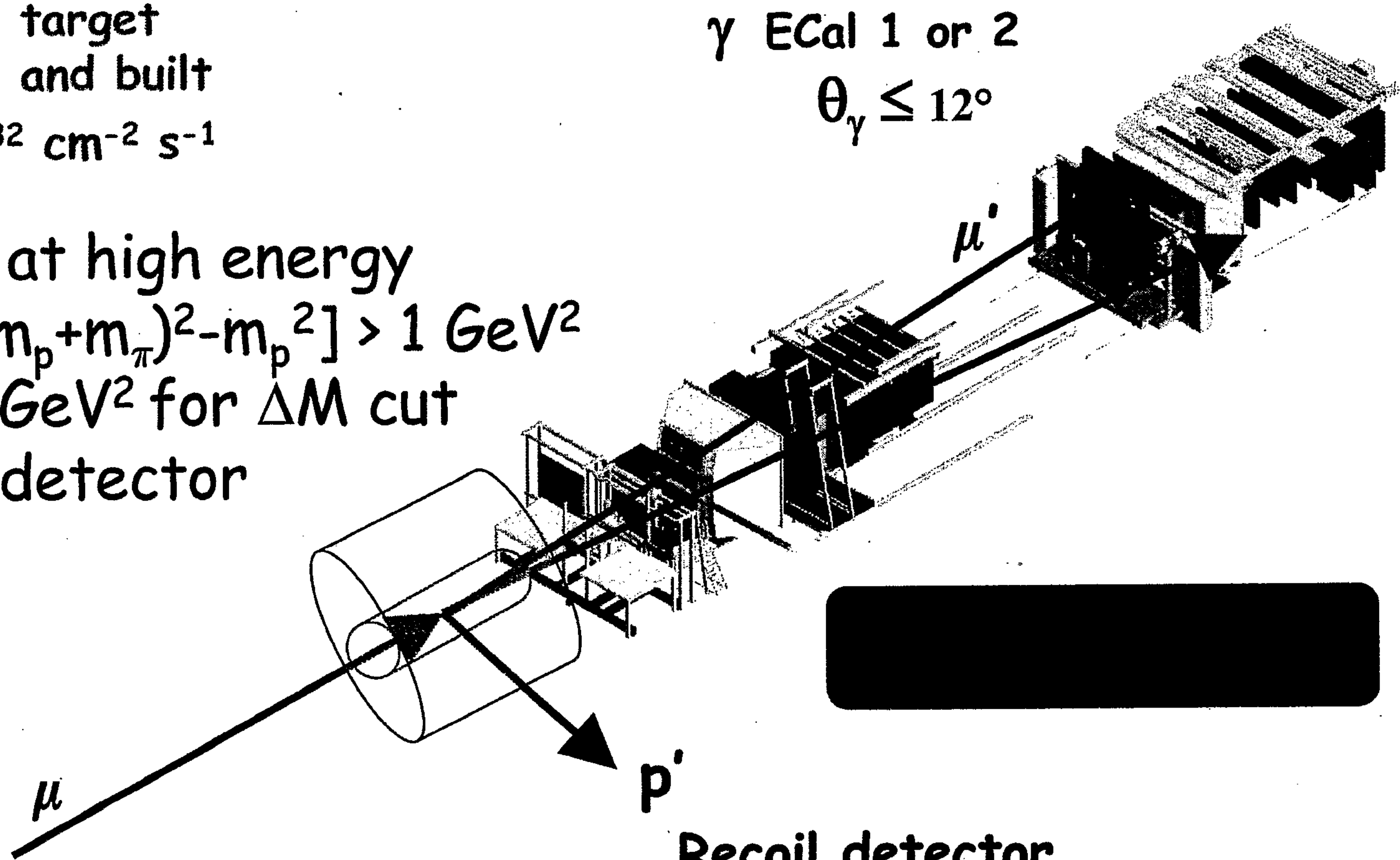
Conclusions on rho

- SCHC $\rightarrow$ R
- σ_{tot} + R $\rightarrow$ σ_L
- when $Q^2 > 2 \rightarrow$ R > 1 : accurate σ_L
- we have transv. target spin asym $\rightarrow$ E/H
  important for Ji sum rule ($\int$E+H)
- exploratory measurement
  (no exclusivity, nuclear target)

Additions to COMPASS setup

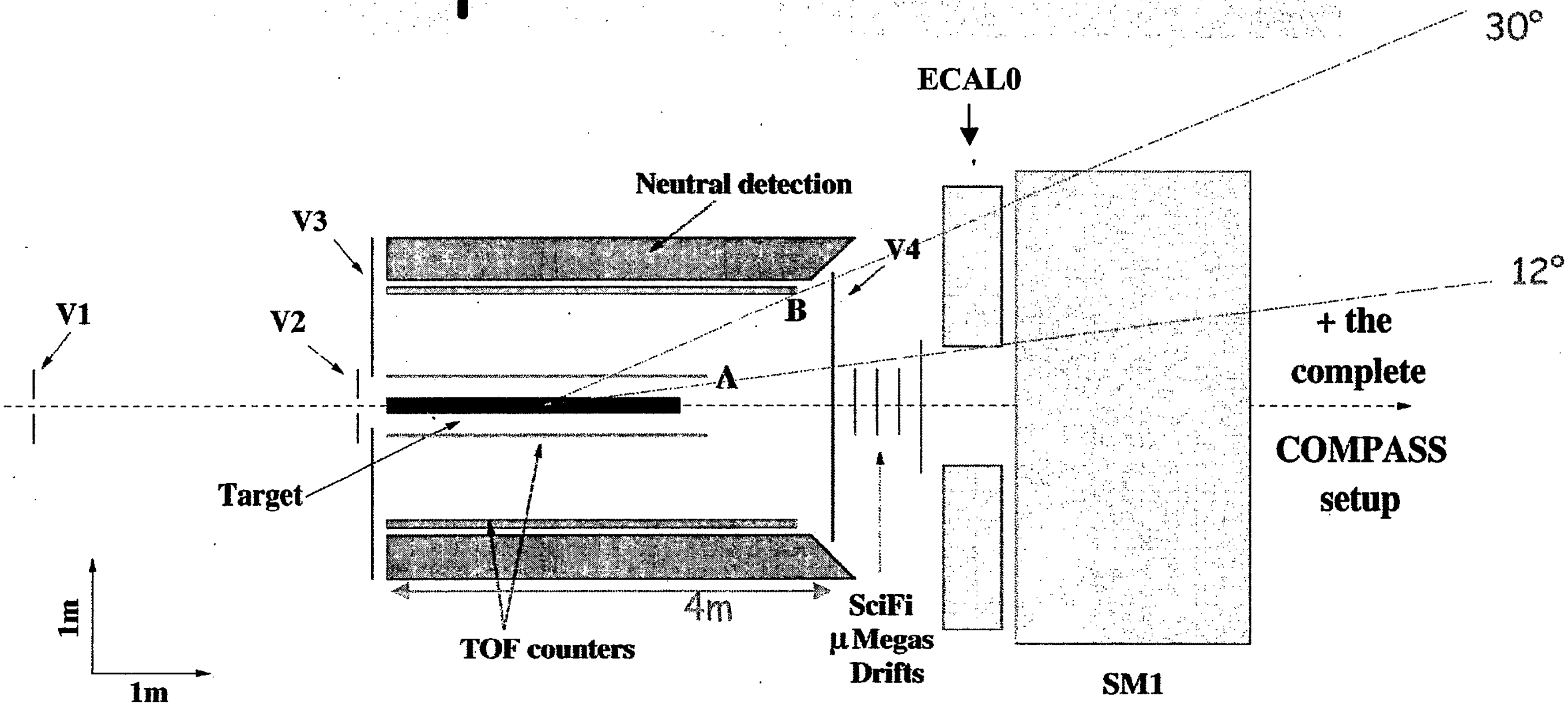
2.5m liquid H2 target
to be designed and built
$\mathcal{L} = 1.3\ 10^{32}\ cm^{-2}\ s^{-1}$

Exclusivity: at high energy
$\delta\Delta M^2 = \delta[(m_p+m_\pi)^2 - m_p{}^2] > 1\ GeV^2$
need $0.25\ GeV^2$ for ΔM cut
→ hermetic detector



Recoil detector
to insure exclusivity
to be designed and built

A possible solution



2004-2007:

Funding by European Union (Bonn-Mainz-Warsaw-Saclay)

45° sector recoil detector

- scintillating material studies (200ps ToF Resolution over 4m)
- fast triggering and multi-hit ADC/TDC system

$\sigma^{\overset{\sigma}{\mu+}} - \sigma^{\overset{\rho}{\mu-}}$ at 100 GeV

$$\sigma^{\overset{\sigma}{\mu+}} - \sigma^{\overset{\rho}{\mu-}} \sim \mathcal{P}\int_{-1}^{+1} dx \frac{H(x,\xi,t)}{x-\xi}$$

Model 1: $H(x,0,t) \sim q(x)\,F(t)$

Model 2: $H(x,0,t) = q(x)\, e^{\,t \langle b_\perp^{\,2} \rangle}$

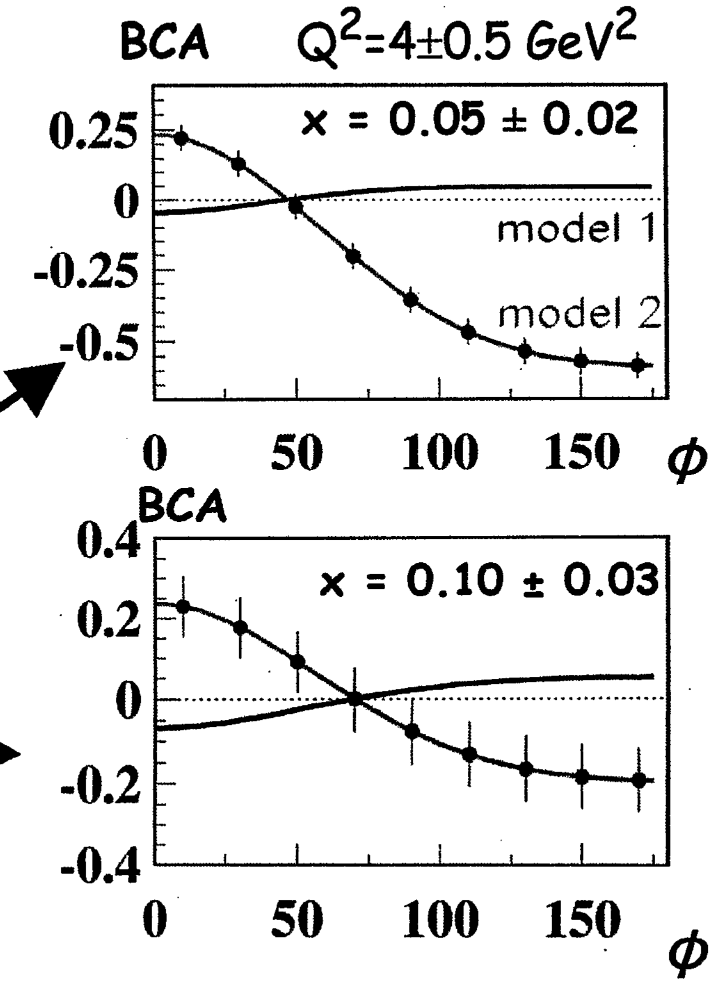
$= q(x) \,/\, x^{\alpha' t}$

assuming:

- $\mathcal{L} = 1.3\ 10^{32}\ cm^{-2}\ s^{-1}$
- 150 days
- efficiency=25%

2 bins shown out of 18:

- 3 bins in x_{Bj}= 0.05, 0.1, 0.2
- 6 bins in Q^2 from 2 to 7 GeV^2



Process Dependence for Single-Spin Asymmetries From Orbital Structures

Dennis Sivers
Portland Physics Institute
University of Michigan Spin Physics Center

The A_τ-odd spin observables generated from a spin-independent hard scattering in a transversely polarized proton inherit a process dependence from the initial- and/or final-state interactions that expose one or more sectors of the polarized proton's underlying orbital structure. This subject is often discussed under the label "non-universality" but the term "process-dependence" more accurately reflects the situation when the set of observables are very far from universal. [1] The presence of large process-dependence in the observables does not imply the absence of an underlying intrinsic property of the quantum orbital structure of a proton. This can be clearly demonstrated by examining the components of a quantum rotator (Fig. 1) and calculating the impact these components can have on specified hard-scattering processes.

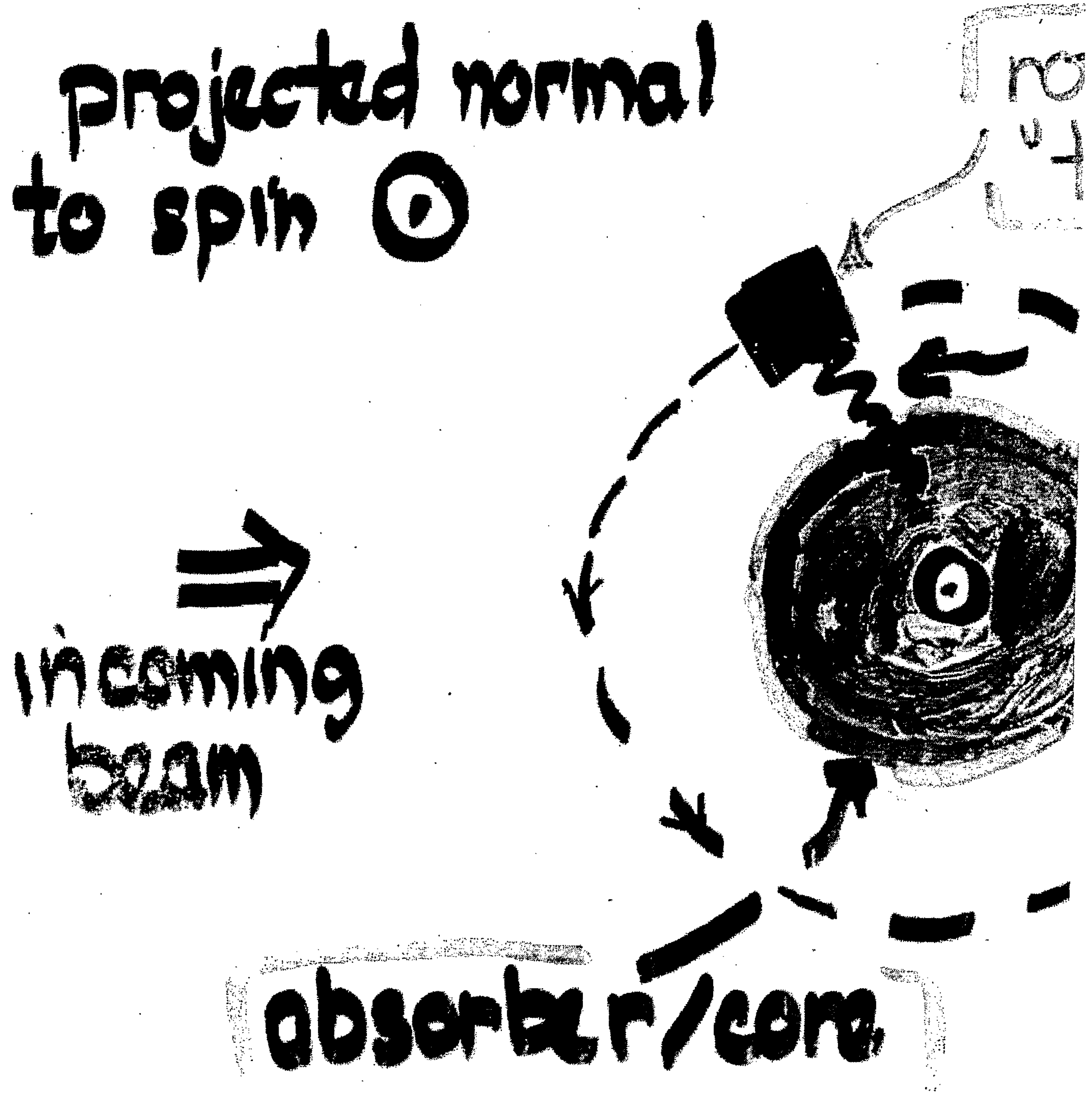
In the convolutions involved in the hard-scattering model, the impact of soft interactions can be separated into non-oriented and spin-oriented components. For the non-oriented component, the interplay of initial- and final-state interactions can be included in a geometrical or optical representation of screening and jet energy loss as illustrated in Fig. 2 for three different processes. As shown in Fig. 3, the spin-oriented component in semi-inclusive DIS can be identified with the lensing property of the confining force as featured in the model of Burkhardt. [2] The Drell-Yan process displays "virtual lensing" as demonstrated in Fig. 4. The combined effect of the screening and lensing for these two processes produces the fundamental Collins conjugation relation [3]

$$(\Delta^{N}{}_{q/p\uparrow})^{DY} = -(\Delta^{N}{}_{q/p\uparrow})^{SIDIS}. \tag{1.1}$$

Hard gluon exchange as shown in Fig. 5 can lead to color liberation and the absence of soft spin-oriented effects in some observables [1] and a more complicated structure in others [4]. The decoding or unwrapping of these effects requires, at least, a systematic program of calculating next-to-leading order effects in the kt-dependent version of the hard-scattering model and comparing the process-dependence of these results with the process-dependence of the higher-twist-expansion [5] in kinematic regions where both approaches are valid. The factorization implied by the absence of A_τ-odd dynamics in perturbative qcd [6,7] plays an important role in this program.

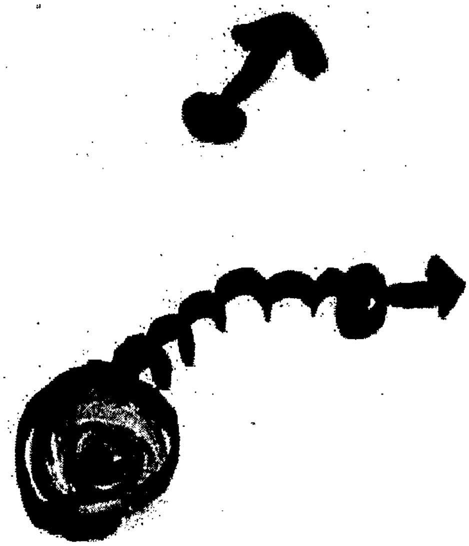
1. D Sivers, work in preparation.
2. M. Burkhardt, Phys. Rev **D69**: 091501 (2004)
3. J.C. Collins, Phys. Lett. **B536**:43-48 (2002)
4. D. Boer, P.J. Mulders and F. Pijlman, Nucl Phys. **B667**, 201 (2003)
5. Feng Yuan , presentation this conference
6. G. Kane, J. Pumplin and W. Repko, Phys Rev. Lett. **41**, 1689 (1978)
7. D. Sivers, Phys. Rev. **D43**, 261 (1991).

Components of a
Rotator



ORIENTED LENSING

high-x quark at "left side of "core"



scattering from electron (γ-exch leaves color st unchanged - fl stretches

mean momentum frame?

VIRTUAL Lensing

high-x quark
on "left" of core

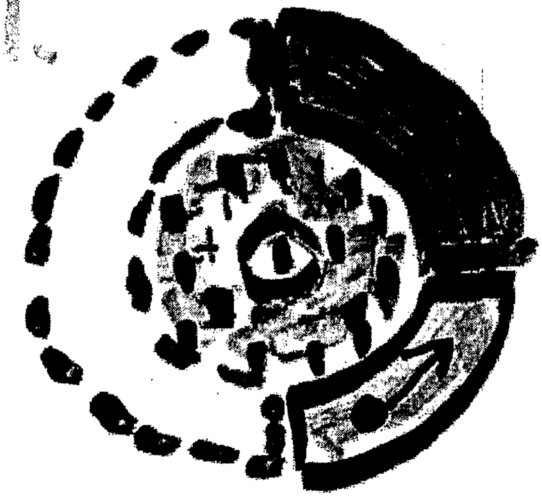
charge annihil
in color singl
occurs (light
front kinemati

e^+e^-)

ISI

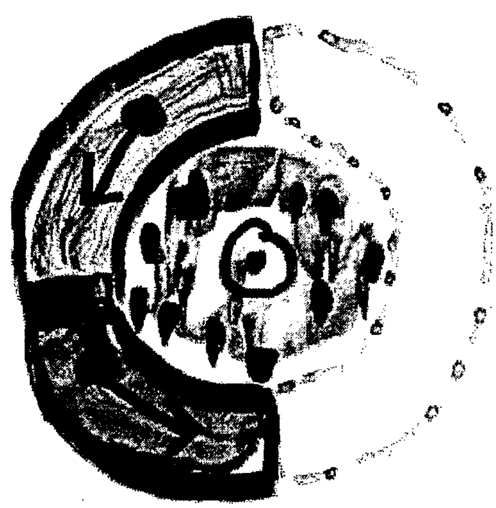
Non-ORIENTED

SIDIS



$$\left(\Delta^N G_{q/p\uparrow}\right)^{SIDIS}_{orb} = (1-\eta)$$

DY



$$\left(\Delta^N G_{q/p\uparrow}\right)^{DY}_{orb} = (1-\eta)$$

Hard Gluon Exchange & Flux Interchange

high-x quark on left side of "core

hard gluon exc liberates quarl from oriented

Using Dijets to Measure the Gluon Sivers Functions at STAR

Renee Fatemi

Massachusetts Institute of Technology

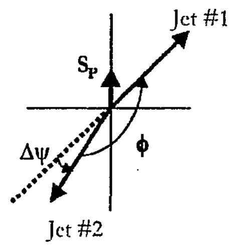
February 28, 2005

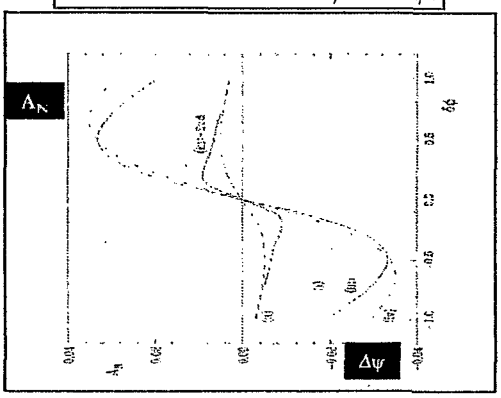
OUTLINE

- STAR has made strong contributions to transverse physics in forward rapidities (see L. Bland's talk)
- STAR has been investigating ways to extend transverse spin studies at mid-rapidity. Leading Charged Particle asymmetries were consistent with zero and interpretation was complicated by possible contributions from Sivers/Collins/higher twist effects.
- Vogelsang/Boer Proposal (early 2004) to Measure Single Spin Asymmetry of Dijet opening angle deviation from $\Delta\Phi=\pi$ provides a clean way to access Sivers at mid-rapidity.
- STAR is preparing to make this measurement in 2006 run. Why STAR and Why Now?
- Estimated Statistical Errors for 2006

Sivers Effect in Dijets

$$A_N(\phi_{j1}=\pi/2)=\frac{1}{P}\frac{Y^{\uparrow}_{\text{Dijet}}-Y^{\downarrow}_{\text{Dijet}}}{Y^{\uparrow}_{\text{Dijet}}+Y^{\downarrow}_{\text{Dijet}}}$$





Deviations from $\phi = \pi$ due to Partonic k_T

i. **Gluon = (U + D) / 2**
ii. **Gluon = 0**
iii. **Gluon = D**
iv. **Gluon = D + $\sqrt{kT^2}$ = 2.5**

Maximal Effects at $\Delta\psi$ = 0.4-0.5. This region experimentally available!

W.Vogelsang and D.Boer Phys Rev D 69 (2004) 094025

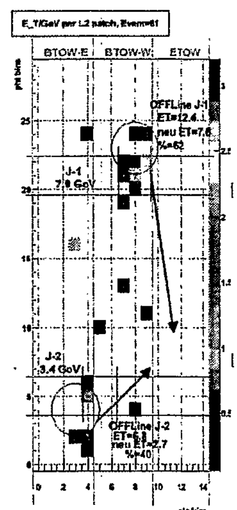
Why STAR? Why 2006?

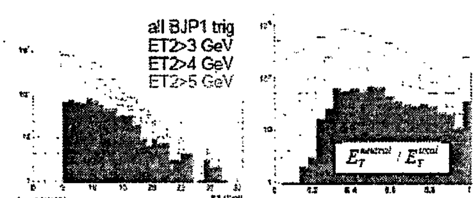
1. Large η-ϕ coverage of STAR Time Projection Chamber + Barrel + Endcap Electromagnetic Calorimeter makes STAR a natural choice for a di-jet measurement.
2. BEMC fully installed - but not fully in trigger - ONLY in 2005!
3. Investigated Sivers dijet analysis in 2003 data but it was clear that sample was statistically limited due to triggering only on half barrel.

4. Several Level 0 jet triggers were implemented, tested and understood in 2005 -- these form the basis for Level 2 triggers.
5. Needed time to develop and test L2 trigger algorithms in order to maximize di-jet sample

Level 2 Dijet Trigger Algorithms

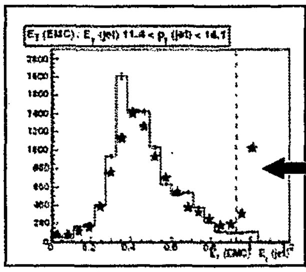
- Goal: Reconstructed di-jet rate of 10Hz which is factor of 5 above 2005 rate. Do this by taking 1/2 dijet sample from L0 Jet Patch Triggers and 1/2 sample from L2.
- L2: Pass events from L0 (Jet Patch * ETOT) Trigger. If reconstruct two localized clusters of transverse energy surpassing thresholds (ET1,ET2) with thrust axis separation $|\Delta\phi| > 1$ radian keep the event.
- L2 treats BEMC+EEMC as uniform detector - in effect taking jets covering $\eta = [-1,2]$ and $\phi = [0,2\pi]$
- L2 algo biases towards jets with higher neutral energy. L0 triggered sample biased towards lower than average neutral jet energy. We are equipped to estimate this trigger bias in simulation.





% of dijet events in sample increases from 10-80% for ET2>5!

L2 algo tested on 2005 data - shows excellent agreement with offline analysis. Thresholds are variable but currently set at ET1=ET2 ==3 GeV.

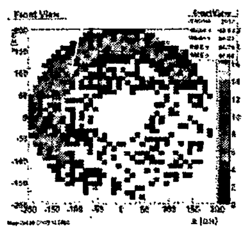


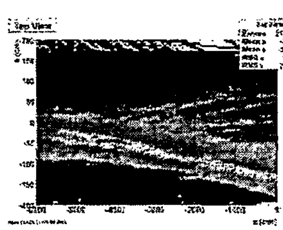
Background Shielding

2003/2004 Inclusive Jet Analysis led to identification of background via enhanced neutral energy in jet spectrum. The background is asymmetric in phi –resulting in asymmetric trigger rates in the Endcap Calorimeter.

Background location could produce large -possibly spin dependent- systematic for di-jet measurement

Tracking developments allowed identification of "straight tracks" which do not originate from the collision vertex to be identified. These tracks reproduce the asymmetric background pattern in the EEMC and point back to an origin 40 m upstream in blue beam.

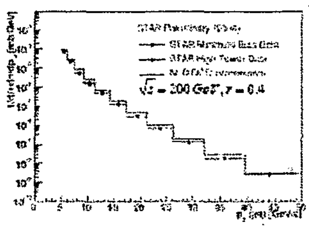


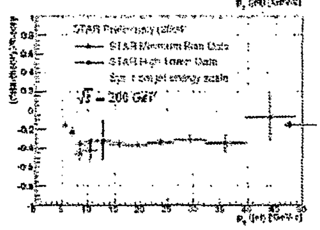


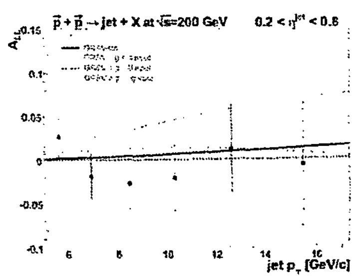
Steel Shielding added near quadrupole triplet in beam tunnels on both side of STAR in order to absorb high-energy hadrons.

STAR JetFinding Algorithms are on Firm Ground

1) Inclusive Jet X-sec agrees within systematic error bars with NLO pQCD predictions
2) Good agreement between data & PYTHIA+GEANT simulations. We are capable of separating trigger and detector effects from physics effects



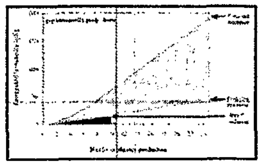




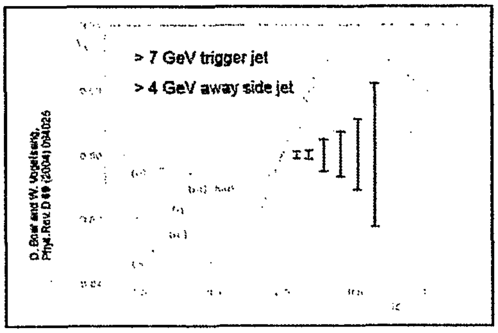
3) Spin Sorting mechanism tested and incorporated into jet analysis framework

4) Necessary tools are ready for relatively quick di-jet analysis

STAR 2006 Beam Use Request



- Place a world class constraint on gluon polarization in the proton
- Delineate the roles of the parton orbital motion/transversity in creating the transverse single spin asymmetry (A_N) observed for inclusive forward pi0 production
- First significant measurement of Sivers Effect asymmetry in di-jet production



- 18 cryogenic weeks
- 13 weeks physics running
- 1.5 wk calibration/trigger commissioning
- 11.5 wks running = 45/15 pb^{-1} delivered/sampled
- **5/10 pb^{-1} transverse/long**

Summary and Discussion

- STAR Collaboration is invested in studying all aspects of spin puzzle.
- Transverse running has high priority for STAR in 2006.
- Recent developments in hardware, shielding and triggering should enable us to produce first statistically significant measurement of dijet $\delta\phi$ asymmetry.

? Do we need to worry about Collins effects from first gluon scattered from polarized quark? How does this effect vary with cone size?

? If size of partonic kT is independent of hard scattering scale (jet pT) then shouldn't this asymmetry become smaller at higher jet pT?

? How will Sivers Functions be extracted from this asymmetry? What is the status of the necessary factorization theorems?

? Can we extract ΔL_g from Sivers?

Can We Learn Quark Orbital Motion from SSAs?

Feng Yuan[1]

[1]*RIKEN BNL Research Center, Building 510A,*

Brookhaven National Laboratory, Upton, NY 11973

In this talk, I argued that the Single-Transverse Spin Asymmetries (SSAs) indeed provide information about the quark orbital angular momentum contribution to the proton spin. This is because the SSAs are proportional to the interference between the hadron helicity non-flip and flip amplitudes, and the latter one definitely involves the nonzero quark orbital angular wave function of the nucleon. Furthermore, by an explicit calculation, we have shown that the Sivers function can be expressed as the overlap of the light-cone wave functions of zero quark orbital angular momentum Fock state and the nonzero orbital angular one in a particular choice of the light-cone gauge (e.g., the advanced boundary condition). However, so far there is no quantitative relation between the measured SSAs (or the extracted Sivers function) and the size of quark orbital angular momentum contribution to the proton spin. This will be a subject needed to be studied further.

In this talk, I also demonstrated that the two mechanisms proposed in the QCD framework for the SSAs are indeed unified. Using Drell-Yan pair production as an example, we explore the relation between two well-known mechanisms for single transverse-spin asymmetries in hard processes: twist-three quark-gluon correlations when the pair's transverse momentum is large, $q_\perp \gg \Lambda_{\rm QCD}$, and time-reversal-odd and transverse-momentum-dependent parton distributions when $q_\perp$ is much less than the pair's mass. Although the two mechanisms have their own domain of validity, they describe the same physics in the kinematic region where they overlap. This unifies the two mechanisms and imposes an important constraint on phenomenological studies of single spin asymmetries.

Can We Learn Quark Orbital Motion from SSAs?

Feng Yuan
RIKEN/BNL Research Center
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Why Does SSA Exist?

- **Single Spin Asymmetry is proportional**
  Im (M_N * M_F)
  where M_N is the normal helicity amplitude
  and M_F is a spin flip amplitude
  - Helicity flip: one must have a reaction mechanism for the hadron to change its helicity (in a cut diagram)
  - Final State Interactions (FSI): to generate a phase difference between two amplitudes

  The phase difference is needed because the structure $S \cdot (p \times k)$ violate the naïve time-reversal invariance

Naïve Parton Model Fails

- If the underlying scattering mechanism is hard, the naïve parton model generates a very small SSA: (G. Kane et al, PRL41, 1978)
  - The only way to generate the hadron helicity-flip is through quark helicity flip, which is proportional to current quark mass m_q
  - To generate a phase difference, one has to have pQCD loop diagrams, proportional to α_S

Therefore a generic pQCD prediction goes like

$$A_N \sim \alpha_S\, m_q/Q$$

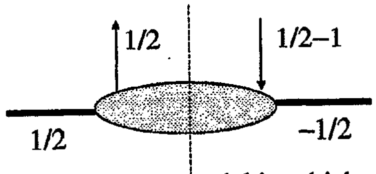
Every factor suppresses the SSA!

Beyond the Naïve Parton Model

- Transverse Momentum Dependent Parton Distributions
  - Sivers function, Sivers 90
  - Collins function, Collins 93
  - Brodsky, Hwang, Schmidt 02
    Collins 02
    Belitsky, Ji, Yuan 02
- Twist-three Correlations
  - Efremov-Teryaev, 82, 84
  - Qiu-Sterman, 91,98

Parton Orbital Angular Momentum and Gluon Spin

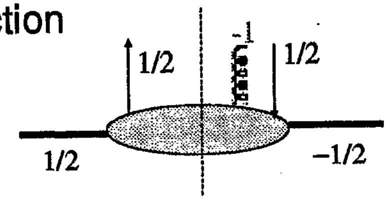
- The hadron helicity flip can be generated by other mechanism in QCD
  - Quark orbital angular momentum (OAM): Therefore, the hadron helicity flip can occur without requiring the quark helicity flip.



Beyond the naïve parton model in which quarks are collinear

Parton OAM and Gluons (cont.)

- A collinear gluon carries one unit of angular momentum because of its spin. Therefore, one can have a coherent gluon interaction

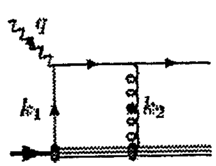


Quark-gluon quark correlation function!

Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

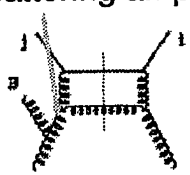
Where are the Phases

- TMD: the factorizable final state interactions --- the gauge link in the definition of the TMI



Brodsky, Hwang, Schmidt, 02
Collins, 02
Ji, Belitsky, Yuan, 02

- Twist-three quark-gluon correlation: poles from the hard scattering amplitudes



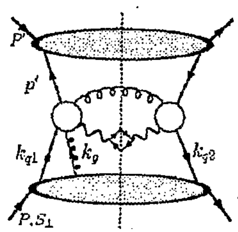
Efremov & Teryaev: 1982 & 1984
Qiu & Sterman: 1991 & 1999

Unifying the Two Mechanisms ($P_\perp$ dependence of DY)

- At low $P_\perp$, the non-perturbative TMD Sivers function will be responsible for its SSA
- When $P_\perp \sim Q$, purely twist-3 contributions
- For intermediate $P_\perp$, $\Lambda_{QCD} \ll P_\perp \ll Q$, we should see the transition between these two
- *An important issue, at $P_\perp \ll Q$, these two should emerge, showing consistence of the theory*

(Ji, Qiu, Vogelsang, Yuan, to appear)

A General Diagram in Twist-3

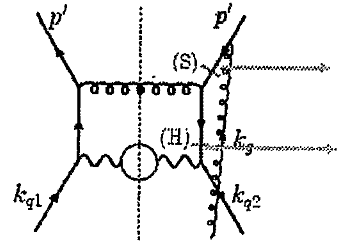


Collinear Factorization:

$$d\sigma \propto \epsilon^{\beta\alpha} S_{\perp\beta} q_{\perp\alpha} \int \frac{dx}{x}\frac{dx'}{x'} \bar{q}(x) T_F(x, x-xg) \times \cdots$$

Qiu,Sterman, 91

Soft and Hard Poles



$$\frac{1}{2p'^{-}P^{+}}\frac{1}{-x_g - i\epsilon}$$

$$\frac{1}{2k_{\gamma^*}^{-}P^{+}}\frac{1}{-x_g + x\hat{t}/(Q^2-\hat{t}) - i\epsilon}$$

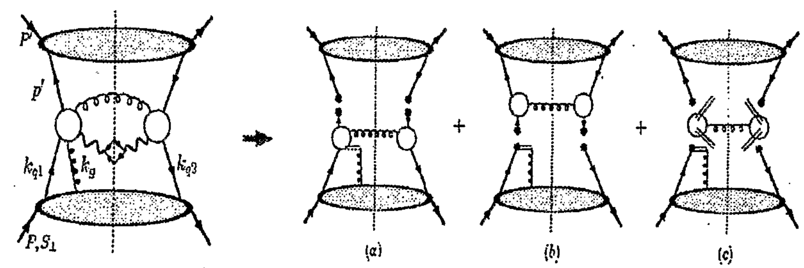
- Soft: $x_g=0$
- Hard: $x_g \neq 0$

Sivers Function at Large $k_\perp$

$$q_T^{(1)}(x,k_\perp) = \frac{\alpha_s}{4\pi^2}\frac{2M_p}{(k_\perp^2)^2}\int\frac{dx}{x}\{A + C_F T_F(x) \times \delta(\xi_1 - 1)\left(\ln \zeta^2/\vec{k}_\perp^2 - 1\right)\}$$

- $1/k_\perp^4$ follows a power counting
- Plugging this into the factorization formula, we indeed reproduce the polarized cross section calculated from twist-3 correlation

Factorization Arguments



Reduced diagrams for different regions of the gluon momentum: along P direction, P', and soft Collins-Soper 81

Final Results

- $P_\perp$ dependence

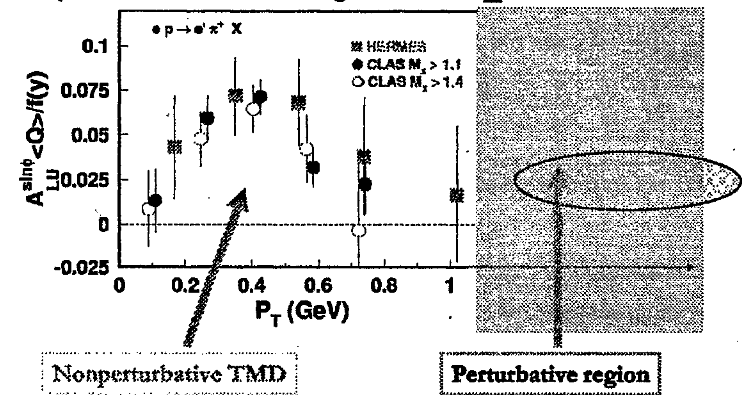
$$\frac{d\triangle\sigma}{d^2q_\perp dy} = \int q_T(z_1,k_\perp)\bar{q}(z_2,k_\perp) + \left(\frac{d\triangle\sigma^{QS}}{d^2q_\perp dy} - \frac{d\triangle\sigma^{QS}}{d^2q_\perp dy}|_{aspt.}\right)$$

Sivers function at low $P_\perp$ — Qiu-Sterman Twist-three

- Which is valid for all $P_\perp$ range

Transition from Perturbative region to Nonperturbative region?

- Compare different region of $P_\perp$



What do we learn from SSA?

Nonzero Sivers function implies

- **Nonzero Quark Orbital Angular Momentum**

  e.g, Siver's function ~ the wave function amplitude with orbital angular momentum!

  Vanishes if quarks only in s-state!

  Friends:
  - Pauli Form Factor $F_2(t)$
  - Spin-dependent structure function $g_2(x)$
  - Generalized Parton Distribution $E(x, \xi, t)$

$L_z \neq 0$ Amplitude and Sivers Function

- All distributions can be calculated using the wave function. The amplitudes are not real because of FSI. Siver's function:

$$q_T(x, k_\perp) = \frac{M}{k_\perp^2} \int d[1]d[2]d[3]\sqrt{x_1 2x_2 2x_3}\, \mathrm{Im}[F_q] \, .$$

The functions F_q for the u-quark is

$$F_u = 2\Big\{\delta^{(3)}(k-k_1)\tilde{\psi}_3^{(1,2)*}(1,2,3)\tilde{\psi}_4^{(3,4)}(1,2,3) - \delta^{(3)}(k-k_2)\tilde{\psi}_3^{(1,2)}(1,2,3)\tilde{\psi}_4^{(3,4)*}(2,1,3)$$

$L_z=0$ $L_z=1$

- Similar expressions for $F_2(Q)$, $g_2(x)$ and $E(x,t)$

Ji, Ma, Yuan, Nucl. Phys. B (2003)

Concluding Remarks

- Nonzero Sivers function indeed indicates the existence of the Quark Orbital Angular Momentum
- However, there is no definite relation between these two so far
- We, as theorists, need to work hard for that goal, as asked by experimentalists

G. Bunce
RBRC and BNL

Transverse Spin at Phenix

These comments on transverse spin at Phenix are from my own perspective. They are flavored by a view that so far most action in transverse spin has been in the "valence" region, or the beam/target fragmentation region. This is not entirely the case, since at the AGS a large π^+ asymmetry was observed for inclusive production at mid rapidity, with no asymmetry for π^- [1]. However, in general, at mid-rapidity a transversity effect would appear unlikely, where the scattered quarks or antiquarks carry polarization. A Sivers effect is possible, where an orbital angular momentum of the partons in the proton associated with the proton spin direction could be present.

The Phenix experiment, for mid-rapidity and at $\sqrt{s}$ =200 GeV and p_T(max)=100 GeV, measured zero asymmetry for pion production to about 1% uncertainty in the few GeV p_T region [2]. The measurement is sensitive to lower momentum fraction partons than for forward particle production. When compared with the large forward asymmetry observed by STAR and BRAHMS at RHIC, the mid-rapidity asymmetry is at least an order of magnitude smaller. When coupled with the description of the cross section for π^0 production by pQCD, the Phenix measurement appears to limit the gluon Sivers function this reaction to a small fraction of the apparent quark Sivers asymmetry observed for forward pion production. Here I use the result reported by Anselmino that the large forward asymmetries are unlikely to be due to transversity.

Another measurement is proceeding at this time, to measure a transverse spin dependent k_T effect directly, following Vogelsang and Boer [3]. We have learned at this meeting that each Sivers type measurement is process dependent. Therefore, the absence of a Sivers effect in pion production at mid-rapidity would not be incompatible with a non-zero k_T asymmetry. This run (2006) should also greatly improve the p_T range and statistics for the single pion asymmetry, due to RHIC running with much higher polarization (55% vs. 15% for the original measurement) and luminosity.

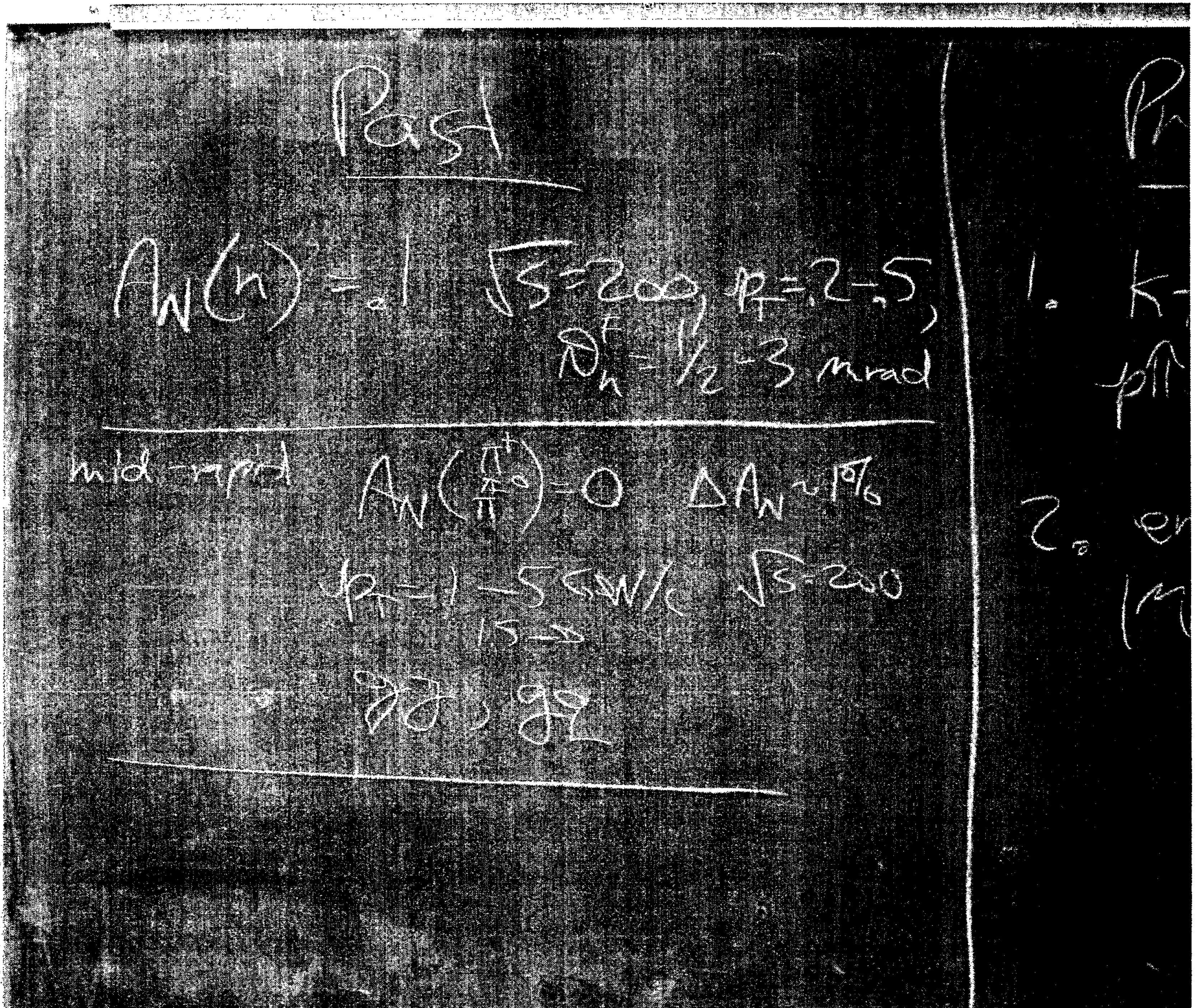
A very large asymmetry was observed at RHIC, $\sqrt{s}$ =200 GeV, for very forward neutron production, p_T=100-200 MeV/c, A_N=-0.1 [4]. This asymmetry is the basis of the local polarimetry that is used to set up and monitor the spin direction of the RHIC beams at Phenix. At the Japan Physical Society meeting this March, the cross section was presented [5]. It is very consistent with earlier ISR cross section data and matches the predicted energy dependence for one pion exchange production.

On new detectors [6]. Phenix installed a forward EM calorimeter just behind the BBC counters, eta=3-4. This may give Phenix the opportunity to explore spin dependent correlations of forward production with mid-rapidity. However, the detector is surrounded by magnet yoke, so the albedo from particle conversions in the iron will be an issue. A vertex detector is being built for installation in 2009-2010. The detector offers heavy quark i.d. and reconstruction of jet axes for correlation measurements with spin. Lastly, a nose cone calorimeter is being considered. The present inert brass nose cones filter muons from the debris of RHIC collisions, for forward production. The muon arms will be the focus for parity violating W boson production, in $\sqrt{s}$ =500 GeV running planned for 2009 to 2012. The proposed calorimeter would allow tests for W isolation, and offer jet information for correlation spin physics.

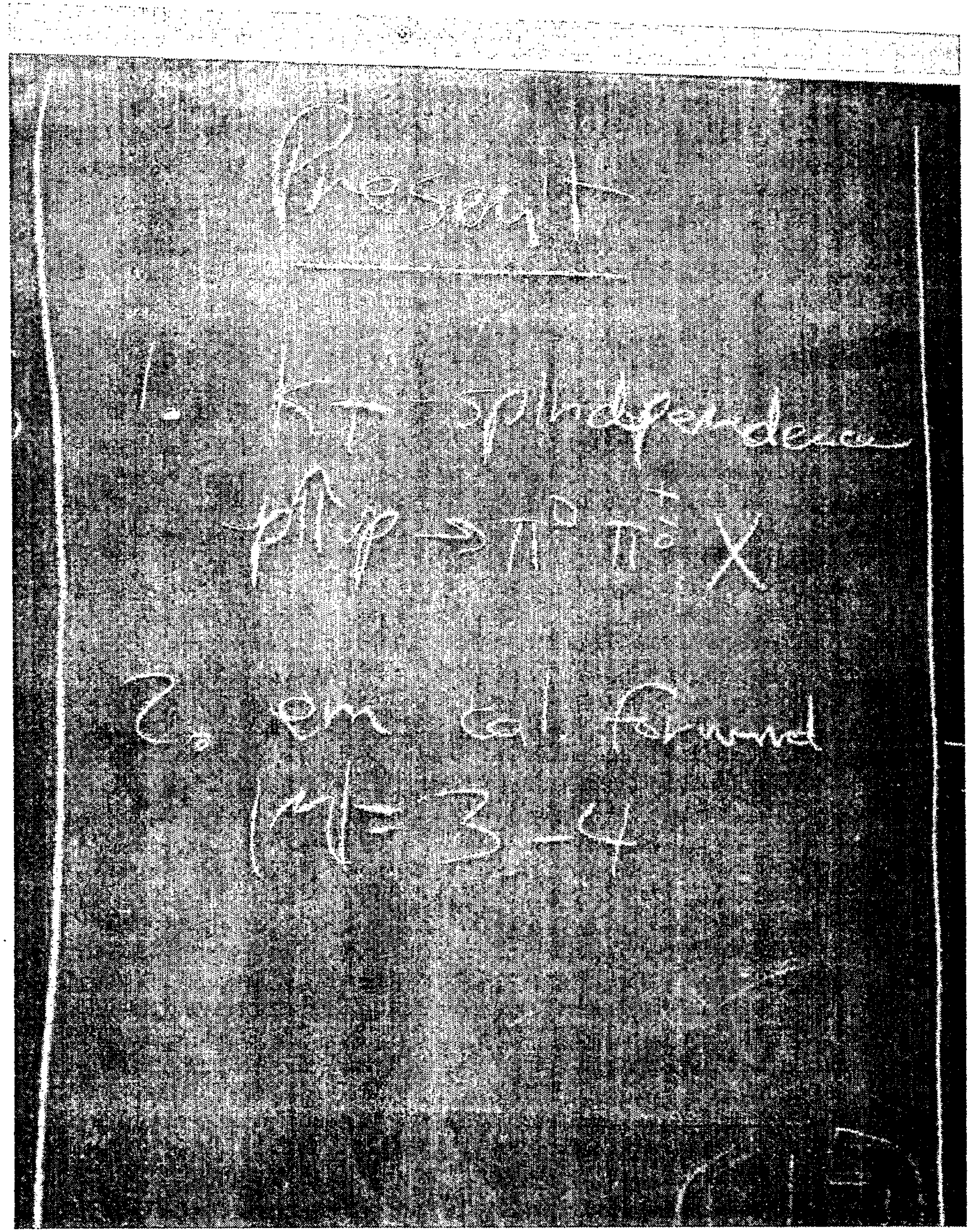
On the far future. eRHIC [7] offers many important measurements. For example, probing the Sivers and transversity effects reported by Hermes and discussed here by Schnell, at collider energy.

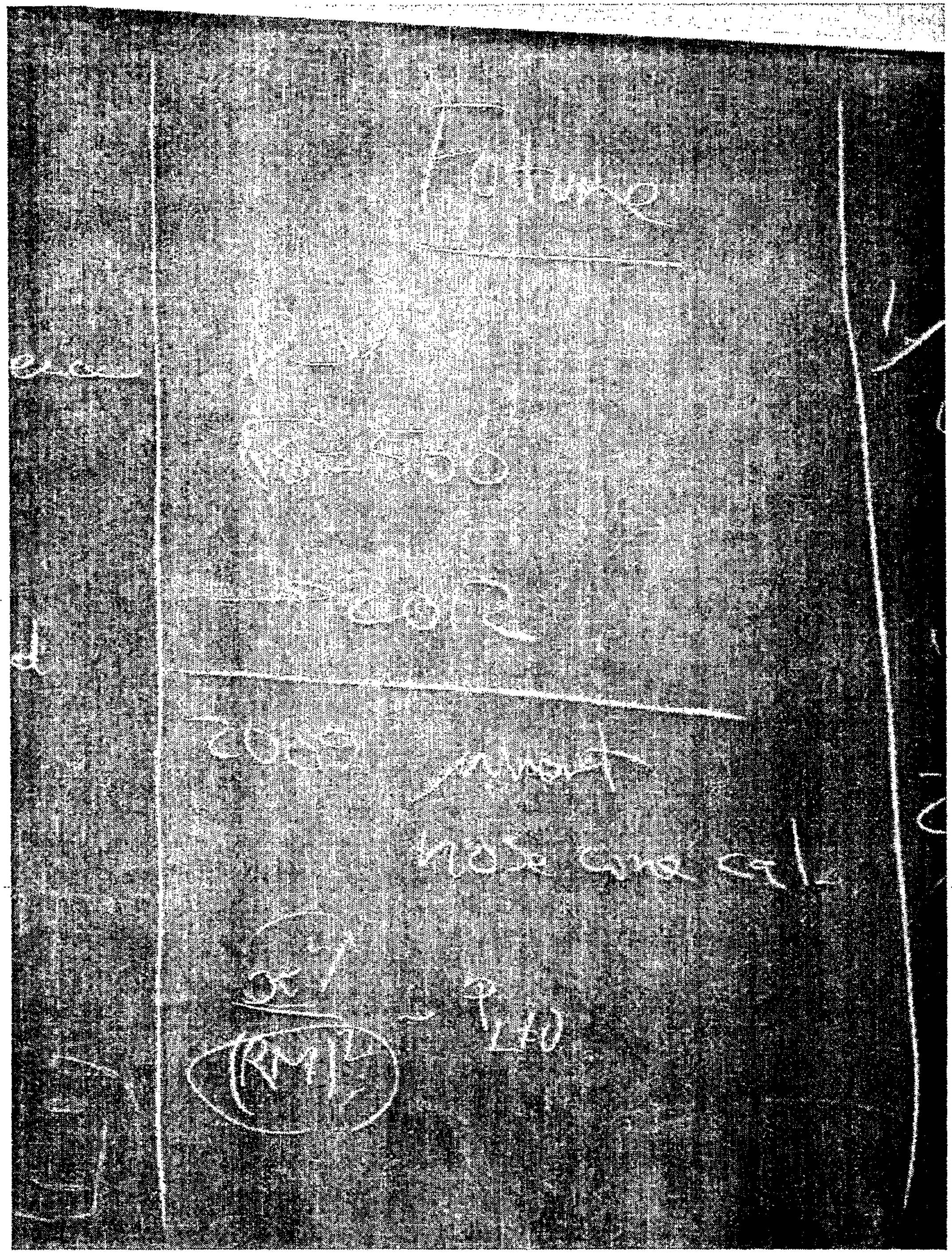
Bibliography

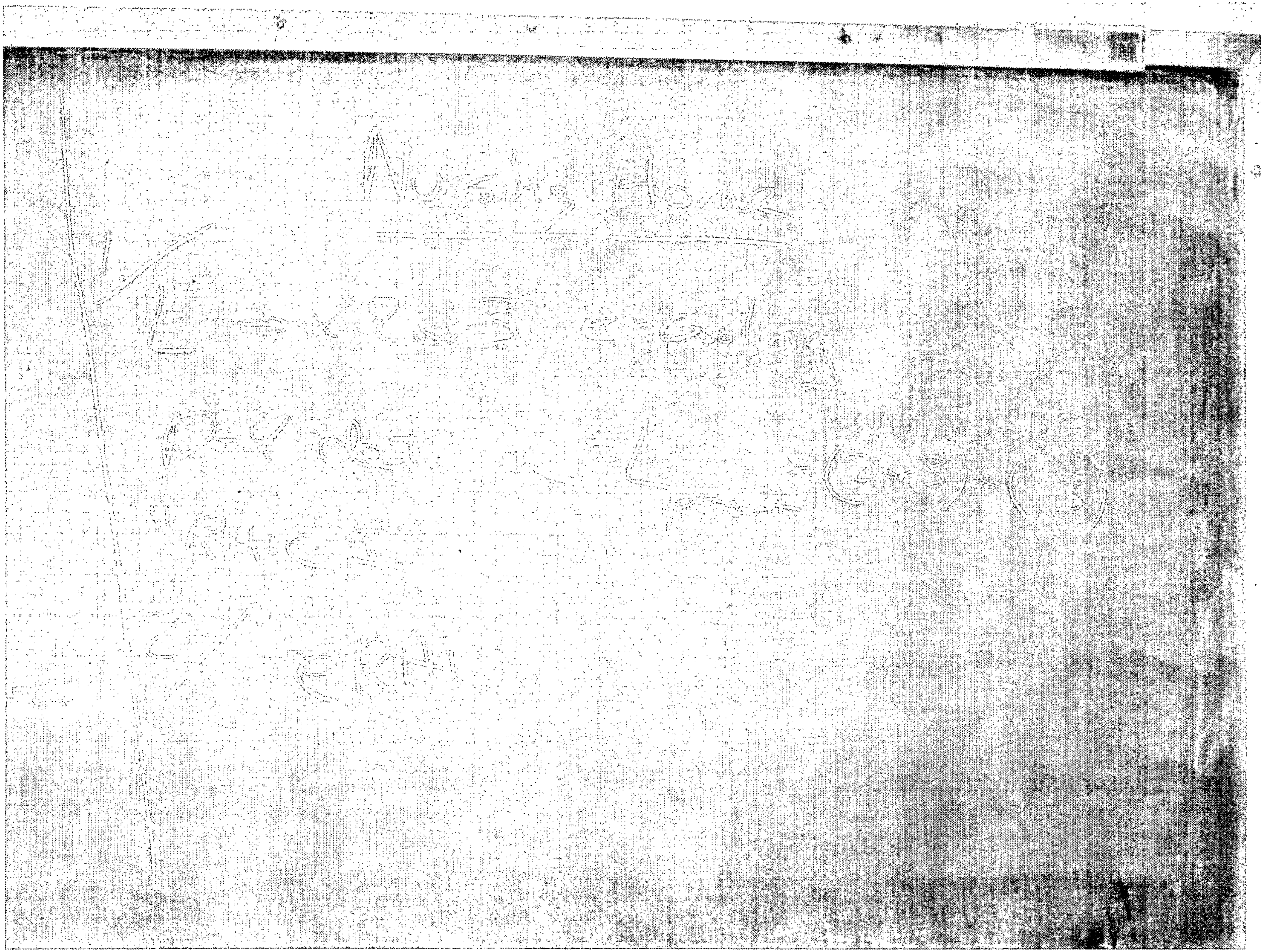
[1] S. Saroff et al., PRL 64, 995 (1990).
[2] S.S. Adler et al., PRL 95, 202001 (2005).
[3] D. Boer and W. Vogelsang, PR D69, 094025 (2004).
[4] A. Bazilevsky et al., Spin2002, AIP Conf. Proc. 675, Y. Makdisi, A. Luccio, W. MacKay editors, 584 (2003).
[5] M. Togawa, JPS March 2006.
[6] Phenix upgrades, http://www.phenix.bnl.gov/plans.html
[7] eRHIC http://www.phenix.bnl.gov/WWW/publish/abhay/Home_of_EIC/


Past
A_N(h) = .1 √s = 200, p_T = 2–5,
θ_h = 1/2–3 mrad
mid-rapid A_N(π+ π0 π-) = 0 ΔA_N ~ 1%
p_T = 1–5 GeV/c √s = 200
1.5–∞
1.
2.

75


1. kT - spin dependence
p↑p → π0 π0 X
2. em cal forward
|η| = 3-4


Future
nose cone calc


Nursing Home

SSA Measurements with a Primary Beam at J-PARC

Yuji Goto

RIKEN and RIKEN BNL Research Center

J-PARC (Japan Proton Accelerator Research Complex) is constructed at Tokai, which is located about 100km north-east of Tokyo. The facility consists of a linac, a 3-GeV synchrotron, and a 50-GeV synchrotron. This is a joint project between KEK and JAEA (Japan Atomic Energy Agency) aimed at not only particle and nuclear physics experiments but also material and life science experiments and a nuclear transmutation. For the particle and nuclear physics, there is a hadron beam facility and a neutrino beam facility to Kamiokande.

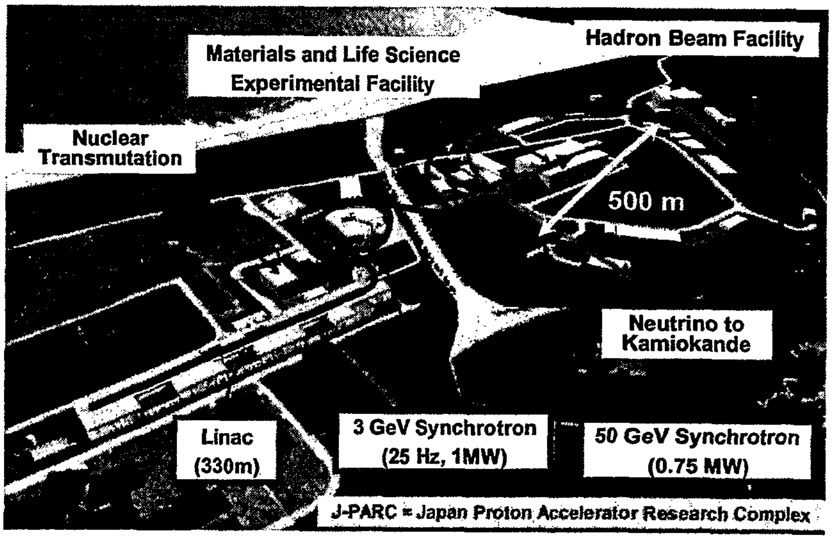
For the spin physics program with a primary beam at J-PARC, a study group for the polarized proton acceleration and physics experiments was formed, and discussions are underway. As one of the key issues in the hadron physics, we want to understand the origin of the nucleon spin 1/2. Polarized DIS experiments showed the quark-spin contribution is only 10-30%. We are working at RHIC to measure the gluon-spin contribution. At PHENIX, we obtained A_{LL} (double-helicity asymmetry) of neutral pion production channel as a preliminary result of 2005 run. We got a result to favor the gluon-spin contribution smaller than 0.4 in statistically one-sigma level. By using this number, the sum of quark-spin contribution and gluon-spin contribution favors smaller than 1/2. The remaining component is the orbital angular momentum. The orbital angular momentum measurements should be developed for the final solution.

For the orbital angular momentum measurement at hadronic-reaction experiments, we have hints from previous hadron experiments. One hint was provided by the Fermilab E704 experiment which showed large SSAs (single-spin asymmetries) of pion production at a large-x_F region. To explain this result, many theoretical models have been developed. The similar asymmetry was shown by the STAR experiment at the RHIC collider energy.

The SSA of the Drell-Yan process is one of the most clean channels to investigate contribution from theoretical models because there is no final-stater effect, and it is sensitive to Sivers effect at a low q_T region and the higher-twist effect at a high q_T region. One experiment we are discussing at J-PARC is a Drell-Yan experiment similar to Fermilab E866/NuSea experiment. It is a closed geometry muon spectrometer with tapered copper beam dump and Cu/C absorbers placed in the first magnet. By using and extending the same apparatus, several other SSA measurements are possible. For example, by measuring a backward SSA of pions, it is sensitive to the gluon Sivers effect at fixed target experiment energies. The sensitivity is lower at collider energies. Another SSA measurement under discussion is that of D-mesons.

Physics and detector studies are ongoing. Collaboration with many groups in the world is very important

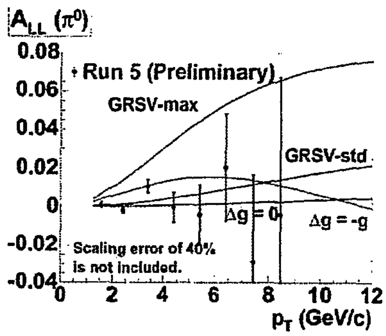
J-PARC facility

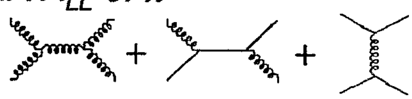


Joint Project between KEK and JAEA

Introduction

- Gluon contribution – PHENIX A_{LL} of π^0





GRSV-max: Δg = 1.84

GRSV-std: Δg = 0.42
at Q^2=1$(GeV/c)^2$
best fit to DIS data

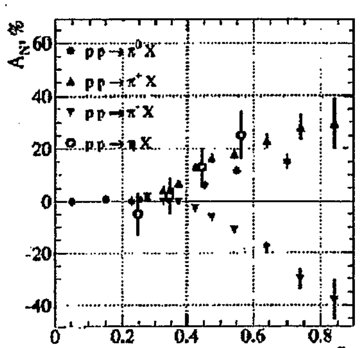
- – PHENIX official statement
  - conclusively excludes GRSV maximal scenario
  - consistent with GRSV standard and GRSV Δg=0 input scenarios
- – Personal statement
  - ~1-sigma region: Δg < 0.4
  - orbital angular momentum measurements should be developed for the final solution

Introduction

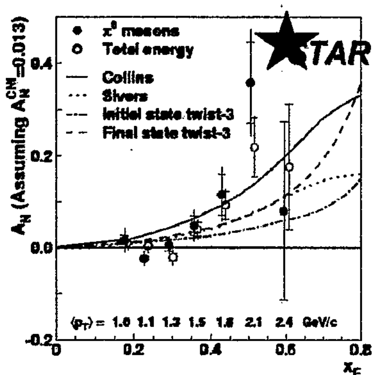
STAR collaboration, hep-ex/0310058, Phys. Rev. Lett. **92** (2004) 171801

- Orbital angular momentum
  - hint in hadron reactions

Fermilab E704: E_{lab} = 200 GeV



STAR at RHIC: $\sqrt{s}$ = 200 GeV

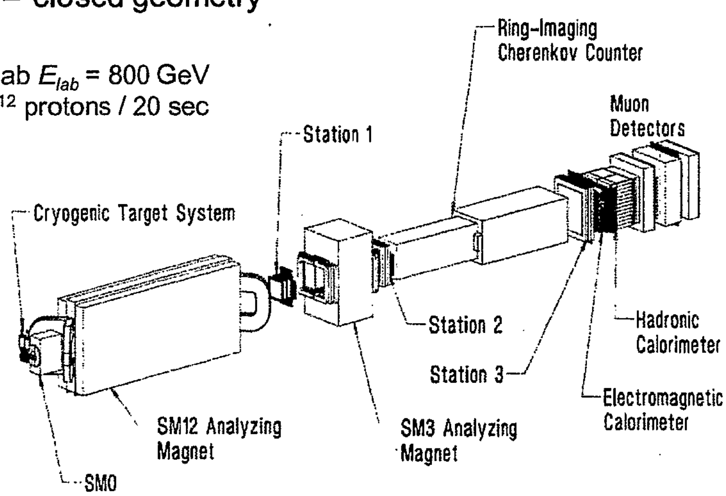


  - asymmetries in angular distribution of semi-inclusive hadron production at polarized DIS exps

Drell-Yan experiment

- Fermilab E866/NuSea and E906 at MI
  - closed geometry

Fermilab E_{lab} = 800 GeV
2×10^{12} protons / 20 sec

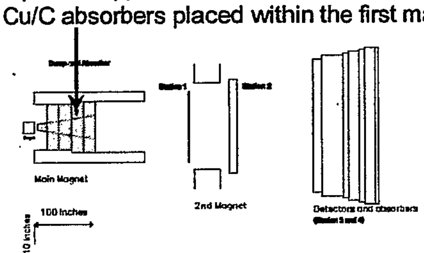


Experimental apparatus

- two vertically bending magnets with p_T kick of 2.47 GeV/*c* and 0.5 GeV/*c*
- closed geometry
- tracking is provided by three stations of MWPC and drift chambers
- muon id and tracking are provided
- 2×10^{12} 50 GeV p/spill
- based on the Fermilab spectrometer for 800 GeV, the length can be reduced but the aperture has to be increased

Schematic view in horizontal plane

tapered copper beam dump and
Cu/C absorbers placed within the first magnet



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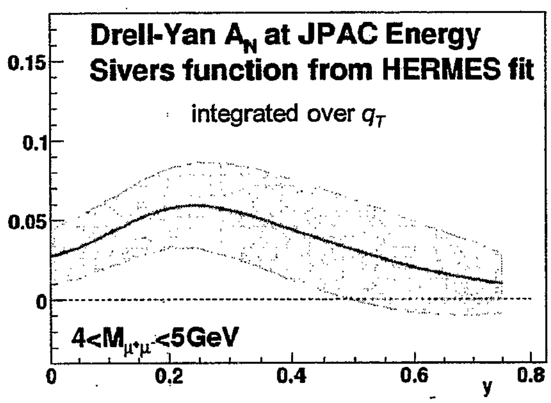
SSA on Drell-Yan

- no final-state effect
- sensitive to Sivers effect at low q_T: $q_T << Q$



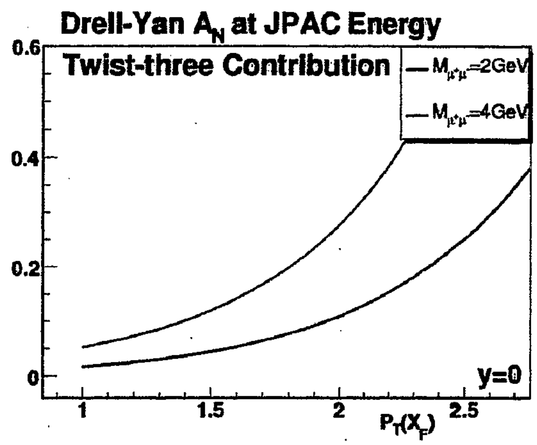
Sivers function fit from Vogelsang & Yuan: PRD 72, 054028 (2005).

(from Xiangdong Ji's slide at J-PARC hadron structure workshop at KEK, December, 2005)

February 25, 2006 Yuji Goto (RIKEN/RBRC) 6

SSA on Drell-Yan

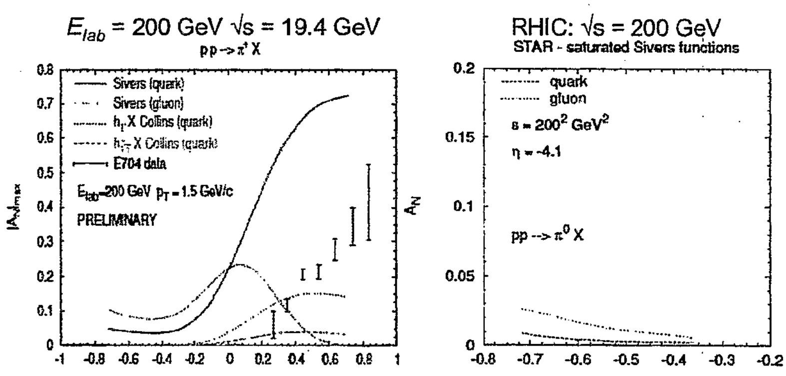
– sensitive to higher-twist effect at high q_T: $\Lambda_{QCD} << q_T$



(from Xiangdong Ji's slide at J-PARC hadron structure workshop at KEK, December, 2005)

SSA measurement of pions

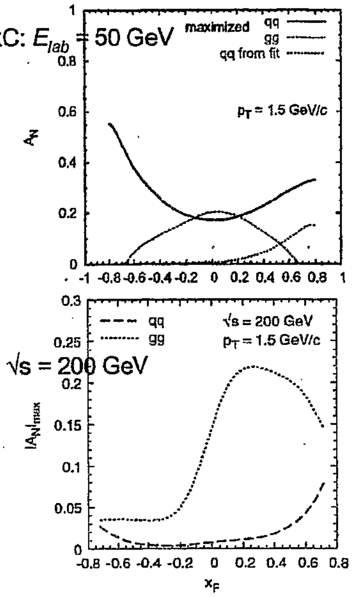
- Forward pions with a polarized target
  - backward A_N (x_F < 0)
  - sensitive to the gluon Sivers effect at fixed-target exp. energies
  - not very sensitive at collider energies



M. Anselmino, U. D'Alesio, F. Murgia, et al.

SSA measurement of D-mesons

- gluon fusion or quark-pair annihilation
- no single-spin transfer to the final state
- sensitive to initial state effect: Sivers effect
  - to be measured at RHIC: PHENIX with silicon upgrade (2009)
- collider energies: gluon-fusion dominant
  - sensitive to gluon Sivers effect
- fixed-target energies: quark-pair annihilation dominant
  - sensitive to quark Sivers effect
- complementary



M. Anselmino, U. D'Alesio, F. Murgia, et al.

Summary

- For the spin physics program with primary beam at J-PARC, study group for the polarized proton acceleration and the physics experiment were formed, and discussions are underway
- Measurement of the orbital angular momentum component in the nucleon is one of the most important goal of the spin physics program at J-PARC
- Drell-Yan experiments are planned
  - SSA measurements of Drell-Yan, pions, D-mesons, etc.
  - gluon polarization at large-x, transversity, etc.
- Physics and detector studies are ongoing
- Collaboration with many groups in the world is very important

$k_\perp$ Dependence and "T-Odd" Effects in TSSAs & Azimuthal Asymmetries

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Abstract

One of the persistent challenges confronting the QCD improved parton model is to account for the large azimuthal and single spin asymmetries that emerge in semi-inclusive electro-production, and di-lepton production in Drell Yan scattering. Going beyond the collinear approximation in PQCD recent progress has been achieved in characterizing these asymmetries in terms of initial and final state interactions. At moderate $P_T \sim \Lambda_{QCD}$ these effects can be described by the so called naive time reversal odd or T-odd transverse momentum parton distribution and fragmentation functions. Thus a study of these asymmetries provide a window to explore novel quark distribution and fragmentation functions which constitute essential information about the spin, transversity and generalized momentum structure of hadrons. Here we consider the leading twist T-odd contributions as the dominant source of the $\cos 2\phi$ azimuthal asymmetry and $\sin(\phi \pm \phi_s)$ SSAs in SIDIS and $p\bar{p} \to \mu\mu^+ X$ di-lepton production in Drell-Yan Scattering. These asymmetries contain information on the distribution of quark transverse spin in an unpolarized proton, $h_1^\perp(x, k_\perp)$. In a parton-spectator framework we estimate these asymmetries at HERMES kinematics and for Drell-Yan scattering at 50 GeV center of mass energy. The latter azimuthal asymmetry is interesting in light of proposed experiments at GSI, where an anti-proton beam is ideal for studying the transversity properties of quarks due to the dominance of *valence* quark effects. With proposed luminosity and detector upgrades at PHENIX and STAR (RHIC II) it is of interest to consider *sea quark* Boer-Mulders and Sivers distribution functions see to predict the $\cos 2\phi$ azimuthal asymmetries for di-lepton production in the Drell Yan $p\,p \to \ell^+\ell^- X$ reaction.

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Provide source of T-Odd Contributions to TSSA and AA

- **Enter the *leading twist* distribution and fragmentation correlators "T-odd" Distribution Functions: Transversity Properties of quarks in Hadrons**

Boer, Mulder: PRD 1998

$$\Delta(z,\boldsymbol{k}_\perp)=\frac{1}{4}\{D_1(z,z\boldsymbol{k}_\perp)\,\not{n}_- + H_1^\perp(z,z\boldsymbol{k}_\perp)\frac{\sigma^{\alpha\beta}k_{\perp\alpha}n_{-\beta}}{M_h}+D_{1T}^\perp\frac{\epsilon_{\mu\nu\rho\sigma}\gamma^\mu n_-^\nu k_\perp^\rho S_{hT}^\sigma}{M_h}+\cdots\},$$

$$\Phi(x,\boldsymbol{p}_\perp)=\frac{1}{2}\{f_1(x,\boldsymbol{p}_\perp)\,\not{n}_+ + h_1^\perp(x,\boldsymbol{p}_\perp)\frac{\sigma^{\alpha\beta}p_{T\alpha}n_{+\beta}}{M}+f_{1T}^\perp(x,\boldsymbol{p}_\perp)\frac{\epsilon^{\mu\nu\rho\sigma}\gamma^\mu n_+^\nu p_\perp^\rho S_T^\sigma}{M}\cdots\}$$

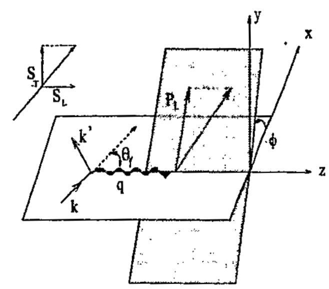
<u>SIDIS cross section</u>

$$\begin{aligned}
d\sigma_{\{\lambda,\Lambda\}}^{\ell N\to\ell\pi X} \;\propto\;& f_1\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes D_1+\frac{k_\perp}{Q}f_1\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes D_1\cdot\cos\phi\\
&+\left[\frac{k_\perp^2}{Q^2}f_1\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes D_1+h_1^\perp\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes H_1^\perp\right]\cdot\cos 2\phi\\
&+|S_T|\cdot h_1\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes H_1^\perp\cdot\sin(\phi+\phi_S)\quad\text{Collins}\\
&+|S_T|\cdot f_{1T}^\perp\otimes d\hat{\sigma}^{\ell q\to\ell q}\otimes D_1\cdot\sin(\phi-\phi_S)\quad\text{Sivers}\\
&+\cdots
\end{aligned}$$

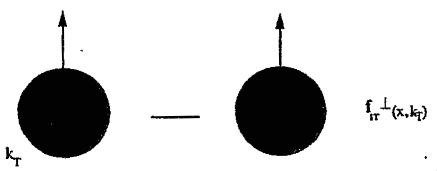
SIDIS-Transversity Properties at Leading Twist

- Collins NPB:1993, Kotzinian NPB:1995, Mulders, Tangerman PLB:1995

$$\langle\frac{P_{h\perp}}{M_\pi}=\sin(\phi+\phi_S)\rangle_{UT}\frac{\int d\phi_s\int d^2P_{h\perp}\frac{P_{h\perp}}{M_\pi}\sin(\phi+\phi_s)\left(d\sigma^\uparrow-d\sigma^\downarrow\right)}{\int d\phi_s\int d^2P_{h\perp}\left(d\sigma^\uparrow+d\sigma^\downarrow\right)}=|S_T|\frac{2(1-y)\sum_q e_q^2 h_1(x)zH_1^{\perp(1)}(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)}$$



- Sivers PRD: 1990, Anselmino & Murgia PLB: 1995 ...

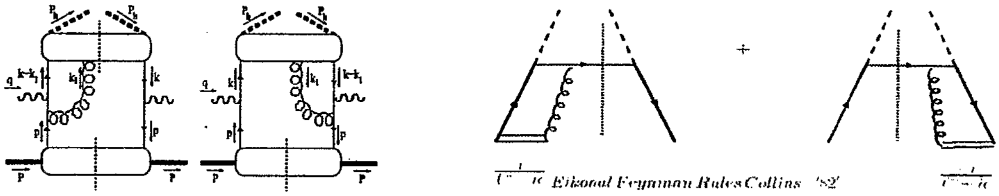


$$\langle\frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\rangle_{UT}=|S_T|\frac{(1+(1-y)^2)\sum_q e_q^2 f_{1T}^{\perp(1)}(x)zD_1^q(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)},$$

- Probes the probability for a transversely polarized target, pions are produced asymmetrically about pion production plane

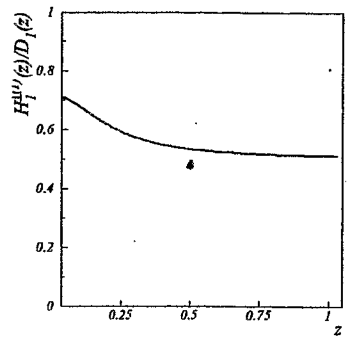
Gauge Link-Pole Contribution to T-Odd Collins Function

L.G.,Goldstein,Oganessyan PRD68,2003 $\Delta^{[\sigma^{\perp-}\gamma_5]}(z,k_\perp) = \frac{1}{4z}\int dk^+ Tr(\gamma^-\gamma^\perp\gamma_5\Delta)\big|_{k^-=P_\pi^-/z}$



Motivation:color gauge .inv frag. correlator "pole contribution"
leading twist T-odd pion fragmentation

$$H_1^\perp(z,k_\perp) = \frac{N'^2 f^2 g^2}{(2\pi)^4}\frac{1}{4z}\frac{(1-z)}{z}\frac{\mu}{\Lambda'(k_\perp^2)}\frac{M_\pi}{k_\perp^2}\mathcal{R}(z,\boldsymbol{k}_\perp^2)$$

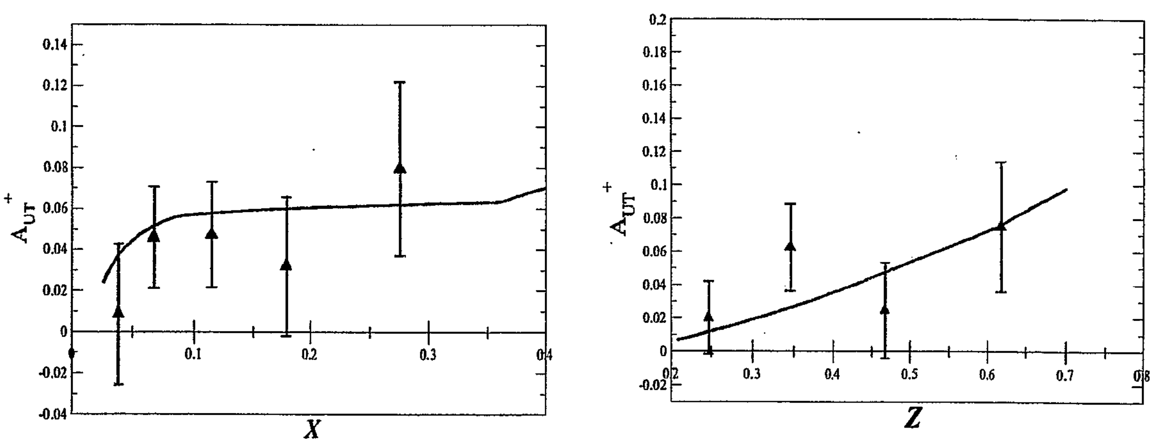


Collins Asymmetry

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

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

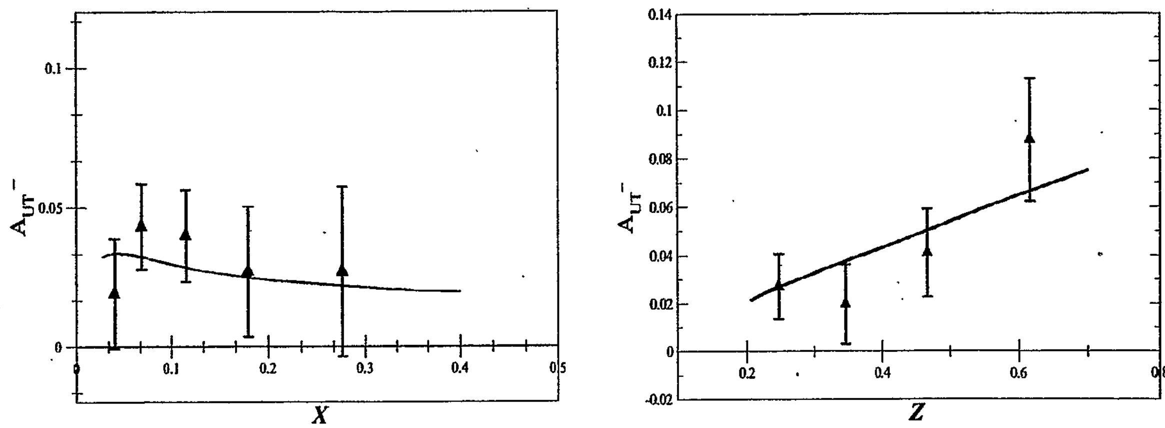
Data from A. Airapetian et al. PRL94,2005



Estimates for Sivers Asymmetry

Data from A. Airapetian et al. PRL94,2005

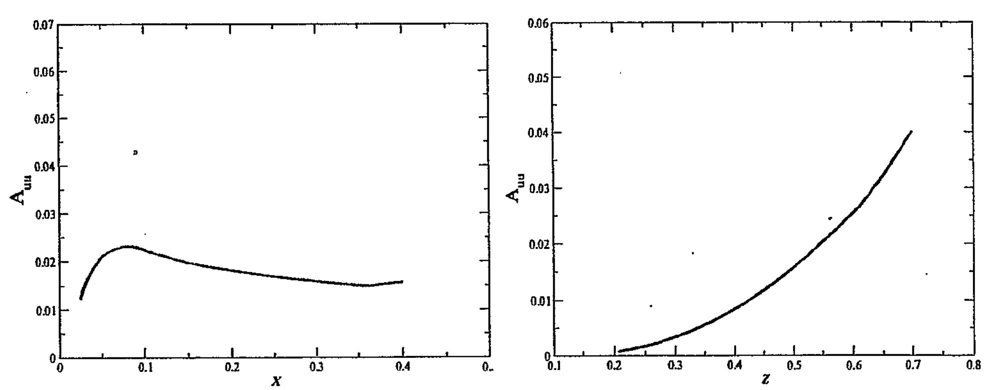
$$\langle \frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\rangle_{UT} = \frac{\int d^2P_{h\perp}\frac{|P_{h\perp}|}{M}\sin(\phi-\phi_S)\,d\sigma}{\int d^2P_{h\perp}\,d\sigma} = \frac{(1+(1-y)^2)\sum_q e_q^2 f_{1T}^{\perp(1)}(x)zD_1^q(z)}{(1+(1-y)^2)\sum_q e_q^2 f_1(x)D_1(z)},$$



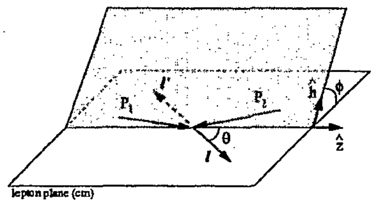
Double T-odd $\cos 2\phi$ asymmetry

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

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



Boer-Mulders Effect in Unpolarized DRELL YAN $\cos 2\phi$



$$\bar{p} + p \to \mu^- \mu^+ + X$$

$$\frac{dN}{d\Omega} = (\frac{d\sigma}{d^4q})^{-1} \frac{d\sigma}{d^4q d\Omega} = \frac{3}{4\pi} \frac{1}{\lambda + 3} \left(1 + \lambda \cos^2\theta + \mu \sin^2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi\right) \qquad (4)$$

Angles refer to the lepton pair orientation in their COM frame relative and the initial hadron's plane. Asymmetry parameters, λ, μ, ν, depend on $s, x, m^2_{\mu\mu}, q_T$

Boer PRD: 1999, Boer, Brodsky, Hwang PRD: 2003 Collins SoperPRD: 1977 subleading twist

- Leading twist $\cos 2\phi$ azimuthal asymmetry depends on T-odd distribution $h_1^\perp$.

$$\nu = \frac{2 \sum_a e_a^2 \mathcal{F} \left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp) \frac{h_1^\perp(x, \boldsymbol{k}_T) \bar{h}_1^\perp(\bar{x}, \boldsymbol{p}_T)}{M_1 M_2} \right]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1 \bar{f}_1]} \qquad (5)$$

Higher twist comes in

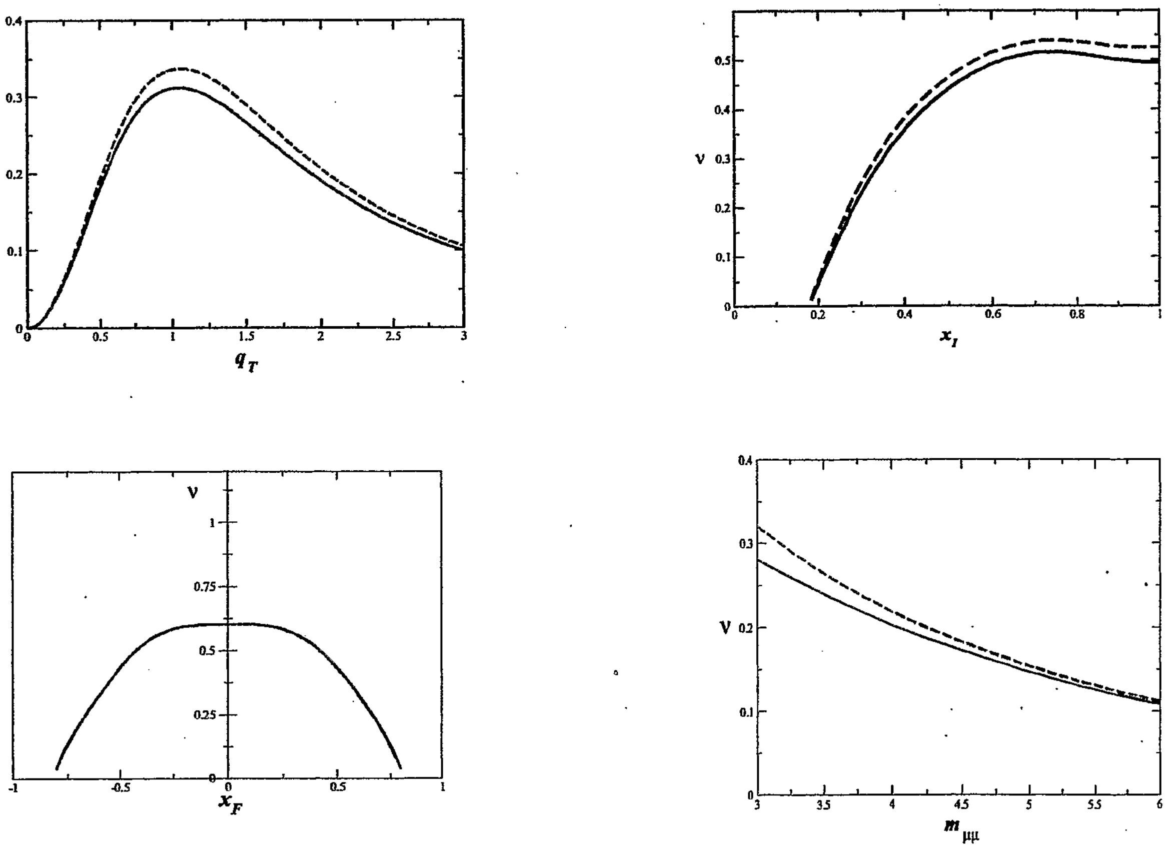
$$\nu = \frac{2 \sum_a e_a^2 \mathcal{F} \left[(2\boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp - \boldsymbol{p}_\perp \cdot \boldsymbol{k}_\perp) \frac{h_1^\perp(x, \boldsymbol{k}_T^2) \bar{h}_1^\perp(\bar{x}, \boldsymbol{p}_T)}{M_1 M_2} \right] + \nu_4 [w_4 f_1 \bar{f}_1]}{\sum_{a,\bar{a}} e_a^2 \mathcal{F}[f_1 \bar{f}_1]}$$

$$\nu_4 = \frac{\frac{1}{Q^2} \sum_a e_a^2 \mathcal{F} \left[w_4 \, f_1(x, \boldsymbol{k}_\perp) \bar{f}_1(\bar{x}, \boldsymbol{p}_\perp) \right]}{\sum_a e_a^2 \mathcal{F} \left(f_1(x, \boldsymbol{k}_\perp) \bar{f}_1(\bar{x}, \boldsymbol{p}_\perp) \right)},$$

Weight

$$w_4 = 2 \left(\hat{\boldsymbol{h}} \cdot (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp) \right)^2 - (\boldsymbol{k}_\perp - \boldsymbol{p}_\perp)^2$$

Convolution integral $\mathcal{F} \equiv \int d^2\boldsymbol{p}_\perp d^2\boldsymbol{k}_\perp \delta^2(\boldsymbol{p}_\perp + \boldsymbol{k}_\perp - \boldsymbol{q}_\perp) f^a(x, \boldsymbol{p}_\perp) \bar{f}^a(\bar{x}, \boldsymbol{k}_\perp)$



L.G., Goldstein hep-ph/0506127 $s = 50\,GeV^2$, $x = [0.2 - 1.0]$, and $q = [3.0 - 6.0]\ GeV$, $q_T = 0 - 3.0\,GeV$

SUMMARY

- Going beyond the collinear approximation in PQCD recent progress has been achieved characterizing transverse SSA and azimuthal asymmetries in terms of absorptive scattering.
- Central to this understanding is the role that transversity properties of quarks and hadrons assume in terms of correlations between transverse momentum and transverse spin in QCD hard scattering.
- These asymmetries provide a window to explore novel quark distribution and fragmentation functions which constitute essential information about the spin, transversity and generalized momentum structure of hadrons.
- Along with the chiral odd transversity T-even distribution function, existence of T-odd distribution and fragmentation functions can provide an explanation for the substantial asymmetries that have been observed in inclusive and semi-inclusive scattering reactions.
- We should consider the angular correlations in SDIS at 12 GeV for $\cos 2\phi$ from the standpoint of "rescattering" mechanism which generate T-odd, intrinsic transverse momentum, $k_\perp$, dependent *distribution and fragmentation* functions at leading twist
- Addressing issues of Universality of Collins Function

⋆ Azimuthal asymmetries in Drell Yan and SSA measured at HERMES and COMPASS, JLAB, Belle, GSI-PAX, JPARC *may* reveal the extent to which these leading twist T-odd effects are generating the data

Forward Particle Production and Transverse Spin Asymmetries

L.C.Bland, *Brookhaven National Laboratory*

Measurements of neutral pions produced at forward angles ($3.3 \leq \eta \leq 4.0$) in p+p collisions at $\sqrt{s}$ = 200 GeV have been completed by the STAR collaboration [1,2] at the Relativistic Heavy Ion Collider (RHIC). The measured π^0 production cross sections are generally in agreement with next-to-leading order perturbative QCD calculations [3] using the same distribution and fragmentation functions that describe midrapidity results [4]. This agreement is in contrast to what is found at lower $\sqrt{s}$ where measured cross sections far exceed NLO pQCD predictions [5]. Transverse single-spin asymmetries (SSA) are found to be large at RHIC energies when the produced π^0 carries a large fraction of the longitudinal momentum of the colliding transversely polarized proton (large Feynman x). The transverse SSA measurements exploit the unique capabilities of RHIC to accelerate, store and collide spin polarized proton beams. Transverse SSA are not expected in naïve applications of pQCD and require extensions to the theory involving spin- and transverse-momentum (k_T) dependent distribution functions (Sivers effect [6]) or a non-zero transversity distribution function analyzed by spin- and transverse-momentum dependent fragmentation functions (Collins/Heppelmann effect [7]). Higher twist effects involving quark and gluon correlations have also been suggested but can have significant overlap with k_T-dependent approaches. Both Sivers and Collins contributions have been identified in semi-inclusive deep inelastic scattering from a transversely polarized hydrogen target by the HERMES collaboration, as described at this workshop. The Sivers contribution is interpreted as evidence of orbital motion of the partons within a proton.

The STAR collaboration is embarking on an upgrade of their forward detection capability by the construction of a Forward Meson Spectrometer (FMS) [8]. An engineering test of the STAR FMS has been assembled for RHIC run 6 that is underway as of the writing of this contribution. The extended forward coverage by the modular calorimeters at STAR for RHIC run 6 will enable measurements of transverse SSA for multi-photon final states that exhibit jet-like properties, as described in this contribution. The design of the modular calorimeters ensures azimuthal symmetry about the thrust axis of the forward jet. Integration over this azimuthal symmetry isolates Sivers contributions to the forward π^0 transverse SSA. An observed dependence of the transverse SSA on the azimuthal distribution of additional photons would signal non-zero contributions from the Collins/Heppelmann effect. In addition, the modular forward calorimeters at STAR should provide measurements of the cross section for large rapidity direct photon production. Both transverse SSA and two-spin asymmetries with longitudinal polarization for large-rapidity direct photon production will be possible upon the completion of the STAR FMS.

[1] J.Adams *et al.* (STAR collaboration), Phys. Rev. Lett. **92** (2004) 171801.
[2] J. Adams *et al.* (STAR collaboration), submitted to Phys. Rev. Lett. [nucl-ex/0602011].
[3] B. Jager, A. Schafer, M. Stratmann and W. Vogelsang, Phys. Rev. D **67** (2003) 054005.
[4] S.S. Adler *et al.* (PHENIX collaboration), Phys. Rev. Lett. **91** (2003) 241803.
[5] C. Bourrely and J. Soffer, Eur. Phys. J. **C36** (2004) 371.
[6] D. Sivers, Phys. Rev. D **41** (1990) 83; **43** (1991) 261.
[7] J. Collins, Nucl. Phys. **B396** (1993) 161; J. Collins, S.F. Heppelmann, G.A. Ladinsky, Nucl. Phys. **B420** (1994) 565.
[8] L.C. Bland *et al.* Eur. Phys. J. **C43** (2005) 427.

Forward Particle Production and Transverse Single Spin Asymmetries

OUTLINE

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

L.C. Bland
Brookhaven National Laboratory
RBRC Workshop on Parton
Orbital Angular Momentum
Albuquerque 25 February 2006

STAR Forward Meson Spectrometer
[hep-ex/0502040]

F. Bieser[2], L. Bland[1], R. Brown[1], H. Crawford[2], A. Derevschikov[4], J. Drachenberg[5], J. Engelage[2], L. Eun[3], C. Gagliardi[5], S. Heppelmann[3], E. Judd[2], V. Kravtsov[4], Yu. Matulenko[4], A. Meschanin[4], D. Morozov[4], L. Nogach[4], S. Nurushev[4], A. Ogawa[1], C. Perkins[2], G. Rakness[1,3], K. Shestermanov[4], and A. Vasiliev[4]

[1] Brookhaven National Laboratory
[2] University of Berkeley/Space Sciences Institute
[3] Pennsylvania State University
[4] IHEP Protvino
[5] Texas A&M University

2/25/2006

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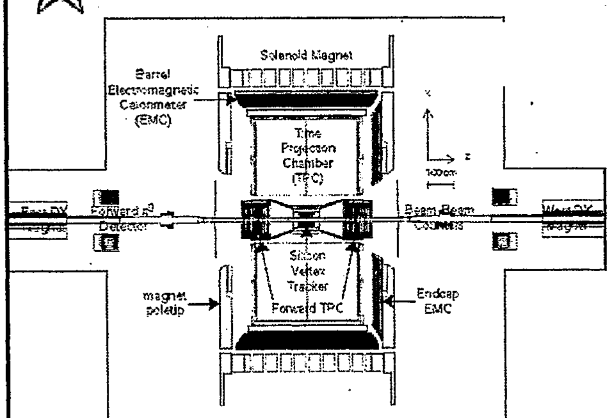
STAR detector layout

STAR



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

STAR characterized by azimuthally complete acceptance over broad range of pseudorapidity.

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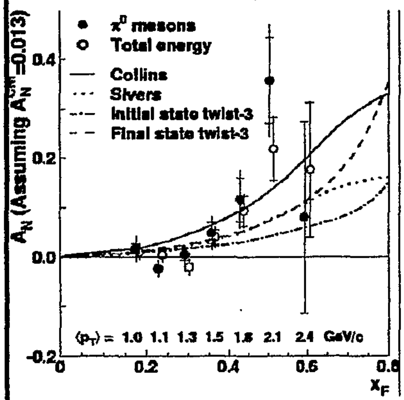
First A_N Measurement at STAR

prototype FPD results

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



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

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

Can be described by several models available as predictions:

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

Present Status

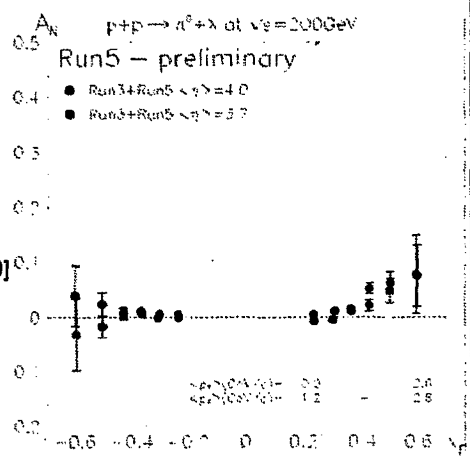
Run 2 Published Result.

Run 3 Preliminary Result.
-More Forward angles.
-FPD Detectors.

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

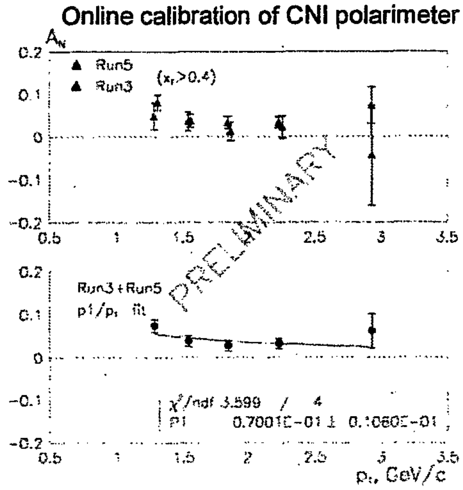
A. Ogawa, for STAR: [hep-ex/0502040]

Run 3 + Run 5 Preliminary
$\langle\eta\rangle$=3.7,4.0
D. Morozov, for STAR [hep-ex/0512013]



$A_N(p_T)$ from run3+run5 at $\sqrt{s}$=200 GeV

- Combined statistics from run3 and run5 allowed to distinguish nonzero effect in $A_N(p_T)$
- There is an evidence that analyzing power at x_F>0.4 decreases with increasing p_T
- To do: systematics study



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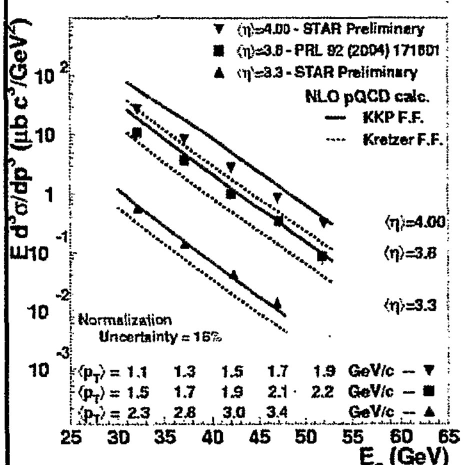
pp→π^0X cross sections at 200 GeV



- The error bars are point-to-point systematic and statistical errors added in quadrature
- The inclusive differential cross section for π^0 production is consistent with NLO pQCD calculations at 3.3 < η < 4.0
- The data at low p_T are more consistent with the Kretzer set of fragmentation functions, similar to what was observed by PHENIX for π^0 production at midrapidity.

D. Morozov (IHEP), XXXXth Rencontres de Moriond - QCD, March 12 - 19, 2005

NLO pQCD calculations by Vogelsang, et al.

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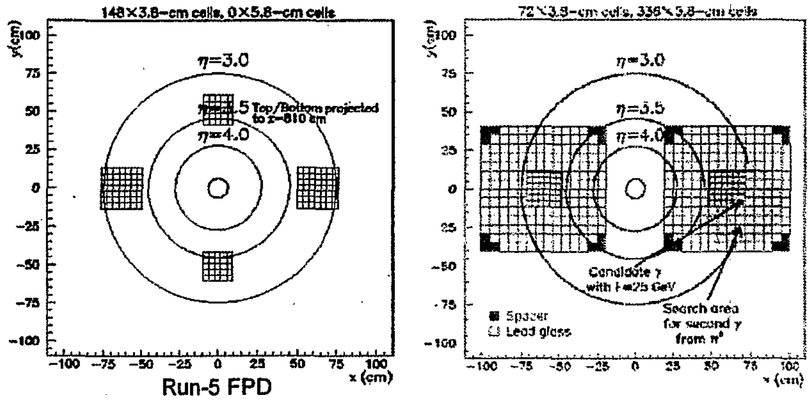
FPD++ Physics for Run6

We intend to stage a large version of the FPD to prove our ability to detect jet-like events, direct photons, etc.



The center annulus of the run-6 FPD++ is similar to arrays used to measure forward π^0 SSA. The FPD++ annulus is surrounded by additional calorimetry to increase the acceptance for jet-like events and direct γ events.

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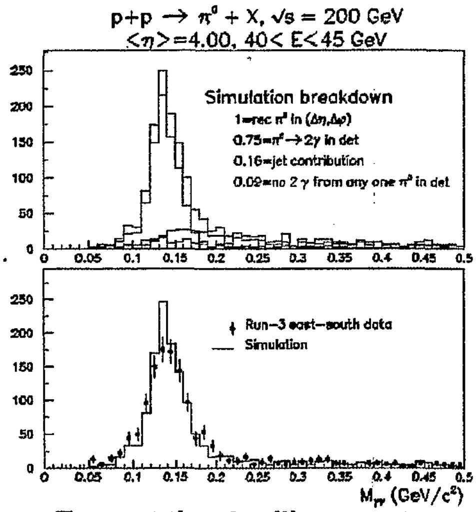
Jet spin asymmetry

- Is the single spin asymmetry observed for π^0 also present for the jet the π^0 comes from?
- Answer discriminates between Sivers and Collins contributions
- Trigger on energy in small cells, reconstruct π^0 and measure the energy in the entire FPD++
- Average over the Collins angle and define a new x_F for the event, then measure analyzing power versus x_F



Expect that jet-like events are ~15% of π^0 events

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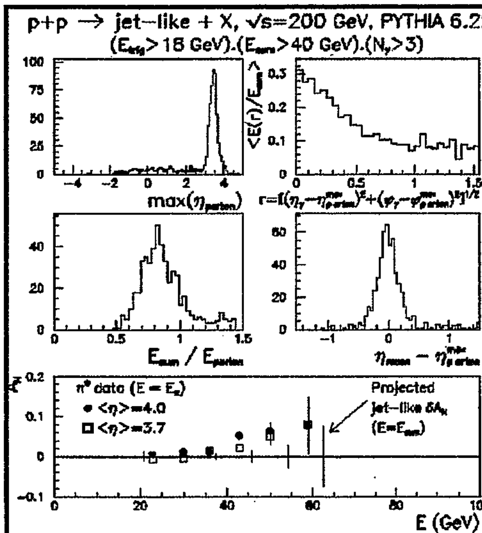

Jet-Like Events

L.C. Bland (hep-ex/0602012)

- N_γ>3 requirement should allow π^0–π^0 analysis
- (upper left) for each event, examine PYTHIA record for final-state hard scattered partons ⇒ event selection chooses jet-like events.
- (upper right) event-averaged correlation between photon energy and distance in η,ϕ space from thrust axis ⇒ events are expected to exhibit similar jet characteristics as found at $\eta \approx 0$
- (middle) multi-photon final states enable reconstruction of parent parton kinematics via momentum sum of observed photons.
- (bottom) projected statistical accuracy for data sample having 5 pb^{-1} and 50% beam polarization.

Azimuthal symmetry of FPD++ around thrust axis, selected by E_{trig} condition, enables

- integration over the Collins angle ⇒ isolating the Sivers effect, or
- dependence on the Collins angle ⇒ isolating the Collins/Heppelmann effect

Summary / Outlook

- Large transverse single spin asymmetries are observed for large rapidity π^0 production for polarized p+p collisions at $\sqrt{s}$ = 200 GeV
  - ➢ A_N grows with increasing x_F for x_F>0.35
  - ➢ A_N is zero for negative x_F
- Large rapidity π^0 cross sections for p+p collisions at $\sqrt{s}$ = 200 GeV is in agreement with NLO pQCD, unlike at lower $\sqrt{s}$. Particle correlations are consistent with expectations of LO pQCD (+ parton showers).
- Plan partial mapping of A_N in x_F–p_T plane for π^0 and measurement of A_N for jet-like events in RHIC run-6
- Propose increase in forward calorimetry in STAR to probe low-x gluon densities and further studies of transverse SSA (complete upgrade by 11/06).

Parton Orbital Angular Momentum Workshop

February 24-26, 2006
University of New Mexico - Albuquerque, NM

Workshop Participants

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Joint UNM / RBRC Workshop

Parton Orbital Angular Momentum

February 24-26, 2006
Albuquerque, New Mexico

Agenda

Thursday, February 23, 2006

7:45 p.m.	Pickup at Hotel	
8:00 p.m.	**RECEPTION**	**(The Lodestar Astronomy Center)**

Friday, February 24, 2006

8:00 a.m.	Pickup at Hotel	
8:30 a.m.	Stanley J. Brodsky	"Orbital Angular Momentum on the Light-Front and QCD Observables."
9:30 a.m.	Mauro Anselmino	"The average intrinsic k_perp of quarks"
10:15 a.m.	Douglas Fields	"Orbital Angular Momentum from Helicity Dependent kt"
11:00 a.m.	Werner Vogelsang	"Some thoughts on the helicity dependence of jet kt"
11:45 a.m.	Matthias Burkhardt	"Aspects of Quark Orbital Angular Momentum."
12:45 p.m.	**LUNCH**	
5:30 p.m.	Harut Avagyan	"Studies of OAM at Jlab"
6:15 p.m.	Gunar Schnell	"Probing Orbital Angular Momentum at HERMES"
7:00 p.m.	Jean-Marc Le Goff	"COMPASS plans to measure GPDs"
7:30 p.m.	**DINNER**	

Saturday, February 25, 2006

9:00 a.m.	Pickup at Hotel	
9:30 a.m.	Dennis Sivers	"Process Dependence of Single-Spin Asymmetries from Orbital Structures."
10:15 a.m.	Renee H. Fatemi	"Using Dijets to Measure the Gluon Sivers Functions at STAR"
11:00 a.m.	Feng Yuan	"Can we learn quark orbital motion from the SSAs?"
11:45 a.m.	Gerry Bunce	"Transverse Spin at PHENIX"
12:30 p.m.	**LUNCH**	
2:30 p.m.	Yuji Goto	"SSA measurements with primary beam at J-PARC"
3:15 p.m.	Leonard Gamberg	"k_t Dependence and T-odd Fragmentation"
4:00 p.m.	Les Bland	"Forward Particle Production and Transverse Single-Spin Asymmetries"
4:45 p.m.	Discussion	Dennis Sivers
7:30 p.m.	**DINNER**	

Additional RIKEN BNL Research Center Proceedings:

Volume 81 – Parton Orbital Angular Momentum (Joint RBRC/University of New Mexico Workshop) February 24-26, 2006 – BNL-
Volume 80 – Can We Discover the QCD Critical Point at RHIC? BNL-75692-2006
Volume 79 – Strangeness in Collisions, February 16-17, 2006 – BNL-
Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649
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
Volume 70 – Strongly Coupled Plasmas: Electromagnetic, Nuclear & Atomic – BNL-73867-2005
Volume 69 – Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
Volume 67 – High Performance Computing with BlueGene/L and QCDOC Architectures – BNL-
Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – Lattice QCD at Finite Temperature and Density – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003

Additional RIKEN BNL Research Center Proceedings:

Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003
Volume 46 – Large-Scale Computations in Nuclear Physics using the QCDOC – BNL-52678
Volume 45 – Summer Program: Current and Future Directions at RHIC – BNL-71035
Volume 44 – RHIC Spin Collaboration Meetings VIII, IX, X, XI – BNL-71117-2003
Volume 43 – RIKEN Winter School – Quark-Gluon Structure of the Nucleon and QCD – BNL-52672
Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
Volume 17 – Hard Parton Physics in High-Energy Nuclear Collisions – BNL-52574

Additional RIKEN BNL Research Center Proceedings:

Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569

Volume 15 – QCD Phase Transitions – BNL-52561

Volume 14 – Quantum Fields In and Out of Equilibrium – BNL-52560

Volume 13 – Physics of the 1 Teraflop RIKEN-BNL-Columbia QCD Project First Anniversary Celebration – BNL-66299

Volume 12 – Quarkonium Production in Relativistic Nuclear Collisions – BNL-52559

Volume 11 – Event Generator for RHIC Spin Physics – BNL-66116

Volume 10 – Physics of Polarimetry at RHIC – BNL-65926

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

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

Volume 7 – RHIC Spin Physics – BNL-65615

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

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

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

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

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

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

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RIKEN BNL RESEARCH CENTER

RBRC-UNM Workshop

Parton Orbital Angular Momentum

February 24-26, 2006

Li Keran

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

Speakers:

Mauro Anselmino
Harut Avagyan
Les Bland
Stanley J. Brodsky
Gerry Bunce
Matthias Burkardt
Douglas Fields
Renee H. Fatemi
Leonard Gamberg
Yuji Goto
Jean-Marc Le Goff
Gunar Schnell
Dennis Sivers
Werner Vogelsang
Feng Yuan

Organizers: Gerry Bunce, Douglas Fields and Werner Vogelsang