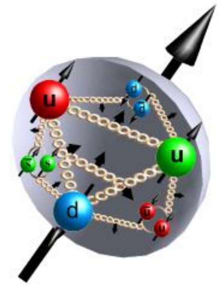


Spin Physics of the Nucleon

With New Quantities

Bo-Qiang Ma (马伯强)

PKU (北京大学)

2011 两岸粒子物理与宇宙学研讨会，清华大学，新竹

April 3, 2011

Collaborators: Enzo Barone, Stan Brodsky, Jacques Soffer, Andreas Schafer, Ivan Schmidt, Jian-Jun Yang, Qi-Ren Zhang,
and students: Zhun Lu, Bing Zhang, Jun She, Jiacai Zhu

It has been 20 years

of the proton "spin crisis" or "spin puzzle"

- **Spin Structure:**

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.020$$

↓

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

spin "crisis" or "puzzle": where is the proton's missing spin?

The Proton "Spin Crisis"

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

In contradiction with the naïve quark model expectation:

Naive Quark Model:

$$\Delta u = \frac{4}{3}; \qquad \Delta d = -\frac{1}{3}; \qquad \Delta s = 0$$

$$\Sigma = \Delta u + \Delta d + \Delta s = 1$$

The Ellis-Jaffe sum rule & Its violation

$$A_1^p = \int_0^1 dx g_1^p(x) = \frac{1}{2}\left[\frac{4}{9}\Delta u + \frac{1}{9}\Delta d + \frac{1}{9}\Delta s\right]$$

- **Neutron beta decay and isospin symmetry**

$$\Delta u - \Delta d = \frac{G_A}{G_V} = 1.261$$

- **Strangeness changing hyperon decay and SU(3) symmetry**

$$\Delta u + \Delta d - 2\Delta s = 0.675$$

- **The assumption of zero strange spin constribution** $\Delta s = 0$

The Ellis-Jaffe sum $A_1^p = \int_0^1 dx g_1^p(x) = 0.198$

However, what EMC measured $A_1^p = \int_0^1 dx g_1^p(x) = 0.126$

The first stage of experiments

- **Non-zero strange spin constribution**

$$\Delta u = 0.750$$

$$\Delta d = -0.511$$

$$\Delta s = -0.218$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.020$$

A large strange spin contribution?

A previous global fit:

SU(3) symmetry+measured g_1^p g_1^n

$$\Delta u = 0.83 \pm 0.03$$

$$\Delta d = -0.43 \pm 0.03$$

$$\Delta s = -0.10 \pm 0.03$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.3$$

The second stage of experiments.

The third stage of experiments:
g_1^p g_1^n +semi-inclusive DIS process

$$\Delta u = 0.599 \pm 0.022 \pm 0.065$$

$$\Delta d = -0.280 \pm 0.026 \pm 0.057$$

$$\Delta s = 0.028 \pm 0.033 \pm 0.009$$

$$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.347 \pm 0.024 \pm 0.040$$

HERMES Collaboration, PRL92 (2004) 012005.

The strange contribution
to the proton spin

$$\Delta s \approx -0.2 \rightarrow -0.1 \rightarrow 0.03$$

$$\Delta s \neq 0, \quad \text{how large?}$$

Many Theoretical Explanantions

- The sea quarks of the proton are largely negatively polarized
- The gluons provide a significant contribution to the proton spin

It was though that the spin "crisis" cannot be understood within the quark model: " the lowest uud valence component of the proton is estimated to be of only a few percent." R.L. Jaffe and Lipkin, PLB266(1991)158

The proton spin crisis

& the Melosh-Wigner rotation

- It is shown that the proton "spin crisis" or "spin puzzle" can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation.
- The quark helicity Δq measured in polarized deep inelastic scattering is actually the quark spin in the infinite momentum frame or in the light-cone formalism, and it is different from the quark spin in the nucleon rest frame or in the quark model.

B.-Q. Ma, J.Phys. G 17 (1991) L53

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

Pion Spin Structure and Form Factor

Based on collaborated works with T.Huang and Q.-X.Shen

[1] T. Huang, B.Q. Ma, and Q.X. Shen, Phys. Rev. D **49**, 1490 (1994).

[2] B. Q. Ma, Z. Phys. A **345**, 321 (1993).

[3] B.Q. Ma and T.Huang, J. Phys. G **21**, (765) (1995).

Fu-Guang Cao, Tao Huang, and Bo-Qiang Ma, Phys.Rev.D 53 (1996) 6582-6585.

Fu-Guang Cao, Jun Cao, Tao Huang, and Bo-Qiang Ma, Phys.Rev.D 55 (1997) 7107-7113.

Jun Cao, Fu-Guang Cao, Tao Huang, Bo-Qiang Ma, Phys. Rev. D 58 (1998) 113006.

PHYSICAL REVIEW D VOLUME 49, NUMBER 3 1 FEBRUARY 1994

Analysis of the pion wave function in the light-cone formalism

Tao Huang, Bo-Qiang Ma, and Qi-Xing Shen
*Center of Theoretical Physics, China Center of Advanced Science and Technology (World Laboratory), Beijing, China and Institute of High Energy Physics, Academia Sinica, P.O. Box 918(4), Beijing 100039, China**

(Received 22 January 1991; revised manuscript received 12 August 1993)

We analyze several general constraints on the pionic valence-state wave function. It is found that the present model wave functions used in the light-cone formalism of perturbative quantum chromodynamics have failed to reproduce the Chernyak-Zhitnitsky (CZ) distribution amplitude which is required to fit the pionic form factor data and the reasonable valence-state structure function which does not exceed the pionic structure function data for $x \to 1$ simultaneously. A possible model wave function which can satisfy all the general constraints has been suggested and analyzed.

PACS number(s): 12.38.−t, 12.39.−x, 13.60.−r

calculation. Also, we have shown that there are two higher helicity $(\lambda_1+\lambda_2=\pm 1)$ components in the light-cone wave function for the pion as a natural consequence from the Melosh rotation and it is speculated that these components should be incorporated into the perturbative quantum chromodynamics. Some progress has been

Pion Spin-Space Wave Function in Rest Frame

In the pion rest frame, the instant-form spin space wave-function of pion is

$$\chi_T = (\chi_1^{\uparrow}\chi_2^{\downarrow} - \chi_2^{\uparrow}\chi_1^{\downarrow})/\sqrt{2},$$

in which $\chi_i^{\uparrow,\downarrow}$ are the two-component Pauli spinors.

Melosh Rotation for Spin-1/2 Particle

The connection between spin states in the rest frame and infinite momentum frame

Or between spin states in the conventional equal time dynamics and the light-front dynamics

$$\chi^{\uparrow}(T) = w[(q^{+} + m)\chi^{\uparrow}(F) - q^{R}\chi^{\downarrow}(F)];$$

$$\chi^{\downarrow}(T) = w[(q^{+} + m)\chi^{\downarrow}(F) + q^{L}\chi^{\uparrow}(F)].$$

The Wigner Rotation

for a rest particle $(m,\vec{0}) = p^{\mu}$ $(0,\vec{s}) = \mathrm{w}^{\mu}$

for a moving particle $\mathrm{L}(p)p = (m,\vec{0})$ $(0,\vec{s}) = \mathrm{L}(p)w/m$

$\mathrm{L}(p) =$ ratationless Lorentz boost

Wigner Rotation

$\vec{s}, p_{\mu} \to \vec{s'}, p'_{\mu}$

$\vec{s'} = R_w(\Lambda, p)\vec{s}$ $p' = \Lambda p$

$R_w(\Lambda, p) = \mathrm{L}(p')\Lambda \mathrm{L}^{-1}(p)$ a pure rotation

E.Wigner, Ann.Math.40(1939)149

The Lowest Valence State Wave Function in Light-Cone

$$|\psi^{\pi}_{q\overline{q}}> = \psi(x,\mathbf{k}\_,\uparrow,\downarrow)|\uparrow\downarrow> + \psi(x,\mathbf{k}\_,\downarrow,\uparrow)|\downarrow\uparrow>$$

$$+\psi(x,\mathbf{k}\_,\uparrow,\uparrow)|\uparrow\uparrow> + \psi(x,\mathbf{k}\_,\downarrow,\downarrow)|\downarrow\downarrow>,$$

where

$$\psi(x,\mathbf{k}\_,\lambda_1,\lambda_2) = C_0^F(x,\mathbf{k}\_,\lambda_1,\lambda_2)\varphi(x,\mathbf{k}\_).$$

Here $\varphi(x,\mathbf{k}\_)$ is the momentum space wave function in the light-cone formalism.

The Spin Component Coefficients

The spin component coefficients C_0^F have the forms,

$$C_0^F(x,q,\uparrow,\downarrow) = w_1 w_2[(q_1^- + m)(q_2^- + m) - \mathbf{q}_\perp^2]/\sqrt{2};$$

$$C_0^F(x,q,\downarrow,\uparrow) = -w_1 w_2[(q_1^- + m)(q_2^- + m) - \mathbf{q}_\perp^2]/\sqrt{2};$$

$$C_0^F(x,q,\uparrow,\uparrow) = w_1 w_2[(q_1^- + m)q_2^L - (q_2^- + m)q_1^L]/\sqrt{2};$$

$$C_0^F(x,q,\downarrow,\downarrow) = w_1 w_2[(q_1^- + m)q_2^R - (q_2^- + m)q_1^R]/\sqrt{2}.$$

C_0^F satisfy the relation

$$\Sigma_{\lambda_1,\lambda_2} C_0^F(x,\mathbf{k}_\perp,\lambda_1,\lambda_2) C_0^F(x,\mathbf{k}_\perp,\lambda_1,\lambda_2) = 1.$$

From field theory vertex calculation

$$\frac{\overline{v}(p_2^+, p_2^-, -\mathbf{k}_\perp)}{\sqrt{p_2^+}} \gamma_5 \frac{u(p_1^+, p_1^-, \mathbf{k}_\perp)}{\sqrt{p_1^+}},$$

$$\begin{cases} \frac{\overline{v}_\downarrow}{\sqrt{p_2^+}} \gamma_5 \frac{u_\uparrow}{\sqrt{p_1^+}} & = & -\frac{2mP^+}{4mx(1-x)P^{+2}}, \\ \frac{\overline{v}_\downarrow}{\sqrt{p_2^+}} \gamma_5 \frac{u_\uparrow}{\sqrt{p_1^+}} & = & +\frac{2mP^+}{4mx(1-x)P^{+2}}, \\ \frac{\overline{v}_\uparrow}{\sqrt{p_2^+}} \gamma_5 \frac{u_\uparrow}{\sqrt{p_1^+}} & = & +\frac{2(k_1+ik_2)P^+}{4mx(1-x)P^{+2}}, \\ \frac{\overline{v}_\downarrow}{\sqrt{p_2^+}} \gamma_5 \frac{u_\downarrow}{\sqrt{p_1^+}} & = & +\frac{2(k_1-ik_2)P^+}{4mx(1-x)P^{+2}}, \end{cases}$$

Xiao & Ma, PRD71(2005)014034

The proton spin crisis

& the Melosh-Wigner rotation

- It is shown that the proton "spin crisis" or "spin puzzle" can be understood by the relativistic effect of quark transversal motions due to the Melosh-Wigner rotation.
- The quark helicity Δq measured in polarized deep inelastic scattering is actually the quark spin in the infinite momentum frame or in the light-cone formalism, and it is different from the quark spin in the nucleon rest frame or in the quark model.

B.-Q. Ma, J.Phys. G 17 (1991) L53

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

What is Δq measured in DIS

- Δq is defined by $\Delta q\ s_\mu = \langle p,s|\bar{q}\gamma_\mu\gamma_5 q|p,s\rangle$

$$\Delta q = \langle p,s|\bar{q}\gamma^+\gamma_5 q|p,s\rangle$$

- Using light-cone Dirac spinors

$$\Delta q = \int_0^1 \mathrm{d}x\left[q^\uparrow(x) - q^\downarrow(x)\right]$$

- Using conventional Dirac spinors

$$\Delta q = \int \mathrm{d}^3\vec{p} M_q\left[q^\uparrow(\vec{p}) - q^\downarrow(\vec{p})\right]$$

$$M_q = \frac{(p_0 + p_3 + m)^2 - \vec{p}_\perp^{\,2}}{2(p_0 + p_3)(p_0 + m)}$$

Thus Δq is the light-cone quark spin or quark spin in the infinite momentum frame, not that in the rest frame of the proton

Quark spin sum is not a Lorentz invariant quantity

Thus the quark spin sum equals to the proton in the rest frame does not mean that it equals to the proton spin in the infinite momentum frame

$$\sum_q \vec{s}_q = \vec{S}_p \quad \text{in the rest frame}$$

does not mean that

$$\sum_q \vec{s}_q = \vec{S}_p \quad \text{in the infinite momentum frame}$$

Therefore it is not a surprise that the quark spin sum measured in DIS does not equal to the proton spin

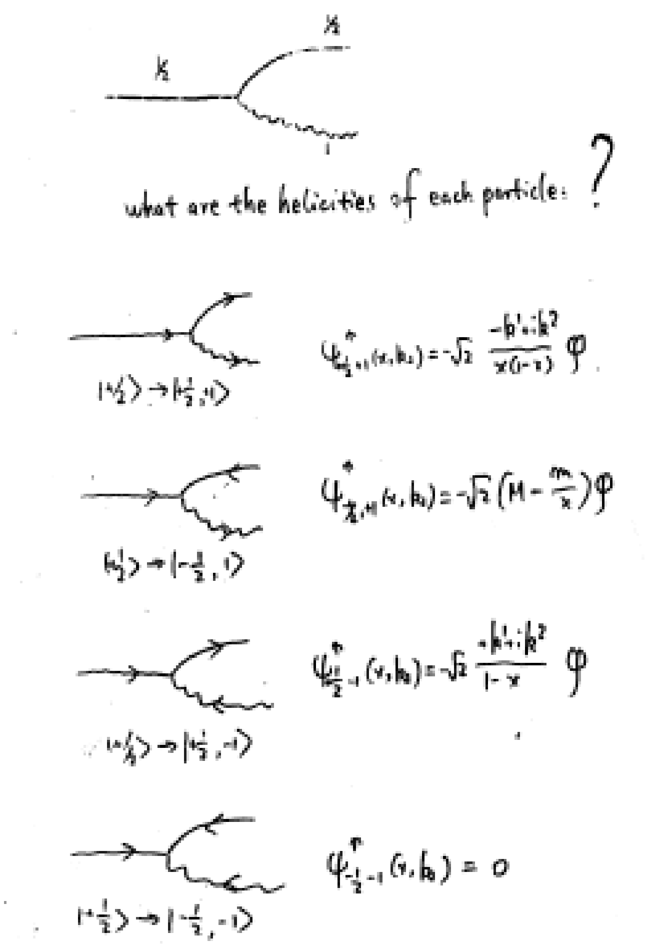
A general consensus

The quark helicity Δq defined in the infinite momentum frame is generally not the same as the constituent quark spin component in the proton rest frame, just like that it is not sensible to compare apple with orange.

H.-Y.Cheng, hep-ph/0002157，
Chin.J.Phys.38:753,2000

A QED Example of Relativistic Spin Effect

S.J. Brodsky, D.S. Hwang, B.-Q. Ma, I. Schmidt, Nucl. Phys. B 593 (2001) 311



The lowest spin states of a composite system must contain the orbital angular momentum contribution.

$$\Delta s_{\text{non-rel}} + L_{\text{non-rel}} = \Delta s_{\text{rel}} + L_{\text{rel}}$$

Other approaches with same conclusion

Contribution from the lower component of Dirac spinors in the rest frame:

B.-Q. Ma, Q.-R. Zhang, Z.Phys.C 58 (1993) 479-482

D.Qing, X.-S.Chen, F.Wang, **Phys.Rev.D58:114032,1998.**

P.Zavada, **Phys.Rev.D65:054040,2002**.

The Spin Distributions in Quark Model

The spin distribution probabilities in the quark-diquark model

$$u_V^{\uparrow} = \frac{1}{18}; \quad u_V^{\downarrow} = \frac{2}{18}; \quad d_V^{\uparrow} = \frac{2}{18}; \quad d_V^{\downarrow} = \frac{4}{18};$$
$$u_S^{\uparrow} = \frac{1}{2}; \quad u_S^{\downarrow} = 0; \quad d_S^{\uparrow} = 0; \quad d_S^{\downarrow} = 0. \tag{7}$$

Naive Quark Model:

$$\Delta u = \frac{4}{3}; \qquad \Delta d = -\frac{1}{3}; \qquad \Delta s = 0$$

$$\Sigma = \Delta u + \Delta d + \Delta s = 1$$

Relativistic Effect due to Melosh-Rotation

$$\Delta u_v(x) = u_v^{\uparrow}(x) - u_v^{\downarrow}(x) = -\frac{1}{18}a_V(x)W_V(x) + \frac{1}{2}a_S(x)W_S(x);$$

$$\Delta d_v(x) = d_v^{\uparrow}(x) - d_v^{\downarrow}(x) = -\frac{1}{9}a_V(x)W_V(x).$$

from

$$a_S(x) = 2u_v(x) - d_v(x);$$

$$a_V(x) = 3d_v(x).$$

We obtain

$$\Delta u_v(x) = [u_v(x) - \frac{1}{2}d_v(x)]W_S(x) - \frac{1}{6}d_v(x)W_V(x);$$

$$\Delta d_v(x) = -\frac{1}{3}d_v(x)W_V(x).$$

Relativistic SU(6) Quark Model

Flavor Symmetric Case

Relativistic Correction: $M_q = 0.75$

$\Delta u = \frac{4}{3} M_q = 1; \quad \Delta d = -\frac{1}{3} M_q = -0.25; \quad \Delta s = 0$

$\Sigma = \Delta u + \Delta d + \Delta s = 0.75$

$F_2^n(x)/F_2^p(x) \geq \frac{2}{3}$ for all x

Relativistic SU(6) Quark Model

Flavor Asymmetric Case

Relativistic Correction: $M_u \approx 0.6$; $M_d \approx 0.9$

$\Delta u = \frac{4}{3} M_u = 0.8$; $\Delta d = -\frac{1}{3} M_d = -0.3$; $\Delta s = 0$

$\Sigma = \Delta u + \Delta d + \Delta s \approx 0.5$

$F_2^n(x)/F_2^p(x) \to \frac{1}{4}$ at large x

B.-Q. Ma, Phys. Lett. B 375 (1996) 320.

Relativistic SU(6) Quark Model

Flavor Asymmetric Case + Intrinsic Sea

For Intrinsic $d\bar{d}$ Sea ($\sim 15\%$): $\quad \Delta d_{sea} \approx -0.07$

For Intrinsic $s\bar{s}$ Sea ($\sim 5\%$): $\quad \Delta s_{sea} \approx -0.03$

Thus: $\quad \Sigma = \Delta u + \Delta d + \Delta s + \Delta d_{sea} + \Delta s_{sea} \approx 0.4$

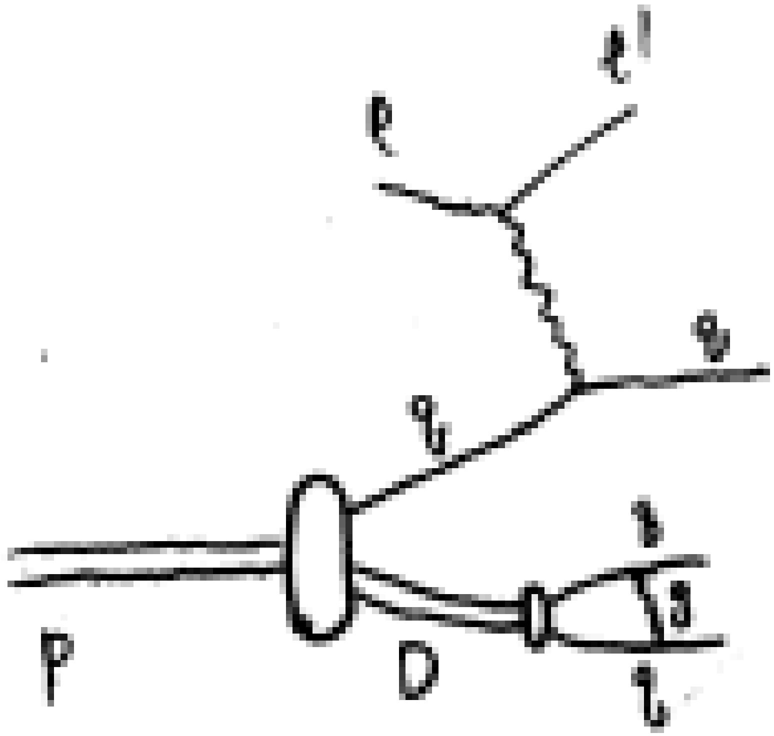
S. J. Brodsky and B.-Q.Ma, Phys. Lett. **B 381** (1996) 317.

More detailed discussions, see, B.-Q.Ma, J.-J.Yang, I.Schmidt, Eur.Phys.J.A12(2001)353

Understanding the Proton Spin "Puzzle" with a New "Minimal" Quark Model

Three quark valence component could be as large as 70% to account for the data

A relativistic quark-diquark model



A relativistic quark-diquark model

- The unpolarized distribution of quark q in hadron h can be written as

$$q(x) = c_q^S a_S(x) + c_q^V a_V(x),$$

where $a_D(x)$ is

$$a_D(x) \propto \int [\mathrm{d}^2 \mathbf{k}_\perp] |\phi(x, \mathbf{k}_\perp)|^2 \quad (D = S \text{ or } V),$$

- BHL prescription of the light-cone momentum space wave function for quark-diquark

$$\phi(x, \mathbf{k}_\perp) = A_D \exp\left\{-\frac{1}{8\alpha_D^2}\left[\frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}\right]\right\},$$

B.-Q. Ma, Phys.Lett. B 375 (1996) 320-326.
B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

A relativistic quark-diquark model

- longitudinally polarized quark distribution

$$\Delta q(x) = \tilde{c}_q^S \tilde{a}_S(x) + \tilde{c}_q^V \tilde{a}_V(x)$$

where

$$\tilde{a}_D(x) = \int [\mathrm{d}^2 \mathbf{k}_\perp] W_D(x, \mathbf{k}_\perp) |\phi(x, \mathbf{k}_\perp)|^2 \quad (D = S \text{ or } V)$$

- Melosh-Winger rotation factor

Longitudinally polarized

$$W_D(x, \mathbf{k}_\perp) = \frac{(k^+ + m_q)^2 - \mathbf{k}_\perp^2}{(k^+ + m_q)^2 + \mathbf{k}_\perp^2}$$

where $k^+ = x\mathcal{M}$, $\mathcal{M}^2 = \frac{m_q^2 + \mathbf{k}_\perp^2}{x} + \frac{m_D^2 + \mathbf{k}_\perp^2}{1-x}$.

The Melosh-Wigner rotation

in pQCD based parametrization of quark helicity distributions

"**The helicity distributions measured on the light-cone are related by a Wigner rotation (Melosh transformation) to the ordinary spin S_i^z of the quarks in an equal-time rest-frame wavefunction description. Thus, due to the non-collinearity of the quarks, one cannot expect that the quark helicities will sum simply to the proton spin.**"

S.J.Brodsky, M.Burkardt, and I.Schmidt,

Nucl.Phys.B441 (1995) 197-214, p.202

pQCD counting rule

$$q_{\mathrm{h}}^{\pm} \propto (1-x)^{p}$$

$$p = 2n - 1 + 2\,|\Delta s_z| \qquad \Delta s_z = s_q - s_N$$

- **Based on the minimum connected tree graph of hard gluon exchanges.**
- **"Helicity retention" is predicted -- The helicity of a valence quark will match that of the parent nucleon.**

Parameters in pQCD counting rule analysis

In leading term

$$q_i^+ = \frac{\tilde{A}_{q_i}}{B_3} x^{-\frac{1}{2}} (1-x)^3$$

$$q_i^- = \frac{\tilde{C}_{q_i}}{B_5} x^{-\frac{1}{2}} (1-x)^5$$

Baryon	q_1	q_2	$\tilde{A}_{q_1}$	$\tilde{C}_{q_1}$	$\tilde{A}_{q_2}$	$\tilde{C}_{q_2}$
p	u	d	1.375	0.625	0.275	0.725

B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys.Rev.D63(2001) 037501.

New Development: H. Avakian, S.J.Brodsky, D.Boer, F.Yuan, Phys.Rev.Lett.99:082001,2007.

Two different sets of parton distributions

- SU(6) quark-diquark model

$$\Delta u_v(x)=[u_v(x)-\frac{1}{2}d_v(x)]W_S(x)-\frac{1}{6}d_v(x)W_V(x),$$
$$\Delta d_v(x)=-\frac{1}{3}d_v(x)W_V(x).$$

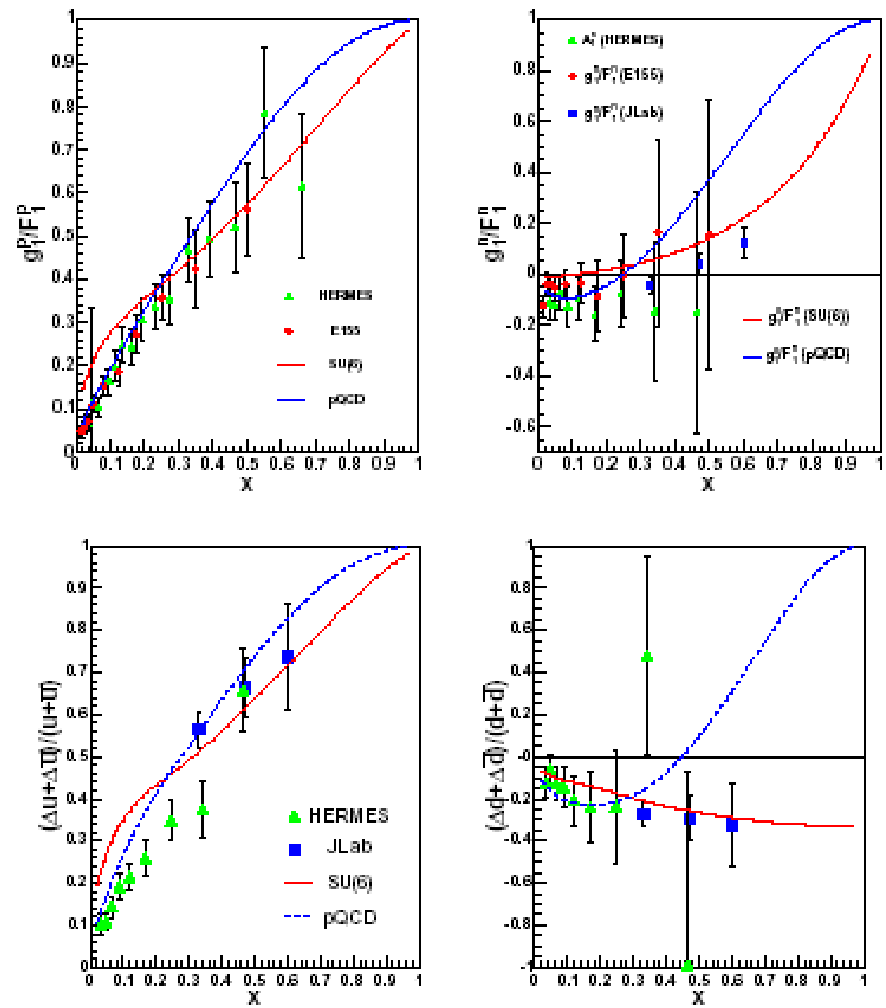
- pQCD based counting rule analysis

$$\begin{aligned}
u_v^{\text{pQCD}}(x) &= u_v^{\text{para}}(x),\\
d_v^{\text{pQCD}}(x) &= \frac{d_v^{\text{th}}(x)}{u_v^{\text{th}}(x)}u_v^{\text{para}}(x),\\
\Delta u_v^{\text{pQCD}}(x) &= \frac{\Delta u_v^{\text{th}}(x)}{u_v^{\text{th}}(x)}u_v^{\text{para}}(x),\\
\Delta d_v^{\text{pQCD}}(x) &= \frac{\Delta d_v^{\text{th}}(x)}{u_v^{\text{th}}(x)}u_v^{\text{para}}(x),
\end{aligned}$$

- CTEQ5 set 3 as input.

Different predictions in two models

- Helicity distribution
  - SU(6) quark-diquark model: $\Delta u(x)/u(x) \to 1$ as $x \to 1$. $\Delta d(x)/d(x) \to -\frac{1}{3}$ as $x \to 1$.
  - pQCD based counting rule analysis: $\Delta u(x)/u(x) \to 1$ as $x \to 1$. $\Delta d(x)/d(x) \to 1$ as $x \to 1$.



$W^{\pm}$ production at RHIC

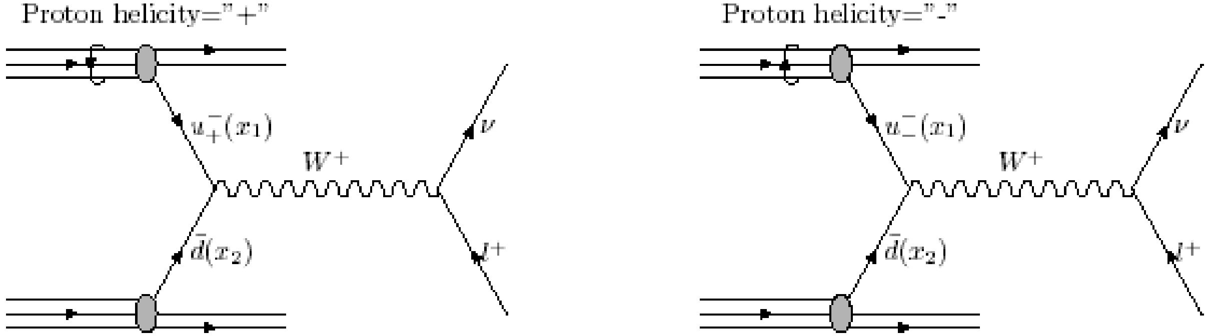
- Parity-violating asymmetry

$$A_L = -\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}, \quad A_L = -\frac{1}{P} \times \frac{N'_+ - N'_-}{N'_+ + N'_-},$$

- The maximum parity violation of W bosons.
- $u\bar{d} \to W^+$ and $\bar{u}d \to W^-$.
- At LO, the parity-violating asymmetry will approach $\Delta q(x)/q(x)$ when the rapidity of $W^{\pm}$, y_W, is large.

C. Bourrely, J. Soffer, Nucl. Phys. B423(1994) 329

One of the possible leading order production of W^+ production.



$$A_L^{W^+} = \frac{u_-^-(x_1)\bar{d}(x_2) - u_+^-(x_1)\bar{d}(x_2)}{u_-^-(x_1)\bar{d}(x_2) + u_+^-(x_1)\bar{d}(x_2)} = \frac{\Delta u(x_1)}{u(x_1)}$$

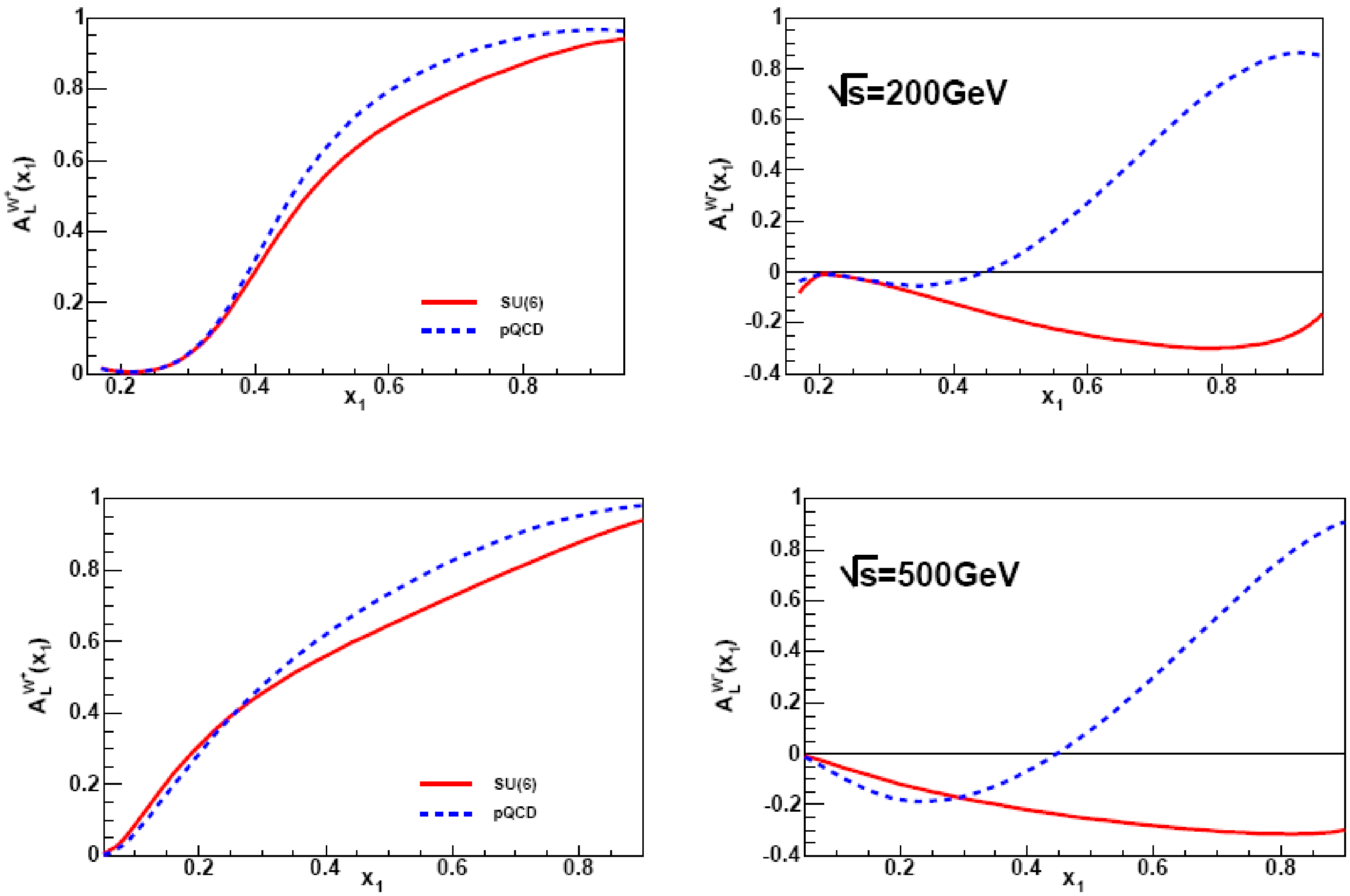
$$A_L^{W^+} = \frac{\Delta u(x_1)\bar{d}(x_2) - \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)}$$

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

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

$$A_L^{W^-} = \frac{\Delta d(x_1)\bar{u}(x_2) - \Delta\bar{u}(x_1)d(x_2)}{d(x_1)\bar{u}(x_2) + \bar{u}(x_1)d(x_2)}$$

X. Chen, Y. Mao, B.-Q. Ma, NPA A759(2008)188



It is possible to pin down flavor-dependence of spin distribution through polarized proton proton collider

- **Quark-diquark model and pQCD have different predictions on flavor-dependence of quark helicity and transversity distributions.**
- **Such flavor dependence can be measured through polarized proton proton scattering in STAR.**
- **It is necessary to measure different combinations of polarization processes to extract flavor-dependent helicty and transversity quark distributions.**

The Melosh-Wigner rotation
is not the whole story

- **The role of sea is not addressed**
- **The role of gluon is not addressed**

It is important to study the roles played by the sea quarks and gluons. Thus more theoretical and experimental researches can provide us a more completed picture of the nucleon spin structure.

Chances：New Research Directions

- New quantities：Transversity, Generalized Parton Distributions, Collins Functions, Silver Functions, Boer-Mulders Functions, Pretzelosity

- Hyperon Physics：The spin structure of Lambda and Sigma hyperons

B.-Q. Ma, I. Schmidt, J.-J. Yang
Phys. Lett. B 477 (2000) 107
Phys. Rev. D 61 (2000) 034017

The Melosh-Wigner Rotation in Transversity

$$2\,\delta q = \langle\, p,\uparrow | \bar{q}_{\lambda} \gamma^{\perp} \gamma^{+} q_{-\lambda} | p,\downarrow \rangle$$

$$\delta q(x) = \int [\mathrm{d}^2 \boldsymbol{k}_{\perp}]\, \tilde{M}_q(x,\boldsymbol{k}_{\perp})\, \Delta q_{\mathrm{RF}}(x,\boldsymbol{k}_{\perp})$$

$$\tilde{M}_q(x,\boldsymbol{k}_{\perp}) = \frac{(k^{+}+m)^2}{(k^{+}+m)^2+\boldsymbol{k}_{\perp}^2}$$

I.Schmidt&J.Soffer, Phys.Lett.B 407 (1997) 331

Transversity with Melosh-Wigner rotation in the quark-diquark model

$$\delta u_v(x) = \left[u_v(x) - \frac{1}{2}d_v(x)\right]\hat{W}_S(x) - \frac{1}{6}d_v(x)\hat{W}_V(x),$$

$$\delta d_v(x) = -\frac{1}{3}d_v(x)\hat{W}_V(x),$$

B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

The transversity in pQCD, in similar to helicity distributions

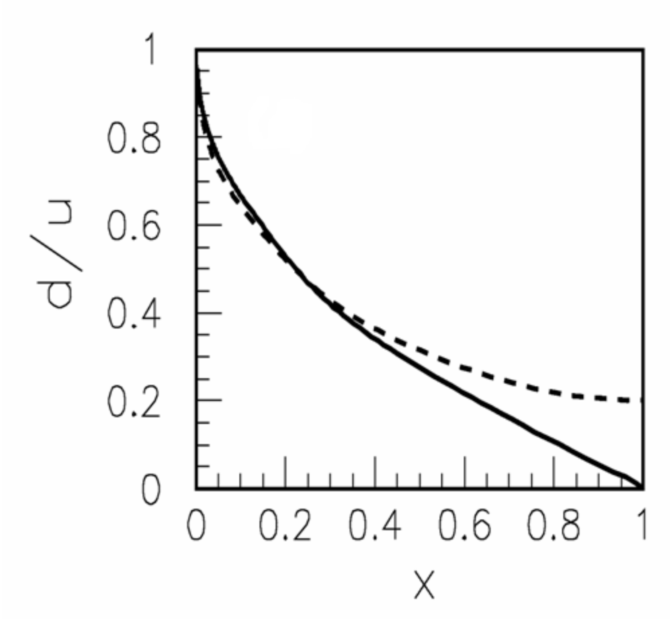
$$\delta q(x) = \frac{\tilde{A}_q}{B_3} x^{(-1/2)} (1-x)^3 - \frac{\tilde{C}_q}{B_5} x^{(-1/2)} (1-x)^5$$

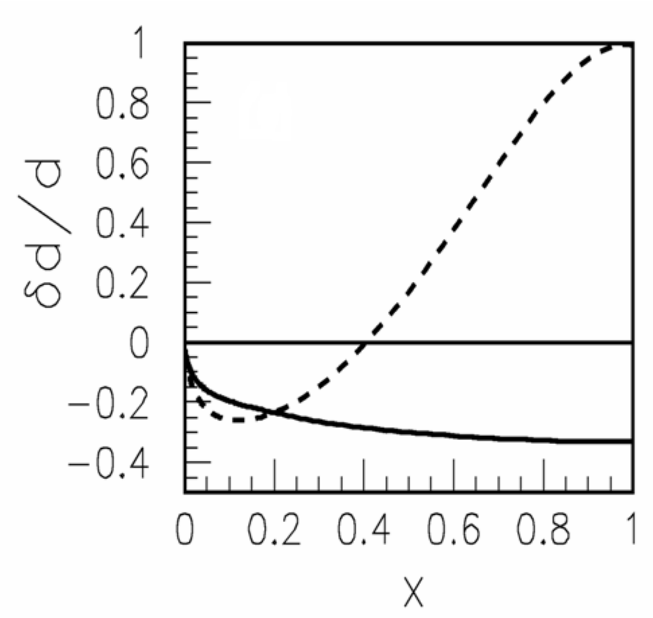
Baryon	q_1	q_2	$\tilde{A}_{q1}$	$\tilde{C}_{q1}$	$\tilde{A}_{q2}$	$\tilde{C}_{q2}$	$\hat{A}_{q1}$	$\hat{C}_{q1}$	$\hat{A}_{q2}$	$\hat{C}_{q2}$
p	u	d	1.375	0.625	0.275	0.725	1.52	0.48	0.305	0.695

B.-Q. Ma, I. Schmidt, J.-J. Yang, Phys.Rev.D63(2001) 037501.

SU(6) quark-diquark model VS pQCD based analysis

Ma, Schmidt and Yang, PRD 65, 034010 (2002)





solid curve for SU(6) and dashed curve for pQCD

Collins asymmetry in semi-inclusive production

$$A_{UT}^{Collins} = \frac{1}{|S_\perp|}\frac{d\sigma_{UT}^{Collins}}{d\sigma_{UU}}$$ After integration over specific weighting functions

$$A_T(x,y,z) = -\frac{(1-y)\sum_q e_q^2 \delta q(x) H_1^{\perp(1)q}(z)}{(1-y+y^2/2)\sum_q e_q^2 q(x) D_1^q(z)}$$

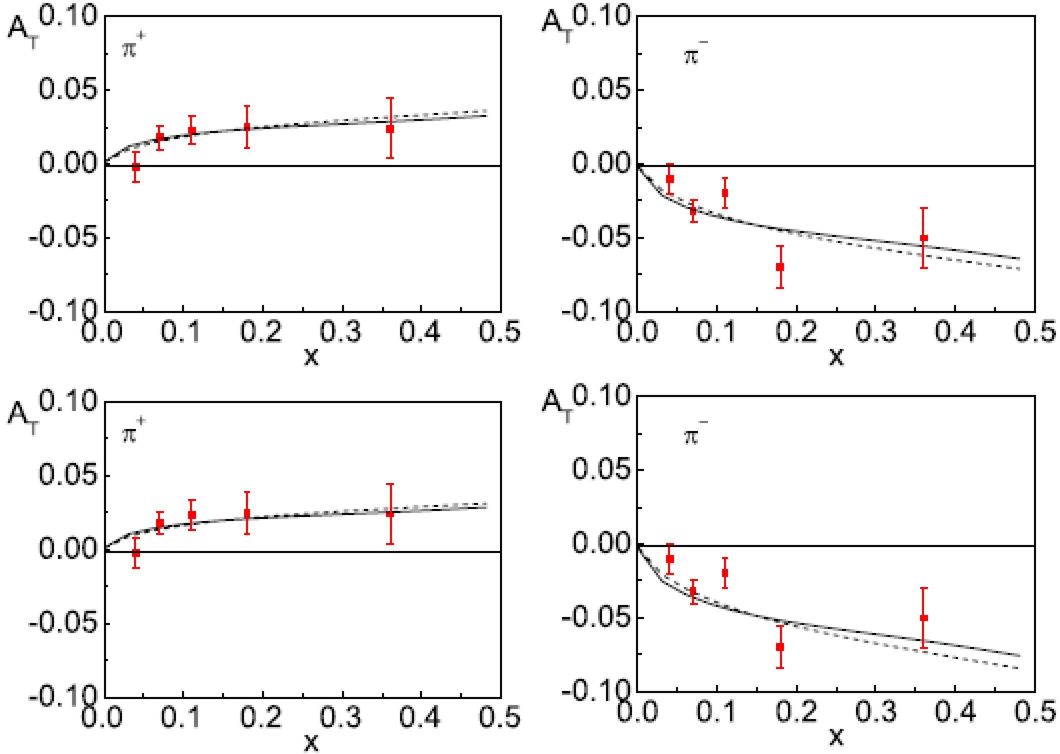
$q(x)$ unpolarized quark distrtion

$\delta q(x)$ transversity

$D_1(x)$ unpolarized fragmentation function

$H_1^{\perp(1)q}(x)$ Collins function

Including unfavored fragmentation in HERMES condition



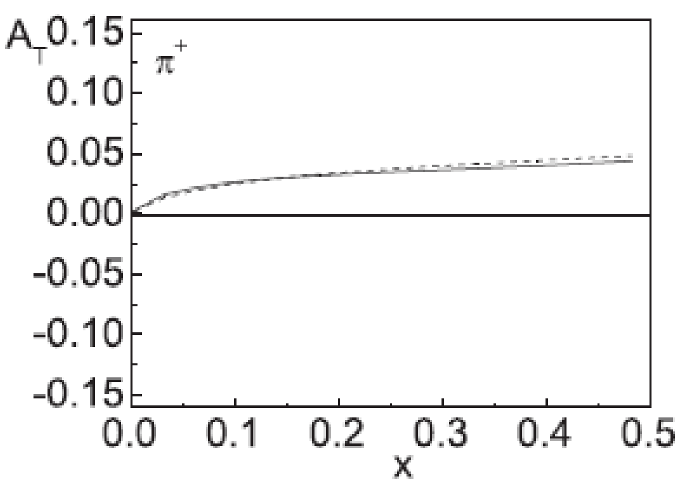
set I

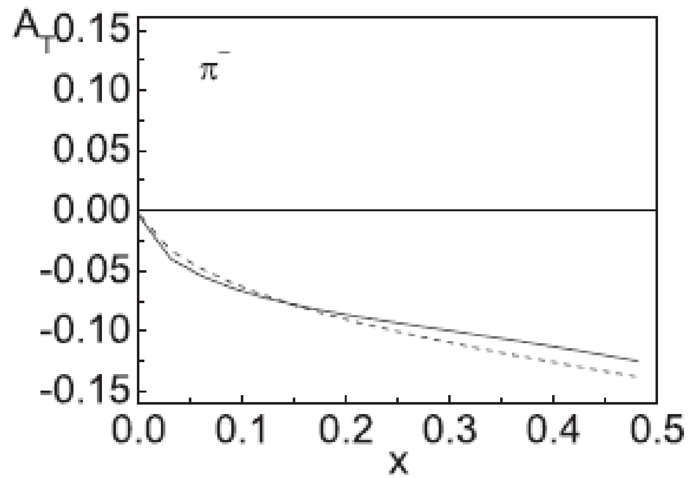
set II

Y. Huang, J. She, and B.-Q. Ma, Phys. Rev. D76 (2007) 034004.

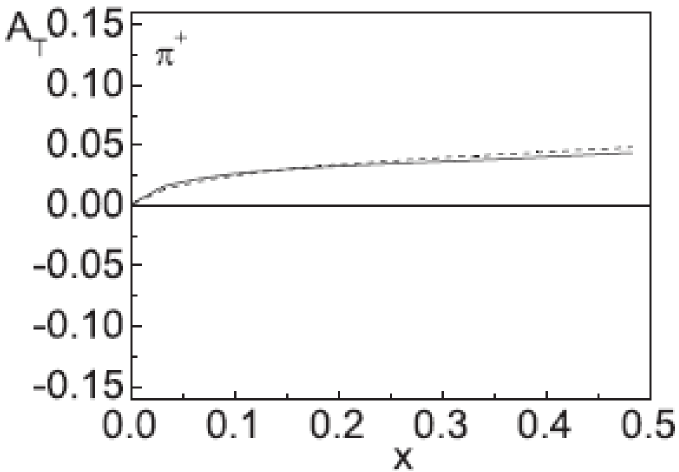
Prediction in JLab condition (proton target)

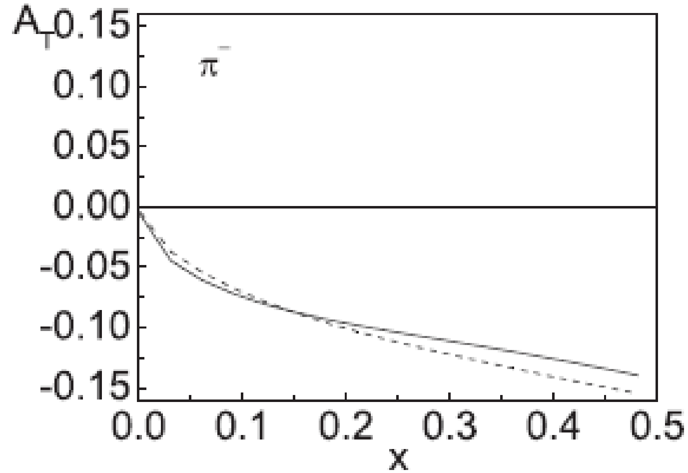
Set I





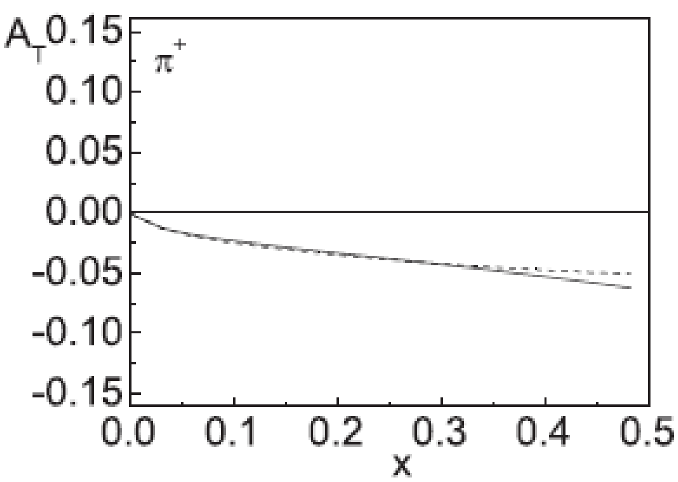
Set II

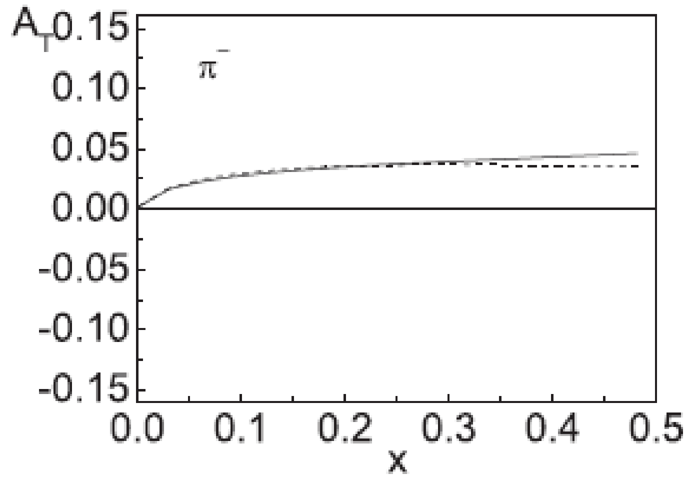




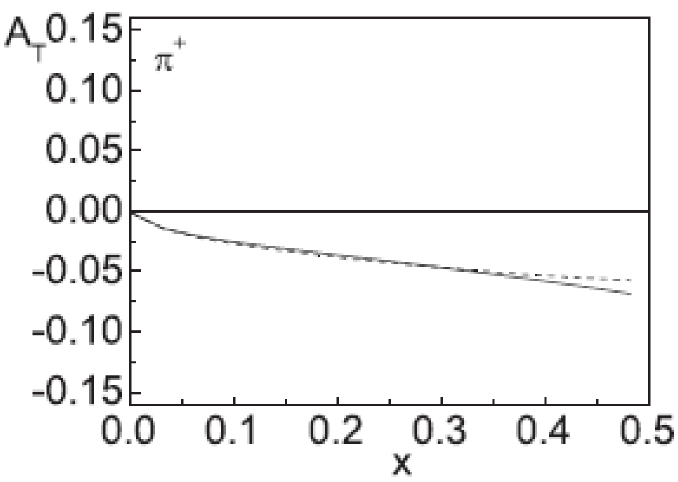
Prediction in JLab condition (neutron target)

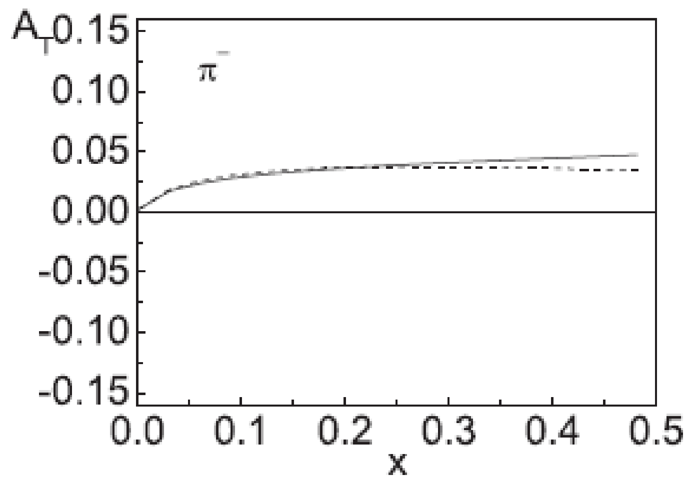
Set I





Set II





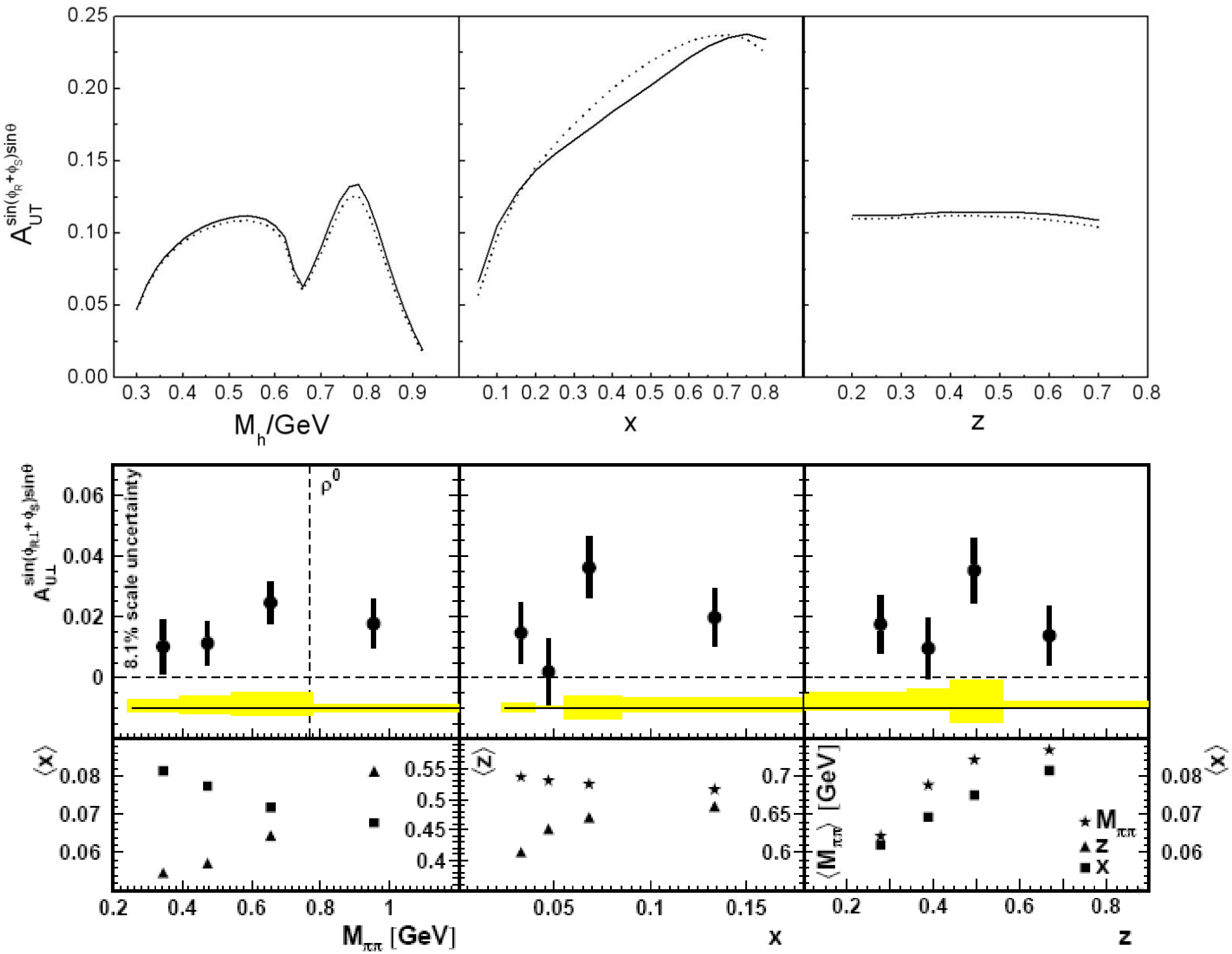
Transversity
from two pion interference fragmentation

$$A_{UT}^{\langle 2\sin(\phi_R+\phi_S)/\sin\theta\rangle} = -\frac{\sum_a e_a^2 \delta f^a(x) \int d\zeta \frac{|\vec{R}|}{M_h} H_1^{\sphericalangle a}(z,\zeta,M_h^2)}{\sum_a e_a^2 f^a(x) \int d\zeta D_1^a(z,\zeta,M_h^2)}$$

New fragmentation functions are introduced: the dihadron FFs, including the chiral odd interference FF.

- Jaffe, Jin and Tang, PRL 80, 1166 (1998)
- Radici, Jakob and Bianconi, PRD, 65, 074031 (2002)
- Bacchetta and Radici, PRD 74, 114007 (2006)

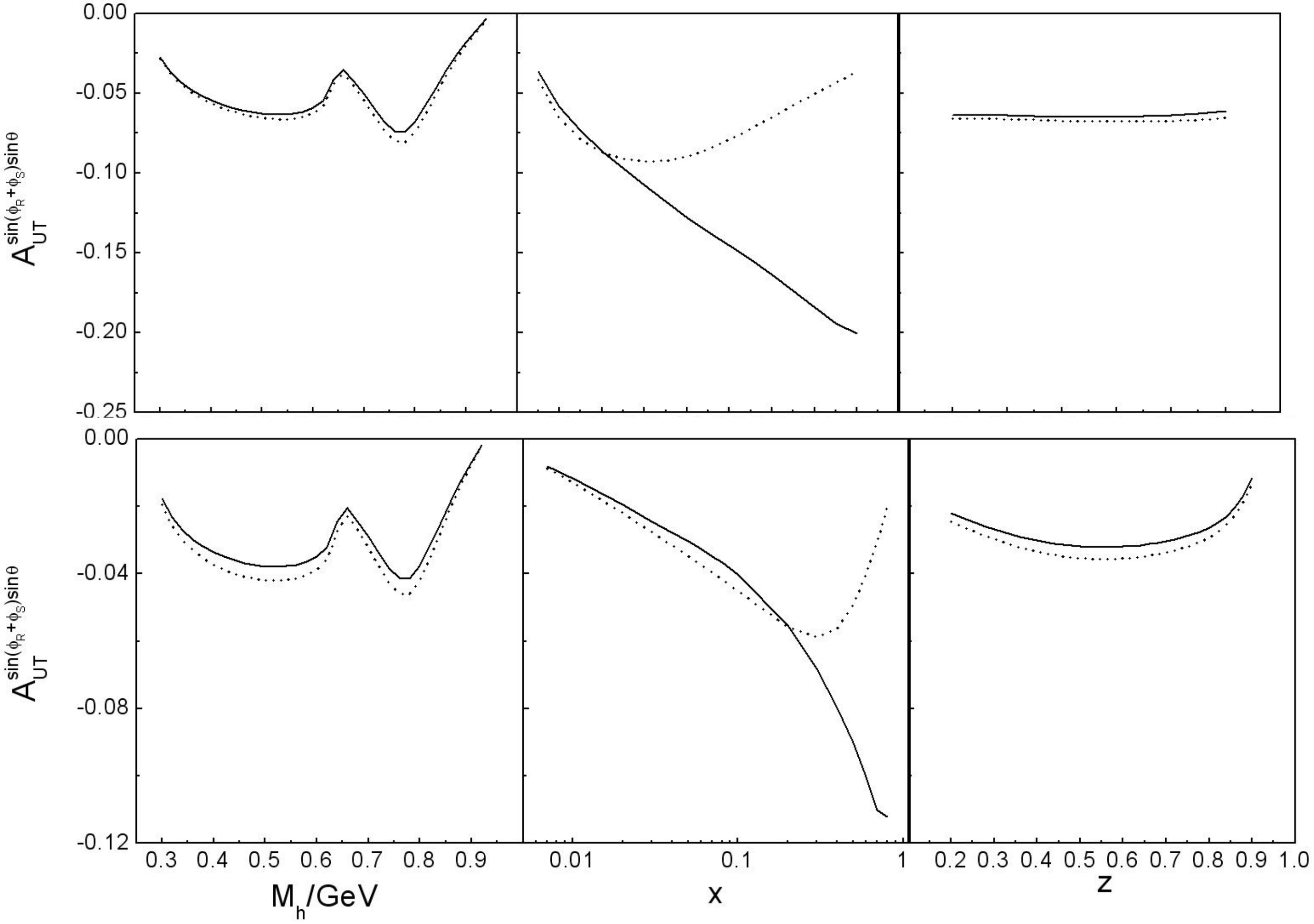
Prediction on the proton target



Prediction on neutron target

HERMES

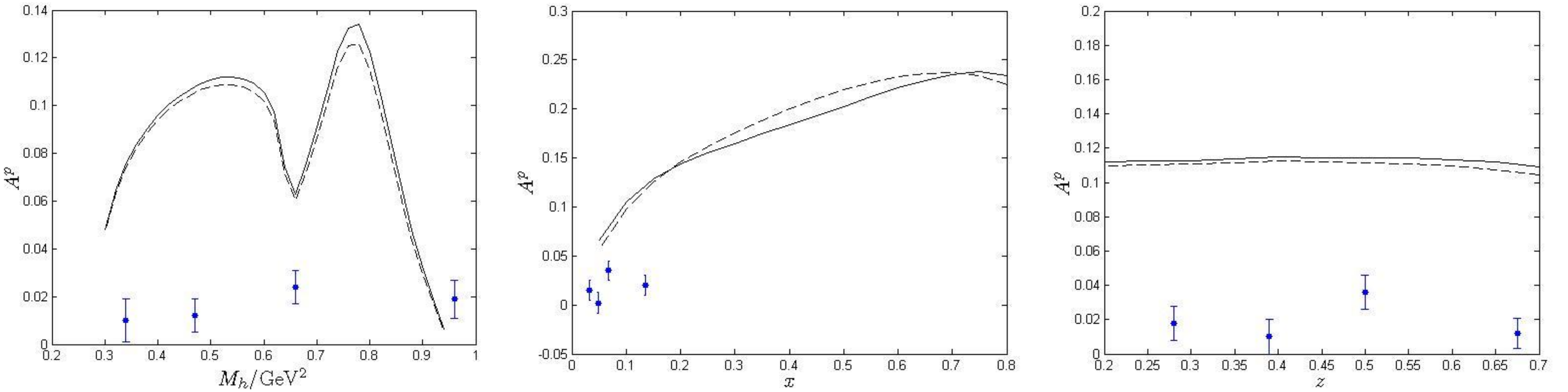
COMPASS



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

Comparison with HERMES Data

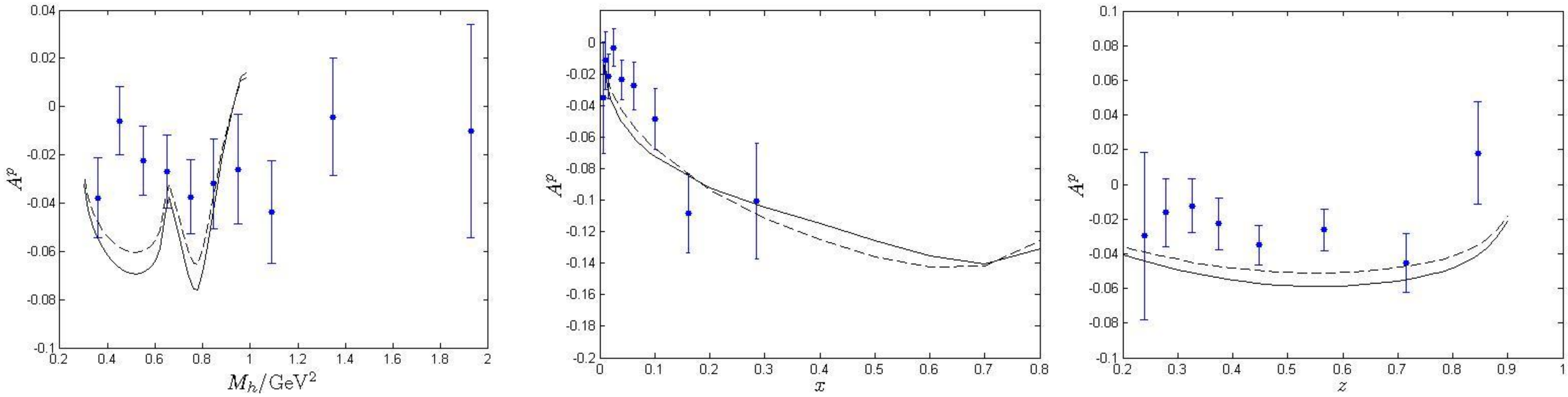
HERMES, JHEP 0806:017,2008



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

Comparison with COMPASS Data

COMPASS Preliminary, arXiv:0907.0961



J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

Comparison with COMPASS Data

COMPASS, arXiv:1009.0819 [hep-ex]

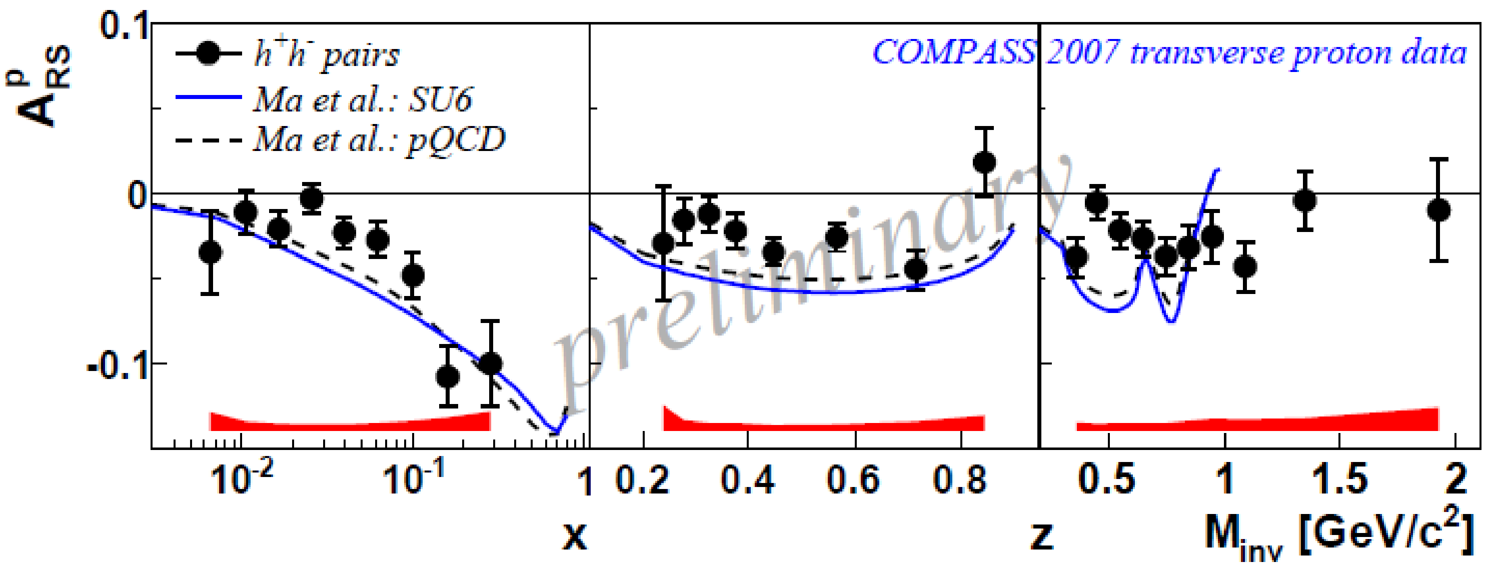


Figure 1: Two-hadron asymmetry A_{RS} as a function of x, z and M_{inv}, compared to predictions of [16]. The lower bands indicate the systematic uncertainty of the measurement.

J. She, Y.Huang, and B.-Q. Ma, Phys. Rev. D77 (2008) 014035.

The Melosh-Wigner Rotation in Quark Orbital Angular Moment

$$\hat{L}_q = -i\left(k_1 \frac{\partial}{\partial k_2} - k_2 \frac{\partial}{\partial k_1} \right).$$

$$L_q(x) = \int [d^2 k_\perp] M_L(x, k_\perp) \Delta q_{QM}(x, k_\perp)$$

$$M_L(x, k_\perp) = \frac{k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

Three QCD spin sums for the proton spin

$$\vec{J}_{QCD} = \int d^3x \psi^\dagger \frac{\vec{\Sigma}}{2} \psi + \int d^3x \psi^\dagger \vec{x} \times (-i\nabla)\psi$$
$$+ \int d^3x \vec{E}^a \times \vec{A}^a + \int d^3x E^{ai} \vec{x} \times \nabla A^{ai}$$
$$\equiv \vec{S}_q + \vec{L}_q + \vec{S}_g + \vec{L}_g,$$

$$\vec{J}_{QCD} = \int d^3x \psi^\dagger \frac{\vec{\Sigma}}{2} \psi + \int d^3x \psi^\dagger \vec{x} \times (-i\vec{D})\psi + \int d^3x \vec{x} \times (\vec{E} \times \vec{B})$$
$$\equiv \vec{S}_q + \vec{L}_q + \vec{J}_g,$$

$$\vec{J}_{QCD} = \int d^3x \psi^\dagger \frac{\vec{\Sigma}}{2} \psi + \int d^3x \psi^\dagger \vec{x} \times (-i\vec{D}_{pure})\psi$$
$$+ \int d^3x \vec{E}^a \times \vec{A}^a_{phys} + \int d^3x E^{ai} \vec{x} \times \nabla A^{ai}_{phys}$$
$$\equiv \vec{S}_q + \vec{L}_q + \vec{S}_g + \vec{L}_g,$$

X.-S.Chen, X.-F.Lu, W.-M.Sun, F.Wang, T.Goldman, PRL100(2008)232002

Spin and orbital sum in light-cone formalism

$$\frac{1}{2}M_q + M_L = \frac{1}{2}$$

$$M_q(x,k_\perp) = \frac{(k^+ + m)^2 - k_\perp^2}{(k^+ + m)^2 + k_\perp^2} \qquad M_L(x,k_\perp) = \frac{k_\perp^2}{(k^+ + m)^2 + k_\perp^2}$$

$$\frac{1}{2}\Delta q(x) + L_q(x) = \frac{1}{2}\Delta q_{QM}(x)$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

Relations of quark distributions

$$\Delta q_{QM}(x) + \Delta q(x) = 2\,\delta q(x)$$

B.-Q. Ma, I. Schmidt, J. Soffer, Phys.Lett. B 441 (1998) 461-467.

$$\frac{1}{2}\Delta q(x) + L_q(x) = \frac{1}{2}\Delta q_{QM}(x),$$

$$\Delta q(x) + L_q(x) = \delta q(x),$$

Ma&Schmidt, Phys.Rev.D 58 (1998) 096008

The Melosh-Wigner Rotation in "Pretzelosity"

$$g_1^q(x, k_\perp) - h_1^q(x, k_\perp) = h_{1T}^{\perp(1)q}(x, k_\perp) \ .$$

$$\frac{(k^+ + m)^2 - \mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} - \frac{(k^+ + m)^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2} = -\frac{\mathbf{k}_\perp^2}{(k^+ + m)^2 + \mathbf{k}_\perp^2}$$

$$\mathrm{Pretzelosity} = \Delta \mathrm{q} - \delta \mathrm{q} = -\mathrm{L_q}$$

$$\mathrm{Pretzelosity} = -\int [\mathrm{d}^2 \mathbf{k}_\perp] \frac{\mathbf{k}_\perp^2}{(\mathrm{k}^+ + \mathrm{m})^2 + \mathbf{k}_\perp^2} \Delta \mathrm{q_{QM}}(\mathrm{x}, \mathbf{k}_\perp)$$

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

What is “Pretzelosity” ?

- Pretzelosity: one of the eight leading twist transverse dependent parton distributions (TMDs).
- The quark-quark correlator up to the leading twist

$$
\begin{aligned}
\Phi(x, \mathbf{p}_\perp) = \frac{1}{2}\{ & f_1 \not{n}_+ - f_{1T}^\perp \frac{\epsilon_\perp^{ij} p_\perp^i S_\perp^j}{M_N} \not{n}_+ \\
& + (S_\parallel g_{1L} + \frac{\mathbf{p}_\perp \cdot \mathbf{S}_\perp}{M_N} g_{1T}) \gamma_5 \not{n}_+ + h_{1T} \frac{[\not{S}_\perp, \not{n}_+]\gamma_5}{2} \\
& + (S_\parallel h_{1L}^\perp + \frac{\mathbf{p}_\perp \cdot \mathbf{S}_\perp}{M_N} h_{1T}^\perp) \frac{[\not{p}_\perp, \not{n}_+]\gamma_5}{2M_N} + i h_1^\perp \frac{[\not{p}_\perp, \not{n}_+]}{2M_N} \}. \quad (7)
\end{aligned}
$$

P.J. Mulders and R.D. Tangerman, Nucl. Phys. **B 461**, 197 (1996), Erratum-ibid. **B 484**, 538 (1997). K. Goeke, A. Metz, and M. Schlegel, Phys. Lett. **B 618**, 90 (2005).

Transverse Momentum Dependent Quark Distributions

→ Nucleon Spin → Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	f_1 =		$h_1^{\perp}$ = − Boer-Mulder
	L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Worm Gear
	T	$f_{1T}^{\perp}$ = − Sivers	g_{1T} = − Worm Gear	h_{1T} = − Transversity $h_{1T}^{\perp}$ = − Pretzelosity

What is "Pretzelosity" ?

$$\frac{p_\perp^x p_\perp^y}{M_N^2} h_{1T}^\perp(x, p_\perp^2) = \int \frac{d\xi^- d^2\boldsymbol{\xi}_\perp}{16\pi^3} e^{i(xP^+\xi^- - \mathbf{p}_\perp \cdot \boldsymbol{\xi}_\perp)} \times \langle PS^y|\bar{\psi}(0) i\sigma^{1+}\gamma_5 \psi(0, \xi^-, \xi_\perp)|PS^y\rangle, \quad (12)$$

$|PS^y\rangle$: the hadronic state with a polarization in the y direction.

- Some properties of pretzelosity:
  1. It is chiral-odd, and needs a chiral-odd partner in the SIDIS.
  2. There is no gluon analog of pretzelosity.
  3. In a large class of models, it is the difference of helicity and transversity, and hence a measure for relativistic effects.

H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355.

A Simple Relation

- The difference of helicity and transversity is the first moment of pretzelosity.

$$h_{1T}^{\perp(1)qv}(x,\mathbf{p}_\perp) \equiv \frac{p_\perp^2}{2M_N^2} h_{1T}^{\perp qv}(x,\mathbf{p}_\perp) = g_1^{qv}(x,\mathbf{p}_\perp) - h_1^{qv}(x,\mathbf{p}_\perp),$$

- This relation has already been obtained in
  H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355. B. Pasquini, S. Cazzaniga and S. Boffi, Phys. Rev. **D 78**, 034025 (2008).
- But this relation is not fully satisfied in
  A. Bacchetta, F. Conti, and M. Radici, Phys. Rev. **D 78**, 074010 (2008).

Connection with Quark Orbital Angular Momentum

- The rotation factor for $\vec{x} \times -i\nabla$ is $\frac{p_\perp^2}{(x\mathcal{M}_D+m_q)^2+p_\perp^2}$
  B.-Q. Ma, I. Schmidt, Phys. Rev. **D 58**, 096008 (1998).
- a simple relation between the pretzelosity and the quark orbital angular momentum

$$L^{qv}(x, \mathbf{p}_\perp) = -h_{1T}^{\perp(1)qv}(x, \mathbf{p}_\perp) = h_1^{qv}(x, \mathbf{p}_\perp) - g_1^{qv}(x, \mathbf{p}_\perp), (21)$$

or at the integration level

$$L^{qv}(x) = \int d^2\mathbf{p}_\perp L^{qv}(x, \mathbf{p}_\perp) = -h_{1T}^{\perp(1)qv}(x) = h_1^{qv}(x) - g_1^{qv}(x).$$

- A measurement of pretzelosity may reveal the information on the quark orbital angular momentum.

Pretzelosity in SIDIS

- Pretzelosity can be measured through $\sin(3\phi_h - \phi_S)$ asymmetry in the SIDIS process, where the cross section can be written as

$$\frac{d^6\sigma_{UT}}{dxdyd\phi_S dzd^2\mathbf{P}_{h\perp}} = \frac{2\alpha^2}{sxy^2}\{(1-y+\frac{1}{2}y^2)F_{UU} + S_\perp \sin(3\phi_h - \phi_S)(1-y)F_{UT}^{\sin(3\phi_h-\phi_S)} + \ldots\}, \quad (23)$$

with $F_{UU} = \mathcal{F}[\omega_1 f_1 D_1]$, $F_{UT}^{\sin(3\phi_h-\phi_S)} = \mathcal{F}[\omega_2 h_{1T}^{\perp} H_1^{\perp}]$

- The $\sin(3\phi_h - \phi_S)$ asymmetry

$$A_{UT}^{\sin(3\phi_h-\phi_S)} = \frac{\frac{2\alpha^2}{sxy^2}(1-y)F_{UT}^{\sin(3\phi_h-\phi_S)}}{\frac{2\alpha^2}{sxy^2}(1-y+\frac{1}{2}y^2)F_{UU}}. \quad (24)$$

Approach 0 to TMDs

- Starting with the equation

$$
\begin{aligned}
h_{1T}^{\perp(uv)}(x) &= \left[f_1^{(uv)}(x) - \frac{1}{2} f_1^{(dv)}(x)\right] \hat{W}_S(x) - \frac{1}{6} f_1^{(dv)}(x) \hat{W}_V(x), \\
h_{1T}^{\perp(dv)}(x) &= -\frac{1}{3} f_1^{(dv)}(x) \hat{W}_V(x), \qquad (25)
\end{aligned}
$$

  where $\hat{W}_D(x) = \int d^2\mathbf{p}_\perp \varphi^2(x, \mathbf{p}_\perp) W_D(x, \mathbf{p}_\perp) / \int d^2\mathbf{p}_\perp \varphi^2(x, \mathbf{p}_\perp)$
- $f_1(x)$: CTEQ6L as an input. $h_{1T}^{\perp}(x)$: from Eq. 25
- Transverse momentum dependence: Gaussian form.
- How to fit the Gaussian width? $p_{av}/k_{av} \approx 2$?
  H. Avakian, A.V. Efremov, P. Schweitzer, and F. Yuan, arXiv:0805.3355.

Approach 1 to TMDs

- Model calculation.

$$f_1^{(uv)}(x, \mathbf{p}_\perp) = \frac{1}{16\pi^3} \times (\frac{1}{3}\sin^2\theta\varphi_V^2 + \cos^2\theta\varphi_S^2),$$
$$f_1^{(dv)}(x, \mathbf{p}_\perp) = \frac{1}{8\pi^3} \times \frac{1}{3}\sin^2\theta\varphi_V^2.$$

$$h_{1T}^{\perp(uv)}(x, \mathbf{p}_\perp) = -\frac{1}{16\pi^3} \times (\frac{1}{9}\sin^2\theta\varphi_V^2 W_V - \cos^2\theta\varphi_S^2 W_S),$$
$$h_{1T}^{\perp(dv)}(x, \mathbf{p}_\perp) = -\frac{1}{8\pi^3} \times \frac{1}{9}\sin^2\theta\varphi_V^2 W_V.$$

- $\varphi_D(x, \mathbf{p}_\perp)$: adopting the BHL form:

$$\varphi_D(x, \mathbf{p}_\perp) = A_D \exp\{-\frac{1}{8\alpha_D^2}[\frac{m_q^2 + p_\perp^2}{x} + \frac{m_D^2 + p_\perp^2}{1-x}]\},$$

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

Approach 2 to TMDs

- Staring with the equation (an unintegrated version)

$$
\begin{aligned}
h_{1T}^{\perp(uv)}(x,\mathbf{p}_\perp) &= \left[f_1^{(uv)}(x,\mathbf{p}_\perp) - \frac{1}{2}f_1^{(dv)}(x,\mathbf{p}_\perp)\right] W_S(x,\mathbf{p}_\perp) \\
&\quad -\frac{1}{6}f_1^{(dv)}(x,\mathbf{p}_\perp) W_V(x,\mathbf{p}_\perp), \\
h_{1T}^{\perp(dv)}(x,\mathbf{p}_\perp) &= -\frac{1}{3}f_1^{(dv)}(x,\mathbf{p}_\perp) W_V(x,\mathbf{p}_\perp).
\end{aligned} \tag{27}
$$

- $f_1(x,\mathbf{p}_\perp)$: a Gaussian form

$$
f_1(x,\mathbf{p}_\perp) = f_1(x)\frac{\exp(-p_\perp^2/p_{av}^2)}{\pi p_{av}^2}, \tag{28}
$$

with CTEQ6L parametrization for $f_1(x)$.

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

$h_{1T}^{\perp(1)}(x)$ and $f_1(x)$

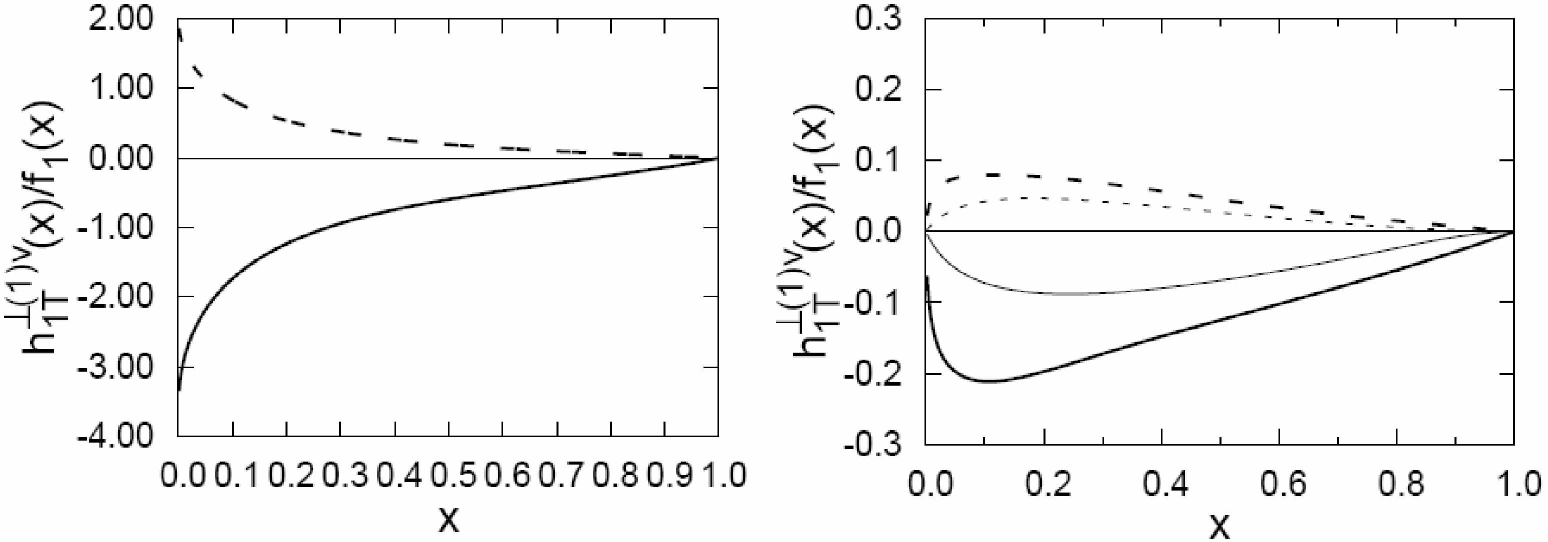


Figure: The ratio $h_{1T}^{\perp(1)(x)}/f_1(x)$. Left panel for approach 0 and right panel for approach 1 (thin curves) and approach 2 (thick curves). Solid curves for the u quark, and dashed curves for the d quark. Only valence quarks are considered.

J.She, J.Zhu, B.-Q.Ma, Phys.Rev.D79 (2009) 054008

Results at HERMES kinematics.

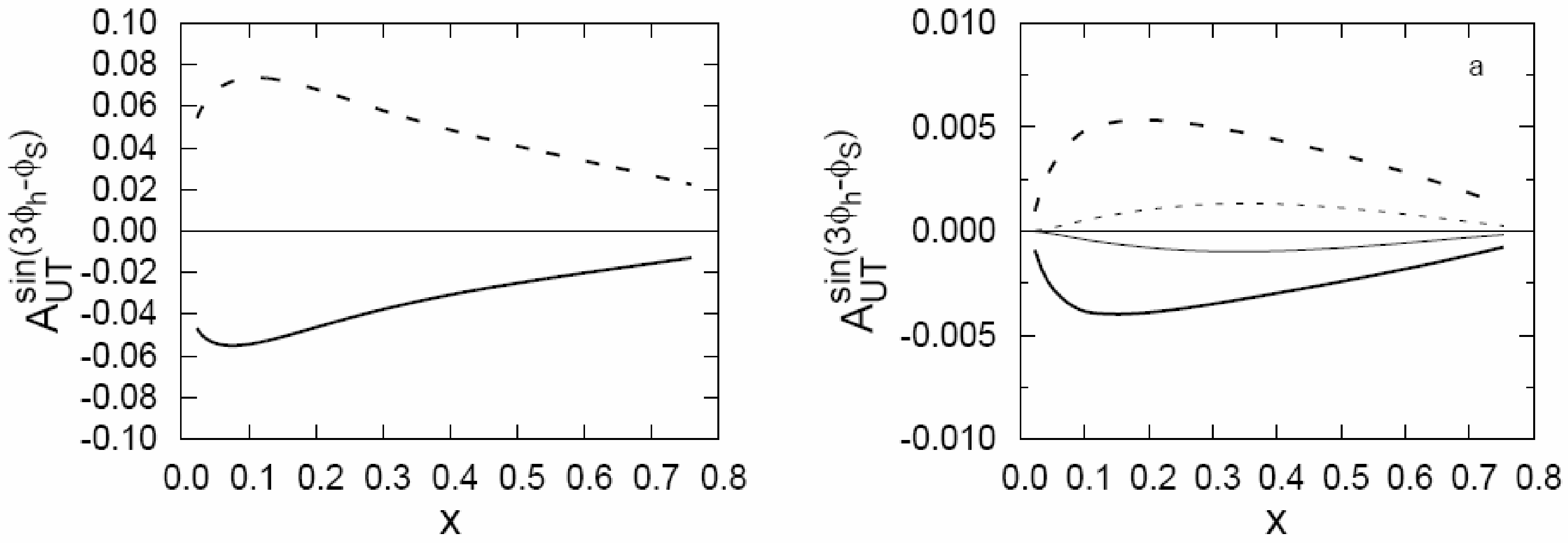


Figure: The results for HERMES kinematics with a proton target. Left panel for approach 0 and right panel for approach 1 (thin curves) and approach 2 (thick curves). Solid curves for the π^+ production, and dashed curves for the π^- production.

Results at COMPASS kinematics.

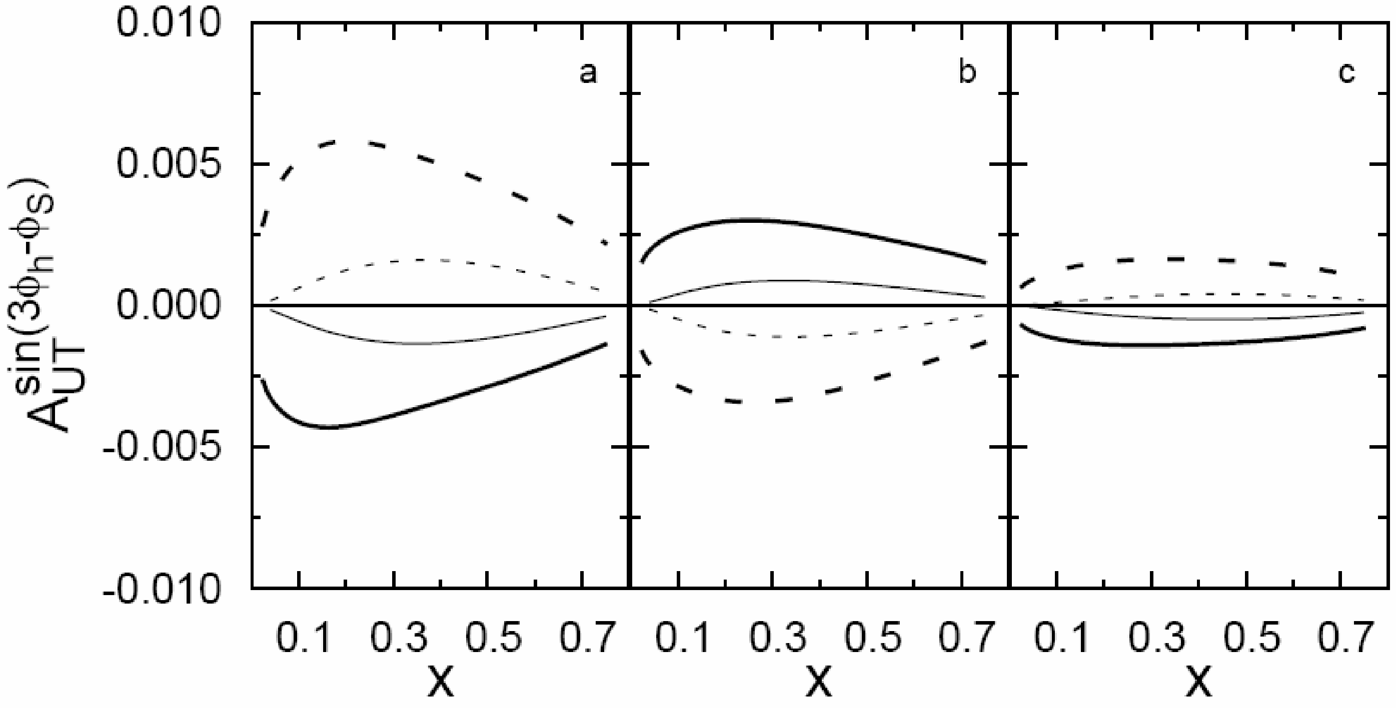


Figure: The results for COMPASS kinematics. a) proton target, b) neutron target, and c) deuteron target.

Results at JLab kinematics.

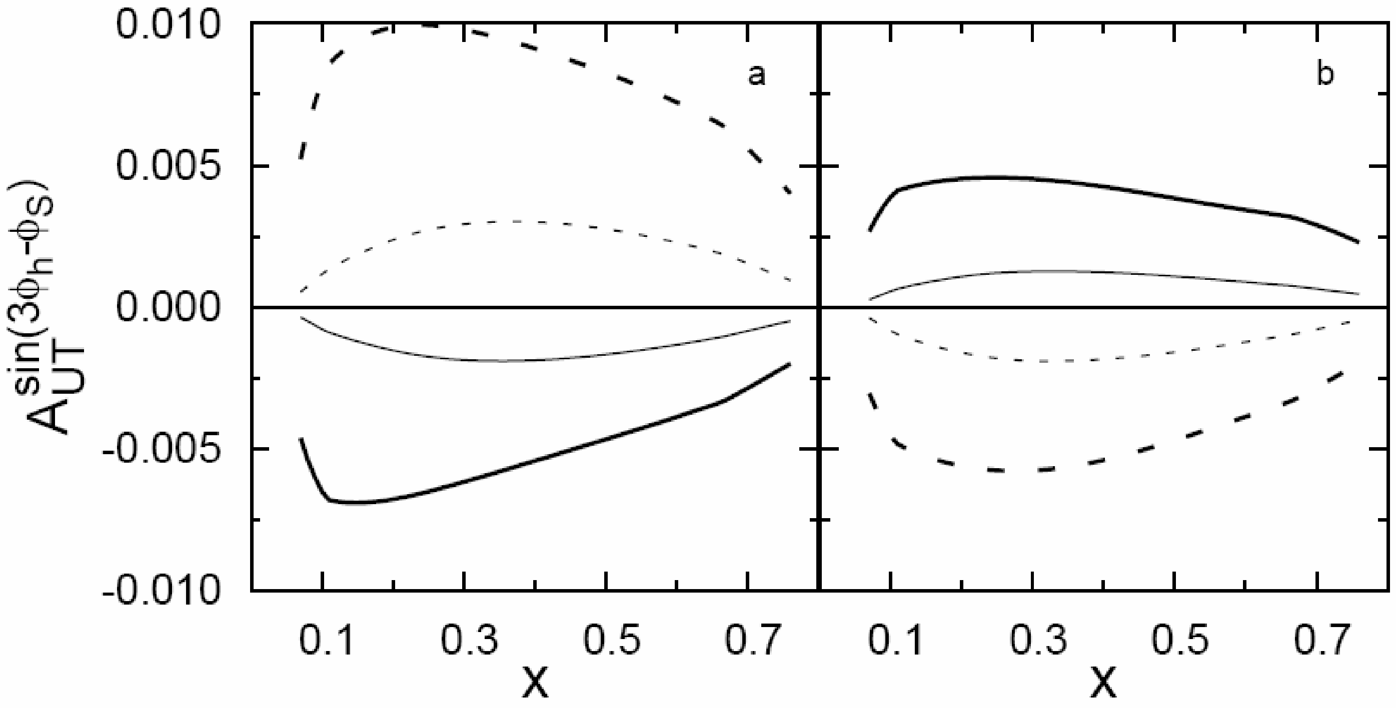


Figure: The results for JLab kinematics. a) proton target and b) neutron target.

Recent calculation to measure pretzelosity from polarized proton antiproton collider

The leading order differential cross section for the double transversely polarized Drell-Yan process reads [17]

$$\frac{d\sigma}{dx_a dx_b d\boldsymbol{q}_T d\Omega} = \frac{\alpha_{em}^2}{4Q^2}\Big\{F_{UU}^1 + |\boldsymbol{S}_{aT}||\boldsymbol{S}_{bT}|\sin^2\theta\big[\cos(2\phi-\phi_a-\phi_b)F_{TT}^{\cos(2\phi-\phi_a-\phi_b)} + \cos(2\phi+\phi_a-\phi_b)F_{TT}^{\cos(2\phi+\phi_a-\phi_b)}\big] + \ldots\Big\}.$$

$$F_{UU}^1 = \mathcal{C}\big[f_1\bar{f}_1\big], \quad F_{TT}^{\cos(2\phi-\phi_a-\phi_b)} = \mathcal{C}\big[h_1\bar{h}_1\big], \quad F_{TT}^{\cos(2\phi+\phi_a-\phi_b)} = \mathcal{C}\Big[\frac{2(\boldsymbol{h}\cdot\boldsymbol{k}_{aT})^2 - k_{aT}^2}{2M_a^2}h_{1T}^{\perp}\bar{h}_1\Big],$$

J.Zhu, B.-Q.Ma, Phys.Rev.D82 (2011) 114022

The asymmetries to measure pretzelosity

$$A_{TT}^{\cos(2\phi+\phi_a-\phi_b)} = \frac{\frac{\alpha_{em}^2}{4Q^2}\mathcal{C}\left[\frac{2(\boldsymbol{h}\cdot\boldsymbol{k}_{aT})^2-k_{aT}^2}{2M_N^2}h_{1T}^{\perp}h_1\right]}{\frac{\alpha_{em}^2}{4Q^2}\mathcal{C}\left[f_1 f_1\right]},$$

$$A_{TT}^{\frac{q_T^2}{2M_N^2}\cos(2\phi+\phi_a-\phi_b)}(x_F)$$

$$=\frac{\sum_q e_q^2[h_{1T}^{\perp(2)q}(x_a)h_1^q(x_b) + h_{1T}^{\perp(2)\bar{q}}(x_a)h_1^{\bar{q}}(x_b)]}{\sum_q e_q^2[f_1^q(x_a)f_1^q(x_b) + f_1^{\bar{q}}(x_a)f_1^{\bar{q}}(x_b)]},$$

The weighted asymmetry to measure pretzelosity

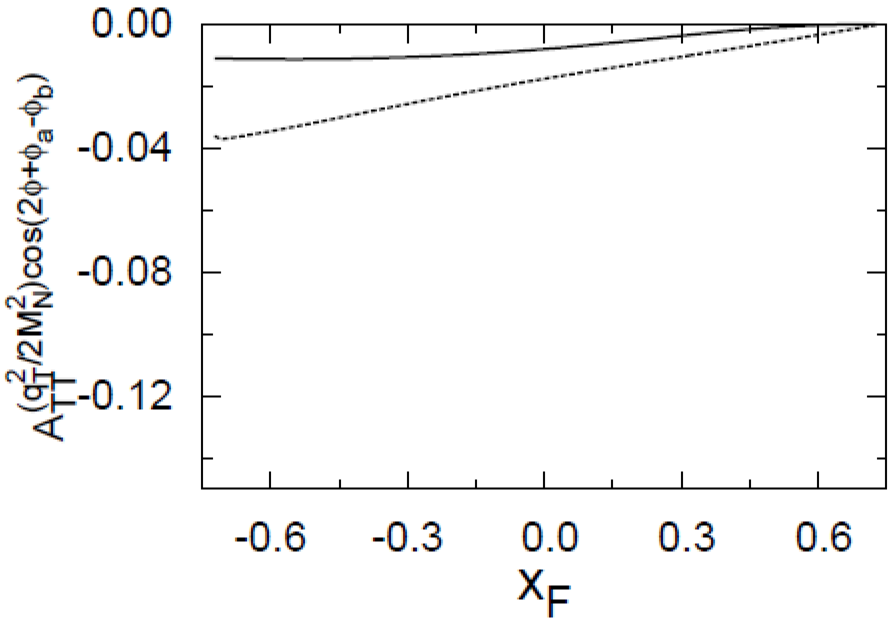


FIG. 2: The weighted $\cos(2\phi + \phi_a - \phi_b)$ asymmetry as a function of x_F for $s = 45$ GeV^2 and $Q^2 = 12$ GeV^2. Solid curve corresponds to approach 1, while dotted curve corresponds to approach 2.

The unweighted asymmetry to measure pretzelosity

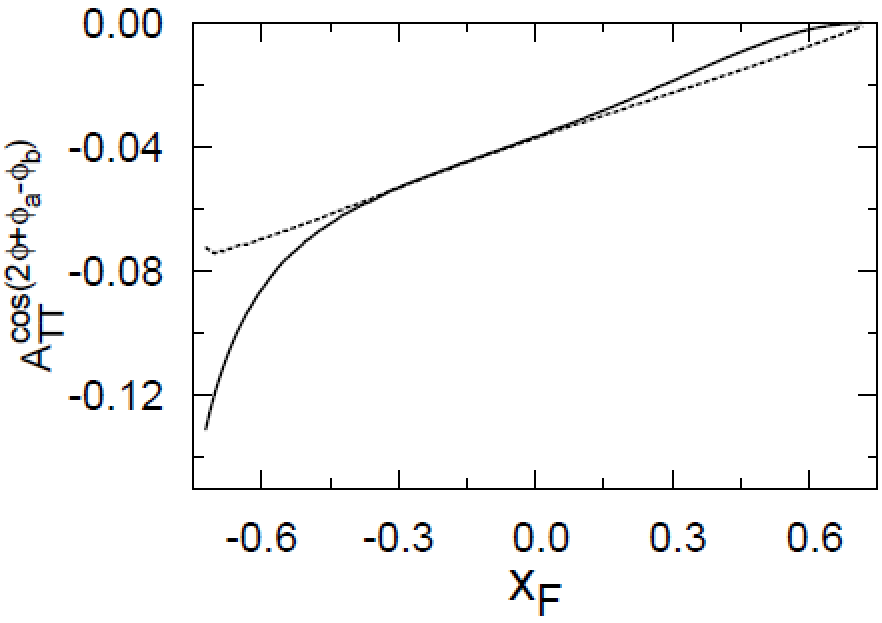


FIG. 3: The unweighted $\cos(2\phi + \phi_a - \phi_b)$ asymmetry as a function of x_F for $s = 45$ GeV^2 and $Q^2 = 12$ GeV^2. Solid curve corresponds to approach 1, while dotted curve corresponds to approach 2.

The Necessity of Polarized p pbar Collider

The polarized proton antiproton Drell-Yan process

is ideal to measure

the pretzelosity distributions of the nucleon.

PHYSICAL REVIEW D **82,** 114022 (2010)

Probing the leading-twist transverse-momentum-dependent parton distribution function $h_{1T}^{\perp}$ via the polarized proton-antiproton Drell-Yan process

Jiacai Zhu

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

Bo-Qiang Ma*

School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
Center for High Energy Physics, Peking University, Beijing 100871, China
(Received 10 October 2010; published 22 December 2010)

Probing Pretzelosity in pion p Drell-Yan Process

COMPASS pion p Drell-Yan process

can also measure

the pretzelosity distributions of the nucleon.

Physics Letters B 696 (2011) 513–517

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Single spin asymmetry in πp Drell–Yan process

Zhun Lu [a,b], Bo-Qiang Ma [c,*], Jun She [c]

[a] Department of Physics, Southeast University, Nanjing 211189, China
[b] Departamento de Física, Universidad Técnica Federico Santa María, and Centro Científico-Tecnológico de Valparaíso Casilla 110-V, Valparaíso, Chile
[c] School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

Transverse Momentum Dependent Quark Distributions

→ Nucleon Spin → Quark Spin

		Quark polarization		
		Un-Polarized	Longitudinally Polarized	Transversely Polarized
Nucleon Polarization	U	f_1 =		$h_1^\perp$ = − Boer-Mulder
	L		g_1 = − Helicity	$h_{1L}^\perp$ = − Worm Gear
	T	$f_{1T}^\perp$ = − Sivers	g_{1T} = − Worm Gear	h_{1T} = − Transversity $h_{1T}^\perp$ = − Pretzelosity

Names for New (tmd) PDF: g_{1T} and $h_{1L}^{\perp}$

g_{1T} trans-helicity

$h_{1L}^{\perp}$ longi-transversity / heli-transversity

Physics Letters B 696 (2011) 246–251

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

ELSEVIER

Proposal for measuring new transverse momentum dependent parton distributions g_{1T} and $h_{1L}^{\perp}$ through semi-inclusive deep inelastic scattering

Jiacai Zhu [a], Bo-Qiang Ma [a,b,*]

[a] *School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

[b] *Center for High Energy Physics, Peking University, Beijing 100871, China*

Conclusions

- **The relativistic effect of Melosh-Winger rotation is important in hadron spin physics.**
- **The pretzelosity is an important quantity for the spin-orbital correlation of the nucleon.**
- **It is necessary to push forward experimental measurements of new physical quantities of the nucleon.**