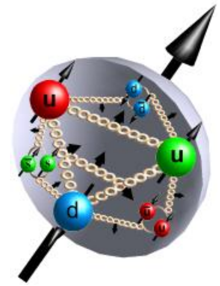

Where is the proton missing spin?

Bo-Qiang Ma (马伯强)

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Talk at "Diffraction 2012" in Lanzarote, Spain

September 12, 2012

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, Xinyu Zhang,Tianbo Liu

It has been 25 years

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

- **Spin Structure:** **experimentally**

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

$$\Downarrow$$

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

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:

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

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

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**

How to get a clear picture of nucleon?

- PDFs are physically defined in the IMF (infinite-momentum frame) or with space-time on the light-cone.
- Whether the physical picture of a nucleon is the same in different frames?

A physical quantity defined by matrix element is frame-independent, but its physical picture is frame-dependent.

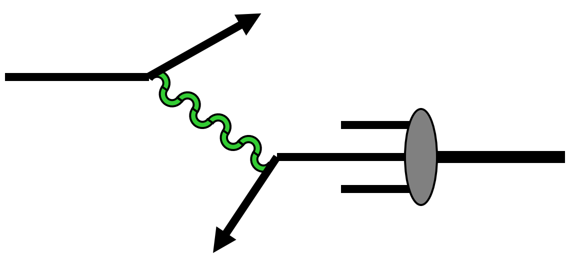
See the two pictures of diffraction in IMF and in rest-frame.

Salek's talk

The parton model (Feynman 1969)

- photon scatters incoherently off massless, pointlike, spin-1/2 quarks
- probability that a quark carries fraction ξ of parent proton's momentum is $q(\xi)$, $(0 < \xi < 1)$

infinite momentum frame



$$F_2(x) = \sum_{q,\bar{q}} \int_0^1 d\xi \; e_q^2 \, \xi \, q(\xi) \, \delta(x-\xi) = \sum_{q,\bar{q}} e_q^2 \, x \, q(x)$$

$$= \frac{4}{9} \, x u(x) + \frac{1}{9} \, x d(x) + \frac{1}{9} \, x s(x) + \ldots$$

- the functions $u(x)$, $d(x)$, $s(x)$, … are called parton distribution functions (pdfs) - they encode information about the proton's deep structure

- **Parton model is established under the collinear approxiamtion:** The transversal motion of partons is neglected or intergrated over.

The improvement to the parton model?

- What would be the consequence by taking into account the transversal motions of partons?
- **It might be trivial in unpolarized situation. However it brings significant influences to spin dependent quantities (helicity and transversity distributions and transversal momentum dependent quantities (TMDs or 3dPDFs).**

The Pion Spin Structure

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

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(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 Notion of Spin

- Related to the space-time symmetry of the Poincaré group
- Generators $P^{\mu} = (H, \vec{P}),$ space-time translator

$J^{\mu\nu}$ infinitesimal Lorentz transformation

$\vec{J}$ $J^{k} = \frac{1}{2}\varepsilon_{ijk} J^{ij}$ angular momentum

$\vec{K}$ $K^{k} = J^{k0}$ boost generator

Pauli-Lubanski vertor $w_{\mu} = \frac{1}{2} J^{\rho\sigma} P^{\nu} \varepsilon_{\nu\rho\sigma\mu}$

Casimir operators: $P^{2} = P^{\mu} P_{\mu} = m^{2}$ mass

$w^{2} = w^{\mu} w_{\mu} = s^{2}$ spin

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

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

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

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

$$\psi(x,\mathbf{k}\_,\lambda_1,\lambda_2)=C^F_0(x,\mathbf{k}\_,\lambda_1,\lambda_2)\varphi(x,\mathbf{k}\_).$$

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

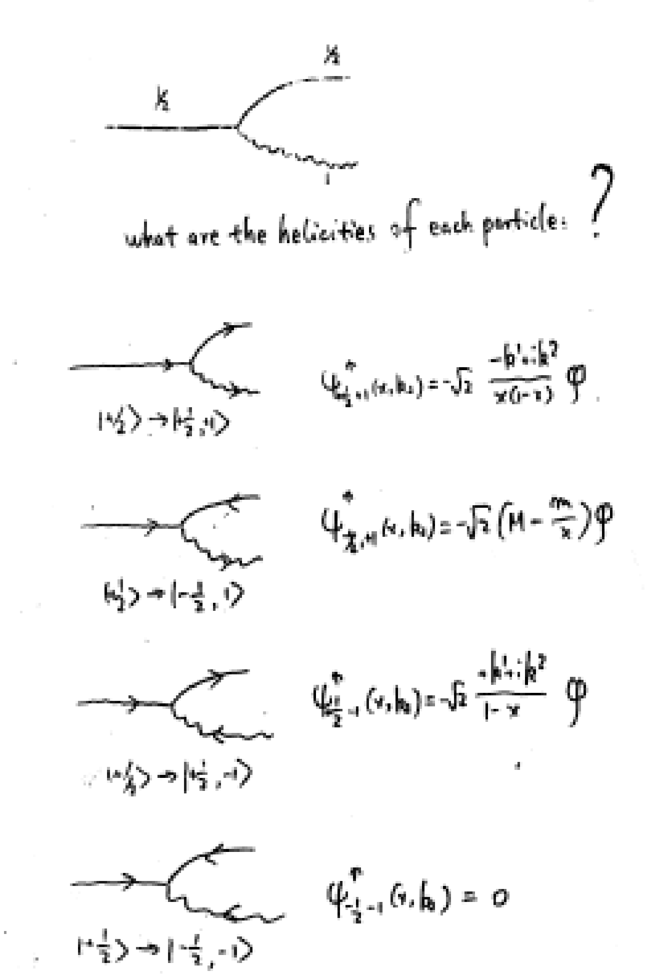
$$\frac{\overline{v}(p_2^+, p_2^-, -\mathbf{k}_\perp)}{\sqrt{p_2^+}} \gamma_5 \frac{u(p_1^+, p_1^-, \mathbf{k}_\perp)}{\sqrt{p_1^+}},$$

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

Xiao & Ma, PRD71(2005)014034

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.

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

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

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

$$u^{\uparrow}_{V} = \frac{1}{18}; \quad u^{\downarrow}_{V} = \frac{2}{18}; \quad d^{\uparrow}_{V} = \frac{2}{18}; \quad d^{\downarrow}_{V} = \frac{4}{18};$$

$$u^{\uparrow}_{S} = \frac{1}{2}; \quad u^{\downarrow}_{S} = 0; \quad d^{\uparrow}_{S} = 0; \quad d^{\downarrow}_{S} = 0. \qquad (7)$$

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 ($\sim 15\%$): $\quad \Delta d_{\rm sea} \approx -0.07$

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

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

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

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

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

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

- **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

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

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

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

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

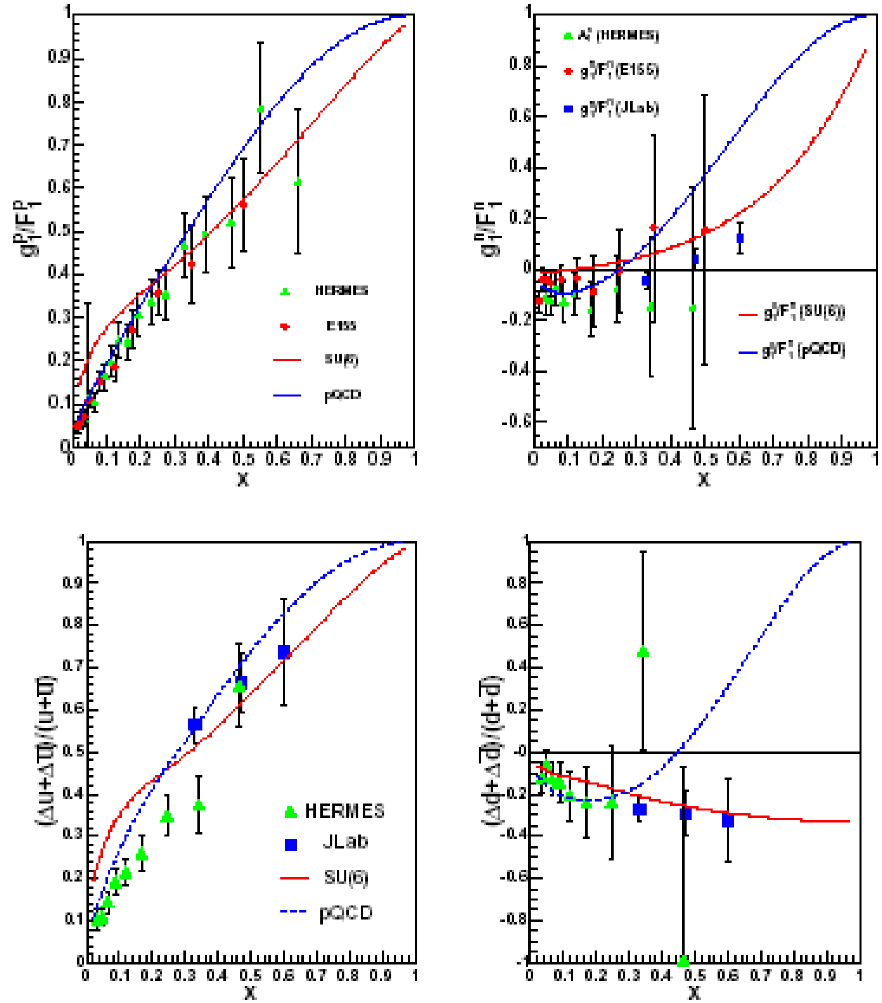
- pQCD based counting rule analysis

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

- CTEQ5 set 3 as input.

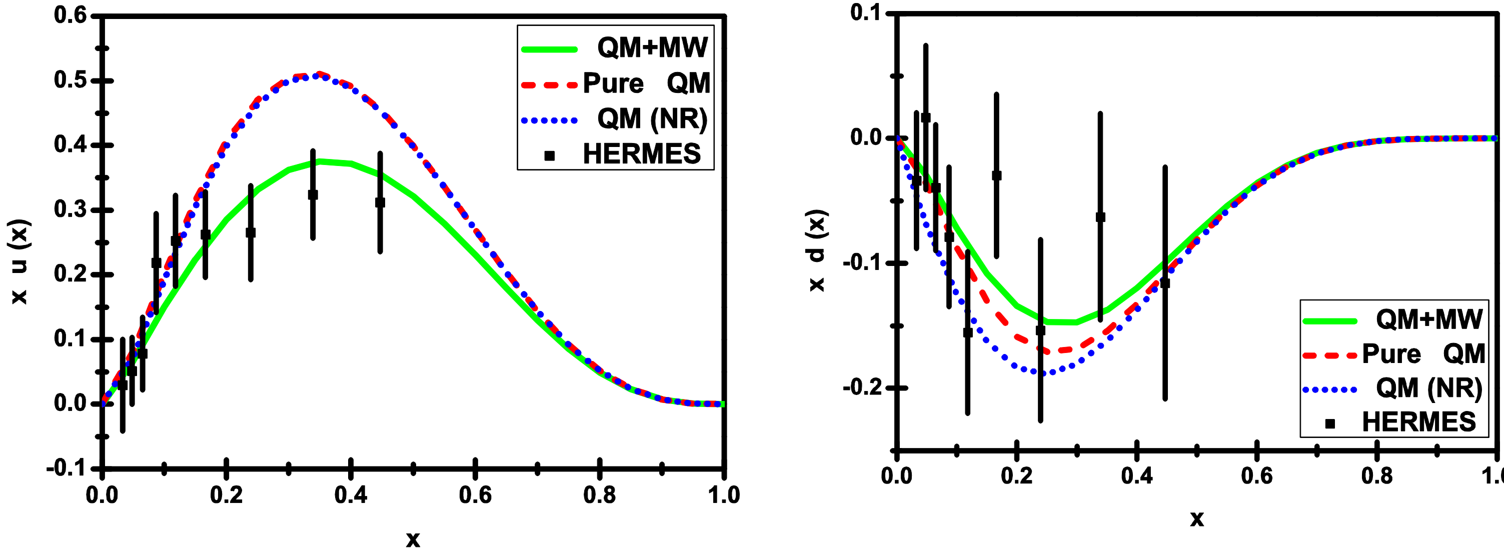
Different predictions in two models

- 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 $x \to 1$.



Y.Zhang, B.-Q. Ma, PRD 85 (2012) 114048.

The proton spin in a light-cone chiral quark model



An upgrade of previous work by including Melosh-Wigner rotation: T. P. Cheng and L. F. Li, PRL 74 (1995) 2872

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, PLB 477 (2000) 107, PRD 61 (2000) 034017
B.-Q. Ma, J. Soffer, PRL 82 (1999) 2250

Leading-Twist TMD PDFs

Nucleon Spin

Quark Spin

		Quark polarization		
		Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	f_1		$h_1^{\perp}$ Boer-Mulders
	L		g_1 Helicity	$h_{1L}^{\perp}$ Long-Transversity
	T	$f_{1T}^{\perp}$ Sivers	g_{1T} Trans-Helicity	h_1 Transversity $h_{1T}^{\perp}$ Pretzelosity

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

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

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

PHYSICAL REVIEW D **78,** 034025 (2008)

Transverse momentum dependent parton distributions in a light-cone quark model

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(Received 23 June 2008; published 21 August 2008)

$$h_{1T}^{\perp q}(x, \boldsymbol{k}_\perp^2) = -P^q \int d[1]d[2]d[3]\sqrt{x_1 x_2 x_3} \times \delta(k - k_3)|\psi(\{x_i\}, \{\boldsymbol{k}_{i\perp}\})|^2 \times \frac{2M^2}{(m + xM_0)^2 + \boldsymbol{k}_\perp^2},$$

The Melosh-Wigner Rotation in "Pretzelosity"

B. Pasquini, S. Cazzaniga, and S. Boffi, Phys. Rev. D 78, 034025 (2008)

The Melosh-Wigner Rotation in "Pretzelosity"

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

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

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

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

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

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

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

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

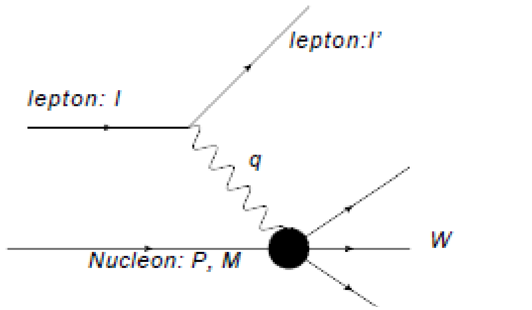
- A measurement of pretzelosity may reveal the information on the quark orbital angular momentum.

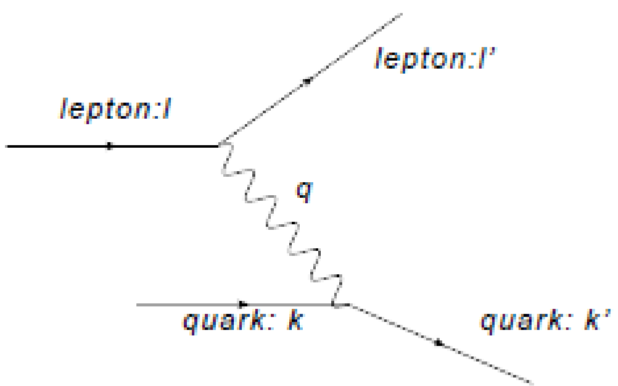
The Melosh-Wigner Rotation in five 3dPDFs

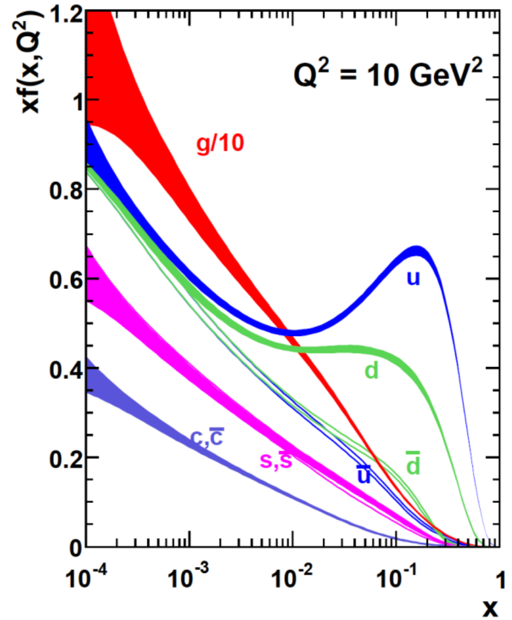
分布函数	Melosh转动因子（$W_D(D=V,\ S)$）
g_{1L}	$[(x\mathscr{M}_D+m_q)^2-p_\perp^2]/[(x\mathscr{M}_D+m_q)^2+p_\perp^2]$
g_{1T}	$2M_N(x\mathscr{M}_D+m_q)/[(x\mathscr{M}_D+m_q)^2+p_\perp^2]$
h_1	$(x\mathscr{M}_D+m_q)^2/[(x\mathscr{M}_D+m_q)^2+p_\perp^2]$
$h_{1L}^\perp$	$-2M_N(x\mathscr{M}_D+m_q)/[(x\mathscr{M}_D+m_q)^2+p_\perp^2]$
$h_{1T}^\perp$	$-2M_N^2/[(x\mathscr{M}_D+m_q)^2+p_\perp^2]$

$\mathscr{M}_D^2=\frac{m_q^2+p_\perp^2}{x}+\frac{m_D^2+p_\perp^2}{1-x}$是旁观双夸克的不变质量。

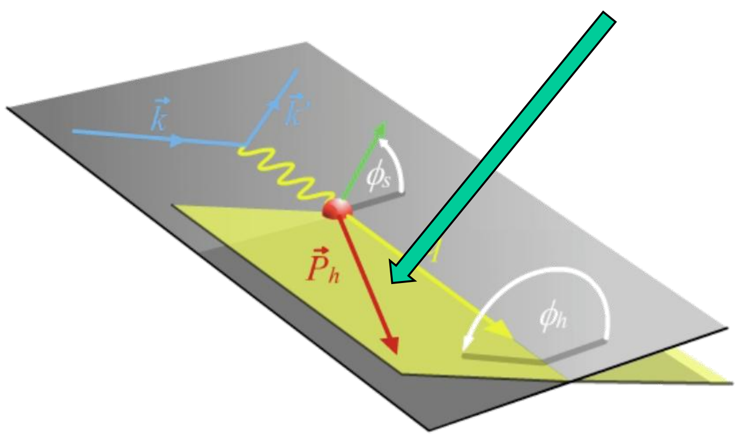
Lepton Scattering - - - - - *A powerful tool*







x=1 dimensional longitudinal momentum



tagging the struck quark through leading hadrons (semi-inclusive DIS)
to image in 3-momentum space

8 New TMD PDFs
f1(x,kT), .. h1(x,kT)

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

g_{1T}	trans-helicity	横纵度
$h_{1L}^{\perp}$	longi-transversity / heli-transversity	纵横度

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

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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

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(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.

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Physics Letters B

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Single spin asymmetry in πp Drell–Yan process

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THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Azimuthal asymmetries in lepton-pair production at a fixed-target experiment using the LHC beams (AFTER)

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unpolarized and single polarized *pp* and *pd* processes. We conclude that it is feasible to measure these azimuthal asymmetries, consequently the three-dimensional or transverse momentum dependent parton distribution functions (3dPDFs or TMDs), at this new AFTER facility.

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.

Conclusions

- The relativistic effect of parton transversal motions plays an significant role in spin-dependent quantities: helicity and transversity.
- The pretzelosity with quark transversal motions is an important quantity for the spin-orbital correlation of the nucleon.
- The Melosh-Winger rotation effect is also important in the new quantities of 3dPDFs or TMDs, such as g_{1T} and $h_{1L}^{\perp}$
- It is necessary to push forward experimental measurements of new physical quantities of the nucleon.