Spin Azimuthal Asymmetries in Semi-Inclusive DIS at JLAB

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- Nucleon spin & transverse momentum of partons
- Transverse-momentum dependent distributions
- Spin-azimuthal asymmetries
- Experimental status of single-spin asymmetries
- Projections for JLab at 12 GeV
- Summary & Outlook

PAC meeting, Jan 17, JLab
Physics Motivation

Orbital Angular Momentum (OAM) in the focus.

Transverse momentum of quarks is a key to OAM.

Parton Distribution Functions generalized to contain information not only on longitudinal, but also on the transverse distribution of partons:

Complementary sets of non-perturbative functions sensitive to different aspects of transverse distributions

- Generalized Parton Distributions (GPD) $H, E \ldots$
- Transverse-momentum dependent (TMD) parton distributions

TMD distributions contain direct information about the quark orbital motion
GPDs and TMDs

In impact parameter space: partons described by their longitudinal momentum fraction \( x \), transverse distance \( b \) from proton center and transfer of longitudinal momentum \( \xi \).

\( \text{(M.Diehl hep-ph/0205208)} \)

**GPDs:** correlate hadronic wave functions with both different momentum fractions and different transverse positions of the partons.

**TMDs:** correlation in transverse position of a single quark. The struck quark has a different transverse location relative to the spectator partons in the initial and final state.
**$k_T$ - Dependent Parton Distributions**

**Twist-2 PDFs**

$f_1^u(x) \equiv u(x), \ g_1^u(x) \equiv \Delta u(x), \ h_1^u(x) \equiv \delta u(x)$

$f_1, g_1$ studied for decades: $h_1$ essentially unknown

$f_1(x) = \int d^2k_T f_1(x,k_T)$

<table>
<thead>
<tr>
<th>Distribution functions</th>
<th>Chirality</th>
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<tr>
<td><strong>Twist-2</strong></td>
<td>even</td>
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<tr>
<td>U</td>
<td>f_1</td>
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<td>L</td>
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<td>$f_1 \perp, g_1 \perp$</td>
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<td>$h_1, h_{1T} \perp$</td>
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<tr>
<td><strong>Twist-3</strong></td>
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<tr>
<td>U</td>
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<td>$h_T, h_T \perp$</td>
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FSI from Brodsky et al. used in gauge invariant definition of TMDs by Collins, Ji et al. 2002

**Classification of PDF** by Mulders et al.
Novel Distributions

Transversity: probes relativistic nature of quarks, does not mix with gluons. First moment - tensor charge:
\[ \delta \Sigma = \sum_f \int_0^1 dx (\delta q_f - \bar{\delta} \bar{q}_f) = 0.56 +/- 0.09 \ (Q^2=2) \]

Sivers function: describes unpolarized quarks in transversely polarized nucleon. A non-zero T-odd \( f_{1T} \), requires final state interactions + interference between different helicity states
(Brodsky et al., Collins, Ji et al. 2002)

Collins function: describes fragmentation of transversely polarized quarks into unpolarized hadrons. Physics mechanisms to generate non-zero T-odd \( H_{1T} \) by Collins 1993, Bacchetta et al. 2002
Semi-Classical Models

Collins effect:
asymmetric fragmentation

Orbital momentum generated in string breaking and $q\bar{q}$ pair creation produces left-right asymmetry from transversely polarized quark fragmentation (Artru-hep-ph/9310323).

Sivers effect:
asymmetric distribution

In the transversely polarized proton $u$ quarks are shifted down and $d$ quark up giving rise to SSA (Burkardt-hep-ph/02091179).
The shift ($\sim 0.4$ fm) is defined by spin-flip GPD $E$ and anomalous magnetic moment of proton.
Collins Effect:

Left-right asymmetry in the fragmentation of transversely polarized quarks
Sivers Effect:

Left-right asymmetry in the distribution function
Transverse Momentum of Partons

Non-zero transverse momenta of partons are accessible in measurements of azimuthal distributions of final state hadrons.

Azimuthal Asymmetries in electroproduction:

- clean test of QCD (Georgi, Politzer 1978)
- intrinsic transverse momentum of partons (Cahn 1979)
- final state interactions (Berger 1980)

The DIS data from EMC (1987) and Fermilab (1993) are most consistent with intrinsic parton transverse momentum squared, $k_T^2$ of ~ 0.25 GeV$^2$
Spin-Azimuthal Asymmetries

Spin asymmetries + azimuthal dependence \rightarrow \text{new class of DIS measurements Spin-Azimuthal Asymmetries:}

Significant progress made recently in studies of \textbf{Single-Spin Azimuthal Asymmetries (SSA)} with longitudinally polarized target (HERMES), transversely polarized target (SMC), and polarized beam (CLAS).

- SSA are sensitive to the orbital momentum of quarks.
- Provide a window to the physics of partonic final and initial state interactions.
- Model calculations indicate that SSA are not affected significantly by a wide range of corrections.
- Good agreement in SSAs measured in a wide energy range in electroproduction and \textit{pp} scattering.

\textbf{SSAs:} appropriate observable at JLAB beam energies and $Q^2$
Polarized Semi-Inclusive DIS

Cross section defined by scale variables $x,y,z$

\[
x = \frac{Q^2}{2ME_\gamma}
\]
\[
y = \frac{E_\gamma}{E}
\]
\[
z = \frac{E_h}{E_\gamma}
\]
\[
\sin \theta_\gamma \approx \frac{2Mx}{Q} \sqrt{1 - y}
\]
\[
\sin \phi = \frac{[\vec{q} \times \vec{k}] \cdot \vec{P}_\perp}{|\vec{q} \times \vec{k}| |\vec{P}_\perp|}
\]

Hadron-Parton transition: by distribution function $f_1^u(x)$:
probability to find a $u$-quark with a momentum fraction $x$

Parton-Hadron transition: by fragmentation function $D_{1u}^{\pi^+}(z)$:
probability for a $u$-quark to produce a $\pi^+$ with a momentum fraction $z$
Contributions to $\sigma$ in $ep \rightarrow e'\pi X$

$\sigma$ for longitudinally polarized leptons scattering off unpolarized protons:

\[
\frac{d\sigma_{UU}}{dx_B dy dz d^2P_\perp} = \frac{4\pi \alpha^2 s}{Q^4} x_B \left\{ \left( 1 - y + \frac{1}{2} y^2 \right) \mathcal{H}_T \\
+ (1 - y) \mathcal{H}_L \\
- (2 - y) \sqrt{1 - y} \cos \phi \mathcal{H}_{LT} \\
+ (1 - y) \cos 2\phi \mathcal{H}_{TT} \right\},
\]

\[
\frac{d\sigma_{LU}}{dx_B dy dz d^2P_\perp} = \lambda e \frac{4\pi \alpha^2 s}{Q^4} x_B y \sqrt{1 - y} \sin \phi \mathcal{H}'_{LT}
\]

Different structure functions can be extracted as **azimuthal moments** of the total cross section.

\[
\frac{1}{2} A_{LU} \sin \phi = \langle \sin \phi \rangle = \frac{1}{P^\pm N^\pm} \sum_{i=1}^{N^\pm} \sin \phi_i.
\]
Contributions to $\sigma$ in Polarized SIDIS

\[
\sigma_{UU} \propto (1 - y + y^2/2) \sum_{a, \bar{a}} e_a^2 x f_1^a(x) D_1^a(z)
\]

\[
\sigma_{UU}^{\cos 2\phi} \propto (1 - y) \cos 2\phi \sum_{a, \bar{a}} e_a^2 x h_1^a(x) H_1^{+a}(z)
\]

\[
\sigma_{LL} \propto \lambda_e S_L y (2 - y) \sum_{a, \bar{a}} e_a^2 x g_1^a(x) D_1^a(z)
\]

\[
\sigma_{LT}^{\cos \phi} \propto \lambda_e S_T y (2 - y) \cos(\phi - \phi_S) \sum_{a, \bar{a}} e_a^2 x g_{1T}(x) D_1^a(z)
\]

\[
\sigma_{UL}^{\sin 2\phi} \propto S_L 2(1 - y) \sin 2\phi \sum_{a, \bar{a}} e_a^2 x h_{1L}^a(x) H_1^{+a}(z)
\]

\[
\sigma_{UT}^{\sin \phi} \propto S_T (1 - y) \sin(\phi + \phi_S) \sum_{a, \bar{a}} e_a^2 x h_1^a(x) H_1^{+a}(z)
\]

\[
\sigma_{UT}^{\sin \phi} \propto S_T (1 - y) \sin(\phi - \phi_S) \sum_{a, \bar{a}} e_a^2 x f_{1T}^a(x) D_1^a(z)
\]

\[
\sigma_{LU}^{\sin \phi} \propto \lambda_e \sin \phi y \sqrt{1 - y} \frac{M}{Q} \sum_{a, \bar{a}} e_a^2 x^2 e^a(x) H_1^{+a}(z)
\]

$\lambda_e, S_L, S_T$ electron and proton long. and trans. pol.

$\sum_{a, \bar{a}} \rightarrow$ sum over quarks and anti-quarks.
Long. Pol Target SSA for $\pi^+$

$A_{UL}$ are consistent both in magnitude and sign with predictions based on Collins mechanism.

Target SSA: CLAS (4.3 GeV) is consistent with HERMES (27.5 GeV)

$$A_{UL} \propto \sin \theta_\gamma \times A_{UT} \propto \sin \theta_\gamma \frac{f_{1T} u(x)}{u(x)}$$
Beam SSA: $\sin \phi$ Moment

$$A_{LU} \propto \lambda_e f(y) \frac{M}{Q} \frac{H_{1u,\pi^+}^{H_1}(z)}{D_{1u,\pi^+}^{D_1}(z)}$$

Beam SSA $A_{LU}$ from CLAS at 4.3 GeV and HERMES (SPIN-2002) at 27.5 GeV

Beam SSA measurements for different beam energies are consistent.
First Extraction of $e(x)$ from CLAS Data

SSA analyzed in terms of the fragmentation effect

- $x$-dependence of CLAS beam SSA ($A_{LU}$)
- $z$-dependence of HERMES target SSA ($A_{UL}$)

First glimpse of Twist-3 $e(x)$

\[
\int_{0}^{1} e(x) = \frac{2\sigma_{\pi N}}{m_u + m_d}
\]

Jaffe, Ji 1992
Long. Pol. Target SSA for $\pi^+$ at 12GeV

The $\sin 2\phi$ asymmetry for 2000 h of projected CLAS++ data.

Direct measurement of $k_T$ dependent leading-twist distribution function

$A_{UL}^{\sin 2\phi} \propto \frac{h_{1L}^u(x)}{u(x)} \frac{H_{1}^{\perp u}(z)}{D_{1}^{u}(z)}$

e $p \rightarrow e' \pi^+ + X$

Efremov et al.
Transverse Target SSA at 12 GeV

\[ A_{UT} \propto \sin \phi_c \frac{h_1^u(x)}{u(x)} \frac{H_1^u}{D_1^u} \]

\[
\begin{align*}
0.5 < z < 0.8 \\
e \rightarrow e^+ \pi^- + X
\end{align*}
\]

Expected precision of the \( A_{UT} \) and extracted \( \delta u/u \) from transverse spin asymmetry.
Other Flavors

More hadrons (K+, ρ ..) allow studies of:

- $x/z$ factorization
- $u$-quark dominance
- flavor dependence
- universality property of factorization

![Graph showing the ratio $K^+/\pi^+$ versus $x$ at different values of $z$.]
Key goal: study the transition between the nonperturbative and perturbative regimes of QCD utilizing JLab’s advantages:

- High luminosity
- Full coverage in azimuthal angle (separate all contributions)
- Wide kinematic range (test factorization, measure HT)
- Good particle ID (compare different final state particles)
Summary

- **Transverse Momentum Dependent** distributions of partons contain direct information about the quark **Orbital Angular Momentum**. They are accessible in measurements of spin-azimuthal asymmetries.

- Current data are consistent with a partonic picture, and can be described by a variety of theoretical models.

- Significantly higher statistics of JLab data at 12 GeV, in a wide kinematical range will provide a full set of data needed to constrain relevant distribution (transversity, Sivers, Collins, …) functions.

- Upgraded Jlab will play a leading role in studies of quark **orbital motion**, providing fundamental insights into important physics quantities like spin, flavor, and multi-parton correlations.
SIDIS tests at JLAB

Open issues

• factorization
• separation of current fragmentation

Proposed tests to make sure simple parton picture work (SIDIS workshop in April 2002):

- $x$ and $z$ factorization
- Ratio of charged pions
- Ratios of pion yields for proton/neutron
- Pion production asymmetries
x,z Factorization

The $z$ distribution for different ranges of Bjorken $x$

No significant variation observed in $z$ dependence for different $x$ ranges.
CLAS data vs LUND-MC

CLAS data (4.3GeV) and LUND-MC comparison

LUND-MC tuned at higher energies
Current Fragmentation Region at CLAS

DIS:
$Q^2 > 1$
$W^2 > 4$
$y < 0.85$

The separation of CFR with $0.5 < z < 0.8$ is not changing significantly with beam energy.