Transversity and Orbital Motion at CLAS

(Past, Present and Future)

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The Players

- **Transversity:** $h_1(x)$, momentum distribution of transversely polarized quarks in a transversely polarized nucleon
- **Boer-Mulders Function:** $h_1^{\text{perp}}(x, \mathbf{k}_{\text{perp}})$, momentum distribution of transversely polarized quarks in an unpolarized nucleon
- **Sivers Function:** $f_{1T}^{\text{perp}}(x, \mathbf{k}_{\text{perp}})$, momentum distribution of unpolarized quarks in a transversely polarized proton.
Outline

• Past
  – No transversely polarized target at CLAS

• Present
  – No transversely polarized target at CLAS

• Future
  – No transversely polarized target planned for CLAS (yet, but it would be nice to get one)

• What then?
  – Use longitudinal or unpolarized targets.
Factorization Theorem

\[ M = \sum_{ij} \int dz dx_i f_{i,T}^{T'}(x_i, x_i - x_B, t) H_{ij}(\frac{x_i}{x_B}, Q, z) \Phi_j^F(z) \]

\( G_{\text{P.D.}} \quad \text{pQCD} \quad \text{distribution amplitude for hadronic state } F \)

\( + \mathcal{O}(1/Q) \) corrections

Factorization Theorem: Collins, Frankfurt, Strikman
PRD 54 (97) 2982.

No proven factorization thm for \( \gamma^* \) (transverse photons) but amplitudes are down by \( 1/\xi \) w.r.t. \( \gamma^* \)
Higher Twist

• A problem (factorization is probably destroyed)
• An opportunity (not all interactions in nature occur at high momentum transfer)
• Necessary to fully understand the nucleon (learn to enjoy it)
• Remarkably hard to pin down experimentally (large $Q^2$ range necessary)
Polarized Semi-Inclusive DIS

Cross section a function of scale variables $x, y, z$

$$\nu = E - E'$$
$$y = \frac{\nu}{E}$$
$$x = \frac{Q^2}{2M\nu}$$
$$z = \frac{E_h}{\nu}$$

Hadron-Parton transition: by distribution function $f_{1u}(x)$:
probability to find a $u$-quark with
a momentum fraction $x$

Parton-Hadron transition: by
fragmentation function $D_{1u}^{\pi^+(\pi^-)}(z)$:
probability for a $u$-quark to produce a $\pi^+(\pi^-)$ with a
momentum fraction $z$
N(e,e’h)X Observables

- $A_{LL} \rightarrow g_1$
- $A_{LT} \rightarrow g_2$
- $A_{UL} \rightarrow$ tangled mess
- $A_{LU} \rightarrow$ ditto
- Asymmetries are functions of $x, y, z, Q^2, p_T, \phi, \phi_S, \theta,$ etc.
- These asymmetries are well-defined experimental quantities for all $Q^2$; however, they have their simplest interpretation at high $Q^2$
Polarized SIDIS and TMD PDFs

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

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

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

\[ \sigma_{UL}^{\sin 2\phi} \propto S_L (1 - y) \sin 2\phi \sum_{a,\bar{a}} e_a^2 x h_1^{L(1)}(x) H_1^{L(1)}(z) \]

\[ \sigma_{UT}^{\sin \phi} \propto S_T (1 - y + y^2/2) \sin(\phi - \phi_S) \sum_{a,\bar{a}} e_a^2 x f_1^T(x) D_1^a \]

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

Gauge invariant definition of TMDs discussed by Collins and Belitsky, Ji & Yuan Nucl. Phys. B656 165, 2003

Two fundamental QCD mechanisms (Collins and Sivers) identified, to generate SSA:
The **CLAS** Detector

- High luminosity, polarized CW beam
- Wide physics acceptance, including exclusive, semi-inclusive processes, current and target fragmentation
- Wide geometric acceptance, allowing detection of multi-particle final states

- **CEBAF**
  - Large
  - Acceptance
  - Spectrometer

- **Forward CALO**

\[ Q^2 \]

\[ x \]

\[ t \]
SIDIS kinematic plane and coverage at 6 GeV

\[
\nu = E - E'
\]

\[
Q^2 = 4EE' \sin(\theta / 2)
\]

\[
x = \frac{Q^2}{2M\nu}
\]

\[
y = \frac{\nu}{E}
\]

\[
z = \frac{E_h}{\nu}
\]
SSA measurements at CLAS (eg1)

\[ A_{UL}(\phi) = \frac{1}{P_T} \frac{N^+ - N^-}{N^+ + N^-} \]

- Significant SSA measured for pions with longitudinally polarized target
- Complete azimuthal coverage crucial for separation of \( \sin \phi \), \( \sin 2\phi \) moments

\[ W^2 > 4 \text{ GeV}^2 \]
\[ Q^2 > 1.1 \text{ GeV}^2 \]
\[ y < 0.85 \]

\[ 0.4 < z < 0.7 \]
\[ M_X > 1.4 \text{ GeV} \]

\[ P_T < 1 \text{ GeV} \]
\[ 0.12 < x < 0.48 \]
Factorization studies in CFR at CLAS

In terms of Collins fragmentation

\[ A_{LU}^{\sin \varphi} \propto \lambda \frac{e(x) H_1^{\perp}(z)}{f(x) D(z)} \]

No significant variation observed in z dependence of \( A_{LU} \) for different x ranges
Collinear Fragmentation

The only fragmentation function at leading twist for pions in $eN_e \pi X$ is $D_1(z)$

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

$E_e = 5.7$ GeV

No significant variation observed in $z$ distributions of $\pi^+$ for different $x$ ranges ($0.4 < z < 0.7$, $M_X > 1.5$) and for $A1p$ as a function of $P_T$
• Indicate a negative $\sin^2 \phi$ moment measured for $\pi^+$.  
• Some indication of negative $\pi^-$ SSA (more data required for $\pi^-$ and $\pi^0$).  
• More data required to correct for exclusive $2\pi$ contribution.
SSA: $P_T$-dependence of $\sin\phi$ moment

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

$A_{UL}$ (CLAS @5.7 GeV) $A_{LU}$ CLAS @4.3 GeV $A_{UT}$ HERMES @27.5 GeV

Beam and target SSA for $\pi^+$ are consistent with increase with $P_T$.
In the perturbative limit is expected to behave as $1/P_T$. 
SIDIS with neutral pions (E05-115)

\[ A_{UL} (\pi^+) \sim H_1^{\text{favored}} \]
\[ A_{UL} (\pi^0) \sim H_1^{\text{favored}} + H_1^{\text{unfavored}} \]

\(\pi^0\) SSA sensitive to the ratio of unfavored to favored polarized fragmentation functions

1) SIDIS \(\pi^0\) production is not contaminated by diffractive \(\rho\)
2) HT effects and exclusive \(\pi^0\) suppressed
3) Simple PID by \(\pi^0\)-mass (no kaon contamination)
4) Provides information complementary to \(\pi^+/\) information on PDFs

SIDIS \(\pi^0\): main focus of the experiment
Experimental Setup (CLAS EG1+IC)

- solid NH$_3$ polarized target
- proton polarization >75%
- high lumi $\sim 1.5\times10^{34}$ s$^{-1}$cm$^{-2}$

Inner Calorimeter (424 PbWO$_4$ crystals) for the detection of high energy photons at forward lab angles (e1-DVCS).
Reconstruction efficiency of high energy $\pi^0$ with IC increases ~ 3 times at large $z$ due to small angle coverage (target in ~60cm from IC)
Factorization studies with $\pi^0$

$$A_1 = \frac{\sum_q g_1^q(x) D_1^q(z)}{\sum_q f_1^q(x) D_1^q(z)}$$

- Double spin asymmetries consistent with simple partonic picture
- $A_{1p}^{\pi^0}$ inclusive and $\pi^0$ can serve as an important check of HT effects and applicability of the simple partonic description.
Longitudinally polarized target SSA using CLAS+IC

\[ \sigma_{UL}^{KM} \approx (1-y)h_{UL}^\perp H_1 \]

- 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

60 days of CLAS+IC (L=1.5.10^{34} cm^{-2}s^{-1})

\[ H_{unf} = -5 H_{fav} \]
\[ H_{unf} = -1.2 H_{fav} \]
\[ H_{unf} = 0 \]

Curves, \( \chi_{QSM} \) from Efremov et al.
The $h_1$ Structure Function

$f_1 = \bullet \quad g_1 = \bullet - \bullet \quad h_1 = \bullet - \bullet$

Characteristics of $h_1$:

- leading twist -> on equal footing with $f_1$ and $g_1$
- chiral-odd -> can NOT be probed in inclusive DIS

Solution: couple $h_1$ to chiral-odd fragmentation function

Two options: 1 or 2 particle semi-inclusive DIS
2-\pi Single Spin Asymmetry

\[ A_{UL}(\phi_{R\perp}) = \frac{1}{|P_T|} \frac{N^\rightarrow(\phi_{R\perp})/L^\rightarrow - N^\leftarrow(\phi_{R\perp})/L^\leftarrow}{N^\rightarrow(\phi_{R\perp})/L^\rightarrow + N^\leftarrow(\phi_{R\perp})/L^\leftarrow} \]

longitudinally polarized deuterium target

\[ \vec{P}_h \equiv \vec{P}_1 + \vec{P}_2 \]
Theoretical Asymmetries

A. Bacchetta, M Radici, PRD 69 (2004) 074026

\[ A'_{UT} \sim B(y) \sin(\phi_{R\perp} + \phi_S) h_1 H_1^q + V(y) \sin(\phi_S) \frac{M}{Q} (\ldots) \]

\[ A'_{UL} \sim V(y) \sin(\phi_{R\perp}) \frac{M}{Q} (h_L H_1^q + g_1 \tilde{G}^q) \]

\( T/L \rightarrow \) target spin defined w.r.t. virtual photon
Experimental Asymmetries

\[ A_{UL} \approx A'_{UL} - \sin \Theta_\gamma A'_{UT} \]

- Target spin defined w.r.t. beam
- Target spin w.r.t. virtual photon

\[ \langle \sin \Theta_\gamma \rangle = \langle \frac{2Mx}{Q} \sqrt{1-y} \rangle \approx 0.045 \]

If \( H_1^a \neq 0 \):

\[ \implies \text{2 hadron fragmentation can probe transversity!} \]

\[ A_{UL}(\phi) \sim \frac{N_{\rightarrow} - N_{\leftarrow}}{N_{\rightarrow} + N_{\leftarrow}} \]

Fit with:

\[ f(\phi_{R \perp}) = a_0 + a_1 \sin \phi + b_1 \cos \phi + \ldots \]

\( A_{UL}^{\sin \phi} \)
Separations are possible from angular distribution. These require a large acceptance (e.g. CLAS)
Quark Angular Momentum Sum Rule

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

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


Large $x$ contributions important.
Hard Exclusive Processes and GPDs

**DVCS**

- For different polarizations of beam and target provide access to different combinations of GPDs $H, \tilde{H}, E$

- Study the asymptotic regime and guide theory in describing HT.

**DVMP**

- For different mesons is sensitive to flavor contributions ($\rho^0/\rho^+$ select $H, E$, for $u/d$ flavors, $\pi, \eta, K$ select $H, E$)
Exclusive $\rho$ meson production: \( ep \rightarrow ep \rho^0 \)

**CLAS (4.2 GeV)**

- Regge (JML)
- GPD (MG-MVdh)

**CLAS (5.75 GeV)**

GPD formalism (beyond leading order) describes approximately data for \( x_B < 0.4, Q^2 > 1.5 \text{ GeV}^2 \)

Analysis in progress

C. Hadjidakis et al., PLB 605

Two-pion invariant mass spectra

Decent description in pQCD framework already at moderate \( Q^2 \)
Upcoming 12 GeV CLAS Proposal

SIDIS ($\gamma^* p_\pi X$) : Unpolarized target

- Azimuthal moments in pion production in SIDIS
  - $\cos 2\phi$ (Boer-Mulders function $h_{1T}$) and relation with GPDs
  - $\cos \phi$, $\cos 2\phi$ moments to study Cahn effect and Berger HT
  - $\sin \phi$ ($g_\perp$) azimuthal moments of the x-section as a function of $x,Q_2,P_T,z$ to study transition from non-perturbative to perturbative description at large $P_T$
- Target fragmentation (Lambda, azimuthal moments)

Main focus

Study the transverse polarization of quarks in the unpolarized nucleon.
• High luminosity polarized (~80%) CW beam
• Wide geometric acceptance
• Wide physics acceptance

Provides new insight into
- quark orbital angular momentum contributions
- 3D structure of the nucleon’s interior and correlations
- quark flavor polarization
**cos2φ: predictions**

\[ A_{uu} = \cos(2\phi) = \frac{[8(1-y)h_1^{l(t)} H_1^{l(t)}]}{[(1-(1-y)^2)] f_1 D} \]

- Significant Boer-Mulders asymmetry predicted for CLAS12
CLAS6 data

Significant $\cos 2\phi$ observed at large $P_T$

M. Osipenko
CLAS12: kinematic distributions

Large $Q^2$ accessible with CLAS12 are important for $\cos2\phi$ studies.
CLAS12: kinematic distributions

Kinematic distributions of $\pi^+$ (triangles up) $\pi^-$ (triangles down) and $\pi^0$ for $\sim 10$ min of CLAS12 running with hydrogen at luminosity of $10^{35} \text{sec}^{-1}\text{cm}^{-2}$.

CLAS12 allow wide kinematical coverage of SIDIS
In the perturbative limit $1/P_T$ behavior expected

Asymmetries from $k_T$-odd ($g_-, h_{1-}$) and $k_T$-even ($g_1$) distribution functions are expected to have a very different behavior.
Measuring the $Q^2$ dependence of SSA

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

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

- Transversity is more easily studied with a transversely polarized target, but until we get one, we can learn quite a bit with longitudinally polarized targets.
- The large acceptance of CLAS and CLAS++ allows a wide variety of single-spin asymmetry measurements that probe the spin and angular-momentum of the nucleon.