Studies of Spin-Orbit Correlations at JLab

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(for the CLAS Collaboration)
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Outline

• Physics motivation
• Unpolarized and longitudinally polarized target data.
  – Single Spin asymmetries
  – Double Spin asymmetries
• Future studies of PDFs at CLAS at 6 GeV
• 12 GeV update
• Summary
SIDIS kinematical plane and observables

Transverse spin effects are observable as correlations of transverse spin and transverse momentum of quarks.

\[ \nu = (qP)/M \]
\[ Q^2 = (k - k')^2 \]
\[ y = (qP)/(kP) \]
\[ x = Q^2 / 2(qP) \]
\[ z = (qP_h)/(qP) \]

\( P_b, P_t \)  
\( U \) unpolarized  
\( L \) long.polarized  
\( T \) trans.polarized
SIDIS cross section

\[
\frac{d\sigma}{dx \, dy \, d\psi \, dz \, d\phi_h \, dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1-\varepsilon)} \left(1 + \frac{y^2}{2x}\right) \left\{ \begin{array}{c}
F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1+\varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} \\
+ \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda_e \sqrt{2\varepsilon(1-\varepsilon)} \sin \phi_h F_{UU}^{\sin \phi_h} \\
+ S_\parallel \left[ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_h F_{UL}^{\sin \phi_h} + \varepsilon \sin(2\phi_h) F_{UL}^{\sin 2\phi_h} \right] \\
+ S_\parallel \lambda_e \left[ \sqrt{1-\varepsilon^2} F_{LL} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_h F_{LL}^{\cos \phi_h} \right] \\
+ |S_\perp| \left[ \sin(\phi_h - \phi_S) \left( F_{UT,T}^{\sin(\phi_h - \phi_S)} + \varepsilon F_{UT,L}^{\sin(\phi_h - \phi_S)} \right) \\
+ \varepsilon \sin(\phi_h + \phi_S) F_{UT}^{\sin(\phi_h + \phi_S)} + \varepsilon \sin(3\phi_h - \phi_S) F_{UT}^{\sin(3\phi_h - \phi_S)} \\
+ \sqrt{2\varepsilon(1+\varepsilon)} \sin \phi_S F_{UT}^{\sin \phi_S} + \sqrt{2\varepsilon(1+\varepsilon)} \sin(2\phi_h - \phi_S) F_{UT}^{\sin(2\phi_h - \phi_S)} \right] \\
+ |S_\perp| \lambda_e \left[ \sqrt{1-\varepsilon^2} \cos(\phi_h - \phi_S) F_{LT}^{\cos(\phi_h - \phi_S)} + \sqrt{2\varepsilon(1-\varepsilon)} \cos \phi_S F_{LT}^{\cos \phi_S} \\
+ \sqrt{2\varepsilon(1-\varepsilon)} \cos(2\phi_h - \phi_S) F_{LT}^{\cos(2\phi_h - \phi_S)} \right] \right\},
\]

Bacchetta et al., JHEP 0702:093, 2007

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Unpol. target ✅

Long. Pol. target ✅

Trans. Pol. Target

Experiment in preparation (CLAS)

Transversely polarized $^3$He (E06-010/011) and proton/ deuterium targets (E08-015)

18 structure functions !!
Nucleon TMDs

\[ d\sigma^h \propto \sum f^{H\rightarrow q}(x, k_T) \otimes d\sigma_q(y) \otimes D^{q\rightarrow h}(z, p_\perp) \]

leading twist TMDs

<table>
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<th>quark</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
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<tr>
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<td>U</td>
<td>f1</td>
<td>h1^⊥</td>
</tr>
<tr>
<td>nucleon</td>
<td>L</td>
<td>g1</td>
<td>h_{IL}^⊥</td>
</tr>
<tr>
<td>nucleon</td>
<td>T</td>
<td>f_{iT}^⊥, g_{iT}^⊥</td>
<td>h_{iT}^⊥</td>
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</table>

+ Higher twist distribution functions

<table>
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<th>L</th>
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<tbody>
<tr>
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<td>g^⊥</td>
<td>h, e</td>
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<tr>
<td>L</td>
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<td>g_L^⊥</td>
<td>h_L, e_L</td>
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<tr>
<td>T</td>
<td>f_T, f_T^⊥</td>
<td>g_T, g_T^⊥</td>
<td>h_T, e_T, h_T^⊥, e_T^⊥</td>
</tr>
</tbody>
</table>
CLAS configurations

$e p \to e' \pi X$

Inner Calorimeter

Unpolarized, longitudinally and transversely polarized targets

1) Polarized NH$_3$/ND$_3$ (no IC, ~5 days)
2) Unpolarized H (with IC ~ 60 days)
3) Polarized NH$_3$/ND$_3$ with IC 60 days
   10% of data on carbon
4) Polarized HD-Ice (no IC, 25 days)

Unpolarized and longitudinally polarized targets

- Polarizations:
- Beam: ~80%
- NH$_3$ proton 80%, ND$_3$ ~30%
- HD (H-75%, D-25%)

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SIDIS kinematic coverage with IC

Scattering of 5.9 GeV electrons off unpolarized and polarized proton and deuteron targets

- DIS kinematics, $Q^2 > 1\text{ GeV}^2$, $W^2 > 4\text{ GeV}^2$, $M_{x}^2 > 2\text{ GeV}^2$

$\pi^+$

$Q^2$

$\pi^0$

$Q^2$

CLAS provides a wide kinematical coverage

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Dilution factor for NH3/ ND3

\[
\sigma = \frac{\sigma_p + \sigma_n}{2} \quad n \approx \sum_i \rho_i \sigma_i
\]

\[
n_C \approx A_C \sigma
\]

\[
n_{NH3} \approx A_{NH3} \sigma + B_{NH3} \sigma_p
\]

\[
f_{DF} = \frac{B_{NH3} \sigma_p}{A_{NH3} \sigma + B_{NH3} \sigma_p}
\]

A and B hold density information for all materials in the carbon and ammonia targets


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Longitudinally polarized NH3 target
E05-113

arXiv:1003.4549

The $\sin 2\varphi$ moment of the $\pi^+$ at large $x_B$ is dominated by $u$-quarks, therefore with additional input from other experiments can provide a first glimpse of twist 2 $h_{1L}^\perp$ function.
Only 10% of new data with IC for positive pions significantly improves statistical errors and will allow more than one dimensional extraction of $A_{UL}$ an $A_{LL}$.

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Beam Spin Asymmetry of $\pi^0$

$$F_{LU}^{\sin(\phi_h)} = \frac{2M}{Q} \times \int d^2 p_T d^2 k_T \, \delta^{(2)}(p_T - \frac{P_T}{z} - k_T)$$

$$\left\{ \hat{P}_T \cdot \frac{p_T}{M} \left[ \frac{M_h}{M} h_1^+ \frac{\tilde{E}}{z} + x_B g_1^+ D_1 \right] - \hat{P}_T \cdot k_T \left[ \frac{M_h}{M} f_1 \frac{\tilde{G}^+}{z} + x_B cH_1^+ \right] \right\}.$$
Beam Spin asymmetry of $\pi^0$ 

E01-113 experiment results on $A_{LU}$ extends the $x_B$ range and improves uncertainties.
What about $\rho^+ \rightarrow \pi^+\pi^0$?
According to MC VM contribution is less than 5%.
What do I have in data?
Exclusive $\pi^0\pi^+$ on proton
Exclusive $\pi^+\pi^0 A_{LU}$ for any $\pi^0$

Strong single pion $A_{LU}$ dependence vs mass of two pions?

Or strong single pion $A_{LU}$ dependence vs $x_B/P_T/z$ of single pions?

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$\pi^0\pi^+$ pairs

$M(\pi^+\pi^0)$ GeV

$M_x(ep\rightarrow e\pi^+\pi^0\ x)\ GeV$

$A_{UL}$

$<\phi>$

Very Preliminary

Any asymmetry extraction should be done for each $z, P_T, x_B, y$ bin!

Error bars are only Statistical.

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SIDIS with Jlab at 6 GeV

• Inclusive g1p
• Inclusive g1d
• SIDIS $A_{UL} & A_{LL}$ for pions on proton
• SIDIS $A_{UL} & A_{LL}$ for pions on deuteron
• SIDIS $A_{UL} & A_{LL}$ for kaons
• SIDIS pion pairs
• Modifications of azimuthal moments in nuclei
Transversely polarized HD-ice target

- **Target used by LEGS at BNL with photon beam**
  - Small field ($fBdl \sim 0.005-0.05Tm$)
  - Small dilution factor
  - Less radiation length
  - Less nuclear background
  - Wider acceptance

Need to demonstrate that the target can remain polarized for long periods with an electron beam with currents of order of 1-2 nA

- **The target is now at Jlab and all equipment moved to the new HDice lab**
  - Currently installing dilution refrigerators
  - Parallel development of new in-beam cryostat
  - **Installation ~ February 2011**
  - **Test with electrons ~ May 2011**
Preliminary results from Hall A

$^3$He double-spin asymmetry $A_{LT}$

$\propto \frac{g_{1T}^q(x) \otimes D_{1q}^h(z)}{f_1^q(x) \otimes D_{1q}^h(z)}$

- First observation of a none-zero $A_{LT}$.
- First measurement on neutron($^3$He).
- Relate to quark TMD $g_{1T}(x,k_T)$.
- The real part of quark $L=0 \otimes L=1$ interference, “twin-brother” of Sivers.


$\sigma_{n}^{\pi^+} \propto 4d \cdot D_{1}^{fav} + u \cdot D_{1}^{unfav}$

$\sigma_{n}^{\pi^-} \propto 4d \cdot D_{1}^{unfav} + u \cdot D_{1}^{fav}$

down-quark's $g_{1T}(x)$ is rather small.
up-quark's $g_{1T}(x)$ is not small.

$A_{LT}$ on proton should be noticeable (?)
CLAS at 12 GeV

A new generation of experiments is necessary to fully exploit the properties of TMDs, with
- wide kinematic coverage
- high luminosity
- high polarization
- high capability of final hadron separation

Beam Current: 90 μA
Max Pass energy: 2.2 GeV
Max Energy Hall A,B,C: 11 GeV

May 2013
Accelerator Commissioning starts
2013-2015
Pre-Ops (beam commissioning)
PAC approved experiments

• Complete program of TMDs studies for pions and kaons
• Kaon measurements crucial for a better understanding of the TMDs “kaon puzzle”
• Kaon SIDIS program requires an upgrade of the CLAS12 detector.
Summary

- ALU of $\pi^0$ in multidimensional bins.
- CLAS longitudinally polarized NH3 and ND3 target data provides superior sample of events allowing detailed studies of single and double spin asymmetries using multidimensional bins.

- Measurements of spin and azimuthal asymmetries with unpolarized, longitudinally polarized and transversely polarized targets in semi-inclusive processes at Hall-A/B:
  - Measure TMDs of partons in the valence region
  - Provide detailed info on partonic spin-orbit correlations
  - Study quark-gluon correlations (HT)
  - Study nuclear modification of 3D PDFs

- JLab12 will significantly increase the luminosity, kinematical coverage and particle identification capabilities of Hall-A/B

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