Hall A SIDIS

Jefferson Lab

Hall A/C collaboration Meeting
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Xuefei Yan
Duke University
E06-010 Collaboration
Hall A collaboration
The Incomplete Nucleon: Spin Puzzle

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma(\mu) + L_q(\mu) + J_g(\mu)
\]

[X. Ji, 1997]

Other spin sum rules
- Jaffe-Manohar 1990
- Chen et al. 2008
- Wakamatsu 2009, 2010


- DIS \rightarrow \Delta \Sigma \approx 0.30
- RHIC + DIS \rightarrow \Delta g \text{ not small}
- \rightarrow L_q

Orbital angular momentum of quarks and gluons is important

Understanding of spin-orbit correlations (atomic hydrogen, topological insulator…..)

How to access OAM?
Unified View of Nucleon Structure

\[ W_p^u(x, k_T, r_T) \] Wigner distributions

\[ d^2 r_T \]

TMD PDFs
\[ f_1^u(x, k_T), .. \]
\[ h_1^u(x, k_T) \]

\[ d^2 k_T \]

GPDs/IPDs

\[ d^2 r_T \]

3D imaging

\[ d^2 r_T \]

Form Factors
\[ G_E(Q^2), G_M(Q^2) \]

1D

5D Dist.

\[ f_1^u(x) \]
\[ h_1^u(x) \]
## Leading-Twist TMD PDFs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Unpolarized (U)</th>
<th>Longitudinally Polarized (L)</th>
<th>Transversely Polarized (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td></td>
<td>$g_1$</td>
<td>$h_{1\perp}$</td>
</tr>
<tr>
<td>L</td>
<td></td>
<td></td>
<td>$g_1$</td>
<td>$h_{1L\perp}$</td>
</tr>
<tr>
<td>T</td>
<td>$f_{1T\perp}$</td>
<td>$g_{1T}$</td>
<td>$h_1$</td>
<td>$h_{1T\perp}$</td>
</tr>
</tbody>
</table>

- **Quark Polarization**
  - **Unpolarized**: $f_1$
  - **Longitudinally Polarized**: $g_1$
  - **Transversely Polarized**: $h_{1\perp}$

- **Nucleon Spin**
  - **Quark Spin**

- **Helicity**
- **Long-Transversity**
- **Sivers**
- **Trans-Helicity**
- **Transversity**
- **Pretzelosity**

- **Boer-Mulders**
- **Long-Transversity**
- **Transversity**
- **Pretzelosity**
Transverse Spin Structure

- Longitudinal Spin structure function: $g_{1L}$
- Its transverse spin counter part (Transversity): $h_{1T}$

They are not the same due to relativity: rotation and boost do not commute

Probability for quark polarized in the nucleon spin direction

Q: how to probe it?

- Semi-inclusive deep inelastic scattering (SIDIS)
  - Measure the single spin asymmetry (SSA)
  - Transverse Momentum-dependent parton distributions (TMDs)

Transversity: Chiral-odd

- No mixing with gluon
- Simpler evolution effect

Not accessible via DIS process

Must couple to another chiral-odd function: e.g. Collins function
Access TMDs through Hard Processes

SIDIS

Drell-Yan

\[ f_{1T}^q (\text{SIDIS}) = -f_{1T}^q (\text{DY}) \]
\[ h_1^\perp (\text{SIDIS}) = -h_1^\perp (\text{DY}) \]

RHIC Transverse Spin Program
**E06-010: experimental configuration**

- **First** neutron data in SIDIS SSA&DSA
  - Similar $Q^2$ as HERMES experiment
  - Results on SIDIS unpolarized differential cross section

- Electron beam: $E = 5.9$ GeV
  - High luminosity $L \sim 10^{36}$ cm$^{-2}$s$^{-1}$
  - 40 cm transversely polarized $^3$He target
  - Average beam current 12 uA (max: 15 uA as in proposal)

- BigBite at $30^\circ$ as electron arm: $P_e = 0.6 \sim 2.5$ GeV/c
- HRSL at $16^\circ$ as hadron arm: $P_h = 2.35$ GeV/c
Separation of Collins, Sivers and pretzelosity effects through angular dependence

\[ A_{UT} (\varphi_h^l, \varphi_S^l) = \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \]

\[ = A_{UT}^{Collins} \sin(\phi_h + \phi_S) + A_{UT}^{Sivers} \sin(\phi_h - \phi_S) \]

\[ + A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_S) \]

\[ A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp \]

\[ A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1 \]

\[ A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp \]

SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)
Large angular coverage and precision measurement of asymmetries in 4-D phase space is essential.
Published results from E06-010

• SIDIS Single Spin Asymmetries (SSA)
  • X. Qian et al, Phys. Rev. Lett. 107, 072003 (2011): sizable $\pi^+$ Collins asymmetry at $x=0.34$ & negative $\pi^+$ Sivers asymmetries of neutrons
  • Y. Zhang et al. Phys. Rev. C 90, 055209 (2014): Pretzelosity asymmetries consistent with 0 (within experimental uncertainties)

• Inclusive Single Spin Asymmetries (SSA)
  • K. Allada, et al. Phys. Rev. C 89, 042201 (2014): SSA for $K^-$ & proton consistent with 0, SSA for $\pi^\pm$ has opposite sign from $^3\text{He}$ & neutron

• Double Spin Asymmetries (DSA)
  • J. Huang et al., Phys. Rev. Lett. 108, 052001 (2012): None-zero SIDIS $\pi^\pm A_{LT}^{\cos(\phi_h-\phi_s)}$ DSA of neutrons, in CQ model $\rightarrow$ non-zero quark OAM
  • Y. X. Zhao et al. Phys. Rev. C 92 015207 (2015): $\pi^\pm$, $K^\pm$ & Proton Inclusive $A_{LT}$
Results on Neutron

• Sizable Collins $\pi^+$ asymmetries at $x=0.34$?
  – Sign of violation of Soffer’s inequality?
  – Data are limited by stat. Needs more precise data!

• Negative Sivers $\pi^+$ Asymmetry
  – Consistent with HERMES/COMPASS
  – demonstration of negative d quark Sivers function.

Model (fitting) uncertainties shown in blue band.
Experimental systematic uncertainties: red band
Unpolarized differential cross section of Semi-Inclusive DIS

\[
\frac{d\sigma}{dx dy d\phi_S dz d\phi_h dP_{h\perp}^2} = \frac{\alpha^2}{xy Q^2} \frac{y^2}{2(1-\epsilon)} \cdot \{F_{UU} \}
\]

Twist-2: no \( \phi_h \) dependence

\[
+ \sqrt{2\epsilon(1-\epsilon)} \cos \phi_h \cdot F_{UU}^{\cos \phi_h} \\
+ \epsilon \cos(2\phi_h) \cdot F_{UU}^{\cos 2\phi_h} \\
\]

Boer-Mulders & twist-4 Cahn: \( \cos^2 \phi_h \) dependence

• Cahn effect \( \propto f_1 \otimes D_1 \)
  • Non-zero Cahn effect *solely require non-zero quark transverse momentum*
  • Related to quarks’ *intrinsic transverse momentum distribution*

• Boer-Mulders effect \( \propto h_1^\perp \otimes H_1^\perp \)
  • Boer-Mulders TMD PDF: transversely polarized quarks in unpolarized nucleon

• *Twist-4 Cahn effect* could have similar size of contribution to \( \langle \cos(2\phi_h) \rangle \) as Boer-Mulders [Phys. Rev. D. 81:114026 (2010) based on HERMES/COMPASS results]
Naïve x-z factorization & Gaussian ansatz

\[ F_{UU} = \sum_q e_q^2 x f_1(x) D_1(z) \exp \left( -\frac{P_t^2}{\langle P_T^2 \rangle} \right) \left/ \left[ \pi \langle P_T^2 \rangle \right] \right. \]

\[ F_{UU}^{\cos \phi_h} \big|_{\text{Cahn}} = -2 \frac{P_T}{Q} \sum_q e_q^2 x f_1(x) D_1(z) \exp \left( -\frac{P_t^2}{\langle P_T^2 \rangle} \right) \frac{z \langle k_\perp^2 \rangle}{\pi \langle P_T^2 \rangle^2} \]

\[ F_{UU}^{\cos^2 \phi_h} \big|_{\text{Cahn}} = 2 \frac{P_T^2}{Q^2} \sum_q e_q^2 x f_1(x) D_1(z) \exp \left( -\frac{P_t^2}{\langle P_T^2 \rangle} \right) \frac{z^2 \langle k_\perp^2 \rangle^2}{\pi \langle P_T^2 \rangle^3} \]

\[ \langle P_t^2 \rangle = \langle p_\perp^2 \rangle + z^2 \langle k_\perp^2 \rangle \]

Gaussian widths

\[ f_1(x, k_\perp) = f_1(x) \frac{e^{-k_\perp^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle} \]

TMD PDF with Gaussian ansatz

\[ D_1(z, k_\perp) = D_1(z) \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle} \]

TMD FF with Gaussian ansatz

Unpolarized differential cross section

• Combine data with different target and beam polarizations for unpolarized cross section analysis
  • Radiative correction for unpolarized process

• Detector models in simulation for description of experimental acceptance
  • Simulation vs. data in HRS and BigBite detector individually: inclusive DIS and elastic e-p processes

• Updated efficiency and contamination study with higher precision than SSA & DSA analysis (Sys. Uncertainty control)
Experimental acceptance & kinematic correlation
SIDIS differential cross section from data in 1D $\phi_h$ bins

- The $\cos \phi_h$-like behavior is due to kinematic correlation
- If use model to do bin center correction (BCC) here: big model dependence
- Solution: multi-dimensional binning & BCC in small range

$$\sigma^+ [\text{nb GeV}^2]$$

$e + ^3\text{He} \rightarrow e' + \pi^+ + X$
cosφₜ - like signal: x vs. φₜ and x dependence of cross section

φₜ farther away from π corresponds to larger x: lower cross section with/without modulation, look ~like cosφₜ
3D binning

• Pt (2 bins) vs. x (5 bins) vs. $\phi_h$ (10 bins)
• Approximately equal statistical uncertainty in bins

• SIDIS unpolarized differential cross section from data vs. models
3D binning results

- Naïve x-z factorization
- Gaussian ansatz
- Data in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins

Data: all kinematic ranges
- $\chi^2(\sigma_{\text{total}}) = 249$
- $\chi^2(\sigma_{\text{no mod}}) = 440$

Theory in comparison: $\langle k_{\perp}^2 \rangle = 0.14 \text{ GeV}^2$, $\langle p_{\perp}^2 \rangle = 0.42 \times z^{0.54} (1 - z)^{0.37} \text{ GeV}^2$
3D binning results

- **Theory**: best fit of data
- Naïve x-z factorization
- Gaussian ansatz
- Data in $P_t$ (2) vs. $x$ (5) vs. $\phi_h$ (10) bins

Data: all kinematic ranges
- $\chi^2(\sigma_{total})=128$
- $\chi^2(\sigma_{no\ mod})=128$

Theory in comparison: $\langle k_{\perp}^2 \rangle = 0.006$ GeV$^2$, $\langle p_{\perp}^2 \rangle = 0.214$ GeV$^2$
3D binning results

- Data in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Fit data with $f(\phi_h) = A(1 - B \cdot \cos\phi_h)$
- Limited data points provide loose constraints on A & B in each kinematic range
- Limited shape change due to cosine term in kinematic range
Constraint for SIDIS parameters with stand-alone data (E06-010)

• SIDIS cross section with modulation
  • Cahn effect $\propto \langle k^2 \rangle$ (Gaussian ansatz in convolution)
  • Preferable: large $\phi_h$ range in data for fitting Cahn effect $(\cos \phi_h$: sign change)

• SIDIS cross section without azimuthal modulation
  \[ F_{UU}^{\cos \phi_h} = 0 \text{ & } F_{UU}^{\cos 2\phi_h} = 0 \]
  • $\langle k^2 \rangle$ & $\langle p^2 \rangle$ only appear as one variable $\langle p^2 \rangle + z^2 \langle k^2 \rangle$
  • When $z$ in very small range (as in E06-010), data will not constrain both simultaneously with good quality
\( \delta \chi^2 \) contours: with modulation \((\pi^\pm)\)

- 200 data points SIDIS \(\pi^+\) (100) & \(\pi^-\) (100) production in Pt (2) vs. x (5) vs. \(\phi_h\) (10) bins
- Best fit: \(\langle k_\perp^2 \rangle = 0.006\) GeV\(^2\), \(\langle p_\perp^2 \rangle = 0.215\) GeV\(^2\)
  - Conservative systematic uncertainty estimation: minimal \(\chi^2 = 128\)
$\delta \chi^2$ contours: with modulation ($\pi^+$)

- $\delta \chi^2$ contours
- Best fit: solid cross

100 data points SIDIS $\pi^+$ (100) production in Pt (2) vs. $x$ (5) vs. $\phi_h$ (10) bins

Best fit: $\langle k_{\perp}^2 \rangle = 0.019$ GeV$^2$, $\langle p_{\perp}^2 \rangle = 0.215$ GeV$^2$

- Conservative systematic uncertainty estimation: minimal $\chi^2 = 60.6$
$\delta \chi^2$ contours: with modulation ($\pi^-$)

- 100 data points SIDIS $\pi^-$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Best fit: $\langle k_{\perp}^2 \rangle = -0.06$ GeV$^2$, $\langle p_{\perp}^2 \rangle = 0.215$ GeV$^2$
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 65.5$
$\delta \chi^2$ contours: no modulation ($\pi^+$)

- 100 data points SIDIS $\pi^+$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.163$ GeV$^2$, $\langle p_\perp^2 \rangle = 0.167$ GeV$^2$
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 60.5$
$\delta \chi^2$ contours: no modulation ($\pi^-$)

- 100 data points SIDIS $\pi^-$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Best fit: $\langle k_\perp^2 \rangle = -0.011$ GeV$^2$, $\langle p_\perp^2 \rangle = 0.218$ GeV$^2$
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 65.7$

- $\delta \chi^2$ contours
- Best fit: solid cross
Summary and outlook

• Published work on SSA & DSA from E06-010 (Transversity)

• Unpolarized SIDIS cross section extraction
  • 1st measurement using $^3$He target
  • Consistent with (naïve) x-z factorization
  • Constraints on different theoretical functional forms

• Future JLab programs: exploration → precision
SoLID-Spin: SIDIS on $^3$He/Proton @ 11 GeV

E12-10-006: Single Spin Asymmetry on Transverse $^3$He, rating A

E12-11-007: Single and Double Spin Asymmetries on $^3$He, rating A

E12-11-108: Single and Double Spin Asymmetries on Transverse Proton, rating A

Two run group experiments: DiHadron and Ay

Extraction from Experiments:
- Anselmino et al (2013, Table I)

Lattice QCD:
- Alexandrou et al (2014)
- Gockeler et al (2005)

SoLID Projection
Thank you!
Back up
HRS simulation vs. data

# of event

**Data**

**Simulation**

Inclusive DIS on H$_2$ target

Inclusive DIS on $^3$He target

$P_{e'}/$GeV

Vertex $z$/m

Data

Simulation

Inclusive DIS on H$_2$ target

Inclusive DIS on $^3$He target
BigBite simulation vs. data

# of event

Elastic e-p at 1.23 GeV beam

W/GeV

Elastic e-p at 2.4 GeV beam

W/GeV

Inclusive DIS on $^3$He target

$P_e'/\text{GeV}$

Inclusive DIS on $^3$He target

Vertex z /m
Data with efficiency/contamination correction in SIDIS channel

- **PID cut 1-3**: lower $\pi^-$ contamination & higher loss of $e'$ in BigBite
- Consistency: data under 3 different PID cuts, corrected by related contamination and efficiency, respectively

- SIDIS channel: $e + ^3\text{He} \rightarrow e' + \pi^+ + X$
  - $e'$ detected by BigBite
  - $\pi^+$ detected by HRS
Dominant systematic uncertainty: from BigBite

- Acceptance description: 2-7% (most bins), up to 10% (edge bins) with kinematics dependence
- Efficiency & contamination: 2 - 50% for $\pi^+$ channel, 2-30% for $\pi^-$

Relative systematic uncertainty

$$P_{e'} < 0.9 \text{ GeV range has large sys uncertainty}$$

- Trigger: shower threshold non-uniform drift during experiment; off-line cut & loss of efficiency description unprecise
- Photon-induced $e^-$ contamination: up to 40% & contain large uncertainty
- If NOT cut away low P range, unreasonably large uncertainty will go to multiple bins in other variables $x$, $z$, $Q^2$, etc.
Exclusive tail & radiative correction

• Exclusive channel cross section model: in SIMC from JLab \( \pi \) form factor experiments
  • H. P. Blok et al. PRC 78 045202 (2008): \( Q^2 \in (0.6, 2.45) \) GeV\(^2\), \( W=1.95 \) & 2.22 GeV
  • V. Tadevosyan et al. PRC 75 055205 (2007): \( Q^2 \in (0.6, 1.6) \) GeV\(^2\)
  • T. Horn et al. PRL 97 192001 (2006) \( Q^2 \in (1.6, 2.45) \) GeV\(^2\), \( W=2.22 \) GeV
  • \( Q^2 \in (1.3, 3.5) \) GeV\(^2\) in E06-010

• Determined exclusive tail proportion consistent with R. Asaturyan et al. Phys. Rev. C 85, 015202 (2012) in overlapping kinematics range (Hall C SIDIS results)

• Radiative correction based on HAPRAD: SIDIS model iterative tuning
3D binning results

- Naïve x-z factorization
- Gaussian ansatz
- Data in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins

Data: all kinematic ranges
- $\chi^2(\sigma_{total})=486$
- $\chi^2(\sigma_{no\ mod})=611$

Theory in comparison: $\langle k_{\perp}^2 \rangle = 0.037$ GeV$^2$, $\langle p_{\perp}^2 \rangle = 0.126 + 0.506z^2$ GeV$^2$
3D binning results

- Theory: cross section model in Anselmino, et al. JHEP 04 (2014) 005
- Naïve x-z factorization
- Gaussian ansatz
- Data in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins

Data: all kinematic ranges
- $\chi^2(\sigma_{\text{total}}) = 3780$
- $\chi^2(\sigma_{\text{no mod}}) = 632$

Theory in comparison: $\langle k^2 \rangle = 0.57$ GeV$^2$, $\langle p^2 \rangle = 0.12$ GeV$^2$
Constraints: with modulation

- 200 data points SIDIS $\pi^+$ (100) & $\pi^-$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Best fit: $\langle k_\perp^2 \rangle = 0.006 \text{ GeV}^2$, $\langle p_\perp^2 \rangle = 0.214 \text{ GeV}^2$
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 128$
  - If use stat uncertainty only: $\chi^2 > 700$
Constraints: no modulation

- Constant $\chi^2$ contours extends beyond $k_{\perp}^2=0.25$ GeV$^2$
- Best fit: solid triangle

- 200 data points SIDIS $\pi^+$ (100) & $\pi^-$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins
- Best fit: $\langle k_{\perp}^2 \rangle = 0.085$ GeV$^2$, $\langle p_{\perp}^2 \rangle = 0.190$ GeV$^2$
  - Conservative systematic uncertainty estimation: minimal $\chi^2 = 127$
  - If use stat uncertainty only: $\chi^2 > 700$
Comparison at low $\langle k_{\perp}^2 \rangle$

- Constant $\chi^2$ contours

- 200 data points SIDIS $\pi^+$ (100) & $\pi^-$ (100) production in Pt (2) vs. x (5) vs. $\phi_h$ (10) bins