Studies of Nucleon Transverse Spin and TMDs at JLab

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- Introduction
- Transverse Spin (Transversity) and Tensor Charge
- TMDs and Orbital Angular Momentum: Worm-Gear, Pretzelosity, Sivers
- Single Spin Asymmetries from Inclusive Reactions
  - Inclusive hadron productions
  - Inclusive electron: 2-photon exchange to probe nucleon
- TMD Study with JLab12: SoLID Program and CLAS12
- Summary
Introduction

Transverse Spin and TMDs

$x=0.1$
# Leading-Twist TMD PDFs

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

- **Nucleon Spin**
- **Quark Spin**
Access TMDs through Hard Processes

SIDIS

Drell-Yan

\[ f_{1T}^{+q} (\text{SIDIS}) = - f_{1T}^{+q} (\text{DY}) \]
SIDIS: Separation of Collins, Sivers and pretzelosity Asymmetries through Angular Dependence

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

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

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

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

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

$h_1$ - Transversity

and Tensor Charge
Also Sivers
and other TMDs.

Z. Kang, et al.
Jefferson Lab at a Glance (12 GeV now!)

- **CEBAF**
  - High-intensity electron accelerator based on **CW SRF** technology
  - $I_{\text{max}} = 200 \mu$A
  - $\text{Pol}_{\text{max}} = 90\%$
  - $E_{\text{max}} = 6 \text{ GeV}: 1995\text{-}2012$
  - Energy Upgrading to 12 GeV (2012\text{-}now)
  - 12 GeV data taking started

- ~**1400** Active Users
- Produces ~**1/3** of US PhDs in Nuclear Physics
JLab 6 GeV Experiment E06-010

Spokespersons: J. P. Chen, E. Cisbani, H. Gao, X. Jiang and J. C. Peng

7 PhD Thesis Students (graduated) + 2 new students

• First measurement on n (³He)
• Transversely Polarized ³He Target
• Polarized Electron Beam, 5.9 GeV

• Results published in 7 PRL/PRC papers:
  ✓ π⁺- pretzelosity asymmetries: PRC 90 5, 055209(2014)
  ✓ K⁺- Collins/Sivers asymmetries: PRC 90 5, 05520 (2014)
  ✓ Inclusive hadron SSA: PRC 89, 042201 (2014)
  ✓ Inclusive electron SSA: PRL 113, 022502 (2014)
  ✓ Inclusive hadron DSA: PRC 92, 015207 (2015)

³He(\bar{e}, e'\pi^{±})X
³He(\bar{e}, e'K^{±})X
$^3\text{He} \ (n) \ \text{Target Single-Spin Asymmetry in SIDIS}$

JLab E06-010 collaboration, X. Qian at al., PRL 107:072003(2011)

$n^+(e,e'\ h), h = \pi^+ , \pi^-$

neutron Collins SSA small
Non-zero at highest $x$ for $\pi^+$

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties
Precision Study of TMDs: JLab 12 GeV, EIC

- Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
- From exploration to precision study
  - JLab12: valence region; EIC: sea and gluons
- Transversity: fundamental *PDFs*, tensor charge
- *TMDs*: 3-d momentum structure of the nucleon
  - information on quark orbital angular momentum
  - information on QCD dynamics
- Multi-dimensional mapping of *TMDs*
- Precision → high statistics
  - high luminosity and large acceptance
Overview of SoLID
Solenoidal Large Intensity Device

• Full exploitation of JLab 12 GeV Upgrade
  → A Large Acceptance Detector AND Can Handle High Luminosity \(10^{37}-10^{39}\)
  Take advantage of latest development in detectors, data acquisitions and simulations
  Reach ultimate precision for SIDIS (TMDs), PVDIS in high-\(x\) region and threshold \(J/\psi\)

• 5 highly rated experiments approved
  Three SIDIS experiments, one PVDIS, one \(J/\psi\) production (+ 3 run group experiments)

• Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)
  Significant international contributions (Chinese collaboration)
Transversity and Tensor Charge

- Collins Asymmetries \( \sim \) Transversity (x) Collin Function
- Transversity: chiral-odd, not couple to gluons, valence behavior, largely unknown
- Tensor charge (0th moment of transversity): fundamental property
  - Lattice QCD, Bound-State QCD (Dyson-Schwinger), Light-cone Quark Models, ...
- SoLID with trans polarized n \& p \( \rightarrow \) determination of tensor charges for d \& u
- Inputs to other physics: ex. EDM \( \tilde{d}_n = \tilde{d}_u \delta_T d + \tilde{d}_d \delta_T u. \)

Collins Asymmetries

\[ P_T \text{ vs. } x \text{ for one } (Q^2, z) \text{ bin} \]

Total > 1400 data points

Tensor Charges

- SoLID projections
- Extractions from existing data
- LQCD
- DSE
- Models

- Projections with a model
- There are un-measured regions
- QCD evolutions being worked

\( \delta u \)

\( \delta d \)
TMDs and Orbital Angular Momentum

Worm-Gear, Pretzelosity, Sivers
TMDs: Access Quark Orbital Angular Momentum

- TMDs: Correlations of transverse motion with quark spin and orbital motion
- Without OAM, off-diagonal TMDs=0,
  no direct model-independent relation to the OAM in spin sum rule yet
- Sivers Function: QCD lensing effects
- In a large class of models, such as light-cone quark models
  Pretzelosity: $\Delta L=2$ ($L=0$ and $L=2$ interference, $L=1$ and $-1$ interference)
  Worm-Gear: $\Delta L=1$ ($L=0$ and $L=1$ interference)
- SoLID with trans polarized n/p $\rightarrow$ quantitative knowledge of OAM

SoLID Projections Pretzelosity
Pretzelosity Results on Neutron
(from E06-010)

Y. Zhang, et al., PRC 90 5, 055209(2014)

Extracted Pretzelosity Asymmetries

In models, directly related to OAM, L=0 and L=2 interference
Asymmetry $A_{LT}$ Result from E06-010

J. Huang et al., PRL. 108, 052001 (2012).

To leading twist:

$$A_{LT}^{\cos(\phi_h - \phi_s)} \propto F_{LT}^{\cos(\phi_h - \phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

Dominated by $L=0$ (S) and $L=1$ (P) interference

- neutron $A_{LT}$: Positive for $\pi^-$
- Consist w/ model in signs, suggest larger asymmetry

Worm-Gear
Trans helicity

<table>
<thead>
<tr>
<th>N^q</th>
<th>U</th>
<th>L</th>
<th>T</th>
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<tr>
<td>U</td>
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Neutron $A_{LT}^{\cos(\phi_h - \phi_s)}$}

- $\pi^+$
- $\pi^-$

- WW-Type (Prokudin)
- WW-Type (Parsamyan)
- LCQM (Pasaolini)
Worm-gear Functions

**SoLID Projections**

- Dominated by real part of interference between \( L=0 \) (S) and \( L=1 \) (P) states
- No GPD correspondence
- Exploratory lattice QCD calculation: Ph. Hägler et al, EPL 88, 61001 (2009)

\[ g_{1T} = \]
\[ h_{1L}^\perp = \]

**SoLID Neutron Projections**

\[ A_{LT} \sim g_{1T}(x)D_1(z) \]

\[ A_{UL} \sim h_{1L}^\perp(x) \otimes H_{1L}^\perp(z) \]
Single Spin Asymmetries in Inclusive Reactions

Inclusive Hadron Productions
Single Electron : 2-photon Exchange
Inclusive Hadron Electroproduction

\[ \text{e} + \text{N} \uparrow \rightarrow \text{h} + \text{X} \quad (\text{h} = \pi, \text{K}, \text{p}) \]

Why a non-zero \( A_N \) is interesting?

- Analogues to \( A_N \) in \( pp \uparrow \rightarrow hX \) collision
- Simpler than \( pp \uparrow \rightarrow hX \) due to only one quark channel
- Transverse spin effects related SIDIS and \( p-p \) collisions (Sivers, Collins, twist-3)
- Test TMD formalism (at large \( p_T \sim 1 \text{ GeV} \) or more)
E06-010: Inclusive Hadron SSA ($A_N$)

K. Allda et al., PRC 89, 042201 (2014)

- Clear non-zero target SSA
- Opposite sign for $\pi^+$ and $\pi^-$
- Large for $K^+$
- Results consistent with predictions based on Sivers mechanism (valid at high $p_T$)

$$\vec{S}_N \cdot (\vec{l} \times \vec{P}_h) \neq 0$$

$$A_{UT}^{\sin(\varphi_S)}(\varphi_S = 90^0)$$
Inclusive Single Normal Target Spin Asymmetry

\[ A_y(Q^2) = \frac{O^\uparrow - O^\downarrow}{O^\uparrow + O^\downarrow} \]

- Unpolarized e\(^-\) beam incident on \(^3\)He target polarized normal to the electron scattering plane.

- However, \(A_y=0\) at Born level, sensitive to physics at order \(\alpha^2\); two-photon exchange.

\[ A_y \propto \frac{Im(T_{1\gamma}T_{2\gamma}^*)}{|T|^2} \]

- In DIS case: related to integral of Sivers
- Physics Importance discussed in A. Metz’s paper
First Observation of a Non-Zero Target-Normal Single-Spin Asymmetry

*Jefferson Lab E07-013, Hall A, Polarized $^3\text{He}$ Collaboration,*


- Un-polarized electrons, transversely polarized target, inclusive DIS reaction $^3\text{He}(e,e')X$
- **No Born contribution** due to time-reversal invariance
- Direct access to nucleon dynamics through two-photon processes
- Parton model predictions $A_y^n \approx 10^{-2}$ to $10^{-4}$, **sign not known**
- Predictions have opposite signs using input from SIDIS vs. hadron-hadron collisions

- First measurement of target single-spin asymmetry for neutrons
- First non-zero measurement ($3\sigma$) of target single-spin asymmetry
- Consistent with model using SIDIS Sivers input
- Result: $A_y^n = (-1.09 \pm 0.38) \times 10^{-2}$ ($W > 2$ GeV)
Inclusive Target Normal Single Spin Asymmetry

SoLID Projections

Figure: Expected statistical uncertainties in $A_y(Q^2)$ vs. $Q^2$ for the $^3$He target. Left one is for 11 GeV. Right one is for 8.8 GeV. Arbitrarily choose $A_y = 0.01$. Expected statistical uncertainty: $dA_y \ll 10^{-4}$. 

-0.0095

-0.0096

-0.0097

-0.0098

-0.0099

-0.01

-0.0101

-0.0102

-0.0103

-0.0104

-0.0105

$Q^2$ (GeV$^2$)

$A_y(Q^2)$
The last experiment was in 1970, set an upper limit of 1~2%. T. Powell et al, PRL 753, 24 (1970).

• **First observation of a non-zero target single-spin asymmetry in this reaction**

  Co-Speakers: T. Averett (W&M), J.-P. Chen (JLab) and X. Jiang (LANL).

• Non-zero $A_y$ has never been measured.
• New observable for nucleon structure, provides access to the moments of nucleon’s Generalized-Parton-Distributions (GPDs).

\[ A_y \propto (\vec{e} \times \vec{e}') \cdot \vec{S}_N \]

\[ A_y \equiv 0 \text{ under } 1\gamma \text{ exchange} \]
\[ A_y \neq 0 \text{ with } 1\gamma \otimes 2\gamma \text{ interference} \]
More on Planned TMD Studies with JLab 12

Multi-Hall Program, SoLID
JLab 12: Multi-Halls TMD Program

**Hall A/SOLID**
High Lumi and acceptance – 4D

**Hall A/SBS**
High x - $Q^2$, 2-3D

**Hall B/CLAS12**
General survey, medium luminosity

**Hall C/SHMS**
L-T studies, precise $\pi^+ / \pi^-$ ratios

$^3$He, NH$_3$

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$H_2/D_2$, NH$_3$/ND$_3$, HD
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

Key of SoLID-Spin program:
- Large Acceptance
- High Luminosity
- 4-D mapping of asymmetries
- Tensor charge, TMDs …
- Lattice QCD, QCD Dynamics, Models.
Projected Sivers Function

Expected improvement of Sivers function (A. Prokudin)

Valence quark region has not been accessed at all so far
Measure Transversity via Dihadron with SoLID

- Precision dihadron ($\pi^+/$$\pi^-$) production on a transversely polarized $^3$He (n)
- Extract transversity on neutron
- Provide crucial inputs for flavor separation of transversity

Wide $x_b$ and $Q^2$ coverages

Projected Statistics error for one ($M_{\pi\pi}z_{\pi\pi}$) bin, integrated over all $y$ and $Q^2$. 
SoLID Timeline and Status

- 2010-2012 Five SoLID experiments approved by PAC with high rating
  3 SIDIS with polarized $^{3}\text{He}/p$ target, 1 PVDIS, 1 threshold $J/\psi$
- 2014-2015: three run-group proposals approved: Dihadron, Ay, TCS; LOI DDVCS
- 2013: CLEO-II magnet formally requested and agreed
- 2014: Site visits, plan transportation to JLab (now-2017)

2010-2014: Progress
- Spectrometer magnet, modifications
- Detailed simulations
- Detector pre-R&D
- DAQ

✓ 2014: pre-CDR submitted
✓ 2015: Director’s Review

Next:
- Pre-R&D, full simulation, pCDR $\rightarrow$ TDR
- MIE proposal
- DOE Science Review: soon
- Construction: starting 2018?
- Experiment starting: 2022?
CLAS12 $A_{UT}$ with transverse proton target

Stat. error for a 4D analysis of the $\pi^+$ Sivers asymmetry on proton ($\times$1.5 on D) target

Summary

- Transverse Spin, Tensor Charge
- TMDs and Access Quark OAM
- Single Spin Asymmetries in Inclusive Reactions
- Highlights of JLab 6 GeV Results with Polarized neutron/3He
- TMD @ JLab 12 GeV: SoLID Program, CLAS12 and …

  Precision Multi-dimensional Mapping

→ Understanding nucleon spin, 3-d structure, QCD dynamics and more
Extra: Other SoLID Programs
Parity Violation with SoLID

Qweak and SoLID will expand sensitivity that will match high luminosity LHC reach with complementary chiral and flavor combinations

SoLID ~ 10 times improvement over 6 GeV result

Current World Fit

JLab 6-GeV PVDIS results
Wang et al., Nature 506, 7486, 67 (2014)

6 GeV PVDIS

• High Luminosity on LD2 and LH2
• Better than 1% errors for small bins over large range kinematics
• Test of Standard Model
• Quark structure:
  - charge symmetry violation
  - quark-gluon correlations
  - d/u at large-x

SoLID projection

[2 g^u - g^d]_{AV}

[2 g^u - g^d]_{VA}

PVES + APV
SLAC-E122
JLab-Hall A
all published
SM
SoLID (proposal)
Threshold $J/\Psi$ production, probing strong color field in the nucleon, QCD trace anomaly (important to proton mass budget)

$e\, p \rightarrow e'\, p'\, J/\psi(e^-\, e^+)$

$\gamma\, p \rightarrow p'\, J/\psi(e^-\, e^+)$

Imaginary part: related to the total cross section through optical theorem

Real part: contains the conformal (trace) anomaly

Lumi $1.2 \times 10^{37}$/cm$^2$/s 50 Days