Experimental TMD Program at JLab
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3-D Modeling Workshop @ JLab, March, 2017

- Introduction
- TMDs: 3-D Structure of the Nucleon in Momentum Space
  - Spin-Flavor, Orbital Angular Momentum
  - Transeversity and Tensor Charge
  - Sivers, Worm-Gear, Pretzelosity
- JLab Multi-Hall Program
  - Hall C: Cross Sections, L/T separation, $P_T$ study
  - Hall B: Medium luminosity/large acceptance, general survey,
  - Hall A/SBS: pi and Kaon, large $x/Q_2$
  - Hall A/SoLID: High luminosity/large acceptance with polarized n/p
    Precision 4-d mapping of TMD asymmetries
- Summary

Thanks to my colleagues for help with slides: H. Avagyan, M. Cantalbrigo, E. Cisbani, R. Ent, H. Gao, D. Gaskell, T. Liu, A. Prokudin, A. Puckett, …
Introduction

TMDs: Transverse Structure of Nucleon in Momentum Space

![Graph of TMDs for u and d quarks at x=0.1](image-url)
Wigner distributions (Belitsky, Ji, Yuan)

5D

\[ W(x, b_T, k_T) \]
Wigner Distributions

\[ \int d^2 b_T \]
transverse momentum distributions (TMDs)
semi-inclusive processes

\[ \int d^2 k_T \]
impact parameter distributions

3D

\[ f(x, k_T) \]
Fourier trf.
\[ b_T \leftrightarrow \Delta \]

\[ f(x, b_T) \]
generalized parton distributions (GPDs)
exclusive processes

\[ t = -\Delta^2 \]

\[ \xi = 0 \]

1D

\[ \int d^2 k_T \]
parton densities
inclusive and semi-inclusive processes

\[ \int d^2 b_T \]
form factors
elastic scattering

\[ \int dx \]
generalized form factors
lattice calculations

\[ \int dxx^{n-1} \]

(X. Ji, D. Mueller, A. Radyushkin)
### Leading-Twist TMD PDFs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Leading-Twist TMD PDFs</th>
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<tbody>
<tr>
<td></td>
<td>Unpolarized (U)</td>
<td>Longitudinally Polarized (L)</td>
</tr>
<tr>
<td>U</td>
<td>$f_1$</td>
<td>$g_1$</td>
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<tr>
<td>L</td>
<td></td>
<td>$h_1^L\perp$</td>
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<tr>
<td>T</td>
<td>$f_{1T}^\perp$</td>
<td>$g_{1T}$</td>
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- **Boer-Mulders**: $h_1^\perp$
- **Long-Transversity**: $h_1^L\perp$
- **Transversity**: $h_{1T}^\perp$
- **Sivers**: $f_{1T}^\perp$
- **Trans-Helicity**: $g_{1T}$
- **Helicity**: $g_1$
TMDs

8 functions in total (at leading Twist)

Each represents different aspects of partonic structure

Each function is to be studied

<table>
<thead>
<tr>
<th>N</th>
<th>q</th>
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<th>T</th>
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<td>$g_1$</td>
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<td>$h_1$ $h_{1T}$</td>
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Alexei Prokudin
Access TMDs through Hard Processes

**SIDIS**

- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

**Drell-Yan**

\[ f_{1T}^{\perp q} (\text{SIDIS}) = - f_{1T}^{\perp q} (\text{DY}) \]
Tool: Semi-inclusive DIS (SIDIS)

- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics
Explore TMD with JLab 6 GeV

- Demonstrate Feasibility
- Initial study on $P_T$ spin-flavor dependence
- First measurements with transversely polarized $^3\text{He}$ (neutron)
Is JLab Energy High Enough?

- To extract TMDs from SIDIS, more demanding in energy than in DIS
- Is JLab 12 GeV and/or 6 GeV energy high enough?

**Hall C E00-108 Exp.**

\[ e + \text{LH}_2/\text{LD}_2 \rightarrow e' + \pi^+ / \pi^- + X \]

**Ebeam = 5.5 GeV**

Low Energy SIDIS xsec reproduced by calculation using high energy parameters and PDF

T. Navasardyan et al. PRL 98, 022001 (2007)

R. Asaturyan et al. PRL 85, 015202 (2012)
From Form Factors to Transverse Densities

Unpolarized Transverse Densities

Flavor-dependence in form factors can be translated into flavor-dependence of transverse densities
Unpolarized TMD: Flavor $P_T$ Dependence?

Flavor in transverse-momentum space

Is the up distribution wider or narrower than the down?
And the sea?
How wide are the distributions?

A. Bacchetta, Seminar @ JLab, JHEP 1311 (2013) 194
Flavor $P_T$ Dependence from Theory

- Chiral quark-soliton model (Schweitzer, Strikman, Weiss, JHEP, 1301 (2013)) → sea wider tail than valanee

Indications from lattice QCD

Pioneering lattice QCD studies hint at a down distribution being wider than up

- Fragmentation model, Matevosyan, Bentz, Cloet, Thomas, PRD85 (2012) → unfavored pion and Kaon wider than favored pion
Hall C Results: Flavor $P_T$ Dependence

First indications from experiments

Asaturyan et al., E00-108, Hall C, PRC85 (2012)

Conclusion: up is wider than down and favored wider than unfavored
pi+ and pi- production on He3

X. Yan et al., Hall A Collaboration, arXiv:1610.02350, Accepted by PRC
average quark transverse momentum distribution squared
vs. average quark transverse momentum in fragmentation squared

with modulation

no modulation

Hall A Results: Transverse Momentum dependence
CLAS data suggests that width of $g_1$ is less than the width of $f_1$. 

$$A_1(P_T) \propto \frac{\sum_q e_q^2 g_1^q(x) D_1^q \rightarrow \pi(z)}{\sum_q e_q^2 f_1^q(x) D_1^q \rightarrow \pi(z)}$$

$$A_1(x, z, P_T) = A_1(x, z) \frac{\langle P_T^{2, unp} \rangle}{\langle P_T^{2, pol} \rangle} \exp(-P_T^2/\langle P_T^{2, pol} \rangle - P_T^2/\langle P_T^{2, unp} \rangle)$$

$$\mu_2^2/\mu_0^2 = 0.692 \pm 0.039 \pm 0.045$$
Planned Precision TMD Studies with JLab 12

Multi-Hall Program, SoLID
Precision Study of TMDs: JLab 12 GeV

• Explorations: HERMES, COMPASS, RHIC-spin, JLab6,…
• From exploration to precision study
  JLab12: valence region
  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/or large acceptance
JLab 12: Multi-Halls TMD Program

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

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

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

- $^3\text{He, NH}_3$
- $\text{H}_2/\text{D}_2$, $\text{NH}_3/\text{ND}_3$, HD
- $\text{H}_2\text{D}_2$

*Images of experimental setups for each hall.*
The Multi-Hall SIDIS Program at 12 GeV


The complete mapping of the multi-dimensional SIDIS phase space will allow a comprehensive study of the TMDs and the transition to the perturbative regime.

Flavor separation will be possible by the use of different target nucleons and the detection of final state hadrons.

Measurements with pions and kaons in the final state will also provide important information on the hadronization mechanism in general and on the role of spin-orbit correlations in the fragmentation in particular.

Higher-twist effects will be present in both TMDs and fragmentation processes due to the still relatively low $Q^2$ range accessible at JLab, and can apart from contributing to leading-twist observables also lead to observable asymmetries vanishing at leading twist. These are worth studying in themselves and provide important information on quark-gluon correlations.
Cross section measurements with magnetic focusing spectrometers (HMS/SHMS) will play important role in JLab SIDIS program

→ Demonstrate understanding of reaction mechanism, test factorization
→ Able to carry out precise comparisons of charge states, $\pi^+/\pi^-$

at small $P_T$, access to large

SHMS/HMS will allow precise L-T separations
→ Does $R_{DIS} = R_{SIDIS}$?

Measure $P_T$ dependence to access $k_T$ depedence of parton distributions
Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

**E12-13-007**

Neutral pions:
- Scan in \((x, z, P_T)\)
- Overlap with E12-09-017 & E12-09-002

Parasitic with E12-13-010

**E00-10**
- 8 (6 GeV)

**E12-06-104**
- L/T scan in \((z, P_T)\)
- No scan in \(Q^2\) at fixed \(x\): \(R_{DIS}(Q^2)\) known

**E12-09-017**
- Scan in \((x, z, P_T)\)
- + scan in \(Q^2\) at fixed \(x\)

**E12-09-002**
- + scans in \(z\)

Courtesy R. Ent
CLAS12: Evolution and \( k_T \)-dependence of TMDs

- Large acceptance of CLAS12 allows studies of \( P_T \) and \( Q^2 \)-dependence of SSAs in a wide kinematic range

- Comparison of JLab12 data with HERMES, COMPASS (and EIC) will pin down transverse momentum dependence and the non-trivial \( Q^2 \) evolution of TMD PDFs in general, and Sivers function in particular.
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)
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.
Collins Asymmetry: Transversity

Transverse Spin, Tensor Charge
JLab6: $^3$He (n) Target Single-Spin Asymmetry in SIDIS

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

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

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

Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties
Accessing transversity in dihadron production at JLab

Measurements with polarized protons

Measurements with polarized neutrons

SoLID
Transversity from SoLID

- Collins Asymmetries ~ Transversity (x) Collin Function
- Transversity: chiral-odd, not couple to gluons, valence behavior, largely unknown
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with trans polarized n & p → Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, …) on impact study

Collins Asymmetries

*PT vs. x for one \(Q^2, z\) bin
Total > 1400 data points

Z. Ye et al., PLB 767, 91 (2017)
Tensor Charge from SoLID

- Tensor charge (0th moment of transversity): fundamental property
  Lattice QCD, Bound-State QCD (Dyson-Schwinger), ...
- SoLID with trans polarized n & p → determination of tensor charge

![Graph showing tensor charges with data points from various sources.]

**Tensor Charges**
Tensor Charge and Neutron EDM

Tensor charge and EDM

\[ d_n = \delta_T u/d_u + \delta_T d/d_d + \delta_T s/d_s \]

[Graph showing the relationship between \( d_u/10^{-25}\text{e cm} \) and \( d_d/10^{-25}\text{e cm} \).]

Current neutron EDM limit: \(|d_n| < 2.9 \times 10^{-26}\text{ e \cdot cm}\)
Sivers Function

3-D Imaging, QCD dynamics
Access to 3D imaging

\[ f(x, k_T, S) = f_1(x, k_T^2) - \frac{[k_T \times \hat{P} \cdot S_T]}{M} f_{1T}^\perp(x, k_T^2) \]

Sivers function from experimental data HERMES and COMPASS

Anselmino et al 2005

Dipole deformation

Alexei Prokudin
JLab6: $^3$He (n) Target Single-Spin Asymmetry in SIDIS

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

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

neutron Collins SSA small
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Blue band: model (fitting) uncertainties
Red band: other systematic uncertainties
Hall A SBS Projection: pi/K Sivers

11 GeV SIDIS: Expected Effects

Squeeze model uncertainty corridor

Prokudin model fit

E12-09-018
Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries $\sim$ Sivers Function $(x, k_T, Q^2)$ $(x)$
- Fragmentation Function $(z, p_T, Q^2)$
- Leading-twist/not $Q$ power suppressed: Gauge Link/ QCD Final State Interaction
- Transverse Imaging
- QCD evolutions
- SoLID: precision multi-d mapping
- Collaborating with theory group: impact study

**Sivers Asymmetries**

$P_T$ vs. $x$ for one $(Q^2, z)$ bin
Total $> 1400$ data points

Liu, Sato, Prokudin,…
What do we learn from 3D distributions?

\[ f(x, k_T, S_T) = f_1(x, k_T^2) - f_{1T}(x, k_T^2) \frac{k_T}{M} \]

The slice is at:
\[ x = 0.1 \]

Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

Picture is still quite uncertain
What do we learn from 3D distributions?

\[ f(x, k_T, S_T) = f_1(x, k_T^2) - f_{1T}(x, k_T^2) \frac{k_{T1}}{M} \]

The slice is at:
\[ x = 0.1 \]

Low-x and high-x region is uncertain
JLab 12 and EIC will contribute

No information on sea quarks

In future we will obtain much clearer picture
Nuclear Effect in $^3\text{He}$ for neutron TMD Study

- Effective polarization
- PWIA
- FSI through distorted spectral function


Preliminary results for Collins and Sivers Asymmetries

- The effective polarizations $p_{p(n)}$ differs by 15-20%, but they have to be considered in combination with the dilution factor and the products in the asymmetries extraction change very little.
- Therefore, the extraction procedure seems to be safe.
- The extraction procedure can be carefully tested in MC simulating the phase space of the JLab $^3\text{He}$ target dedicated experiments.

Ref:
TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$), Sivers: Related to GPD E through Lensing Function
Nucleon spin \( \frac{1}{2} = \frac{1}{2} \Delta \Sigma + L_q + J_g \)
\[ = \frac{1}{2} \Delta \Sigma + L_q + \Delta G + L_g \]

Ji (gauge invariant)
Jeffe-Manohar (light-cone)

- Spin Puzzle: missing piece, orbital angular momentum (OAM)
- Indirect evidence \( \rightarrow \) OAM is significant
- Lattice Calculation: \( u \) and \( d \) cancellation?
- Ji’s sum rule:
  \[ J_{q,g} = \frac{1}{2} \int dxx (H_{q,g}(x, 0, 0) + E_{q,g}(x, 0, 0)) \]

measure GPDs to access the total angular momentum
needs GPD \( E \) (and \( H \)) be measured in all \( x \) at fixed \( \xi \)
DVCS only access GPDs @ \( x=\xi \) ridge
experimentally difficult to measure GDPs at all \( x \) with fixed \( \xi \), if not impossible
DDVCS?
OAM and Parton Distributions

- How best to access/measure quark orbital angular momentum? Extensively discussed in the last decade or so. X. Ji, et al., arXiv:1202.2843; 1207.5221
  “Thus a partonic picture of the orbital contribution to the nucleon helicity necessarily involves parton’s transverse momentum. In other words, TMD parton distributions are the right objects for physical measurements and interpretation.”

- Transversely polarized nucleon:
  \[ J_q = \frac{1}{2} \sum_i \int dxx [q_i(x) + E_i(x, 0, 0)] \]

- Longitudinally polarized nucleon: related to Twist-3 GPDs (more difficult?)

- Intuitive definition: \( L = r \times p \) → can be defined in Wigner Distributions
  \[ L(x) = \int (\vec{b}_\perp \times \vec{k}_\perp) W(x, \vec{b}_\perp, \vec{k}_\perp) d^2\vec{b}_\perp d^2\vec{k}_\perp \]
  access through both TMDs and GPDs
  possible direct measurement of Wigner distributions? J. Qiu, S. Liuti

- Parton spin-orbital correlations → transverse momentum
  TMDs provide direct information

- TMD information related to \( L_q \) and /or \( \mathcal{L}_q \)?
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
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

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SoLID Projections
Pretzelosity
SoLID Impact on Pretzelosity

$Q^2 = 2.41 \text{GeV}^2$

C. Lefky et al., PR D 91, 034010 (2015).

SoLID transversely polarized $^3$He, E12-10-006.

95% C.L.

by Tianbo Liu (Duke & DKU)
Angular Momentum (1)

OAM and pretzelosity:

model dependent

\[ L_z = -\int dxd^2 k_\perp \frac{k_\perp^2}{2M_p^2} h_{1T}^T(x, k_\perp^2) \]

J. She et al., PR D 79, 058008 (2009).

SoLID impact:

Lefky et al. (2015)

SoLID
6 GeV Exploration: Asymmetry $A_{LT}$ Results

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

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Worm-Gear Dominated by $L=0$ (S) and $L=1$ (P) interference
**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)

\[
\begin{align*}
A_{LT} & \sim g_{1T}(x)D_1(z) \\
A_{UL} & \sim h_{1L}(x) \otimes H^\perp_1(z)
\end{align*}
\]
Angular Momentum (2)

Sivers and GPD $E$: model dependent

$$f_{1T}^{(0)}(x, Q_0^2) = -L(x) E(x, 0, 0, Q_0^2)$$

$$L(x) = \frac{K}{(1-x)\eta}$$

lensing function

K and $\eta$ are fixed by anomalous magnetic moments $\kappa^p$ and $\kappa^n$.

$$J = \frac{1}{2} \int dxdx [H(x, 0, 0) + E(x, 0, 0)]$$

A. Bacchetta et al., PR L 107, 212001 (2011).

SoLID:
Summary

• TMDs:
  - transverse imaging
  - transverse spin, tensor charge
  - QCD dynamics
  - access quark orbital angular momentum

• JLab-TMD Program
  - Multi-Hall to study TMDs from all directions
  - Precision multi-dimensional mapping in the valence region

EIC will continue the study for sea quarks and gluons

→ Understanding nucleon 3-d structure, study QCD dynamics, quark orbital angular momentum and more