SIDIS Program at JLab Hall A and C
Jian-ping Chen, Jefferson Lab, Virginia, USA
FF2019 Workshop @ Duke, March 14-16, 2019

- Introduction: SIDIS - Convolution of PDFs and Fragmentation Functions
- Results from JLab 6 GeV Experiments and 12 GeV Program
- Multi-Hall SIDIS Program
  - Hall C: high luminosity/small acceptance
cross sections, L/T separation, P_T study
  - Hall B: medium luminosity/large acceptance, polarized p
  - Hall A/SBS: high luminosity/medium acceptance, polarized n
  - 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: Transversity/Hall A and SoLID collaborators and D. Gaskell, R. Ent for Hall C slides, A. Puckett … for SBS slide
Introduction: SIDIS

1-d: Spin-Flavor Structure and Fragmentation Functions

3-d: TMDs: Transverse Momentum Dependent PDFs and Transverse Momentum Dependent Fragmentation Functions

$x=0.1$
Tool: Semi-inclusive DIS (SIDIS)

- Flavor tagging for spin-flavor study
- Gold mine for TMDs
- Access all eight leading-twist TMDs through spin-comb. & azimuthal-modulations
- Tagging quark flavor/kinematics
1-d: Spin Flavor Structure

- SIDIS for flavor tagging: \( (P_T \text{ integrated}) \)
  1. unpolarized: E00-108, E12-06-104, E12-09-002, E12-09-011, E12-09-017, E12-13-007 @ Hall C
     L/T separations for both pions and Kaons, study factorization
  2. polarized lepton on longitudinally polarized nucleon
     HERMES/COMPASS/JLab6
     JLab12: e-p (E12-06-109 @ Hall B)
     e-n \((^3\text{He})\) (PR12-09-013, PR12-14-008, E12-11-007 @ Hall A)
     tagging \(\pi^+, \pi^-, K^+, K^-\)
     8 observables + 2 from inclusive channels
     LO: \( \rightarrow 6 \) polarized light quark PDFs + 4 fragmentation functions
     NLO: some combinations might help to work at NLO level
     in general: global fits (combining with e+e- and pp, …)

- Issues:
  1. experimentally only finite PT range covered
  2. in current fragmentation region? more significant for Kaons: Kaon FF?
# 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>
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<td>$g_1$</td>
<td>$h_{1\perp}$</td>
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<td>L</td>
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<td>$g_1$</td>
<td>$h_{1L\perp}$</td>
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<td>$g_{1T}$</td>
<td></td>
<td>$h_{1\perp}$</td>
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</table>

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

- **Boer-Mulders**
- **Long-Transversity**
- **Transversity**
- **Pretzelosity**

- **Helicity**
- **Sivers**
- **Trans-Helicity**
### TMD Fragmentation Functions

<table>
<thead>
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<th>hadron pol.</th>
<th>quark pol.</th>
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<tbody>
<tr>
<td>U</td>
<td>D(_1)</td>
</tr>
<tr>
<td>L</td>
<td>G(_1)</td>
</tr>
<tr>
<td>T</td>
<td>D(_{1T})</td>
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</tbody>
</table>
Access TMDs through Hard Processes

SIDIS

Drell-Yan

Partonic scattering amplitude
Fragmentation amplitude
Distribution amplitude
JLab 6 GeV SIDIS Experiments

- Demonstrate Feasibility
- Initial study on $P_T$ spin-flavor dependence
- First measurements with transversely polarized $^3$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.  
\[ e + LH_2/LD_2 \rightarrow e' + \pi^+/- + X \]

Ebeam=5.5 GeV

Low Energy SIDIS xsec reproduced by calculation using high energy parameters and PDF
Unpolarized TMD: Flavor $P_T$ Dependence?

Flavor in transverse-momentum space

**up quark**

**down quark**

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 valance

**Indications from lattice QCD**

- $f_{1u}/f_{1d}$
  - "less" up quarks

- 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
Hall A SIDIS Cross Section Results From E06-010 (Transversity):

pi+ and pi- production on He3
X. Yan et al., Hall A Collaboration, PRC 95 (2017) 035209

pi+ results \( \Phi_h \) (rad)
Hall A Results: Transverse Momentum dependence

average quark transverse momentum distribution squared
vs. average quark transverse momentum in fragmentation squared

with modulation

no modulation
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

$^3\text{He}, \text{NH}_3$

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

$H_2/D_2, \text{NH}_3/\text{ND}_3, \text{HD}$

$H_2 D_2$
Hall C – Cross Sections in SIDIS

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, π+/π–

At small $P_T$, access to large $P_T$ at fixed $\phi$ SHMS/HMS will allow precise L-T separations
→ Does $R_{DIS} = R_{SIDIS}$?

Measure $P_T$ dependence to access $k_T$ dependence of parton distributions
Hall C SIDIS Program – HMS+SHMS

Accurate cross sections for validation of SIDIS factorization framework and for L/T separations

Charged pions:

- 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
Hall C SIDIS Program – HMS+SHMS+NPS

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

**E00-108 (6 GeV)**

**E12-13-010**

**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 \(z\)

**Charged pions:**

** Courtesy R. Ent **
Transverse momentum of pion = convolution of $k_t$ of quark and $p_t$ generated during fragmentation

$$P_t = p_t + z k_t + O(k_t^2/Q^2)$$

Transverse momentum of up and down quarks by measuring $P_T$ dependence of $\pi^+/$$\pi^-$ cross sections and ratios from LH2 and LD2

Results from Hall C 6 GeV data
E12-09-017 Status

- Ran for about 28 days in Spring 2018
- Ran for another 2 weeks in Fall 2018 to complete experiment

→ Initial raw yield ratios look reasonable
→ High precision ratios will require more detailed analysis
  – understanding tracking at high rates in new SHMS in particular (also important for E12-09-002)

Kinematics:
1. $x=0.31, Q^2=3.1 \text{ GeV}^2$
   → $z=0.9-0.45$ at $P_T=0, P_T=0.6$ at $z=0.35$
2. $x=0.3, Q^2=4.1 \text{ GeV}^2$
   → $z=0.9-0.45$ at $P_T=0, P_T=0.6$ at $z=0.35$
3. $x=0.45, Q^2=4.5 \text{ GeV}^2$
   → $z=0.9-0.45$ at $P_T=0, P_T=0.6$ at $z=0.35$
**E12-09-002: Charge Symmetry Violating Quark Distributions via $\pi^+/\pi^-$ in SIDIS**

**Experiment:** Measure Charged pion electroproduction in semi-inclusive DIS off deuterium

Ratio of $\pi^+/\pi^-$ cross sections sensitive to CSV quark distributions

$$R_{\gamma}(x, z) = \frac{\gamma^{0\pi^-}(x, z)}{\gamma^{0\pi^+}(x, z)}$$

where $\delta d - \delta u$ and $\delta d = d^p - u^n$ and $\delta u = u^p - d^n$

→ $\bar{u}(x) \neq \bar{d}(x)$ extraction relies on the implicit assumption of charge symmetry

→ Viable explanation for NuTeV anomaly → $\sin^2 \theta_W$

→ CS is a necessary condition for many relations between structure functions

IN addition, precise cross sections and $\pi^+/\pi^-$ ratios will provide information on SIDIS reaction mechanism at JLab energies

Spokespersons: W. Armstrong, D. Dutta, D. Gaskell, K. Hafidi
E12-09-002 Status

E12-09-002 took data at lower $Q^2$ values in Fall 2018
→ Data taking for largest $x$, $Q^2$ in progress now!
→ In addition to data on deuterium for CSV extraction, took data on hydrogen for cross sections, factorization checks

Barely offline results
→ Ratios roughly consistent with MC expectation
→ One setting out of 8 taken in Fall 2018
Solenoidal Large Intensity Device (SoLID)

- Full exploitation of JLab 12 GeV Upgrade to maximize scientific return

A Large Acceptance Detector AND Can Handle High Luminosity \((10^{37}-10^{39})\)

- Reach ultimate precision for tomography of the nucleon
- PVDIS in high-x region - providing sensitivity to new physics at 10-20 TeV
- Threshold J/Psi - probing strong color fields in the nucleon and the origin of its mass (trace anomaly)

- Strong collaboration (300 collaborators from 72 institutions, 13 countries)
  - Significant international contributions
  - Strong theoretical support

- 2015 LRP recommendation IV
  - We recommend increasing investment in small-scale and mid-scale projects and initiatives that enable forefront research at universities and laboratories.

SoLID – mid-scale project
**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**

Three run group experiments: DiHadron, Ay and SIDIS-Kaon

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Key of SoLID-Spin program:

- Large Acceptance
- + High Luminosity
- → **4-D** mapping of asymmetries
- → Tensor charge, TMDs …
- → Lattice QCD, QCD Dynamics, Models.
**SoLiD: a Bridge to EIC Science on full imaging of nucleons**

(TMD examples)

**Transversity: valence quark effect**
Collins Asymmetry: Transversity and Collins FF

Transverse Spin, Tensor Charge
JLab6: $^3\text{He} (n)$ 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

neutron Sivers SSA:
negative for $\pi^+$
Agree with Torino Fit
Transversity from SoLID

- Collins Asymmetries \( \sim \) 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 \( \rightarrow \) Precision extraction of u/d quark transversity
- Collaborating with theory group (N. Sato, A. Prokudin, ...) on impact study

**Collins Asymmetries**

\( P_T \) 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

- Diagram showing extraction from existing data and models not shown.
Sivers Function

3-D Imaging, QCD Dynamics
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
Non-zero at highest x for $\pi^+$

Neutron Sivers SSA:
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- Agree with Torino Fit

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

kaons

Prokudin model fit

pions

E12-09-018
Mapping Sivers Asymmetries with SoLID

- Sivers Asymmetries ~ 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

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

Total > 1400 data points

\[ Q^2 = 2.4 \text{ GeV}^2 \]
Summary

- **TMDs:**
  - both TMD pdfs and TMD FFs
  - transverse spin, tensor charge
  - QCD dynamics, quark orbital angular momentum
  - angular correlations in fragmentation process

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

EIC will expand the study to sea quarks and gluons
Related News from China

- BESIII
  Collins FF (pion) Extraction: PRL 116 (2016) 042001
  Kaon data under analysis
  $P_T$ dependence under analysis

- EIC @ China (EicC) is under intense discussions
  polarized $e$, polarized $p$: 3.5 x 20 GeV, luminosity $\sim (2-4) \times 10^{33}$
  COM energy range: (3-5) x (15-25) GeV $\rightarrow $ $\sqrt{s} \sim 10-20$ GeV
  also polarized $d$, $^3$He, unpolarized ions up to Uranium
  Kinematics region complementary to JLab12/US-EIC

- hadron-China2019: 8/22-28/2019 at Nankai University, Tianjin, China
  [https://indico.ihep.ac.cn/event/8987/](https://indico.ihep.ac.cn/event/8987/)
Main changes

- Figure-8 shape ion collider with four long straight sections – detector and cooler
- Two interaction points for detectors
- The high luminosity $2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$, $4 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$

$\sqrt{s} = 18.7 \text{ GeV}$

**Electron injector:**
- SRF Linac-ring
- 3.5GeV
- Top-up

**pRing**
- 25 GeV
- C: 1347 m
- Polarized proton

**eRing**
- 3.5 GeV
- C: 822 m
- Polarized electron

**Bunched cooler**
- 14 MeV
- ERL circulator

**Interaction regions**

**BRing**
- DC cooler
- Siberia snake

**HFRS**

**25GeV p + 3.5GeV e**
EicC-I: $4 \times 10^{-3} < x < \sim 1$ region
1) Valance- and sea-quark
Extras/ Backups
TMDs and Orbital Angular Momentum

Pretzelosity ($\Delta L=2$), Worm-Gear ($\Delta L=1$), Sivers: Related to GPD E through Lensing Function
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
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

Worm-Gear
Trans helicity

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

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

- WW-Type (Prokudin)
- WW-Type (Parsamyan)
- LCQM (Pasaquini)
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)

SoLID Neutron Projections,

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

\[ A_{UL} \sim h_{1L}(x) \otimes H^\perp_1(z) \]
What do we learn from 3D distributions?

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

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

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

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

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 $^3$He for neutron TMD Study

- Effective polarization
- PWIA
- FSI through distorted spectral function

Kinematic domain ($Q^2, x_B$) and DVCS world data