SIDIS Program at 12 GeV Jefferson Lab with SoLID

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Thanks Xuefei Yan for inputs with some slides
Overview of SoLID

Full exploitation of JLab 12 GeV upgrade

- The capability to handle high luminosity $L \sim 10^{37-39}$ cm$^{-2}$ s$^{-1}$.
- Large acceptance with full $2\pi$ azimuthal angle coverage.

Polar angle coverage: $8^\circ\sim24^\circ$. (SIDIS)

Five highly rated approved experiments

- Nucleon structure: three-dimensional imaging of the nucleon in momentum space in valence quark region.
  E12-10-006, E12-11-007, E12-11-008 (SIDIS)
- Fundamental symmetries: new physics in the $10\sim20$ TeV region, complementary to the reach of LHC.
  E12-10-007 (PVDIS)
- $J/\psi$: probe the color field in the nucleon, access to QCD conformal anomaly.
  E12-12-006 ($J/\psi$)
SIDIS @ SoLID

Approved SIDIS experiments 11/8.8 GeV

E12-10-006: Single Spin Asymmetry on Transversely polarized $^3$He, 90 days.

E12-11-007: Single and Double Spin Asymmetry on Longitudinally polarized $^3$He, 35 days.

E12-10-008: Single Spin Asymmetry on Transversely polarized proton (NH$_3$), 120 days.

Run group:
E12-10-006A, E12-11-108A
Dihadron process
Target single spin asymmetry $A_y$

High statistics (example)

Total about 1400 $^3$He bins and 650 proton bins in $x$, $z$, $Q^2$, $P_T$

$p_n = 86\%$, $p_p = -2.8\%$
PVDIS @ SoLID

Approved PVDIS experiment @ 11 GeV

E12-10-007: Parity violating asymmetry in DIS with LH$_2$ and LD$_2$ targets.

SoLID projected and final Qweak results
Approved $J/\psi$ near threshold production @ 11 GeV

E12-12-006: measure $J/\psi$ near threshold production cross section on proton (LH$_2$).

Run group:
E12-12-006A Timelike Compton Scattering (TCS).

Imaginary part: total cross section through the optical theorem.
Real part: contains the conformal anomaly.

Proton mass:

$\overline{MS}$ and $\mu = 2$ GeV

H. Gao et al., The Universe 3, no.2, 18 (2015).

Probing the strong color field in the nucleon, conformal anomaly (has impact on understanding of the proton mass).
Nucleon Spin Decomposition

Proton spin puzzle

\[ \Delta \Sigma = \Delta u + \Delta d + \Delta s \sim 0.3 \]

Spin decomposition

\[ J = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

Access to \( L_{q/g} \)

It is necessary to have transverse information.

Coordinate space: GPDs
Momentum space: TMDs

3D imaging of the nucleon.

Quark spin only contributes a small fraction to nucleon spin.


Unified View of Nucleon Structure

Light-front wave function $\Psi(x_i, k_{Ti})$

GTMD $F(x, \Delta T, k_T)$
- Generalized Transverse Momentum Dependent

$\Delta T = 0$

Wigner distribution $\rho(x, b_T, k_T)$

$\int d^2k_T$

5D

TMD $f(x, k_T)$

3D

GPD $H(x, \xi, t)$

IPD $H(x, \xi, b_T)$

$\int dx$

Form factor $F(t)$

Charge density $\rho(b_T)$

$\int db_T$

1D

PDF $f(x)$

$\int dx$

Charge $g$

$\int dx$

$t = 0$

$t = 0$
Unified View of Nucleon Structure

Light-front wave function $\Psi(x_i, k_{T_i})$

GTMD $F(x, \Delta_T, k_T)$
Generalized Transverse Momentum Dependent

5D

$\Delta_T = 0$

∫ $d^2k_T$

Wigner distribution $\rho(x, b_T, k_T)$

∫ $d^2k_T$

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IPD $H(x, \xi, b_T)$

3D

∫ $d^2k_T$

∫ $dx$

Form factor $F(t)$

Charge density $\rho(b_T)$

∫ $db_T$

1D

PDF $f(x)$

$h_1(x)$ Transversity

∫ $dx$

$t = 0$

$\delta_{Tq}$ Tensor charge

Charge $g$
Structure Functions

SIDIS differential cross section

18 structure functions $F(x, z, Q^2, P_T)$, model independent. (one photon exchange approximation)

$$
\frac{d\sigma}{dxdydzdP_T^2d\phi_hd\phi_S} = \frac{\alpha^2}{xyQ^2} \frac{y^2}{2(1 - \epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right)
\times \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1 + \epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{2\phi_h} \cos 2\phi_h + \lambda_e \sqrt{2\epsilon(1 - \epsilon)} F_{LU}^{\sin \phi_h} \sin \phi_h 
+ S_L \left[ \sqrt{2\epsilon(1 + \epsilon)} F_{UL}^{\sin \phi_h} \sin \phi_h + \epsilon F_{UL}^{2\phi_h} \sin 2\phi_h \right] + \lambda_e S_L \left[ \sqrt{1 - \epsilon^2} F_{LL}^{\cos \phi_h} \cos \phi_h 
+ S_T \left[ (F_{UT,T}^{\sin(\phi_h - \phi_S)} + \epsilon F_{UT,L}^{\sin(\phi_h - \phi_S)}) \sin(\phi_h - \phi_S) + \epsilon F_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) + \epsilon F_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) 
+ \sqrt{2\epsilon(1 + \epsilon)} F_{UT}^{\sin \phi_S} \sin \phi_S + \sqrt{2\epsilon(1 + \epsilon)} F_{UT}^{\sin(2\phi_h - \phi_S)} \sin(2\phi_h - \phi_S) \right] 
+ \lambda_e S_T \left[ \sqrt{1 - \epsilon^2} F_{LT}^{\cos \phi_h} \cos(\phi_h - \phi_S) 
+ \sqrt{2\epsilon(1 - \epsilon)} F_{LT}^{\cos \phi_S} \cos \phi_S + \sqrt{2\epsilon(1 - \epsilon)} F_{LT}^{\cos(2\phi_h - \phi_S)} \cos(2\phi_h - \phi_S) \right] \right\}
$$

In parton model, $F(x, z, Q^2, P_T)$s are expressed as the convolution of TMDs.
### Leading Twist TMDs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark Polarization</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>U</strong></td>
<td></td>
<td>$f_1$</td>
<td>$g_{1L}$</td>
<td>$h_1^\perp$</td>
</tr>
<tr>
<td>unpolarized</td>
<td>helicity</td>
<td></td>
<td>longi-transversity (worm-gear)</td>
<td></td>
</tr>
<tr>
<td><strong>L</strong></td>
<td></td>
<td></td>
<td></td>
<td>$h_{1L}$</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td></td>
<td>$f_{1T}^\perp$</td>
<td>$g_{1T}$</td>
<td>$h_1^\perp$</td>
</tr>
<tr>
<td>Sivers</td>
<td>trans-helicity (worm-gear)</td>
<td></td>
<td>pretzelosity</td>
<td></td>
</tr>
</tbody>
</table>

Boer-Mulders
Unpolarized Quark in $p^\uparrow$

\[ f_{q/p^\uparrow}(x, k_\perp) = f_1^q(x, k_\perp) - f_{1T}^{\perp q}(x, k_\perp) \frac{\vec{P} \times \vec{k}_\perp \cdot \vec{S}}{M} \]

**Sivers distribution**

naively time-reversal odd.

\[ f_{1T}^{\perp q}(x, k_\perp) \bigg|_{\text{SIDIS}} = -f_{1T}^{\perp q}(x, k_\perp) \bigg|_{\text{Dy}} \]

**Measurement in SIDIS**

Single spin asymmetry

(Sivers asymmetry)

\[ A_{UT}^{\sin(\phi_h - \phi_S)} \sim f_{1T}^{\perp q}(x, k_\perp) \otimes D_1(z, p_\perp) \]


Bacchetta, Conti, Radici
PR D 78, 074010 (2008).
Transverse Spin Structure

Transversity

A transverse counterpart to the longitudinal spin structure: helicity $g_{1L}$
They are NOT the same due to relativity.

Chiral-odd

Unique for the quarks.
No mixing with gluons.
Simpler evolution effect.

NOT accessible via inclusive DIS process.
Must couple to another chiral-odd function. (e.g. Collins function $H_1^\perp$)

Measurement in SIDIS

Single spin asymmetry (Collins asymmetry)

$A_{UT}^{\sin(\phi_h+\phi_S)} \sim h_1(x, k_{\perp}) \times H_1^\perp(z, p_{\perp})$

$H_1^\perp(z, p_{\perp})$ Collins fragmentation function

Soffer’s Inequality

Soffer’s bound

\[ |h_1(x)| \leq \frac{1}{2} [f_1(x) + g_{1L}(x)] \]

Derived by using the positivity constraint on the forward scattering helicity amplitude.

Global fits of transversity

Test Soffer’s inequality @ SoLID

Z.-B. Kang et al., PR D 93, 014009 (2016).

M. Anselmino et al., PR D 92, 114023 (2015).
Pretzelosity

Pretzelosity distribution

\[ h^\perp_{1T} \]

Chiral-odd. NO gluon analogy. Interference of light-front wave functions differing by \( \Delta L = 2 \). Measuring the difference between helicity and transversity, and hence relativistic effects. (spherically symmetric models)

Relation to OAM (canonical)

\[ L^q_z = - \int dx d^2k_{\perp}\frac{k^2_{\perp}}{2M^2} h^\perp_{1T}(x, k_{\perp}) = - \int dx h^\perp_{1T}^{(1)q}(x) \]  

(model dependent)

Measurement in SIDIS

Single spin asymmetry

\[ A_{UT}^{\sin(3\phi_h-\phi_S)} \sim h^\perp_{1T}(x, k_{\perp}) \otimes H^\perp_1(z, p_{\perp}) \]

A global fit to 175 data from COMPASS, HERMES, and JLab found comparable with null signal hypothesis at 72% C.L..


6 GeV JLab E06-010, Y. Zhang et al., PR C 90, 055209 (2014).
Radiative Correction @ 6 GeV

Transversity experiment at Hall A: E06-010

by Xuefei Yan

HAPRAD built in MC.

I. Akushvich et al., PL B 672, 35 (2009).
Radiative Correction @ SoLID

Transverse polarized $^3\text{He}$: E12-10-006 (proposal: a simple estimation)

Estimated by Pythia with RADGEN.
RC under Development @ SoLID

- Internal radiative correction (HAPRAD, etc.) built in MC
  - internal and external RC combination
  - full end-to-end MC under development

- Cross section model adjustability: for iterative processes
  - reduce model dependence

- Capability for bin-by-bin and unfolding

- Exclusive tail: there will be data at the same kinematic for model updating

- Collaborating with theorists and other groups to develop full procedure
Present Status On TMD Extractions

Sivers Transversity Pretzelosity

Anselmino et al, EPJA39, 89 (2009)
Anselmino et al, PRD92, 114023 (2015)

Collins fragmentation

Anselmino et al, PRD92, 114023 (2015)
PRD93, 034025 (2016)
SoLID Impact on Sivers

\[ f_{1T}^{(1)}(x) = \int \frac{k_{\perp}^2}{2M^2} f_{1T}(x, k_{\perp}) \, d^2 k_{\perp} \]

\begin{align*}
Q^2=2.4 \text{ GeV}^2 \\
95\% \text{ C.L.}
\end{align*}

parametrization by M. Anselmino et al., EPJ A 39, 89 (2009).

SoLID projection with transversely polarized neutron and proton data.
Quark Transverse Momentum in $p^{↑}$

95% C.L.

- parametrization by M. Anselmino et al., EPJ A 39, 89 (2009).
- SoLID projection with transversely polarized neutron and proton data.

Transverse momentum:

$$\langle k_{\perp} \rangle = -M \int dx \frac{1}{x} f_{1T}^{(1)}(x) (S \times \hat{P})$$

Anselmino et al. (2009)

SoLID
SoLID Impact on Transversity

95% C.L.

parametrization by M. Anselmino et al., PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.
SoLID Impact on Pretzelosity

95% C.L.

parametrization by C. Lefky et al., PR D 91, 034010 (2015).
SoLID projection with transversely polarized neutron and proton data.

OAM:

\[ L_z^q = - \int dx d^2 k_{\perp} \frac{k_{\perp}^2}{2 M^2} h_{1T}^{q}(x, k_{\perp}) = - \int dx \tilde{h}_{1T}^{q}(x) \]
Tensor Charge

Definition

\[ \langle P, S | \bar{\psi}_q i \sigma^{\mu\nu} \psi_q | P, S \rangle = \delta_Tq \bar{u}(P, S)i \sigma^{\mu\nu}u(P, S) \]

\[ \delta_Tq = \int_0^1 \left[ h_1^q(x) - \bar{h}_1^q(x) \right] dx \]


SoLID impact

Extraction from Experiments:
- Anselmino et al (2013a)
- Anselmino et al (2013b)

Lattice QCD:
- Alexandrou et al (2014)

SoLID Projection
Tensor Charge and Neutron EDM

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

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

Anselmino et al. with \( |d_n| < 2.9 \times 10^{-28} e \cdot cm \)

SoLID with \( |d_n| < 2.9 \times 10^{-26} e \cdot cm \)

SoLID with \( |d_n| < 2.9 \times 10^{-28} e \cdot cm \)
Summary

- Lepton scattering is a powerful tool to probe the internal structure of the nucleon.
- Unprecedented precision with high luminosity and large acceptance at JLab 12-GeV with SoLID.
- SoLID-SIDIS program: multi-dimensional mapping in valence quark region with high precision.
- TMD: transverse imaging of the nucleon, access to orbital angular momentum.
- Tensor charge and neutron EDM, constraint on new physics.
- Developing full procedure for RC and physics extraction.

Thank you!
Backup
Exclusive tail @ 6 GeV

Transversity experiment at Hall A: E06-010

by Xuefei Yan

SoLID Impact on Transversity TMD

95% C.L.

parametrization by M. Anselmino et al., PR D 87, 094019 (2013).

SoLID projection with transversely polarized neutron and proton data.
What Else in SIDIS @ SoLID

Worm-gears

Trans-helicity (worm-gear).
Interference of light-front wave functions differing by $\Delta L = 1$.

Measured by DSA

$$A_{LT}^{\cos(\phi_h - \phi_S)} \sim g_{1T}(x, k_\perp) \otimes D_1(z, p_\perp)$$

(The other worm-gear from $A_{UL}^{\sin 2\phi_h} \sim h_{1L}(x, k_\perp) \otimes H_1^\perp(z, p_\perp)$.)

Subleading twist effect

Beam spin asymmetry $A_{LU}^{\sin \phi_h}$ from twist-3 TMDs.

Other subleading twist asymmetries, e.g.

$$A_{UT}^{\sin(2\phi_h - \phi_S)}, A_{UT}^{\sin \phi_S}, A_{LT}^{\cos \phi_S} \ldots$$

Unpolarized process

Multiplicity or differential cross section.

Cahn effect $f_1 \otimes D_1$  
Boer-Mulders effect $h_{1L}^\perp \otimes H_1^\perp$