SoLID SIDIS Physics Case

SoLID Collaboration Meeting
September 11-12, 2015

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Duke University, Duke Kunshan University
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 and data acquisitions
    - Reach ultimate precision for SIDIS (TMDs), providing three-dimensional imaging of nucleon in momentum space
    - PVDIS in high-\(x\) region providing sensitivity to new physics at 10-20 TeV, and QCD
    - Threshold J/\(\psi\), probing strong color field in the nucleon, trace anomaly

- 5 highly rated experiments approved
  Three SIDIS experiments, one PVDIS, one J/\(\psi\) production
  Run group experiments: di-hadron, Inclusive-SSA, and much more …

- Strong collaboration (250+ collaborators from 70+ institutes, 13 countries)
  Significant international (Chinese) contributions and strong theoretical support
Unified View of Nucleon Structure

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

\[ d^2r_T \]

TMD PDFs

\[ f_1^u(x,k_T), \ldots \]
\[ h_1^u(x,k_T) \]

3D imaging

\[ d^2k_T \]

GPDs/IPDs

\[ d^2k_T \]

dx & Fourier Transformation

Form Factors

\( G_E(Q^2), G_M(Q^2) \)

1D

PDFs

\[ f_1^u(x), \ldots \]
\[ h_1^u(x) \]
# Leading Twist TMDs

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Transversely Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Un-Polarized</td>
<td>Longitudinally Polarized</td>
<td>Transversely Polarized</td>
</tr>
<tr>
<td>$f_1$</td>
<td>$g_1$</td>
<td>$h_{1L}$</td>
</tr>
<tr>
<td></td>
<td>$h_{1L}$</td>
<td>Boer-Mulder</td>
</tr>
<tr>
<td>Longitudinally Polarized</td>
<td>$g_1$</td>
<td>$h_{1T}$</td>
</tr>
<tr>
<td></td>
<td>$h_{1T}$</td>
<td>Transversity</td>
</tr>
<tr>
<td></td>
<td>$h_{1T}$</td>
<td>Pretzelosity</td>
</tr>
<tr>
<td>Transversely Polarized</td>
<td>$h_{1T}$</td>
<td></td>
</tr>
</tbody>
</table>

**Nucleon Spin**

**Quark Spin**
SoLID-Spin: SIDIS on $^3$He/Proton @ 11 GeV

**E12-10-006:** Single Spin Asymmetry on Transverse $^3$He @ 90 days, **rating A**

**E12-11-007:** Single and Double Spin Asymmetry on $^3$He @ 35 days, **rating A**

**E12-11-108:** Single and Double Spin Asymmetries on Transverse Proton @ 120 days, **rating A**

Two ``bonus'' experiments approved

International collaboration with 200 collaborators from 11 countries

Key of SoLID-Spin program:
Large Acceptance
+ High Luminosity
→ 4-D mapping of asymmetries
→ Tensor charge, TMDs …
→ Lattice QCD, QCD Dynamics, Models.
Transversity and Tensor Charge

- Tensor charge (0th moment of transversity): intrinsic property (charge, magnetic moment), also input for beyond Standard Model physics searches
- Lattice QCD, Bound-State QCD (Dyson-Schwinger), Light-cone Quark Models, …
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with trans. polarized n & p → determination of tensor charges for d & u

Collins Asymmetries

12-GeV SoLID projections together with existing extractions and predictions

Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam
X. Qian et al in PRL 107, 072003
Transversity and Tensor Charge

- Tensor charge (0th moment of transversity): intrinsic property (charge, magnetic moment), also input for beyond Standard Model physics searches (EDM)
  - Lattice QCD, Bound-State QCD (Dyson-Schwinger), Light-cone Quark Models, …
- Global model fits to experiments (SIDIS and e+e-)
- SoLID with trans. polarized n & p → determination of tensor charges for d & u

Collins Asymmetries

(Transversity (x) Collins Function)

Total 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam
X. Qian et al in PRL 107, 072003

12-GeV SoLID projections together with existing extractions and predictions
Projected measurements in 1-D ($x$)

Expected improvement of Sivers function (A. Prokudin)
Projected measurements in 1-D ($x$)

Expected improvement of Sivers function (A. Prokudin)

Valence quark region has not been accessed at all so far
SoLID-SIDIS compared with SBS & CLAS12
<table>
<thead>
<tr>
<th>Factor</th>
<th><strong>SoLID</strong> E12-10-006 (A) (neutron)</th>
<th><strong>SBS</strong> E12-09-018 (A-) (only neutron approved)</th>
<th><strong>SoLID</strong> E12-11-108, A (proton)</th>
<th><strong>CLAS12 C12-11-111</strong> (only proton conditional approved)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Targets</td>
<td>He3 ( “n” )</td>
<td>He3 ( “n” )</td>
<td>NH3( “p” )</td>
<td>HDice ( “p” )</td>
</tr>
<tr>
<td>Polarization (P)</td>
<td>65% (60% in beam)</td>
<td>65% (&lt;60% in beam)</td>
<td>70%</td>
<td>60%</td>
</tr>
<tr>
<td>Dilution-Factor (f)</td>
<td>0.15~0.3</td>
<td>0.15~0.3</td>
<td>0.13</td>
<td>0.33*80%</td>
</tr>
<tr>
<td>Polarized Lumonisity (L)</td>
<td>1.0x10^{36} cm^{-2}s^{-1}</td>
<td>2.7x10^{36} cm^{-2}s^{-1}</td>
<td>1.0x10^{35} cm^{-2}s^{-1}</td>
<td>1.4x10^{33} cm^{-2}s^{-1} (quoted: 5.10^{33} cm^{-2}s^{-1})</td>
</tr>
<tr>
<td>Solid-Angle (\Omega_e \cdot \Omega_h)</td>
<td>0.067</td>
<td>Quoted: 0.0026</td>
<td>0.067</td>
<td>1.32sr</td>
</tr>
<tr>
<td></td>
<td>(e: \theta \rightarrow 8^\circ\sim25^\circ, \Phi \rightarrow 0^\circ\sim360^\circ, \eta: \theta \rightarrow 8^\circ\sim14.5^\circ, \Phi \rightarrow 0^\circ\sim360^\circ)</td>
<td>(h:SBS: \theta \rightarrow 26.5^\circ\sim35^\circ, \Phi \rightarrow -24^\circ\sim24^\circ, e-BB: \theta \rightarrow 10^\circ\sim19.5^\circ, \Phi \rightarrow -30^\circ\sim30^\circ)</td>
<td>(e: \theta \rightarrow 8^\circ\sim25^\circ, \Phi \rightarrow 0^\circ\sim360^\circ, h: \theta \rightarrow 8^\circ\sim14.5^\circ, \Phi \rightarrow 0^\circ\sim360^\circ)</td>
<td></td>
</tr>
<tr>
<td>FOM in the same kine. (L<em>P2</em>f2*Omega)</td>
<td>5.43x10^{32}</td>
<td>5.69x10^{31}</td>
<td>5.55x10^{31}</td>
<td>4.64x10^{31} (2.35x10^{30} with SoLID angular range)</td>
</tr>
<tr>
<td>SIDIS \pi^+ Events<em>P^2</em>f^2</td>
<td>100M</td>
<td>0.21M</td>
<td>5.06M</td>
<td>3.07M (2.02M with SoLID acceptance)</td>
</tr>
</tbody>
</table>

Based on the 1-D Projection results
**SoLID vs. SBS Neutron-SIDIS Comparison**

Figure of Merit comparison at the same kinematic setting with the same cuts.
SoLID vs. SBS Neutron-SIDIS Comparison

SoLID bins are to match the SBS ones and thus are not optimized for SoLID kinematics.
SoLID vs. SBS Neutron-SIDIS Comparison

SBS:
• 3D binning: \(0.1 < x < 0.7, 0.2 < z < 0.7, 0 < p_T (\text{GeV}) < 1.2\)
• Typically 120 bins, dependence on \(Q^2\) gives fully-differential analysis

SoLID:
• 4D-MAPPING: \(0.05 < x < 0.6, 0.3 < z < 0.7, 0 < p_T (\text{GeV}) < 1.0, 1.0 < Q^2 < 7.0 \text{ GeV}^2\)
• 1400 bins
**SoLID vs. CLAS12 Proton-SIDIS Comparison**

- SoLID data were rebinned to match CLAS12’s bins.
SoLID vs. CLAS12 on Proton-SIDIS Comparison

- SoLID data were rebinned to match CLAS12’s bins.
- CLAS12 Projection was redone with SoLID’s Acceptance and Kinematic cuts (Courtesy of Luciano Pappalardo).
**Impact on Tensor Charge: SoLID vs. CLAS12**

- A model dependent study (directly compare to Alexei's work data fit)
- Using multi-dimensional binning results from SoLID and CLAS12 (match SoLID's cuts)
- Only statistical errors are considered for the projected results.

Ongoing work by Alexei Prokudin, Nobuo Sato, Kalyan Allada and Zhihong Ye
What else can we learn in SoLID?

- Test QCD and TMD factorization
  \[ f_{1T}^q \bigg|_{S(D)IS} = f_{1T}^q \bigg|_{DY} \quad h_1^q \bigg|_{S(D)IS} = h_1^q \bigg|_{DY} \]
- Sea quark TMDs, esp BM \( h_1^q \) and Sivers \( f_{1T}^q \) (Kaon capability)
- Twist-3 TMDs, e.g. \( f_L^q \) \( h_L^q \) \( f_T^q \) \( h_T^q \) \( f_T^q \) \( g_L^q \) \( g_T^q \)
- Target fragmentations (fracture functions)

Tianbo Liu joined Duke group
Summary of SoLID SIDIS program

- SoLID: unique combination of large acceptance and high luminosity – truly utilize 12-GeV upgrade to its full potential, most precise data from spin-dependent SIDIS

- SoLID SIDIS: comprehensive program with both proton and "neutron" targets in the same setup allows for flavor separation with better control of systematics

- Multi-dimensional binning of the data with high precision help reduce theoretical uncertainties in extracting TMDs

- Apart from three approved experiments, two "bonus" experiments will accumulate data without additional beam time, providing complementary way to access transversity, and new information, and expect more such bonus
Backup
SBS Coverage

BigBite:

counter, a two-layer electromagnetic calorimeter and a scintillator hodoscope. The value of the solid angle for 60 cm long target was found to be of 45 msr.

SBS:

For the proposed SIDIS experiment, the magnet will be placed at the distance 245 cm from the target to the return yoke, providing a solid angle of 42(53) msr. The magnet inter-

From their kinematic coverage plot:

$$\Theta_e \rightarrow 0.465 \sim 0.620 \text{ rad}$$
$$\Phi_e \rightarrow -0.42 \sim 0.42 \text{ rad}$$

$$\Theta_\pi \rightarrow 0.175 \sim 0.340 \text{ rad}$$
$$\Phi_\pi \rightarrow -0.52 \sim 0.52 \text{ rad}$$

$$\Omega_{e\pi} = 0.0029 \text{ sr}$$

<table>
<thead>
<tr>
<th>Distance from the target to the detector, cm</th>
<th>417</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central angle $\theta_c$, degree</td>
<td>14</td>
</tr>
<tr>
<td>$\Delta \theta_h$, degree</td>
<td>$\pm 3.6$</td>
</tr>
<tr>
<td>$\Delta \theta_v$, degree</td>
<td>$\pm 12$</td>
</tr>
<tr>
<td>Angular resolution: $\sigma_{\theta_e}$, degree</td>
<td>0.02</td>
</tr>
<tr>
<td>Vertex resolution (along beam), cm</td>
<td>0.2</td>
</tr>
<tr>
<td>Momentum resolution $\sigma_p/p$</td>
<td>$0.001 \times p[\text{GeV}]$</td>
</tr>
</tbody>
</table>

Table 5.1: DIS events selection, kinematical cuts and main

<table>
<thead>
<tr>
<th>Unit</th>
<th>Proposed Exp.</th>
<th>HERMES</th>
<th>HallA 6 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q^2$ GeV$^2$</td>
<td>&gt; 1</td>
<td>&gt; 1</td>
<td>&gt; 1.31</td>
</tr>
<tr>
<td>$W$ GeV</td>
<td>2.3</td>
<td>&gt; 3</td>
<td>&gt; 2.33</td>
</tr>
<tr>
<td>$W'$ GeV</td>
<td>&gt; 1.5</td>
<td>&lt; 0.9</td>
<td>&lt; 0.95</td>
</tr>
<tr>
<td>$y$ GeV</td>
<td>&lt; 0.9</td>
<td>&lt; 0.95</td>
<td>&gt; 0.1</td>
</tr>
<tr>
<td>$z$</td>
<td>&gt; 0.2</td>
<td>&gt; 0.2</td>
<td>&lt; 0.7</td>
</tr>
<tr>
<td></td>
<td>&lt; 0.7</td>
<td>&lt; 0.7</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: 11 GeV kinematics, phase space of the two detected particle momenta and angles, with the SIDIS cuts applied.
CLAS Coverage

\[ \Theta_\pi \rightarrow 5^\circ \sim 40^\circ \]
\[ \Phi_\pi \rightarrow 360^\circ \times 80\% \text{ (20\% gaps)} \]

\[ \Theta_\epsilon \rightarrow 6.5^\circ \sim 40^\circ \]
\[ \Phi_\epsilon \rightarrow 360^\circ \times 80\% \text{ (20\% gaps)} \]

\[ \Omega_{e\pi} = 1.32\text{sr} \]

From their 1D projection stat. error bars: \( N(\pi^+) = 3.07\text{M}, \ N(\pi^-) = 0.87\text{M} \);

The proposal didn't mention whether they are corrected by Pol&Dilution or not.

Accounting for calibration runs, empty target runs, and supportive tests. The expected number of SIDIS pions and kaons within the kinematic limits: \( Q^2 > 1 \text{ GeV}^2 \) (corresponding to \( x > 0.05 \)), \( W^2 > 4 \text{ GeV}^2 \), \( 0.10 < y < 0.85 \) and \( 0.3 < z < 0.7 \) are:

17.6 M, 5.8 M and 3.9 M for \( \pi^+ \), \( \pi^- \), and \( \pi^0 \), respectively, and 1.9 M and 0.4 M for \( K^+ \) and \( K^- \), respectively. A squared missing mass greater than 2 GeV\(^2\) was required.
TMD Projection

- **Global fit to the world data**
- **Obtain a set of parameters for each TMDs**
- **Use SoLID-SIDIS' kinematic variables and the fitted parameters to generate pseudo-data based on the current uncertainties**
- **Re-weight the pseudo-data with the projected statistical errors from SoLID**

\[
\chi_k^2 = \sum_{i=1}^{Bin} \left( \frac{A_i^{SoLID}}{A_i^{Fit}} - A_i^{Fit} \right)^2
\]

\[
w_k = e^{-\frac{1}{2} \chi_k^2} \frac{N}{\sum_{k=1}^{N} e^{-\frac{1}{2} \chi_k^2}}
\]

- **Calculate the new expectation values and uncertainties with the new weights**

\[
\left< O \right>_{\text{w/o SoLID}} = \sum_{k=1}^{N} \frac{1}{N} O_k
\]

\[
\delta(O) = \sqrt{\sum_{k=1}^{N} \frac{1}{N} (O_k - \left< O \right>)^2}
\]

\[
\left< O \right>_{\text{w/SoLID}} = \sum_{k=1}^{N} w_k O_k
\]

\[
\delta(O) = \sqrt{\sum_{k=1}^{N} w_k (O_k - \left< O \right>)^2}
\]
Other TMD programs at JLab

**E12-09-018 at JLab Hall-A**

**Physics Goal:** measure transverse target SSA \((A_{UT})\) in \(^3\text{He}(e,e'\bar{h})X\) in the valence region
- SIDIS at 8.8 and 11 GeV, luminosity: \(4.10^{36}\) cm\(^{-2}\) s\(^{-1}\), 40 \(\mu\)A
- 3D binning: \(6 (0.1 < x < 0.7) \times 5 (0.2 < z < 0.7) \times 6 (0 < p_T \text{ (GeV) } < 1.2)\)
- Typically 120 bins, dependence on \(Q^2\) gives fully-differential analysis

**SoLID E12-10-006:** 1400 bins, 4D-MAPPING.
\(0.05 < x < 0.6, 0.3 < z < 0.7, 0 < p_T \text{ (GeV) } < \sim 1, 1 < Q^2 \text{ (GeV}^2) < 8 \text{ with } \Delta Q^2 = 2\text{ GeV}^2\)

**CLAS12 Program at 11GeV**

- Pol. NH\(_3\) and ND\(_3\) target (if pol. \(10^{35}\) cm\(^2\) s\(^{-1}\) at 10 nA)
  - E12-09-007: long. pol. **Measures** \(x(\Delta\bar{u}-\Delta\bar{d})\)
    unpol. for **multiplicity and strange PDF measurements**
  - E12-09-008: unpol. **Measures** \(A_{UU}(\cos 2\phi \text{ of charged kaons})\)
  - E12-09-009, long pol.  \[\text{Measure } A_{UL} \text{ and } A_{LL} \]
    \((\sin 2\phi \text{ of charged pions})\)
  - E12-07-107, long. pol. NH\(_3\) target,

**Programs complimentary to SoLID, but no competition for precision**