SoLID SIDIS Program

Sanghwa Park
(Stony Brook University)
for the SoLID Collaboration
Solenoidal Large Intensity Device

Take full advantage of JLab 12 GeV Upgrade:
A high luminosity ($10^{37}$-$10^{39}$) and large acceptance detector with full azimuthal coverage

Rich physics program to address important fundamental questions in nuclear physics:
Nucleon structure and proton mass
Fundamental symmetries
5 highly rated experiments approved + 4 run group experiments

Strong and growing collaboration:
300 collaborators from 72 institutions, 13 countries
Significant international contributions (China, Canada)
Solenoidal Large Intensity Device (SoLID) Physics

SoLID provides unique capability:

✓ high luminosity \(10^{37-39}\)
✓ large acceptance with full \(\phi\) coverage

→ multi-purpose program to maximize the 12-GeV science potential

1) Precision in 3D momentum space imaging of the nucleon

\[-x f_{1T} (x, k_{\perp})\]

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

2) Precise determination of the electroweak couplings

\[\text{weak coupling 1: } [2g^{eu} - g^{ed}]_{AV}\]

→ A search for new physics in the 10-20 TeV region, complementary to the reach at LHC.

3) \(J/\psi\) production cross section

→ Constrain the QCD trace anomaly, Proton mass, LHCb charmed pentaquark
SoLID Physics Program

- **SIDIS program:**
  E12-10-006: Single Spin Asymmetry in SIDIS on Transversely Polarized 3He (90 days)
  E12-11-007: Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized 3He (35 days)
  E12-11-008: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)
  + Run groups: Dihadron (E12-10-006A), Ay (E12-11-108A/E12-10-006A)

- **PVDIS experiments:**
  E12-10-007: Parity Violating Asymmetry in DIS with LH2 and LD2 (169 days)

- **J/psi program:**
  E12-12-006: Near Threshold Electroproduction of J/psi at 11 GeV (60 days)
  + Run group: Time-Like Compton Scattering (E12-12-006A)

- **GPD program:**
  Run group: Deep Exclusive pion production with polarized 3He target and SIDIS configuration (E12-10-006B)
  DDVCS on proton (LOI12-12-005), DVMP under development
Leading Twist TMDs

- Nucleon spin
- Quark spin

<table>
<thead>
<tr>
<th>Nucleon Polarization</th>
<th>Quark polarization</th>
<th>Unpolarized (U)</th>
<th>Longitudinally Polarized (L)</th>
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<tbody>
<tr>
<td>U</td>
<td>$f_1$ = [Diagram]</td>
<td></td>
<td></td>
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- Boer-Mulders
- Worm Gear (Kotzinian-Mulders)
- Sivers
- Transversity
- Pretzelosity
- Helicity
SoLID SIDIS Program

**E12-10-006**: Single Spin Asymmetry in SIDIS on Transversely Polarized 3He (90 days)

**E12-11-007**: Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized 3He (35 days)

**E12-11-008**: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)

- Highly rated pion SIDIS experiments approved
- 4-dimensional binning with high statistics and well controlled systematics
- Strong collaboration with theorists - impact studies of the SoLID physics
SoLID-SIDIS Configuration

Large-Angle:
Detect electrons

Polarized 3He and NH3 targets

e/π⁺ Coverage:
→ Forward-Angle: 0 < φ < 2π, 8° < θ < 14.8°, 1 < P < 7 GeV/c
→ Large-Angle: 0 < φ < 2π, 16° < θ < 24°, 3.5 < P < 7 GeV/c (e only)

K⁺ Coverage:
Same as pions, maximum momentum is limited by TOF time resolution

Resolution:
δP/P ~ 2%, θ ~ 0.6 mrad, φ ~ 5 mrad

Forward-Angle:
Detect electrons and hadrons
Transversity

- One of three parton distribution functions
- Least known due to its chiral odd nature
- Experimentally observed in combination with additional spin dependent final state effects (e.g. Collins FF)
- Collins asymmetries \( \sim \) Transversity \( \times \) Collins FF
- Also Transversity via Interference FF (Dihadron run group experiment)

\[
A_{UT}^{\sin(\phi_R + \phi_S)} \sim h_1(x, k_\perp) \otimes H_1(z, p_\perp)
\]

- Impact study with SoLID Collins asymmetries and e+e- data from BELLE and BABAR
- TMD evolution included
Tensor Charge

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

- Lowest moment of transversity
- Fundamental quantity of nucleon. Valence quark dominant.
- Provide constraints on quark EDMs

\[ \delta_T = \int_0^1 \left[ h_1(x) - h_0(x) \right] dx \]
SoLID Impact on Sivers

- **Sivers distribution**

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

- Relates to intrinsic parton motion
- Connected to orbital momentum
- Sivers sign change: Important test for QCD factorization

\[ f^{\text{SIDIS}}_{q/h^1}(x, k_T, Q^2) = -f^{\text{DY}/W^*/Z}_{q/h^1}(x, k_T, Q^2) \]
SoLID Impact on Sivers

- **Sivers distribution**

\[ A_{UT}^{\sin(\phi_h-\phi_S)} \sim f_{IT}^{1/2}(x, k_{\perp}) \otimes D_1(z, p_{\perp}) \]

- Relates to intrinsic parton motion
- Connected to orbital momentum
- Sivers sign change: Important test for QCD factorization

\[ f_{q/h_1}^{\text{SIDIS}}(x, k_T, Q^2) = -f_{q/h_1}^{\text{DY/W/Z}}(x, k_T, Q^2) \]

- Monte Carlo method with nested sampling algorithm
- TMD evolution is not included
Pretzelosity

\[A^\sin(3\phi_R-\phi_S) \sim h_{1T}^+(x, k_\perp) \otimes H_1^+(z, p_\perp)\]

- Measure relativistic effects of quark
- Interference of light-front wave functions differing by \(\Delta L = 2\)
- Related to OAM (model dependent)

\[L_z = -\int dx \, d^2k \, \frac{k^2}{2M^2} \, h_{1T}^+(x, k^2)\]

Also, Worm-gear: Interference between \(L=0\) and \(L=1\) states

\(Q^2=2.41\ \text{GeV}^2\)

95% C.L.

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

Lefky et al. (2015)
SoLID projection
Kaon SIDIS Program

- Provide important input to separate contributions from all light flavors combined with pion measurements
- Unique sensitivity to sea quarks
- Recent theory development on a criteria to separate fragmentation regions: *Phys. Lett. 639 B 766, 245 (2017)*

\[
R_1 = \frac{P_h \cdot k_f}{P_h \cdot k_i}
\]

- 20% of data from Current fragmentation region
Kaon SIDIS Program

- New run group proposal submitted to PAC46
- Run in parallel with already approved SoLID experiments with existing experimental setups
- Extract the Kaon Collins, Sivers, and other TMD asymmetries in offline analysis
- K/π separation up to 7 GeV/c with Heavy Gas Cherenkov and MRPC TOF detectors
Kaon Identification

- Combination of the Heavy Gas Cherenkov and MRPC
- Heavy Gas Cherenkov:

  - U of Regina is producing one sector from their R&D grant
  - The HGC uses C4F8O/C4F10 gas at 1.5 atm under 20 C
  - Designed for pi/K separation from 2.2 GeV/c to 7 GeV/c
  - During the offline analysis, the veto signals of the HGC can suppress pions and detect kaons
  - Preliminary Geant4 simulation study shows that the HGC can suppress pions by 1/100 at 2.5 GeV/c and by 1/400 at 7 GeV/c
Kaon Identification

- Combination of the Heavy Gas Cerenkov and MRPC
- MRPC Time of Flight (TOF) detector:

  The TOF-Beta has been a powerful quantities to perform PID

  Particles with same momenta but different masses spend different amount of time when travelling the same distance:

  $\Delta t = t_1 - t_2 \simeq \frac{Lc}{2p^2}(m_1^2 - m_2^2)$

  Clean separation of Kaons and protons even with 50 ps time resolution up to 7 GeV/c
  pi/K up separation up to 7 GeV/c with 20 ps time resolution and 6 GeV/c with 30 ps time resolution.

  R&D progress from the Chinese collaboration
  - Recent cosmic test shows ~27 ps time resolution
  - Further improvement in electronics and reconstruction method as well as in-beam test plan
Kaon Identification

MRPC-TOF performs better pi/K separation at lower momenta

HGC performs better pi/K separation at higher momenta

Take into account the “actual” pi/K ratios at different momenta + the HGC suppression factors on pions
Kinematic Coverage

SoLID-SIDIS with NH3 at 11GeV

SoLID-SIDIS with He3 at 11GeV
3He Projection

- 4D binning ($Q^2$, $z$, $p_T$, $x$) for He3 setup
- Total 430 bins

- Kinematic cuts applied:
  $Q^2 > 1$ GeV$^2$, $W > 2.3$ GeV, $W' > 1.6$ GeV
- Total detector efficiency of 85% assumed
NH3 Projection

- 3D binning (z, \( p_T \), x), integrated over \( Q^2 \)
- 120 bins for Sivers and Collins TSA separately
Summary

- SoLID has Rich, highly rated physics program to address important questions in Nuclear physics
- SIDIS program provides high precision data for 3D imaging of nucleon structure
- New proposal on the Kaon SIDIS measurements has been submitted to PAC46
- Addressed Director’s Review Recommendations and updated pre-CDR submitted
- Progress is being made in simulation studies, pre R&D
- Working toward a DOE Science Review
backup
The systematic budgets of the Kaon measurements is almost same as the pion measurements
- Additional 3% due to the pion contamination
From 1D structure of nucleon

Three parton distribution functions unveil the information on the internal structure of hadrons at leading order in a collinear framework

- **Unpolarized PDFs**: quark with a momentum fraction $x$ in a nucleon
- **Helicity PDFs**: quark with spin parallel to the nucleon spin in a longitudinally polarized nucleon
- **Transversity PDFs**: quark with spin parallel to the nucleon spin in a transversely polarized nucleon
2+1D Imaging of Nucleon Structure

- Imaging the transverse and longitudinal structure of the nucleon
- Confined motion of quarks and gluons inside the nucleon
- Spin-orbit correlations of quark-quark and quark-nucleon

Wigner Distributions

\( W(x, k_\perp, r_\perp) \)

Transverse Momentum Dependent Distributions (TMDs)

Generalized Parton Distributions (GPDs)

Momentum space

Coordinate space

Parton Distribution Functions

\( f(x) \)

Form Factors
## Leading Twist TMDs

*→ Nucleon spin  
→ Quark spin*

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<td>$f_1 = \bigcirc$</td>
<td>$h_1^\perp = \bigcirc - \bigcirc$ Boer-Mulders</td>
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<tr>
<td><strong>L</strong></td>
<td>$g_1 = \bigcirc - \bigcirc$ Helicity</td>
<td>$h_{1L}^\perp = \bigcirc - \bigcirc$ Worm Gear (Kotzinian-Mulders)</td>
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<td><strong>T</strong></td>
<td>$f_{1T}^\perp = \bigcirc - \bigcirc$ Sivers</td>
<td>$h_1 = \bigcirc - \bigcirc$ Transversity</td>
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<tr>
<td></td>
<td>$g_{1T} = \bigcirc - \bigcirc$ Worm Gear</td>
<td>$h_{1T}^\perp = \bigcirc - \bigcirc$ Pretzelosity</td>
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Leading Twist TMDs

- Nucleon spin
- Quark spin

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E12-10-006: Single Spin Asymmetry in SIDIS on Transversely Polarized 3He (90 days)
E12-11-008: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)
Leading Twist TMDs

- Nucleon spin
- Quark spin

### Table: Quark polarization

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**E12-11-007:** Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized 3He (35 days)

- $g_1$: Helicity
- $f_{1T}^\perp$: Sivers
- $g_{1T}$: Worm Gear
- $h_{1L}^\perp$: Worm Gear (Kotzinian-Mulders)
- $h_1$: Transversity
- $h_{1T}^\perp$: Pretzelosity
Access TMDs with SIDIS

- Access all 8 leading-twist TMDs
- SIDIS differential cross section

\[
\frac{d\sigma}{dxdydzdP_T^2d\phi_hd\phi_S} = \frac{\alpha^2}{xyQ^2} \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \epsilon F_{UU,L} + \sqrt{2\epsilon(1+\epsilon)} F_{UU}^{\cos\phi_h} \cos\phi_h + \epsilon F_{UU}^{\cos2\phi_h} \cos2\phi_h + \lambda_\epsilon \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin\phi_h} \sin\phi_h \\
+ S_L \sqrt{2\epsilon(1+\epsilon)} F_{UL}^{\sin\phi_h} \sin\phi_h + \epsilon F_{UL}^{\sin2\phi_h} \sin2\phi_h \right\} \left[ 1 - \epsilon^2 F_{LL}^{\cos\phi_h} \cos\phi_h \\
+ S_T \left( F_{UT,L}^{\sin(\phi_h-\phi_s)} + \epsilon F_{UT,L}^{\sin(\phi_h-\phi_s)} \right) \sin(\phi_h - \phi_s) + \epsilon F_{UT}^{\sin(\phi_h+\phi_s)} \sin(\phi_h + \phi_s) + \epsilon F_{UT}^{\sin(3\phi_h-\phi_s)} \sin(3\phi_h - \phi_s) \\
+ \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin\phi_s} \sin\phi_s + \sqrt{2\epsilon(1+\epsilon)} F_{UT}^{\sin(2\phi_h-\phi_s)} \sin(2\phi_h - \phi_s) \right\} \\
+ \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos\phi_s} \cos\phi_s + \sqrt{2\epsilon(1-\epsilon)} F_{LT}^{\cos(2\phi_h-\phi_s)} \cos(2\phi_h - \phi_s) \right\} \\
\]

- Target Single Spin Asymmetry
  \[ A_{UT} = \frac{1}{P} N^\uparrow - N^\downarrow \]
  \[ A_{UT} = A_{UT}^{\text{Collins}} \sin(\phi_h + \phi_s) + A_{UT}^{\text{Sivers}} \sin(\phi_h - \phi_s) + A_{UT}^{\text{Pretzelosity}} \sin(3\phi_h - \phi_s) + \ldots \]

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<tr>
<th>TMDs via SIDIS</th>
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<td><strong>Nucleon Polarization</strong></td>
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<td>U</td>
<td>( F_{UU} \propto f_1 \otimes D_1 )</td>
<td>( F_{UU}^{\cos2\phi_h} \propto h_+ \otimes H_+^\perp )</td>
<td>( F_{UU}^{\cos2\phi_h} \propto h_+ \otimes H_+^\perp )</td>
</tr>
<tr>
<td>L</td>
<td>( A_{UL} \propto g_1 \otimes D_1 )</td>
<td>( A_{UL}^{\sin2\phi_h} \propto h_L \otimes H_+^\perp )</td>
<td>( A_{UL}^{\sin2\phi_h} \propto h_L \otimes H_+^\perp )</td>
</tr>
<tr>
<td>T</td>
<td>( A_{UT}^{\sin(\phi_h-\phi_s)} \propto f_1 \otimes D_1 )</td>
<td>( A_{UT}^{\cos(\phi_h+\phi_s)} \otimes g_1 \otimes D_1 )</td>
<td>( A_{UT}^{\sin(\phi_h+\phi_s)} \otimes h_+ \otimes H_+^\perp )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>( A_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T} \otimes H_+^\perp )</td>
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Boer-Mulders
Helicity
Transversity
Pretzelosity
6 GeV results
6 GeV result

![Graph showing Neutron and π⁺, π⁻ results with various models compared.](image)
criteria
Kaon Identification

- Multiple-gaps Resistant-Plate Chamber (MRPC):
  - The SoLID TOF detector is the MRPC (50 super-modules w/ 3MRPC modules for each super-module)
  - Each MRPC contains 10 gas gaps (0.25mm each gas layer + 0.7mm each glass)
  - Maximum rate capability – 50 KHz/cm².

- The MRPC prototype built by Tsinghua University had 50 ps resolution with 95% efficiency with cosmic ray.
- The beam-test during G2p experiment showed 80 ps resolution with 94% efficiency at 15 KHz/cm².
Physics Projection

- Monte-Carlo Simulation
  - Use the conventional SIDIS event generator used for SoLID, but with improved models for Kaons
  - Generate events uniformly in a phase-space larger than the SoLID acceptance
  - Use Geant4-GEMC to obtain the acceptance of electrons and kaons in SoLID
  - Built in polarization, detector efficiency, approved beam-time, target luminosities, etc., from the approved pion experiments.

<table>
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<th>Polarized Target</th>
<th>$^3\text{He}$ (”n”)</th>
<th>NH$_3$ (”p”)</th>
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<tr>
<td><strong>Beam Energy</strong></td>
<td>8.8 GeV</td>
<td>11 GeV</td>
</tr>
<tr>
<td>e-(FAEC+LAEC)+$K^+$ (FAEC)</td>
<td>359.3</td>
<td>575.6</td>
</tr>
<tr>
<td>e-(LAEC+LAEC)+$K^-$ (FAEC)</td>
<td>83.2</td>
<td>144.1</td>
</tr>
<tr>
<td>e-(FAEC+LAEC)+$\pi^+$ (FAEC)</td>
<td>1555.0</td>
<td>2185.9</td>
</tr>
<tr>
<td>e-(LAEC+LAEC)+$\pi^-$ (FAEC)</td>
<td>1012.5</td>
<td>1449.6</td>
</tr>
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</table>
Acceptance and Kinematic Coverage

SoLID-SIDIS with NH3 at 11GeV

SoLID-SIDIS with He3 at 11GeV
3He Projection - Collins

- 4D binning ($Q^2$, $z$, $p_T$, $x$) for He3 setup
- Total 430 bins

Kinematic cuts applied:
$Q^2 > 1 \text{ GeV}^2$, $W > 2.3 \text{ GeV}$, $W' > 1.6 \text{ GeV}$, $0.3 < z < 0.7$
- Total detector efficiency of 85% assumed
3He Projection - Sivers

- 4D binning for He3 setup
- Total 430 bins

(a) $\bar{n}(e, e'K^+)X$

(b) $\bar{n}(e, e'K^-)X$
NH3 Projection

- 3D binning ($z$, $p_T$, $x$), integrated over $Q^2$
- 120 bins for Sivers and Collins TSA separately