Overview and status of SoLID

JLab Hall A Collaboration Meeting
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Duke University
On behalf of the SoLID collaboration
Outline

• Introduction

• The three pillars of the SoLID program
  ➢ SIDIS
  ➢ PVDIS
  ➢ $J/\Psi$ production near threshold

• Status of SoLID program

• Summary
High precision in multi-dimension or small cross-section processes requires very high statistics

Essence of large acceptance and high luminosity

SoLID will maximize the science return of the 12-GeV CEBAF upgrade by combining

- SIDIS
  - Approved experiments: E12-10-006, E12-11-007 and E12-11-108
  - Aims to measure the Transverse Momentum Dependent PDFs (TMDs) with ultimate precision

- Parity Violating Deep Inelastic Scattering (PVDIS) at high x region
  - Approved experiment E12-10-007
  - Provide sensitivity to new physics at 10-20 TeV

- $J/\Psi$ production near threshold
  - Approved experiment E12-12-006
  - Provides information on trace anomaly, which is very important part for the origin of proton mass

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- SIDIS and Subsystems

- Coincidence detection of electrons and charged pions
- $^3$He target: transverse and longitudinal polarization
- NH$_3$ target: transverse polarization
- Large acceptance with full azimuthal coverage
- DAQ rate: up to 100 kHz (unpol. Lumi $10^{37}$ cm$^{-2}$ s$^{-1}$ ($^3$He))

- Target is located upstream
- 8 detectors inside the coil
- MRPC not included in baseline but if include increase the time resolution of the setup

Run group experiments approved for TMDs, GPDs, and spin

- E12-10-006: Single Spin Asymmetries on Transversely Polarized $^3$He @ 90 days
  Spokespersons: J.P. Chen, H. Gao (contact), J.C. Peng, X. Qian

- E12-11-007: Single and Double Spin Asymmetries on Longitudinally Polarized $^3$He @ 35 days
  Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

- E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days
  Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani
TMDs- confined motion inside the nucleon

**Transversely Polarized Nucleon TMDs**
- **Nucleon Spin**
- **Quark Spin**

**Relevant Vectors**
- $S_T$: Nucleon Spin
- $s_q$: Quark Spin
- $k_\perp$: Quark Transverse Momentum
- $P$: Virtual photon 3-momentum (defines z-direction)

**Leading twist: 8 TMDs**

<table>
<thead>
<tr>
<th>Quark polarization</th>
<th>Un-Polarized</th>
<th>Longitudinally Polarized</th>
<th>Transversely Polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucleon Polarization</td>
<td>$f_1 = \circ$</td>
<td>$g_1 = \circ$</td>
<td>$h_{1T} = \uparrow - \downarrow$</td>
</tr>
<tr>
<td>$L$</td>
<td>Helicity</td>
<td>$h_{1L} = \downarrow - \uparrow$</td>
<td></td>
</tr>
<tr>
<td>$T$</td>
<td>$f_{1T} = \circ - \circ$</td>
<td>$g_{1T} = \circ - \circ$</td>
<td>$h_{1T} = \uparrow - \rightarrow$</td>
</tr>
<tr>
<td>$B$</td>
<td>Boer-Mulder</td>
<td></td>
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**Sivers**
- $f_{1T}^{\perp} = \circ - \circ$
- $S_T \cdot k_\perp \times P$

**Transversity**
- $h_{1T} = \uparrow - \downarrow$
- $S_T \cdot s_q$

- $h_{1T}$ ($h_1$) = $g_1$ (no relativity)
- $h_{1T}$ tensor charge
- Connected to nucleon beta decay and EDM

**Pretzelosity**
- $h_{1T}^{\perp} = \circ - \circ$
- $S_T \cdot [k_\perp k_\perp] \cdot s_{qT}$

- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

Nucleon spin - quark orbital angular momentum (OAM)
Correlation - zero if no OAM (model dependence)
Separation of Collins, Sivers, and Pretzelosity through angular dependence

- SIDIS SSAs depend on 4-D variables \((x, Q^2, z, P_T)\)
- Small asymmetries demand large acceptance + high luminosity
- SoLID allows measuring asymmetries in 4-D binning with precision!

\[
A_{UT}(\phi_h, \phi_S) = \frac{1}{P_{t, pol}} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}
\]

\[
= A_{Collins}^{UT} \sin(\phi_h + \phi_S) + A_{Pretzelosity}^{UT} \sin(3\phi_h - \phi_S) + A_{Sivers}^{UT} \sin(\phi_h - \phi_S)
\]

\[A_{Collins}^{UT} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^\perp\]

Collins fragmentation function from e^+e^- collisions

\[A_{Pretzelosity}^{UT} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_1^T \otimes H_1^\perp\]

Unpolarized fragmentation function

\[A_{Sivers}^{UT} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1\]
SoLID SIDIS Projection

Compare SoLID with World Data

- Fit Collins and Sivers asymmetries in SIDIS and $e^+e^-$ annihilation
- World data from HERMES, COMPASS
- $e^+e^-$ data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Including both systematic and statistical uncertainties

SoLID baseline used

Anselmino et al., JHEP 04 (2017) 046
PVDIS @ Solid: Experiment E12-10-007

- 12 GeV CEBAF provides extraordinary opportunity to do the ultimate PVDIS measurement
- Better than 1% statistical errors over broad kinematic range: sensitive Standard Model test and detailed study of hadronic structure contributions
- CLEO magnet with the LD$_2$ or LH$_2$ target in the center provides the desired acceptance
- Kinematic requirements
  \[ x_B [0.25 – 0.7], \quad W^2 > 4\text{GeV}^2, \quad Q^2 \text{ range a factor of 2 in each } x \text{ bin} \]
- Achieving High luminosity: 50 μA beam, 40 cm LD$_2$ target, high rate GEM tracking
- Baffle provides curved channels that blocks positive and neutral background particles
- PID and trigger: LGC identify $e^-$ for trigger, EMCal (coincident trigger, further PID)

Spokesperson: Paul Souder
Parity Violating Deep Inelastic Scattering (PVDIS)

Off the simplest isoscalar nucleus and at high Bjorken-x

\[ A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi \alpha} \left[ g_A \frac{F_1^{\gamma Z}}{F_1^\gamma} + g_V \frac{f(y) F_3^{\gamma Z}}{2 F_1^\gamma} \right] \]

\[ Q^2 > 1 GeV^2, \quad W^2 > 4 GeV^2 \]

\[ A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi \alpha} \left[ a(x) + f(y)b(x) \right] \]

At high x, \( A_{iso} \) becomes independent of pdfs, x & W, with well-defined SM prediction for \( Q^2 \) and y

\[ A_{iso} = \frac{\sigma^r - \sigma^l}{\sigma^r + \sigma^l} \]

\[ = - \left( \frac{3G_F Q^2}{\pi \alpha 2\sqrt{2}} \right) \frac{2C_{1u} - C_{1d} (1 + R_s)}{5 + R_s} + Y \left( 2C_{2u} - C_{2d} \right) R_v \]

\[ R_s(x) = \frac{2S(x)}{U(x) + D(x)} \quad \text{Large } x \to 0 \]

\[ R_v(x) = \frac{u_v(x) + d_v(x)}{U(x) + D(x)} \quad \text{Large } x \to 1 \]

Interplay with QCD

- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT) – quark-quark correlation
Projected Results

Improvement in couplings

- Measure the d/u ratio for the proton at high x
- PVDIS is complementary to the rest of the JLab d/u program
- PVDIS has no nuclear effects
J/Ψ production near Threshold @SoLID: Experiment E12-12-006

- 50 days of 3 μA beam on a 15 cm long LH$_2$ target (10$^{37}$ cm$^{-2}$ s$^{-1}$)
- 10 more days including calibration/background run
- SoLID configuration overall compatible with SIDIS
- Electroproduction trigger: 3-fold coincidence of e, e$^-e^+$
- Photoproduction trigger: 3-fold coincidence of p, e$^-e^+$
- Additional trigger: 4-fold coincidence of ep, e$^-e^+$
- And (inclusive) 2-fold coincidence e$^+e^-$

\[ e^- + p \rightarrow e^- + p + J/\psi (e^+ + e^-) \]

\[ \gamma p \rightarrow p' J/\psi(e^-e^+) \]

Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao
Proton Mass and Trace Anomaly

- Ji’s mass decomposition: \( M_N = M_q + M_m + M_g + M_\alpha \)

  - Quarks kinetic and potential energy \( M_q = \frac{3}{4} \left( a - \frac{b}{1 + \gamma_m} \right) M_N \)
  - Gluons kinetic and potential energy \( M_g = \frac{3}{4} (1 - a) M_N \)
  - Quarks masses \( M_m = \frac{4 + \gamma_m}{4(1 + \gamma_m)} M_N \)
  - Trace anomaly \( M_\alpha = \frac{1}{4} (1 - b) M_N \)

- Access the trace anomaly using VMD and photo-production \( J/\psi \) cross section:

\[
\left. \frac{d\sigma_{\gamma N \rightarrow J/\psi N}}{dt} \right|_{t=0} = \frac{3 \Gamma(J/\psi \rightarrow e^+e^-)}{\alpha m_{J/\psi}^2} \left( \frac{k_{J/\psi N}}{k_{\gamma N}} \right)^2 \left. \frac{d\sigma_{J/\psi N \rightarrow J/\psi N}}{dt} \right|_{t=0} = \frac{1}{64\pi} \frac{1}{m_{J/\psi}^2 (\lambda^2 - m_N^2)} \left| F_{J/\psi N} \right|^2
\]

- First three contributions can be determined from PDFs and pi-N sigma term and also from lattice QCD

- Measuring quantum anomalous energy contribution in experiments is an important goal in the future
  - Can be accessed through heavy quarkonium threshold, \( J/\Psi \) and Upsilon production

R. Wang, X. Chen and J. Evslin
EPJC 80, no.6 507 (2020)
Sensitivity at threshold at about $10^{-3} \text{ nb}$!
GPDs program at SoLID

Following the 2015 Director’s Review recommendation “The SoLID Collaboration should investigate the feasibility of carrying out a competitive GPD program. Such a program would seem particularly well suited to their open geometry and high luminosity”, there are several GPD experiments in different stages of study/approval:

- Deep Exclusive $\pi$ Production using Transversely Polarized $^3$He Target
  - G.M. Huber, Z. Ahmed, Z. Ye
  - Approved as run group with Transverse Pol. $^3$He SIDIS (E12-10-006B)

- Timelike Compton Scattering (TCS) with circularly polarized beam and unpolarized LH$_2$ target
  - Z.W. Zhao, P. Nadel-Turonski, J. Zhang, M. Boer
  - Approved as run group with J/$\psi$ (E12-12-006A)

- Double Deeply Virtual Compton Scattering (DDVCS) in di–lepton channel on unpolarized LH$_2$ target
  - E. Voutier, M. Boer, A. Camsonne, K. Gnanvo, N. Sparveri, Z. Zhao
  - LOI12-12-005 reviewed by PAC43

- DVCS on polarized proton and 3He targets
  - Z.Y. Ye, N. Liyanage, W. Xiong, A. Cansomme and Z.H. Ye (under study)
Approved SoLID run group experiments

- **SIDIS Dihadron with Transversely Polarized $^3\text{He}$**
  J.-P. Chen, A. Courtoy, H. Gao, A. W. Thomas, Z. Xiao, J. Zhang
  Approved as run group (E12-10-006A)

- **SIDIS in Kaon Production with Transversely Polarized Proton and $^3\text{He}$**
  T. Liu, S. Park, Z. Ye, Y. Wang, Z.W. Zhao
  Approved as run group (E12-11-108B/E12-10-006D)

- **$A_y$ with Transversely Polarized Proton and $^3\text{He}$**
  T. Averett, A. Camsonne, N. Liyanage
  Approved as run group (E12-11-108A/E12-10-006A)

- **$g_2n$ and $d_2n$ with Transversely and Longitudinally Polarized $^3\text{He}$**
  C. Peng, Y. Tian
  Approved as run group (E12-11-007A/E12-10-006E)
Timeline

- Since 2010: Five SolID experiments approved by PAC with high rating
  - 3 SIDIS with polarized $^3$He/$p$ target, 1PVDIS, 1 threshold $J/\Psi$
  - Six additional run-group experiments approved
  - SolID collaboration, with JLab support, has been continuously working on pre-conceptual design and pre-R&D

- 2013: CLEO-II magnet requested, agreed, arrived at JLab 2016
- 2014: pCDR submitted to JLab with cost estimation
- 2015: 1st Director’s Review: positive with many recommendations
- 2017: Updated pCDR submitted to JLab with responses to the recommendations
- 2018: DOE NP visit and discussion: update cost estimation
- 1/2019: Updated pCDR (new cost estimation) submitted to JLab
- 9/2019: 2nd Director’s Review: successful with only few recommendations
- Late 2019: Pre-R&D plan approved, funding started 2/2020
- 2/2020: SolID MIE (with updated pCDR) submission to DOE
- 3/2021: SolID DOE science review
Cherenkov Beam Test

- **Detector package**
  - Cherenkov tank (CO$_2$ at 1 atm)
  - 2 Scintillator planes
  - 9 Calorimeter blocks
  - 16 MaPMTs (quadrant and sum channels) or LAPPD (64 pixels)

- Readouts: JLab FADC250

- MaPMTs tested, total rate up to 8MHz/PMT well above the SoLID running condition (4MHz/PMT)
- Observed rate agrees with the simulation
- MaPMT works well high-rate environment similar to SoLID
- LAPPD tested and performs well
Bench test setup for ring in MaPMT-MAROC

- Pulsed LED synchronized with clock for signal
- Second LED operated with DC voltage for continuous random background

\[
\text{Accuracy} = \frac{\text{Number of accepted signal events}}{\text{total signal events}}
\]

\[
\text{Accuracy} = \frac{\text{Number of rejected events}}{\text{total background events}}
\]

- LED background agrees well with the estimation
- Separation between signal and background peaks are very clear at lower rate, NPE cut is sufficient
- Above 200 kHz/pixel using Hough transformation we achieved accuracy >90%
Ecal Test at FermiLab Test Beam Facility (FTBF)

- Jan 13—27, 2021
- **Goal**: Determine the detector resolution and efficiency of preshower and shower calorimeter modules

**Detectors:**
- Preshower: 2-cm thick Pb blocks (x3)
- Shower: Shashlyk (Pb + scintillator layers), 80-cm long (x3)
- Scintillator used for triggering

**FNAL beam parameters**
- Composition: Mixture of e-, π-
- Energies: 1, 2, 4, 6, 8, 10, 12, 16 GeV

- Beam test with 3 modules of Ecal using the secondary electron and pion mixture beam at FTBF
- The position resolution of the Ecal and is 1.36 cm (horizontal) and 0.72 cm (vertical)

- Energy resolution of the Ecal \[ \frac{\sigma_E}{E} = 4.6\% \oplus \frac{10.4\%}{\sqrt{E}} \] **PRELIMINARY**
Further Updates

- Shipped from UofR and arrived Duke late Aug 2021, Stored at TUNL
- Including the tank and two aluminum windows and one carbon fiber window
- It can be used for mirror and readout mounting test in future. but we need to do standalone design and test first

Other ongoing tests

- GEM VMM3 testing on high-rate environment
- GEM APV25 test (backup plan)
- FADC fast readout and dead-time measurement for PVDIS
- Magnet cold test ongoing estimation in the summer
- Planned EC/DAQ test in Hall C
Summary

- **SoLID**: A **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab12 potential
  - pushing the limit of the luminosity frontier

- SoLID has rich and vibrant science programs complementary and synergistic to the proposed EIC science program
  - Three pillars on SIDIS, PVDIS and J/ψ production
  - A diverse set of approved run-group experiments including GPD program

- After a decade of hard work, we have a mature pre-conceptual design with expected performance to meet the challenging requirements for the three major science programs

- Recently completed the DOE science review (March 8-10, 2021)

- SoLID collaboration is active and international with many theory collaborators

- We welcome new collaborators!

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Slide courtesy: Haiyan Gao, Jian-Ping Chen, Zein-Eddine Meziani, Paul Souder, Vladimir Khachatryan, Jixie Zhang, Weizhi Xiong, Whit Seay

More information about SoLID @ https://solid.jlab.org