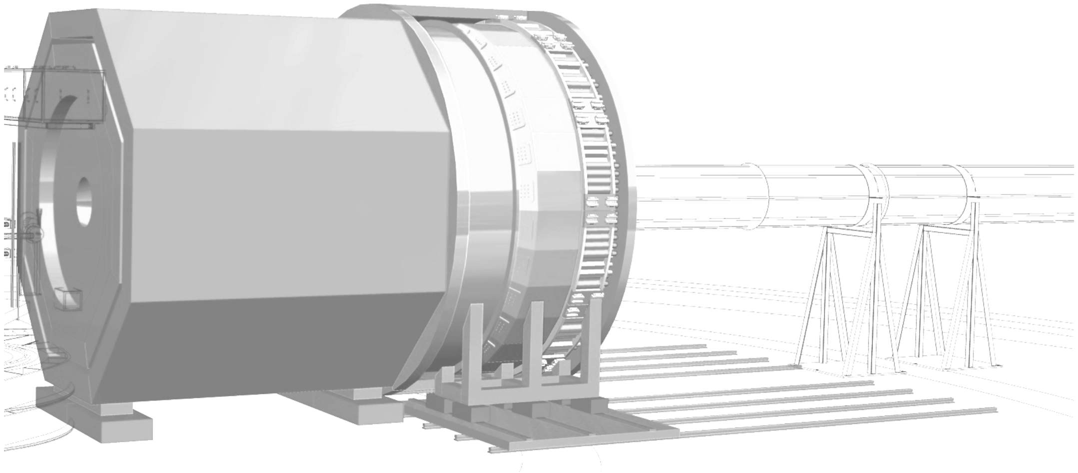
Overview and status of SoLID



JLab Hall A Collaboration Meeting

Feb 10-11, 2022

Bishnu Karki
Duke University
On behalf of the SoLID collaboration

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Outline

- Introduction
- The three pillars of the SoLID program
  - SIDIS
  - PVDIS
  - J/Ψ production near threshold
- Status of SoLID program
- Summary

Introduction

- 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

Large Acceptance	+	**High Luminosity**
Full azimuthal ϕ coverage		$10^{37\text{-}39}$ /cm^2/s
		[>100x CLAS12][>1000x EIC]

- 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

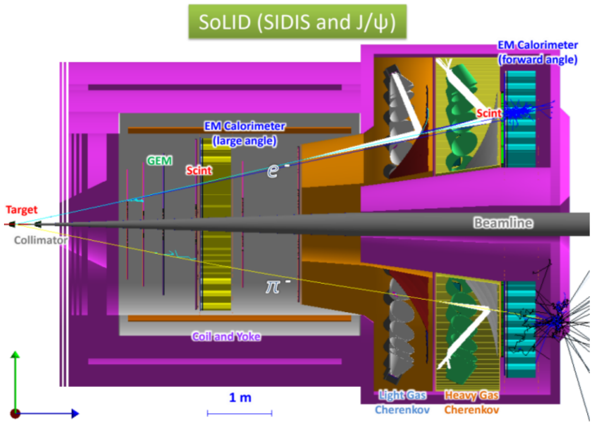
- Parity Violating Deep Inelastic Scattering (PVDIS) at high x region
  - Approved experiment E12-10-007
  - Provide sensitivity to new physics at 10-20 TeV

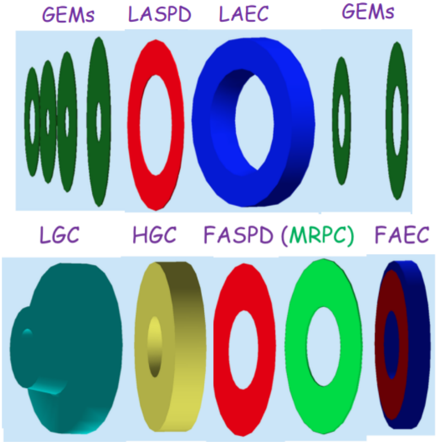
- J/Ψ production near threshold
  - Approved experiment E12-12-006
  - Provides information on trace anomaly, which is very important part for the origin of proton mass

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))





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

Run group experiments approved for TMDs, GPDs, and spin

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

TMDs- confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Relevant Vectors

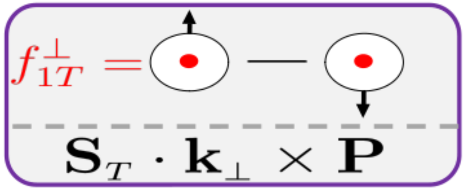
S_T: Nucleon Spin
s_q: Quark Spin
$k_\perp$: Quark Transverse Momentum
P: Virtual photon 3-momentum (defines z-direction)

→ Nucleon Spin
→ Quark Spin

Leading twist: 8 TMDs

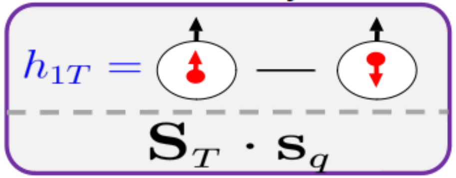
Nucleon Polarization	Quark polarization: Un-Polarized	Quark polarization: Longitudinally Polarized	Quark polarization: Transversely Polarized
U	$f_1 =$		$h_1^\perp =$ – Boer-Mulder
L		$g_1 =$ – Helicity	$h_{1L}^\perp =$ –
T	$f_{1T}^\perp =$ – Sivers	$g_{1T}^\perp =$ –	$h_{1T} =$ – Transversity $h_{1T}^\perp =$ – Pretzelosity

Sivers



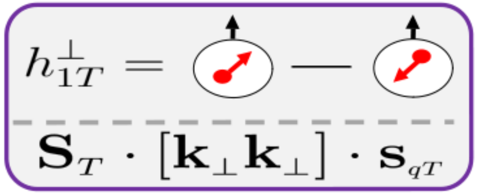
Nucleon spin - quark orbital angular momentum (OAM)
Correlation- zero if no OAM (model dependence)

Transversity



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

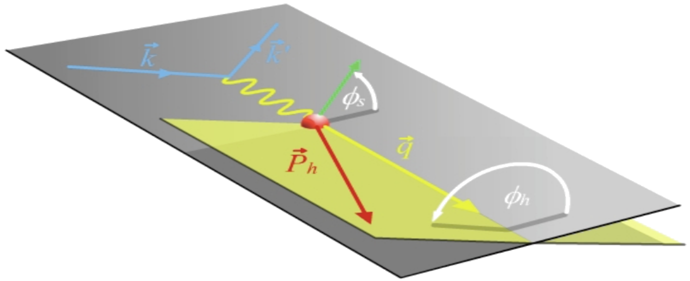
Pretzelosity



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

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!



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

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

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

$$\boxed{A_{UT}^{Pretzelosity}} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins fragmentation function from e^+e^- collisions

$$\boxed{A_{UT}^{Sivers}} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

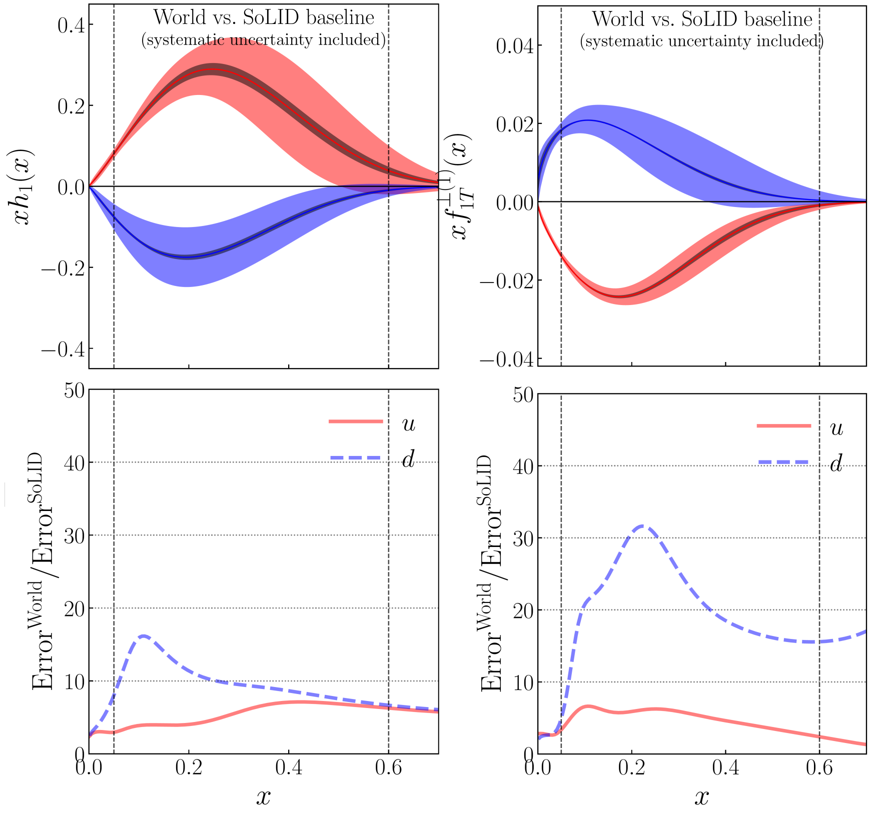
Unpolarized fragmentation function

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

Transversity **Sivers**



SoLID baseline used

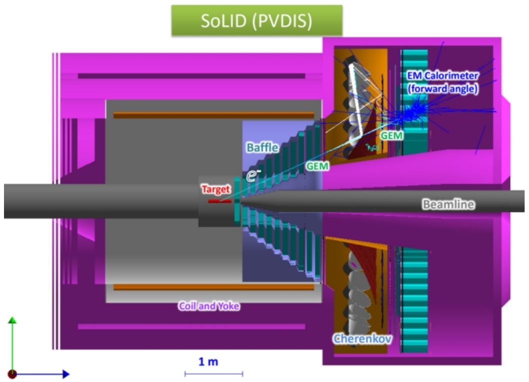
D'Alesio et al., Phys. Lett. B 803 (2020)135347
Anselmino et al., JHEP 04 (2017) 046

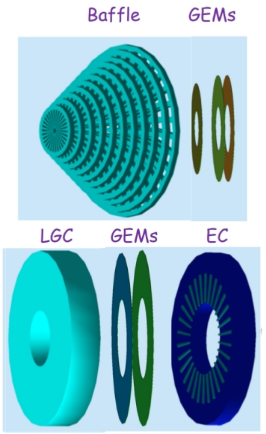
PVDIS @ SoLID:Experiment E12-10-007

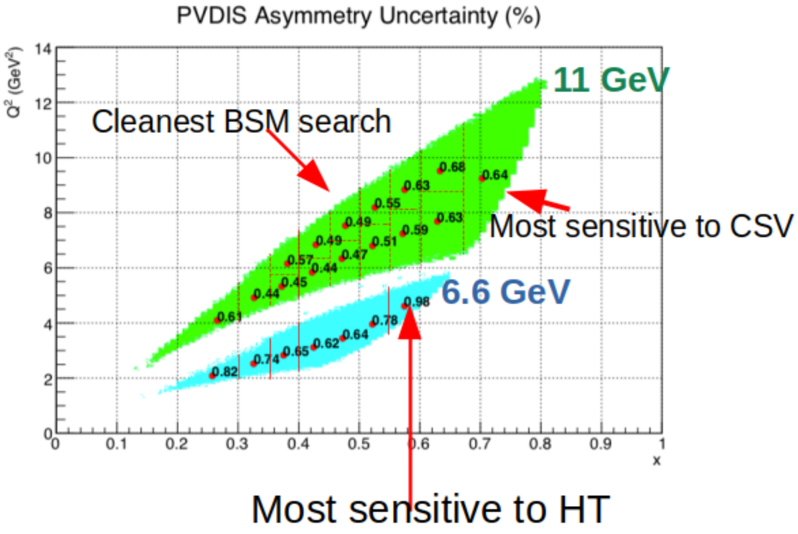
- 12 GeV CEBAF provides extraordinary opportunity to do the ultimate PVDIS measurement
- Better than 1% statistical errors over broad kinematic range: sensitive Standard Model test *and* detailed study of hadronic structure contributions
- CLEO magnet with the LD_2 or LH_2 target in the center provides the desired acceptance
- **Kinematic requirements**

  x_B [0.25 – 0.7], $W^2 > 4GeV^2$, Q^2 range a factor of 2 in each x 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)



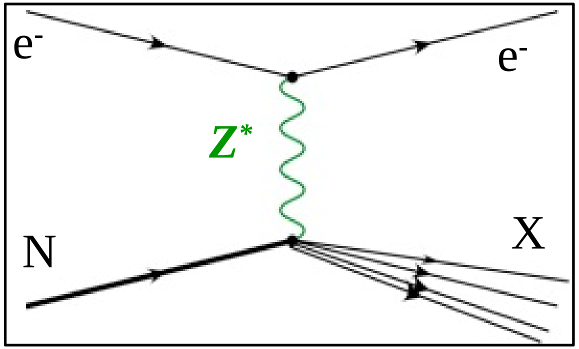




Spokesperson: Paul Souder

Parity Violating Deep Inelastic Scattering (PVDIS)

Off the simplest isoscalar nucleus and at high Bjorken-x



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

$$Q^2 > 1GeV^2,\ W^2 > 4GeV^2$$

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

$$x \equiv x_{Bjorken}$$

$$y \equiv 1 - E'/E$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$$

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

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

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

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

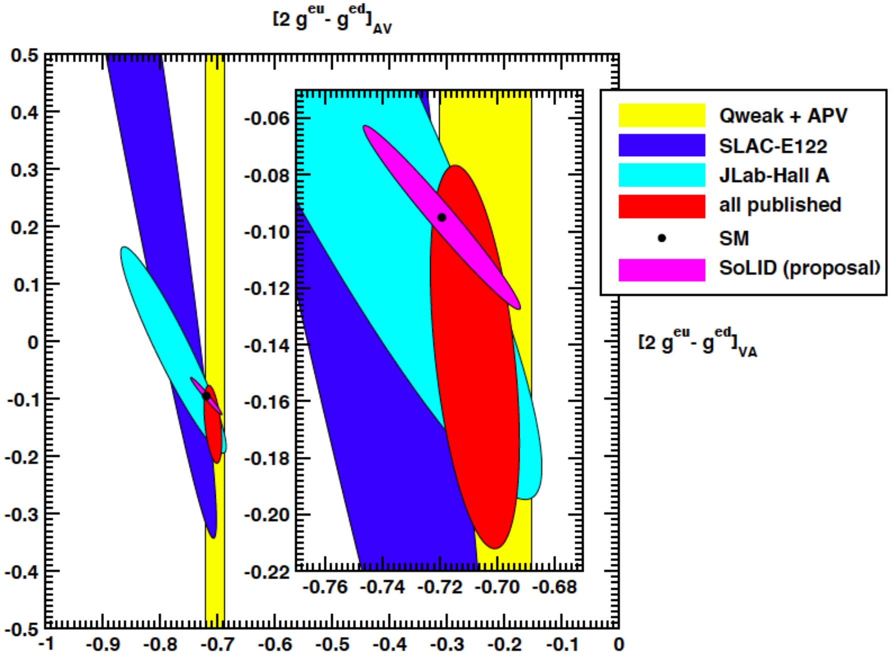
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

Interplay with QCD

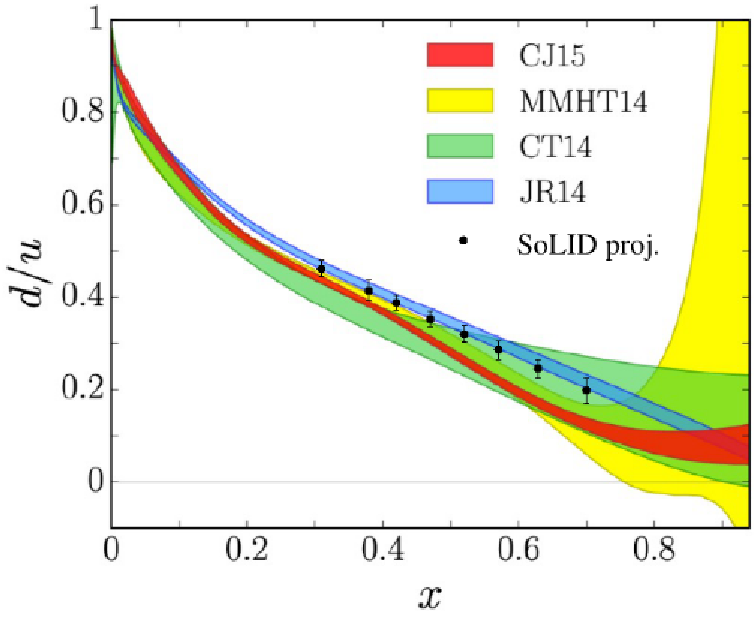
- **Parton distributions (u, d, s, c)**
- **Charge Symmetry Violation (CSV)**
- **Higher Twist (HT) – quark-quark correlation**

Projected Results

Improvement in couplings



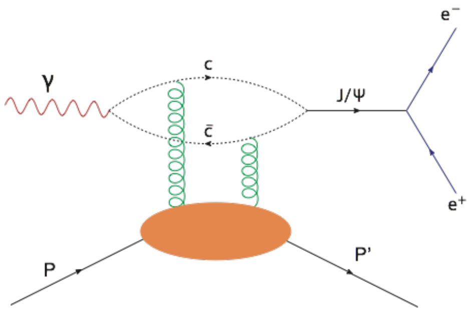
$$A^{p}_{PVDIS}(x) \approx \frac{u(x)+0.91\,d(x)}{u(x)+0.25\,d(x)}$$



- 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

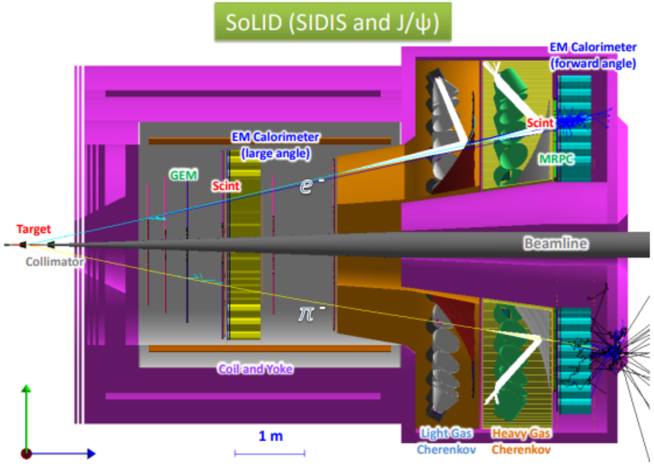
J/Ψ production near Threshold @SoLID: Experiment E12-12-006

- 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^-

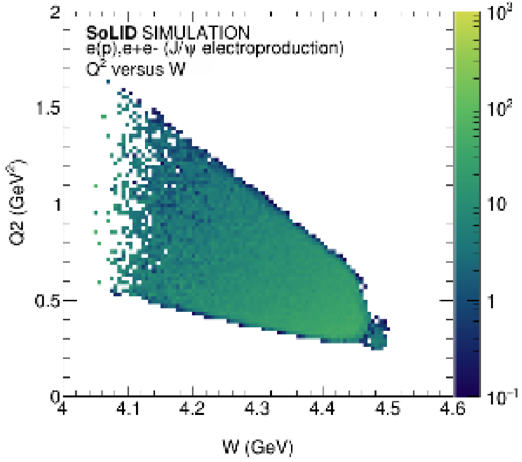


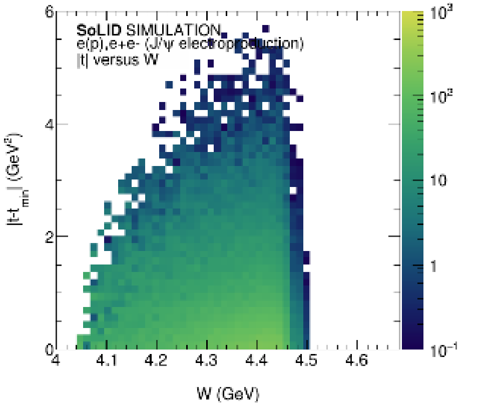
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

$$\gamma\, p \rightarrow p'\, J/\psi(e^-\, e^+)$$



Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao



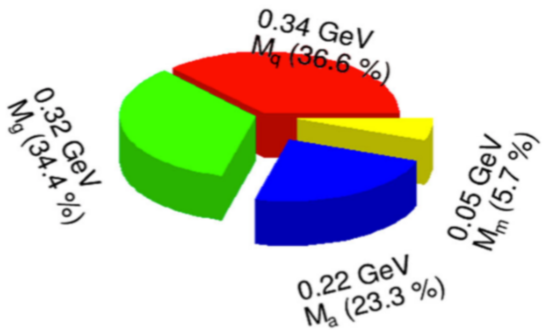


Proton Mass and Trace Anomaly

- Ji's mass decomposition: $M_N = M_q + M_m + M_g + M_a$

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	$M_a = \frac{1}{4}(1-b) M_N$

$\mu^2 = 4.0\ \mathrm{GeV}^2$



R. Wang, X. Chen and J. Evslin
EPJC 80, no.6 507 (2020)

- Access the trace anomaly using VMD and photo-production J/ψ cross section:

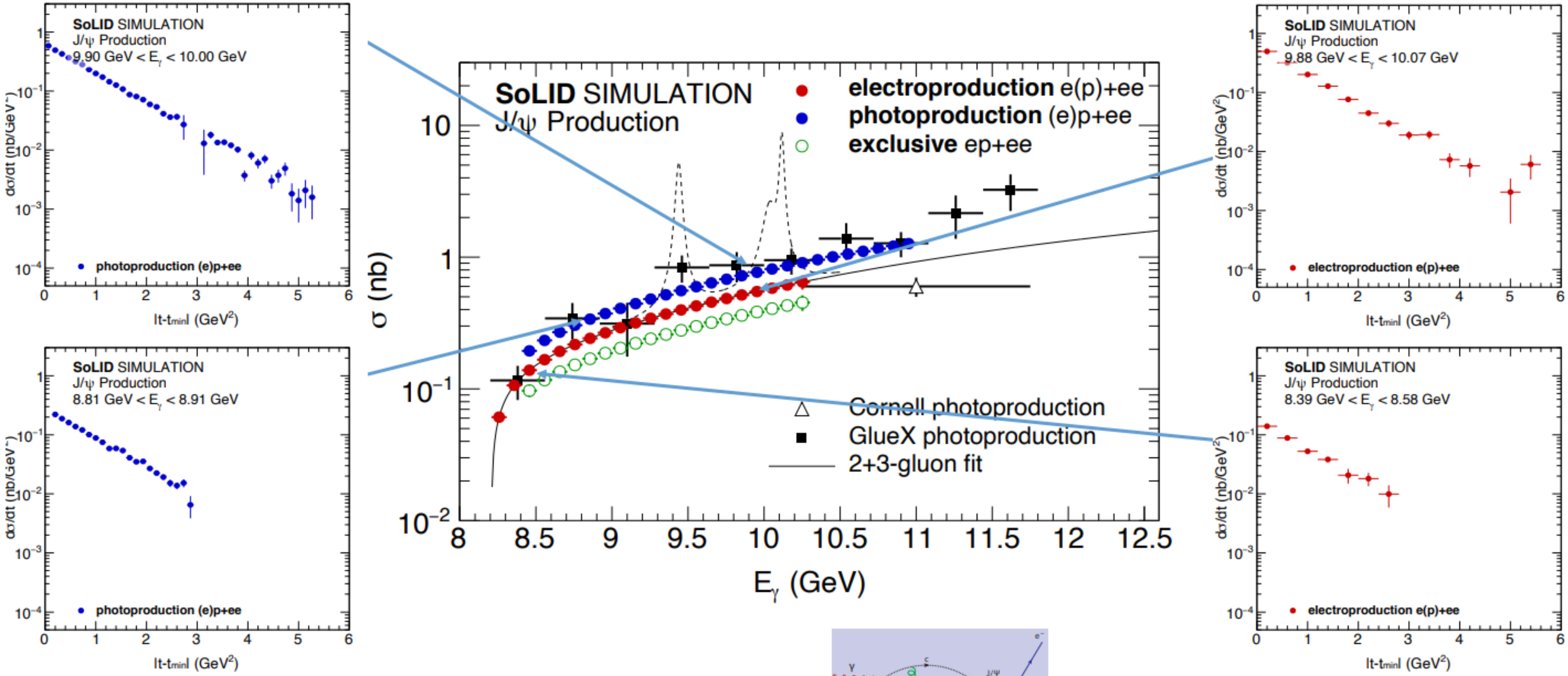
$$\left.\frac{d\sigma_{\gamma N \to J/\Psi N}}{dt}\right|_{t=0} = \frac{3\Gamma(J/\Psi \to e^+e^-)}{\alpha m_{J/\psi}} \left(\frac{k_{J/\Psi N}}{k_{\gamma N}}\right)^2 \left.\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\right|_{t=0}$$

$$\left.\frac{d\sigma_{J/\Psi N \to J/\Psi N}}{dt}\right|_{t=0} = \frac{1}{64\pi} \frac{1}{m_{J/\psi}^2(\lambda^2 - m_N^2)} |F_{J/\Psi N}|^2$$

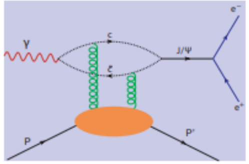
$$\boxed{F_{J/\Psi N} \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2(1-b)}$$

- 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 quarkionium threshold, J/Ψ and Upsilon production

SoLID J/Ψ Projections



Sensitivity at threshold at about 10^{-3} 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 π^- 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/ψ (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}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}He

  T. Liu, S. Park, Z. Ye, Y. Wang, Z.W. Zhao
  Approved as run group (E12-11-108B/E12-10-006D)

- Ay with Transversely Polarized Proton and ^{3}He

  T. Averett, A. Camsonne, N. Liyanage
  Approved as run group (E12-11-108A/E12-10-006A)

- g2n and d2n with Transversely and Longitudinally Polarized ^{3}He

  C. Peng, Y. Tian
  Approved as run group (E12-11-007A/E12-10-006E)

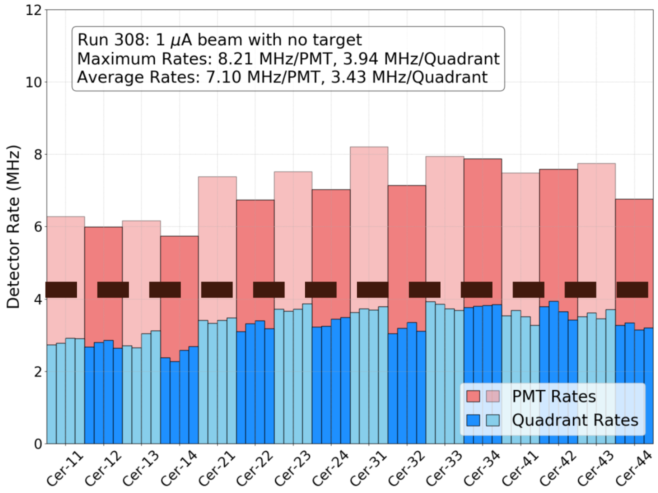
Timeline

- Since 2010: Five SoLID experiments approved by PAC with high rating
  - 3 SIDIS with polarized 3He/p target, 1PVDIS, 1 threshold J/Ψ
    - 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**

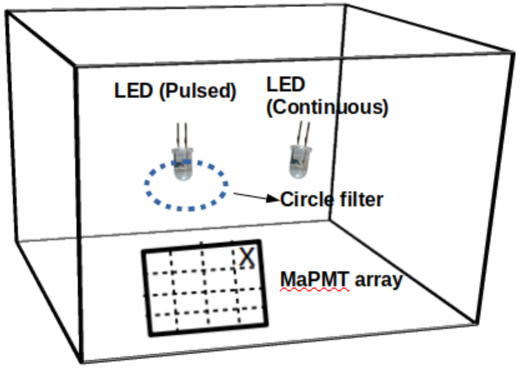
Cherenkov Beam Test

- **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



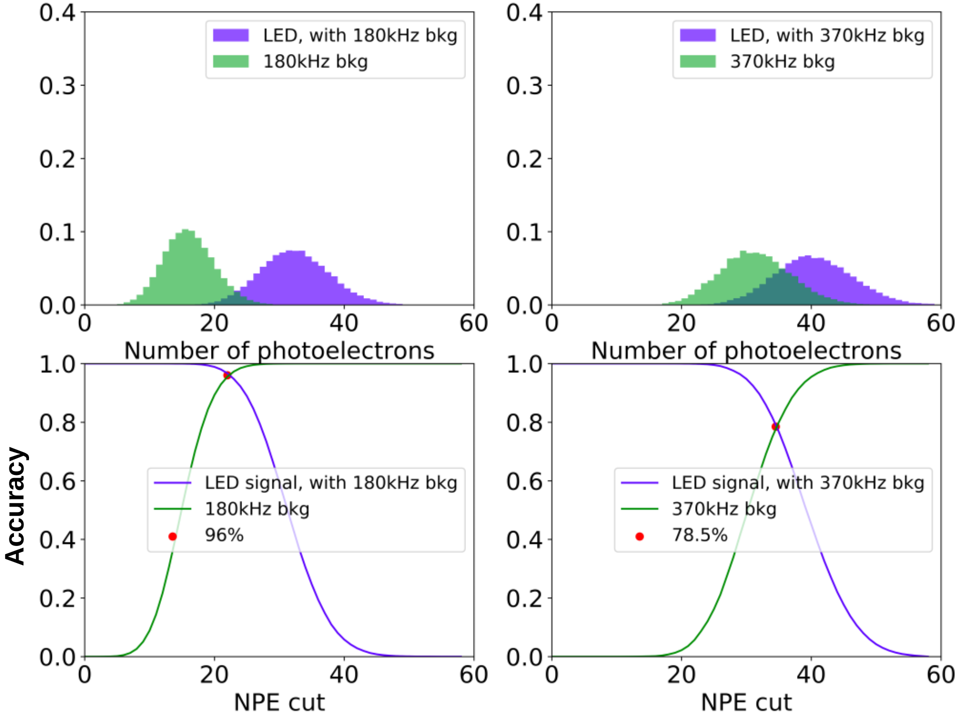
- MaPMTs tested, total rate up to 8MHz/PMT well above the SoLID running condition (4MHz/PMT)
- Observed rate agrees with the simulation
- MaPMT works well high-rate environment similar to SoLID
- LAPPD tested and performs well

Bench test setup for ring in MaPMT-MAROC

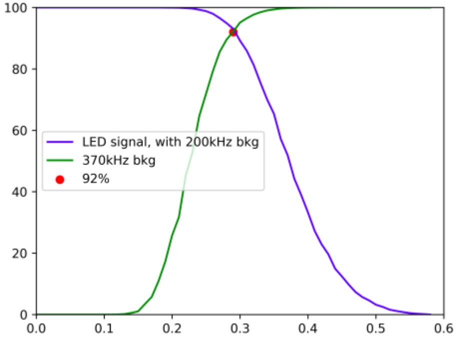


- Pulsed LED synchronized with clock for signal
- Second LED operated with DC voltage for continuous random background

NPE cut



Hough transform



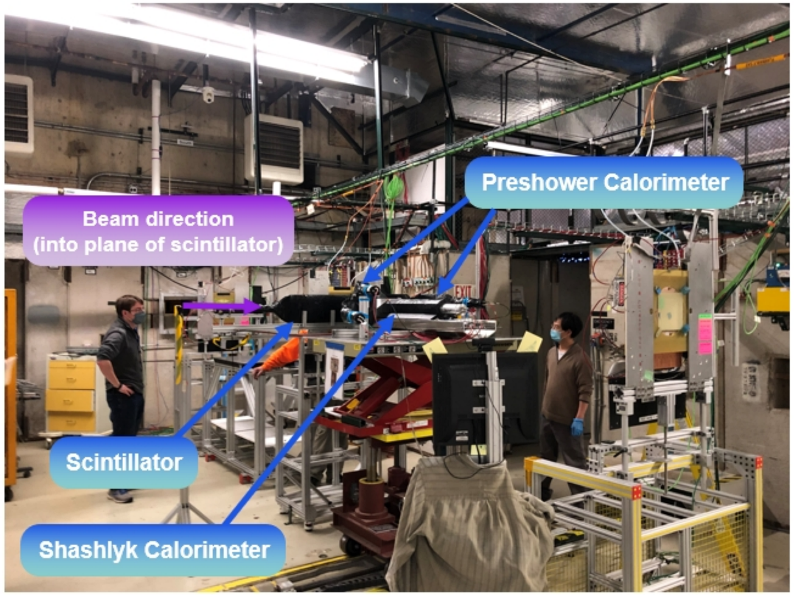
$$Accuracy = \frac{\text{Number of accepted signal events}}{\text{total signal events}}$$

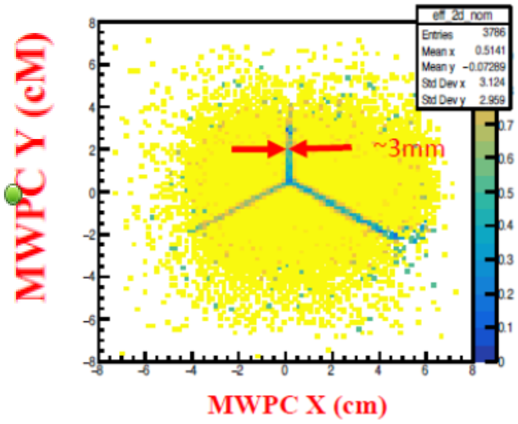
$$Accuracy = \frac{\text{Number of rejected events}}{\text{total background events}}$$

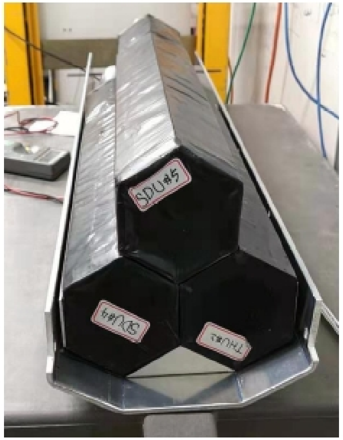
- LED background agrees well with the estimation
- Separation between signal and background peaks are very clear at lower rate, NPE cut is sufficient
- Above 200 kHz/pixel using Hough transformation we achieved accuracy >90%

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



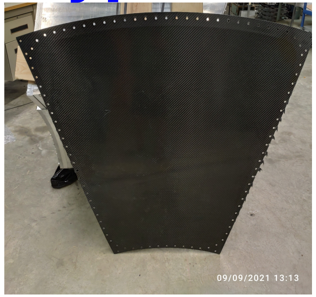


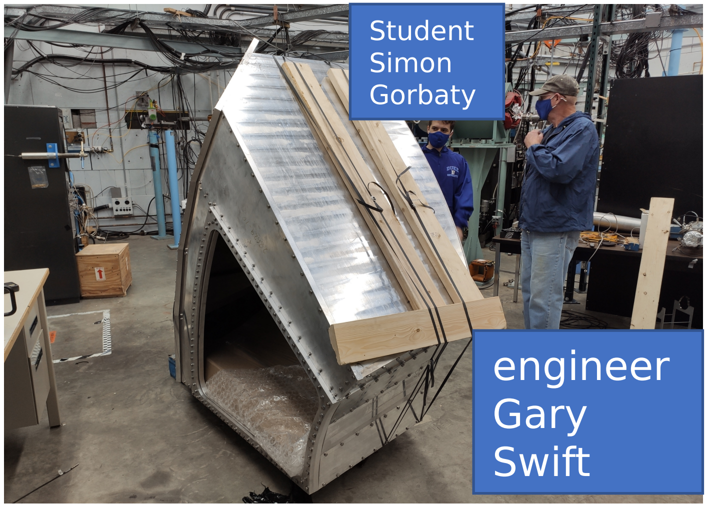


- Beam test with 3 modules of Ecal using the secondary electron and pion mixture beam at FTBF
- The position resolution of the Ecal and is 1.36 cm (horizontal) and 0.72 cm (vertical)
- Energy resolution of the Ecal $\frac{\sigma_E}{E} = 4.6\% \oplus \frac{10.4\%}{\sqrt{E}}$ PRELIMINARY

Further Updates

HGC Prototype





- 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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