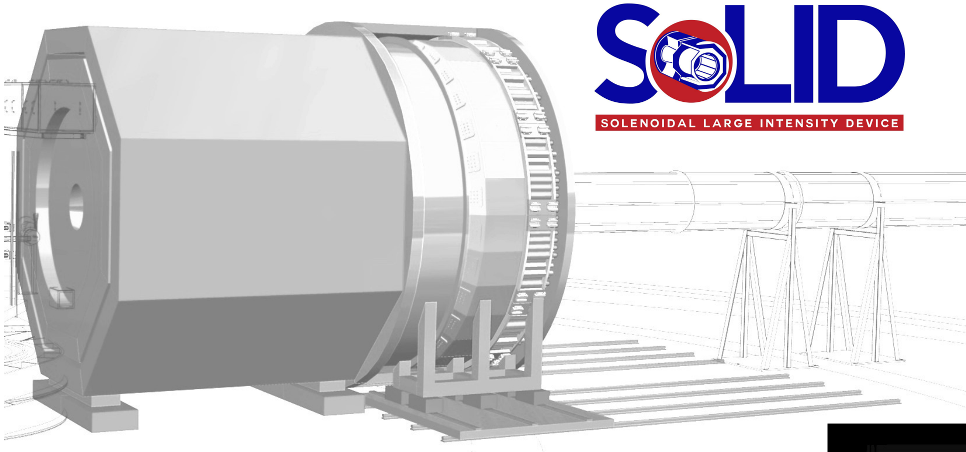
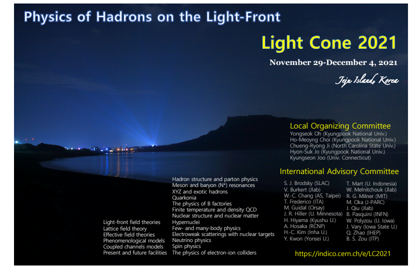
The SoLID Science Program in Hall A at Jefferson Lab



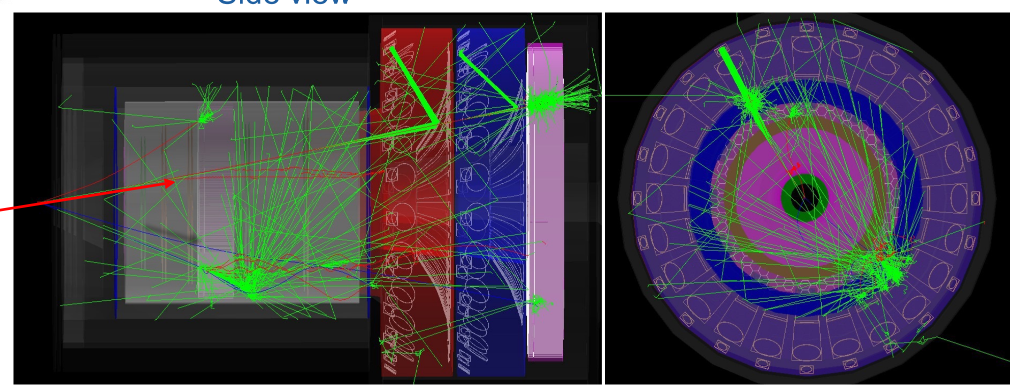
SOLENOIDAL LARGE INTENSITY DEVICE



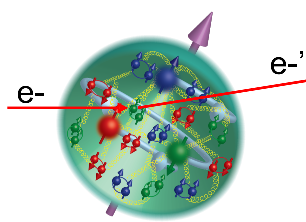
A charmonium production and decay event in SoLID

Side view

Front view



Zein-Eddine Meziani
For the SoLID collaboration
Argonne NATIONAL LABORATORY



With thanks to the SoLID team

LC2021, Seoul S. Korea, November 29, 2021

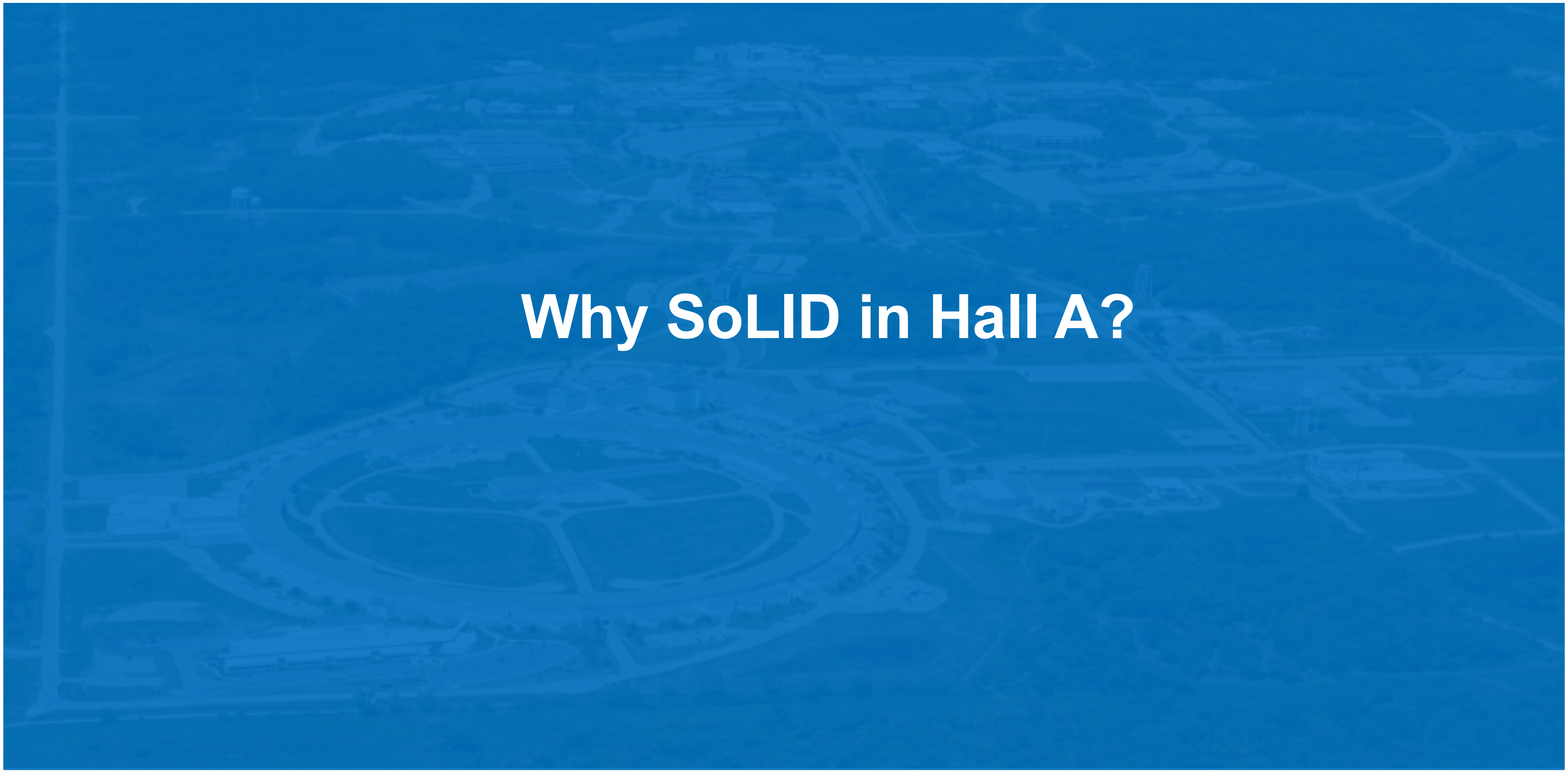
U.S. DEPARTMENT OF ENERGY | Office of Science

Jefferson Lab SoLID Argonne NATIONAL LABORATORY

Outline

1. Introduction
   - Why a Solenoidal Large Intensity Device (SoLID)?
2. Parity Violation in Deep Inelastic Scattering (PVDIS):
   - Test of Standard Model and Precision Hadron Structure
3. Semi-Inclusive Deep Inelastic Program (SIDIS):
   - Transversity and Transverse Momentum Dependent Distributions (TMDs)
4. J/ψ Program: Near threshold Electro- & Photoproduction
   - Strong Color Field and Proton Mass and Radius
5. Other Experiments
6. Summary

Why SoLID in Hall A?

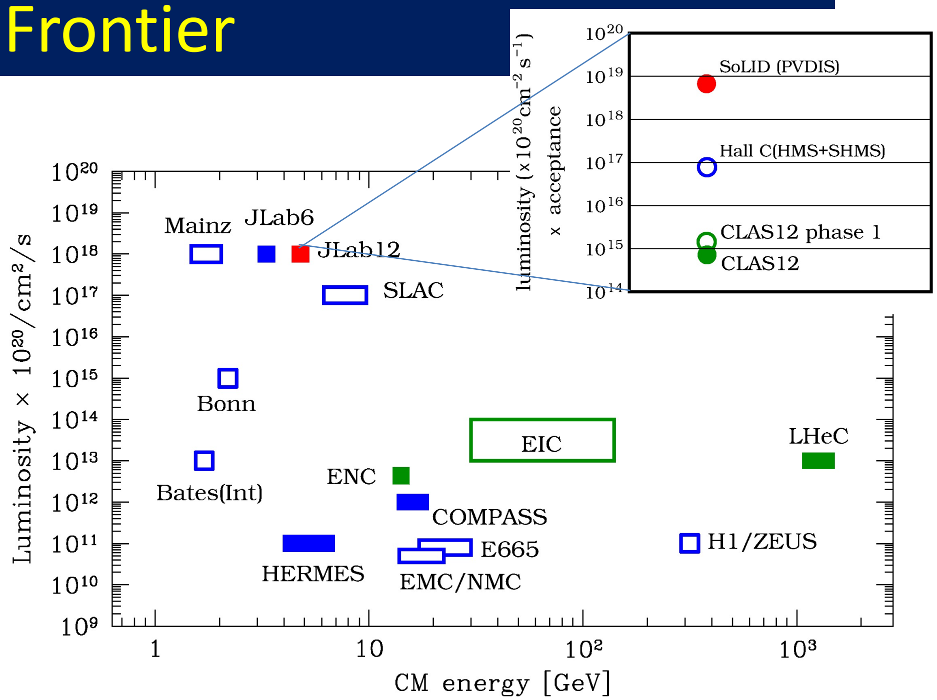


12 GeV experimental capabilities at Jefferson Lab

SoLID@12-GeV JLab Enables QCD at the Intensity Frontier

- ❑ Nucleon spin, proton mass, beyond standard model experiments require precision measurements of small cross sections and asymmetries, combined with multiple particle detection

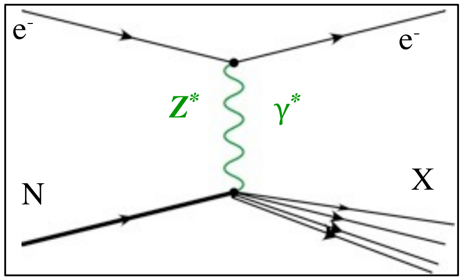
- ▪ There is a critical need for high luminosity and large acceptance working in tandem



PVDIS:Test of Standard Model and Hadron Structure

Parity Violating DIS on Deuteron

Simplest isoscalar nucleus and at high Bjorken *x*



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

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

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

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

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

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

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

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

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

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

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

Interplay with QCD

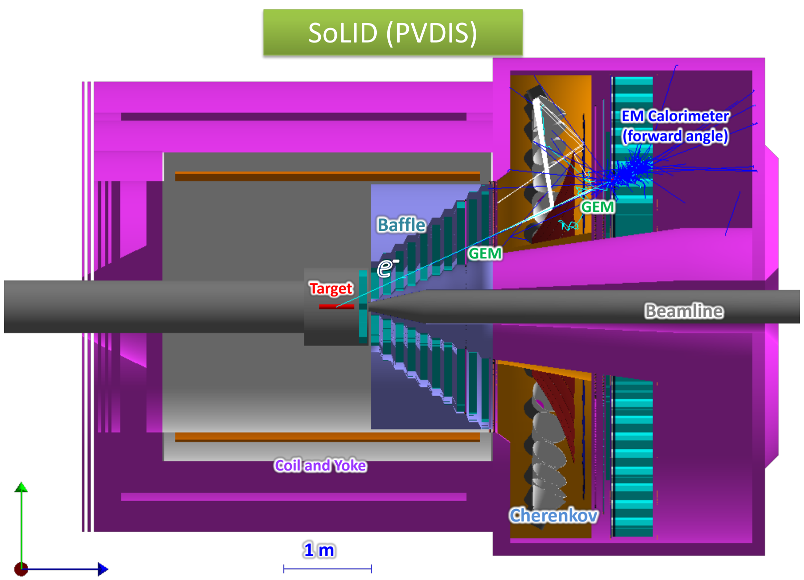
- **Parton distributions (u, d, s, c)**
- **Charge Symmetry Violation (CSV)**
- **Higher Twist (HT) – quark-quark correlation**

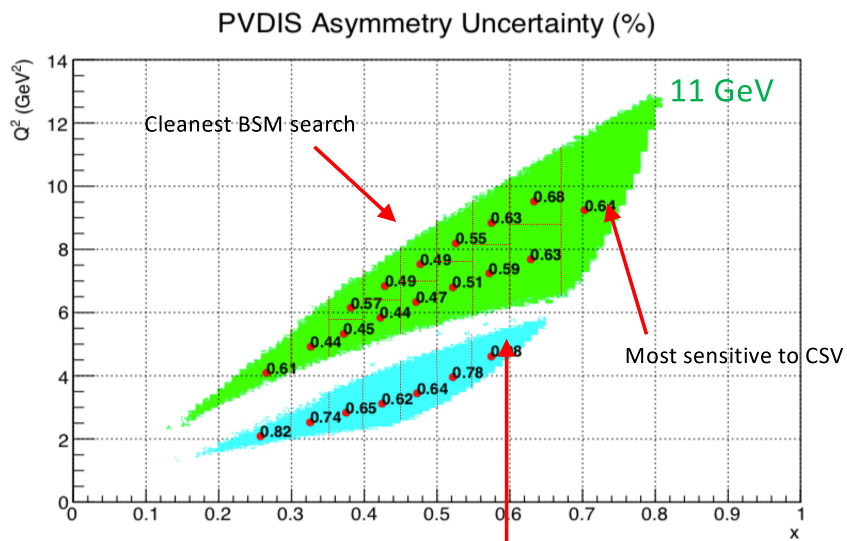
SoLID-PVDIS: Experiment E12-10-007

Spokesperson: Paul Souder

12 GeV CEBAF: Opportunity to do the ultimate PVDIS measurement

sub-1% precision over broad kinematic range:
sensitive Standard Model test *and* **detailed study of hadronic structure contributions**

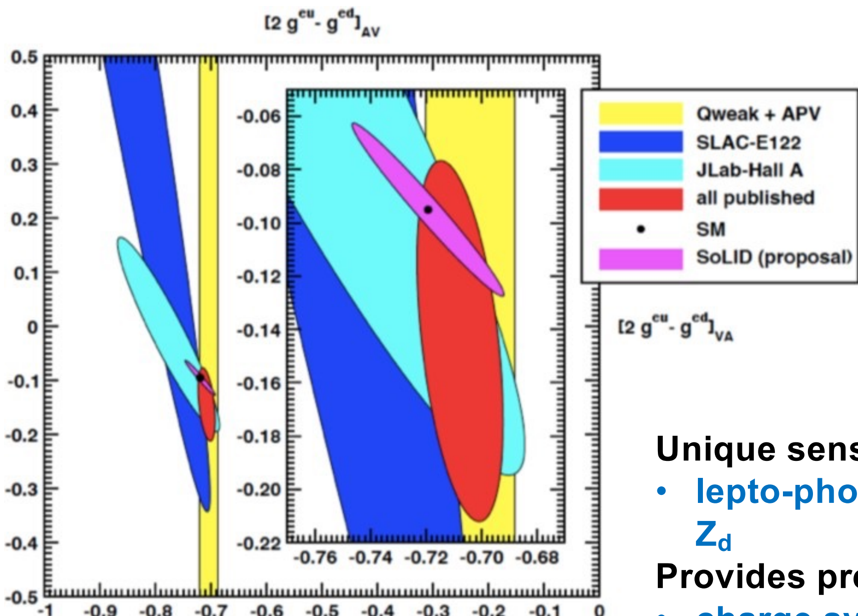




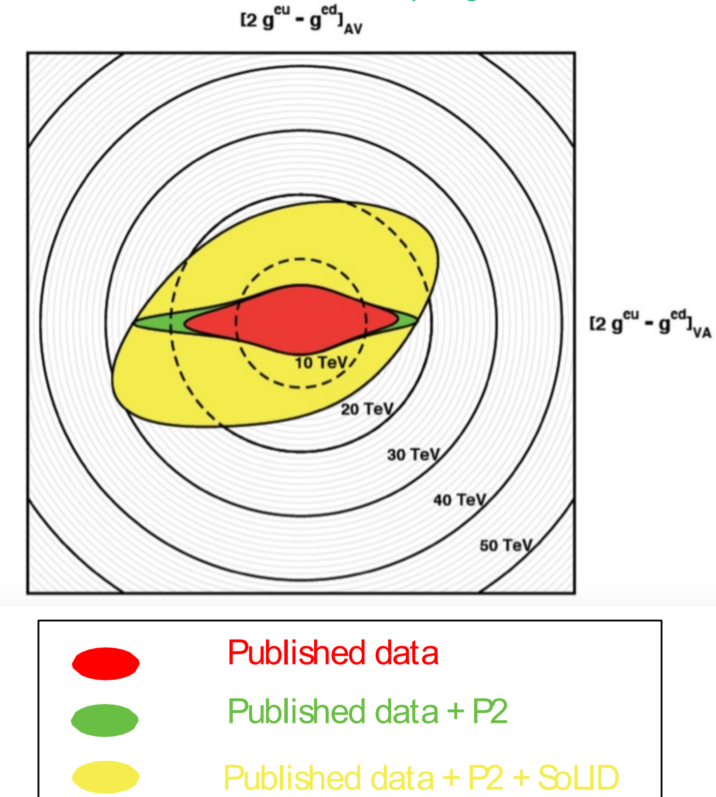
Projected Results on Coupling constants

SoLID makes a unique contribution to the SMEFT program.

Improvement in couplings



Improvement in energy reach for electron-nucleon couplings



Unique sensitivity to
- **lepto-phobic Z', dark boson Z_d**

Provides precision study of
- **charge symmetry violation**
- **high-twist effects**
- **d/u at high-x**

SoLID-SIDIS: Transversity/Tensor Charge and TMDs

TMDs – confined motion inside the nucleon

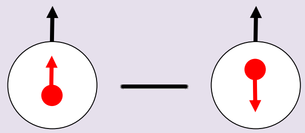
Transversely Polarized Nucleon TMDs

→ 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)

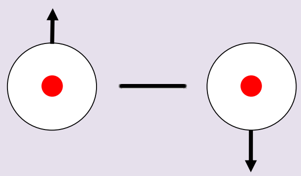
Transversity

$h_{1T} =$ 

$$\mathbf{S}_T \cdot \mathbf{s}_q$$

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

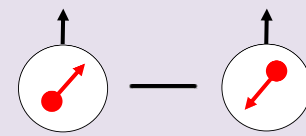
Sivers

$f_{1T}^{\perp} =$ 

$$\mathbf{S}_T \cdot \mathbf{k}_\perp \times \mathbf{P}$$

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

Pretzelosity

$h_{1T}^{\perp} =$ 

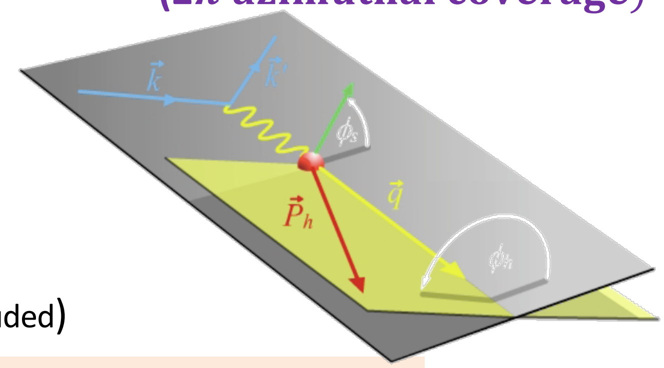
$$\mathbf{S}_T \cdot [\mathbf{k}_\perp \mathbf{k}_\perp] \cdot \mathbf{s}_{qT}$$

- 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

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T) and small asymmetries demand **large acceptance + high luminosity. A**llows precision measurements of asymmetries in 4-D binning!

(2π azimuthal coverage)



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

Leading twist formalism
(higher-twist terms can be included)

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

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

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

Collins fragmentation function from e^+e^- collisions

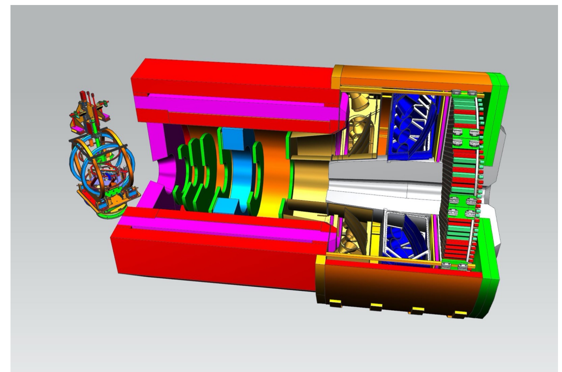
$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

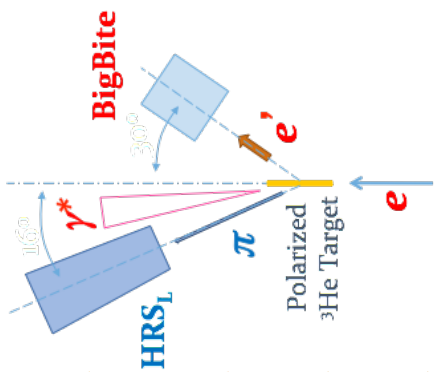
Unpolarized fragmentation function

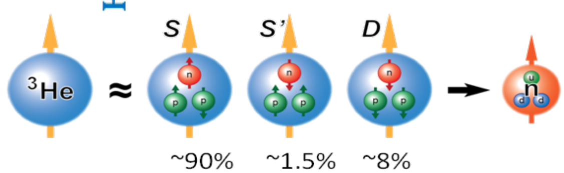
SoLID-SIDIS: Large-Acceptance & High Luminosity

Quantum leap: 4-D binning for the first time!

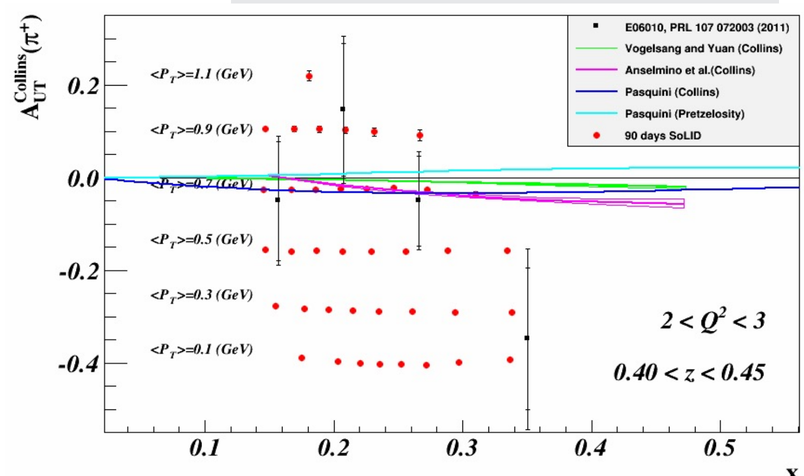
SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity
- 4-D mapping of asymmetries with precision
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics





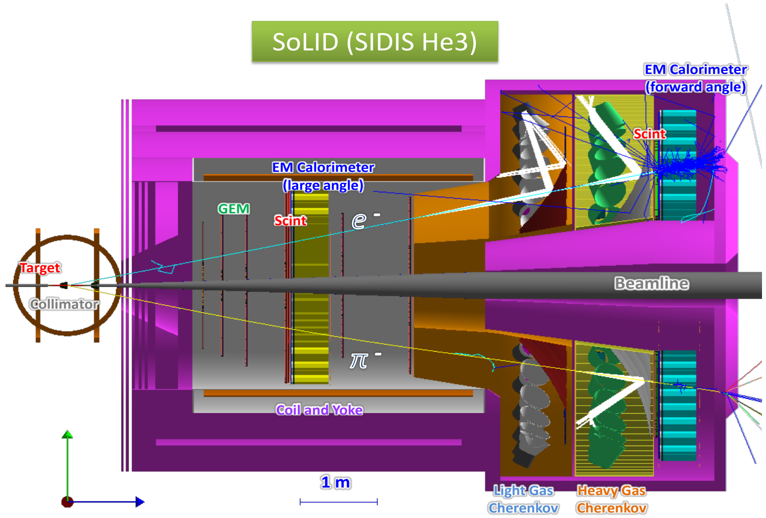


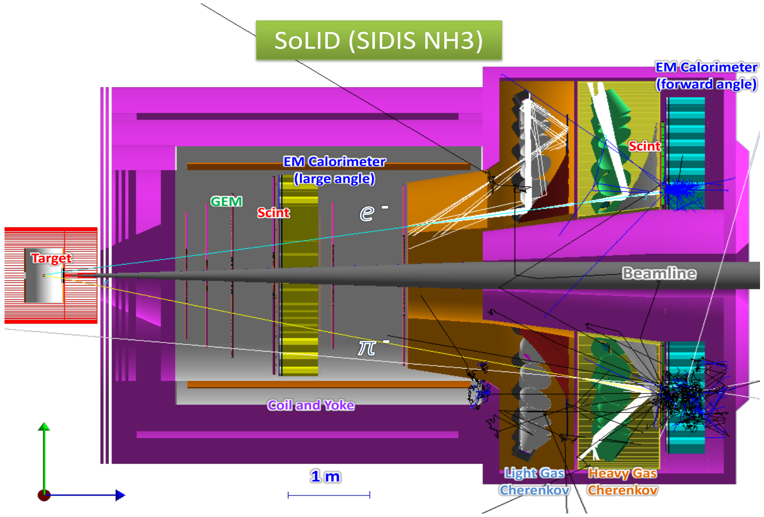
X. Qian et al., PRL107, 072003(2011)



- **More than 1400 bins in x, Q^2, P_T and z for 11/8.8 GeV beam.**

SIDIS with Polarized "Neutron" and Proton @ SoLID





E12-10-006: Single Spin Asymmetries on Transversely Polarized ^{3}He @ 90 days

Rating A 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

Rating A Spokespersons: J.P. Chen (contact), J. Huang, W.B. Yan

E12-11-108: Single Spin Asymmetries on Transversely Polarized Proton @ 120 days

Rating A Spokespersons: J.P. Chen, H. Gao (contact), X.M. Li, Z.-E. Meziani

Run group experiments approved for TMDs, GPDs, and Spin

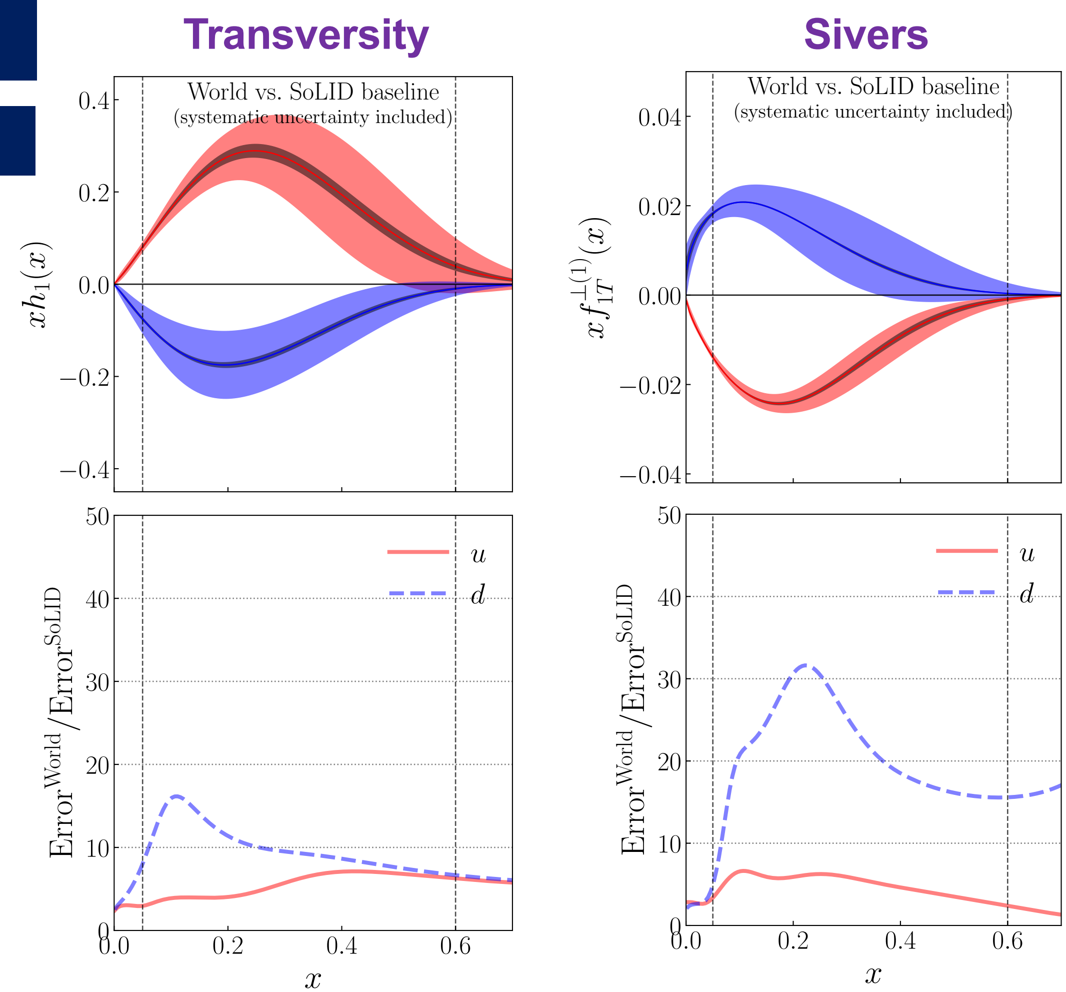
SoLID-SIDIS Projection

Impact of SoLID on 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

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



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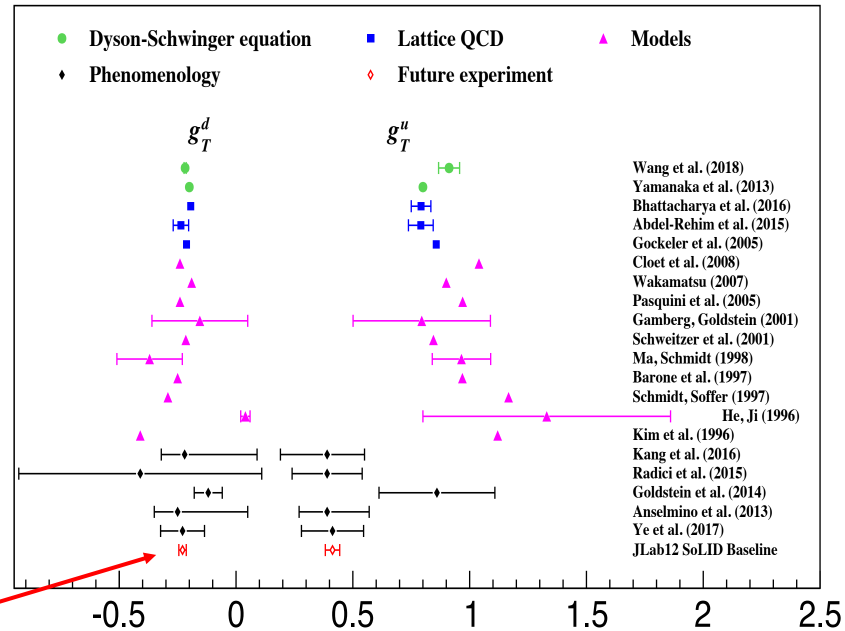
SoLID Impact on Tensor Charge

Definition

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S) \qquad g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

- A fundamental QCD quantity: matrix element of local operators.
- Moment of transversity distribution
- Valence quark dominant
- Precision calculations available from lattice QCD.
- Probe new physics combined with EDMs

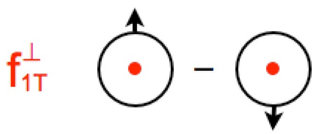
$$d_n = g_T^d\,d_u + g_T^u\,d_d + g_T^s\,d_s$$



SoLID Projections

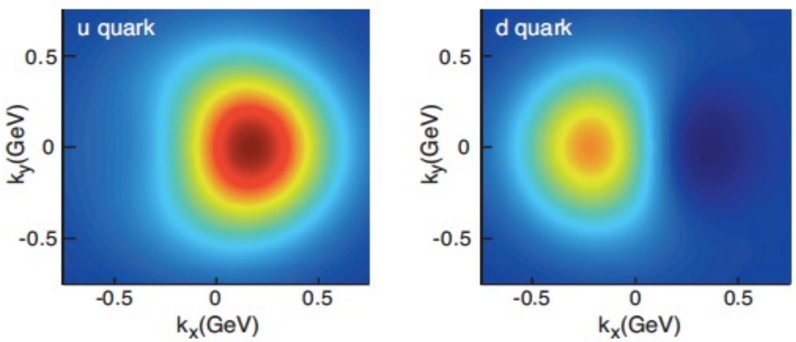
TMDs – confined motion inside the nucleon

Sivers distribution



naively time-reversal odd

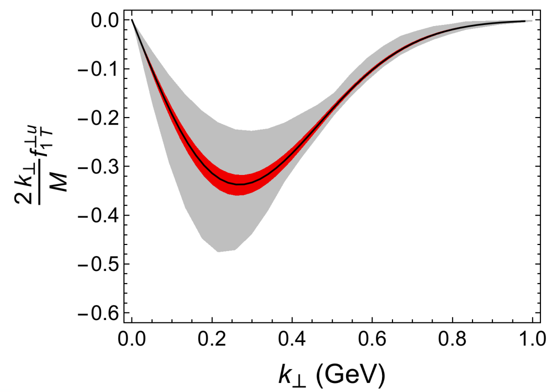
$$f_{1T}^{\perp q}(x,k_\perp)\Big|_{\rm SIDIS} = -f_{1T}^{\perp q}(x,k_\perp)\Big|_{\rm DY}$$

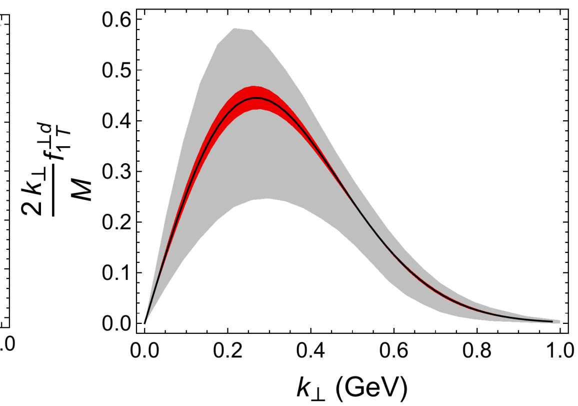


Nucleon spin - quark orbital angular momentum (OAM) correlation

– zero if no OAM (collinear, massless quarks)

Exact finding is model dependent but SoLID impact is model-independent!





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

$$\langle\mathbf{k}_\perp\rangle = -M\int dx\, f_{1T}^{\perp(1)}(x)(\mathbf{S}\times\widehat{\mathbf{P}})$$

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

SoLID projection with transversely polarized n/p

$\langle k_\perp\rangle^u$	$\langle k_\perp\rangle^d$
96^{+60}_{-28} MeV	-113^{+45}_{-51} MeV
$96^{+2.8}_{-2.4}$ MeV	$-113^{+1.3}_{-1.7}$ MeV

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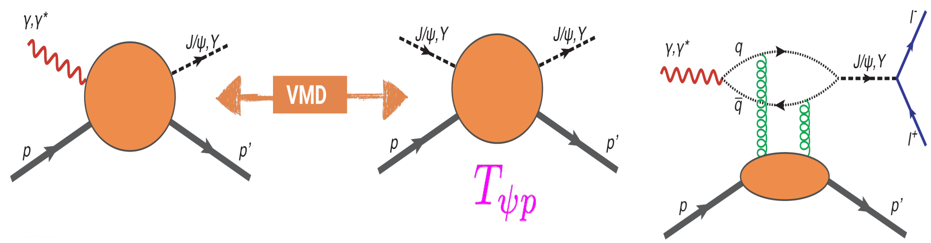
SoLID J/ψ : -Near Threshold Production

-Probe Strong Color Field

-Proton Mass and Radius

From Cross Section to the Trace Anomaly



$$\gamma^* + N \rightarrow N + J/\psi$$

Heavy quark – dominated by two gluons

$$\langle P|T^\alpha_\alpha|P\rangle = 2P^\alpha P_\alpha = 2M_p^2$$

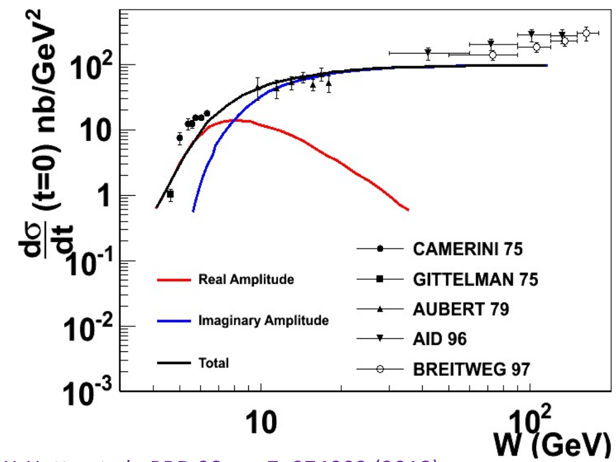
$$\frac{d\sigma_{\gamma N\to\psi N}}{dt}(s,t=0) = \frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2 \frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0)$$

$$\frac{d\sigma_{\psi N\to\psi N}}{dt}(s,t=0) = \frac{1}{64\pi}\frac{1}{m_\psi^2(\lambda^2-m_N^2)}|\mathcal{M}_{\psi N}(s,t=0)|^2$$

VMD relates photoproduction cross section to quarkonium-nucleon scattering amplitude

- **Imaginary part** is related to the total cross section through optical theorem
- **Real part contains the conformal (trace) anomaly;** Dominates the near threshold region and constrained through dispersion relation

D. Kharzeev (1995); Kharzeev, Satz, Syamtomov, and Zinovjev EPJC,9, 459, (1999); Gryniuk and Vanderhaeghen, PRD94, 074001 (2016)



Y. Hatta et al., PRD 98 no. 7, 074003 (2018)
Y. Hatta et al., 1906.00894 (2019)
K. Mamo & I. Zahed, Phys. Rev. D 101, 086003 (2020)
R. Wang, J. Evslin and X. Chen, Eur. Phys. J. C **80**, no.6, 507 (2020)

A measurement near threshold could allow access to the trace anomaly

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Proton Mass and Quantum Anomalous Energy

- **Nucleon mass is the total QCD energy in the rest frame (QED contribution small)**

$$H_{QCD} = H_q + H_m + Hg + H_a$$

$$H_q = \text{Quark energy} \quad \int d^3x\, \psi^\dagger (-i\mathbf{D}\cdot\alpha)\psi$$

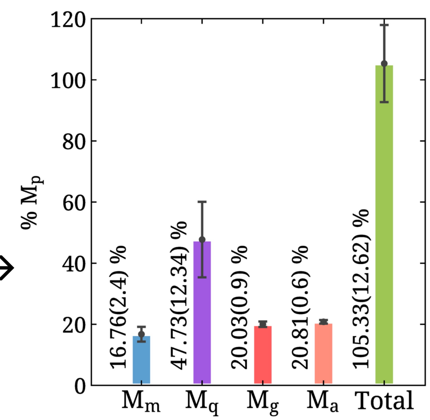
$$H_m = \text{Quark mass} \quad \int d^3x\, \bar{\psi} m \psi$$

$$H_g = \text{Gluon energy} \quad \int d^3x\, \frac{1}{2}(\mathbf{E}^2 + \mathbf{B}^2)$$

$$H_a = \text{Quantum Anomalous energy} \quad \int d^3x\, \frac{9\alpha_s}{16\pi}(\mathbf{E}^2 - \mathbf{B}^2)$$

Sets the scale for the hadron mass!

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



X. Ji PRL 74 1071 (1995),
X. Ji & Y. Liu, arXiv: 2101.04483

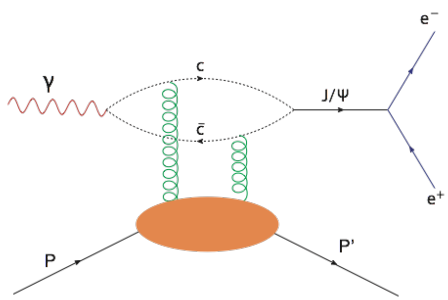
C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

- **Measuring quantum anomalous energy contribution in experiments is an important goal in the future**

Can be accessed through heavy quarkonium threshold (J/psi & Upsilon) production,
D. Kharzeev, Proc. Int. Sch. Phys. Fermi 130, 105 (1996)
R. Wang et al, Eur.Phys.J.C 80 (2020) 6, 507

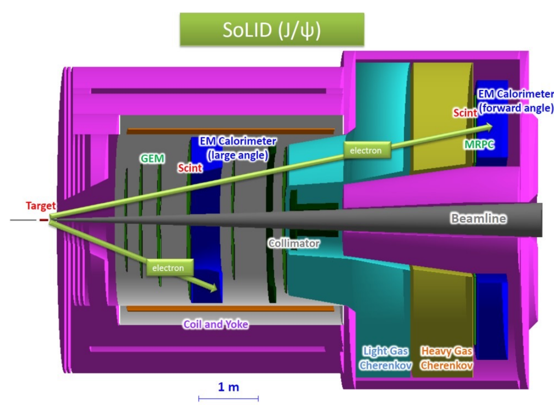
SoLID-J/ψ: Experiment E12-12-006

- 50 days of 3 μA beam on a 15 cm long LH_2 target at $1 \times 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include 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^-

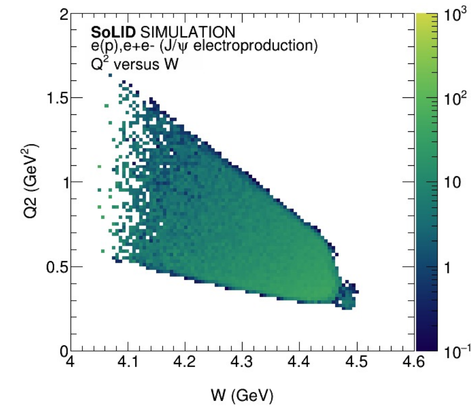


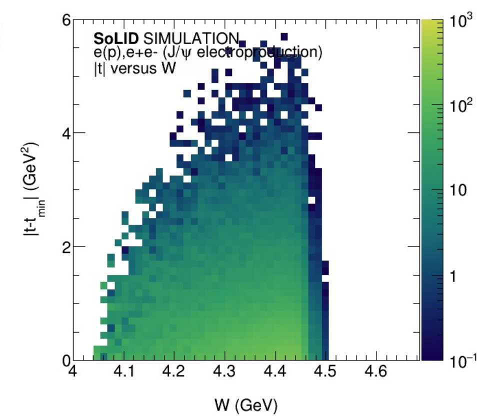
$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

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

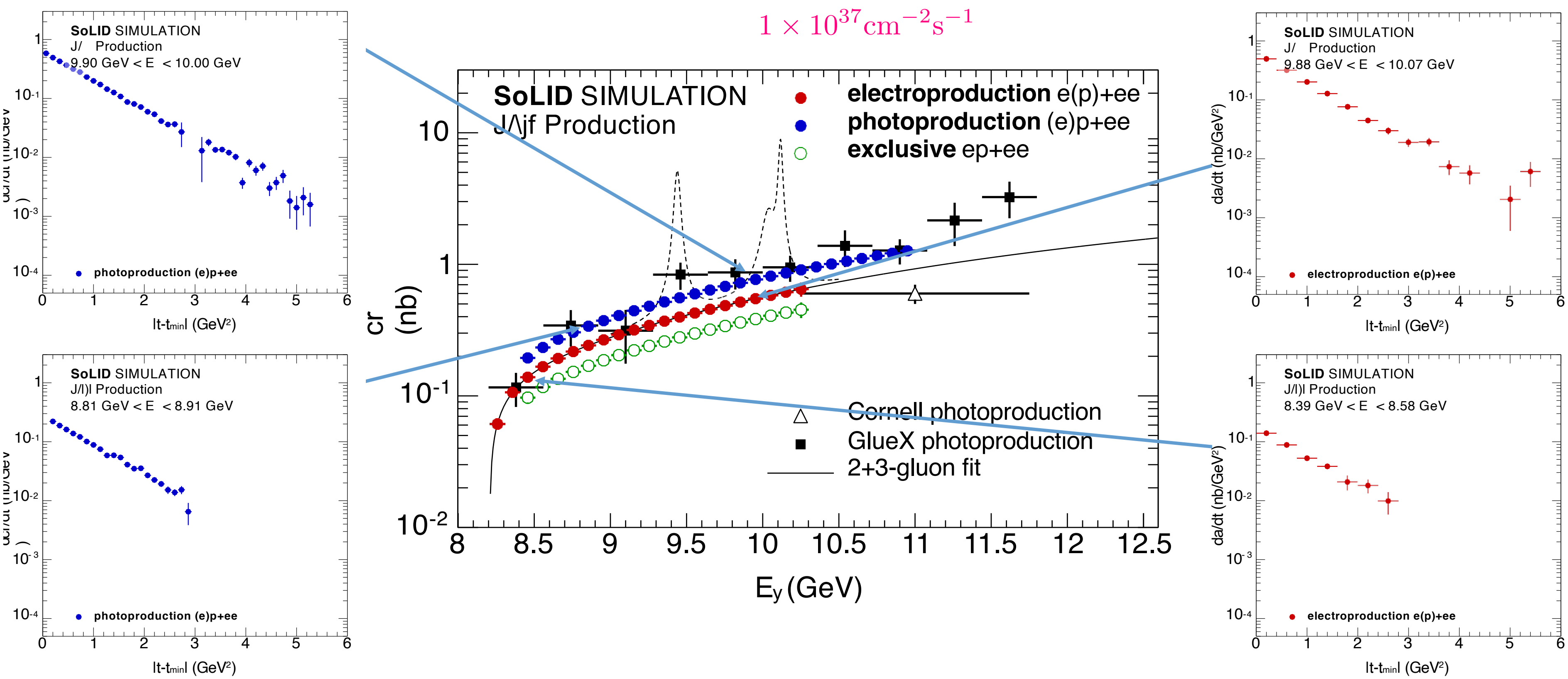


Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao



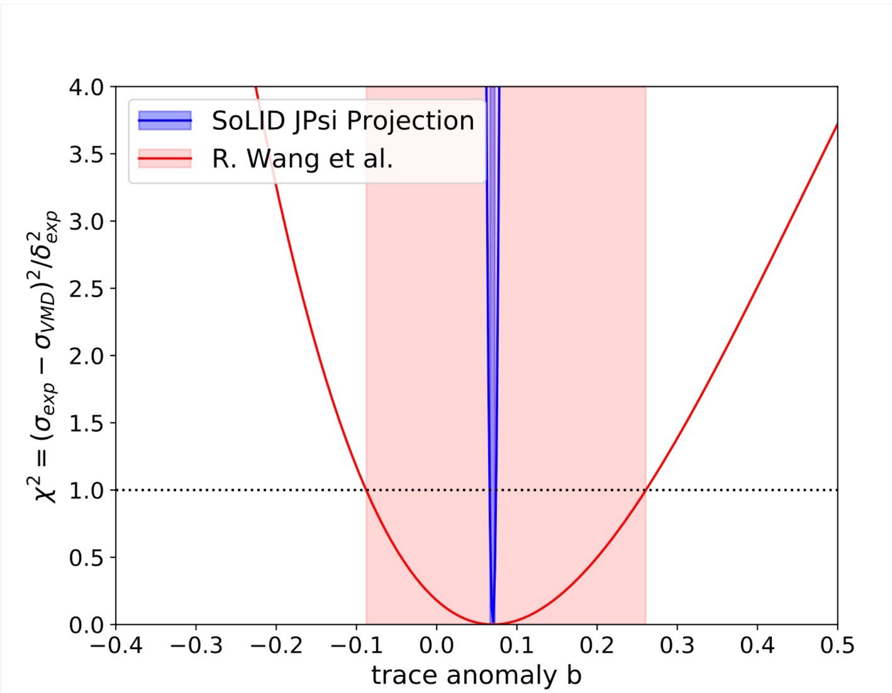


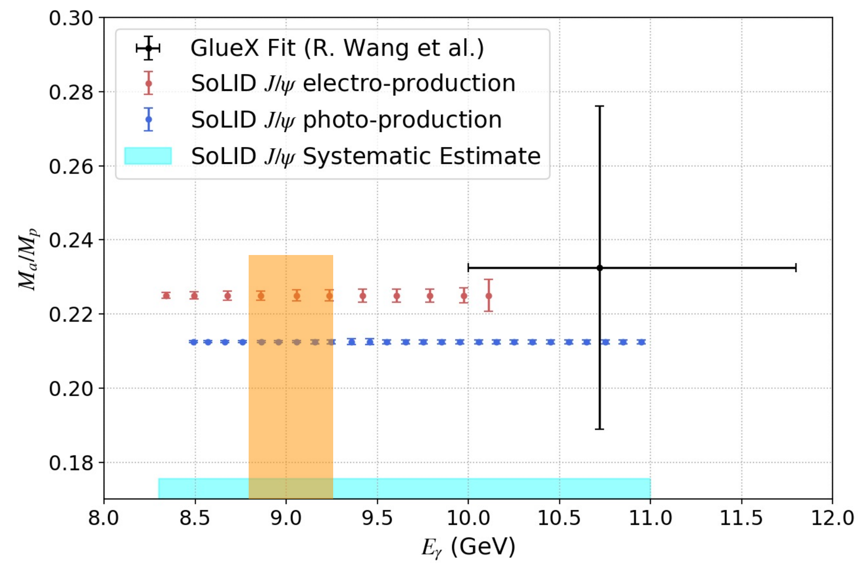
J/Psi Experiment E12-12-006 @ SoLID



Sensitivity at threshold at about 10^{-3} nb!

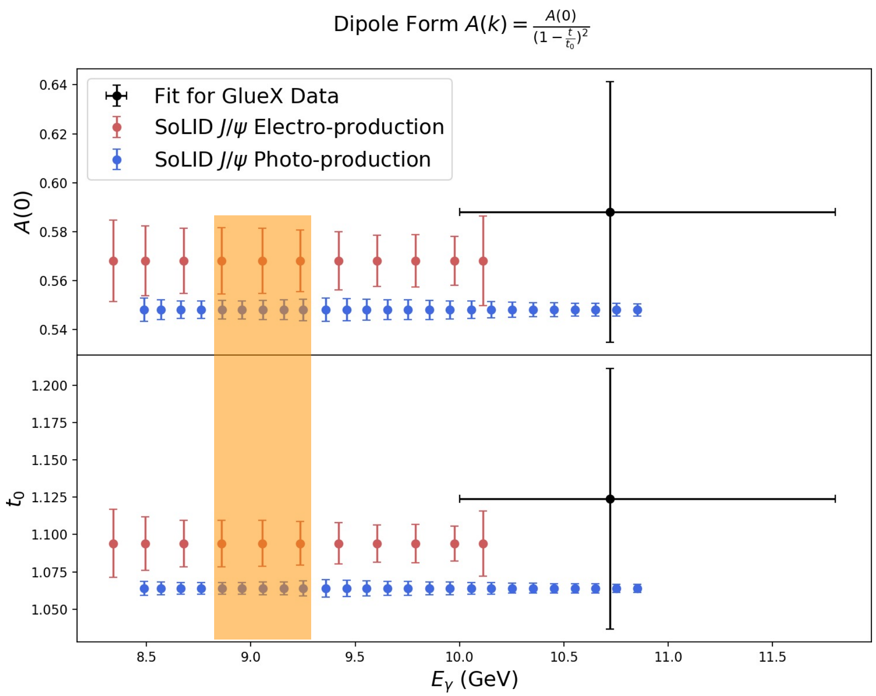
Impact on the Quantum Anomalous Energy Extraction

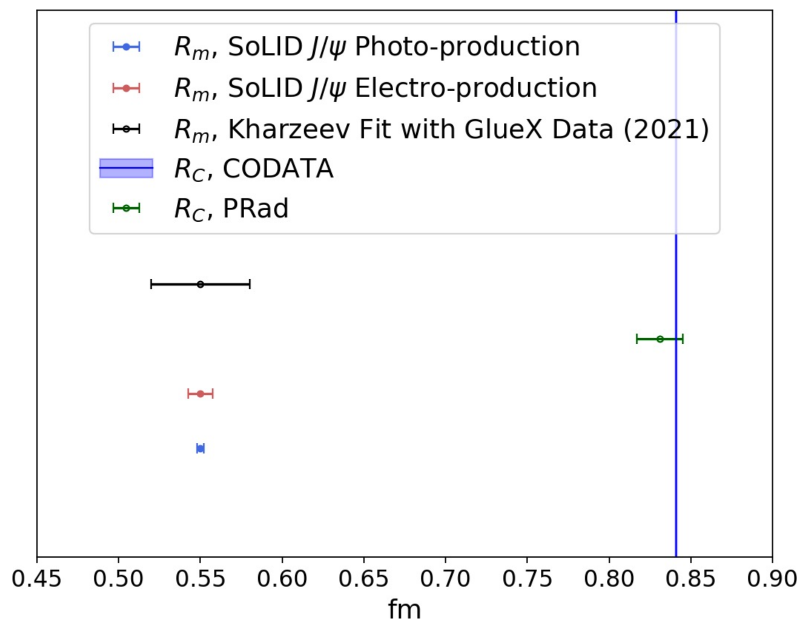




Impact on the mass radius

D. E. Kharzeev, ``The mass radius of the proton,"
arXiv:2102.00110 [hep-ph]





SoLID Program on GPDs

- **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)*

Other 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)

- g_2^n and d_2^n with Transversely and Longitudinally Polarized ^{3}He

  C. Peng, Y. Tian

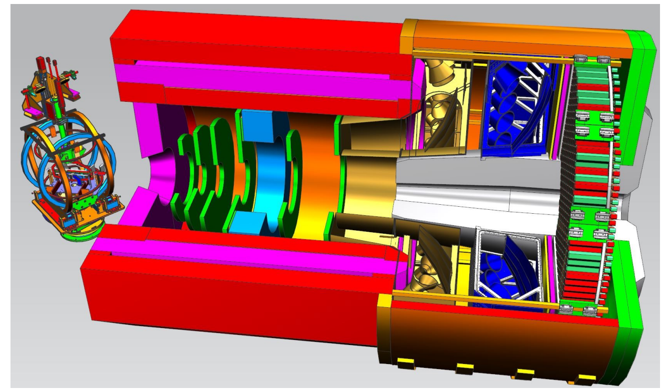
  Approved as run group (E12-11-007A/E12-10-006E)

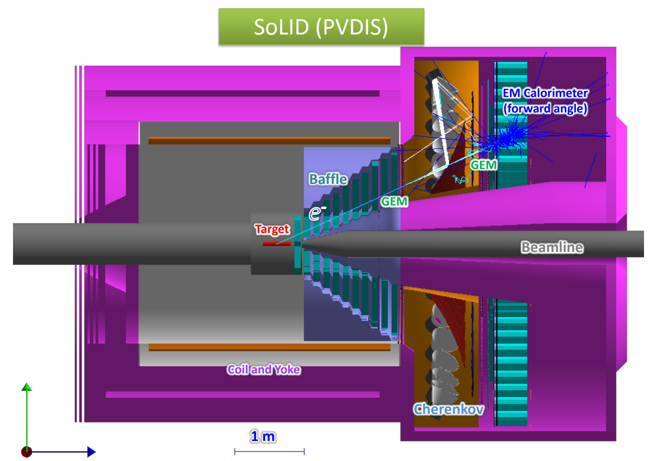
SoLID Apparatus

Requirements are Challenging

- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale
- Modern Technologies
  - GEM's
  - Shashlik ECal
  - Pipeline DAQ
  - Rapidly Advancing Computational Capabilities
- High Performance Cherenkovs
- Baffles

Polarized ^{3}He (``neutron") @ SoLID

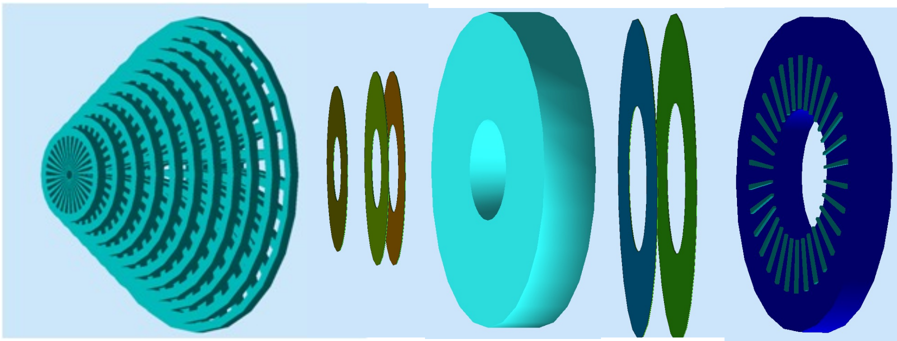


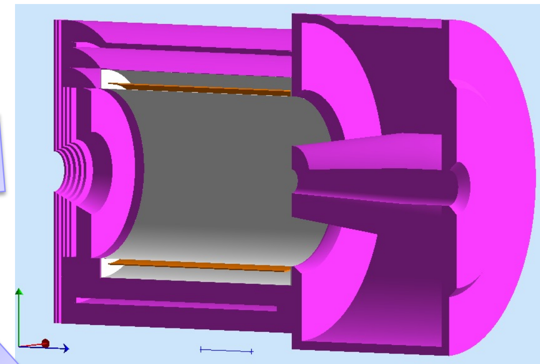


SoLID Detector Subsystems

Uses full capability of JLab electronics

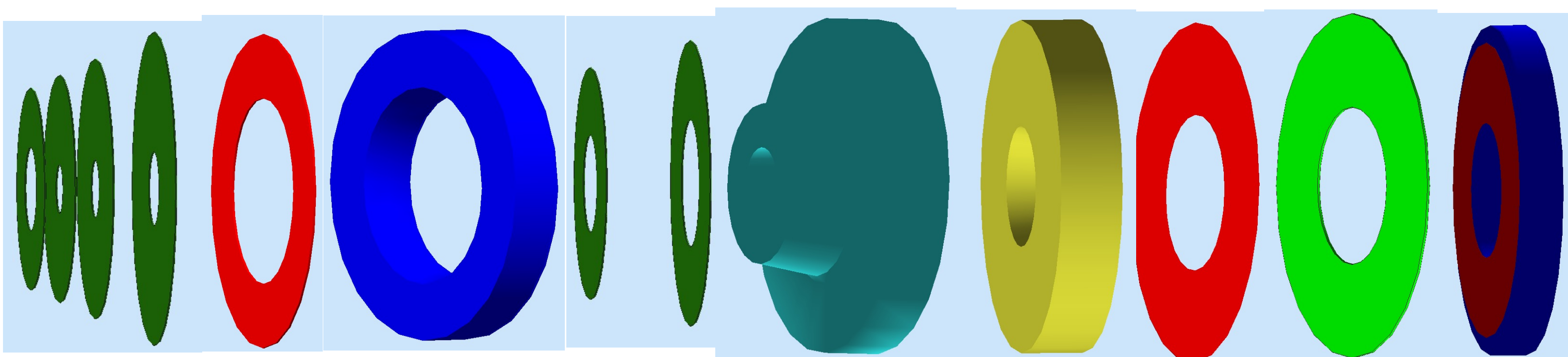
PVDIS: Baffle 3xGEMS LGC 2xGEMs EC





SIDIS& J/psi:

4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



Pre-R&D items: LGC, HGC, GEM's, DAQ/Electronics, Magnet

Summary

SOLID: A Science Program at the Intensity Frontier

- SoLID is a **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab 12 GeV scientific potential by pushing the limit of the intensity frontier

- SoLID has rich and vibrant science programs complementary and synergistic to the proposed EIC science program.
  Three pillars include SIDIS, PVDIS and J/Psi threshold production

- 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 pillars

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

270+ collaborators, 70+ institutions from 13 countries

New collaborators are welcome!

https://solid.jlab.org/