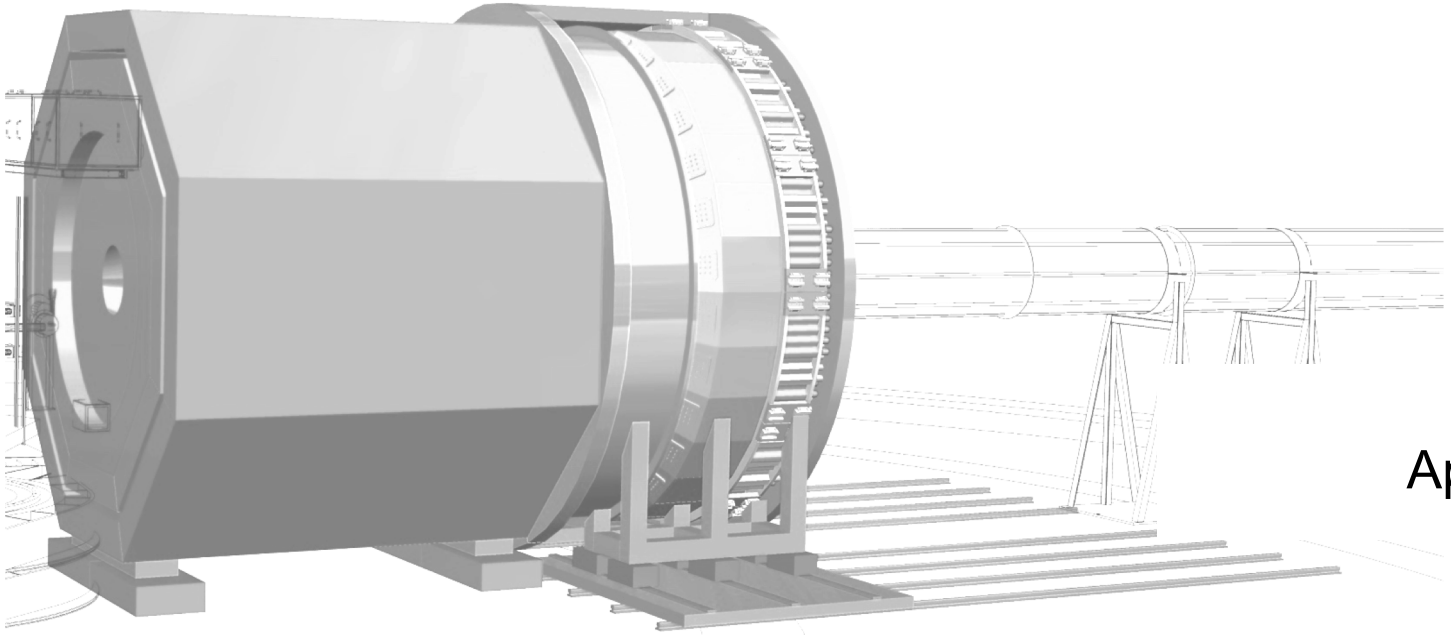
Overview of SoLID



DIS2021
April 12-16, 2021

Jian-ping Chen
Jefferson Lab

On Behalf of SoLID Collaboration

SOLENOIDAL LARGE INTENSITY DEVICE

Acknowledgement: Thanks to Haiyan Gao, Zein-Eddine Meziani, Paul Souder, …
and many other SoLID collaborators.

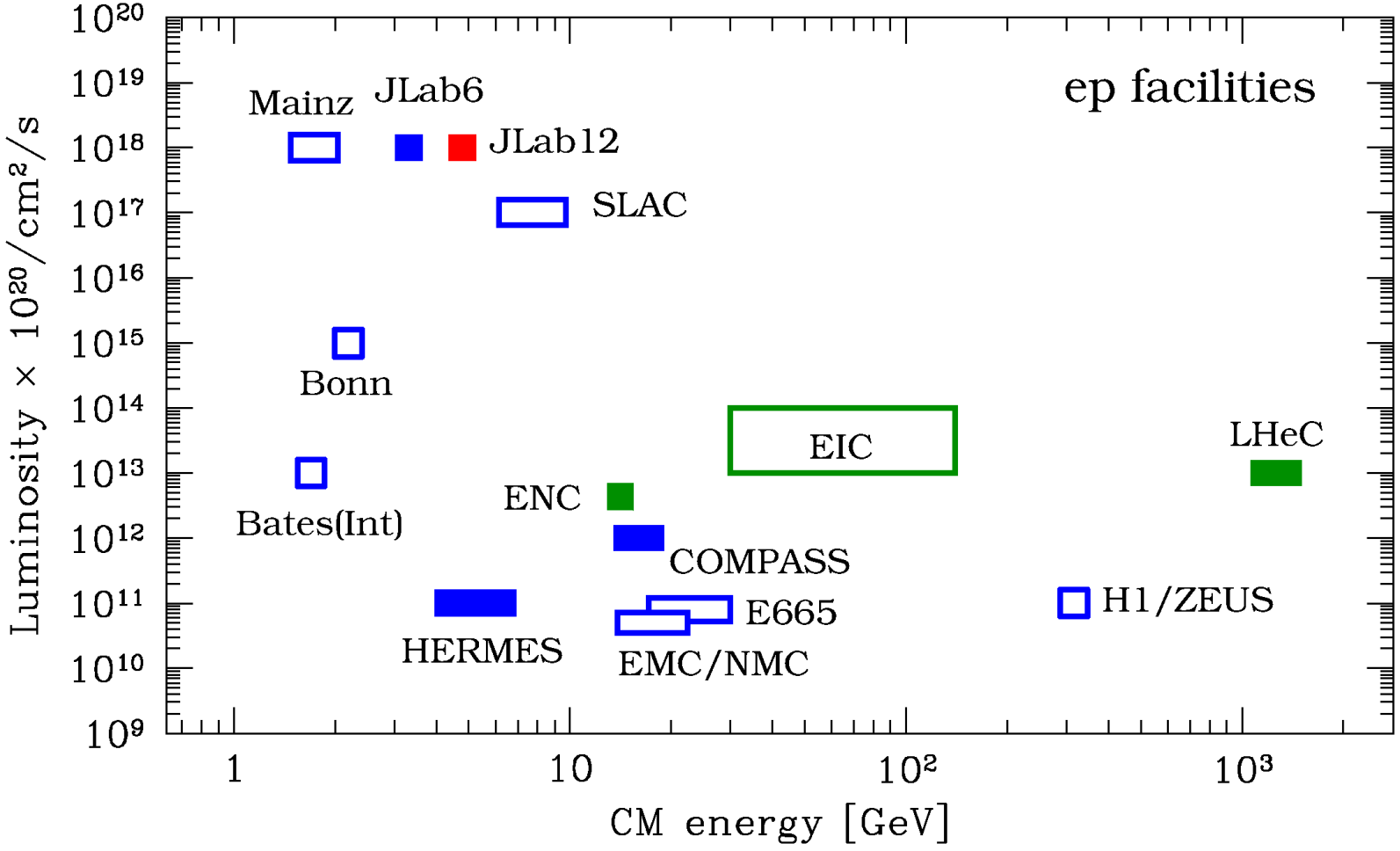
Outline

1. Introduction
2. SoLID-PVDIS Program: Test of Standard Model and Precision Study of Hadron Structure
3. SoLID-SIDIS Program: Transversity and TMDs
4. SoLID-J/ψ Program: Probe Strong Color Field and Proton Mass
5. SoLID Run-group Experiments
6. SoLID Device
7. Summary

1. Introduction

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

- Nucleon spin, proton mass, beyond standard model experiments require precision measurements of small cross sections and asymmetries, combined with multiple particle detection
  - ➢ critical need for high luminosity and large acceptance



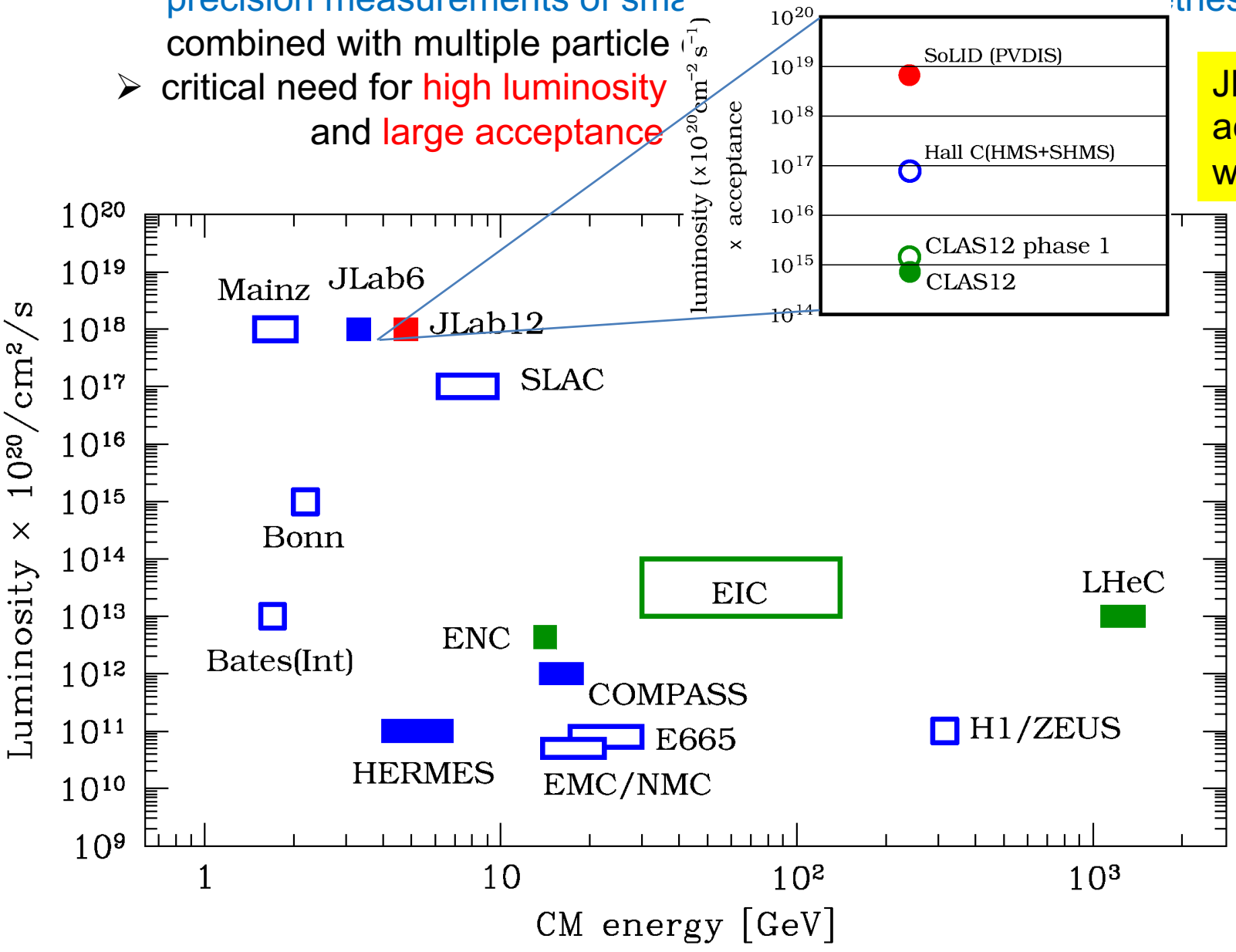
JLab highest ep luminosity globally

But, look even closer…

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

- Nucleon spin, proton mass, beyond standard model experiments require precision measurements of sma tries, combined with multiple particle
  - ➢ critical need for high luminosity and large acceptance

JLab luminosity, acceptance weighted



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

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

High Luminosity
$10^{37\text{-}39}$ /cm^2/s
[>100x CLAS12][>1000x EIC]

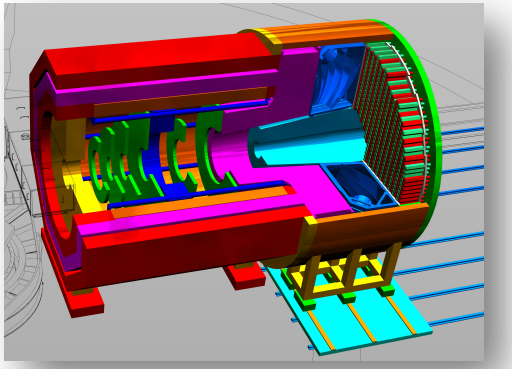
+

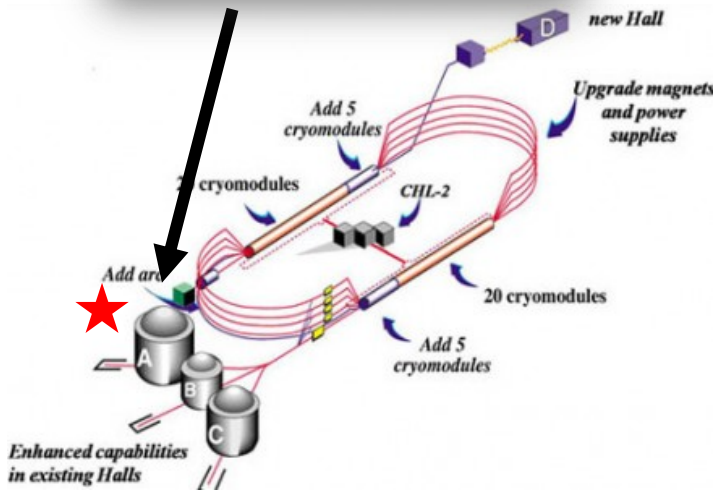
Large Acceptance
Full azimuthal ϕ coverage

Research at **SoLID** will have the ***unique*** capability to **explore** the QCD landscape while **complementing** the research of other key facilities

- Pushing the phase space in the search of new physics and of hadronic physics
- 3D momentum imaging of a relativistic strongly interacting confined system - TMDs (**nucleon spin**)
- Superior sensitivity to the differential electro- and photo-production cross section of J/ψ near threshold (**proton mass**)

Synergizing with the pillars of EIC science (**proton spin** and **mass**) through high-luminosity valence quark tomography and precision J/ψ production near threshold



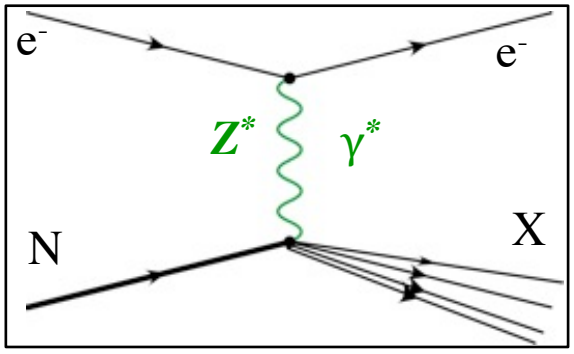


2. SoLID-PVDIS

Test of Standard Model
Precision Study of Hadron Structure

Parity Violating DIS on Deuteron

Off the simplest isoscalar nucleus and at high Bjorken *x*



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

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

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

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

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

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

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

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

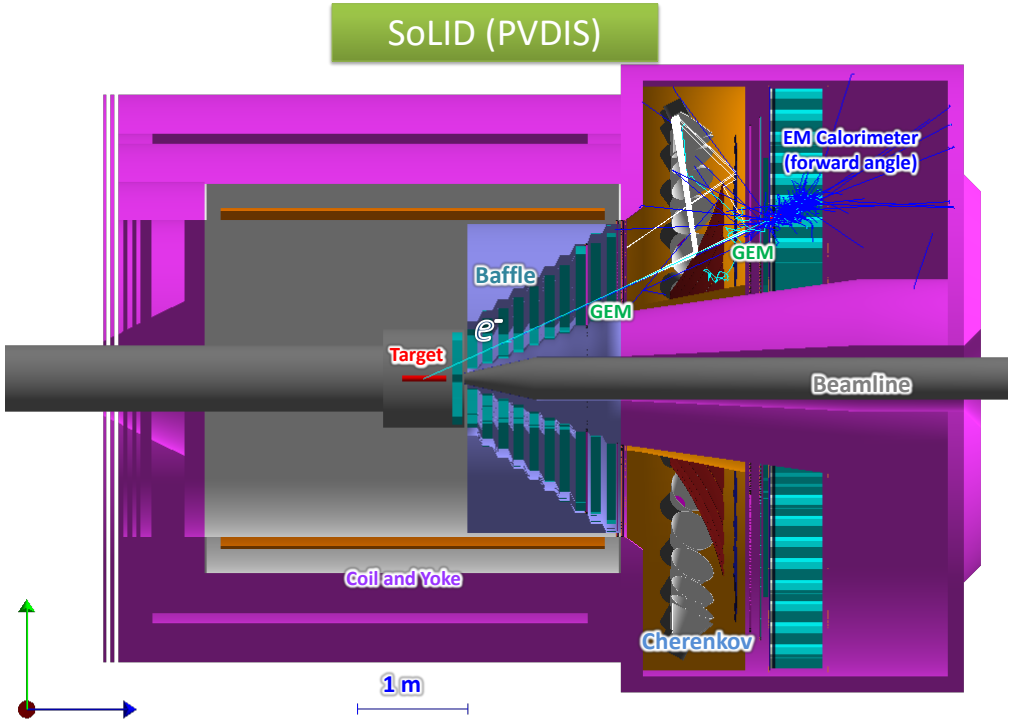
- Parton distributions (u, d, s, c)
- Charge Symmetry Violation (CSV)
- Higher Twist (HT) – quark-quark correlation

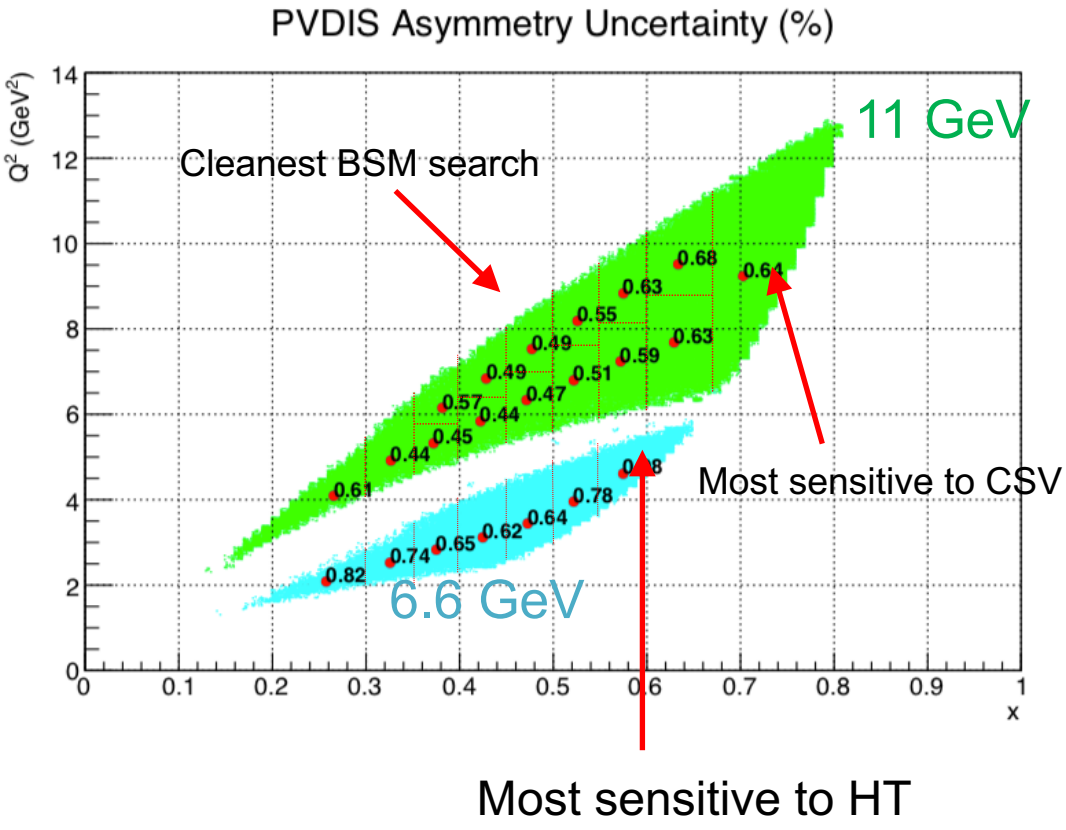
SoLID-PVDIS: Experiment E12-10-007

Spokesperson: Paul Souder

12 GeV CEBAF: Extraordinary opportunity to do the ultimate PVDIS measurement

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

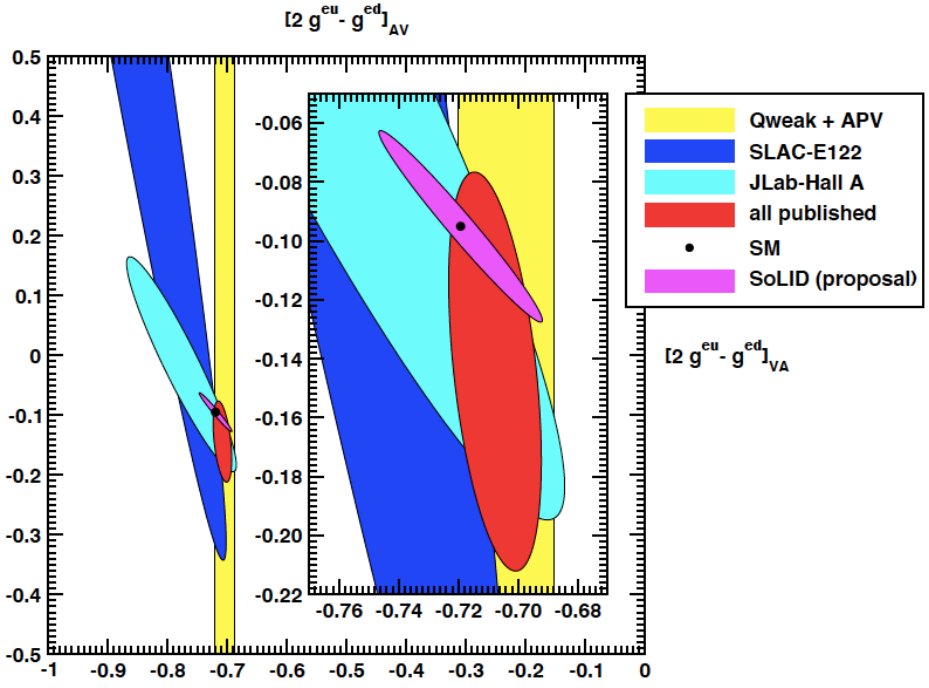




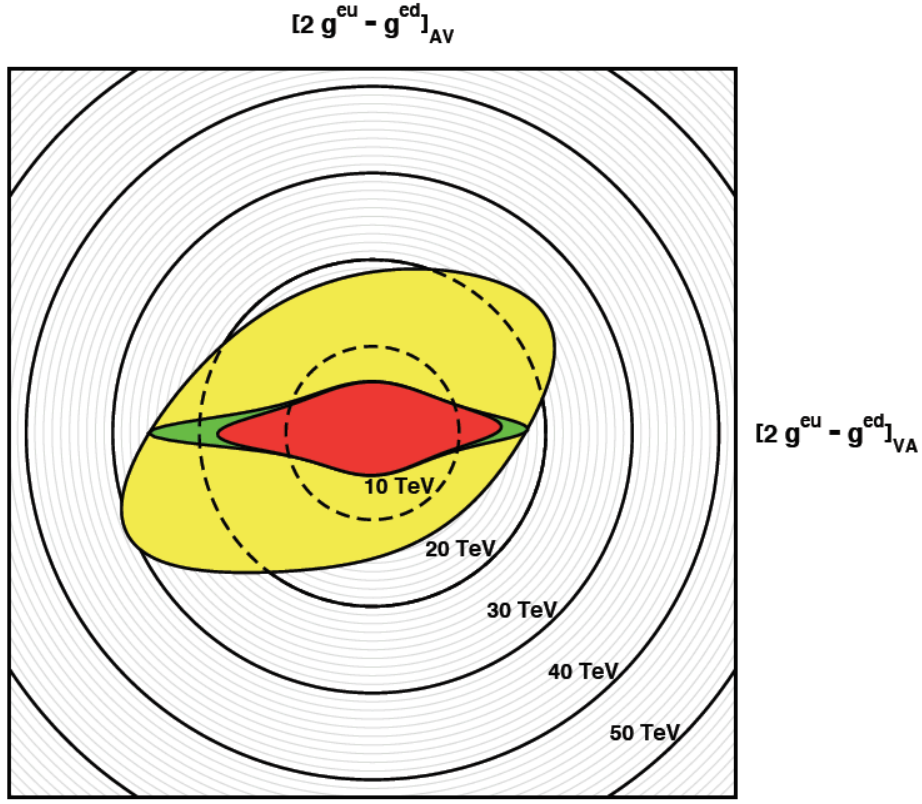
Projected Results

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**

Also provides precision study of

- **charge symmetry violation**
- **high-twist effects**
- **d/u at high-x**

Published data

Published data + P2

Published data + P2 + SoLID

3. SoLID-SIDIS

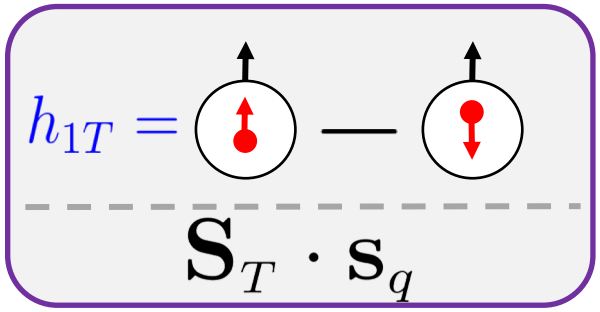
Transversity/Tensor Charge and TMDs

TMDs – confined motion inside the nucleon

Transversely Polarized Nucleon TMDs

→ Nucleon Spin
→ Quark Spin

Transversity

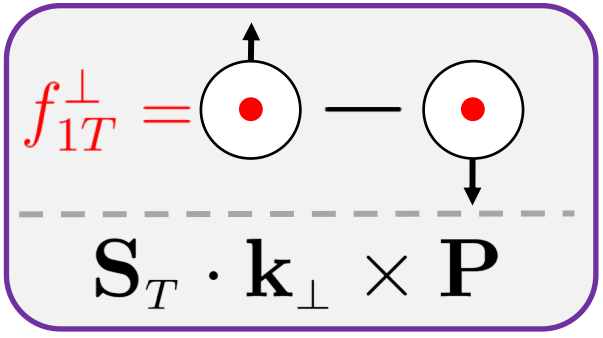


Relevant Vectors

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

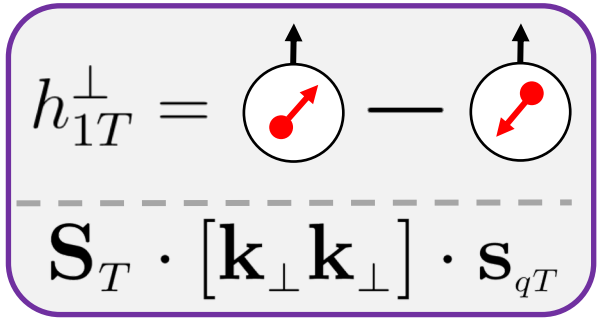
- h_{1T} (h_1) = g_1 (no relativity)
- h_{1T} → tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

Sivers



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

Pretzelosity

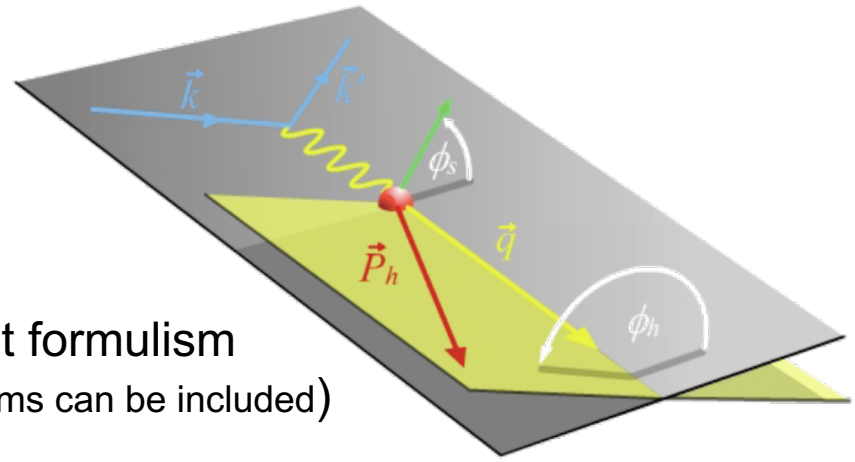


- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

Separation of Collins, Sivers and Pretzelosity

SIDIS SSAs depend on 4-D variables (x, Q^2, z, P_T) and small asymmetries demand **large acceptance** + **high luminosity** allowing for measuring symmetries in 4-D binning with precision!

(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 formulism
(higher-twist terms can be included)

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

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

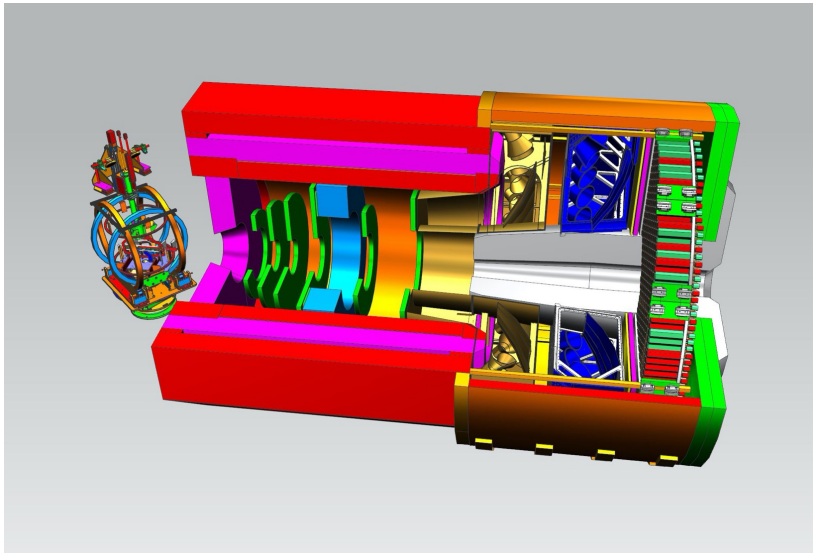
Collins fragmentation function from e^+e^- collisions

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

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

Unpolarized fragmentation function

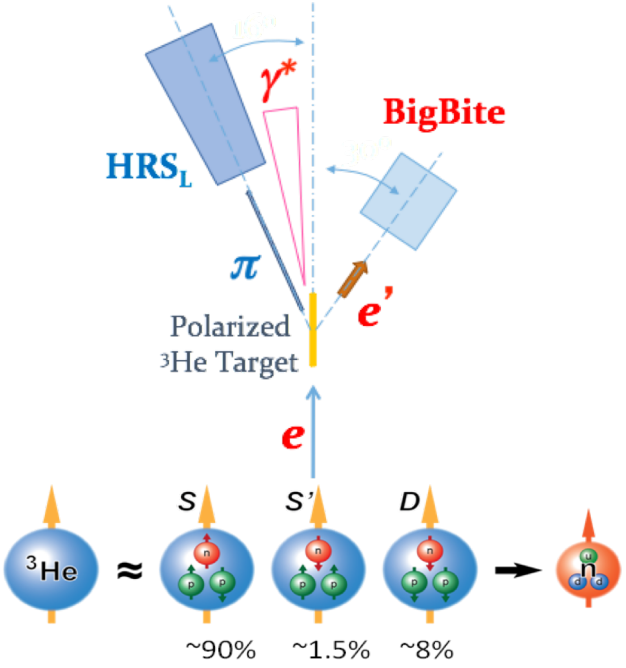
SoLID-SIDIS: Large-Acceptance & High Luminosity



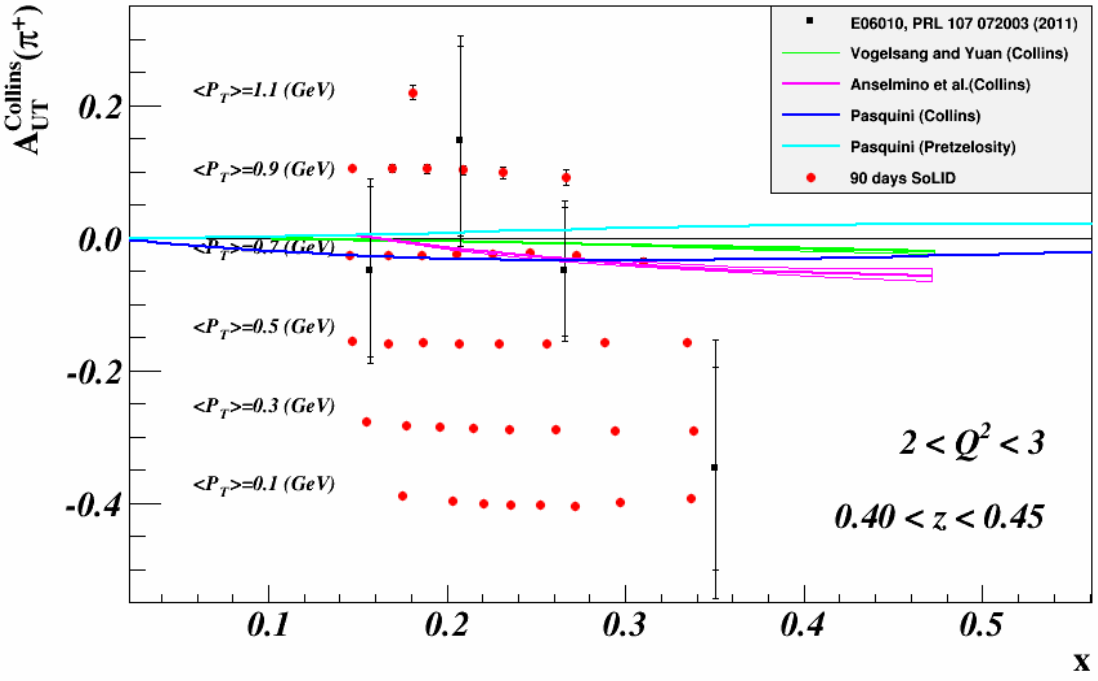
Quantum leap: 4-D binning for the first time!

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

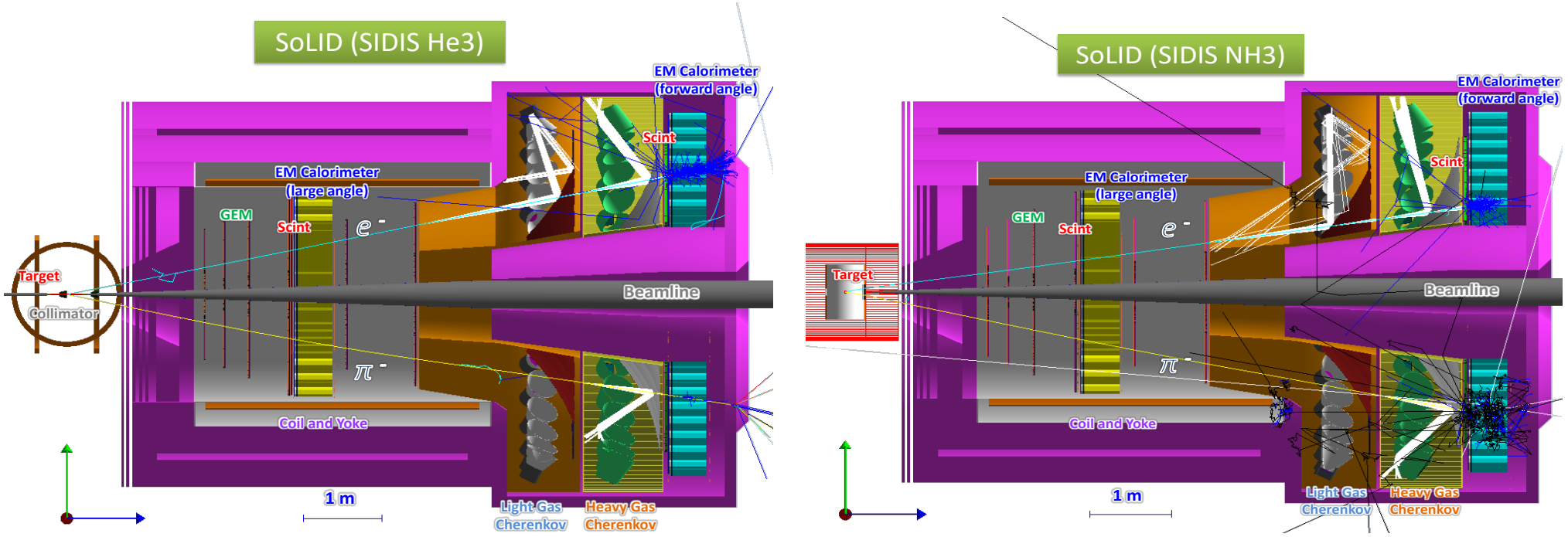


X. Qian et al., PRL107, 072003(2011)



- **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

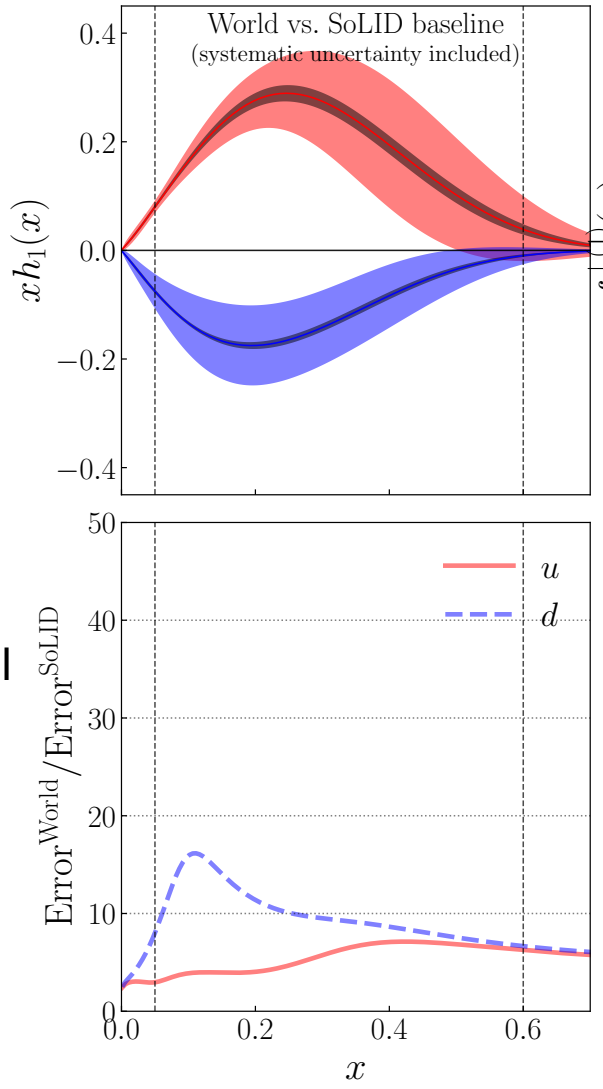
Compare SoLID with World Data

- 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

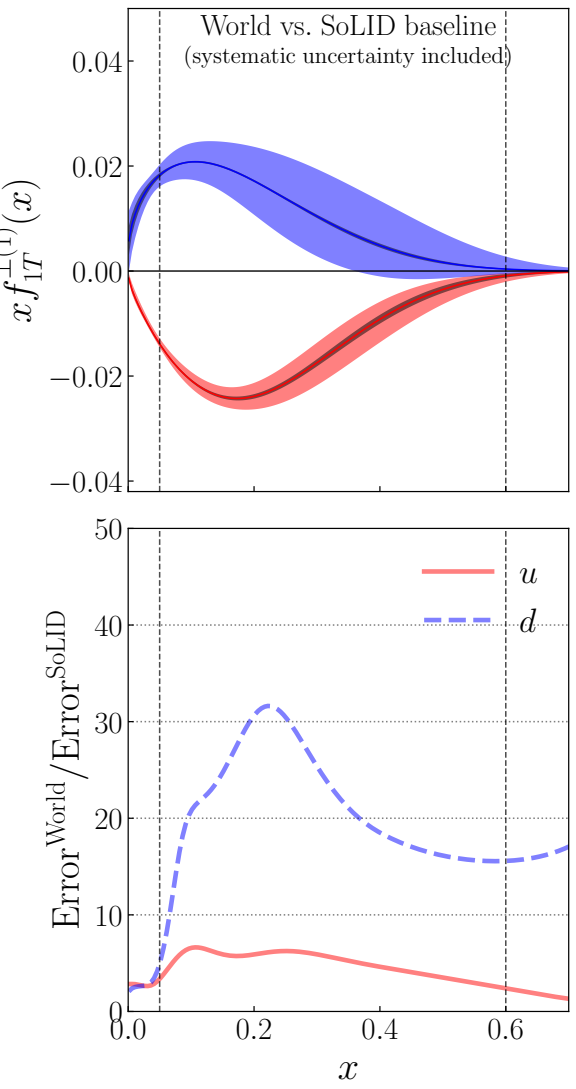
SoLID baseline used

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

Transversity



Sivers



SoLID Impact on Tensor Charge

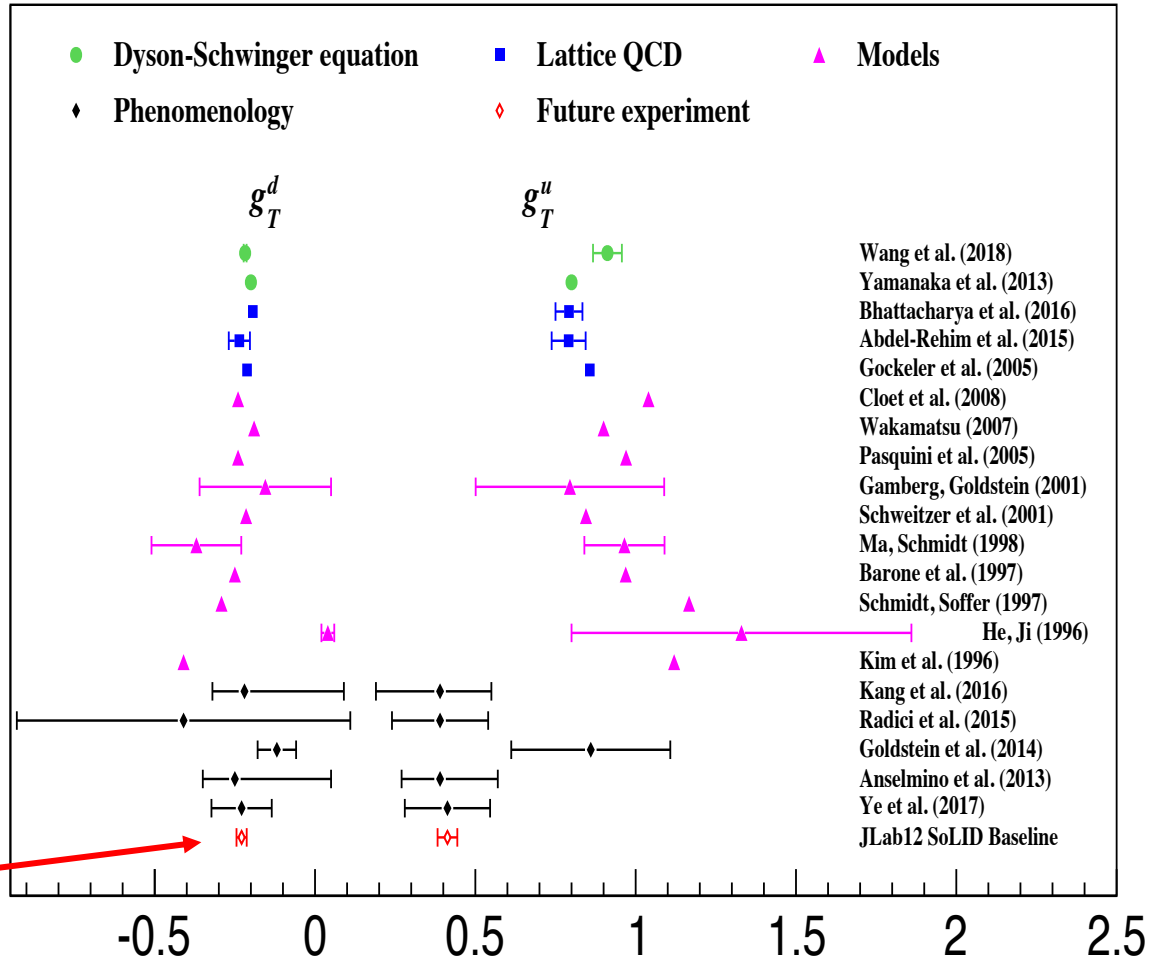
Definition

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

- 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

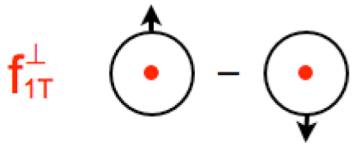
$$d_n = g_T^d\, d_u + g_T^u\, d_d + g_T^s\, d_s$$



SoLID Projections

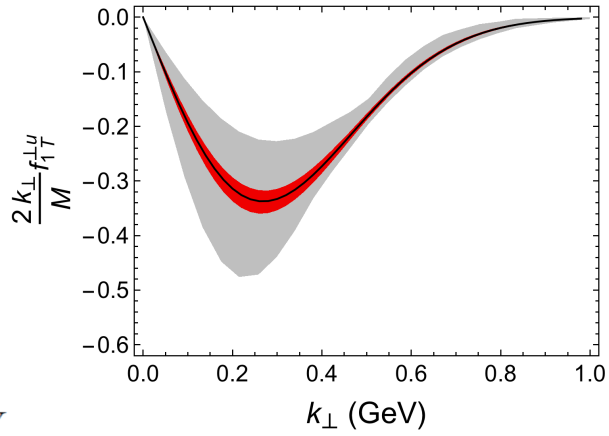
TMDs – confined motion inside the nucleon

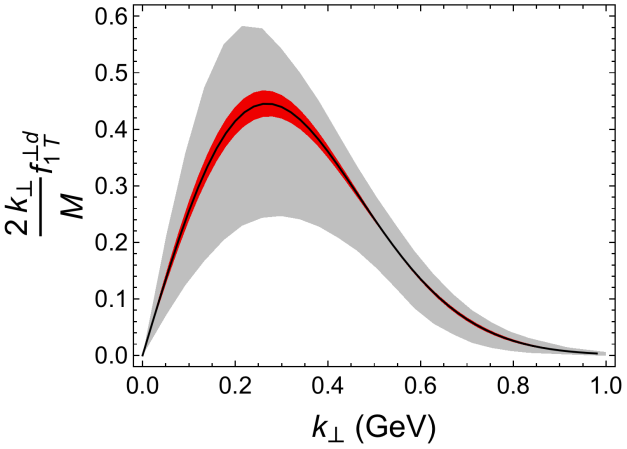
Sivers distribution

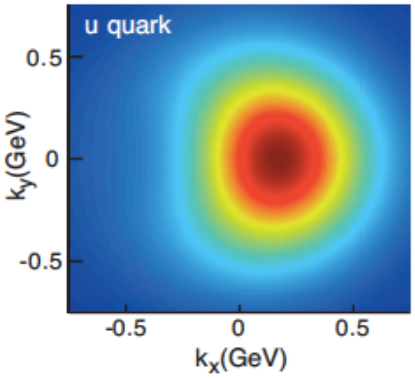


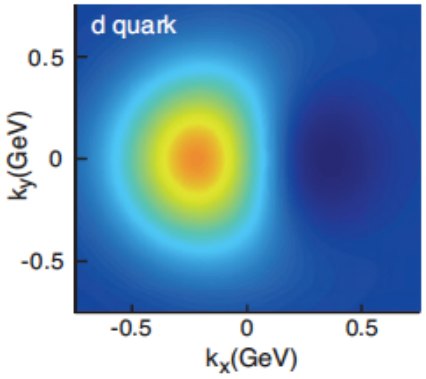
naively time-reversal odd

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









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

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

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

SoLID projection with transversely polarized n/p

Nucleon spin - quark orbital angular momentum (OAM) correlation
– zero if no OAM (collinear, massless quarks)

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

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

4. SoLID-J/ψ

Probe Strong Gluon Field
Proton Mass – Quantum Anomalous Energy

Proton Mass and Quantum Anomalous Energy

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

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

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

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

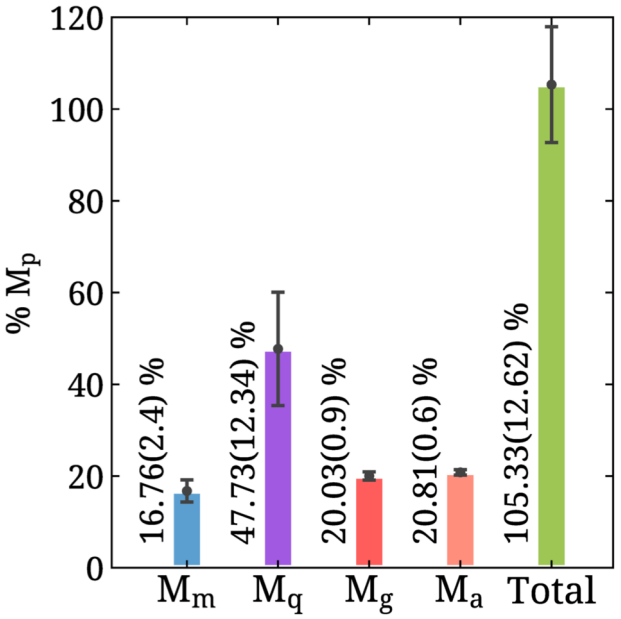
$H_g =$ Gluon energy $\int d^3x\ \frac{1}{2}(\mathbf{E^2} + \mathbf{B^2})$

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

Sets the scale for the hadron mass!

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

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

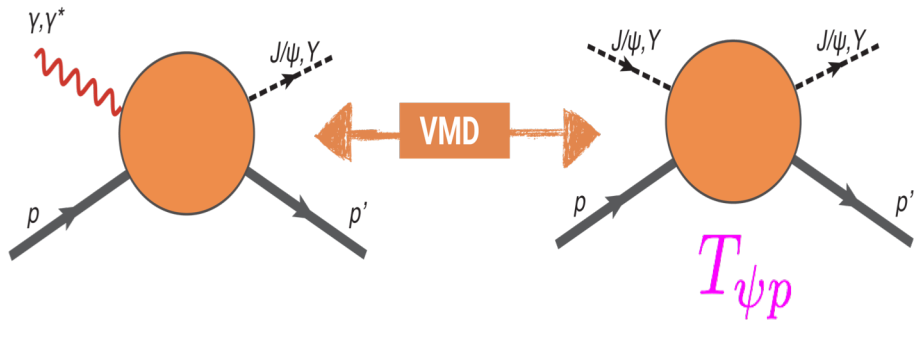


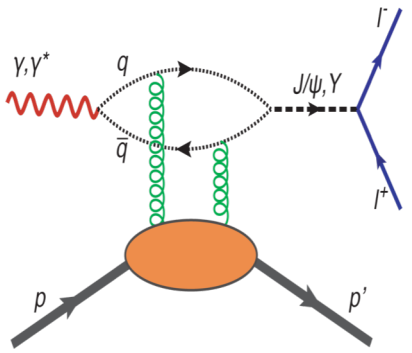
C. Alexandrou et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

- **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

From Cross Section to the Trace Anomaly





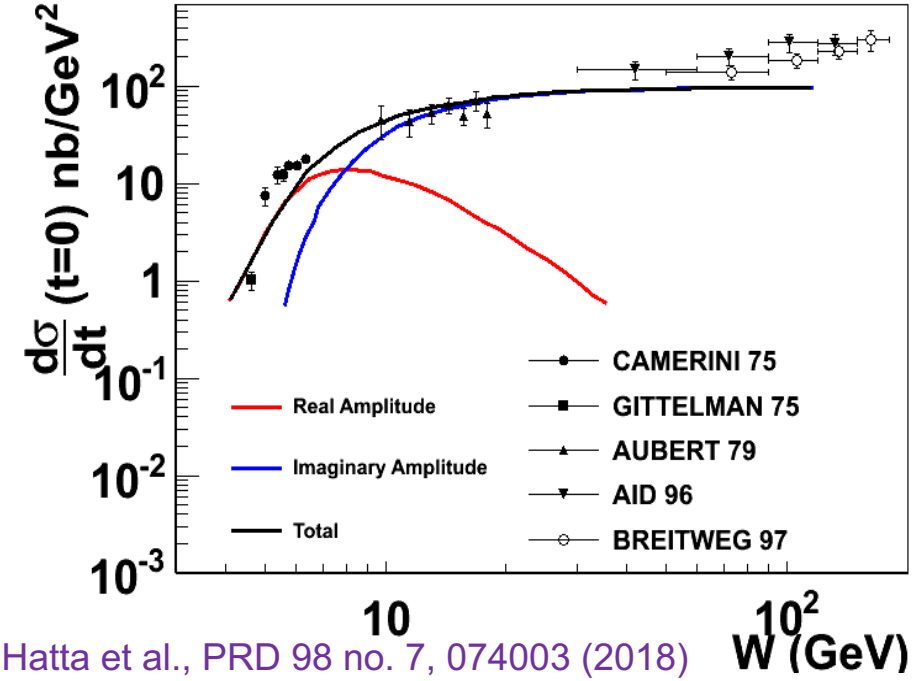
$$\gamma^* + N \to N + J/\psi$$

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 quarknium-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

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)

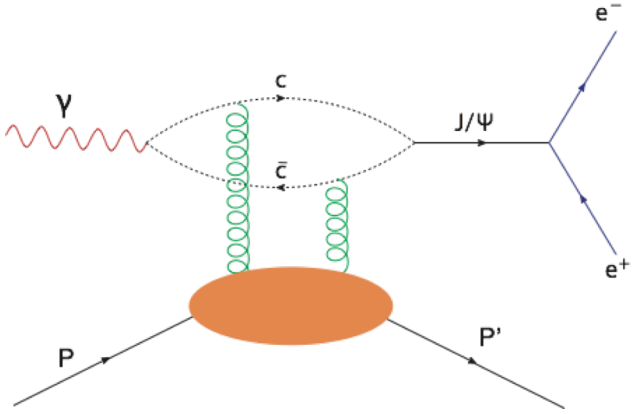
A measurement near threshold could allow access to the trace anomaly

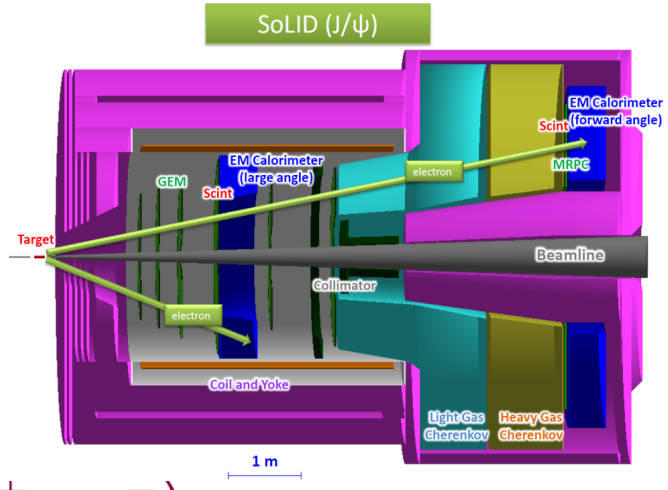
SoLID-J/ψ: Experiment E12-12-006

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

  10 more days include calibration/background run

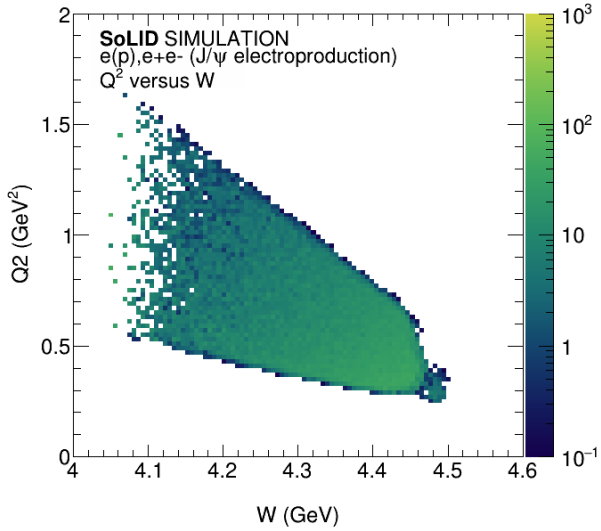
- SoLID configuration overall compatible with SIDIS
  - **Electroproduction trigger**: 3-fold coincidence of e, e^-e^+
  - **Photoproduction trigger:** 3-fold coincidence of p, e^-e^+
  - **Additional trigger:** 4-fold coincidence of ep, e^-e^+
  - And (inclusive) 2-fold coincidence e^+e^-

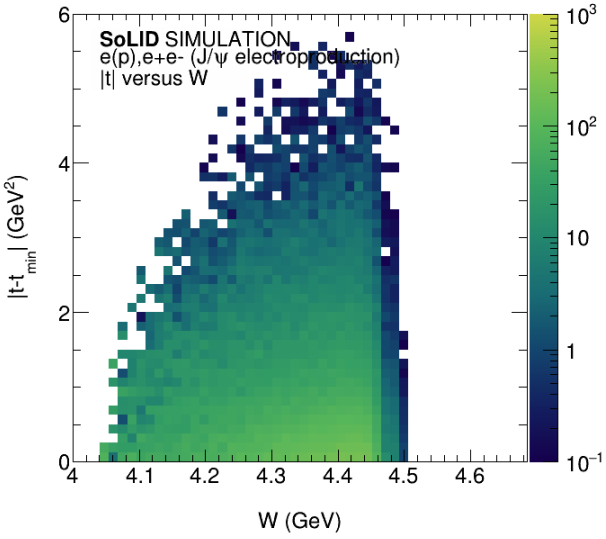




$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

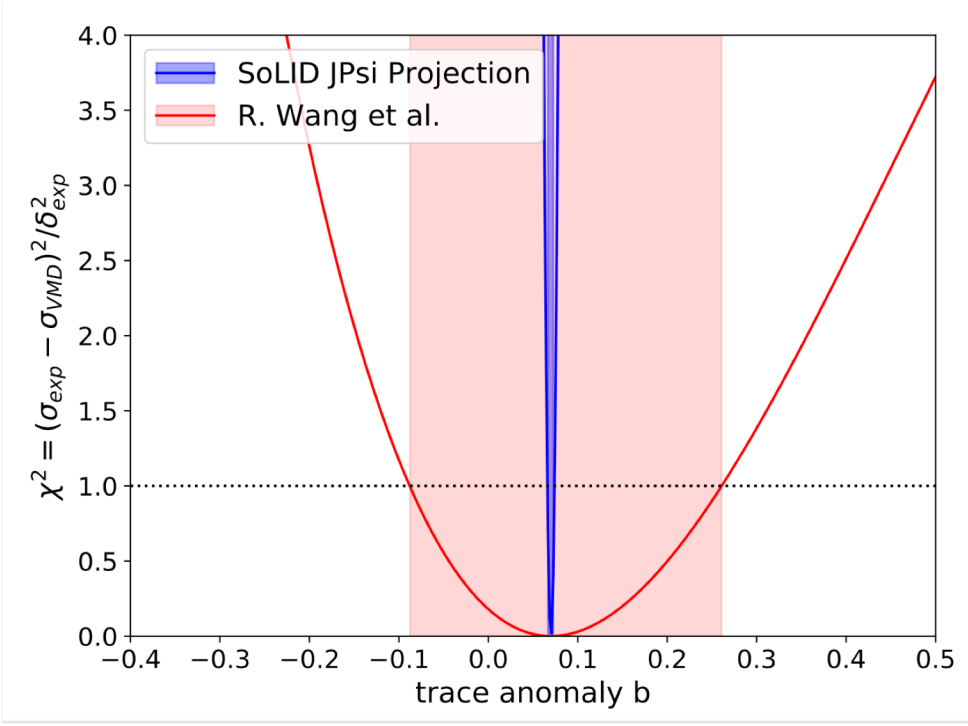
$$\gamma + p \rightarrow p' + J/\psi(e^- + e^+)$$

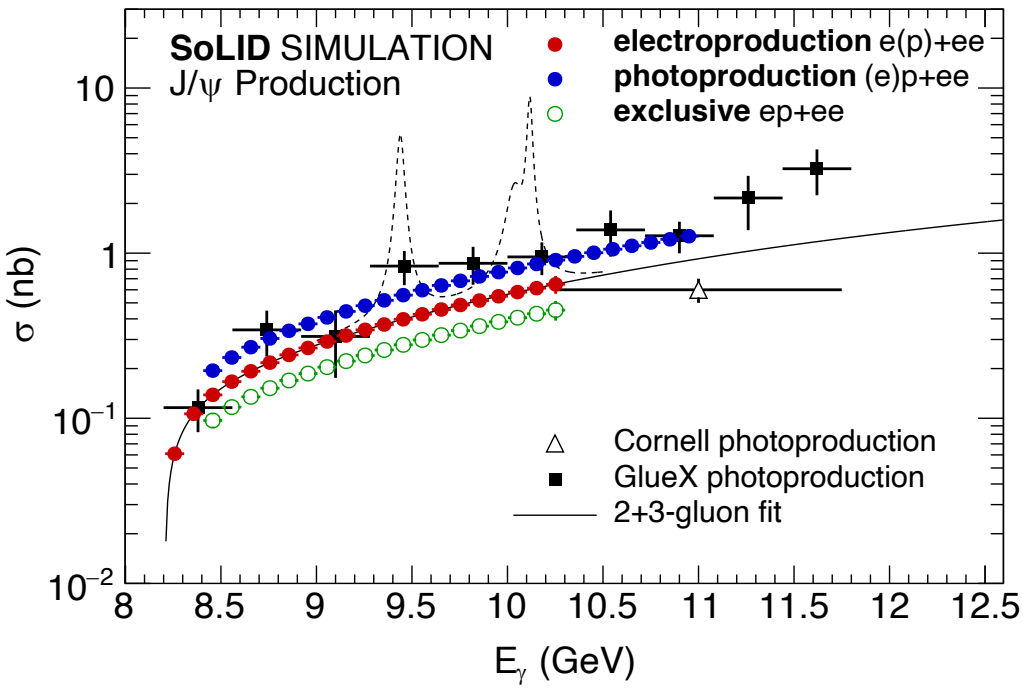




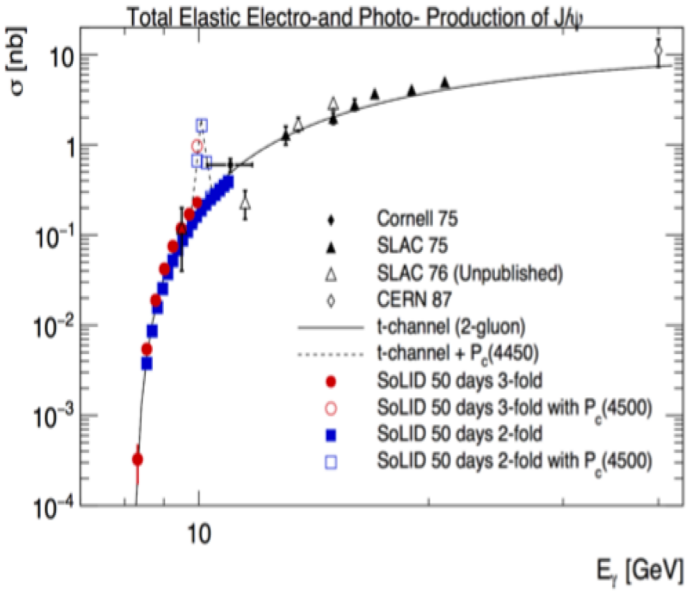
Spokespersons: K. Hafidi, X. Qian, N. Sparveris, Z.-E. Meziani (contact), Z. Zhao

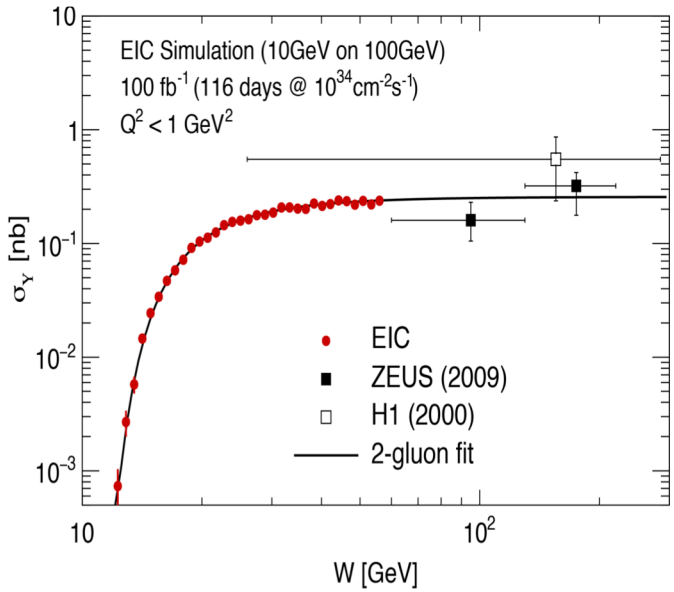
SoLID Impact on Quantum Anomalous Energy and EIC





Charm @ SoLID and Beauty @ EIC





S. Joosten, Z.E. Meziani, PoS 308 (2017) doi.org/10.22323/1.308.0017

Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020) (for update)

GlueX on J/ψ Ali et al., PRL 123, 072001(2019)

5. SoLID run-group experiments

GPDs and More

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)

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

  C. Peng, Y. Tian

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

5. SoLID Device

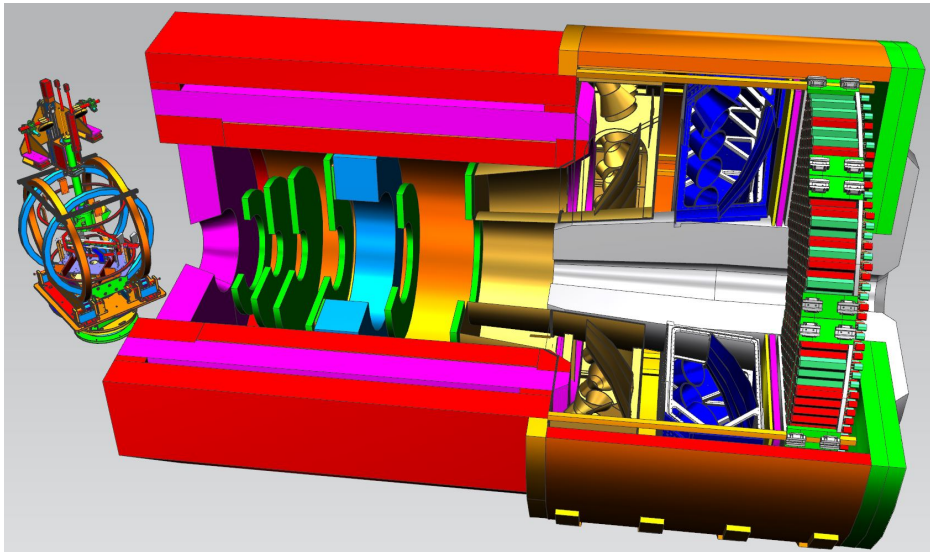
Detectors, Timeline, Collaboration

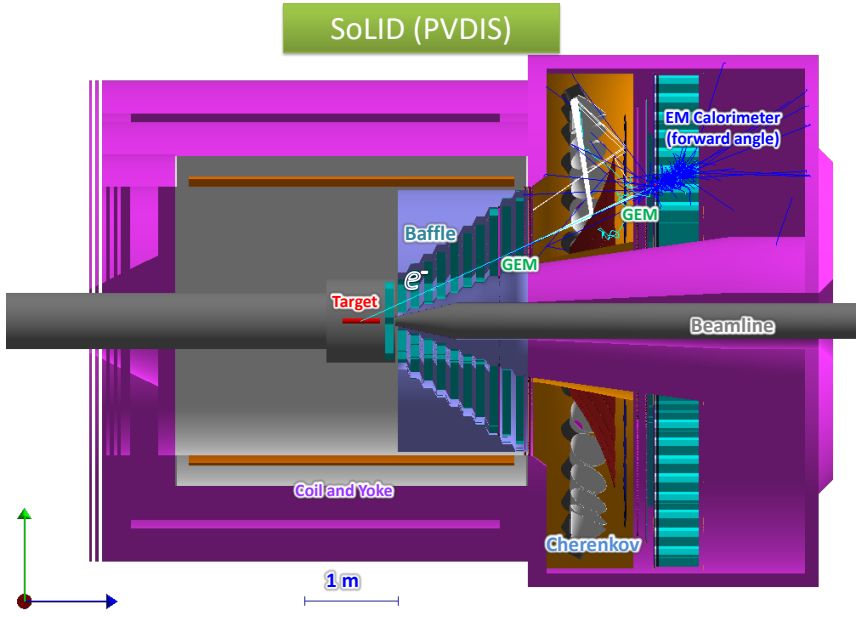
SoLID Apparatus

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

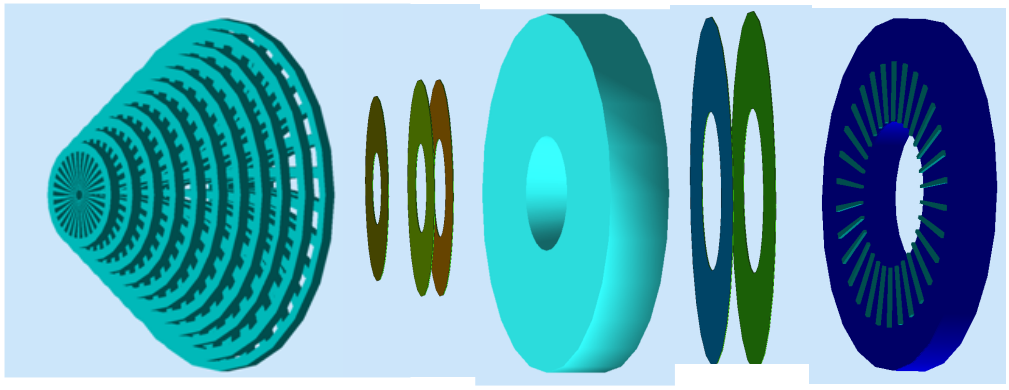


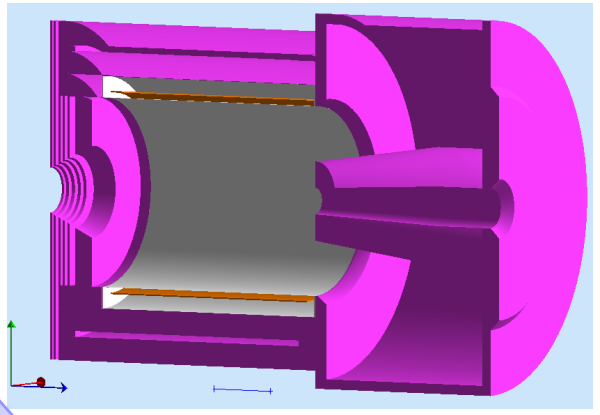


SoLID Detector Subsystems

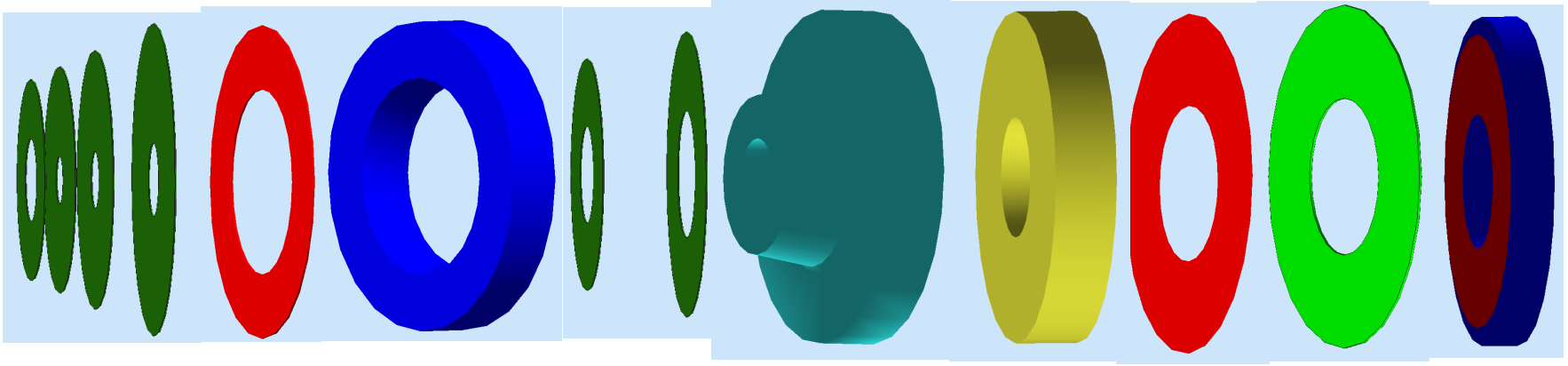
Uses full capability of JLab electronics

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC





SIDIS&J/y:
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



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

7. Summary

Summary

- SoLID: A **large acceptance** device which can handle **very high luminosity** to allow full exploitation of JLab 12 GeV potential

  → 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 on SIDIS, PVDIS and J/Psi production + more

- 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)
- 270+ collaborators, 70+ institutions from 13 countries

  Welcome new collaborators.

https://solid.jlab.org/