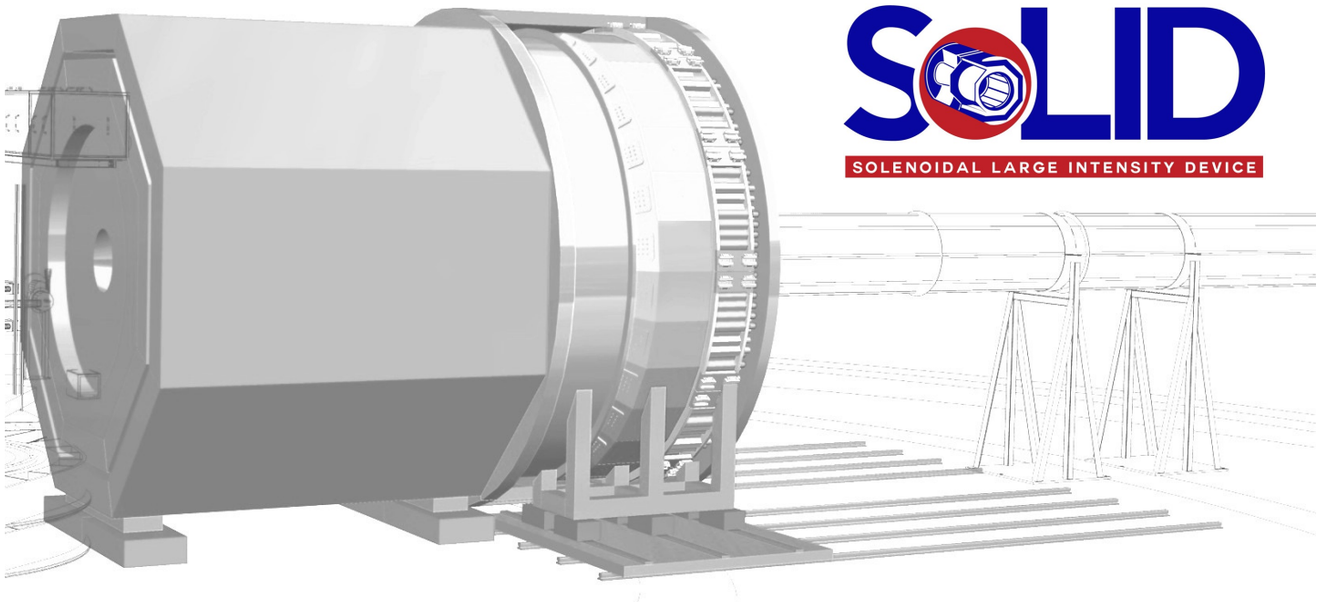
Electron Scattering at the Intensity Frontier with SoLID

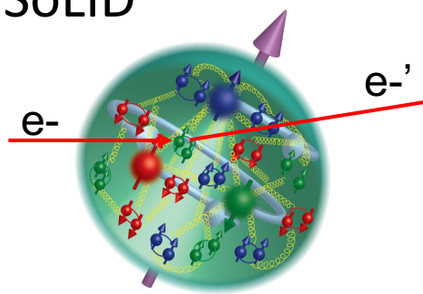


SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

Zein-Eddine Meziani
Argonne National Laboratory

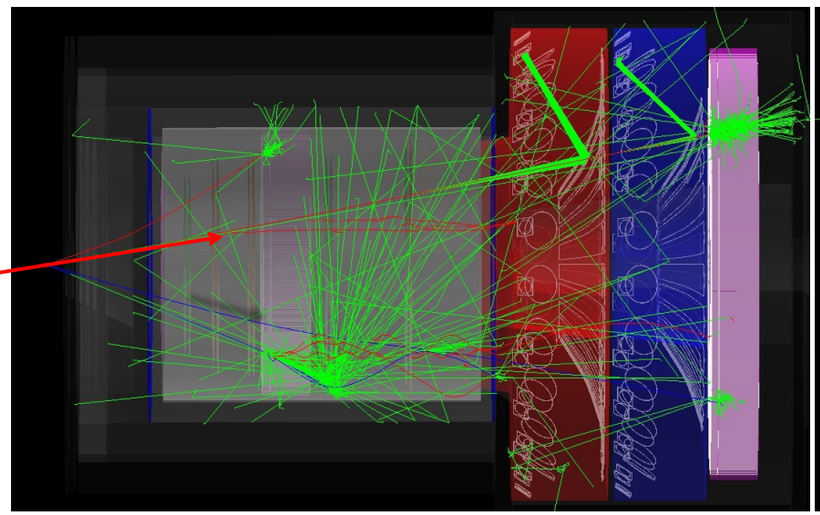
Hot & Cold QCD Town Hall Meeting, MIT
September 23-25, 2022

With thanks to:
Jian-Ping Chen, Haiyan Gao, Paul Souder and Xiaochao Zheng and the SoLID collaboration

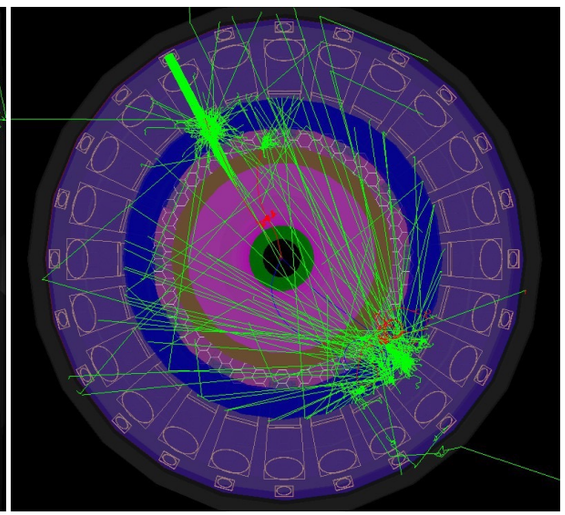


A charmonium production and decay event in SoLID

Side view



Front view



U.S. DEPARTMENT OF ENERGY | Office of Science

Jefferson Lab SoLID Argonne NATIONAL LABORATORY

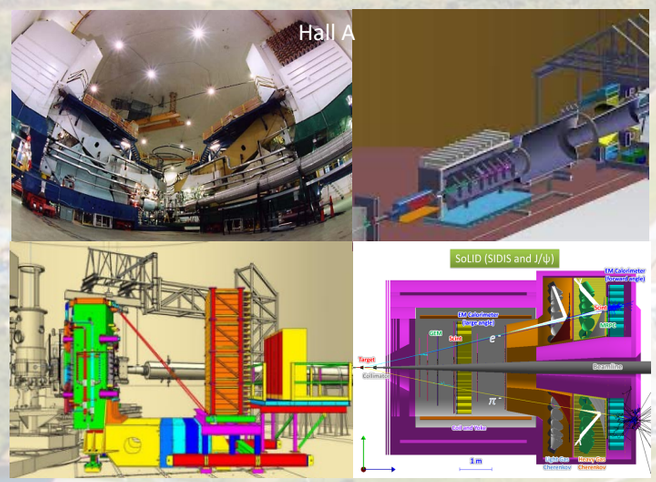
OUTLINE

- 12 GeV Capabilities at Jefferson Lab

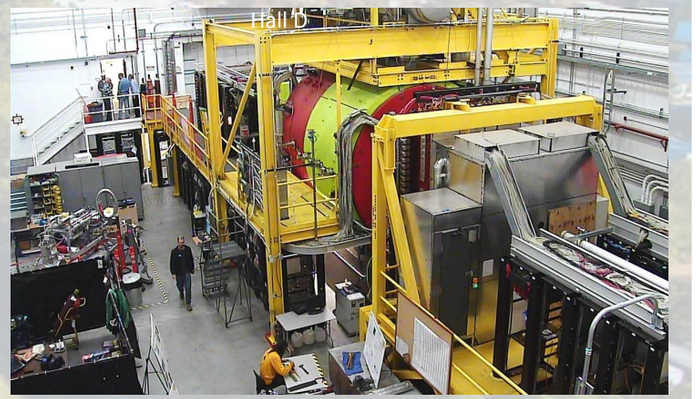
- SoLID Science Program
  - **SIDIS:** Transversity and Transverse Momentum Dependent Distributions (TMDs)
  - **Threshold J/ψ**: Probe Strong Color Fields and Proton Mass
  - **PVDIS**: Precision Test of the Standard Model of Particle Physics
  - *Run-group Experiments: **GPDs**, TMDs and Spin*

- SoLID Device and Project
  - Detectors
  - Cost and Schedule
  - Collaboration

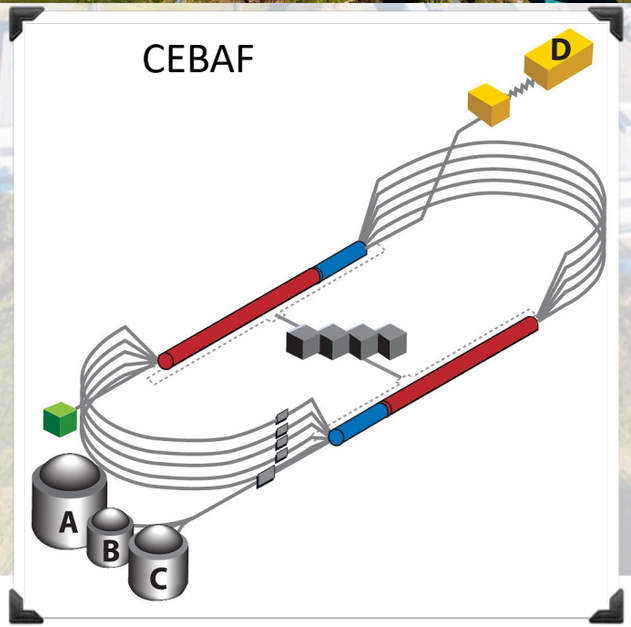
Present 12 GeV experimental capabilities at JLab and possible future



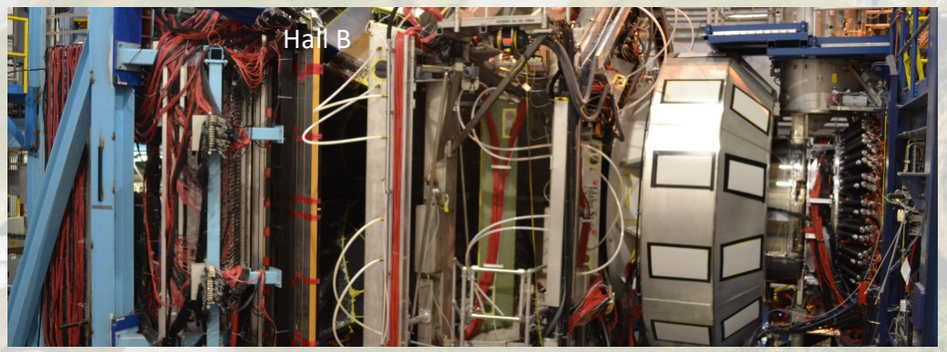
HRS, SBS, Moller & SoLID



Hall D (GlueX)



Hall B



CLAS12 + (luminosity) Upgrade

Hall C (HMS and SHMS)

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Why SoLID at 12 GeV CEBAF?

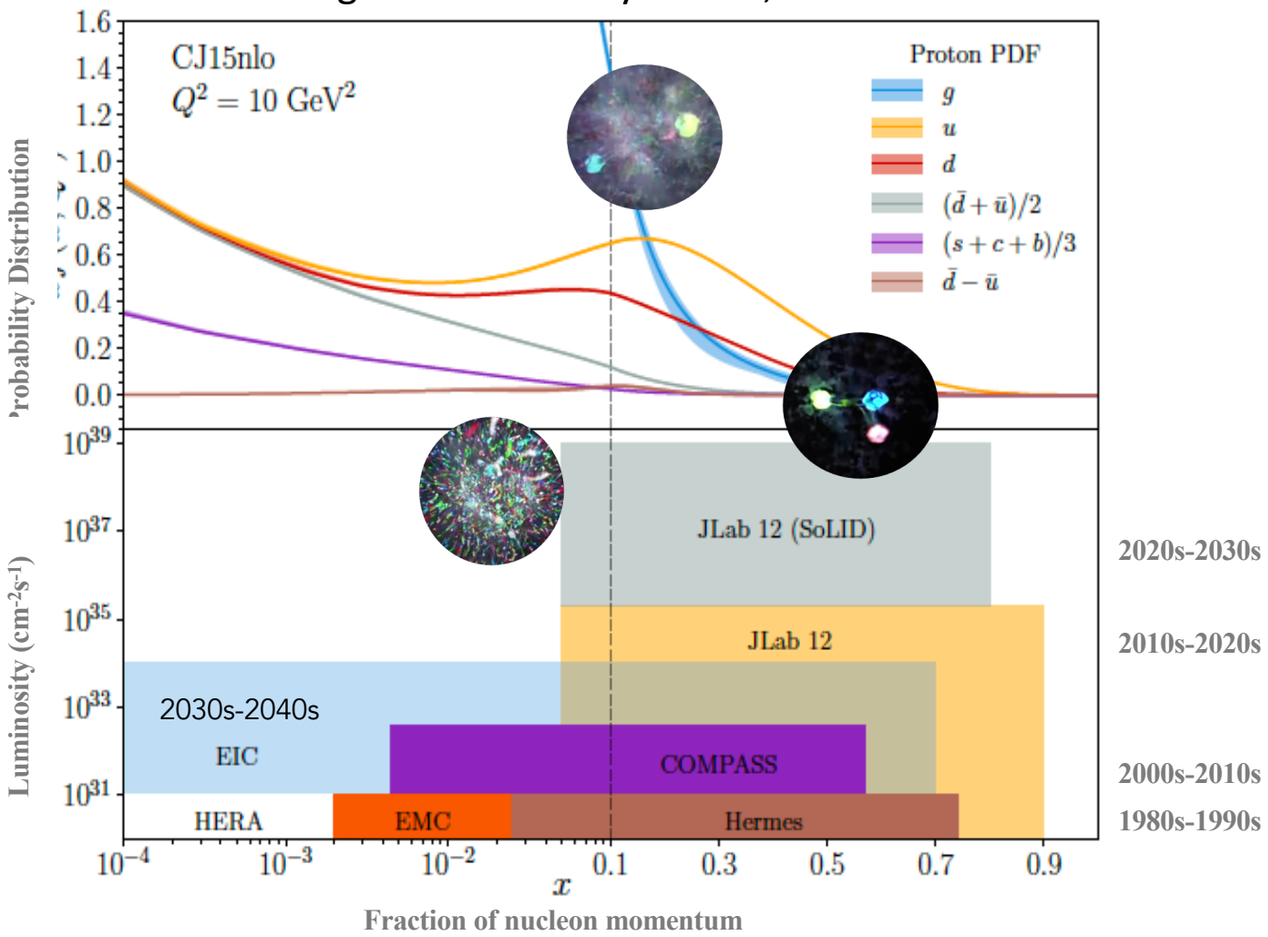
SoLID@JLab 12-GeV Enables QCD at the Intensity Frontier

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

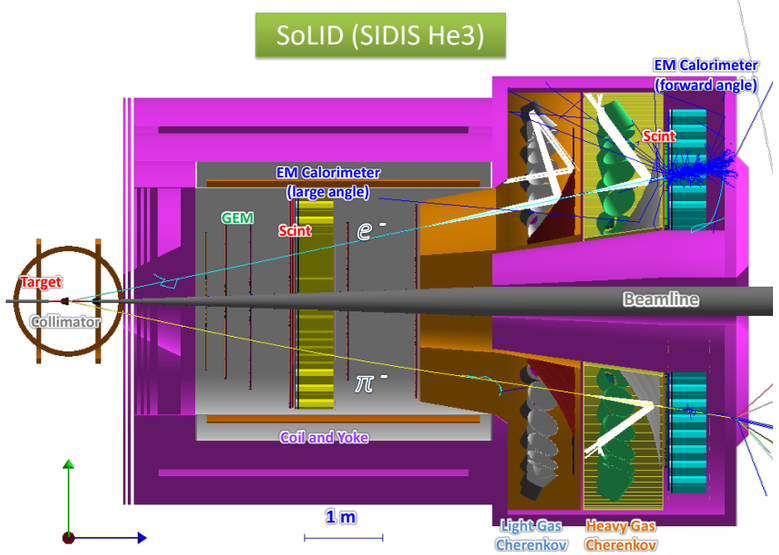
- There is a critical need for high luminosity (10^{37}-10^{39} $cm^{-2}s^{-1}$) and large acceptance working in tandem

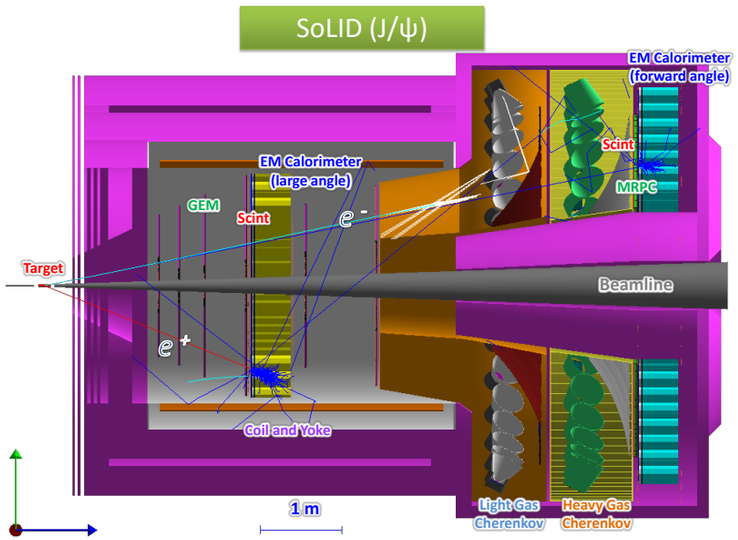
- Science reach:
  - Precision 3D momentum imaging in the valence quark region
  - Exploring the origin of the proton mass and gluonic force in the non-perturbative regime.
  - Beyond the Standard Model searches in tandem with Moller

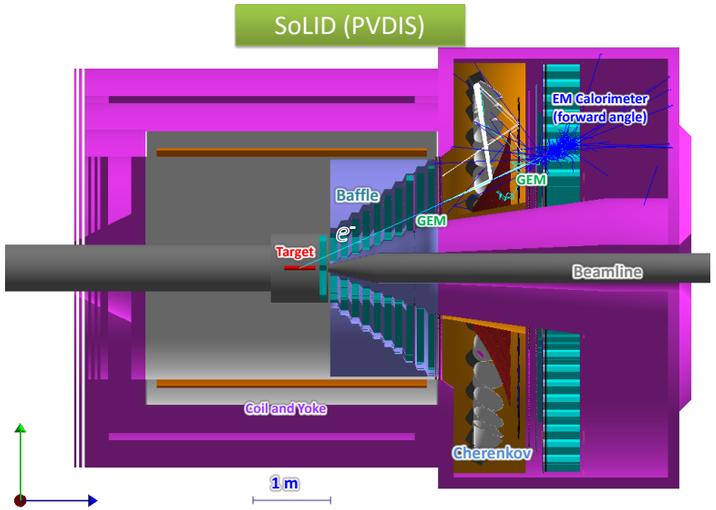
Physics with CEBAF at 12 GeV and future opportunities
Prog. Part. Nucl. Phys. 2022, 103985



SoLID Physics Program: Approved Experiments







- **SIDIS: (3)**
  Rating: A
  Transversely Polarized ^{3}He (n):Transversity, Sivers, Pretzelosity TMDs
  Longitudinally Polarized ^{3}He (n): Worm-gear TMDs
  Transversely Polarized Proton: Transversity/Sivers, Pretzelocity TMDs

- **Threshold J/ψ Production:**
  Rating: A
  Gluon Field, Gluonic Gravitational FFs, Proton Mass

- **PVDIS**:
  Rating: A
  Test of the Standard Model & nucleon structure

- **Run group experiments (6) approved for GPDs, TMDs, and spin**

PAC50 (2022): Approved two new SoLID Experiments: Beam Normal SSA (A- rating) & PVEMC (conditional approval)

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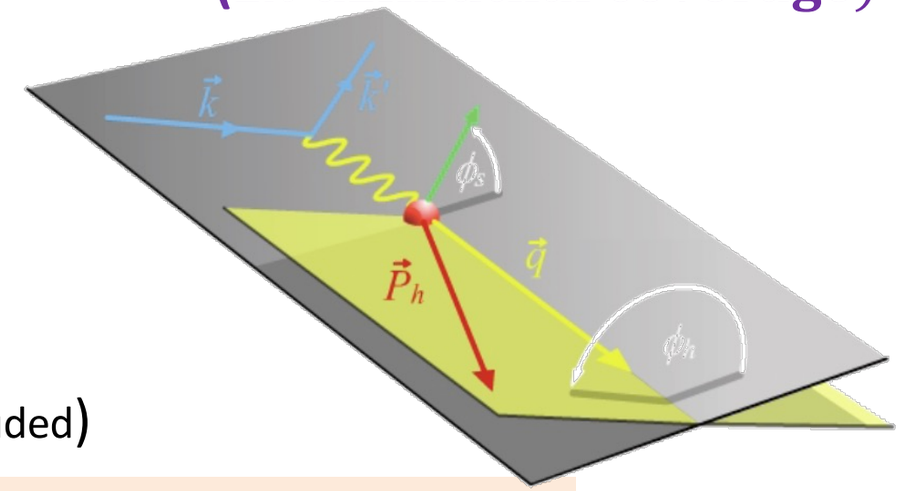
SoLID-SIDIS: Transversity/Tensor Charge and TMDs

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)

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

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

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

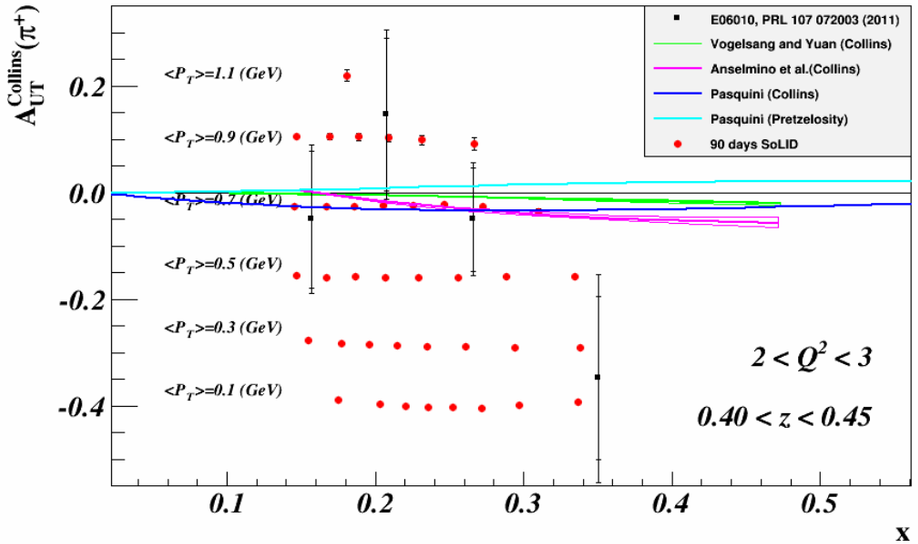
Collins fragmentation function from e^+e^- collisions

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

Unpolarized fragmentation function

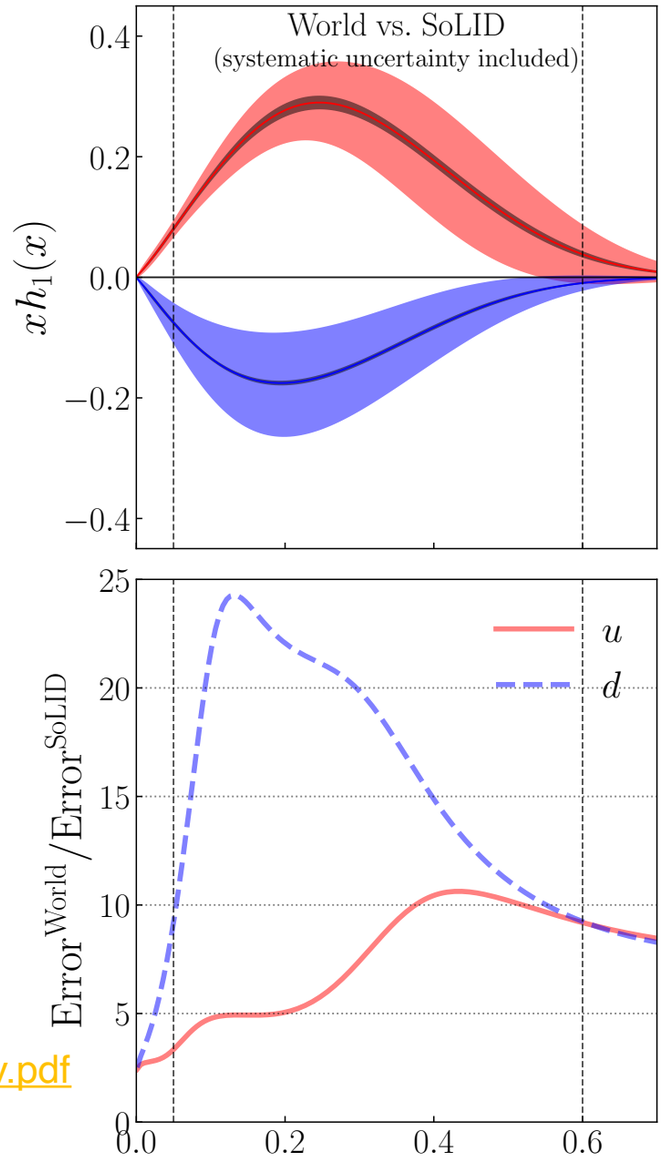
SoLID-SIDIS Projections and Impact

JLab 6-GeV X. Qian et al., PRL107, 072003(2011) &
12 GeV SoLID projections

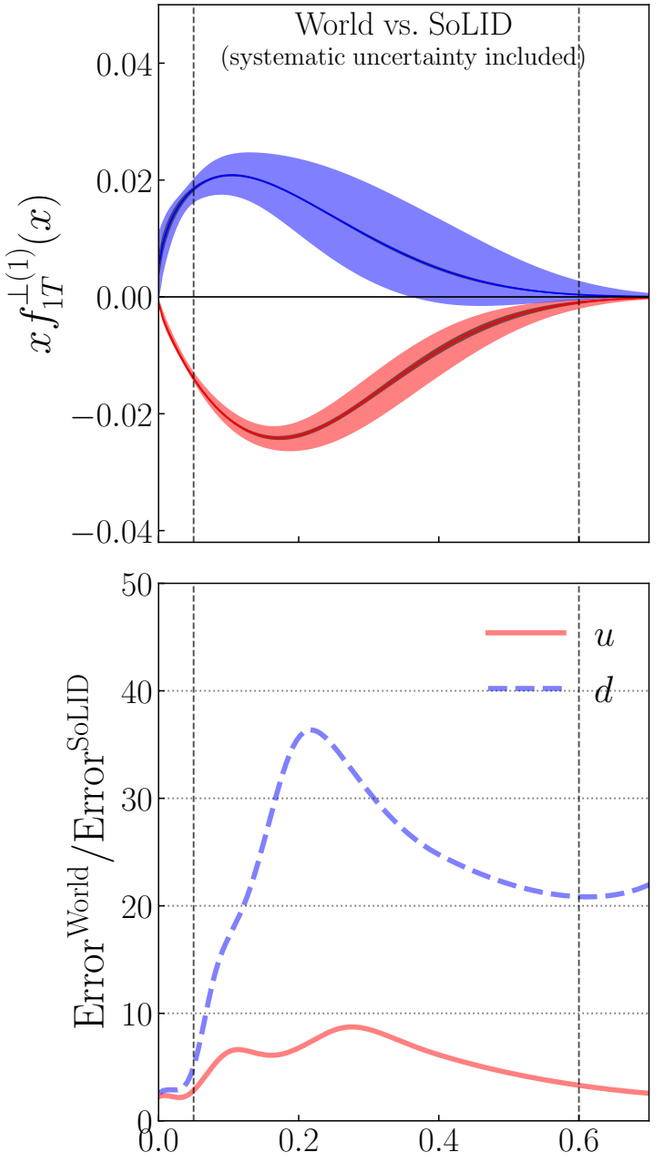


- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Includes both systematic and statistical uncertainties
- *World data according to SoLID (2019) preCDR*
  https://solid.jlab.org/DocDB/0002/000282/001/solid-precdr-2019Nov.pdf

Transversity



Sivers



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

SoLID IMPACT on TENSOR CHARGE

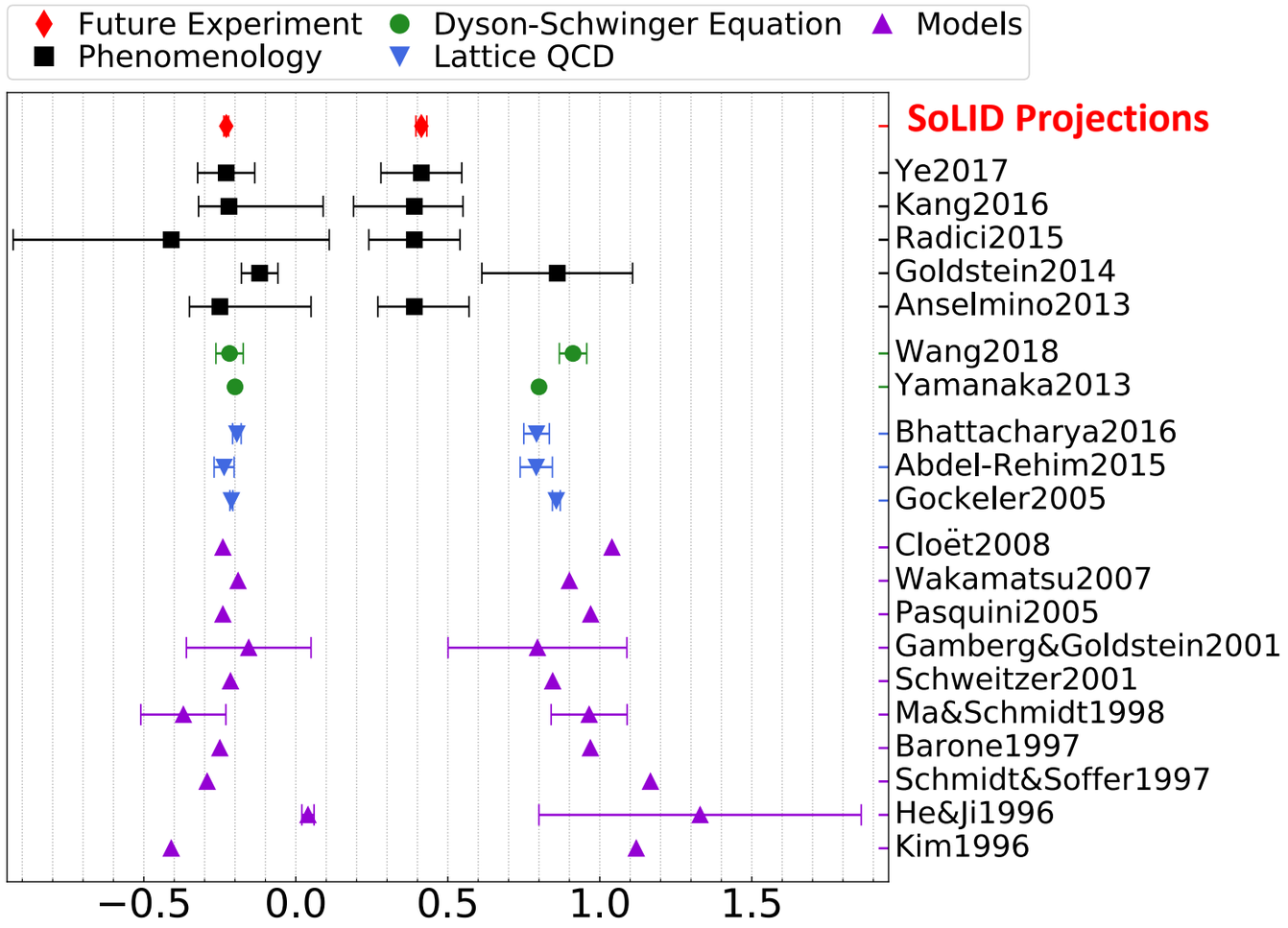
Tensor charge

$$\langle P,S|\bar{\psi}_q i\sigma^{\mu\nu}\psi_q|P,S\rangle = g_T^q\,\bar{u}(P,S)i\sigma^{\mu\nu}u(P,S)$$

$$g_T^q = \int_0^1 [h_1^q(x) - h_1^{\bar{q}}(x)]dx$$

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

- An intrinsic nucleon property as fundamental as the electric charge, the axial charge…
- A moment of the transversity distribution dominated by valence quarks
- Precision lattice QCD benchmark
- Probe of new physics when combined with EDMs



- **SoLID J/ψ** Near Threshold Production

Probing the Strong Color Fields

Origin of Proton Mass and Proton Gluonic Radii

Proton Mass, Trace Anomaly/GGFFs

- **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 $\int d^3x\ \bar{\psi} m \psi$

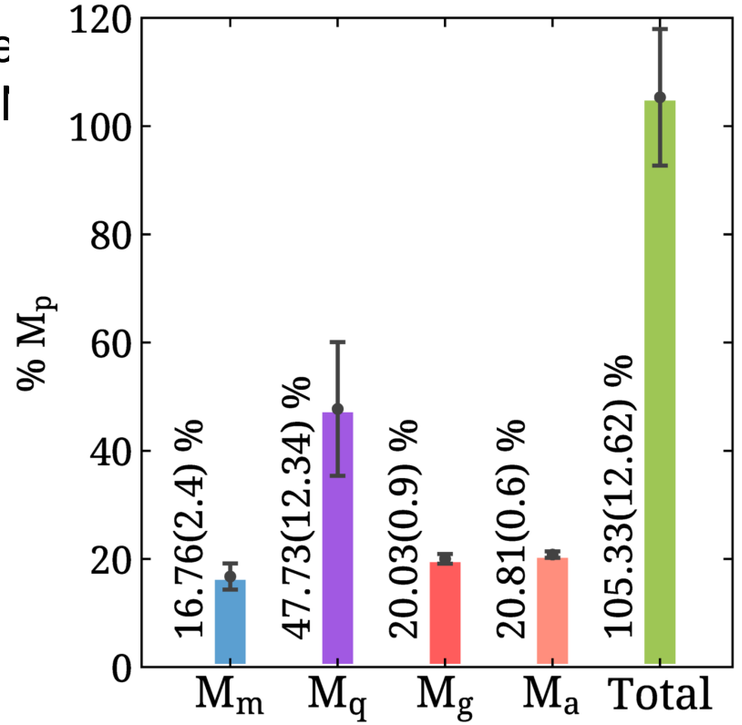
$H_g =$ Gluon energy $\int d^3x\ \frac{1}{2}\left(\mathbf{E^2}+\mathbf{B^2}\right)$

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

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 →

Friday 09/23 talk by Hatta
Friday 09/23 talk by Joosten



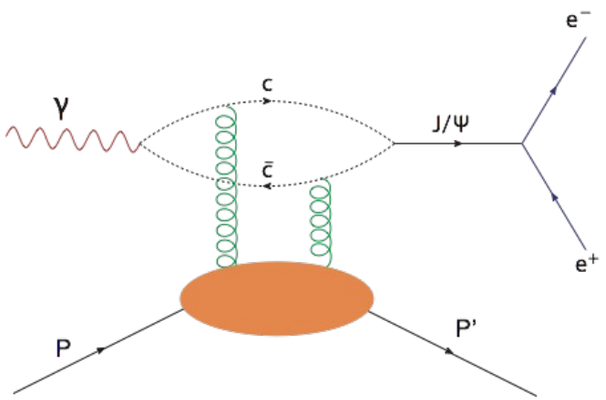
X. Ji PRL 74 1071 (1995),
X. Ji & Y. Liu, arXiv: 2101.04483
C. Lorcé, H. Moutarde and A. P. Trawinski, Eur. Phys. J. C 79 (2019) no.1, 89
A. Metz, B. Pasquini and S. Rodini, Phys. Rev. D 102, 114042 (2020)
C. Lorcé, A. Metz, B. Pasquini and S. Rodini, JHEP 11 (2021), 121]
R. Boussarie and Y. Hatta, Phys. Rev. D 101, 114004 (2020)
Y. Hatta, A. Rajan and D. L. Yang, Phys. Rev. D 100 (2019) 014032

C. Alexandrou2 et al., (ETMC), PRL 119, 142002 (2017)
Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)

- **Accessing directly the Trace Anomaly in experiments is an important goal in the future**
  Can be accessed through heavy quarkonium threshold (J/psi, 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

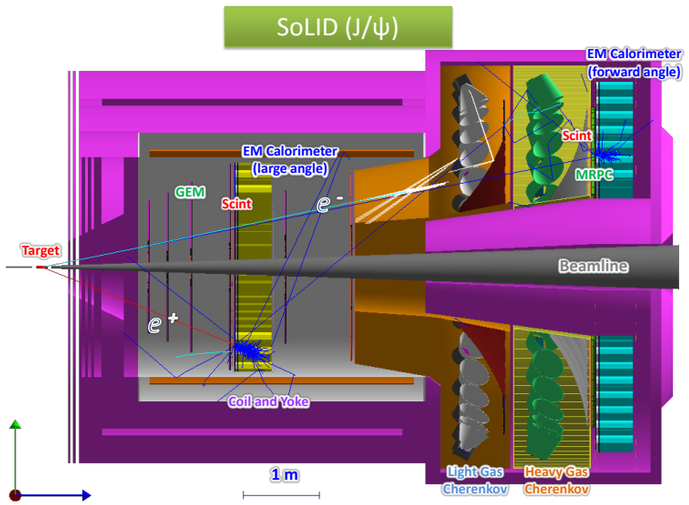
SoLID-J/ψ: Experiment E12-12-006

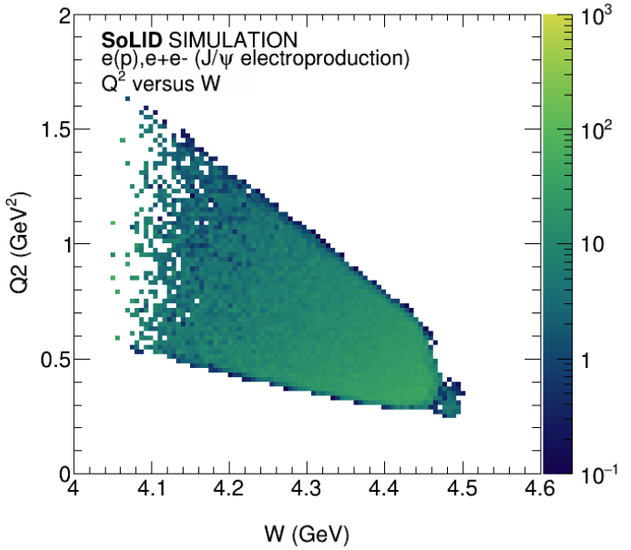
- 50 days of 3 μA beam on a 15 cm long LH_2 target at $1 \times 10^{37} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
  - 10 more days include calibration/background run
- SoLID configuration overall compatible with SIDIS
  - **Electroproduction detection**: 3-fold coincidence of e, e^-e^+
  - **Photoproduction detection:** 3-fold coincidence of p, e^-e^+
  - **Additional detection:** 4-fold coincidence of ep, e^-e^+
  - And (inclusive) 2-fold coincidence e^+e^-

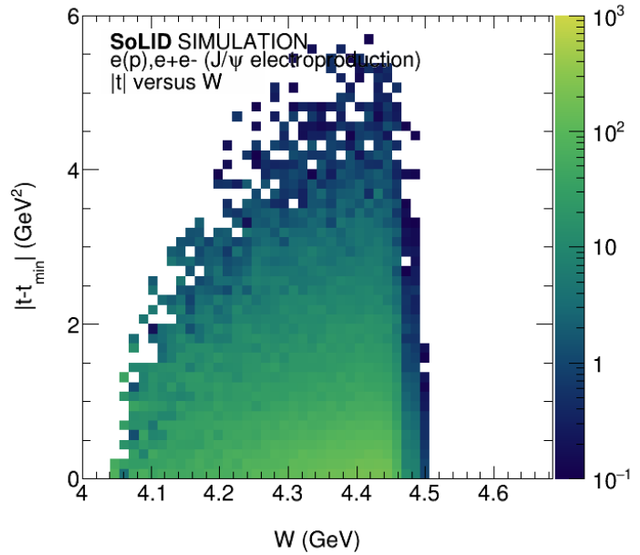


$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

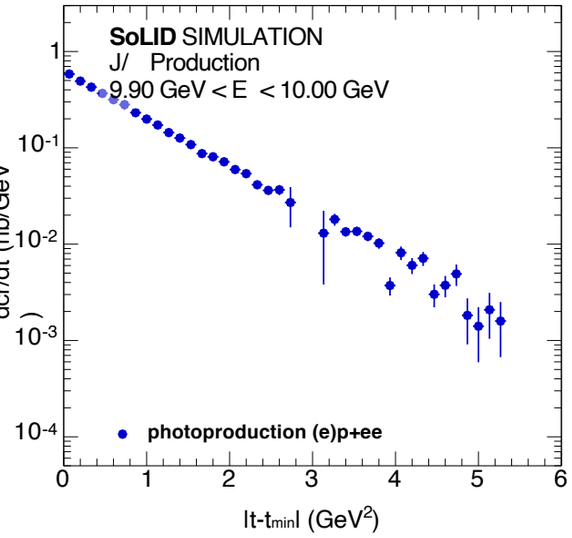
$$\gamma + p \longrightarrow p' + J/\psi(e^+ + e^-)$$

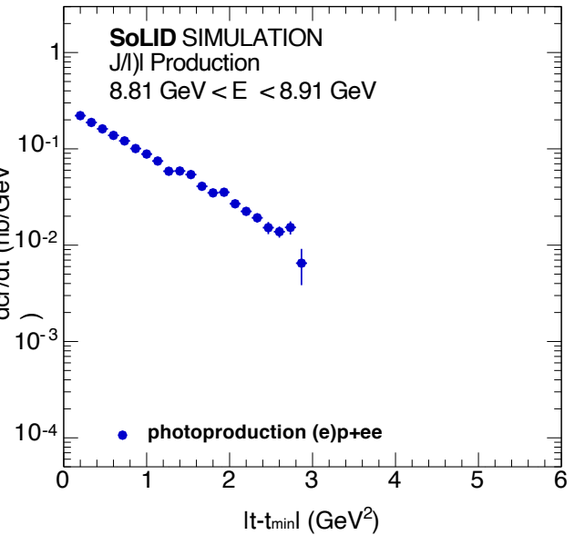




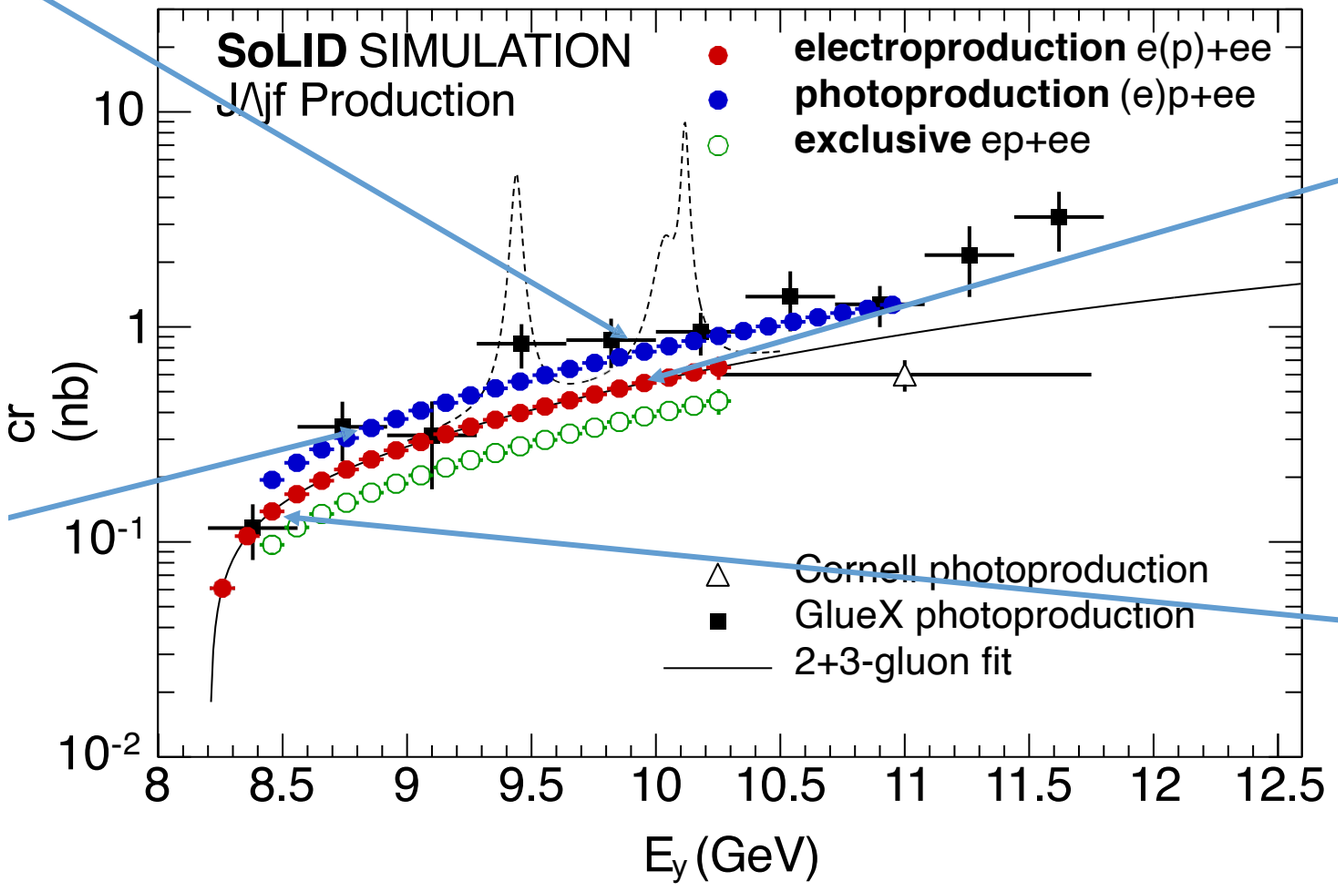


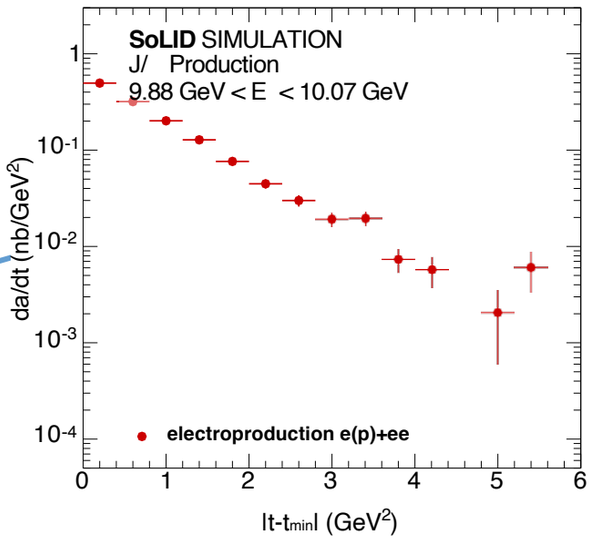
J/ψ Near Threshold: Experiment E12-12-006 @ SoLID

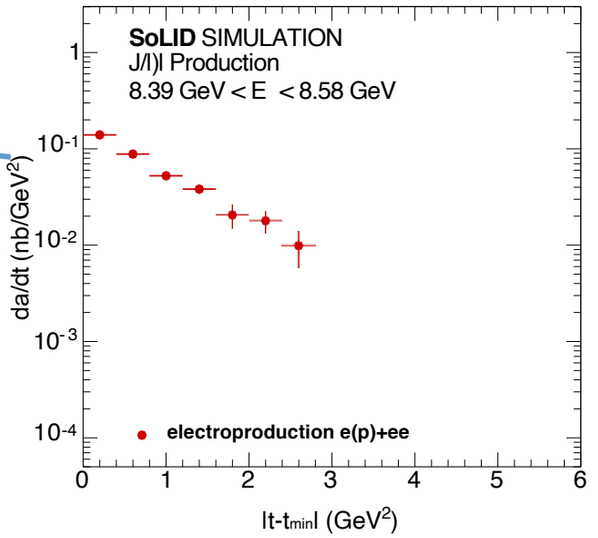




$1 \times 10^{37}\mathrm{cm}^{-2}\mathrm{s}^{-1}$







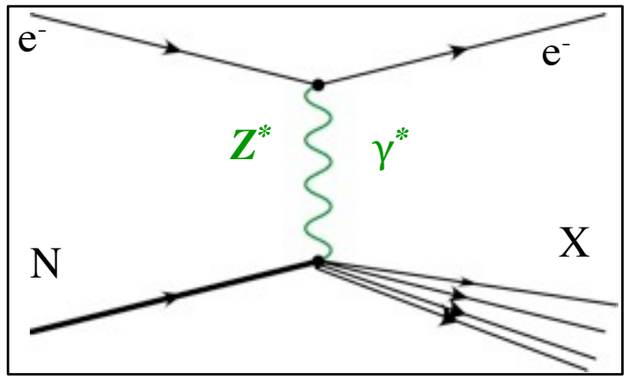
Sensitivity at threshold at about 10^{-3} nb!

PVDIS:Test of the Standard Model and Hadron Structure

Parity Violating DIS on Deuteron

Simplest isoscalar nucleus and at high Bjorken *x*

Paul Souder talk on 09/23



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

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

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

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

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

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

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

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

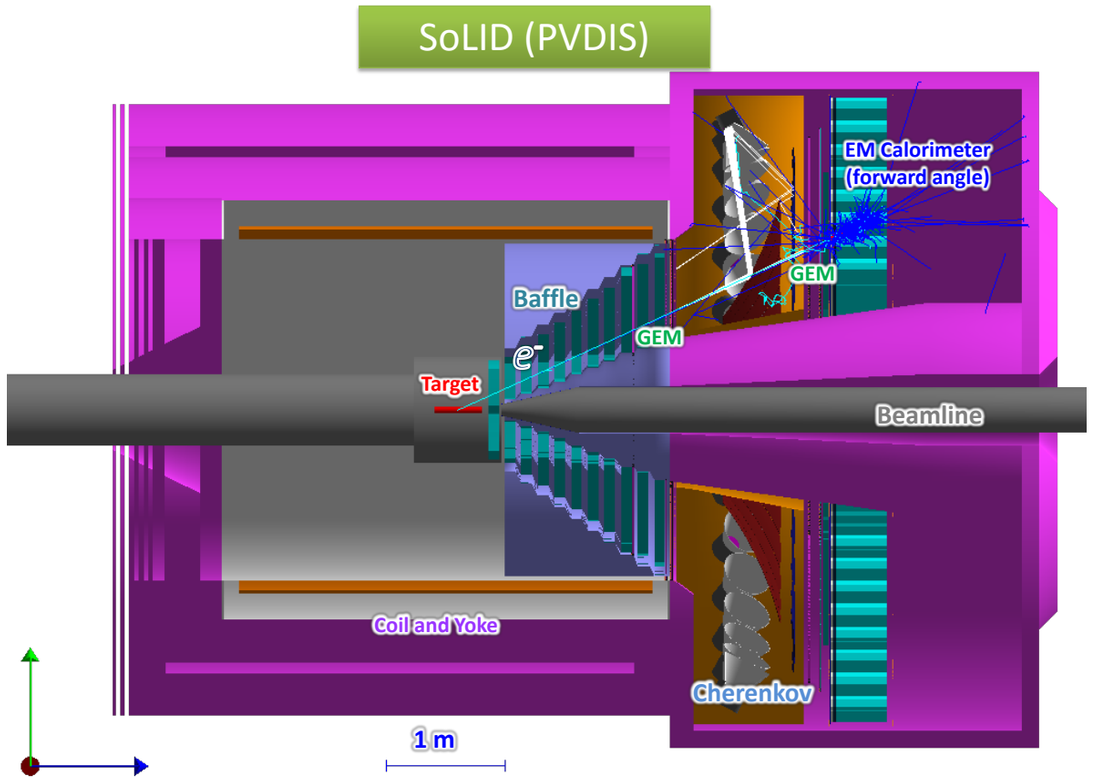
- **Parton distributions (u, d, s, c)**
- **Charge Symmetry Violation (CSV)**
- **Higher Twist (HT) – quark-quark correlation**

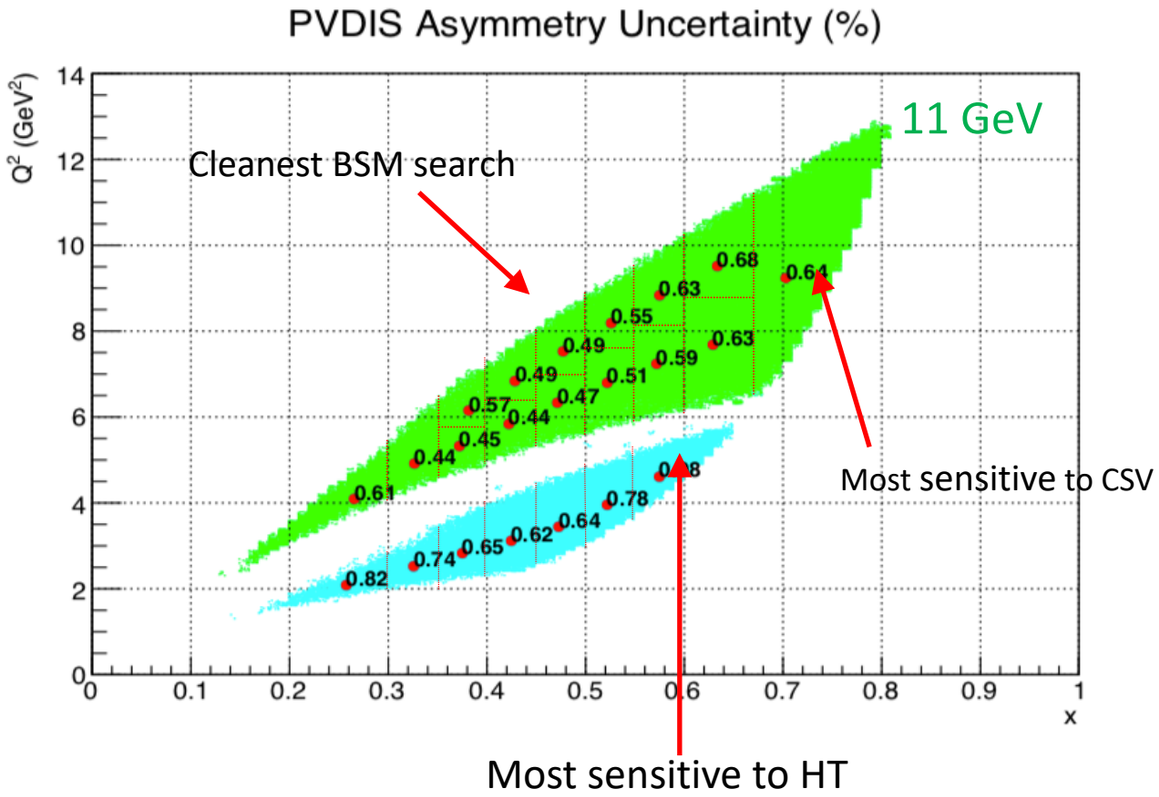
Unique feature is sensitivity to C_2's

SoLID-PVDIS: Experiment E12-10-007

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**

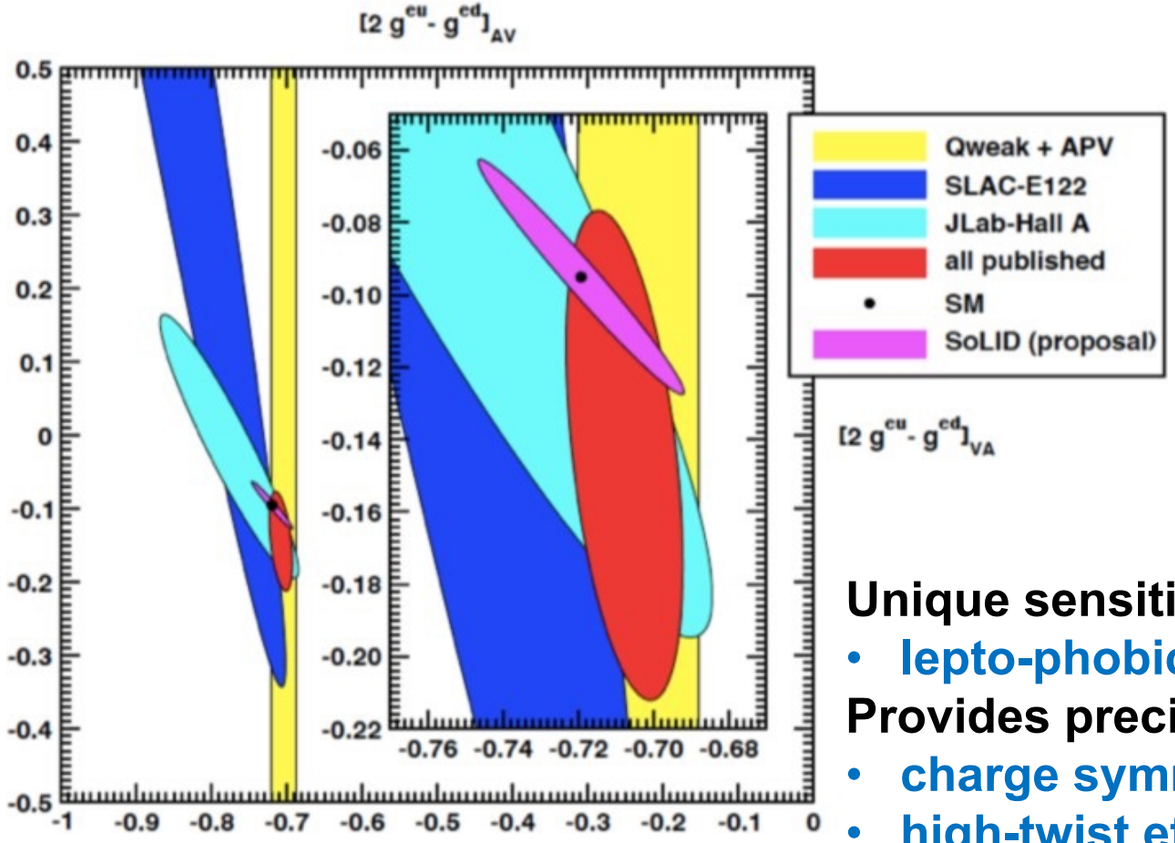




Projected Results on Coupling Constants

SoLID makes a unique contribution to the SMEFT program.

Improvement in couplings



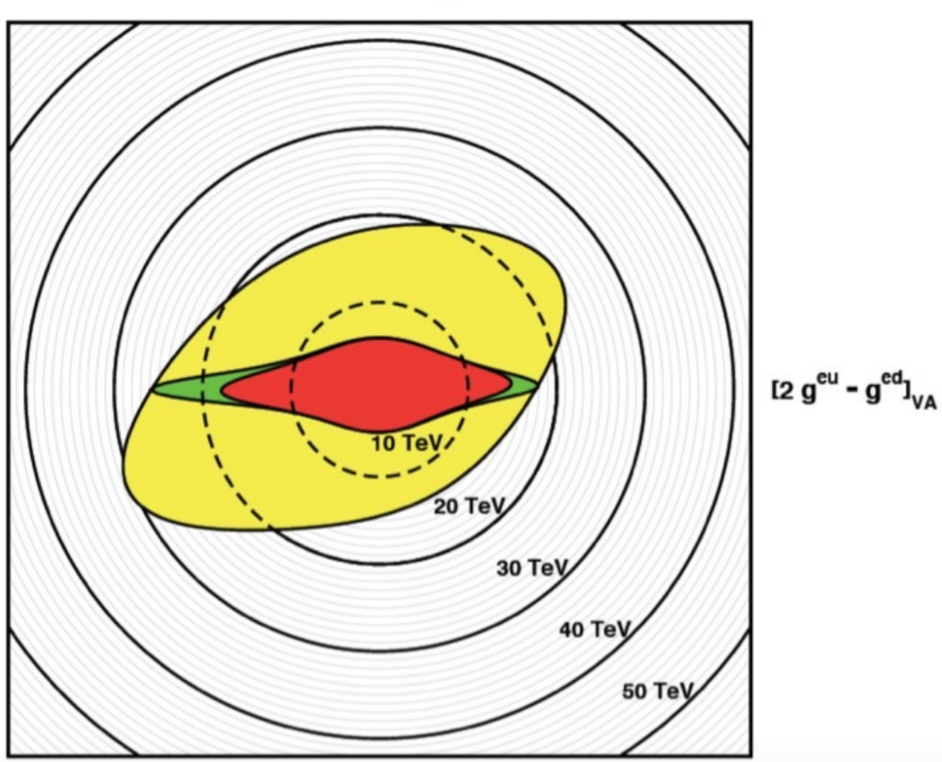
Unique sensitivity to

- **lepto-phobic Z', dark boson Z_d**

Provides precision study of

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

Improvement in energy reach for electron-nucleon couplings



SoLID Detector and Project

Detector subsystems, Cost and Schedule, Collaboration

SoLID Apparatus

Challenging requirements!

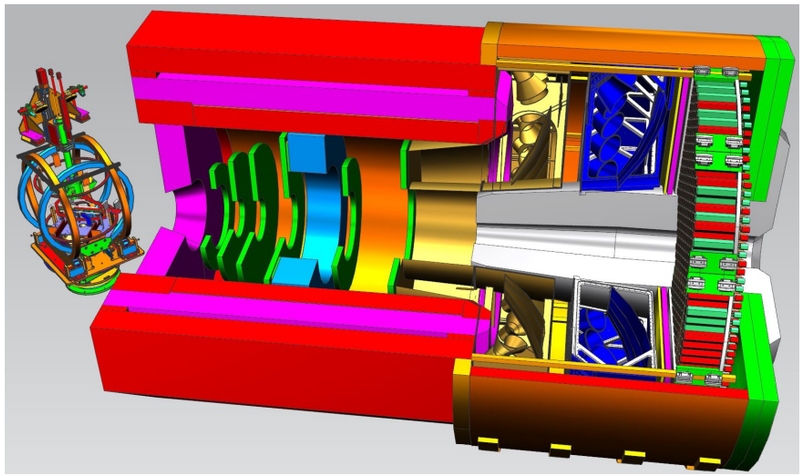
- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale

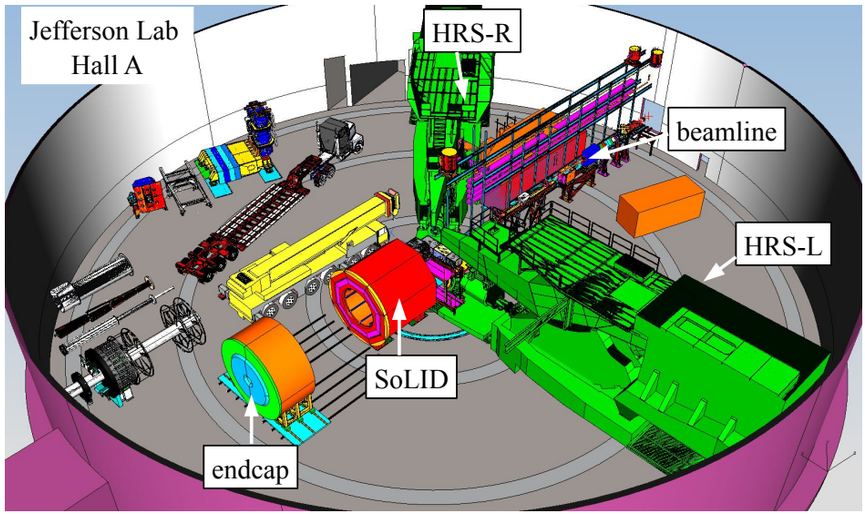
Met by Modern Technologies

- GEM's
- Shashlik Ecal
- Pipeline DAQ
- Rapidly Advancing Computational Capabilities
- High Performance Cherenkovs
- Baffles


Magnet Test

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

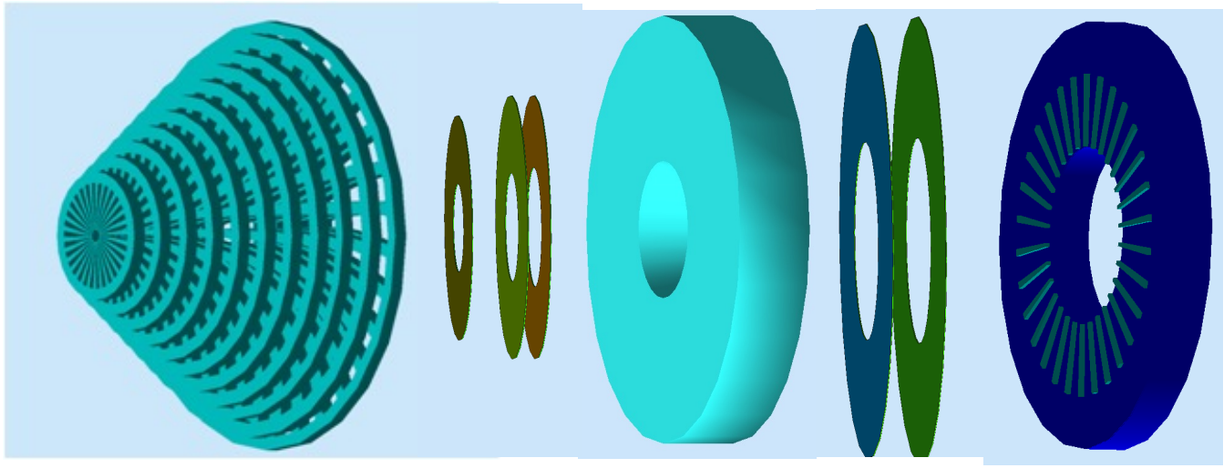




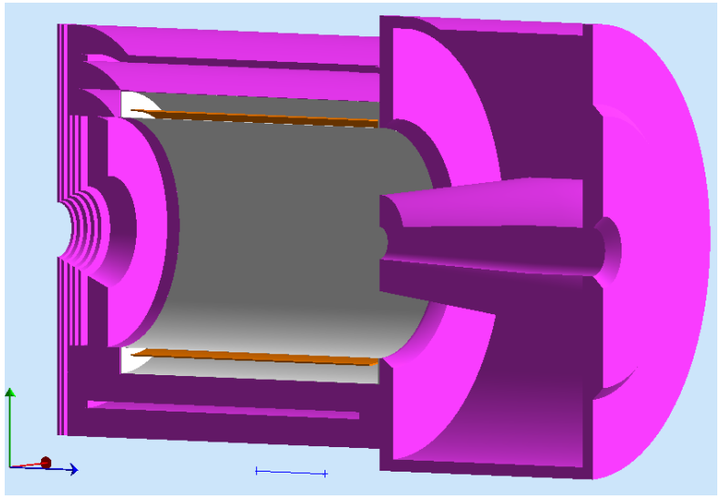
SoLID in Hall A

SoLID Detector Subsystems

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC

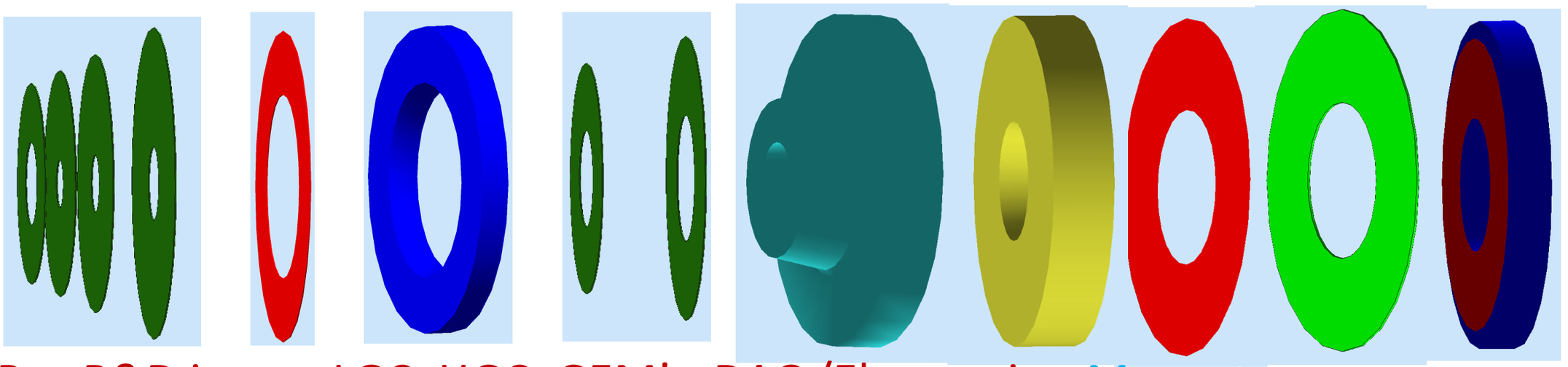


Uses full capability of JLab electronics



SIDIS& J/psi:

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



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

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SoLID Cost Estimation Presented at the Science Review

DOE Science Review (2021)

WBS	Subsystem	Cost –M$ (with overhead)
1.01	PM	1.5
1.02	EM	10.1
1.03	LGC	5.6
1.04	HGC	6.0
1.05	GEM	5.8
1.06	DAQ	6.2
1.07	Software	0.7
1.08	Magnet	7.8
1.09	Infrastructure	9.6
1.10	OPC	

Each L2 WBS includes design and construction

- Cost before contingency and escalation: 53.3 M$
- With contingency 72.2 M$
- With escalation **(Total Estimated Cost)** **82.4 M$**

(Additional escalation for 2022 estimation)

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SoLID Project Schedule Presented at the Science Review

DOE Science Review (March 8-10, 2021)

Assumptions:

- **1.5 Years pre-R&D (in progress)**
- **Project starts in FY2022**, 2 Years Project Engineering and Design (PED) (FY22-FY23), Construction long-lead items start in FY23
- Main construction starts in FY24, 3+ Years **construction, complete by end of 2026.**
- **1 Year Installation 2027**
- Testing/commissioning: start with magnet/testing, then ECal/GEM with DAQ for testing, then HGC/LGC
- **Schedule contingency ~ 1 year**
- **Start Physics in 2029**

(With CD0 delayed, above schedule is expected to be late by ~1 year)

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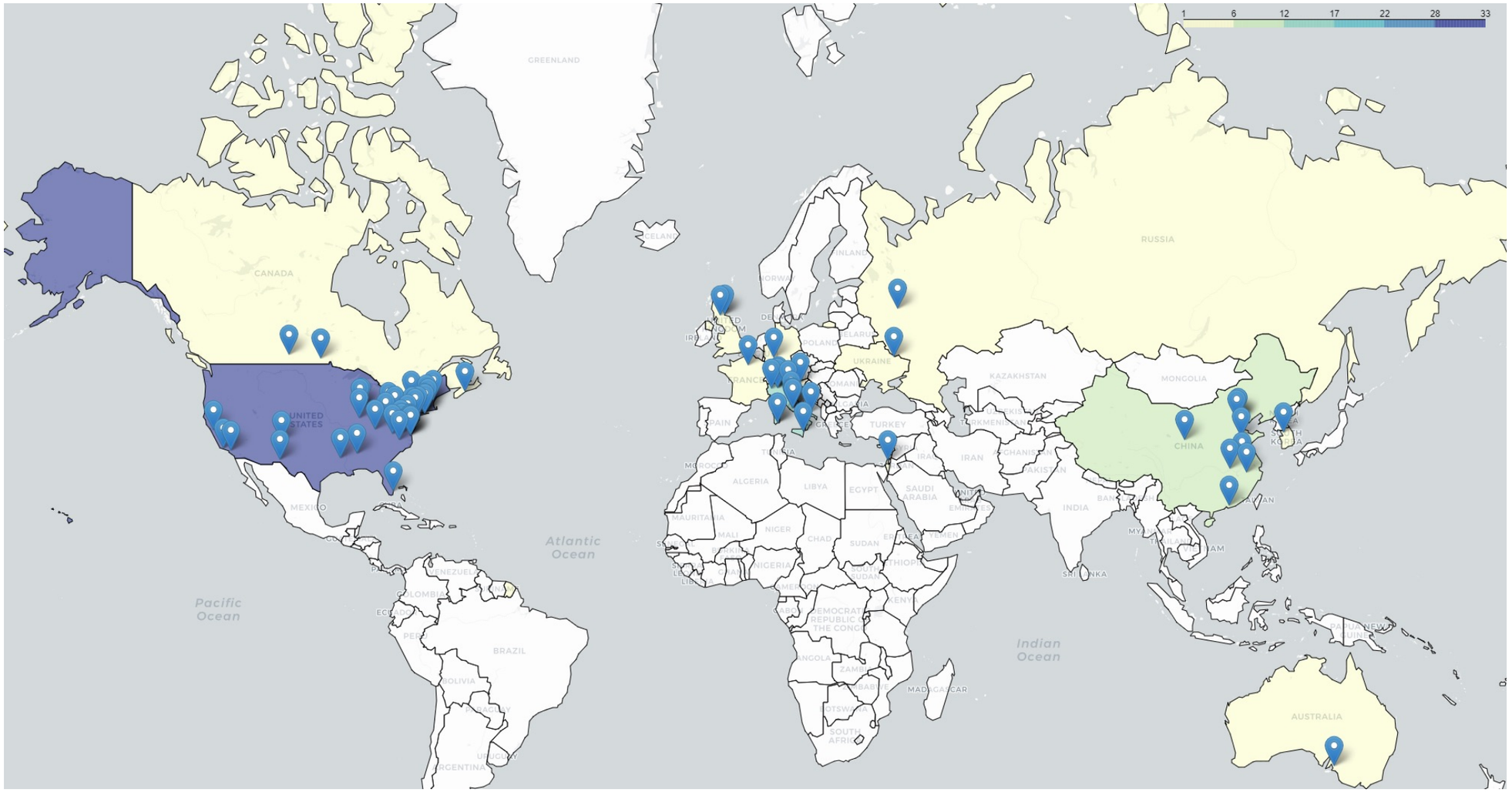
Strong Collaboration

- ❑ 270+ collaborators, 70+ institutions
- ❑ Large international participations and anticipate contributions
- ❑ Strong theory support



full list available at https://solid.jlab.org/collaboration/full.html

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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 the JLab 12 GeV scientific potential

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

- SoLID offers an important training ground for the next generation of science leaders in EIC

- 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

Waiting for CD0!

SoLID Program on GPD / Other SoLID Run Group EXPT.s

- **Deep Exclusive π^- Production in 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)

- **Timeline Compton Scattering (TCS)** with circularly polarized beam and unpolarized LH_2 Target (Carlos Munoz talk on Friday 09/23/2022)

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 dilepton channel on unpolarized LH_2 target

E. Voutier, M. Boer, A Camsonne, K. Gnanvo, N. Sparveris, 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)

- **SIDIS Dihadron with Transversely Polarized ^{3}He target**

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)

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The SoLID collaboration endorses the recommendation below.

Recommendation

The Nuclear Physics Community embraces with highest priority the scientific capitalization of investments made at CEBAF. This will allow CEBAF to realize a broad program of nuclear physics experiments, including unprecedented luminosities with SoLID. Therefore, we strongly support optimal running of the 12 GeV program, including the construction and deployment of SoLID. Furthermore, full utilization of CEBAF during EIC construction will build and strengthen the scientific workforce in preparation for successful operation of the EIC, and provides the opportunity for a future complementary program at Jefferson Lab during EIC operations.