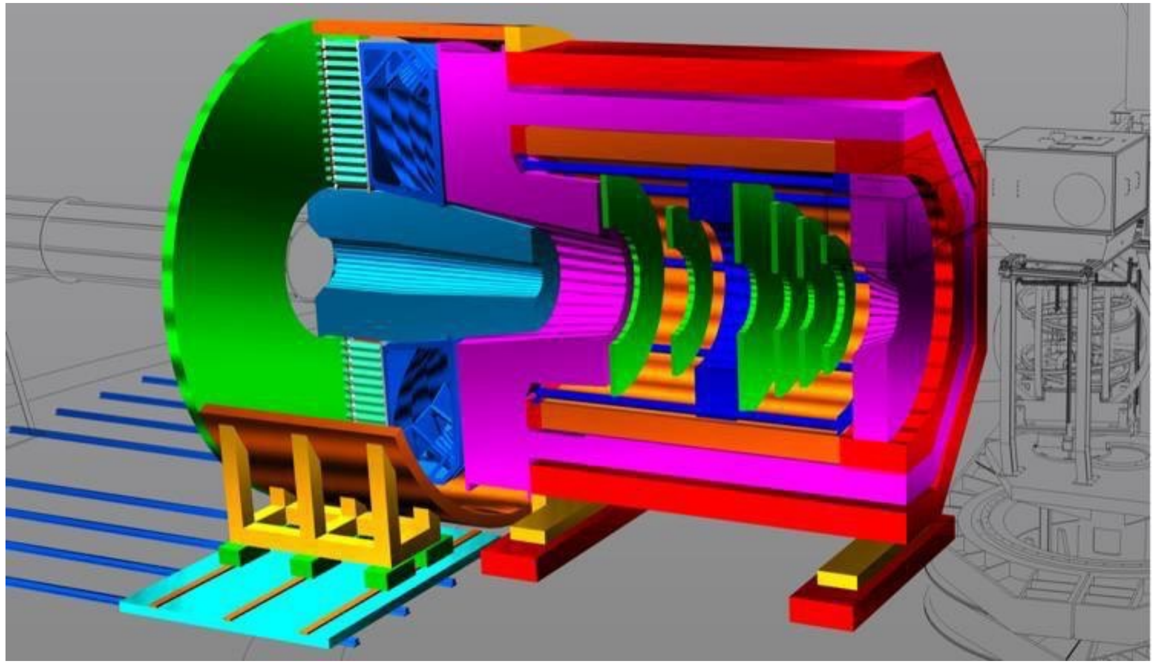
Physics at the Intensity Frontier with SoLID: Current Status and Prospects



SOLENOIDAL LARGE INTENSITY DEVICE

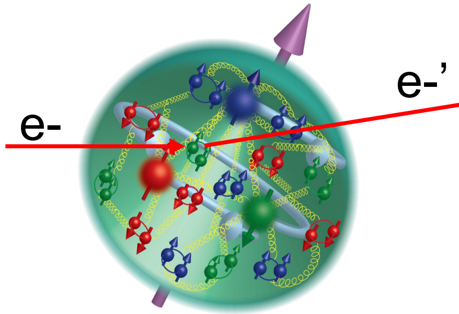
QCD EVOLUTION

Zein-Eddine Meziani

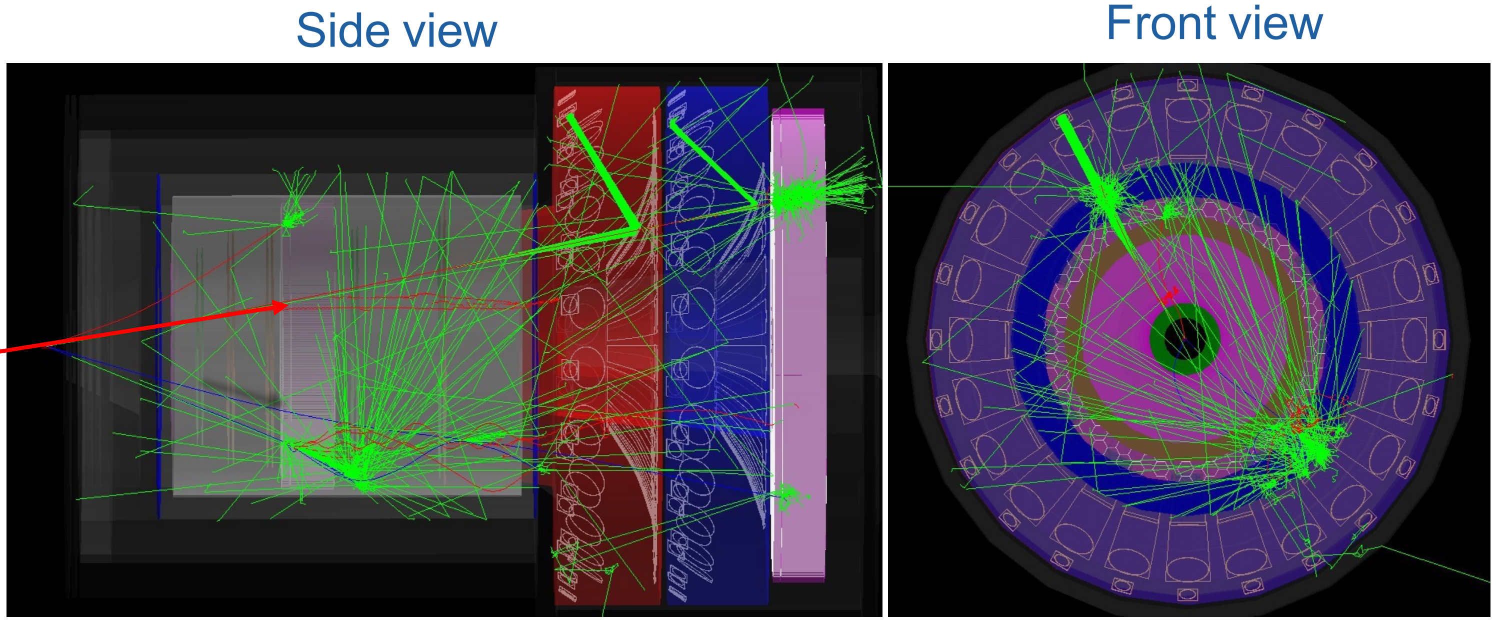
Argonne National Laboratory

For the SoLID collaboration

J. Arrington *et al.* [Jefferson Lab SoLID] ``The solenoidal large intensity device (SoLID) for JLab 12 GeV,'' J. Phys. G **50** (2023) no.11, 110501 doi:10.1088/1361-6471/acda21



A charmonium production and decay event in SoLID



OUTLINE

- SoLID Project Development Timeline
- 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
  - Collaboration
- Conclusion

SoLID Project Development Timeline

- **Physics program: (2010-present)**

    6 SoLID experiments approved by PAC with high rating (5 A, 1 A-)

    3 SIDIS (3D momentum structure), 1 PVDIS (search for new physics),

    1 threshold J/ψ (gluon observables), 1 A-n (new phenomena)

    + 1 conditional approval + 6 run-group experiments (2D position + 1 momentum and spin structure)

- **Pre-conceptual design, Pre-R&D, reviews and current status (2014-present)**

    2014: pCDR submitted to JLab with cost estimation, updated in 2017, 2019

    Director's Reviews in 2015, 2019 and 2021

    2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE

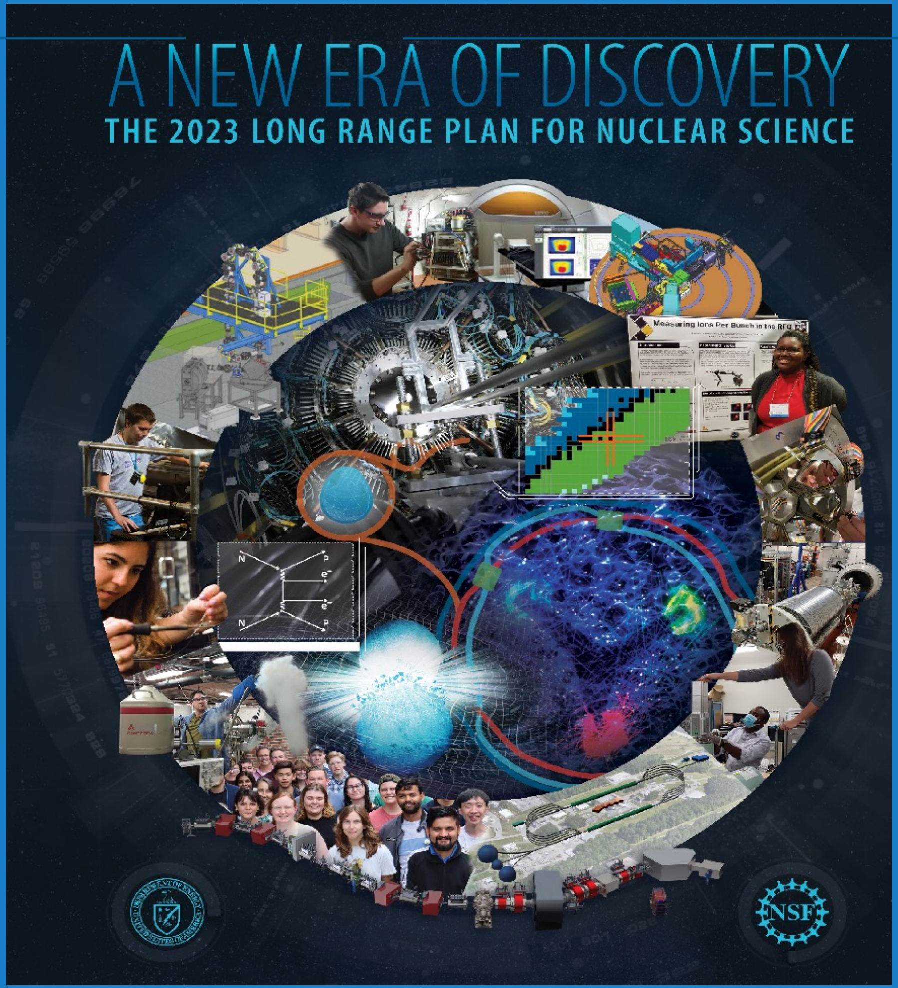
    2020-now: DOE funded pre-R&D activities

    2021: DOE Science Review for SoLID, positive feedback

    2023: Long Range Plan, SoLID highlighted, one of the recommendations

    2024: Facility Review: Ready to Launch

The 2023 Nuclear Physics Long Range Plan Recommendation # 4

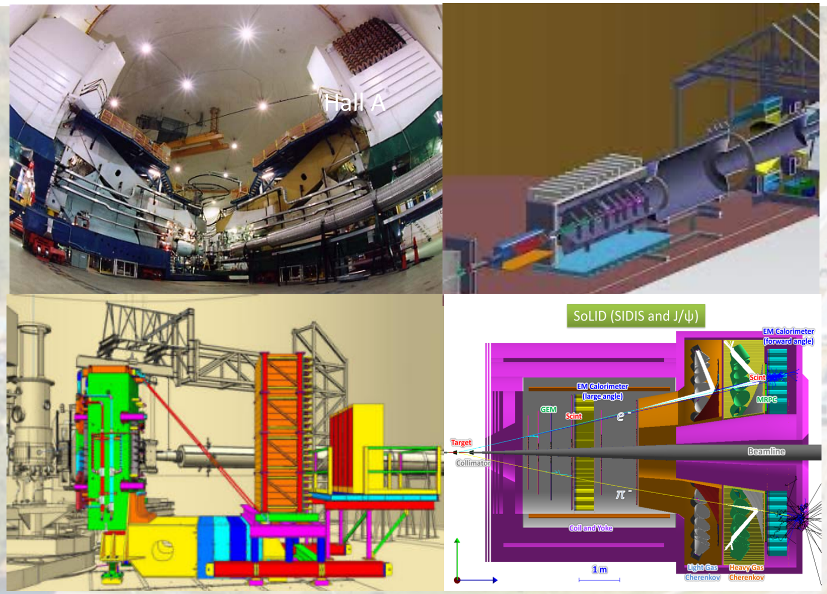


We recommend capitalizing on the unique ways in which nuclear physics can advance discovery science and applications for society by investing in additional projects and new strategic opportunities.

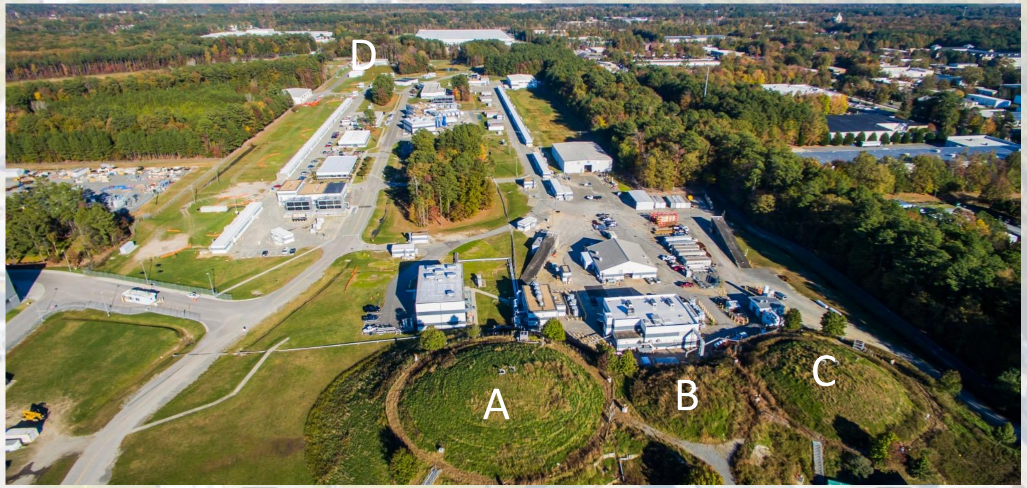
1.3.1. Opportunities to advance discovery

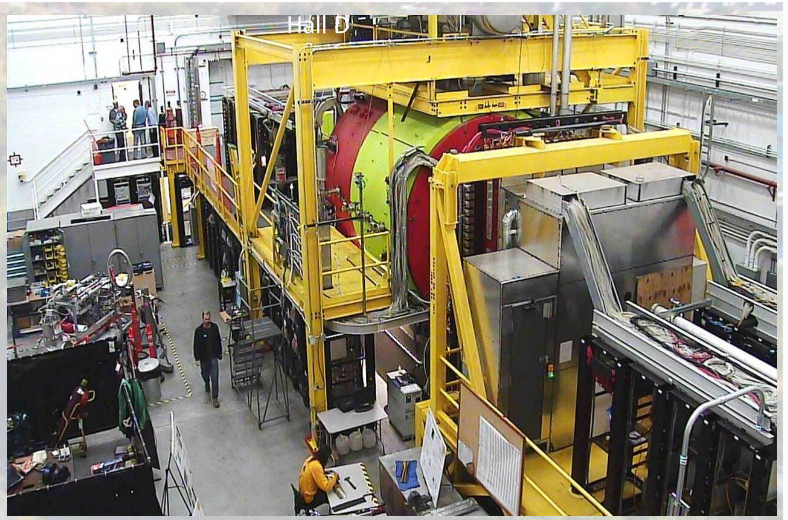
Strategic opportunities exist to realize a range of projects that lay the foundation for the discovery science of tomorrow. These projects include the 400 MeV/u energy upgrade to FRIB (FRIB400), the Solenoidal Large Intensity Device (SoLID) at Jefferson Lab, targeted upgrades for the LHC heavy ion program, emerging technologies for measurements of neutrino mass and electric dipole moments, and other initiatives that are presented in the body of this report.

Present 12 GeV Experimental Capabilities at JLab and the Transformative Future with SoLID

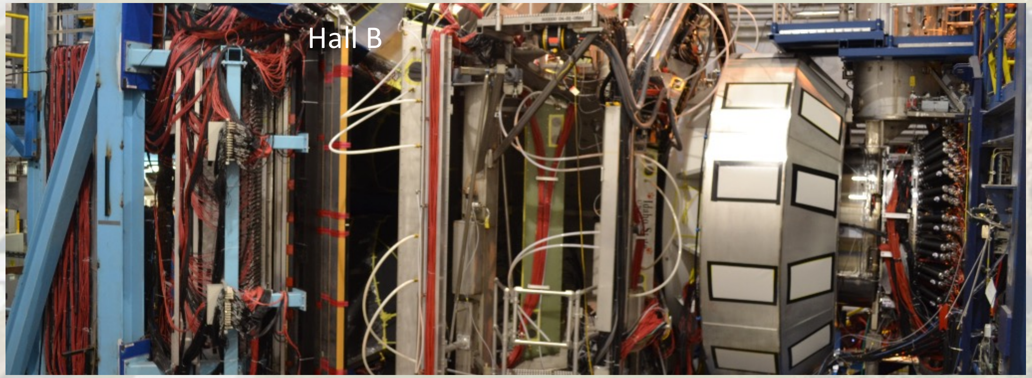


HRS, SBS, Moller & SoLID

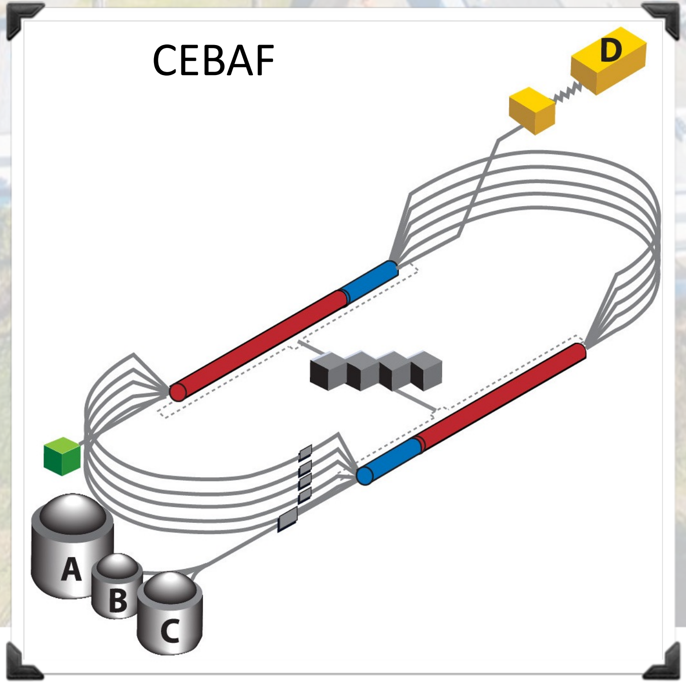




Hall D (GlueX)



CLAS12 + (luminosity) Upgrade



Hall C (HMS and SHMS)

Why SoLID at 12 GeV CEBAF?

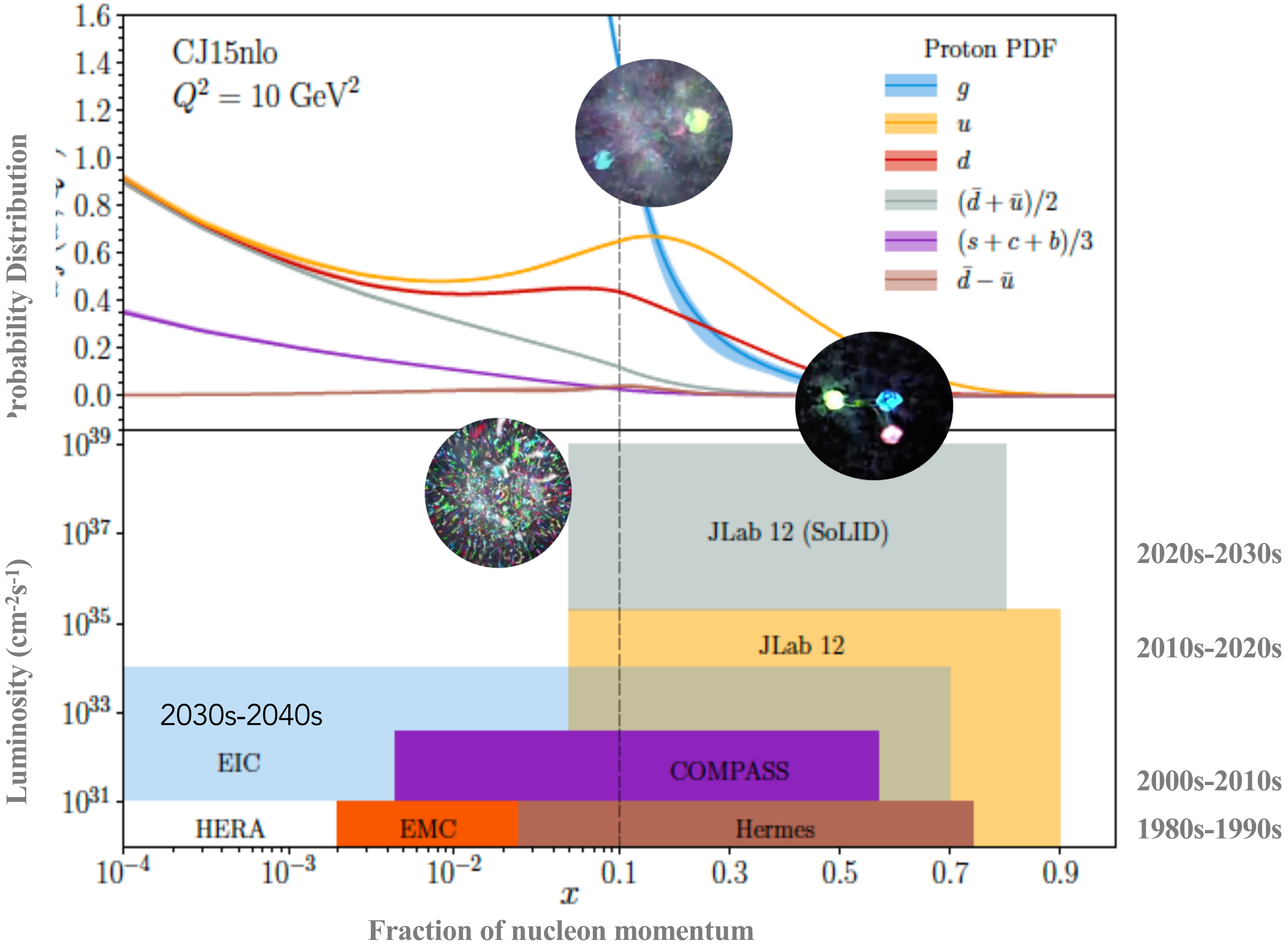
SoLID@JLab 12-GeV Enables QCD at the Intensity Frontier

- 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

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



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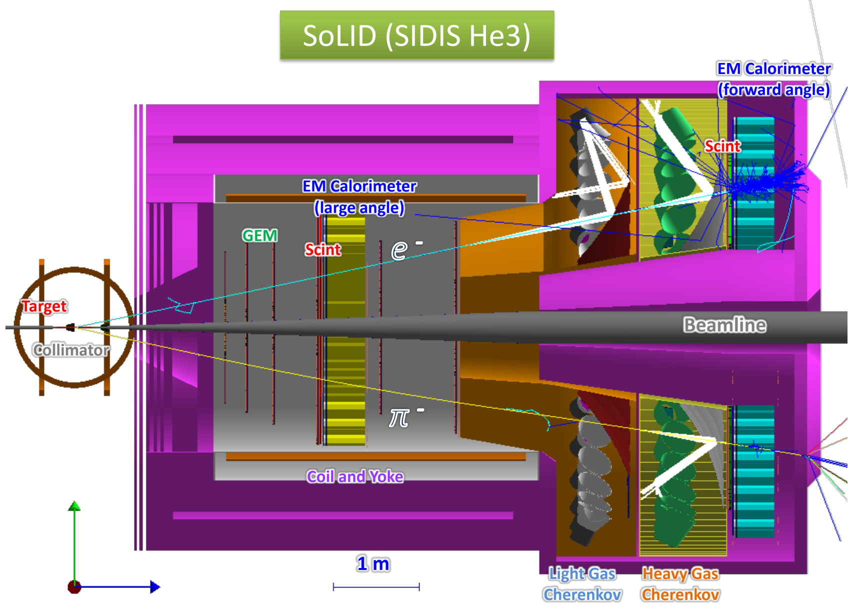
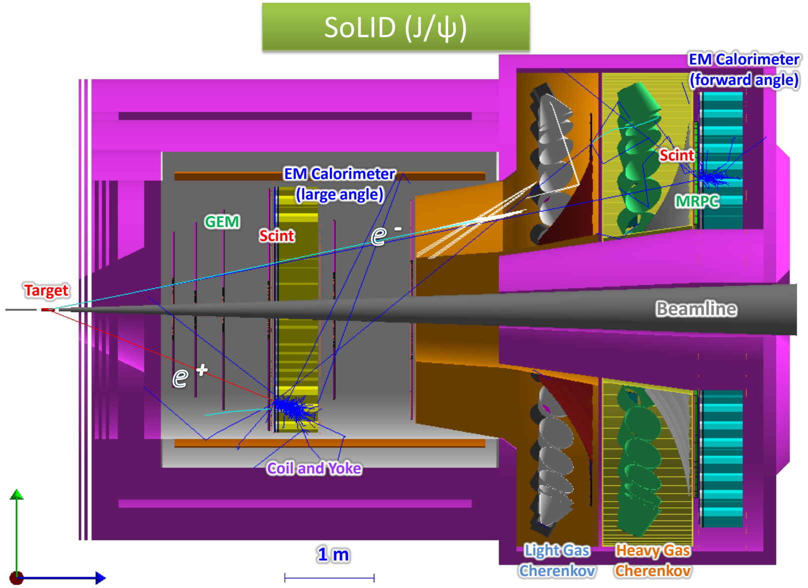
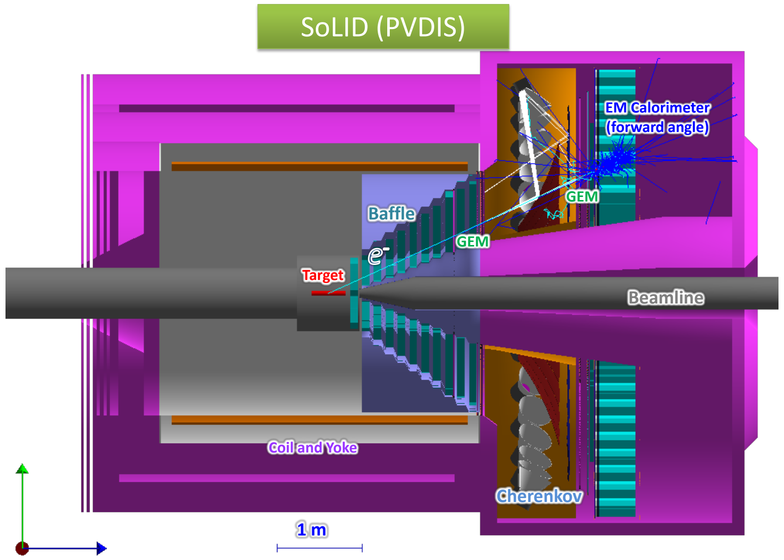
SoLID Physics Program: Approved Experiments







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

  Rating: A

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

  Rating: A

- ❑ **PVDIS**: — Beyonf the Standard Model Physics & Nucleon structure

  Rating: A

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

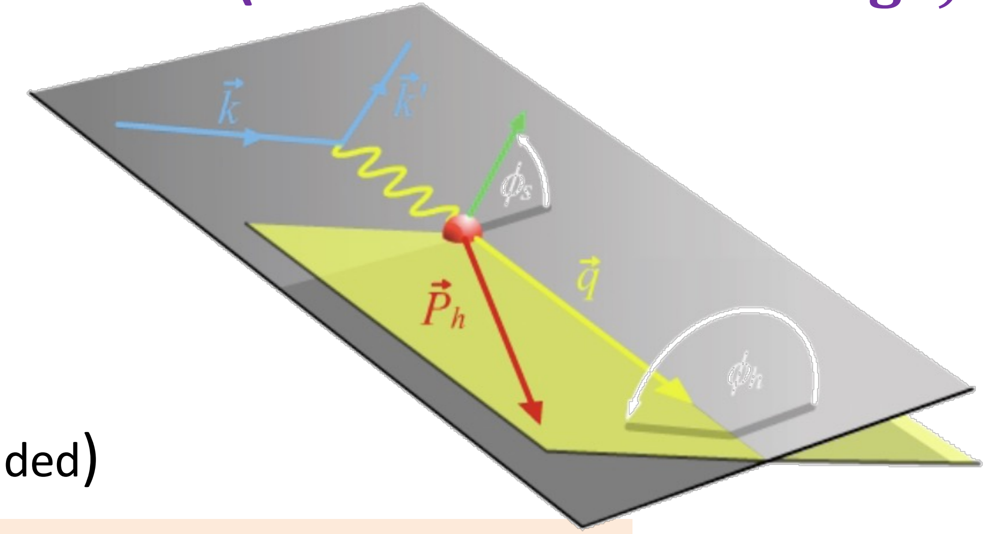
PAC50 (2022): Approved two new SoLID Experiments: Beam Normal SSA (A$^-$ rating) & PVEMC (conditional approval)

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)

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

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

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

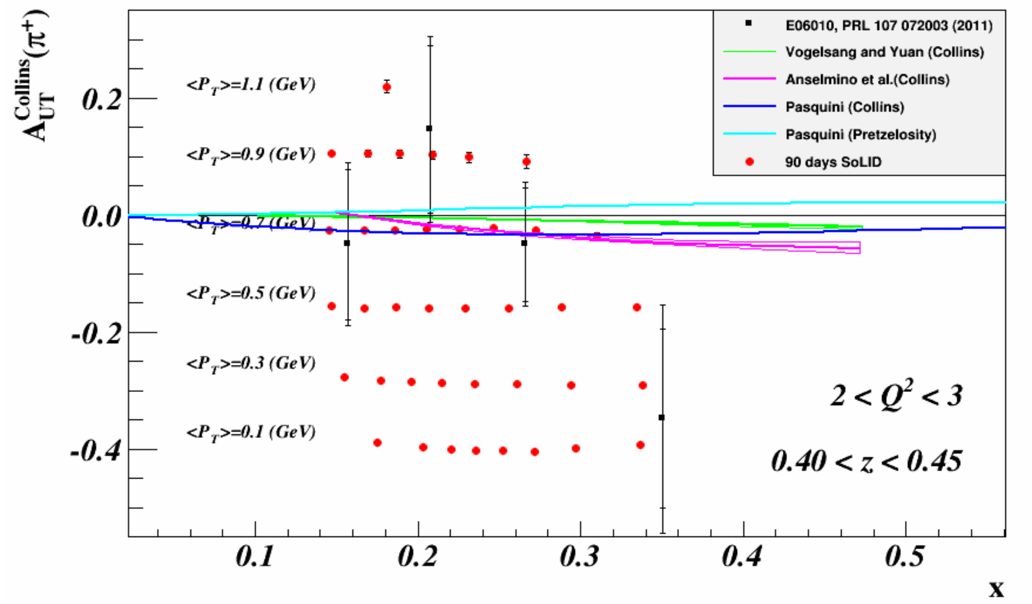
Collins fragmentation function from e^+e^- collisions

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

Unpolarized fragmentation function

SoLID-SIDIS Projections and Impact

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



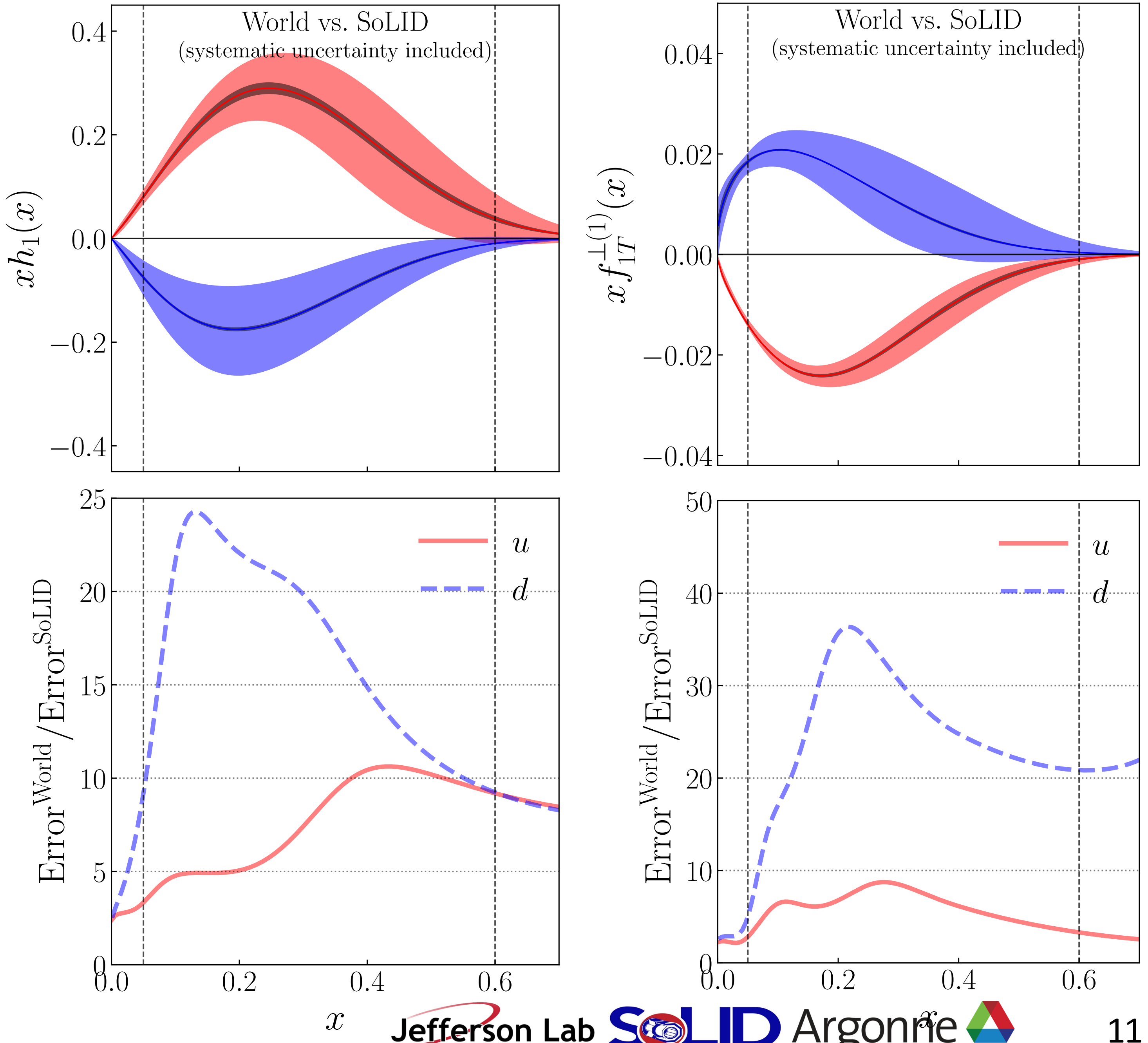
- Fit Collins and Sivers asymmetries in SIDIS and e^+e^- annihilation
- World data from HERMES, COMPASS
- e^+e^- data from BELLE, BABAR, and BESIII
- Monte Carlo method is applied
- Includes both systematic and statistical uncertainties
- World data according to SoLID (2019) preCDR

https://solid.jlab.org/experiments.html

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

Z. Ye et al., PLB 76, 91 (2017)
T. Liu (2018): https://pos.sissa.it/317/036

Transversity | Sivers



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SoLID IMPACT on TENSOR CHARGE

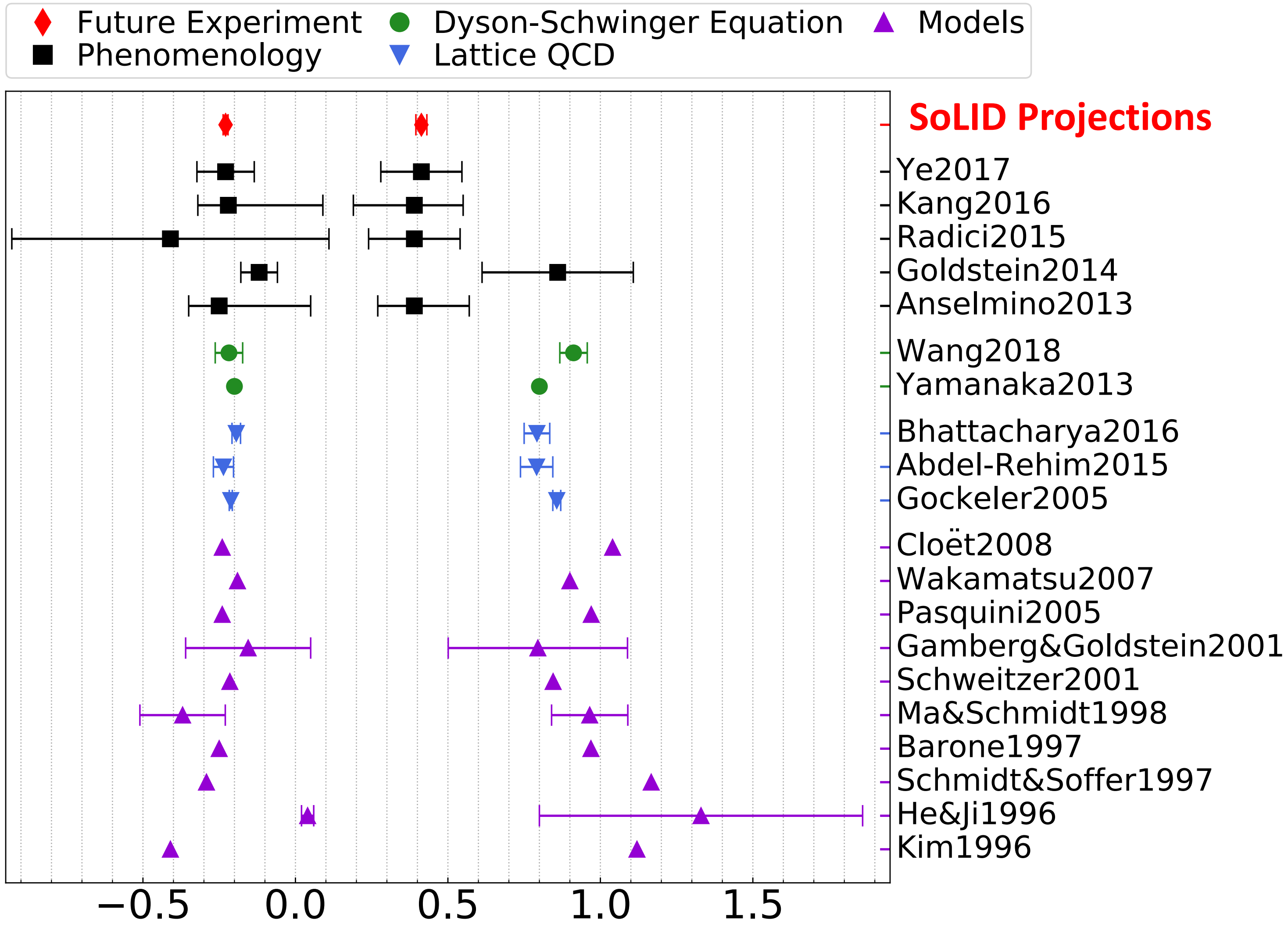
Tensor charge

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

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

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

- An intrinsic nucleon property as fundamental as the axial charge or electric 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/Proton Mass and Scalar Radii

Proton Mass, Trace Anomaly/Gluonic Gravitational Form Factors

- **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 $\int d^3x\, \psi^\dagger (-i\mathbf{D}\cdot\alpha)\psi$

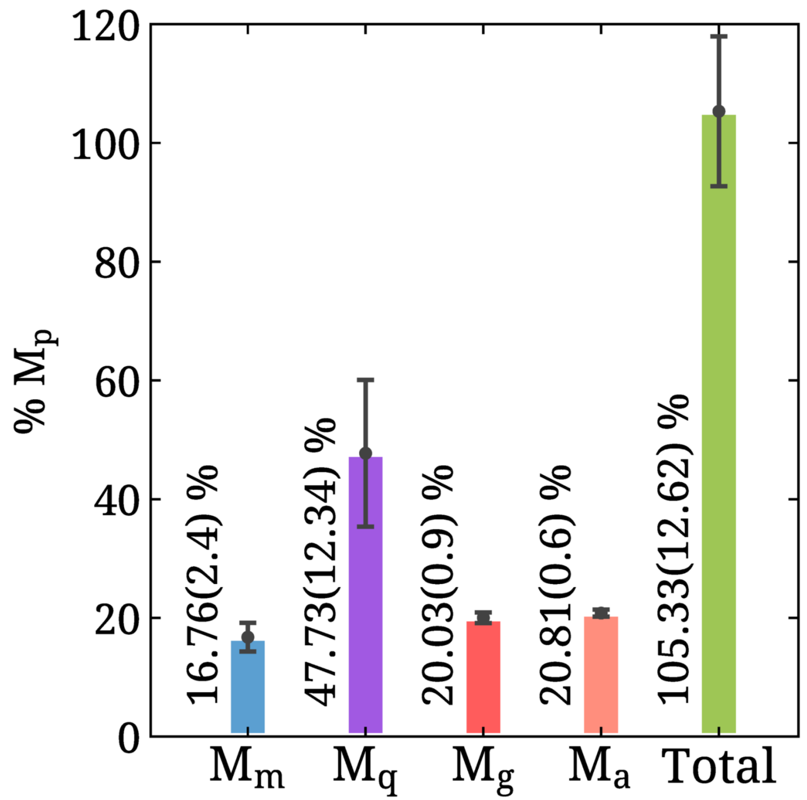
$H_m =$ Quark mass $\int d^3x\, \bar{\psi} m \psi$

$H_g =$ 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!

- 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. 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]

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

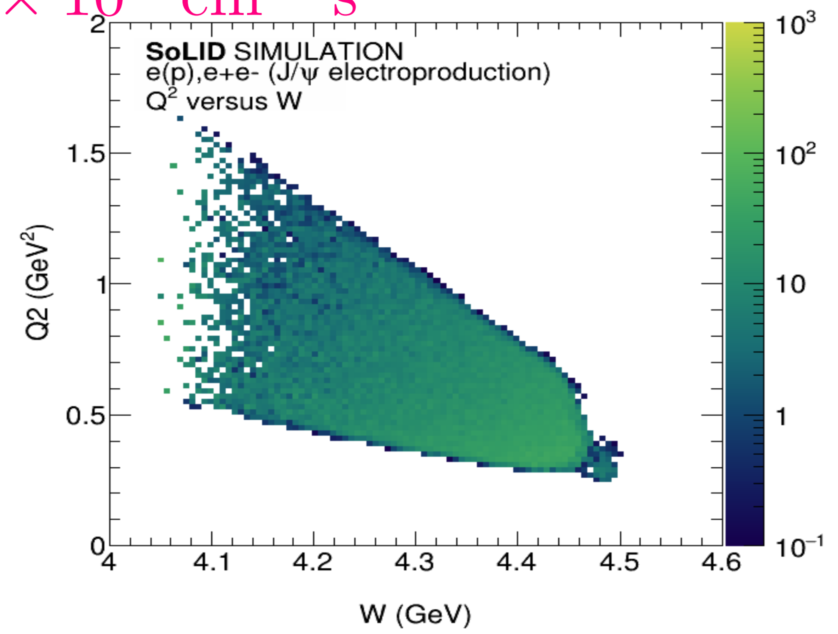
- **Accessing directly the Trace Anomaly in experiments is an important goal in the future**

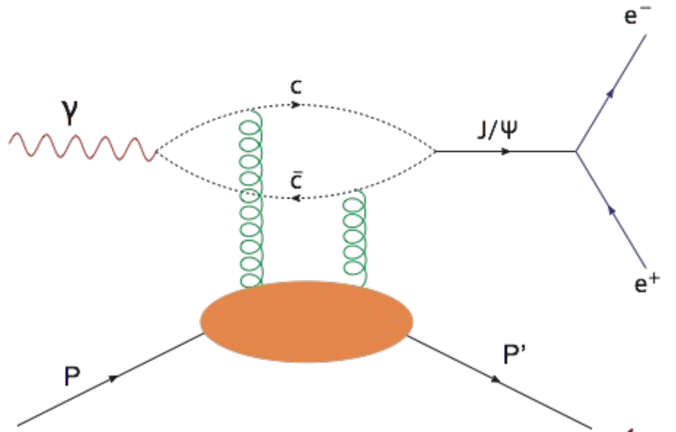
Perhaps can be accessed through threshold (J/ψ, ψ' & Υ) electroproduction at high Q^2.

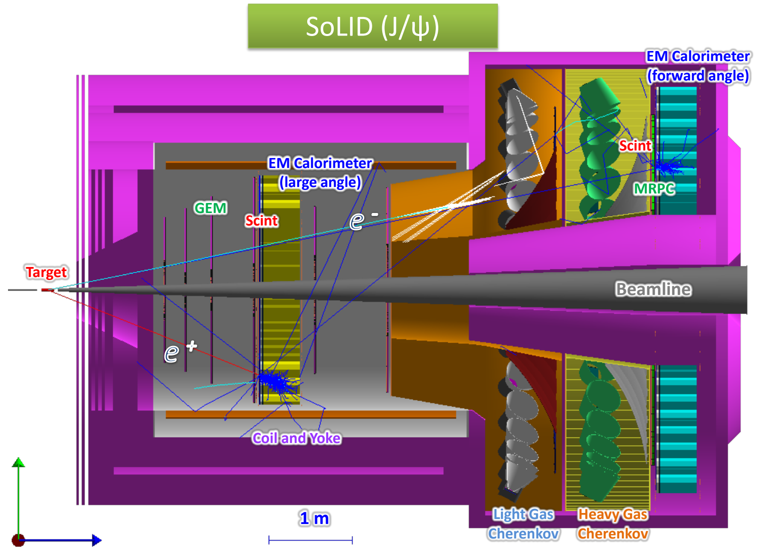
Y. Hatta, A. Rajan and K. Tanaka,, *JHEP* **12**, 008 (2018)

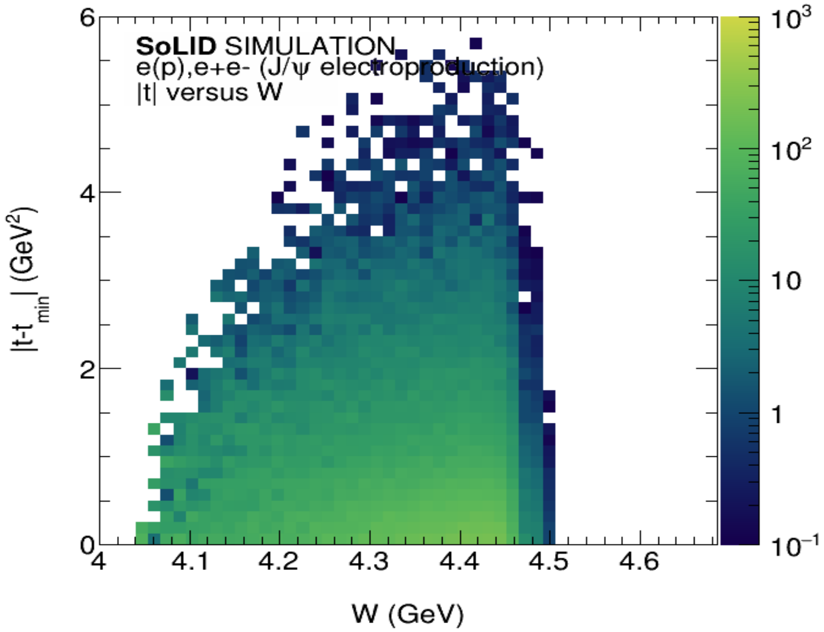
SoLID-J/ψ: Experiment E12-12-006

- 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^-



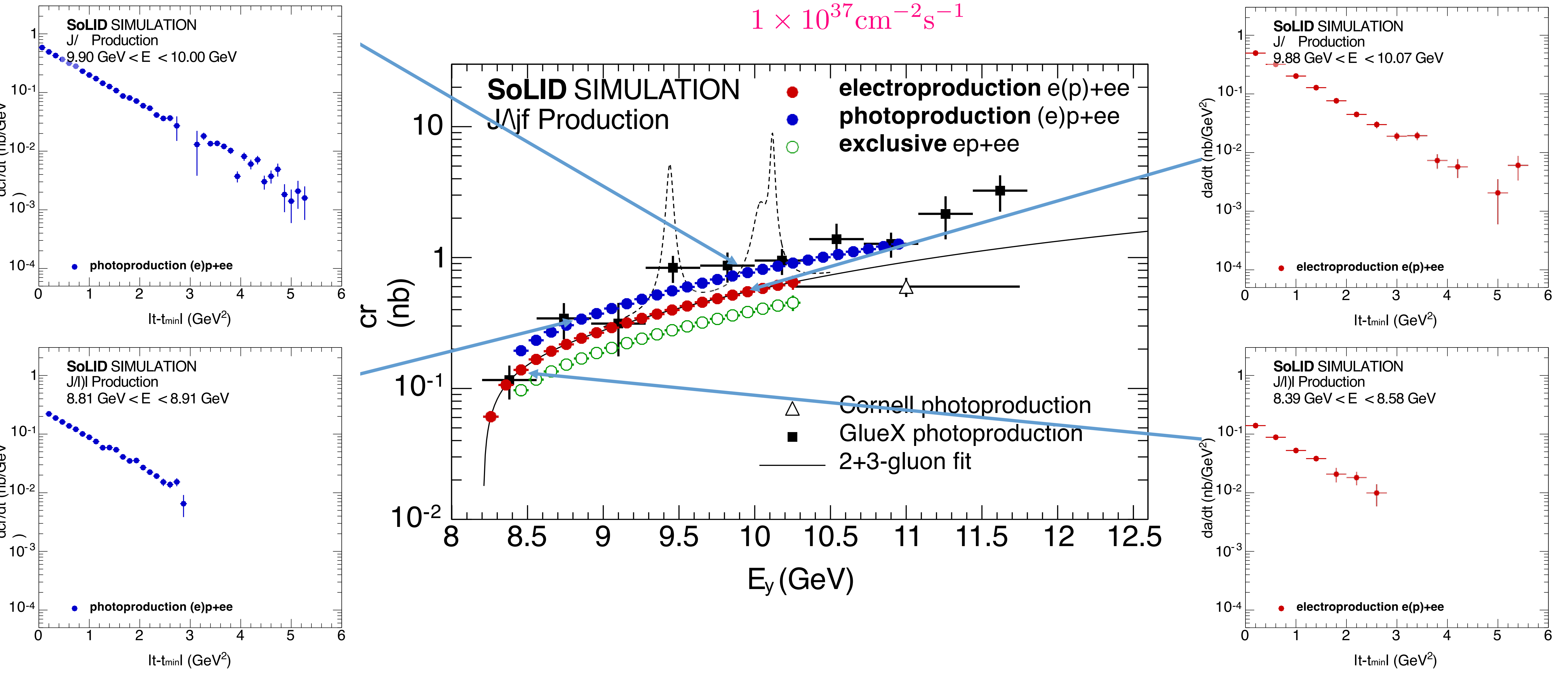






$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$
$$\gamma + p \longrightarrow p' + J/\psi(e^+ + e^-)$$

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



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

Gravitational form factors (GFFs)

Towards observables of the matter structure of the proton

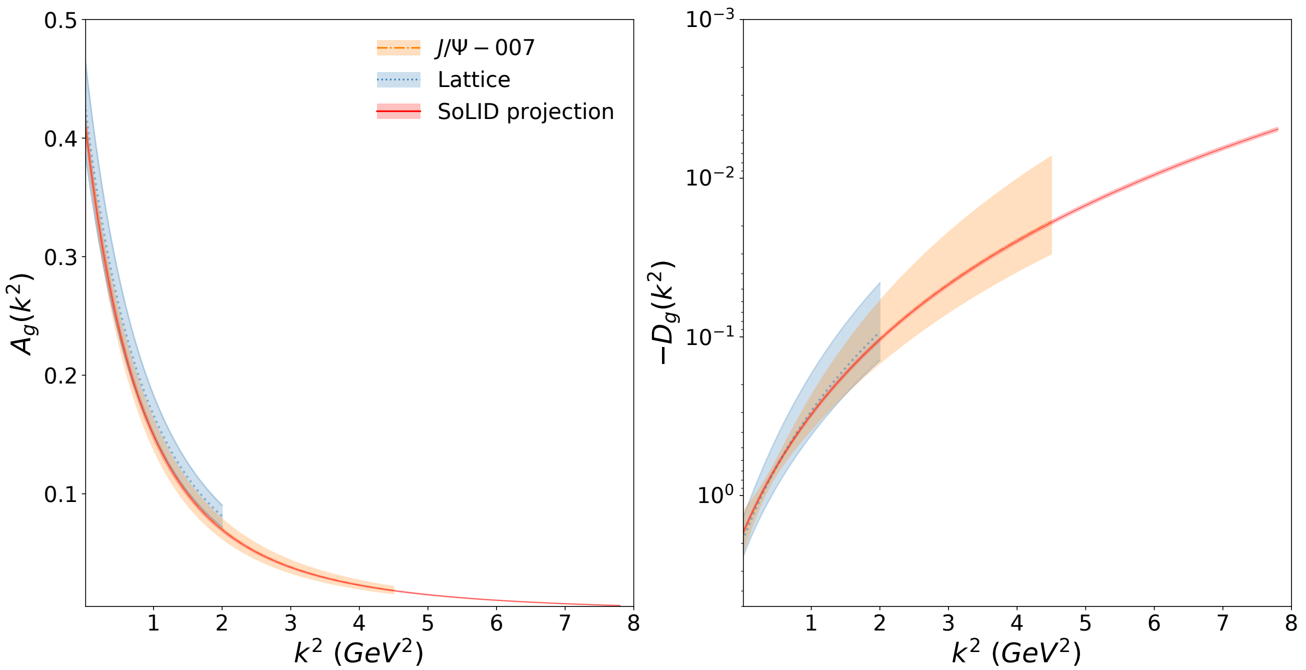
GFFs are matrix elements of the QCD energy-momentum tensor (EMT) for quarks and gluons

$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle$$
$$= \overline{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \overline{C}_{g,q}(t)Mg^{\mu\nu}\right)u(N)$$

EMT physics (mass, spin, pressure, shear forces) is encoded in these GFFs:

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{tot}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

SoLID impact projections compared to J/psi-007



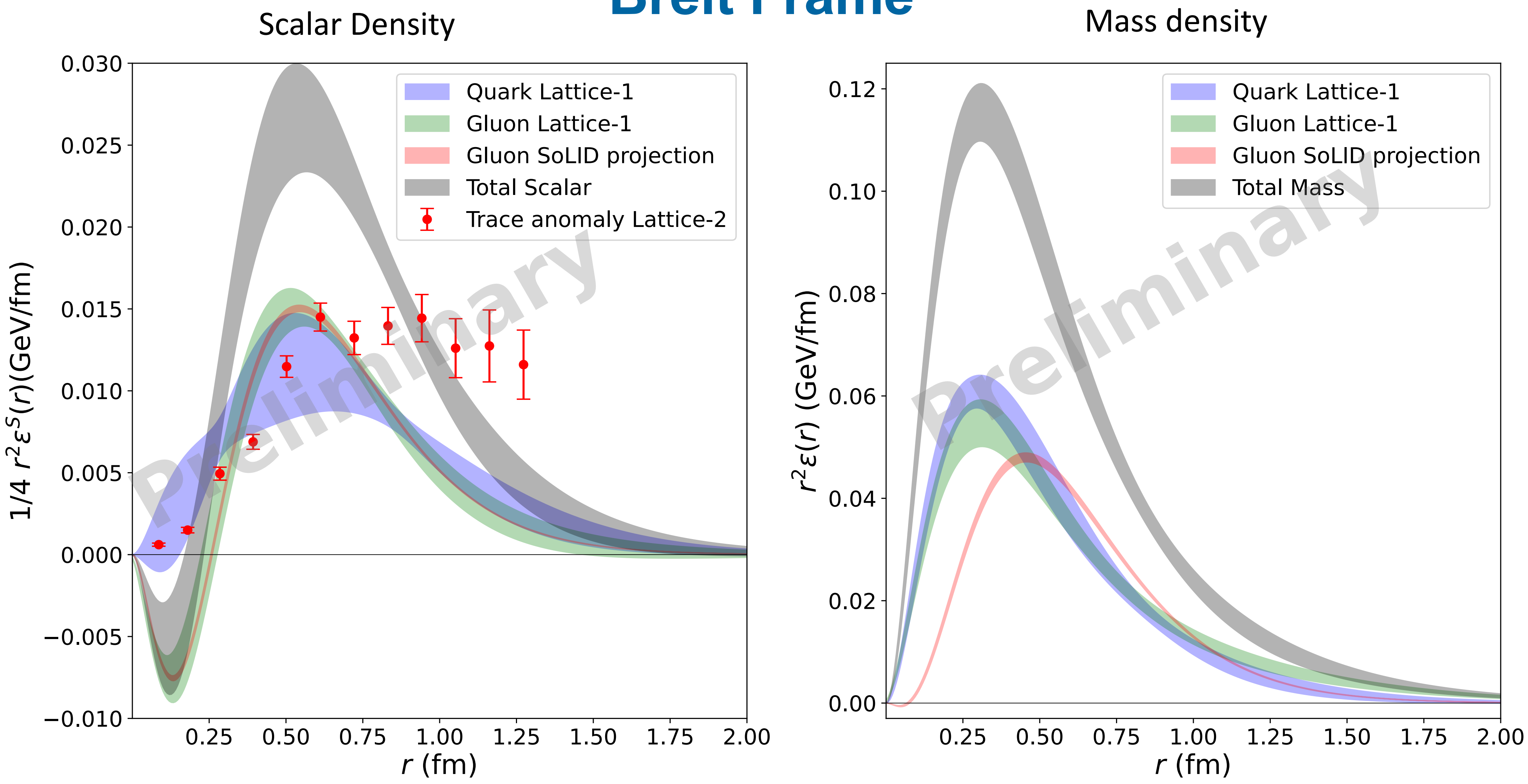
B.Duran, et al., proton, Nature **615**, no.7954, 813-816 (2023)

K. A. Mamo and I. Zahed, *Phys. Rev. D* **106**, no.8, 086004 (2022)

D. A. Pefkou, D. C. Hackett and P. E. Shanahan, *Phys. Rev. D* **105** (2022) no.5, 054509

SoLID impact on gluon scalar and mass density

Breit Frame



Lattice-1

D. C. Hackett, D. A. Pefkou and P. E. Shanahan, Phys. Rev. Lett. **132** (2024) no.25, 251904 doi:10.1103/PhysRevLett.132.251904

B. Wang et al. [χQCD], ' Phys. Rev. **D 109**, no.9, 094504 (2024) doi:10.1103/PhysRevD.109.094504 [arXiv:2401.05496 [hep-lat]].

Lattice- 2

F. He et al, Phys. Rev. **D 104**, no.7, 074507 (2021) doi:10.1103/PhysRevD.104.074507 [arXiv:2101.04942 [hep-lat]]

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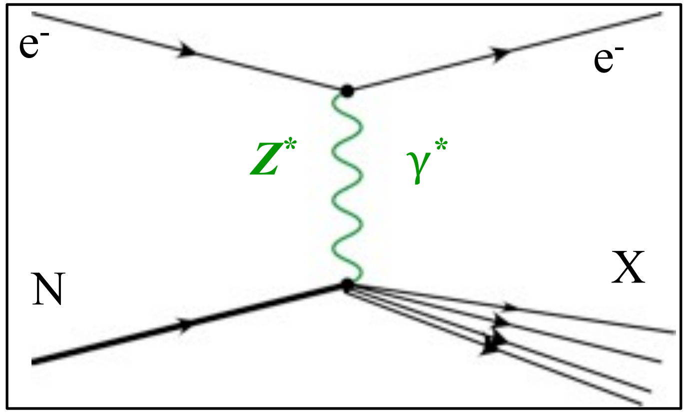
PVDIS:Test of the Standard Model and Hadron Structure

Parity Violating DIS on Deuteron

Simplest isoscalar nucleus and at high Bjorken *x*

Paul Souder talk 09/23/2022



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

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

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

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

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

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

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

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

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

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

Unique feature is sensitivity to C_2's

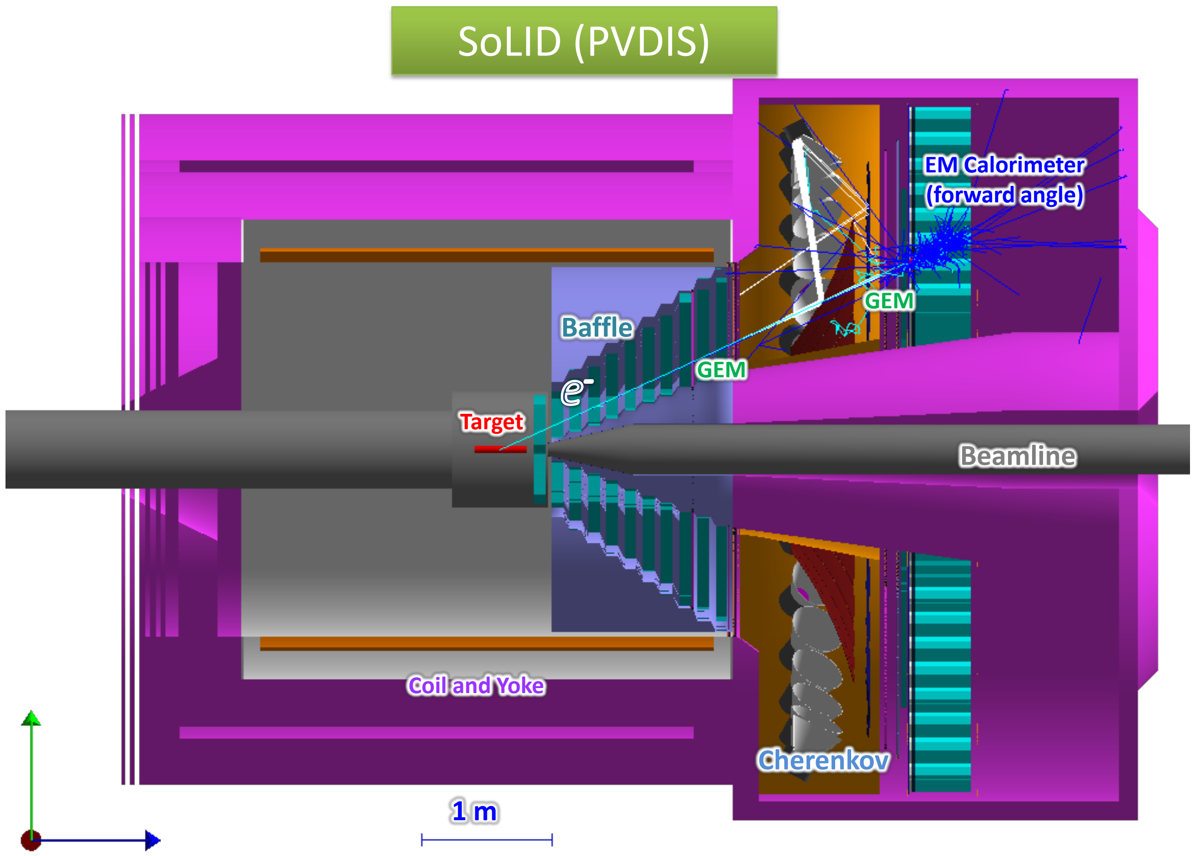
Interplay with QCD

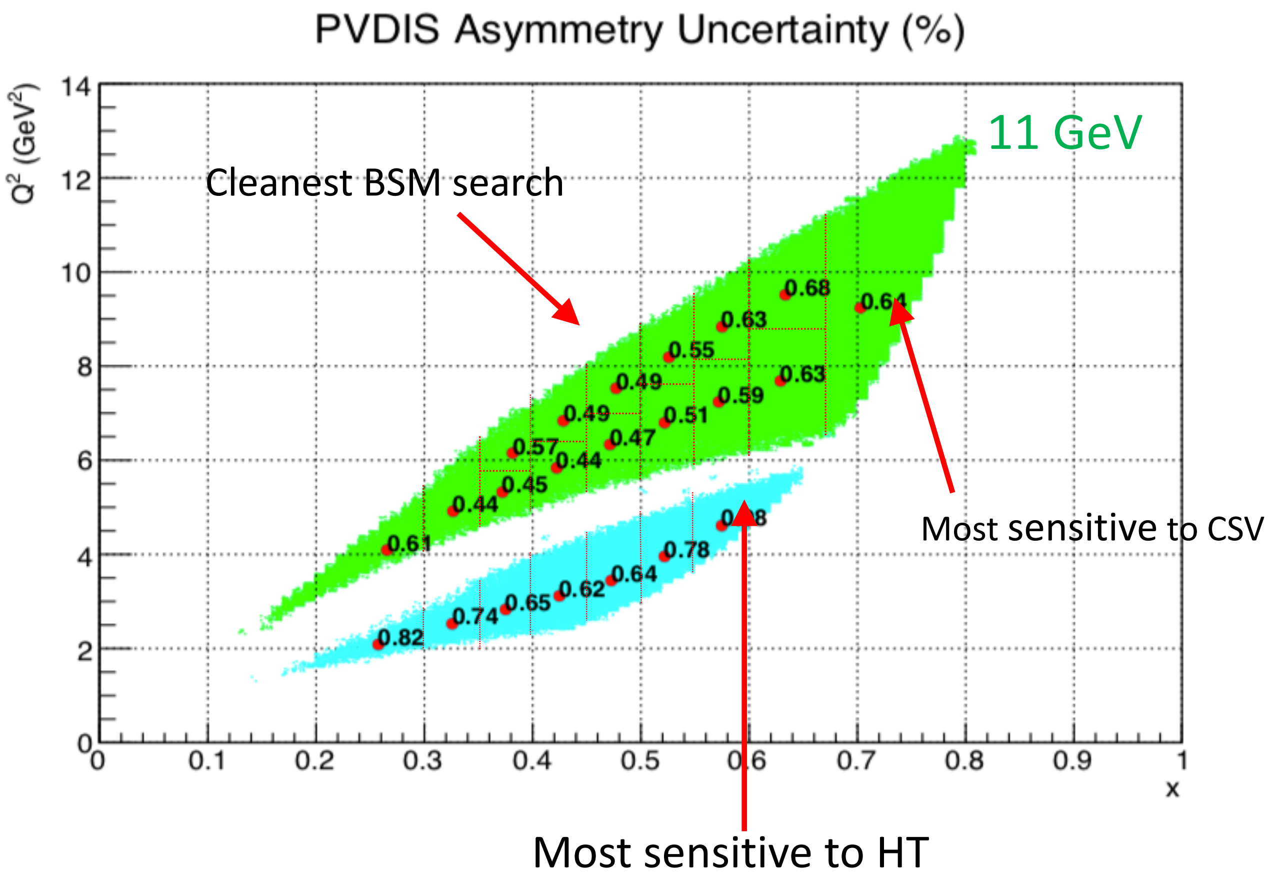
- **Parton distributions (u, d, s, c)**
- **Charge Symmetry Violation (CSV)**
- **Higher Twist (HT) – quark-quark correlation**

SoLID-PVDIS: Experiment E12-10-007

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

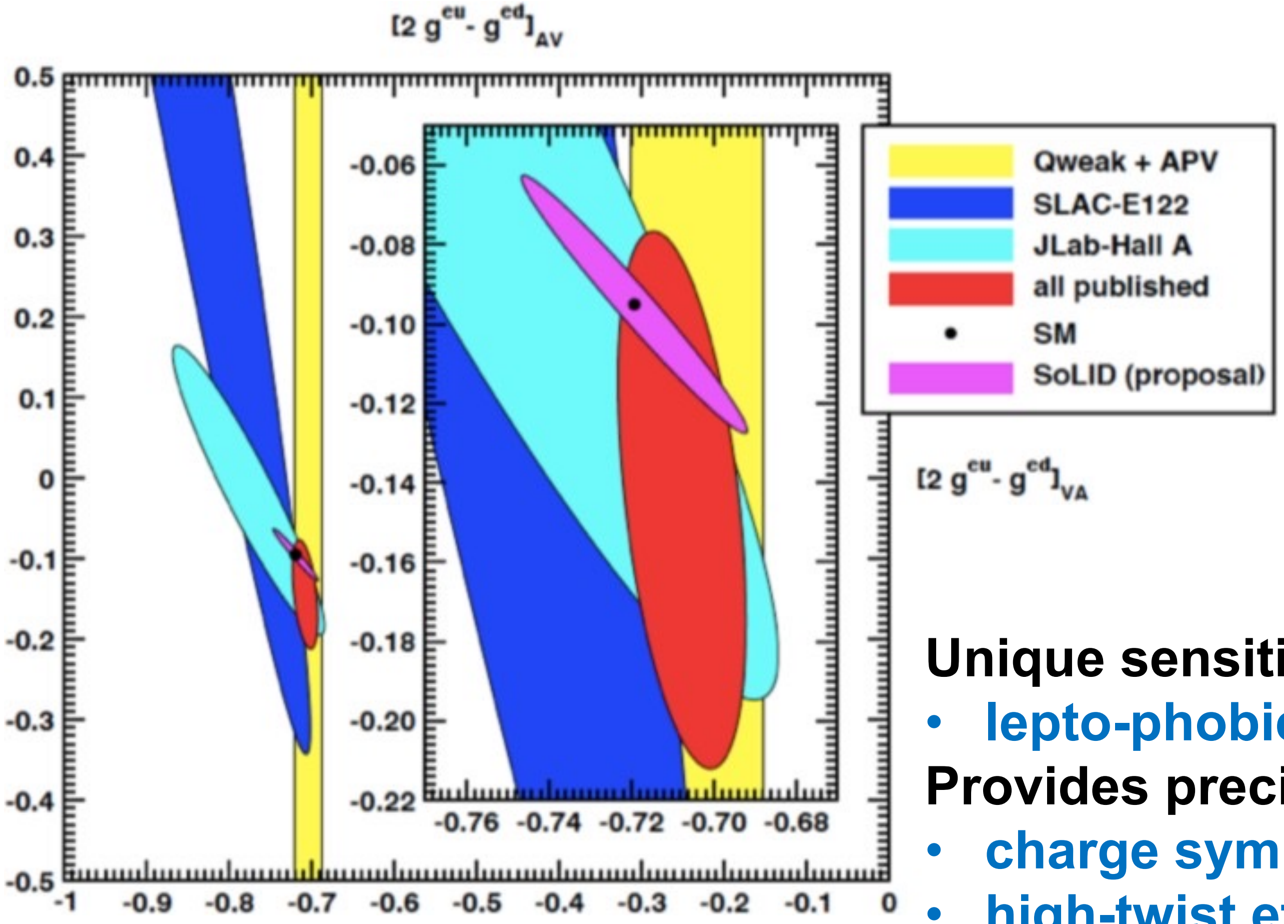




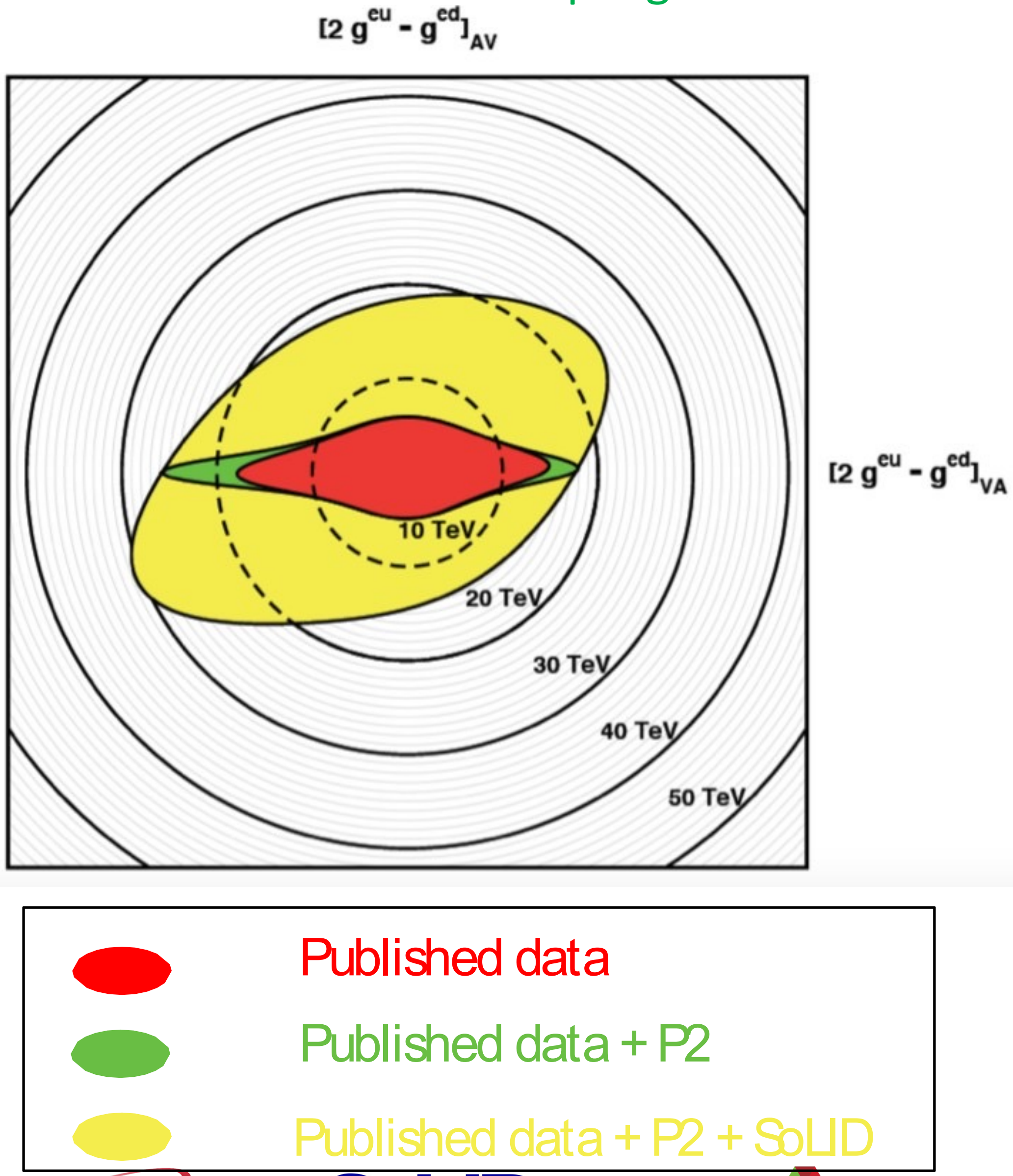
Projected Results on Coupling Constants

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 Detector

Detector subsystems, Collaboration

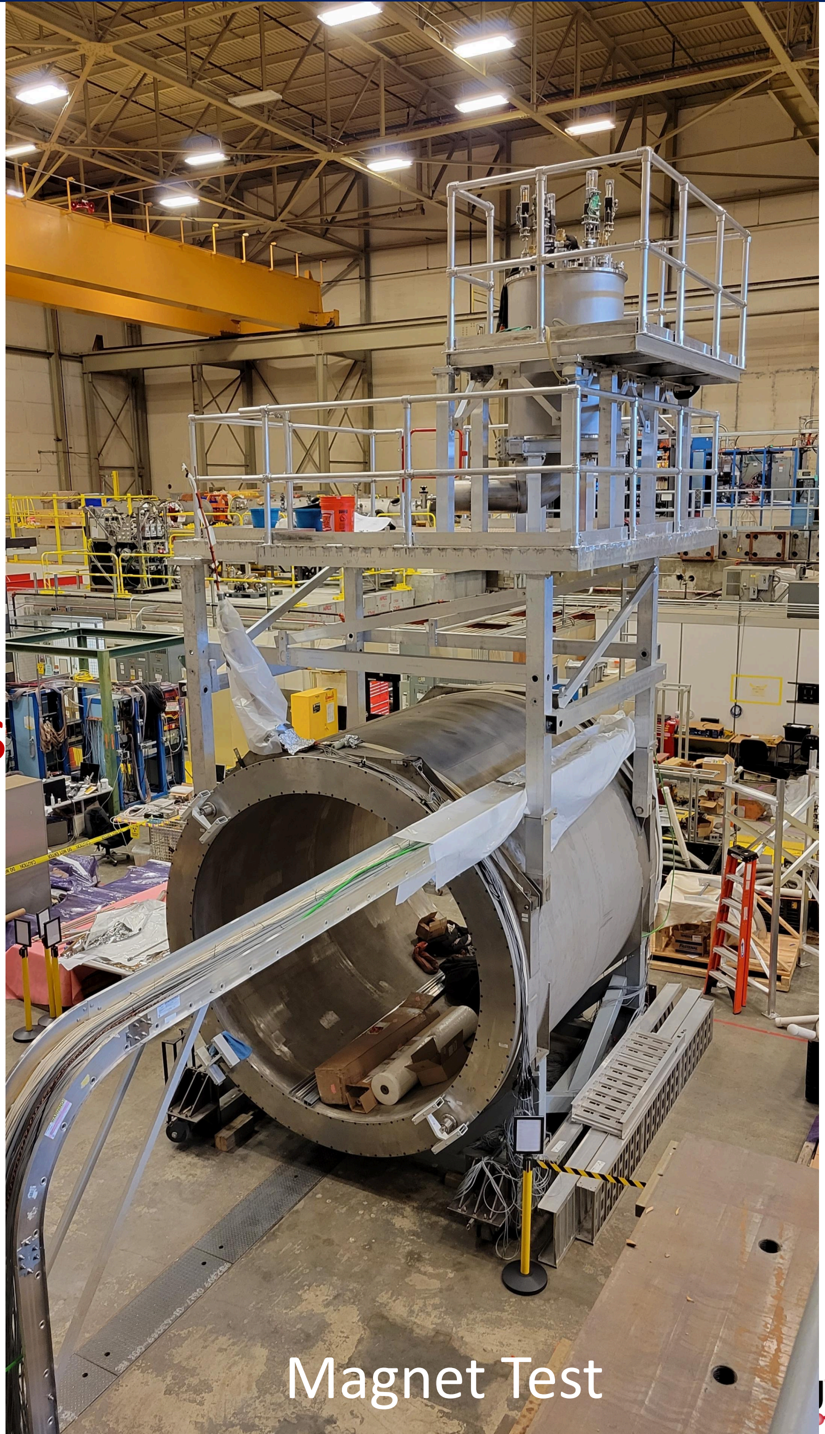
SoLID Apparatus

Challenging requirements!

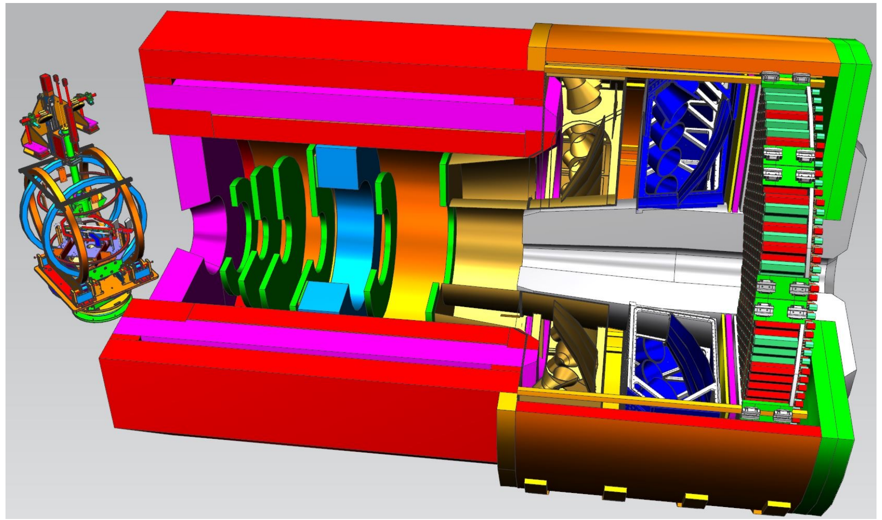
- High Luminosity (10^{37}-10^{39})
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale

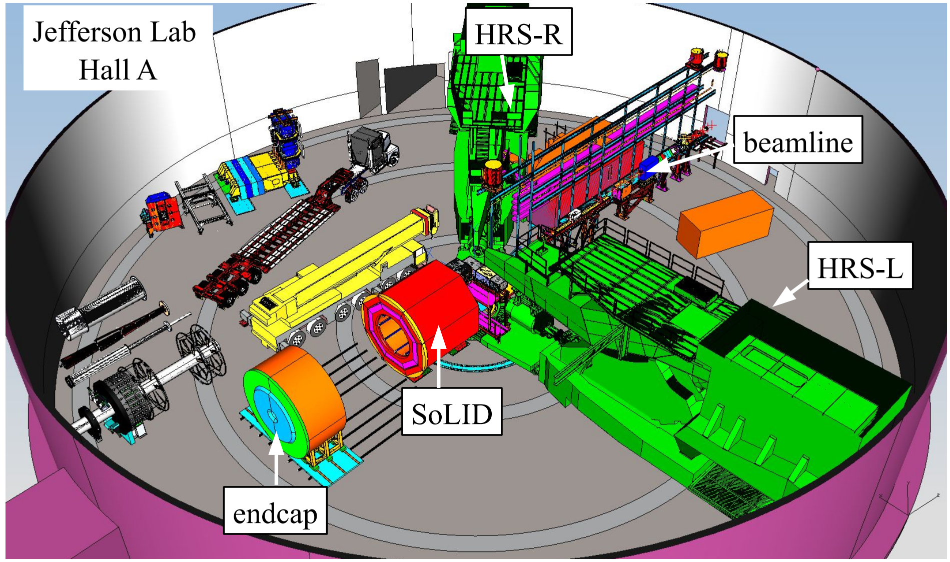
Met by Modern Technologies

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



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



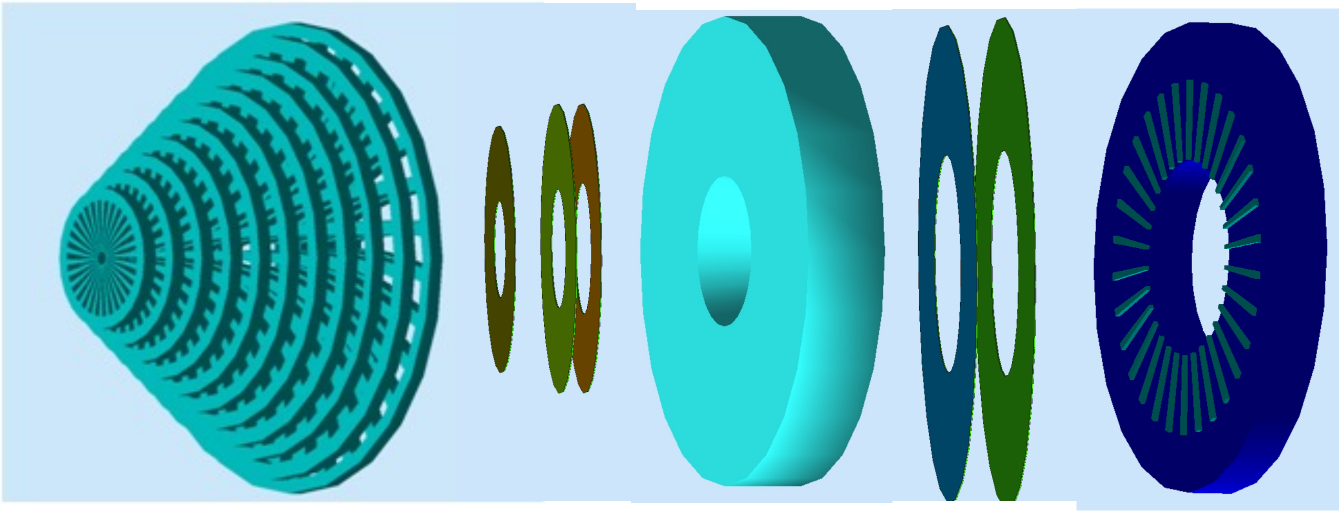


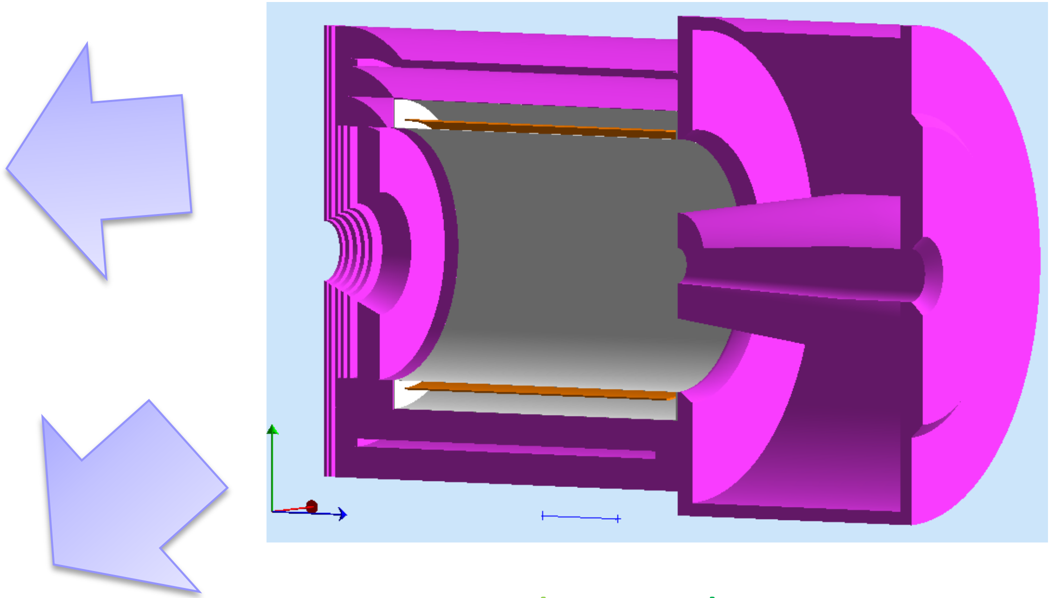
SoLID in Hall A

SoLID Detector Subsystems

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC

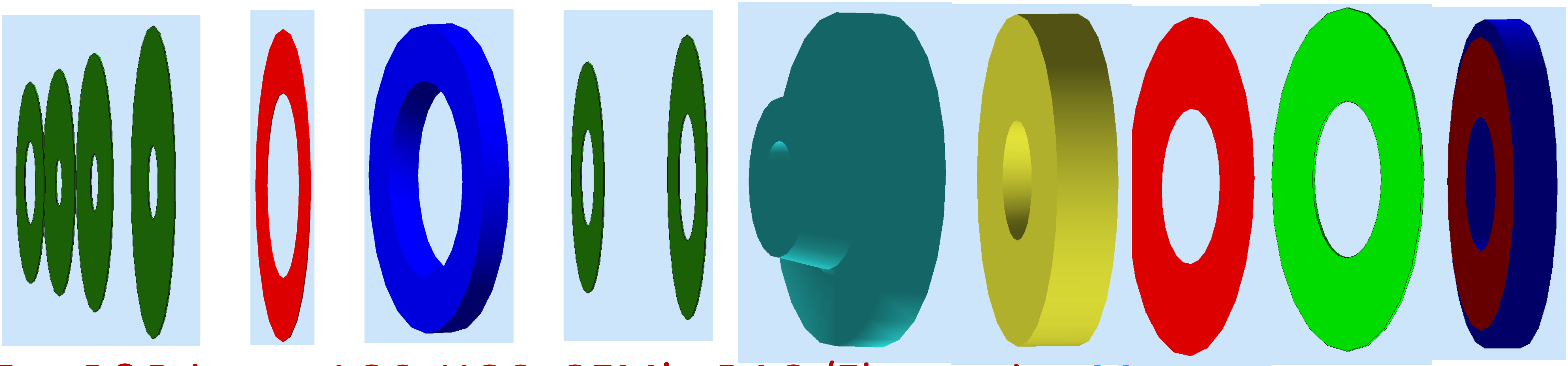
Uses full capability of JLab electronics





SIDIS& J/psi:

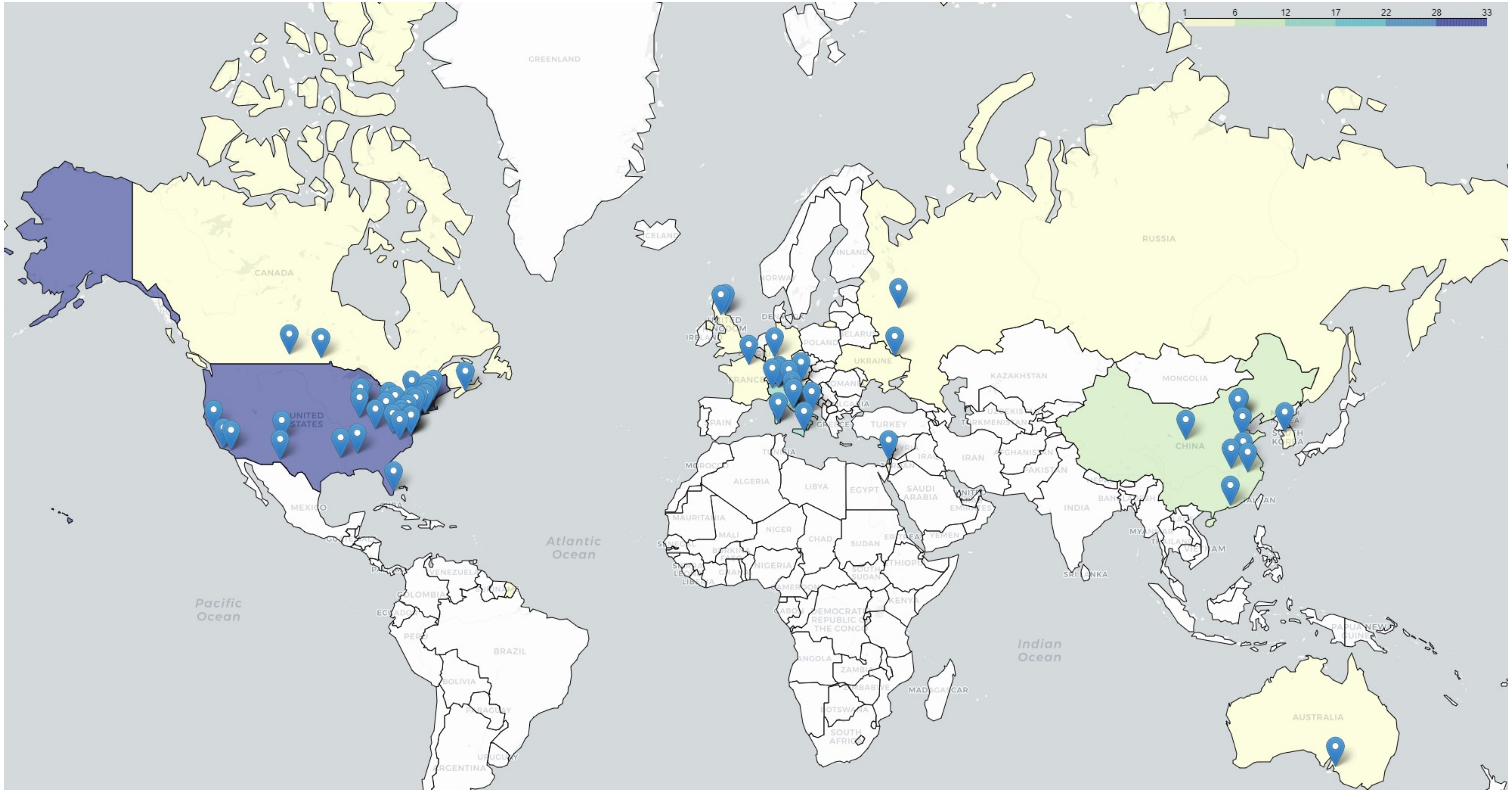
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC



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

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

SoLID Program on GPDs

- **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
  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 ^{3}He targets**
  Z.Y. Ye, N. Liyanage, W. Xiong, A. Camsonne and Z.H Ye (under study)

Other SoLID Run Group EXPT.s

- **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/E12-10-006E0

Summary

- SoLID will make the 12 GeV Jefferson Lab Science Program reach its full potential
- SoLID is a mature design of high luminosity detector. It has been in the making for at least 10 years
- The SoLID collaboration is strong and continues to strengthen the science program with innovative ideas
- SoLID is the natural training ground for the next generation of EIC users