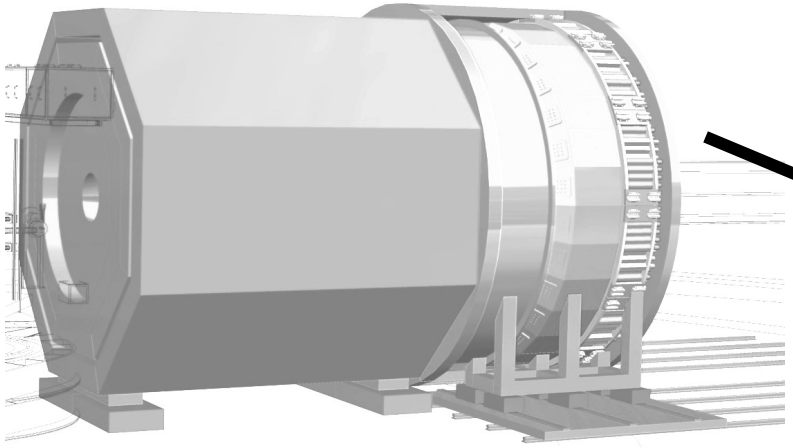
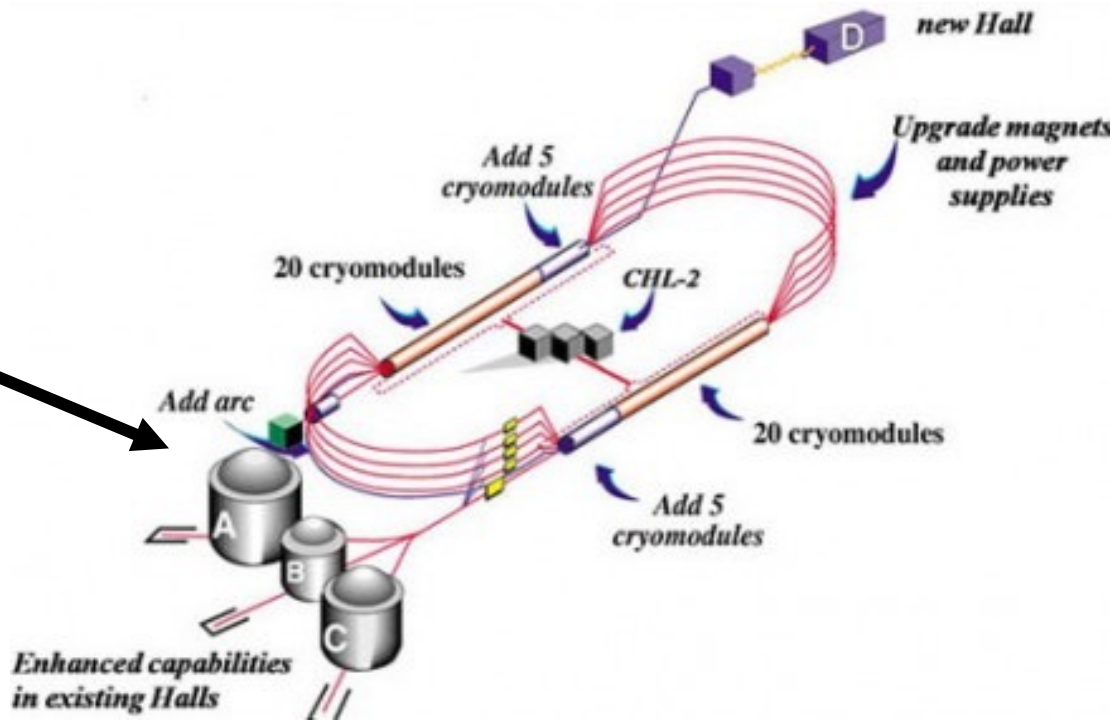
# Opportunities of SoLID with JLab20+

ECT* Workshop on Opportunities with JLab Energy and Luminosity Upgrade
September 26-30, 2022

Jian-ping Chen
Jefferson Lab






JLab12 & Upgrade to JLab20+

Acknowledgement: Thanks to Haiyan Gao, Sylvester Joosten, Vlad Khachatrya, Zein-Eddine Meziani, Paul Souder, Xiaochao Zheng and many other SoLID collaborators.

# Outline

1. Overview of SoLID@JLab12 Physics Program

2. Potential SoLID Measurements with JLab20+
   - i) **SIDIS**
   - ii) **Threshold J/ψ** (S. Joosten's talk)
   - iii) **PVDIS**
   - iv) **GPDs** (M. Boer, A. Camsonne)

3. Summary

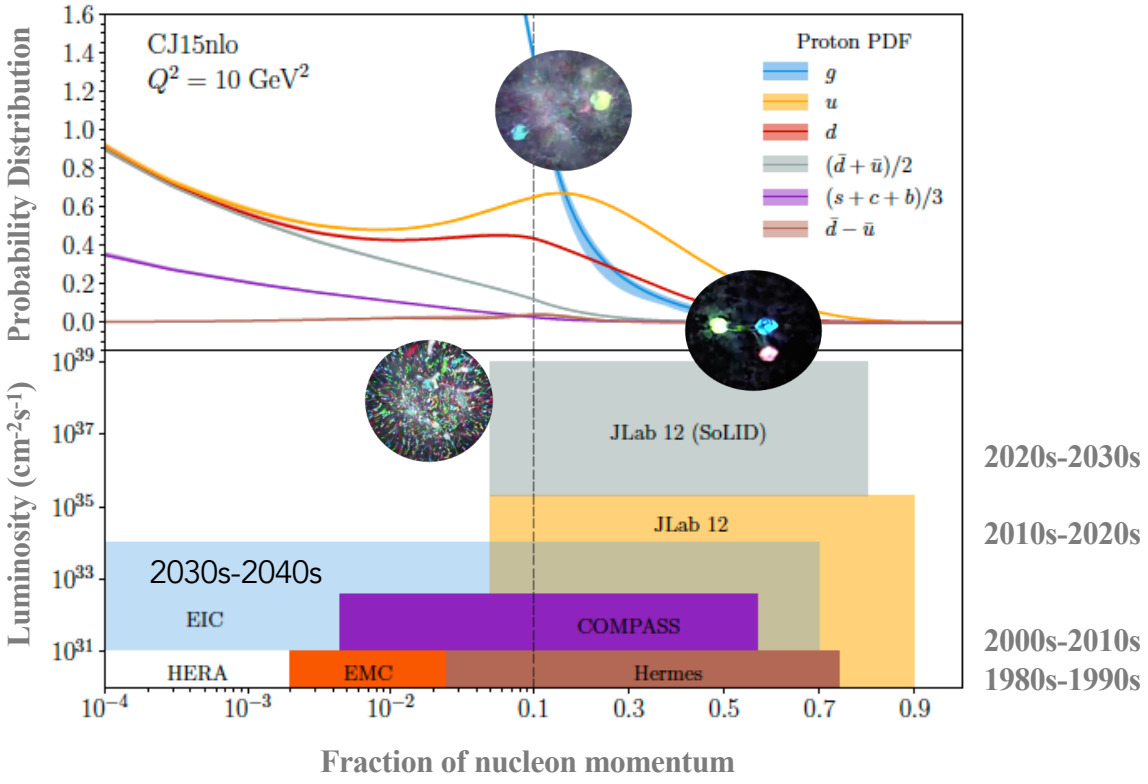
# 1. Overview of SoLID@JLab12 Physics Program

# SoLID@JLab: QCD Intensity Frontier

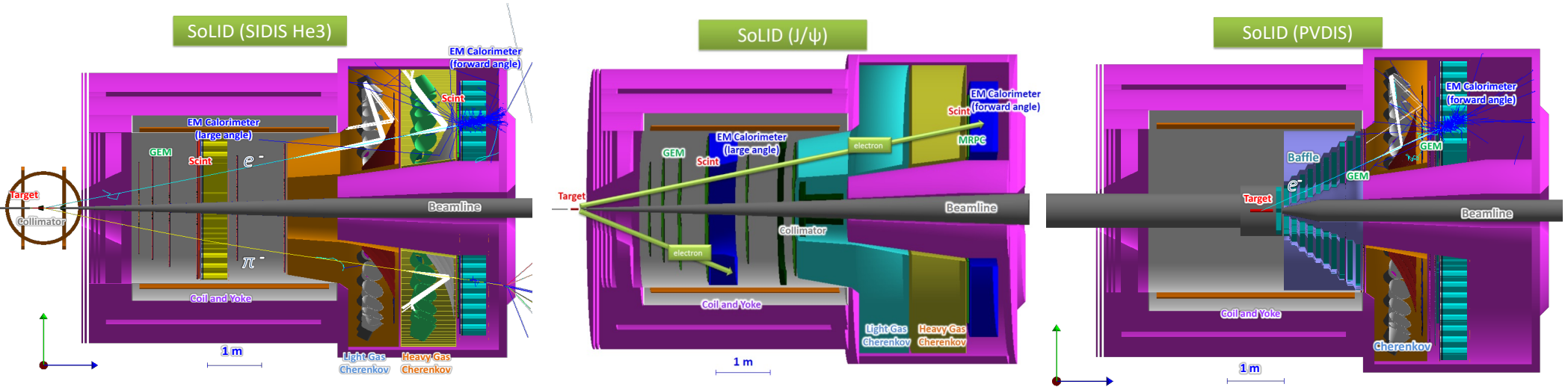
- Nucleon spin, proton mass, beyond standard model experiments require precision measurements of small cross sections and asymmetries, combined with multiple particle detection

➢ critical need for high luminosity ($10^{37}$-$10^{39}$ cm$^{-2}$s$^{-1}$) and large acceptance

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



# Approved SoLID Experiments




**A) SIDIS: (3)** Transversely Polarized $^3$He (n): Transversity, Sivers, Pretzlosity TMDs
**Rating A** Longitudinally Polarized $^3$He (n): Worm-gear TMDs
Transversely Polarized Proton: Transversity/Sivers, Pretzlosicty TMDs

**B) Threshold J/ψ:** **Rating A** Gluon Field, Proton Mass

**C). PVDIS**: **Rating A** Test Standard Model

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

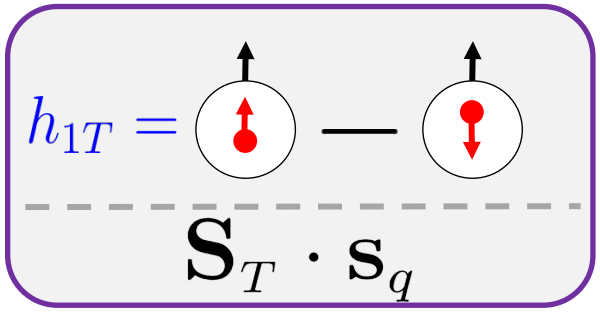
PAC50 (2022): Approved 2 New SoLID Experiments: Beam Normal SSA (A-)
PVEMC (C2)

# TMDs – confined motion inside the nucleon

**Transversely Polarized Nucleon TMDs**

→ Nucleon Spin
→ Quark Spin

## *Transversity*

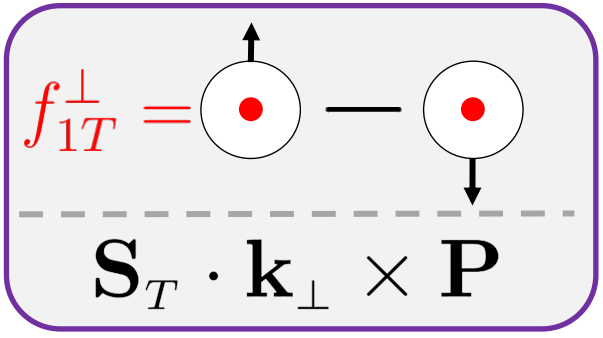



**Relevant Vectors**

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

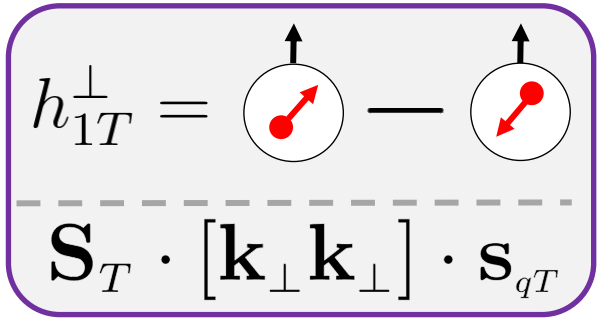
- $h_{1T}$ ($h_1$) = $g_1$ (no relativity)
- $h_{1T}$ → tensor charge (lattice QCD calculations)
- Connected to nucleon beta decay and EDM

## *Sivers*




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

## *Pretzelosity*

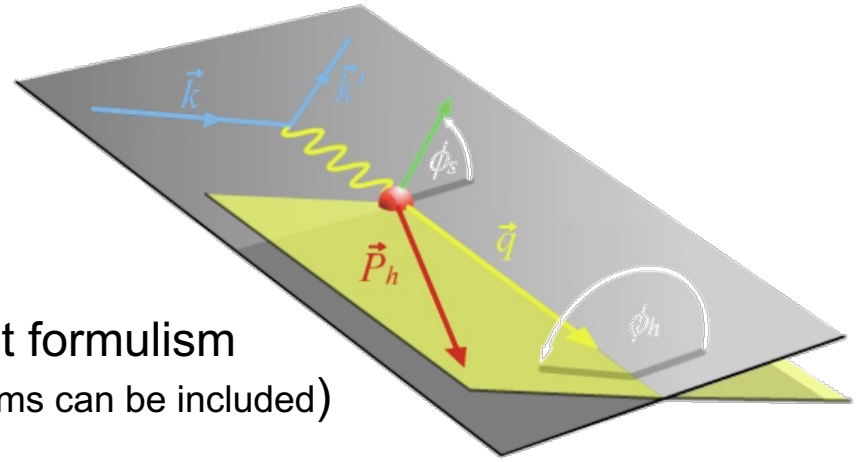



- Interference between components with OAM difference of 2 units (i.e., s-d, p-p) (model dependence)
- Signature for relativistic effect

# 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!

**($2\pi$ 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)

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

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

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

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

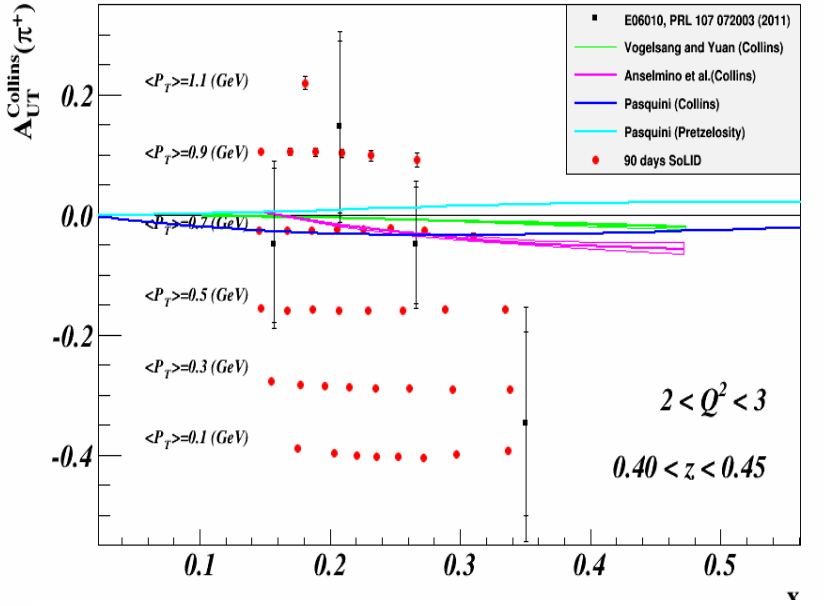
# SoLID-SIDIS: Precision Mapping in Multi-Dimension

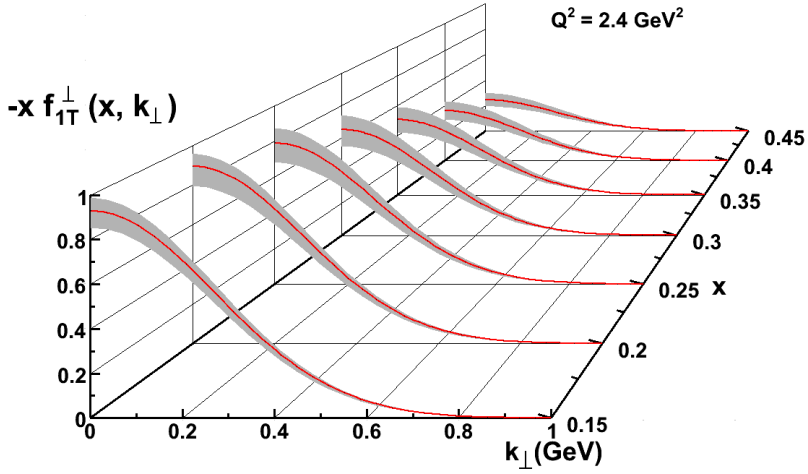
SoLID-SIDIS program: Large acceptance, Full azimuthal coverage + High luminosity

- 4-D mapping of asymmetries with precision
- Constrain models and forms of TMDs, Tensor charge, …
- Lattice QCD, QCD dynamics

***4-D binning for the first time!***

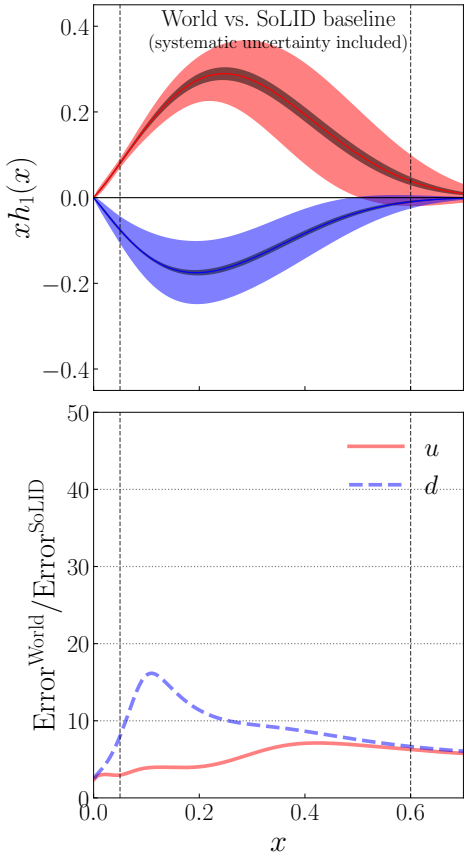
- **More than 1400 bins in x, $Q^2$, $P_T$ and z for 11/8.8 GeV beam.**




- **Sivers:** Confined quark motion
- Quantum correlations between nucleon spin and quark motion
- QCD dynamics

## Transversity



# SoLID Impact on Tensor Charge

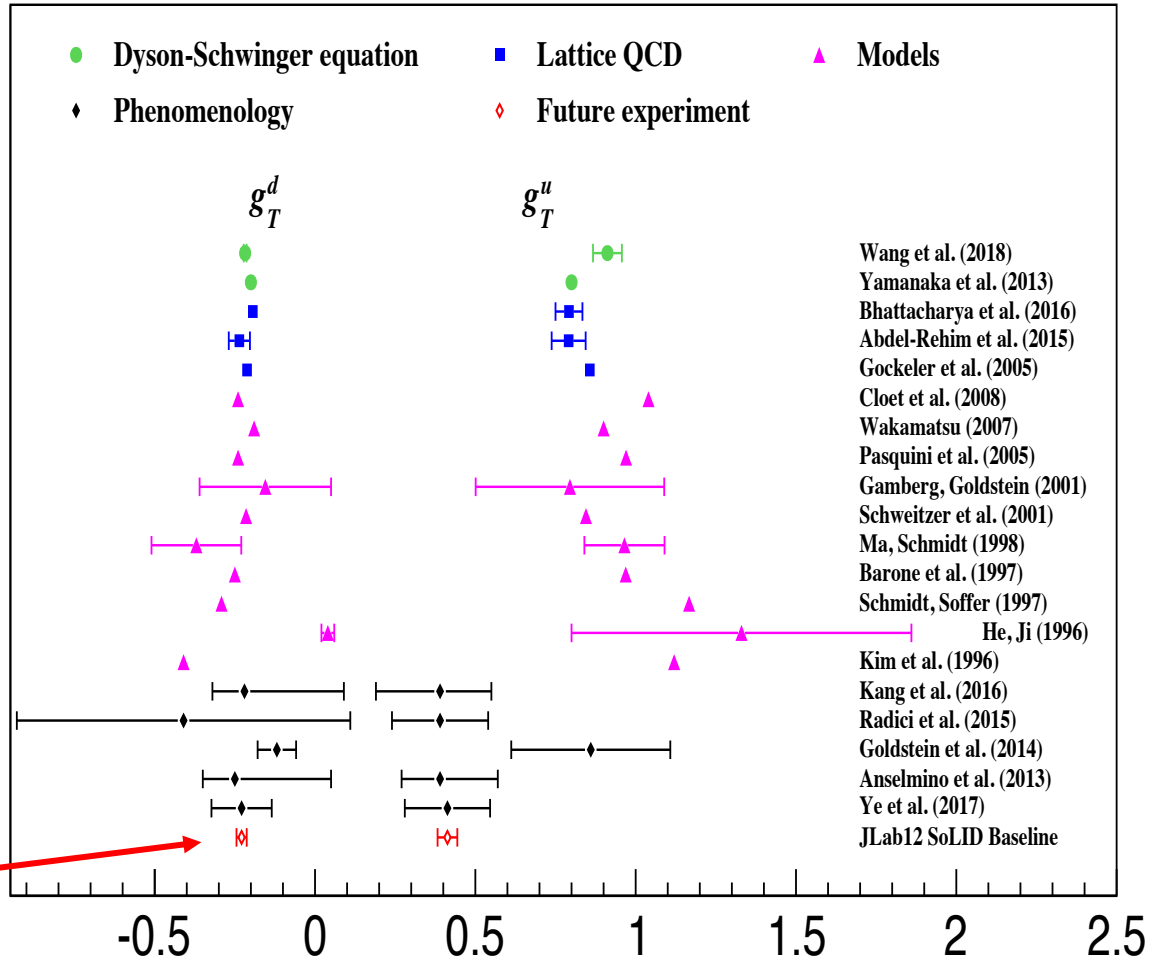
## Definition

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

- 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

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



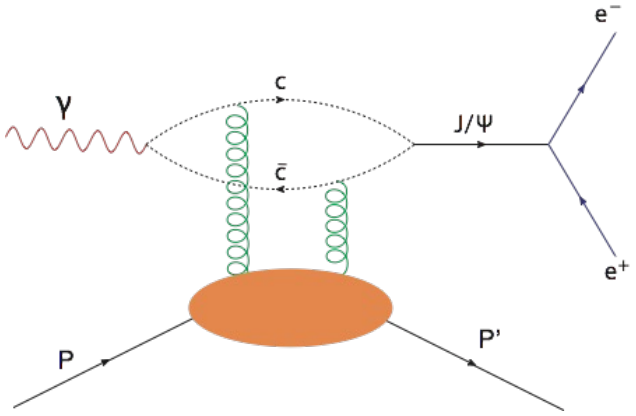

**SoLID Projections**

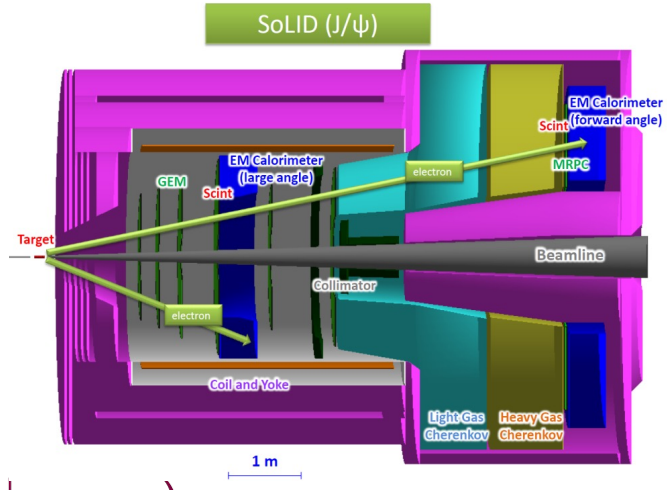
# SoLID-J/ψ: Experiment E12-12-006

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

  10 more days include calibration/background run

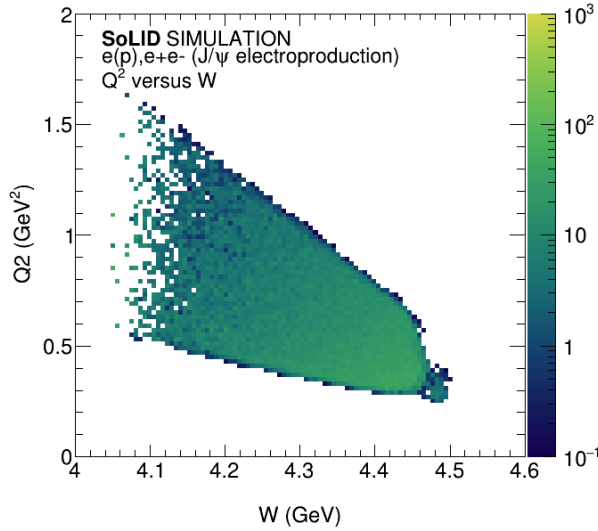
- SoLID configuration overall compatible with SIDIS
  - **Electroproduction trigger**: 3-fold coincidence of e, $e^-e^+$
  - **Photoproduction trigger:** 3-fold coincidence of p, $e^-e^+$
  - **Additional trigger:** 4-fold coincidence of ep, $e^-e^+$
  - And (inclusive) 2-fold coincidence $e^+e^-$

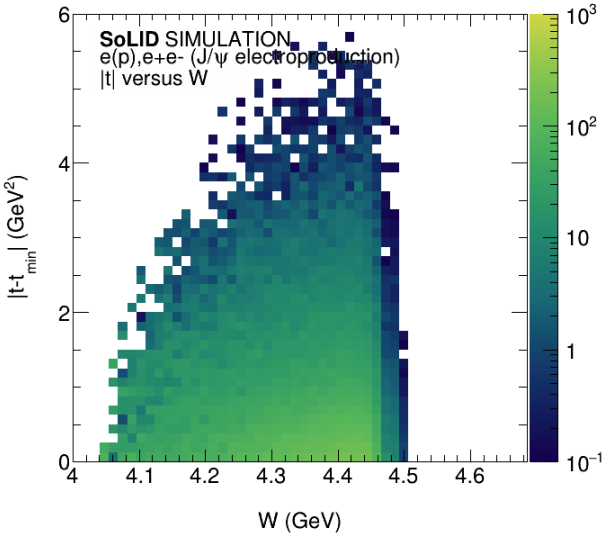


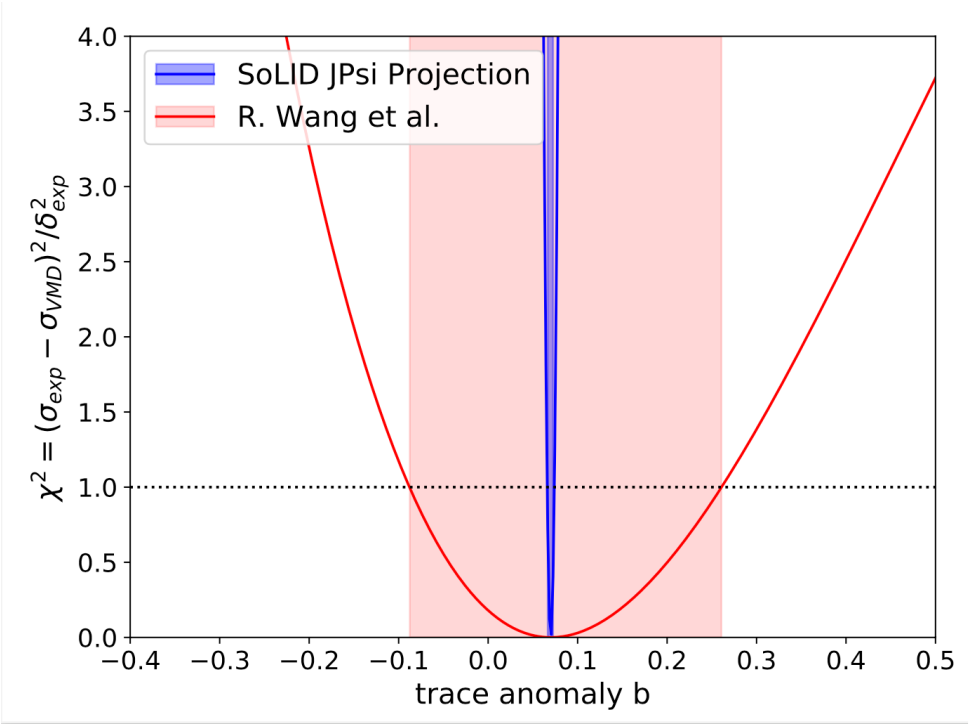

$$e^- + p \longrightarrow e^- + p + J/\psi\,(e^+ + e^-)$$

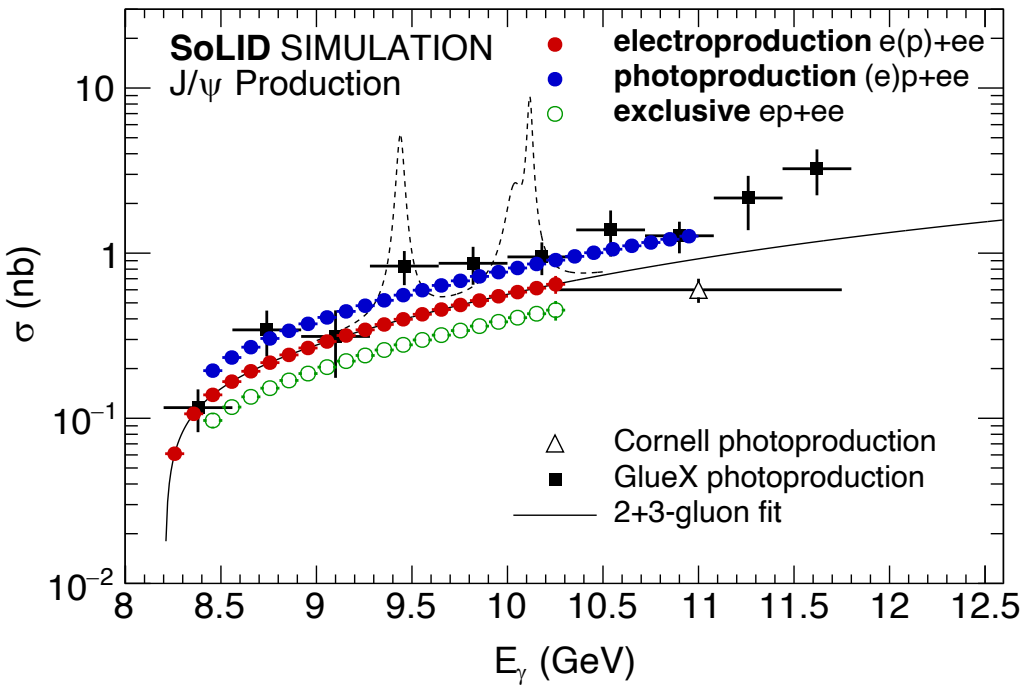
$$\gamma + \mathrm{p} \rightarrow \mathrm{p}' + \mathrm{J/\psi(e^- + e^+)}$$



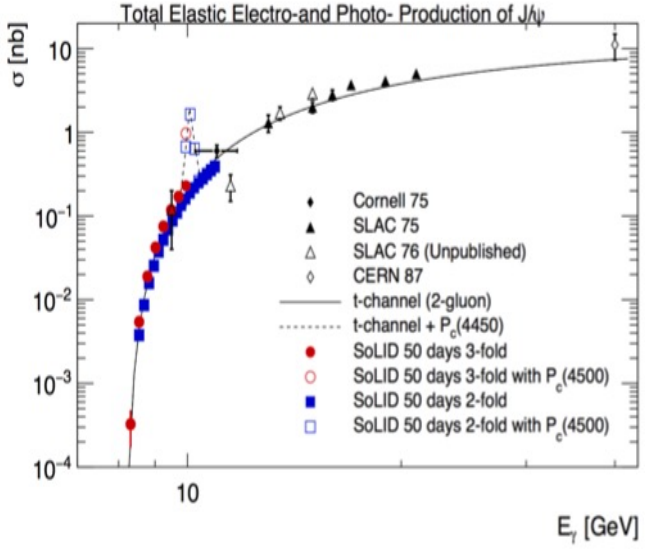



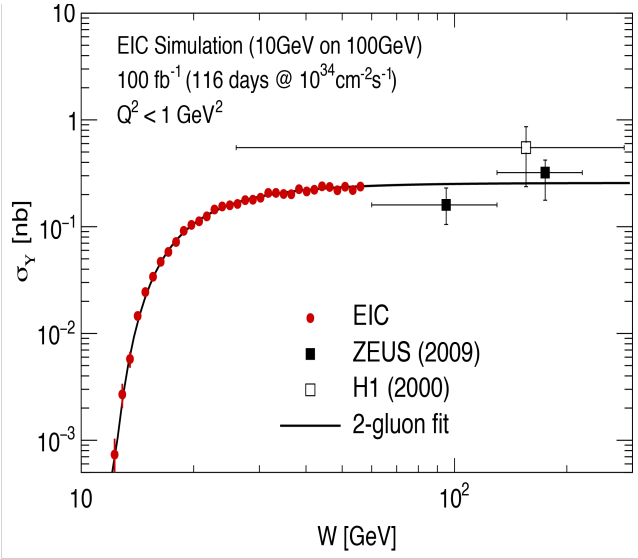
# SoLID-J/ψ (and EIC): Gluon Field and Proton Mass




## Charm @ SoLID and Beauty @ EIC




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

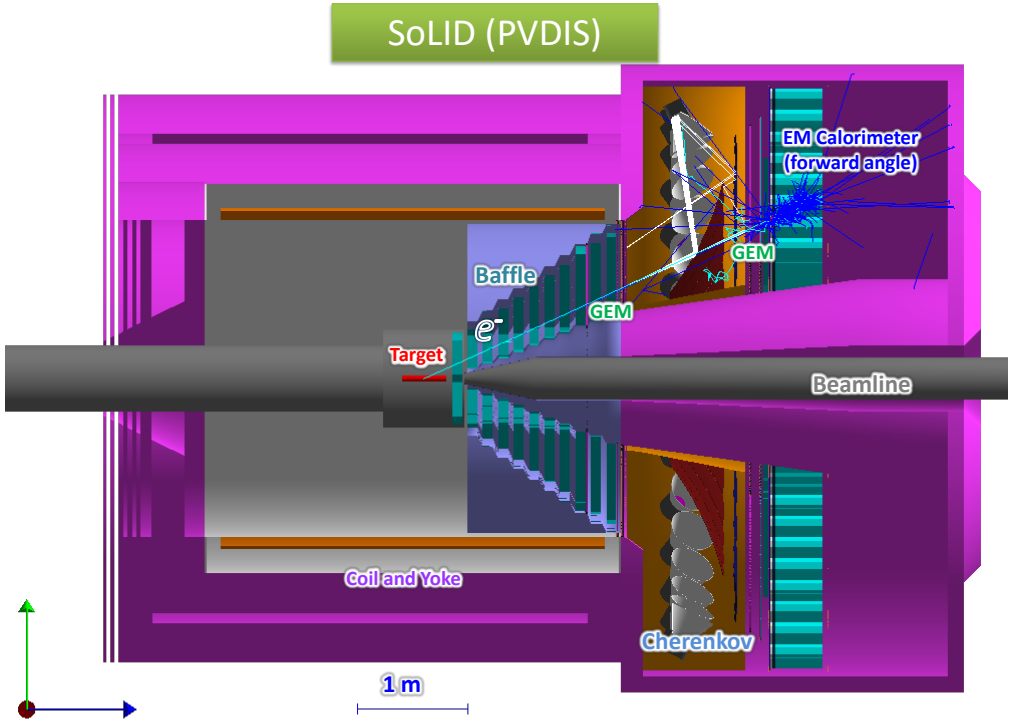
Gryniuk, Joosten, Meziani, and Vanderhaeghen, PRD 102, 014016 (2020) (for update)

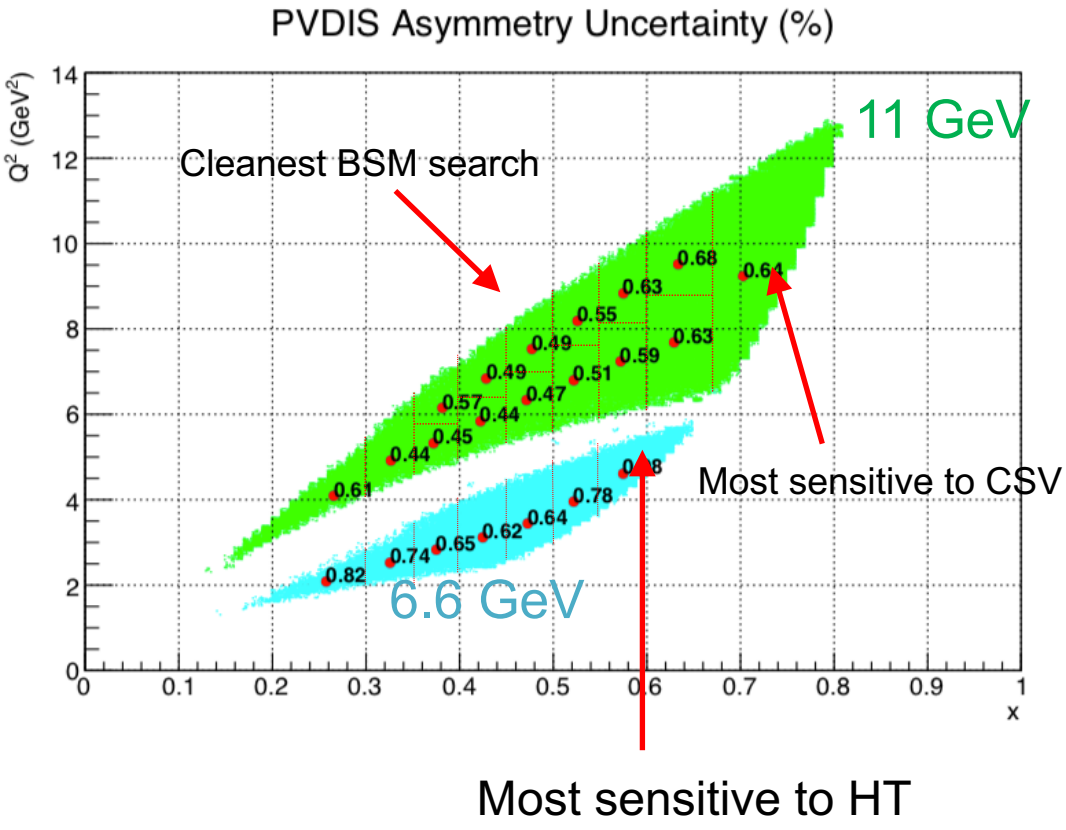
GlueX on J/ψ Ali et al., PRL 123, 072001(2019)

# SoLID-PVDIS: Experiment E12-10-007

**SoLID@JLab: Extraordinary opportunity to do the ultimate PVDIS measurement**

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

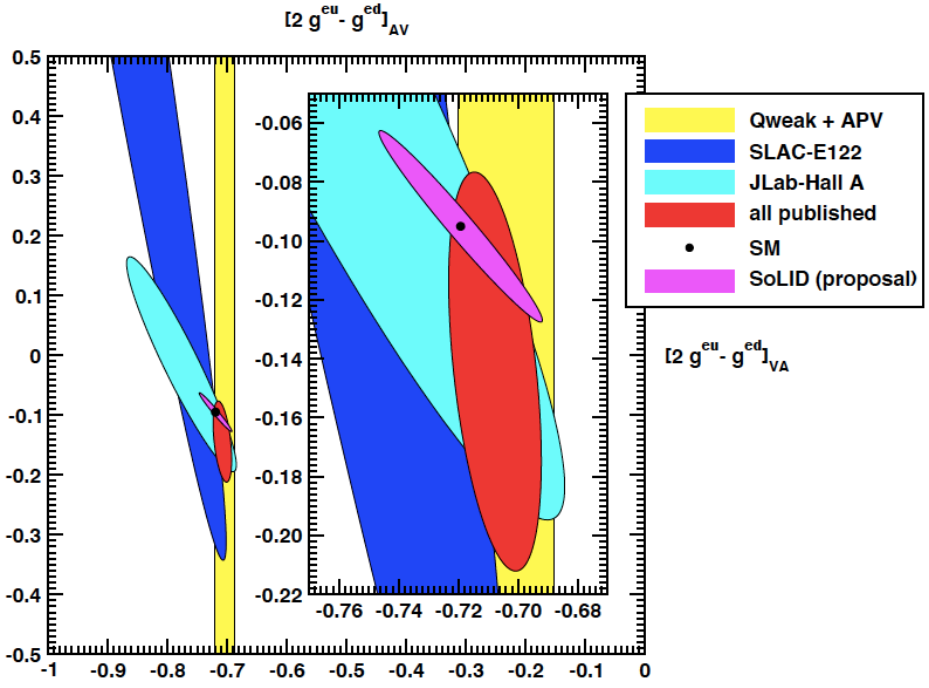


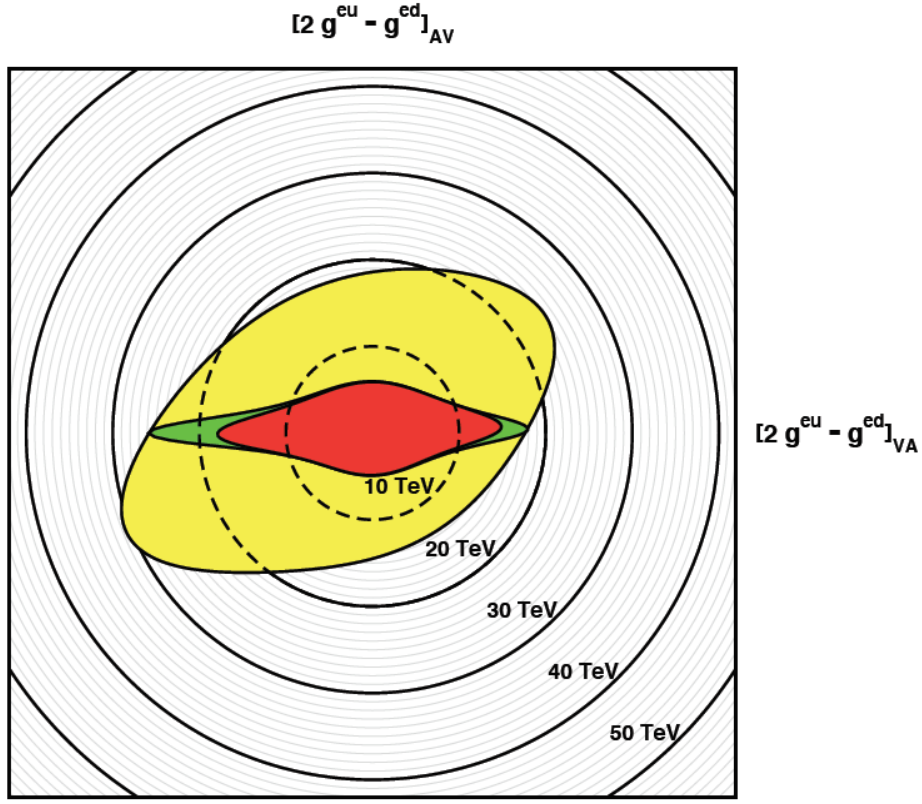
# SoLID-PVDIS: Precision Test of Standard Model

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

# 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 $\pi^-$ 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)*

# SoLID Apparatus

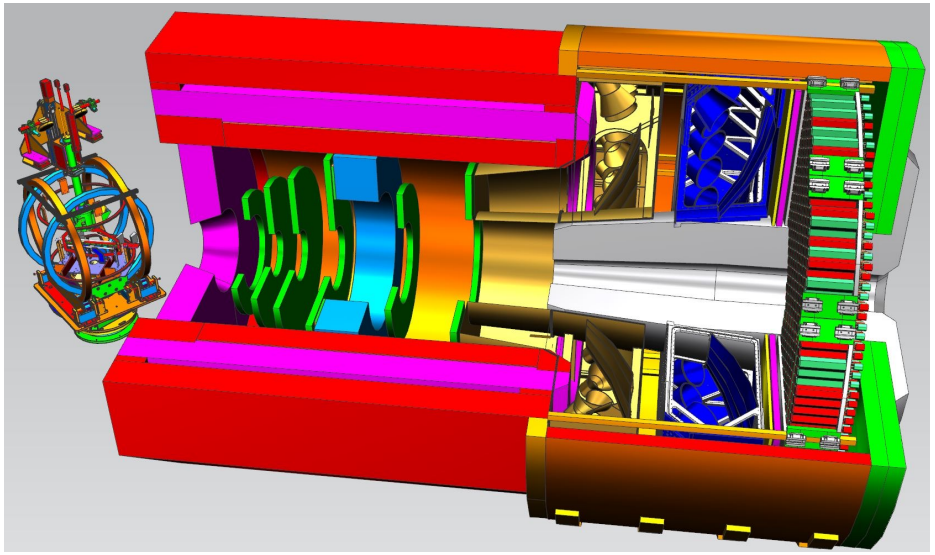
## Challenging Requirements

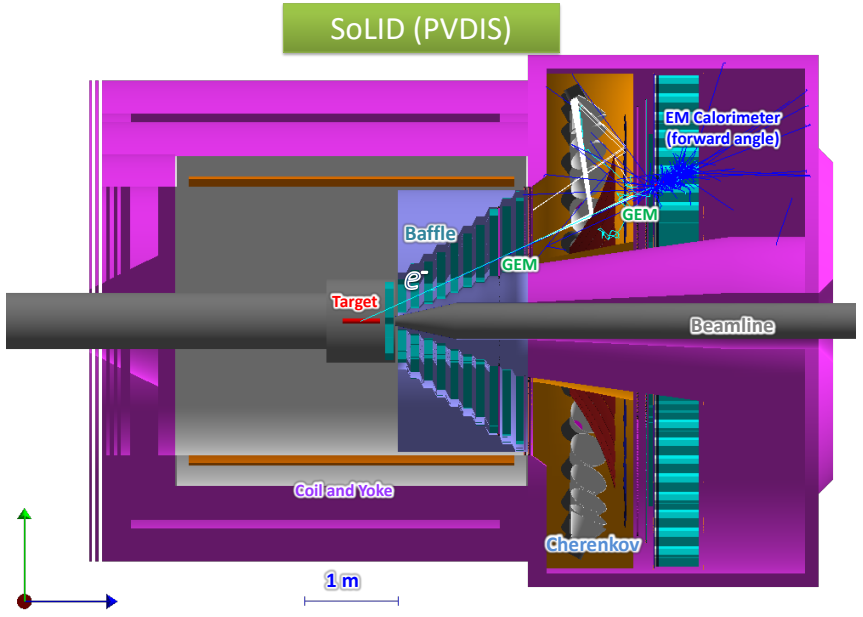
- High Luminosity ($10^{37}$-$10^{39}$)
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale

## Modern Technologies

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

**Polarized $^3$He (``neutron") @ SoLID**

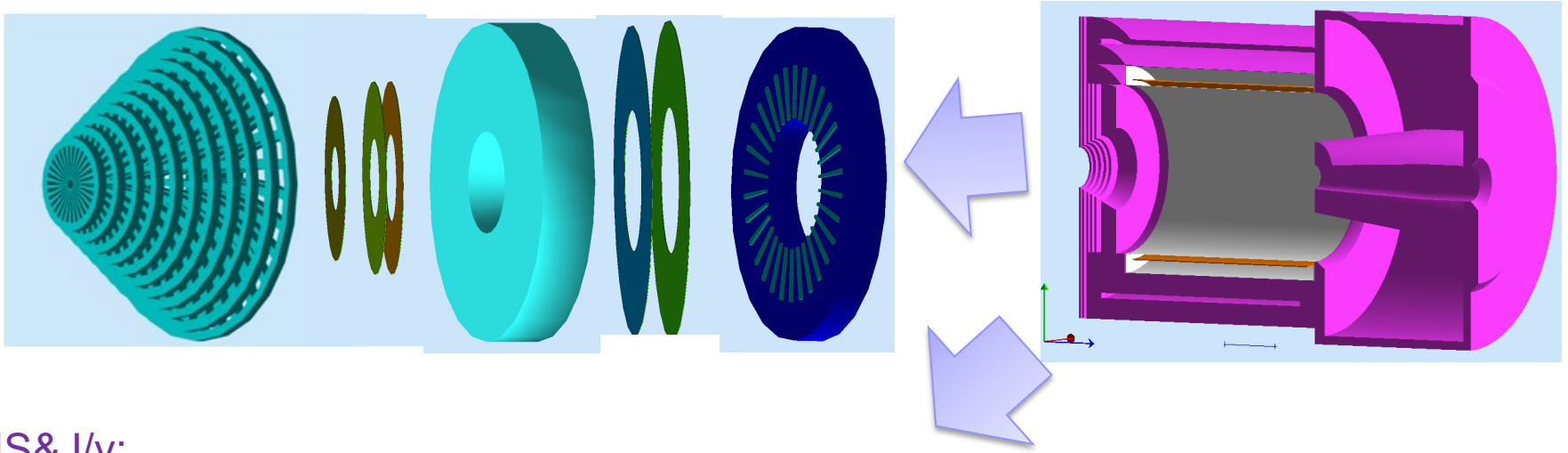




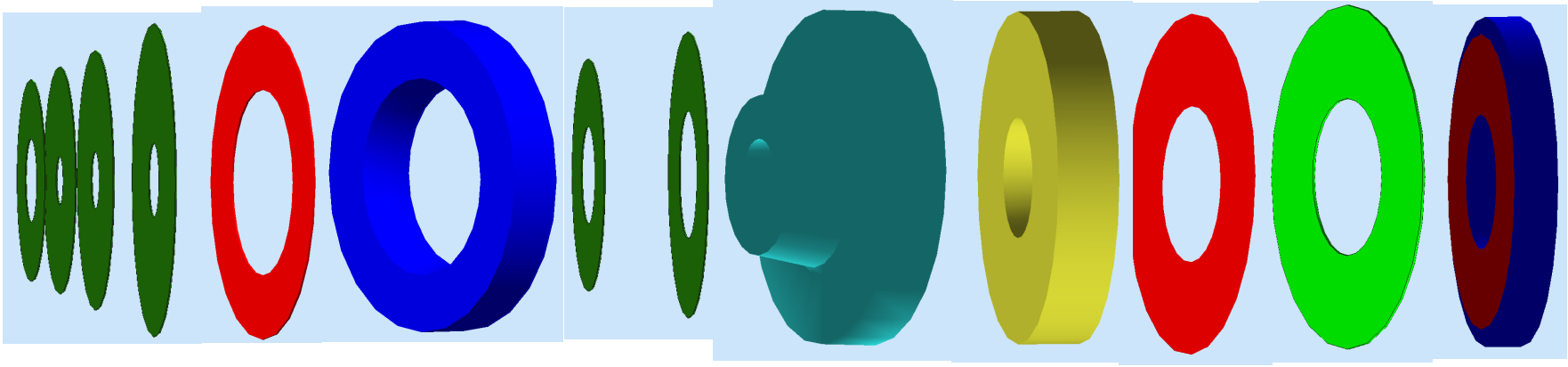
# SoLID Detector Subsystems

Uses full capability of JLab electronics

PVDIS: Baffle 3xGEMS LGC 2xGEMs EC



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



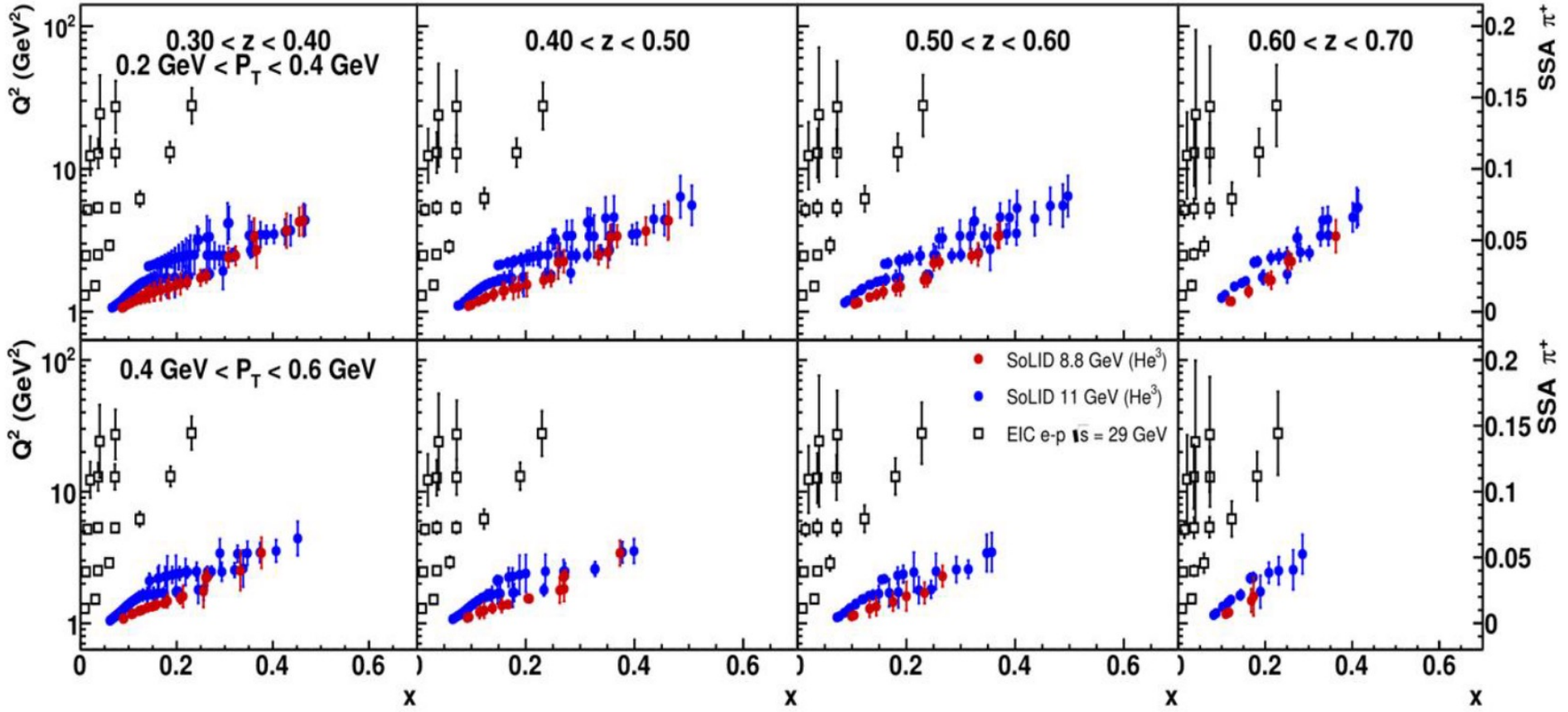
Pre-R&D items: LGC, HGC, GEM's, DAQ/Electronics, Magnet

# 2. Potential SoLID Measurements @JLab20+

SIDIS, J/ψ, PVDIS, GPDs

# SIDIS Projections with SoLID @JLab12 and EIC

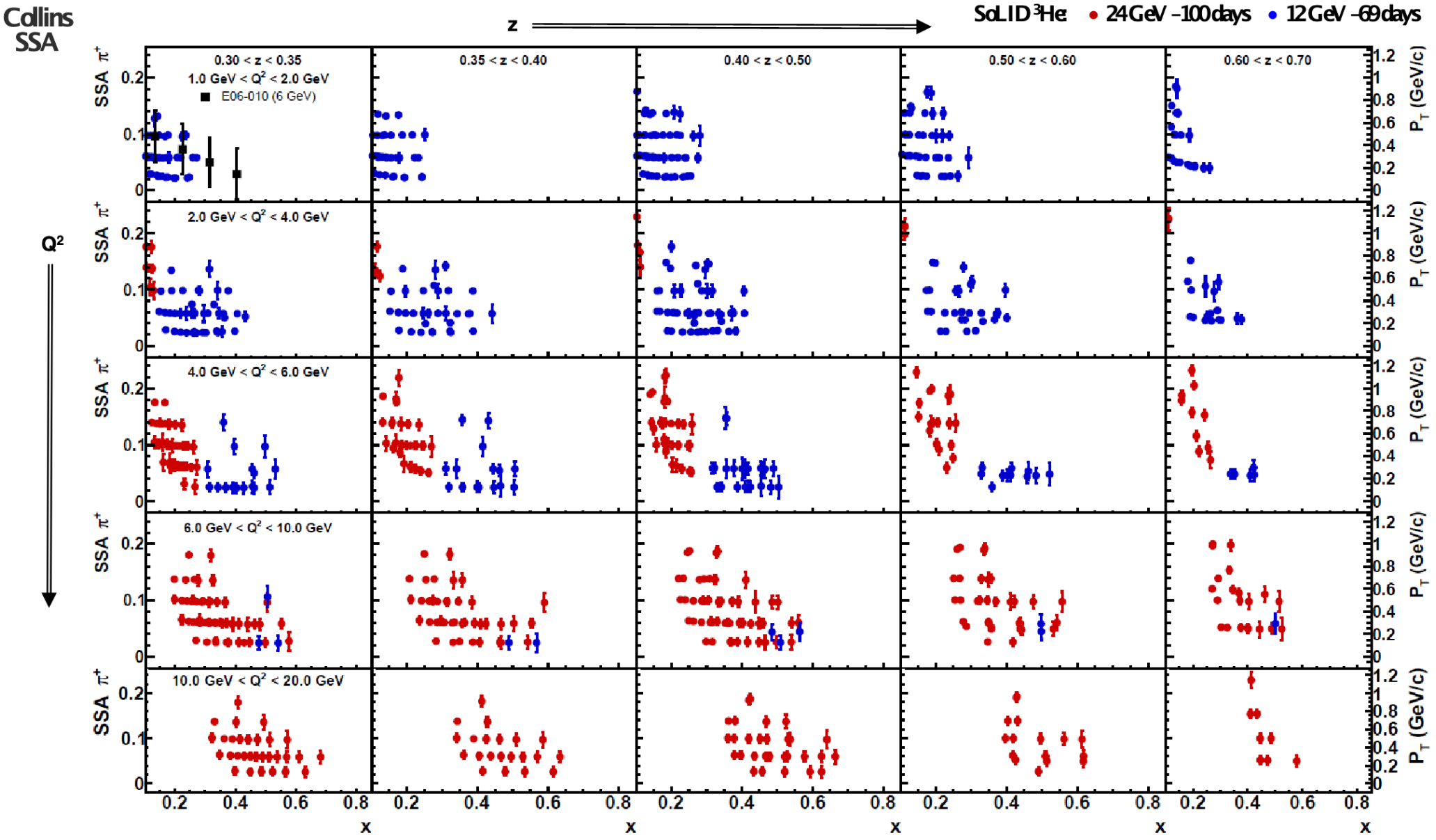
- ❑ Single Spin Asymmetry: SoLID@JLab12 (11 and 8.8 GeV) Transverse Pol $^3$He
- ❑ Single Spin Asymmetry: EIC with Center-of-Mass Energy = 29 GeV
- ❑ SoLID and EIC Complementary to Each Other, by Covering Different x and $Q^2$ Ranges
- ➢ EIC: Clean (Factorization Mostly Holds); Gluon Shower Smears Structure?
- ➢ JLab12: Access 3-d Structure in Momentum Space; Factorization? Contaminations?



# SoLID-SIDIS @JLab20+ : Collins Asymmetry

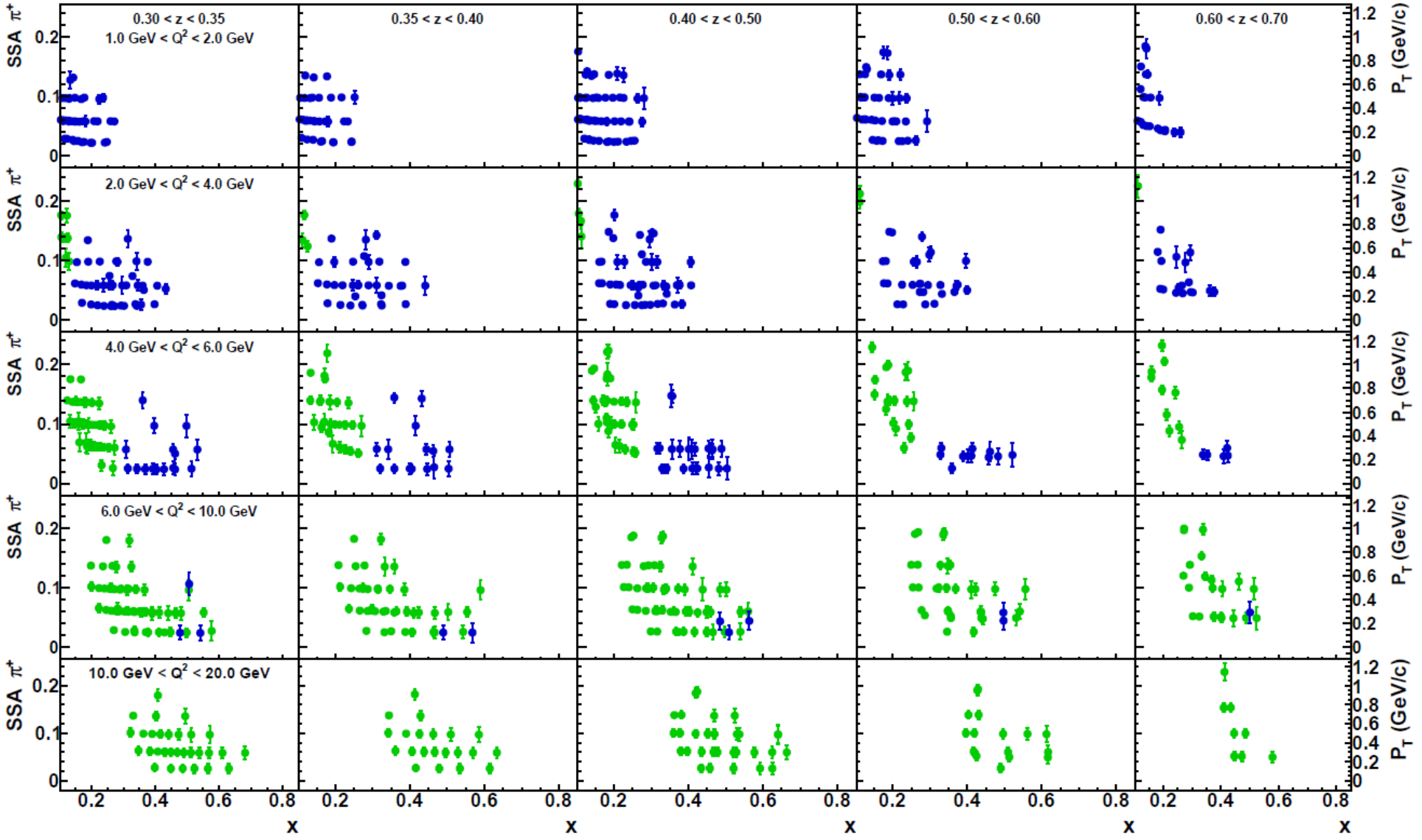
Vlad Khachatrya

SIDIS: Collins Asymmetry: 20 GeV (Preliminary) and 12GeV



# SoLID-SIDIS @JLab20+: Sivers Asymmetry

SIDIS: Sivers Asymmetry: 24 GeV (Preliminary) and 12GeV



# SoLID-SIDIS @JLab20+: Plan for Next Steps

Plan for next steps for SoLID-SIDIS @ JLab20+ study:

- For SIDIS pions, projections for $NH_3$
  combining $NH_3$/$^3$He to update Collins/Sivers SSAs
  greatly expand kinematic reach from JLab12

- SIDIS kaons
  clean extraction of sea quark TMDs only with JLab 20+ (?)

- SiDIS Worm-Gear TMDs $g_1^T$ and $h_1^L$

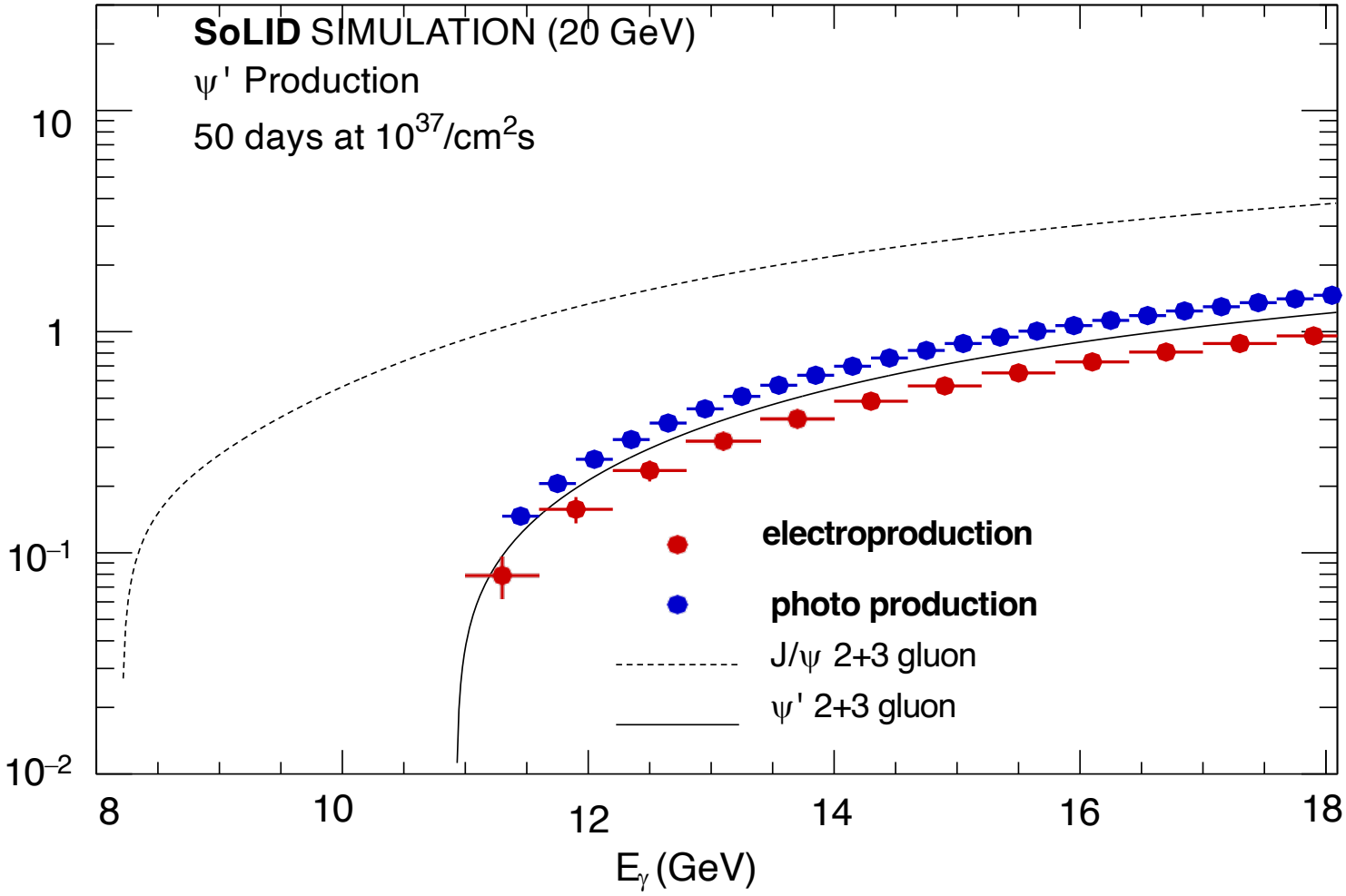
- $g_T$ measurement

- High-$P_T$ inclusive and SIDIS pion (gluon polarization)

# SoLID-J/ψ @JLab20+: ψ(2S)

S. Joosten's talk on Tuesday

ψ' : Complementary probe of the gluonic field (color dipole size)



# SoLID-PVDIS @JLab20+

Improvement From 11 GeV to 22 GeV in Uncertainties for

- Standard Model Test
- Search for Charge Symmetry Violation
- Study of Higher-Twist Effect

Simulation study by an UVa student Alex Emmert (Xiaochao Zheng's group)

| | Stat.(11GeV) | Sys (11GeV)) | Stat(22 GeV) | Sys (22 GeV) |
|---|---|---|---|---|
| $Sin^2(\theta_W)$ | 0.00048. | 0.00053 | 0.00028 | 0.00031 |
| CSV | 0.036 | 0.039 | 0.014 | 0.015 |
| HT | 0.0043 | 0.0045 | 0.0016 | 0.0017 |

Weak coupling C3 study using both e+ and e- with SoLID: LOI by X. Zheng et al.

# SoLID-GPD Study @JLab20+

- DVCS, TCS and more — Mario Boer's talk
- Deep-Exclusive Meson Production (DEMP) — Garth Huber's talk
- DDVCS — Alexandre Camsonne's talk

# Progresses Since Initial Approval of SoLID Experiments

- Since **2010:** Five SoLID experiments approved by PAC with high rating (+ 6 run-group experiments)
  - 3 SIDIS, 1 PVDIS, 1 threshold J/$\psi$
- CLEO-II magnet arrived at JLab in 2016, cold test on-going
- 2014: pCDR submitted to JLab with cost estimation, updated in 2017 and 2019
- **Endorsed in 2015 LRP**
- **Director's Reviews in 2015, 2019 and 2021**
- 02/2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE
- DOE funded Pre-R&D on Cherenkov/GEM/DAQ tests started 02/2020 and mostly completed
- 03/2021: DOE **Science Review for SoLID, successful, waiting for final report**

  **Feedback from DOE: positive report, recommend to move to next step.**
- 7/2022 JLab PAC re-approved all 5 experiments with A rating, approved new A-n ( A-) and PVEMC (conditional)
- **Continuous effort on pre-conceptual design and pre-R&D with the support of JLab and DOE. Beam test on going to verify full capability of detector/DAQ with high luminosity.**
- **Next LRP (now-2023)**

# Strong Support from JLab and QCD Community

✓ **Recommendation 1 to be endorsed in the QCD town meeting: JLab12 including SoLID.**

Survey: Yes 243 /No 7/No Answer 5

Recommendation 1
The highest priority for QCD research is to maintain the U.S. world leadership in nuclear science for the next decade by capitalizing on past investments. We recommend continued support of full operations of the CEBAF 12-GeV and RHIC facilities and maintaining U.S. leadership within the LHC Heavy-Ion program, along with other running facilities, including university-based laboratories, and the scientists involved in these efforts.
This includes the following, unordered, programs:

- The 12-GeV CEBAF hosts a forefront program of using electrons to unfold the quark and gluon structure of visible matter and probe the Standard Model. **We recommend executing the CEBAF 12-GeV program at full capability and capitalizing on the full intensity potential of CEBAF by the construction and deployment of the Solenoid Large Intensity Device (SoLID).**

- RHIC …
- LHC …
- Theory …

# 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 for Cold QCD

- SoLID has a rich and vibrant science program 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 approved experiments

- SoLID@JLab20+

  greatly expand kinematics reach

  new channels for clean extractions of TMDs/GPDs

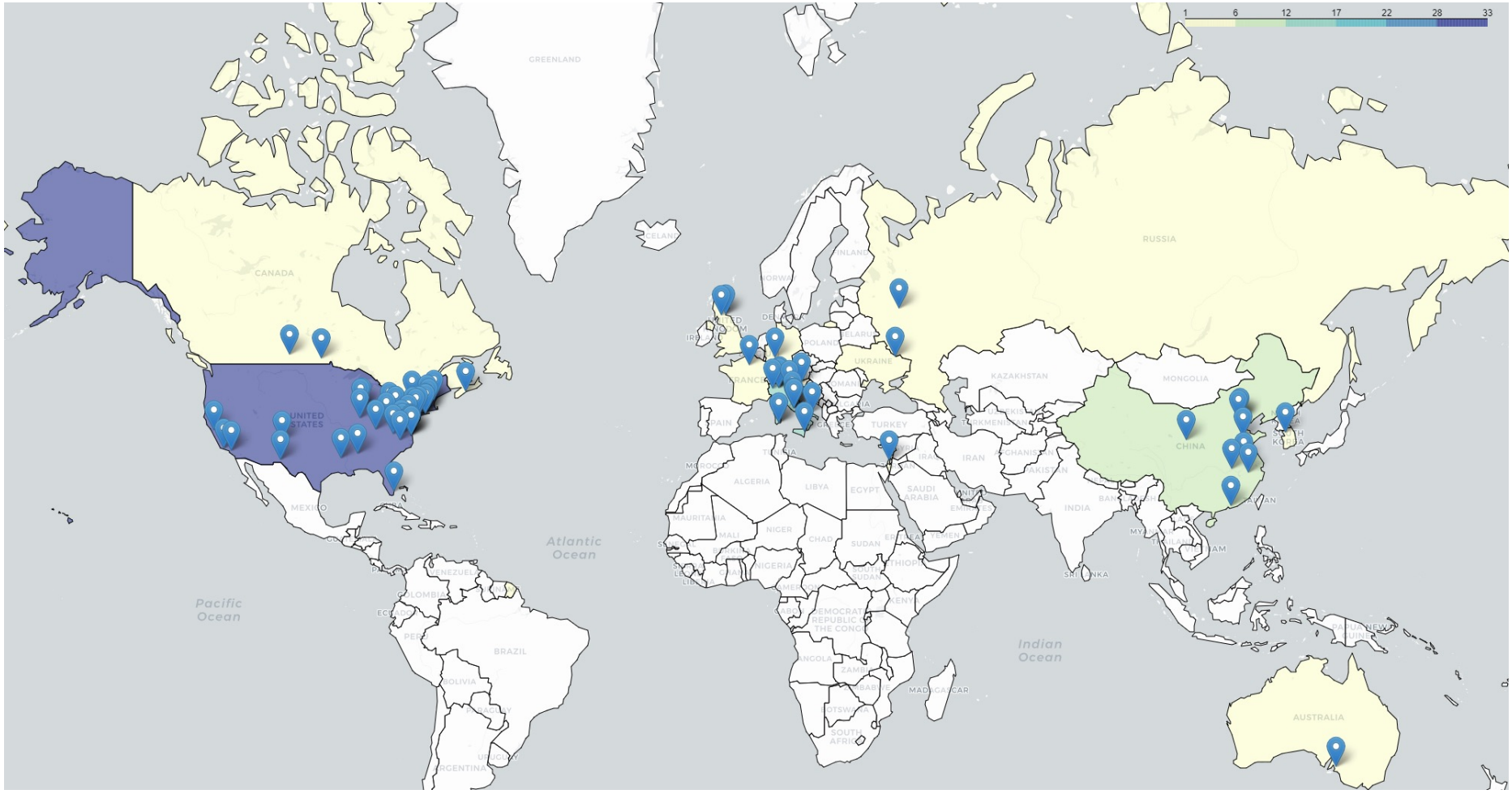
  new channel for study gluon field contribution to proton mass

  complementary to EIC, more sensitive to 3-D structure

**https://solid.jlab.org/**

# Strong Collaboration

- 270+ collaborators, 70+ institutions from 13 countries
- Large international participations and anticipate contributions
- Strong theory support




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