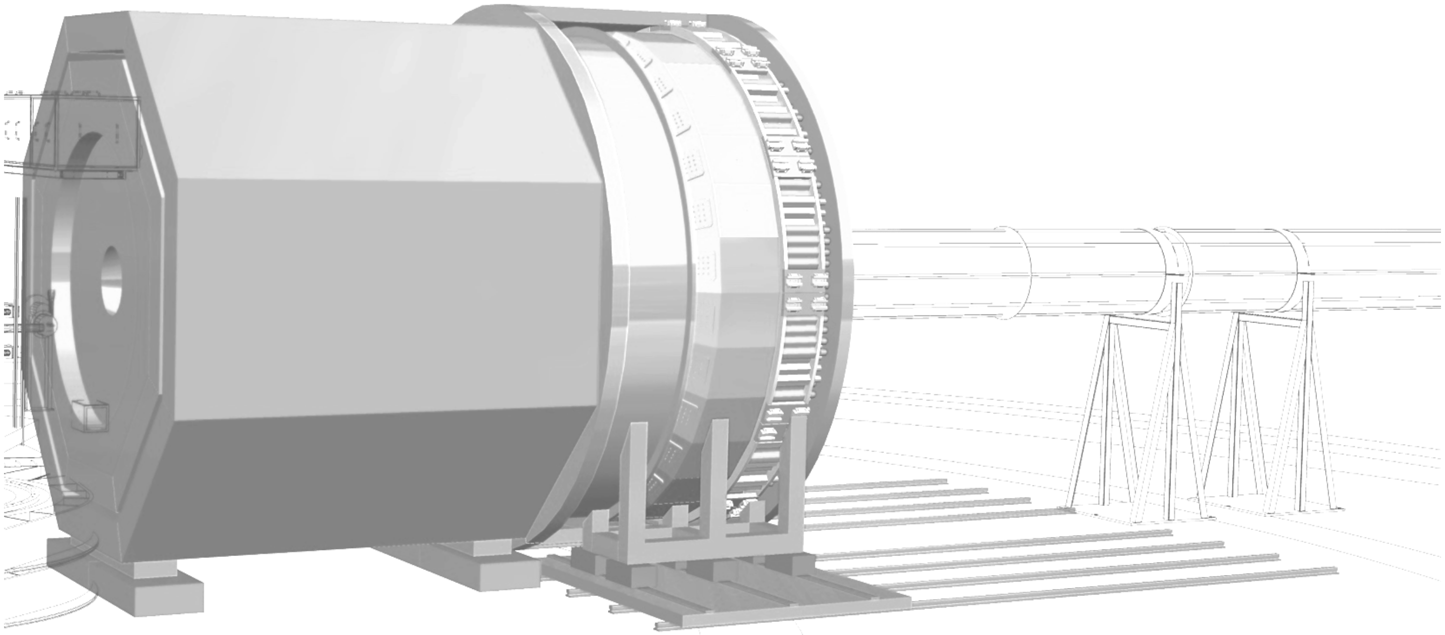
SoLID – The Next-Gen Spectrometer at JLab



JLUO Annual Meeting
June 26-28, 2023

Xiaochao Zheng

University of Virginia

(for the SoLID Collaboration)

solid.jlab.org

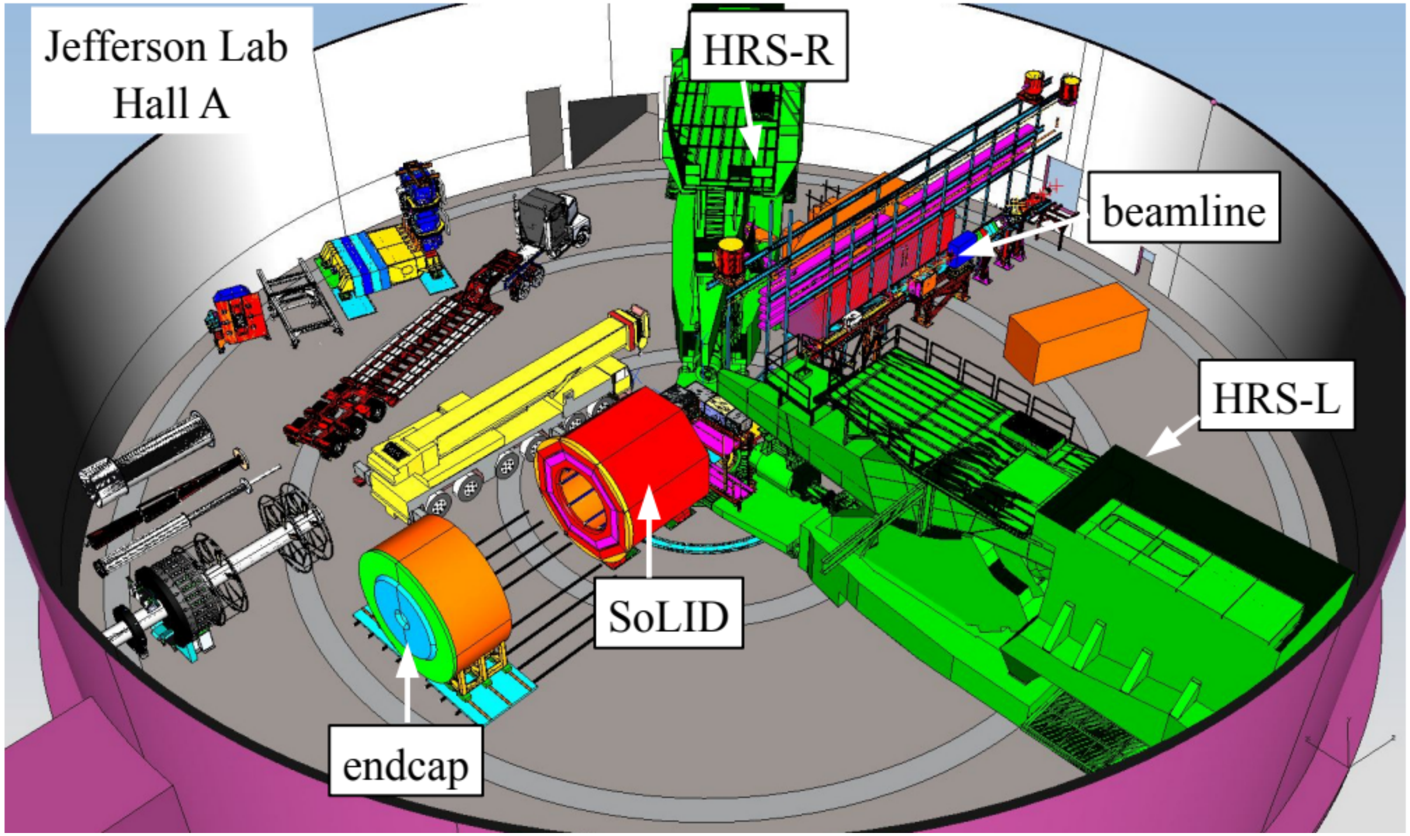
2022 SoLID white paper:
https://arxiv.org/abs/2209.13357
(accepted by J. Phys. G)

Outline

1. Motivation – Why SoLID ?
2. The Physics Program of SoLID
3. Current Status and Outlook

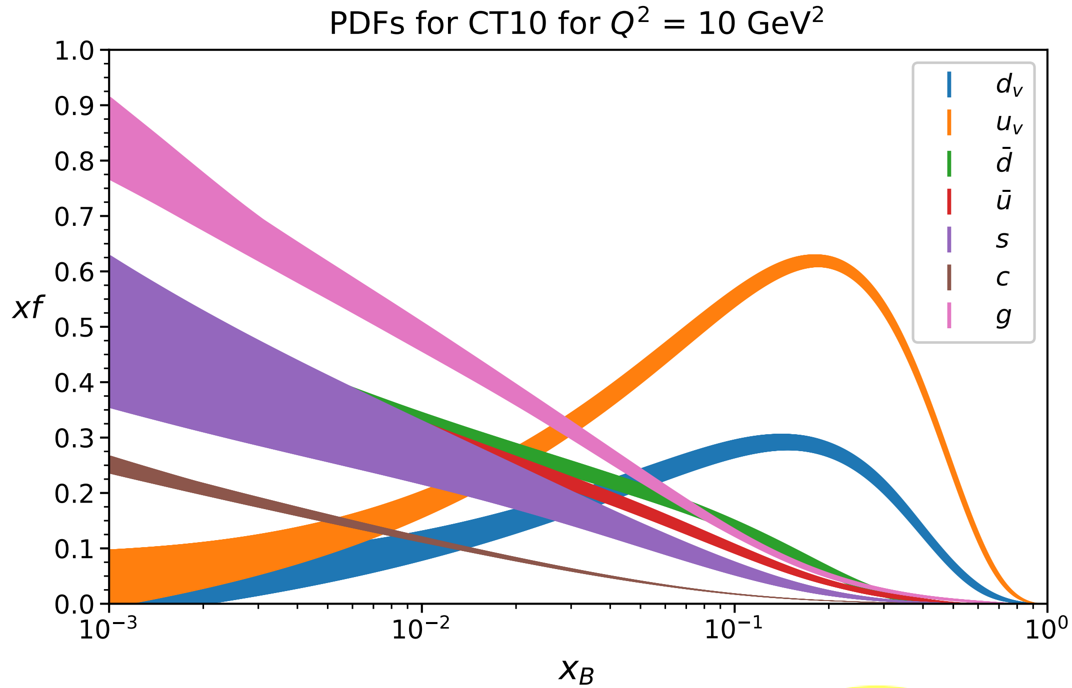
Outline

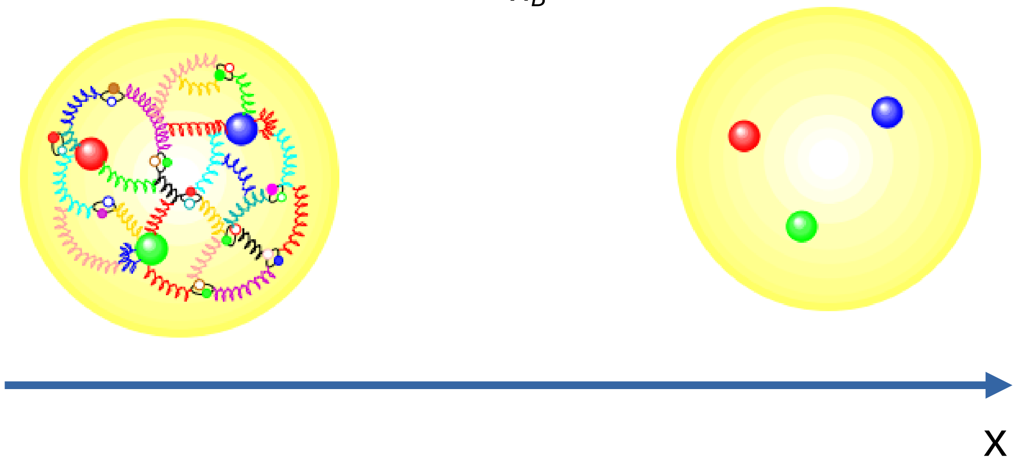
1. Motivation – Why SoLID ?
2. The Physics Program of SoLID
3. Current Status and Outlook



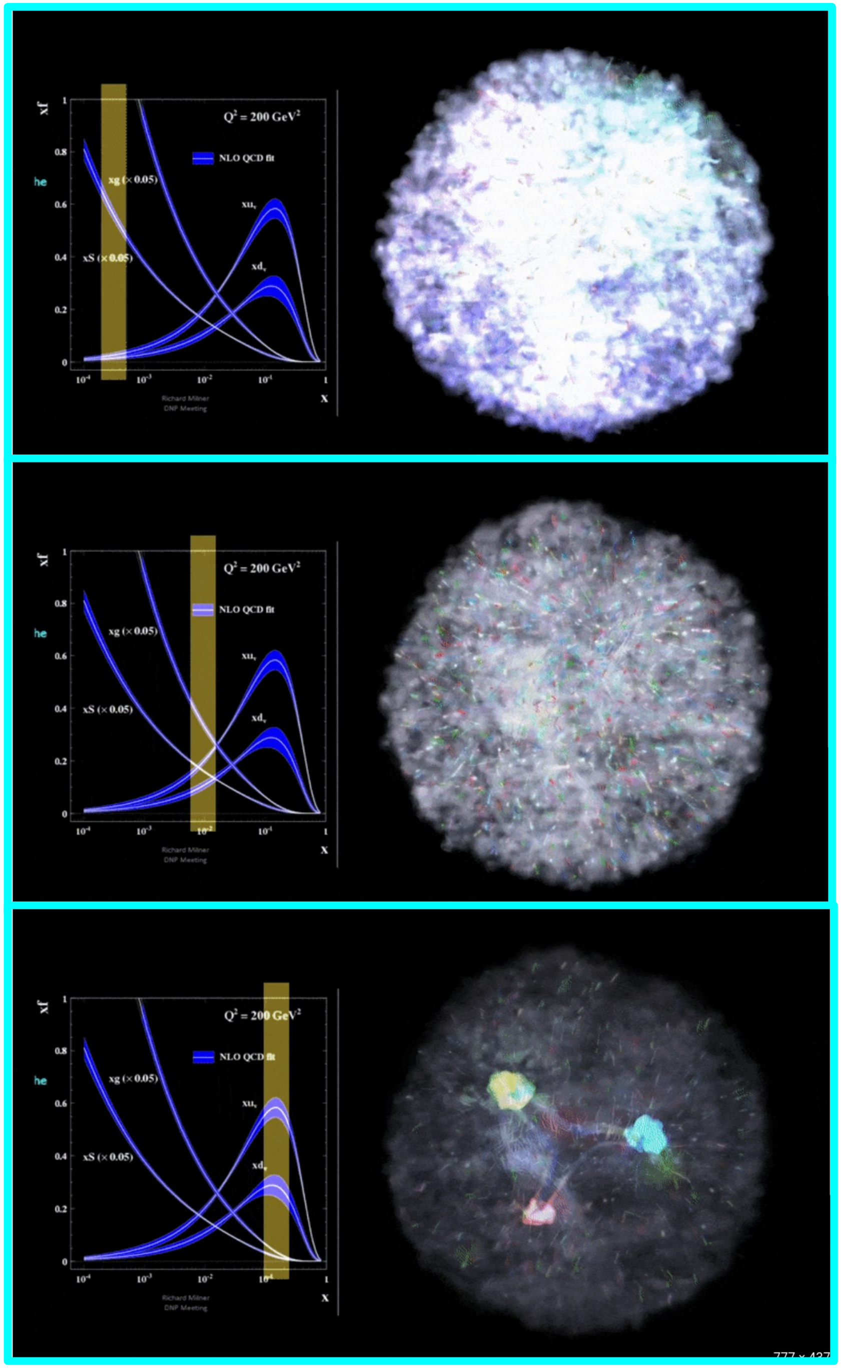
Experimental Frontier of QCD Studies

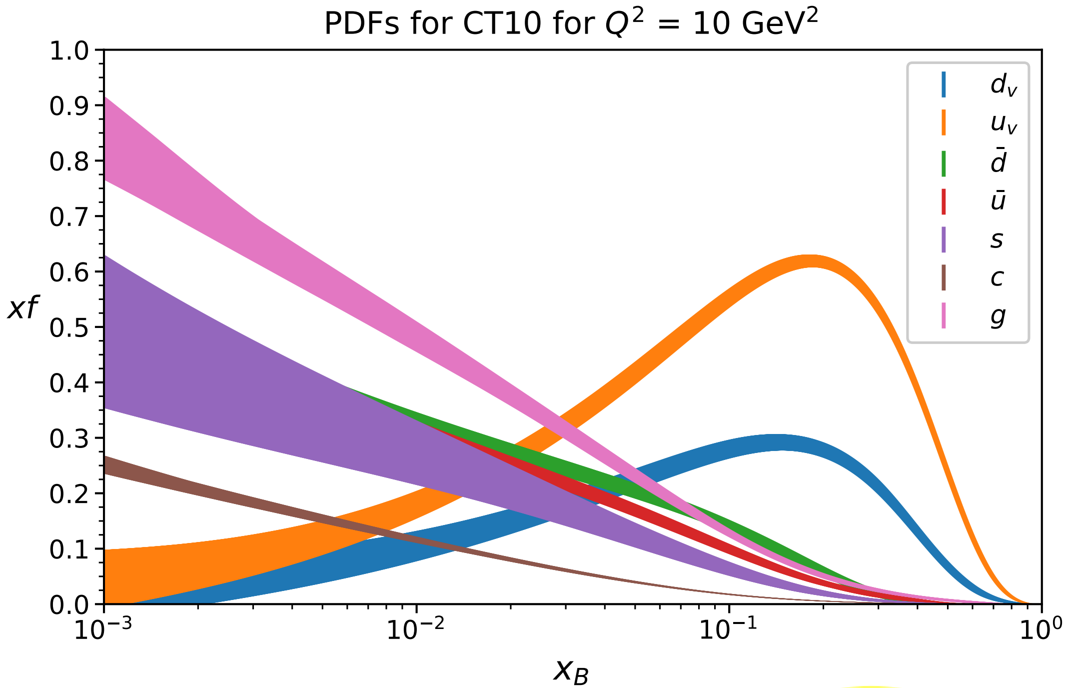
Proton's 1D structure after four decades of study

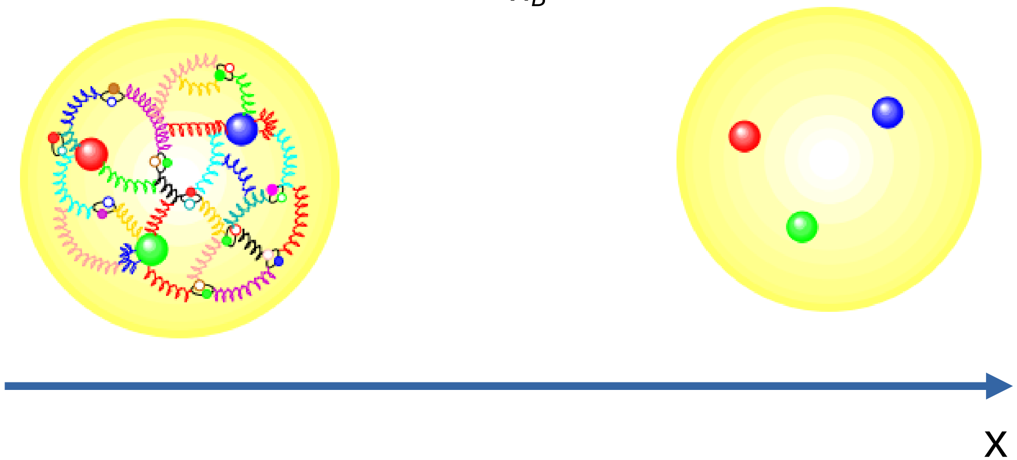




Experimental Frontier of QCD Studies







https://www.youtube.com/watch?v=Dt8FZ4ksWiY

https://arts.mit.edu/visualizing-the-proton/

Experimental Frontier of QCD Studies

- SoLID will measure small cross sections and asymmetries with high or meaningful precision:
  - Imaging the proton from 1D (PDF) to 3D or more (TMD with SIDIS, GPD with DVCS, TCS, DEMP etc.)
  - Threshold studies to probe the proton mass and gluonic field
  - High precision parity-violating electron scattering (PVES) and test of the SM
- SoLID will measure processes never measured before:
  - Deep exclusive processes – DDVCS, etc.

Experimental Frontier of QCD Studies

- SoLID will measure small cross sections and asymmetries with high or meaningful precision:
  - Imaging the proton from 1D (PDF) to 3D or more (TMD with SIDIS, GPD with DVCS, TCS, DEMP etc.)
  - Threshold studies to probe t
  - High precision parity-violatin
- SoLID will measure proces
  - Deep exclusive processes –

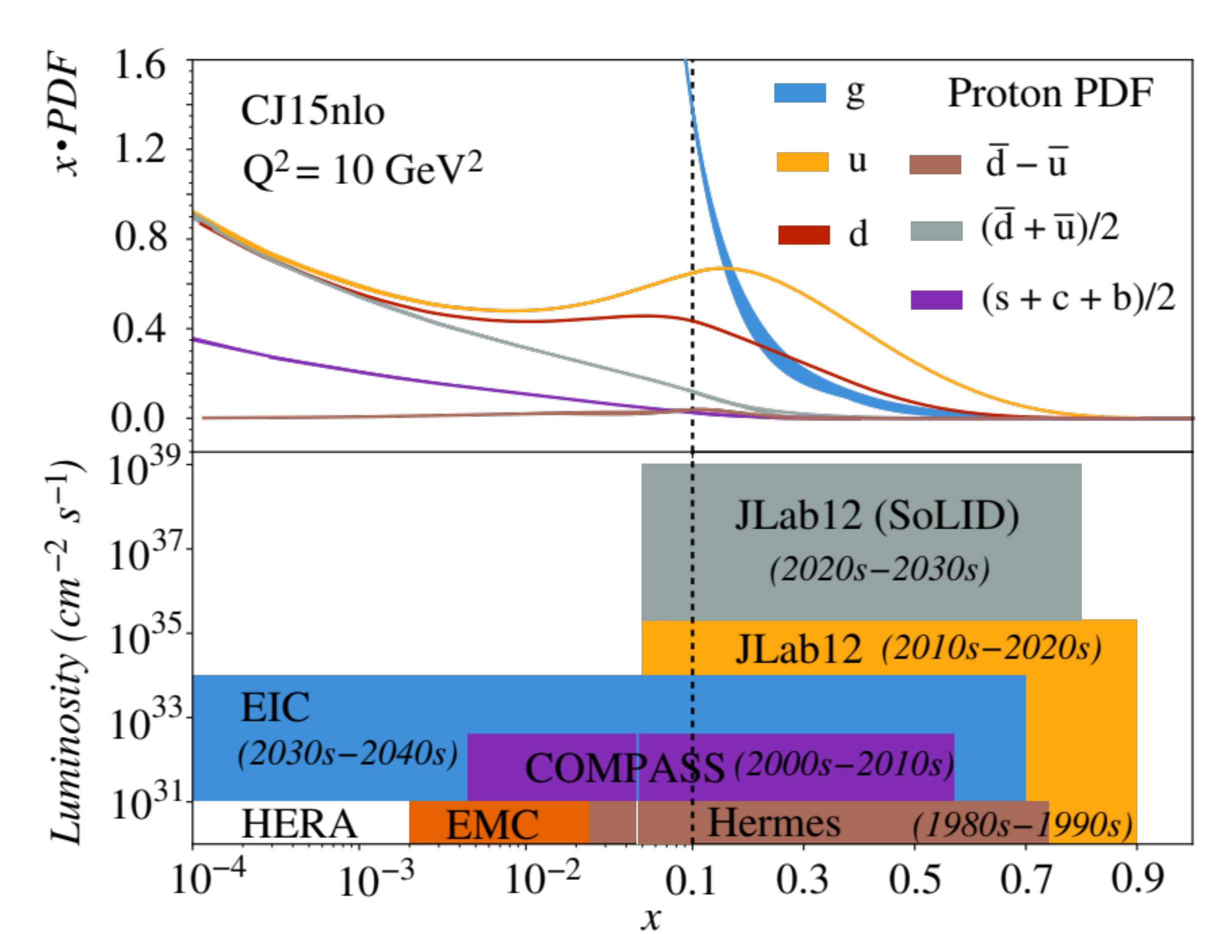


Figure from JLab12 GeV WP, J. Arrington et al., Prog. Part. Nucl. Phys. 127 (2022) 103985, adapted for SoLID 2022 white paper.

SoLID for JLab Hall A – SIDIS and TMDs

$$\vec{p}\left(e, e'\pi^{\pm}\right)X$$

$$^{3}\overrightarrow{He}\left(e, e'\pi^{\pm}\right)X$$

– hadron in final state "tags" transverse motion of quarks inside the proton/neutron

Leading Twist TMDs

: Nucleon Spin : Quark Spin

Nucleon Polarization	Quark polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 =		$h_1^{\perp}$ = − Boer-Mulder
L		g_1 = − Helicity	$h_{1L}^{\perp}$ = − Worm gear
T	$f_{1T}^{\perp}$ = − Sivers	$g_{1T}^{\perp}$ = − Worm gear	Transversity h_{1T} = − Pretzelosity $h_{1T}^{\perp}$ = −

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

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

$$\boxed{A_{UT}^{\text{Collins}}} \propto h_1 \otimes H_1^{\perp}$$

$$\boxed{A_{UT}^{\text{Pretzelosity}}} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

Collins fragmentation function from e^+e^- collisions

$$\boxed{A_{UT}^{\text{Sivers}}} \propto f_{1T}^{\perp} \otimes D_1$$

Unpolarized fragmentation function

Good momentum and angular resolutions in 4-D binning over the kinematic variables (x, z, Q^2, P_T)

Slide from H. Gao, PAC50 talk

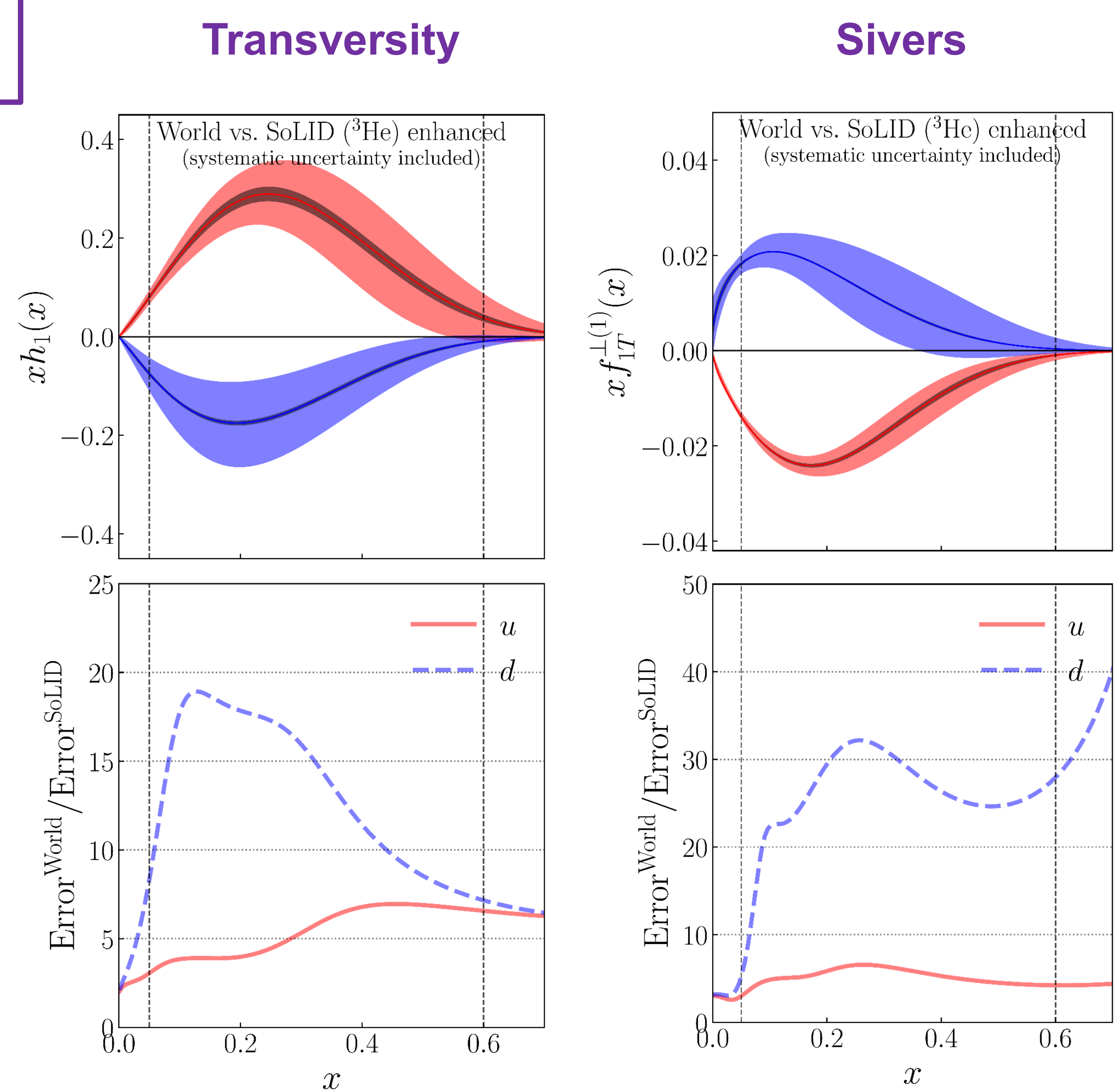
SoLID for JLab Hall A – SIDIS and TMDs

Compare SoLID ^{3}He 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 enhanced = SoLID approved by the PAC

also see
Z. Ye et al., Phys. Lett. B767 (2017) 91-98

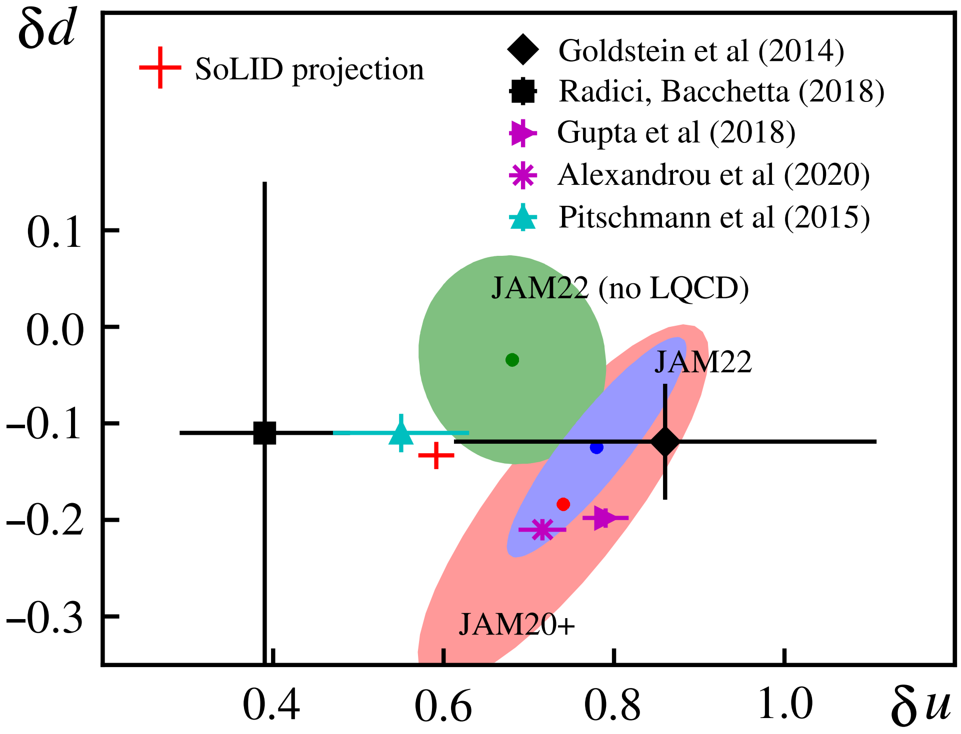


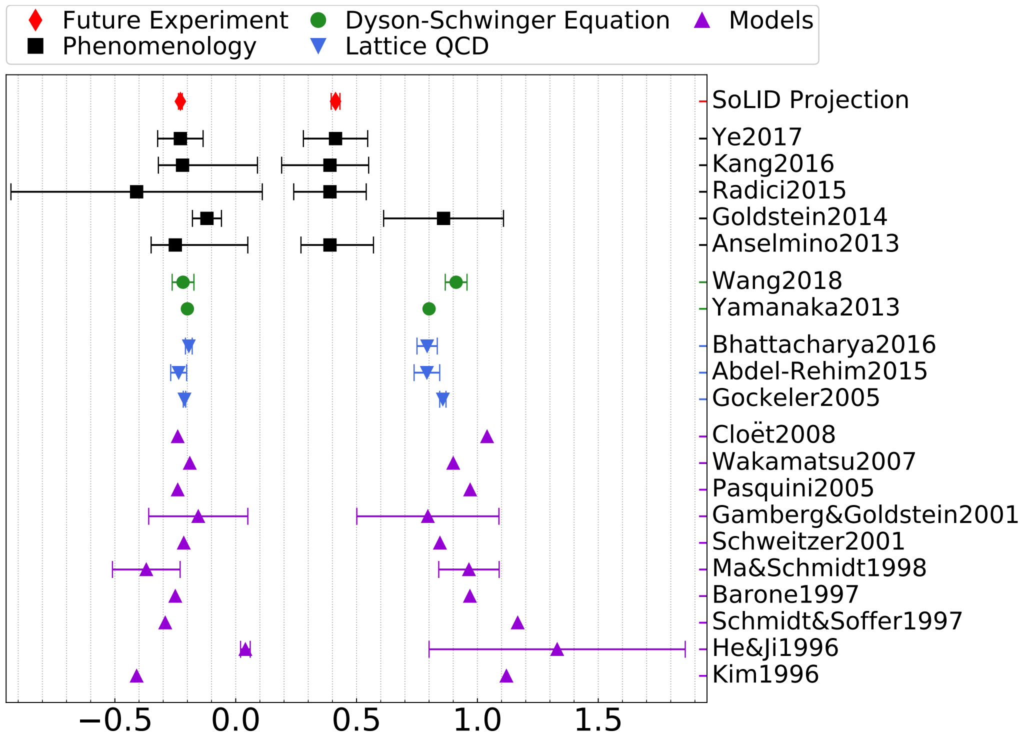
Slide from H. Gao, PAC50 talk

SoLID for JLab Hall A – SIDIS and TMDs

- Nucleon tensor charge as important as its other static properties – electric charge, mass, spin

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

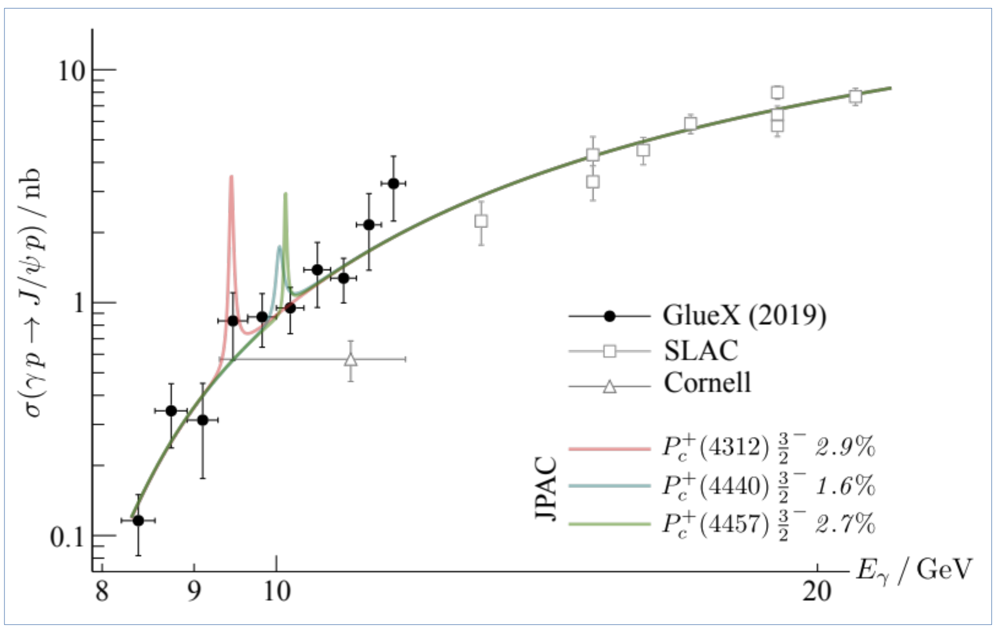


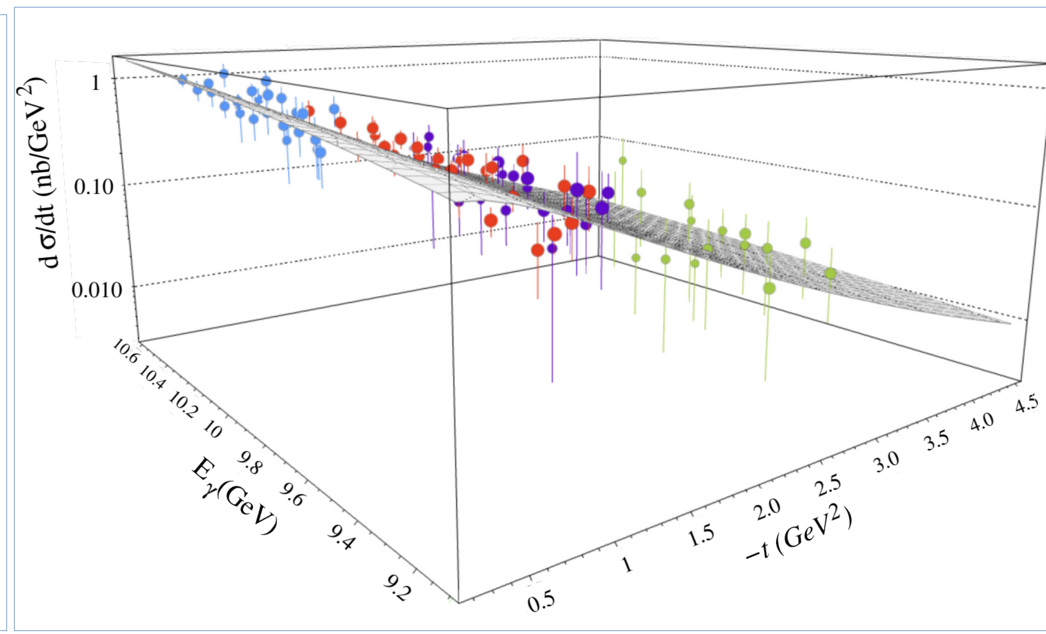


- can be compared with Lattice QCD predictions
- provide inputs to extraction of quark EDM from proton EDM measurements

SoLID for JLab Hall A – J/Psi Threshold Production

- Origin of the proton mass – a prominent topic in contemporary hadronic physics
- Quarkonium production near threshold uniquely sensitive to the non-perturbative gluonic structure of the proton
- Existing measurement by GlueX and Hall C J/psi E12-16-007, probing gluonic gravitational form factors (GFF) of the proton





GlueX: A. Ali *et al*., Phys. Rev. Lett. 123, 072001(2019)

E12-16-007 see: B. Duran et al., Nature 615, 813-816 (2023)

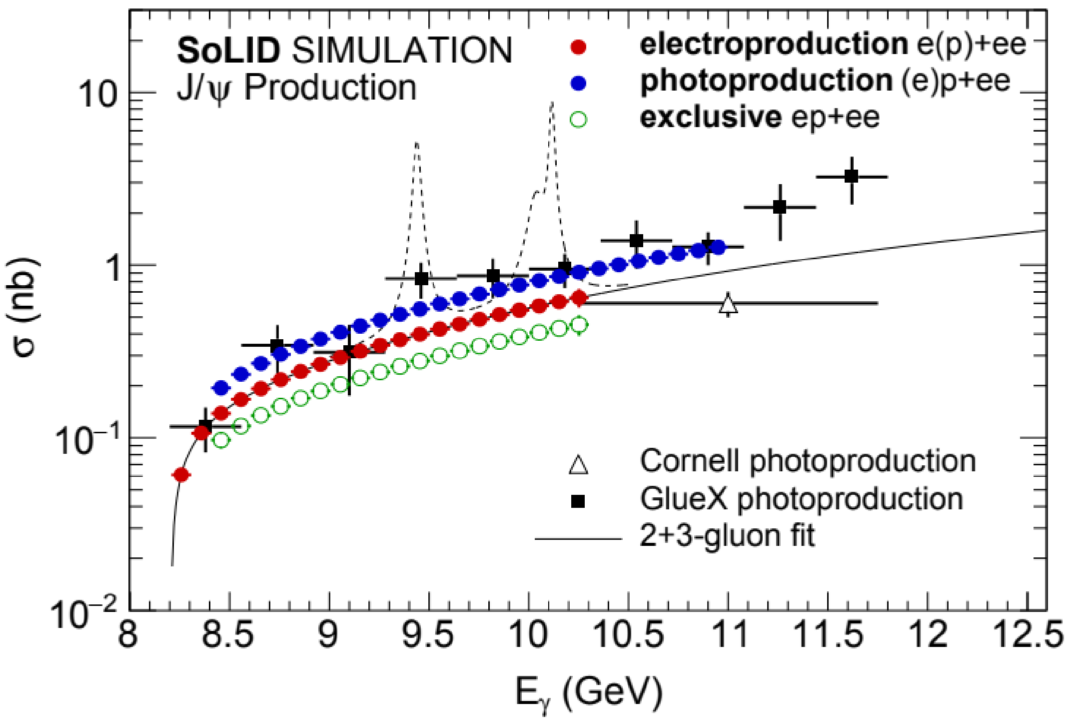
Figure provided by S. Joosten, see P. Achenbach et al., https://arxiv.org/abs/2303.02579

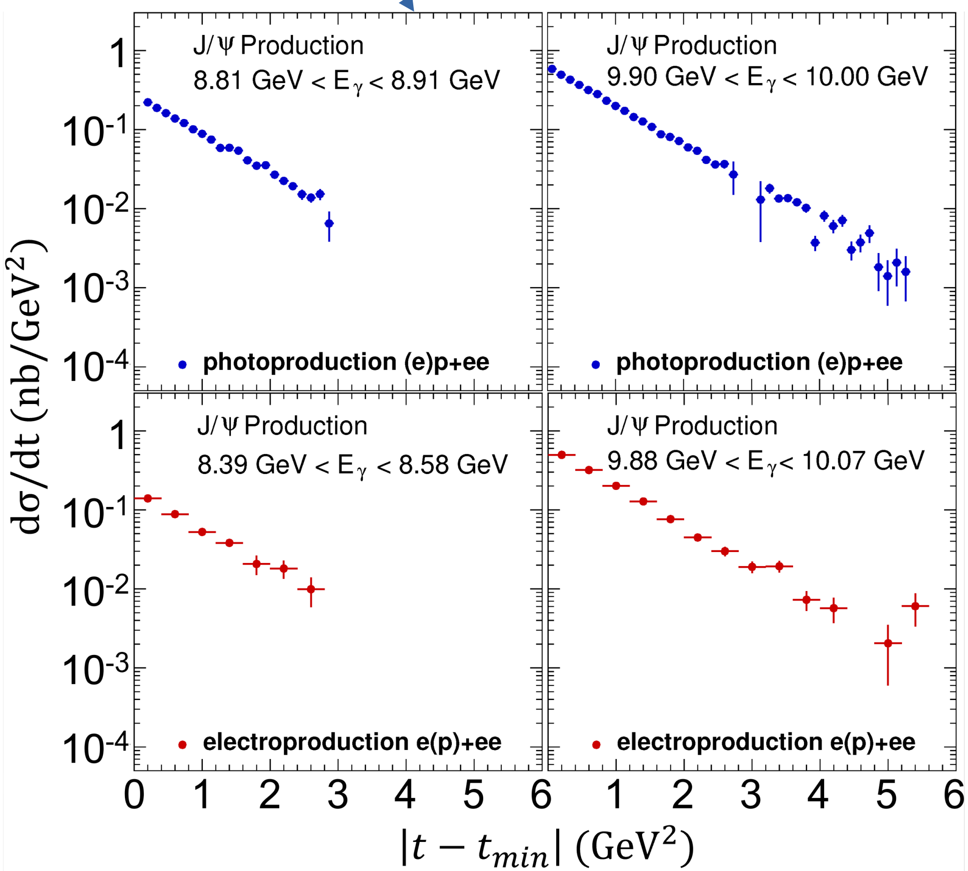
SoLID for JLab Hall A – J/Psi Threshold Production

50 (+10) days of 3uA beam on a 15-cm LH2 target

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

- SoLID allows for study of J/psi production in more than 1D;
- Each graph corresponds to one point on the left





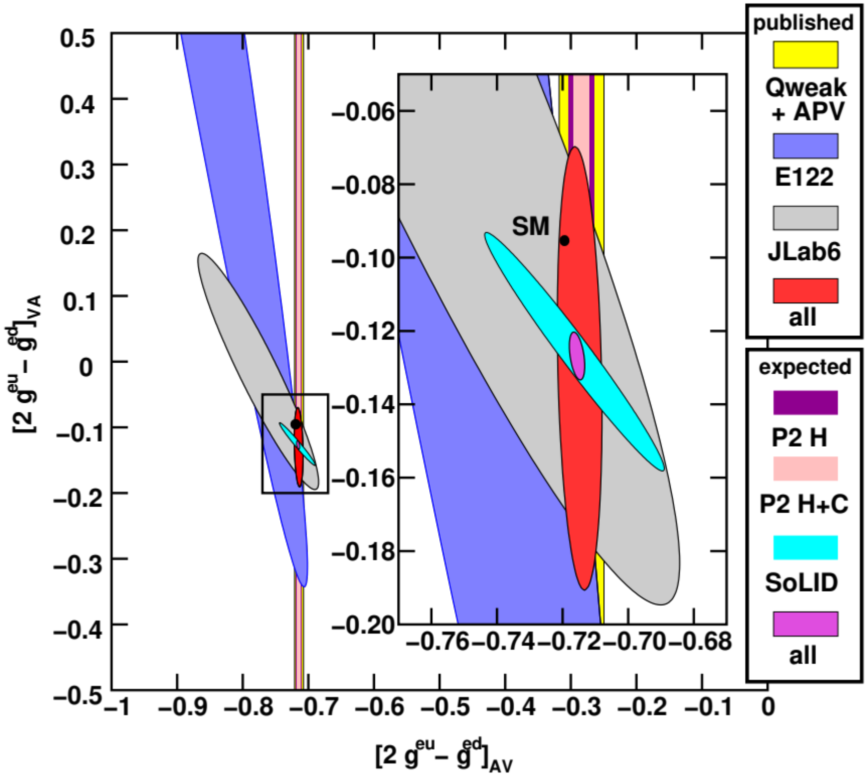
Figures from arxiv.org/abs/2209.13357

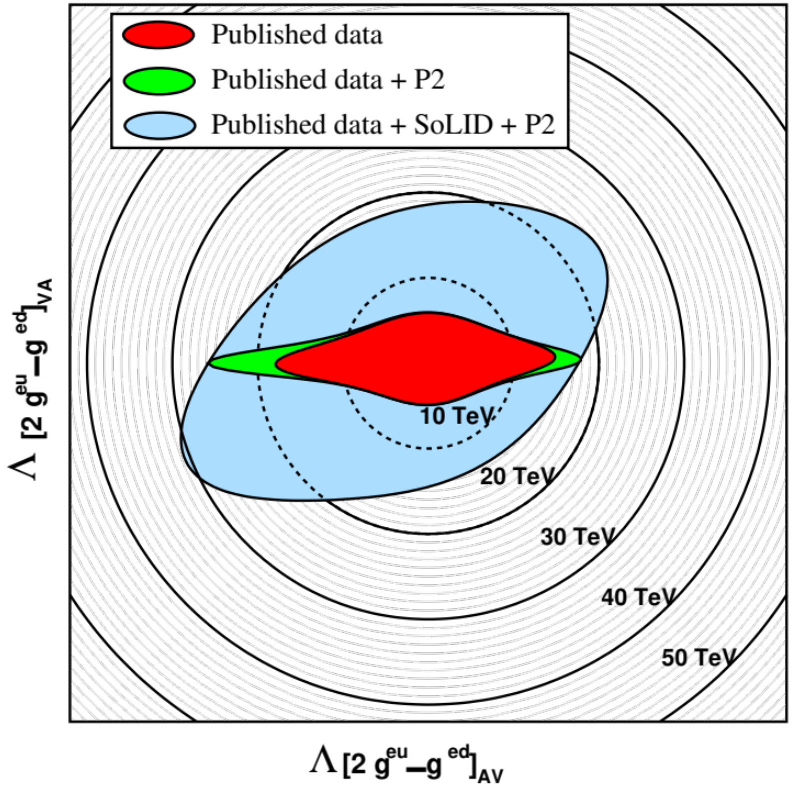
SoLID for JLab Hall A – Parity-Violating DIS

- BSM Physics has large phase space, precision measurements would point the way
- PVDIS deuteron measurement access effective electron-quark couplings

$$\mathcal{L}_{\rm NC}^{eq} = \frac{1}{2v^2}\left(\bar{e}\gamma^\mu\gamma^5 e \sum_{q=u,d} g_{AV}^{eq}\bar{q}\gamma_\mu q + \bar{e}\gamma^\mu e \sum_{q=u,d} g_{VA}^{eq}\bar{q}\gamma_\mu\gamma^5 q\right)$$

$$A_{RL,d}^{\rm DIS} \approx \frac{3}{20\pi\alpha}\frac{Q^2}{v^2}\left[(2g_{AV}^{eu}-g_{AV}^{ed}) + (2g_{VA}^{eu}-g_{VA}^{ed})\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$





$$\frac{G_F}{\sqrt{2}}g_{ij} \rightarrow \frac{G_F}{\sqrt{2}}g_{ij} + \eta_{ij}^q\frac{4\pi}{(\Lambda_{ij}^q)^2}$$

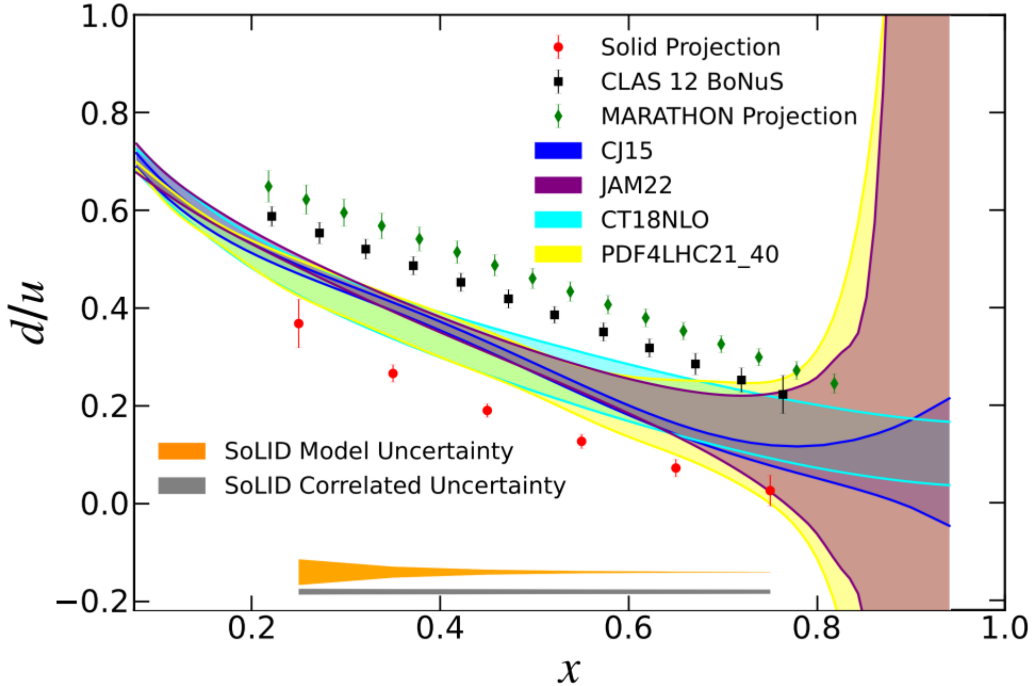
- BSM physics probed: leptophobic Z', dark Z, strong PV (https://arxiv.org/abs/2306.04704)

Slide from P. Souder, PAC50 talk

SoLID for JLab Hall A – Parity-Violating DIS

- PVDIS proton measurement access PDF d/u at high x, without the need of nuclear model

$$A_{RL,p}^{\mathrm{DIS}} \approx \frac{1}{4\pi\alpha}\frac{Q^2}{v^2}\left[\frac{12\,g_{AV}^{eu} - 6\,g_{AV}^{ed}\,d/u}{4 + d/u}\right]$$



Figures from arxiv.org/abs/2209.13357

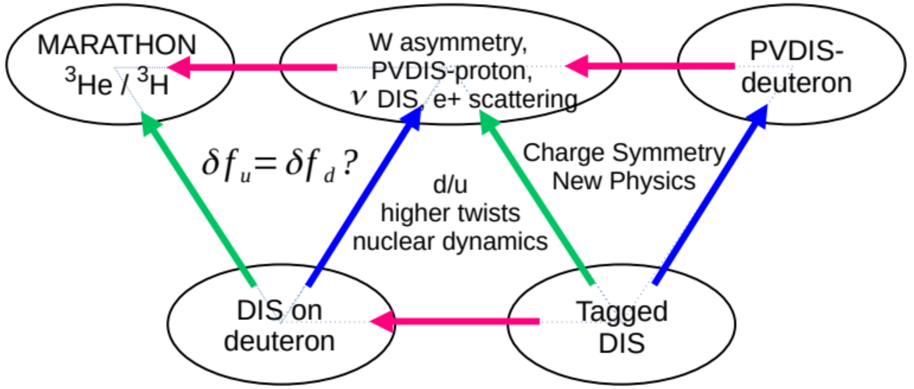
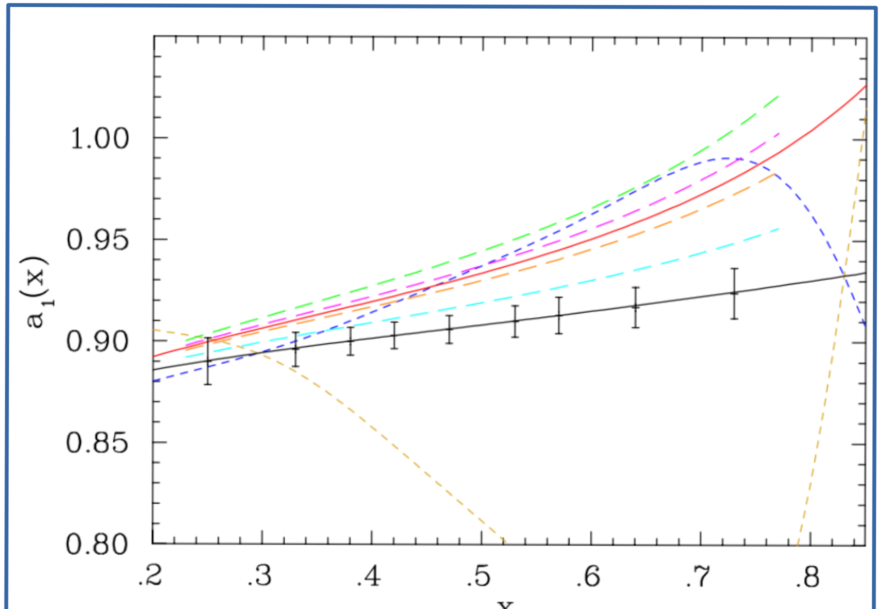


Figure from A. Accardi,
INT workshop on PVDIS at JLab 12 GeV (2022)

- PVDIS ^{48}Ca access flavor dependence of EMC effect

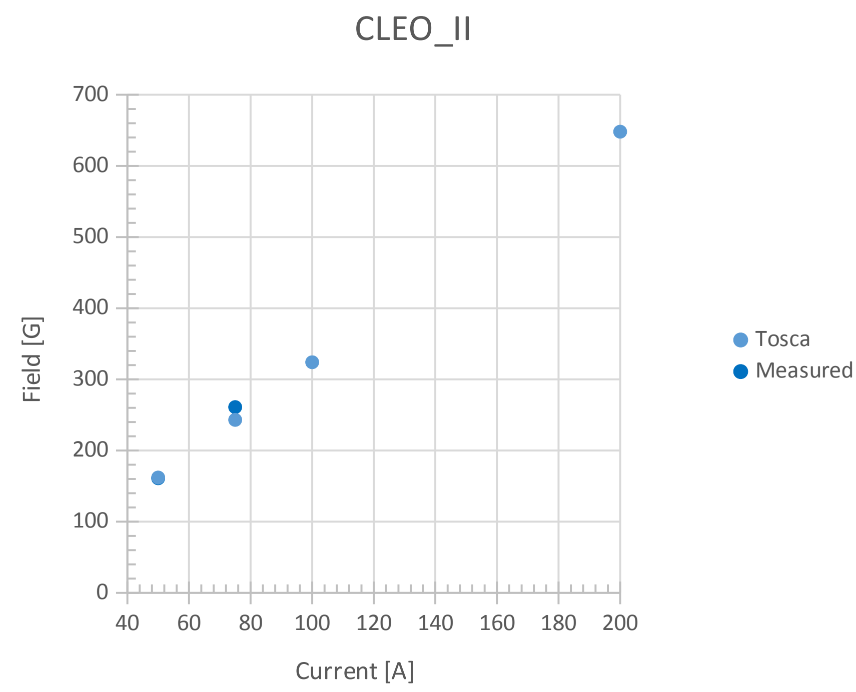
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$

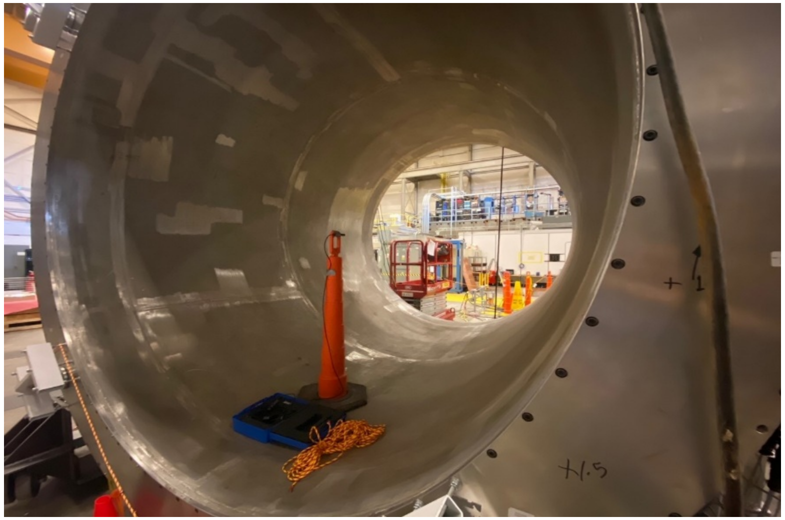


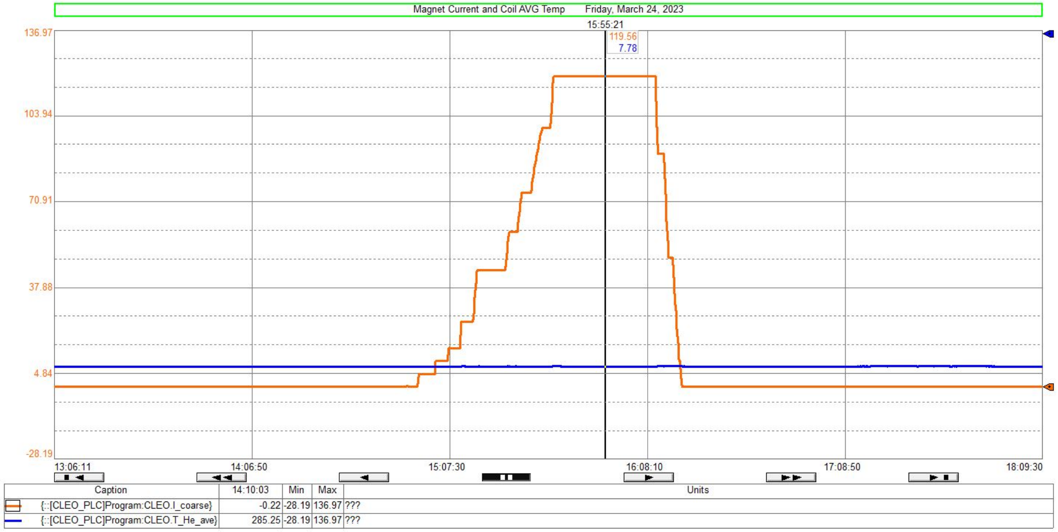
Latest – CLEO-II Magnet Cold Test at JLab

Latest – CLEO-II Magnet Cold Test at JLab

- A low current test conducted on March 24th. The current for this test was ramped up to 120A and was held for 30 mins.
- PSU output voltage ~ 1.15V during ramp up at 0.5A/s.
- No increase in coil voltages observed during ramp up or while at 120A for 30 minutes.
- Coil believed to be superconducting with flat lined nature of temp curves during test.
- A 3 axis Hall probe was installed in the bore of the magnet for each of the tests. Data matched TOSCA model well.
- Coil average temperature remained constant during test.



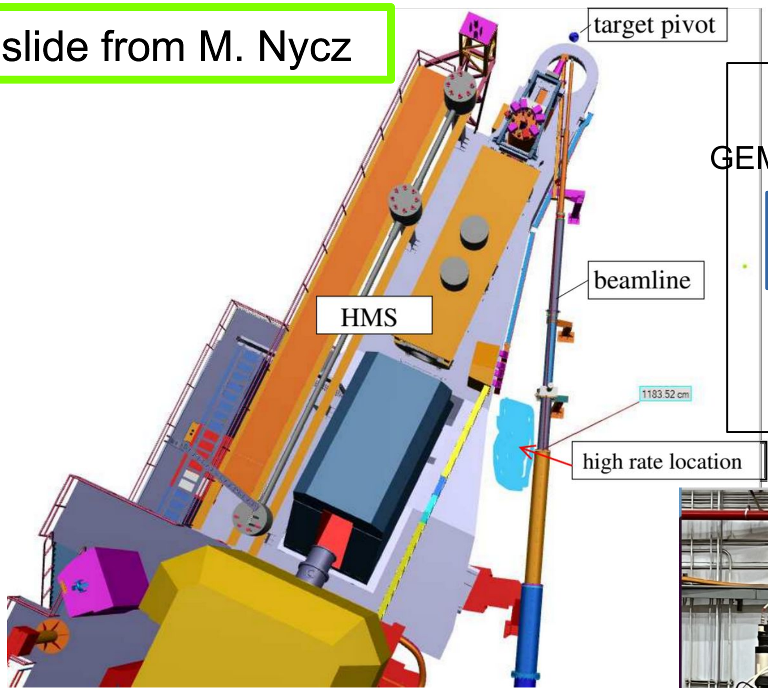


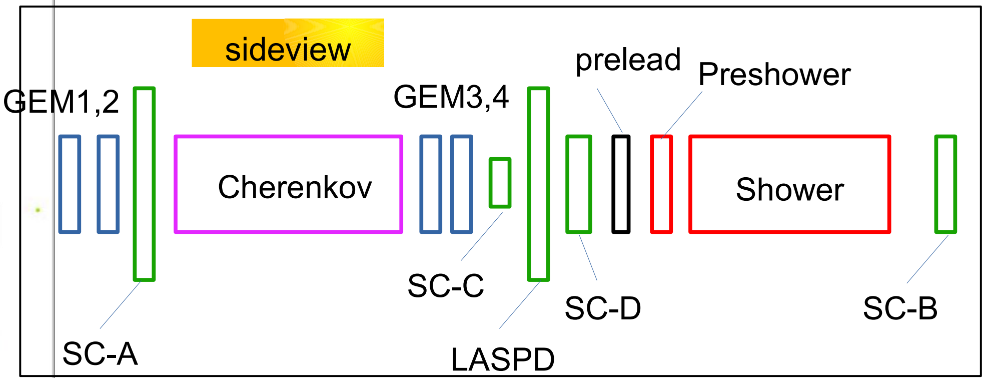


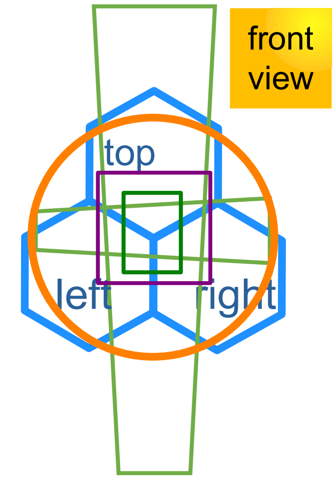
slide from W. Seay

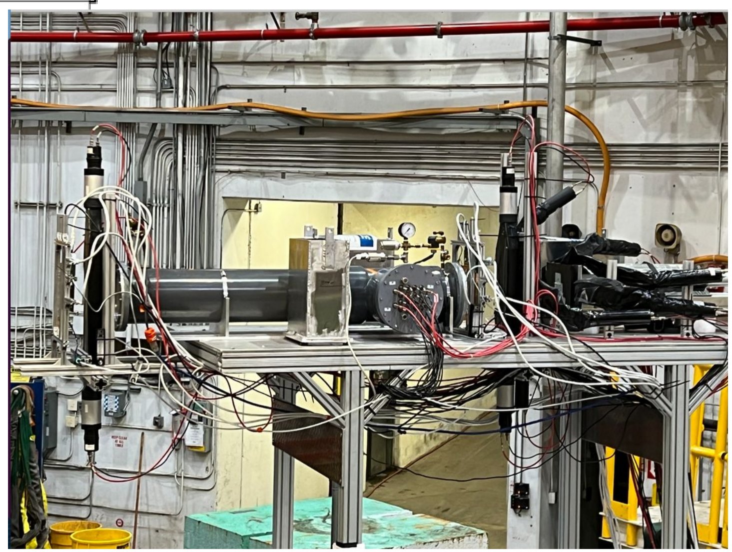
Latest pre-R&D – Detector Beam Test (2022-23 Hall C)

slide from M. Nycz









Three stages:
- June 2022: install at (L) 82°
  - X'mas 2022: cosmic
- Jan 2023: moved to (R) 7°
- Feb 2023: moved to (R) 18°

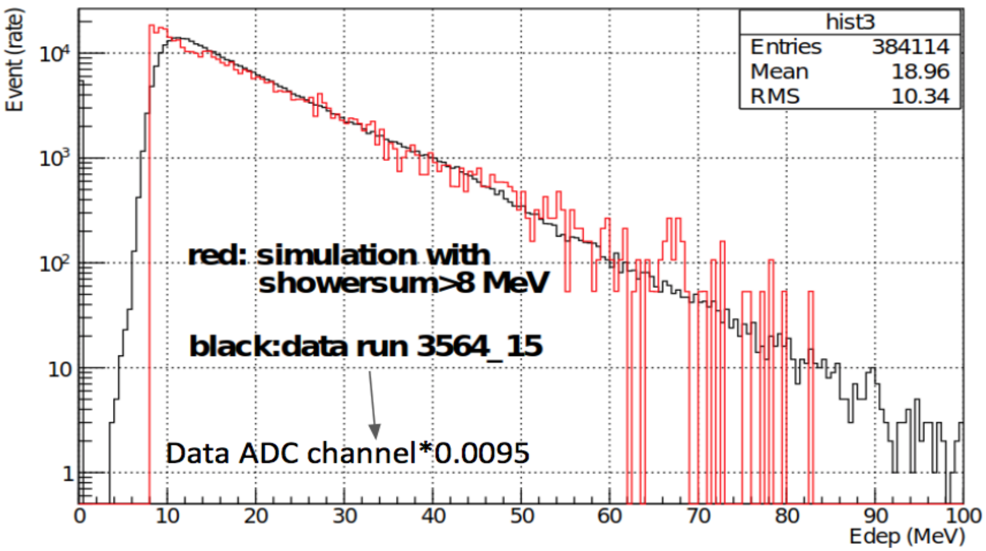
- Similar detector setup as SoLID (1/600), no magnet, ~10^2 krad
- Extensive simulation, PID study with both classical and AI/ML

Collective effort of: X. Bai, A. Camsonne, J. Caylor, C. Hedinger, T. Holmstrom, M. Nycz, C. Peng, Y. Tian, D. Upton, Z. Ye, J. Zhang, Z. Zhao, JLab DAQ group, and Hall C(A) tech/staff

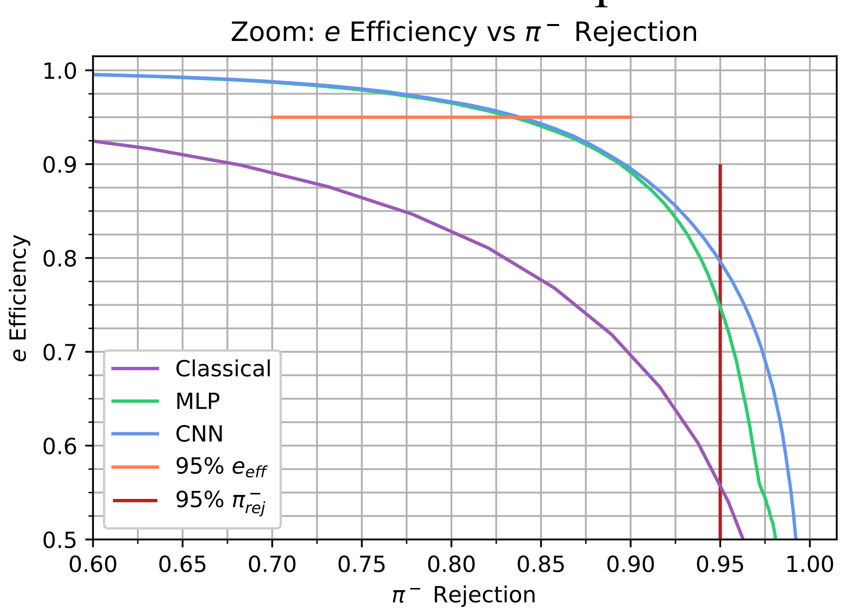
Latest pre-R&D – Detector Beam Test (2022-23 Hall C)

slide from Y. Tian & D. Upton

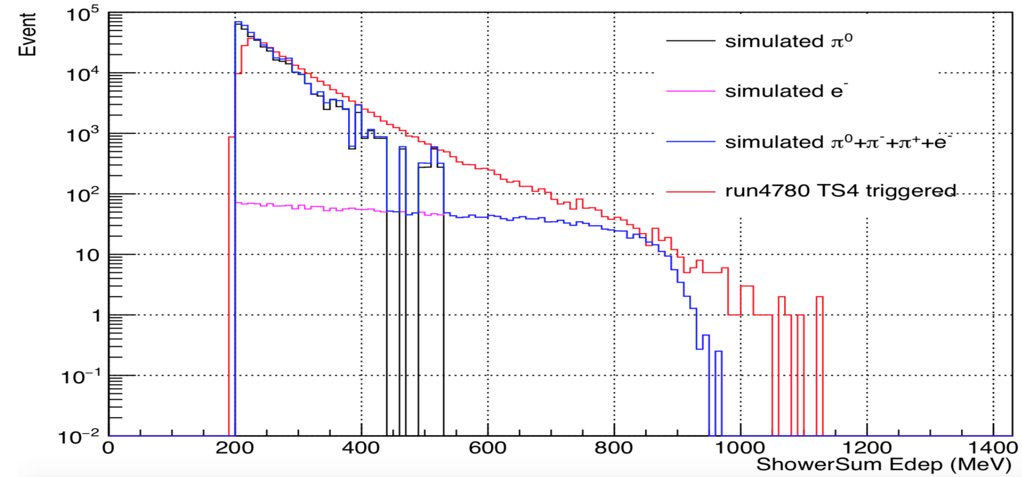
- 82 deg: Shower MIP not visible, calibrate sim/data using spectrum slope

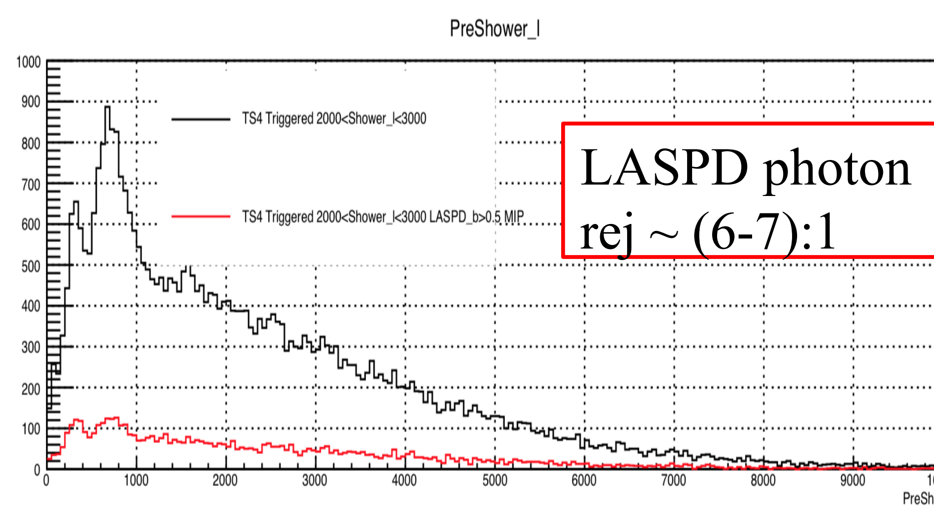


- ML vs. classical PID with “pencil sim”:



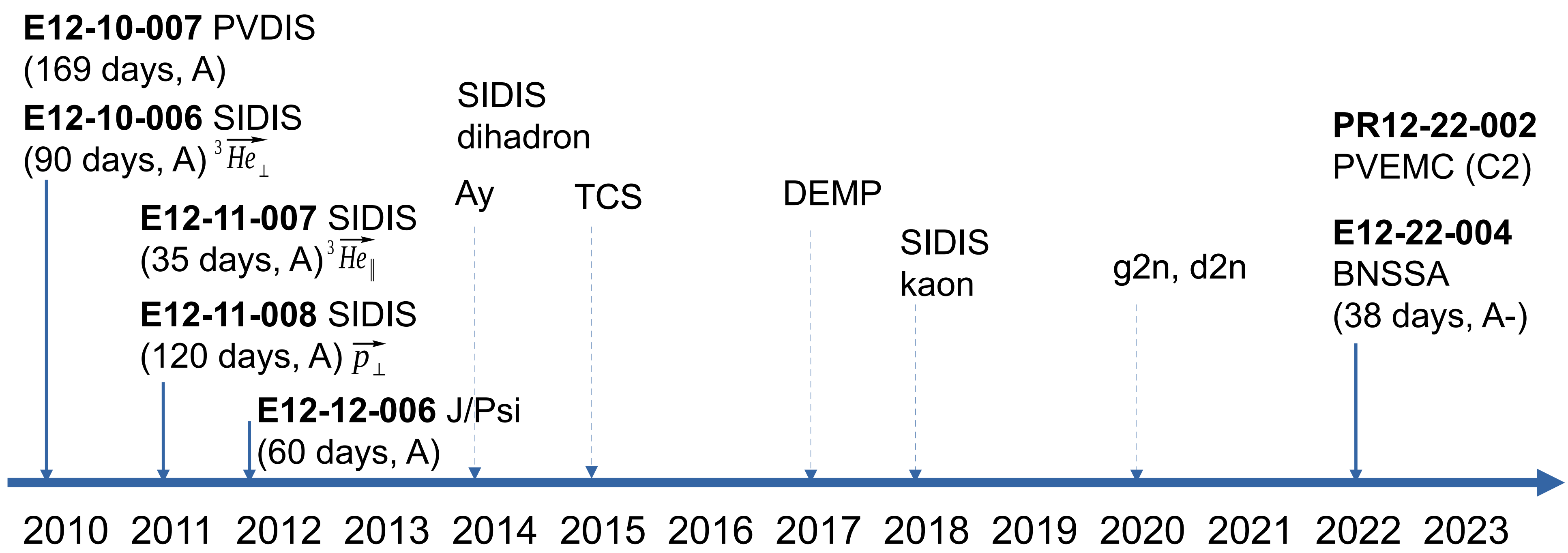
- 7 and 18 deg:
  - ✓ detectors calibrated with sim using MIP location
  - ✓ rates agree with simulation to within (10-15)%



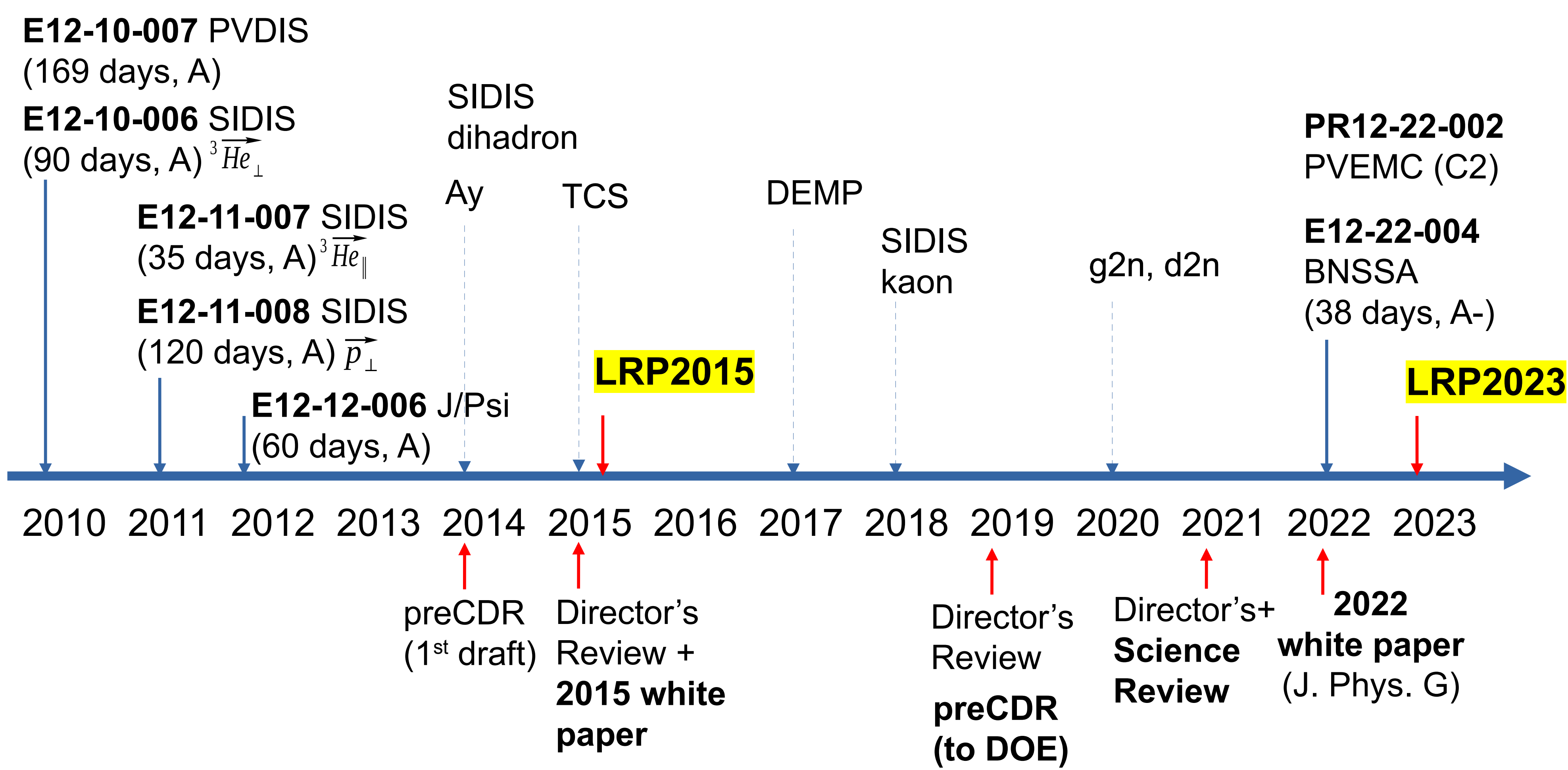


LASPD photon rej ~ (6-7):1

SoLID Timeline



SoLID Timeline



NSAC 2023 LRP Town Meetings – QCD

https://indico.mit.edu/event/538/
https://arxiv.org/abs/2303.02579

Recommendation 1: Capitalizing on past investments *(Yes: 335; No: 3; No Answer: 4)*

The highest priority for QCD research is to maintain U.S. world leadership in nuclear science for the next decade by capitalizing on past investments. Maintaining this leadership also requires recruitment and retention of a diverse and equitable workforce.

We recommend support for a healthy base theory program, full operation 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 the valuable university-based laboratories, and the scientists involved in all 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 Solenoidal Large Intensity Device (SoLID).
- The RHIC facility revolutionized our understanding of QCD, as well as the spin structure of the nucleon. To successfully conclude the RHIC science mission, it is essential to complete the sPHENIX science program as highlighted in the 2015 LRP, the concurrent STAR data taking with forward upgrade, and the full data analysis from all RHIC experiments.
- The LHC facility maintains leadership in the (heavy ion) energy frontier and hosts a program of using heavy-ion collisions to probe QCD at the highest temperature and/or energy scales. We recommend the support of continued U.S. leadership across the heavy ion LHC program.
- Theoretical nuclear physics is essential for establishing new scientific directions, and meeting the challenges and realizing the full scientific potential of current and future experiments. We recommend increased investment in the base program and expansion of topical programs in nuclear theory.

Hot & Cold QCD 2022 Town Hall Meeting

NSAC 2023 LRP Town Meetings – FSNN

https://indico.phy.ornl.gov/event/209/

2) **We recommend increased investments in targeted initiatives with unique sensitivity to violation of time reversal invariance, interactions beyond the Standard Model, and the neutrino masses.**

We highlight the most compelling scientific opportunities:

a. The expeditious **completion** of high-impact experimental campaigns, including the nEDM@SNS, the world's most ambitious search for the neutron electric dipole moment (EDM); and MOLLER@JLab, planning the most precise low energy measurement of a purely leptonic weak neutral current interaction

b. Realizing the full potential of the existing experimental program to address recent questions surrounding CKM unitarity, substantially improve constraints on CP violation, and extend the precision frontier's capability to discover BSM physics.

c. Support of R&D efforts targeting emerging opportunities with demonstrated scientific cases. These include the next generation measurements of the absolute neutrino mass (Project 8), lepton flavor universality in the weak interactions (PIONEER), search for new neutral current interactions (SoLID), as well as EDM searches enabled by FRIB.

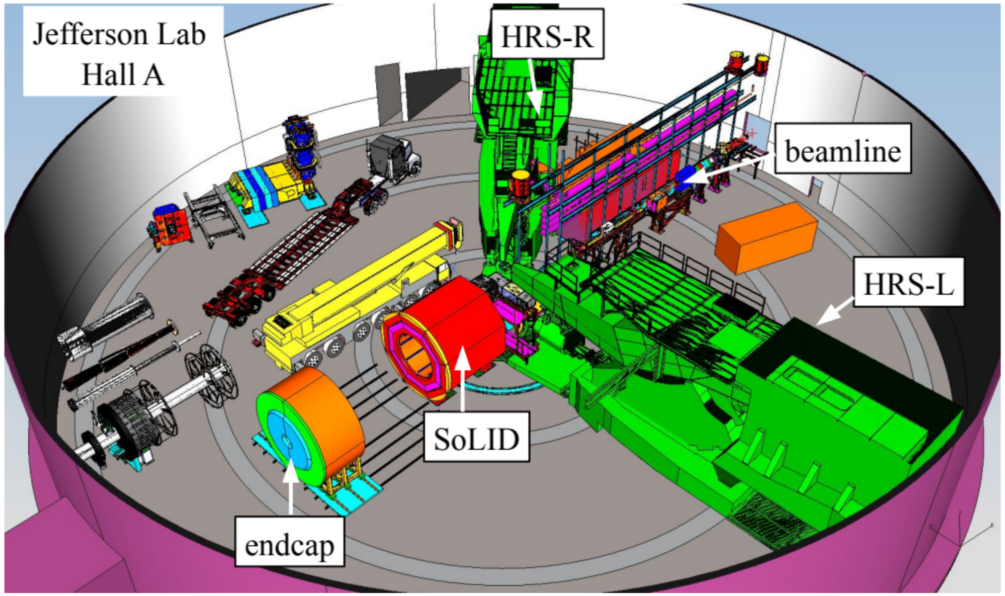
Summary and Outlook

- SoLID will fully capitalize on the 12 GeV CEBAF at the intensity frontier, allowing precision studies of a number of modern topics central to hadronic physics and test of the SM:
  - *SIDIS, J/psi, PVDIS, TCS, DEMP (DVCS, DDVCS, CLFV … …)*
  - *complementary to existing facilities and the EIC*
- The SoLID collaboration, currently consists of 240 collaborators from 69 countries, worked tirelessly on the physics program and conceptual design since the early 2010's.
- SoLID is of high priority:
  - *successful first magnet cold test at JLab*
  - *DOE-funded pre-R&D activities on Cherenkov, GEM readout, and detector beam tests recently completed or well underway*
  - Timely realization of SoLID is essential for the US nuclear science program

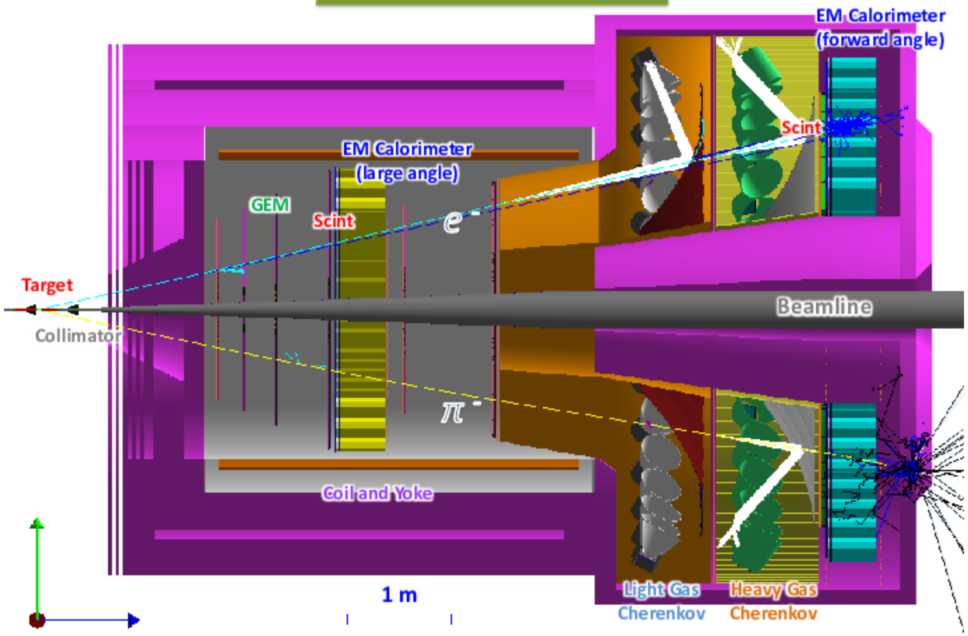
Back up Slides

Outline

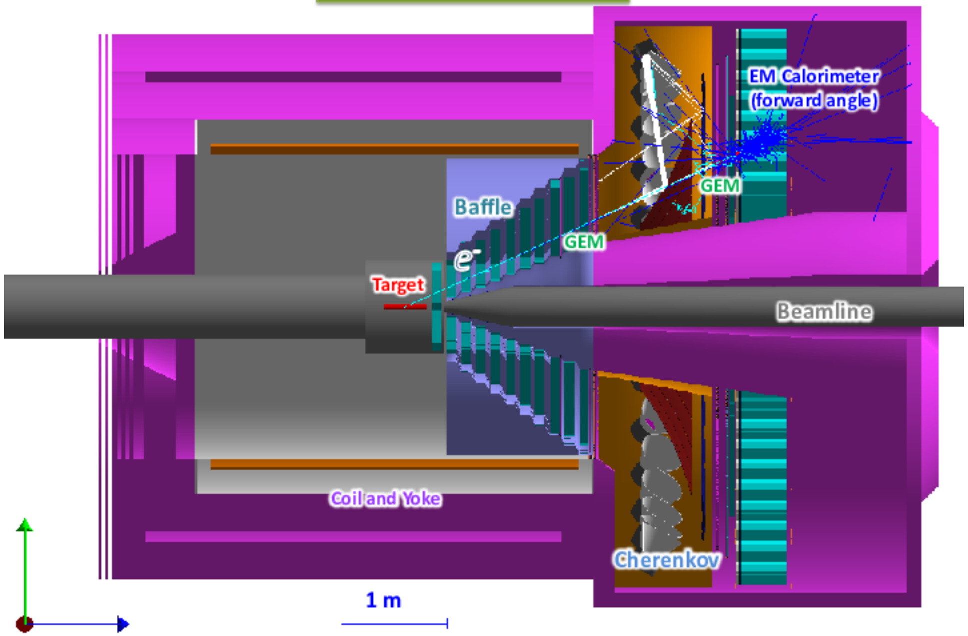
1. Motivation – Why SoLID ?
2. The Physics Program of SoL
3. Current Status and Outlook



SoLID (SIDIS and J/ψ)



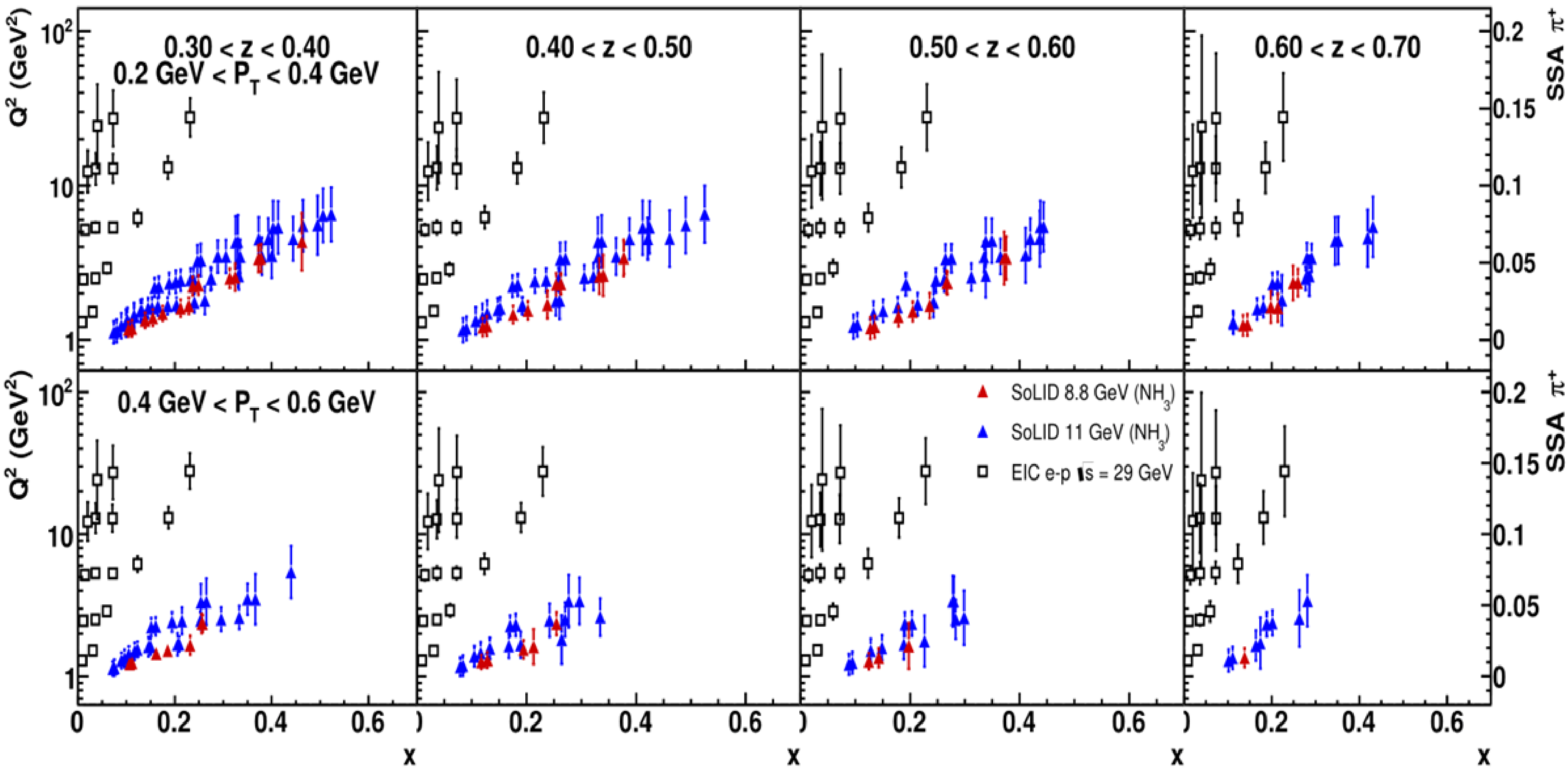
SoLID (PVDIS)



SoLID for JLab Hall A – SIDIS and TMDs

Example: E12-10-006 (SIDIS on Transversely Polarized 3He)

- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV beam energies
- Projections at EIC kinematics for the same observable at 29 GeV CM energy
- SoLID and EIC synergistic towards each other, by covering different x and Q^2 ranges



Slide provided by V. Khachatryan, PAC50 talk