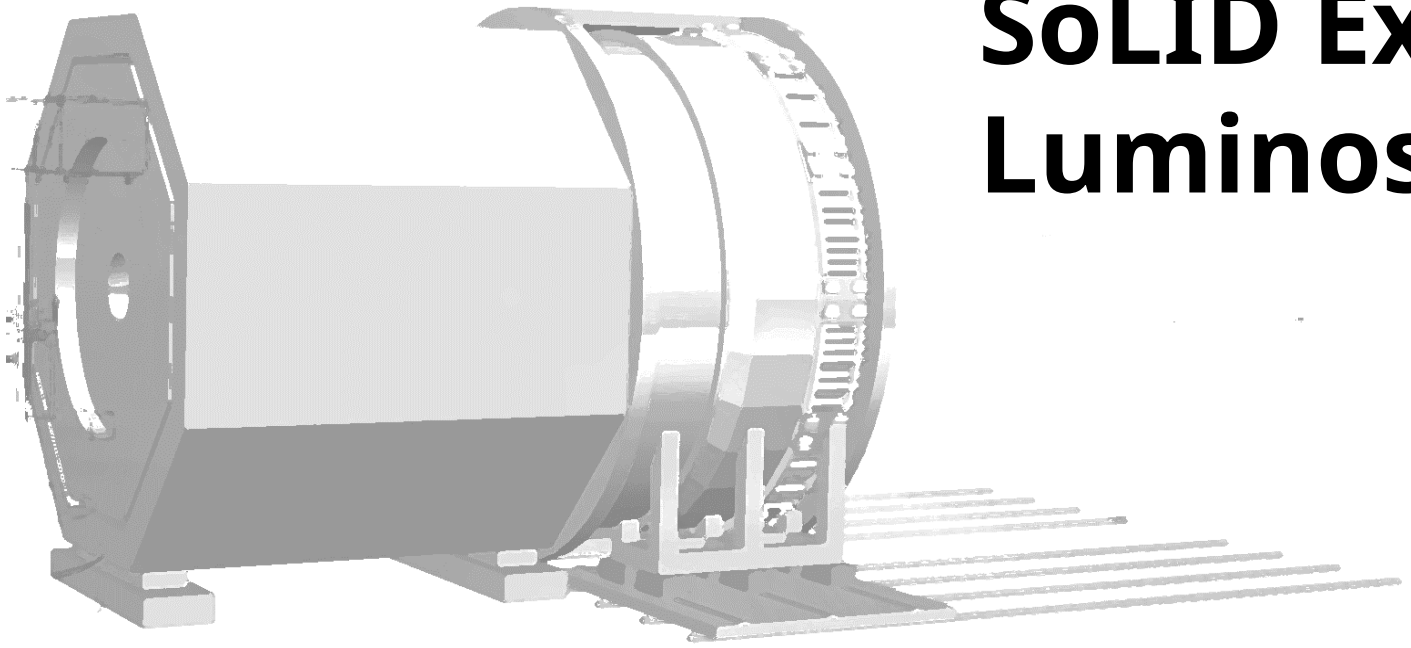


SoLID Experiments at the Luminosity Frontier

Chao Peng (Argonne National Laboratory)

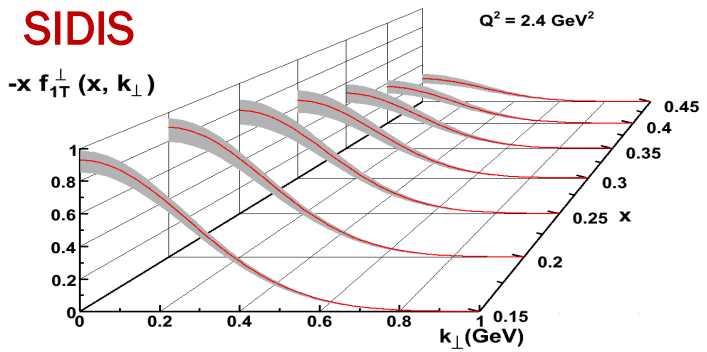
For SoLID Collaboration

07/15/2024

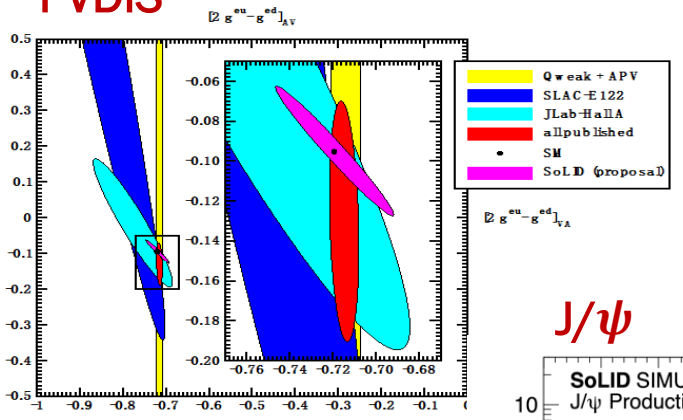
Solenoidal Large Intensity Device (SoLID)

- Maximize scientific outcome of Jefferson Lab 12 GeV upgrade
  - QCD Intensity frontier (high luminosity $10^{37\text{-}39}/cm^2/s$)
  - Large detector acceptance with full azimuthal coverage
- Rich physics programs
  - Precision test of SM and search of new physics
  - 3D momentum imaging of nucleon spin
  - Precision J/ψ production near the threshold
- Complementary and synergistic with the EIC science
  - Proton spin and mass
    - **Spin:** valence quark tomography in momentum space
    - **Mass:** precision J/ψ production near threshold

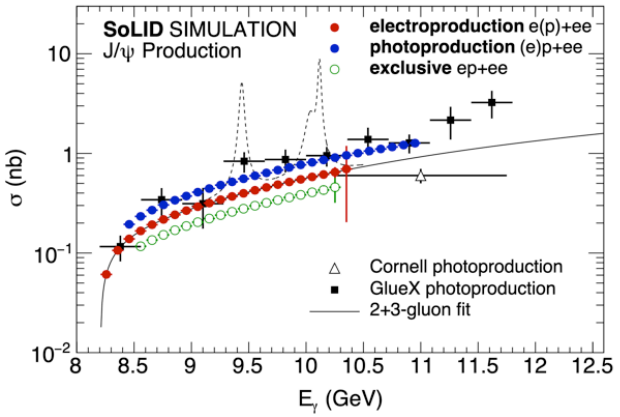
SIDIS



PVDIS



J/ψ



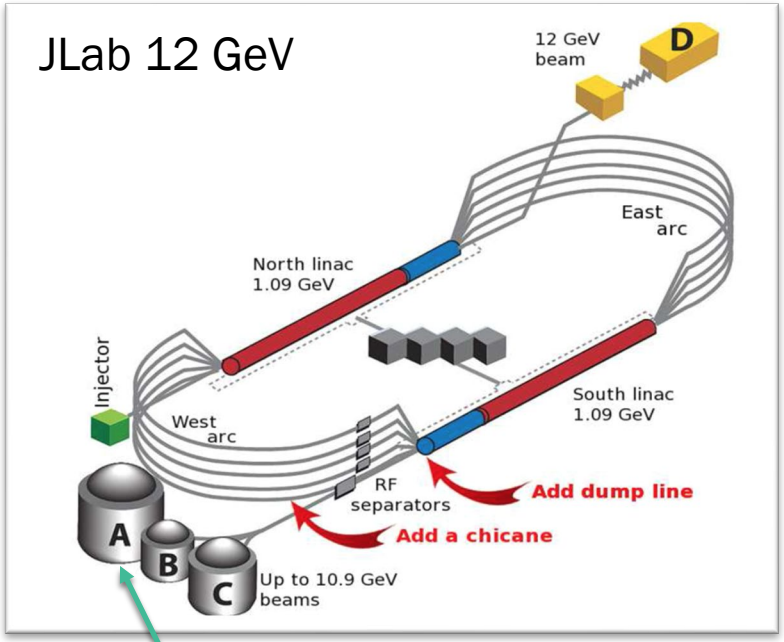
Progresses Since the First Approvals of SoLID Experiments

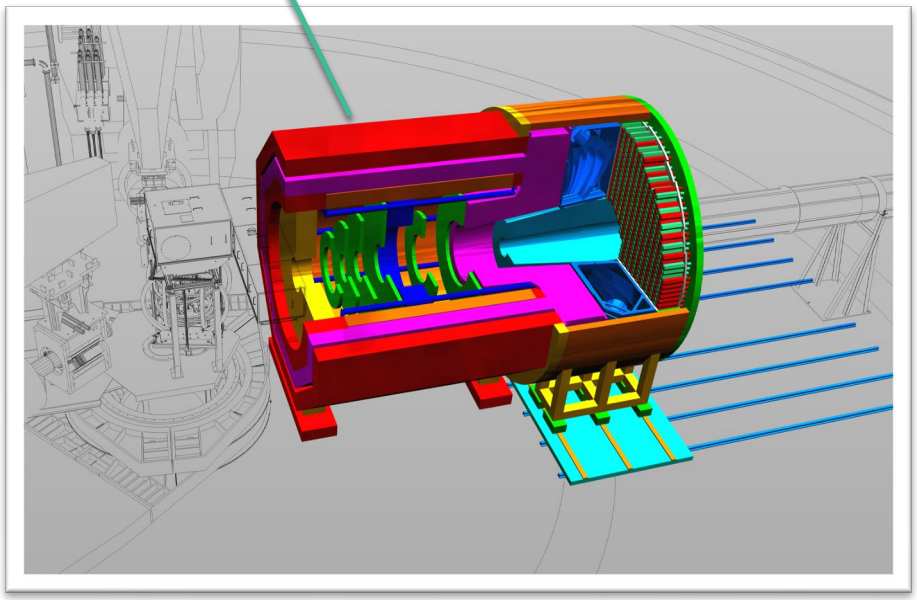
- 2010-2012: Five SoLID experiments approved by JLab PAC with high rating
  - 3 SIDIS, 1 PVDIS, 1 threshold J/ψ
- 2014: pCDR submitted to JLab with cost estimation, updated in 2017, 2019
- Director's Reviews in 2015, 2019 and 2021
- 02/2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE

  DOE funded Pre-R&D started and mostly completed
- 03/2021: SoLID Science Review
- 10/2023: "Opportunities to Advance Discovery" in Recommendation 4 of "A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science"
- 02/2024: NSAC review of major facilities and projects: SoLID included, readiness A
- Continuous efforts in the development of SoLID
  - Pre-conceptual design and pre-R&D with the support of JLab and DOE
  - More SoLID experiments are approved or in development
- Working with JLab on cost-sharing plan to reduce the project cost
  - Physics delivery expected in ~2030

SoLID Detector

- Will be housed at Hall A, TJNAF (Jefferson Lab)
- Two configurations: SIDIS-J/ψ and PVDIS
- Challenges posed by the physics program
  - High luminosity: high data rate, high background, high radiation
  - Low systematics
  - Large scale and large solid angle acceptance
- Modern technologies
  - GEMs
  - Shashlik ECal
  - High performance Cherenkov Detectors
  - Baffles
  - Pipeline DAQ and advanced computing





SoLID Physics Program

- PVDIS
  - E12-10-007: Parity Violating Asymmetry in DIS with LH_2 and LD_2 (169 days)
  - E12-22-004 Beam Normal Single Spin Asymmetry in DIS with LH_2 (38 days)
  - PR12-22-002 Flavor Dependence of Nuclear PDF Modification Using PVDIS with ^{48}Ca (C2 approved)
- SIDIS
  - E12-10-006: Single Spin Asymmetry in SIDIS on Transversely Polarized ^3He (90 days)
  - E12-11-007: Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized ^3He (35 days)
  - E12-11-108: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)
  - Run groups: Dihadron (E12-10-006A), Ay (E12-11-108A/E12-10-006A), Kaon Production (E12-11-108B/E12-10-006D), g2n (E12-11-007A/E12-10-006E)
- J/ψ near-threshold production
  - E12-12-006: Near Threshold Electroproduction of J/ψ at 11 GeV (60 days)
  - Run group: Time-Like Compton Scattering (E12-12-006A)
- GPD program and other physics
  - Run group: Deep Exclusive pion production with polarized ^3He target and SIDIS configuration (E12-10-006B)
  - Under development: DDVCS on proton, DVMP

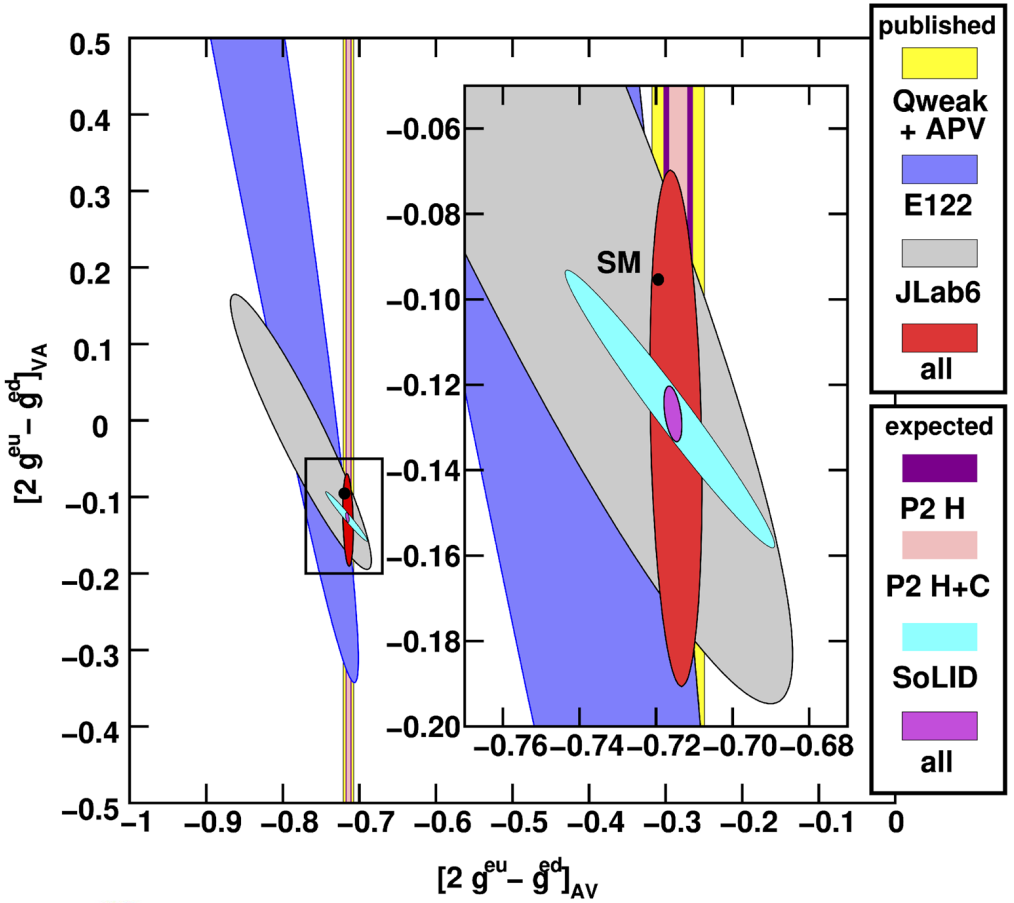
SoLID White Paper

The Solenoidal Large Intensity Device (SoLID) for JLab 12 GeV

J. Phys. G: Nucl. Part. Phys. **50** 110501 (2023)

PVDIS Experiment

- Deuteron Target
  - Measure electroweak parameters
  - Search for BSM physics
  - Search for CSV at the quark level
  - Search for quark-quark higher twist effects
- Proton Target
  - Help determine d/u PDF's
  - Insight into nuclear effects at high x



$$A_{PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r}$$

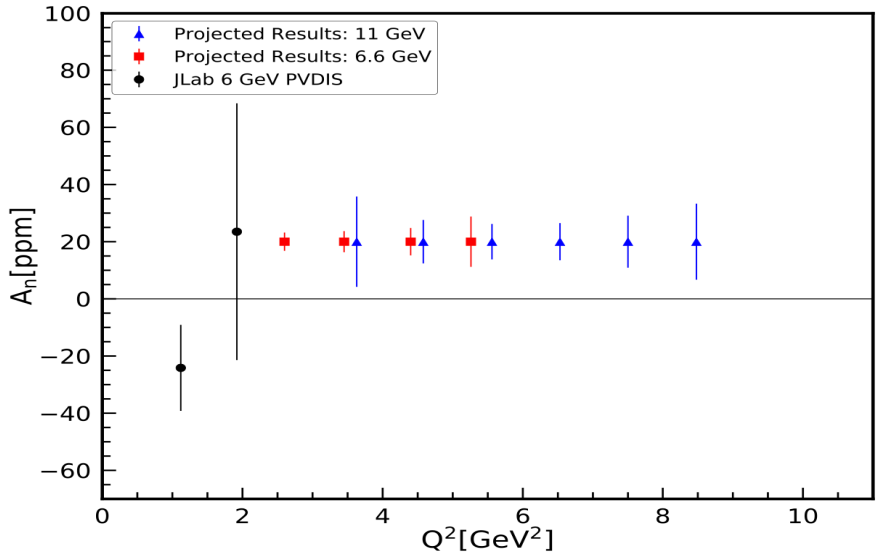
$$\approx \frac{\mathcal{M}^l_{weak,BSM} - \mathcal{M}^r_{weak,BSM}}{\mathcal{M}_{EM}}$$

$$\propto \frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$

$$\sigma = \left| \; + \; + \; \right|^2$$

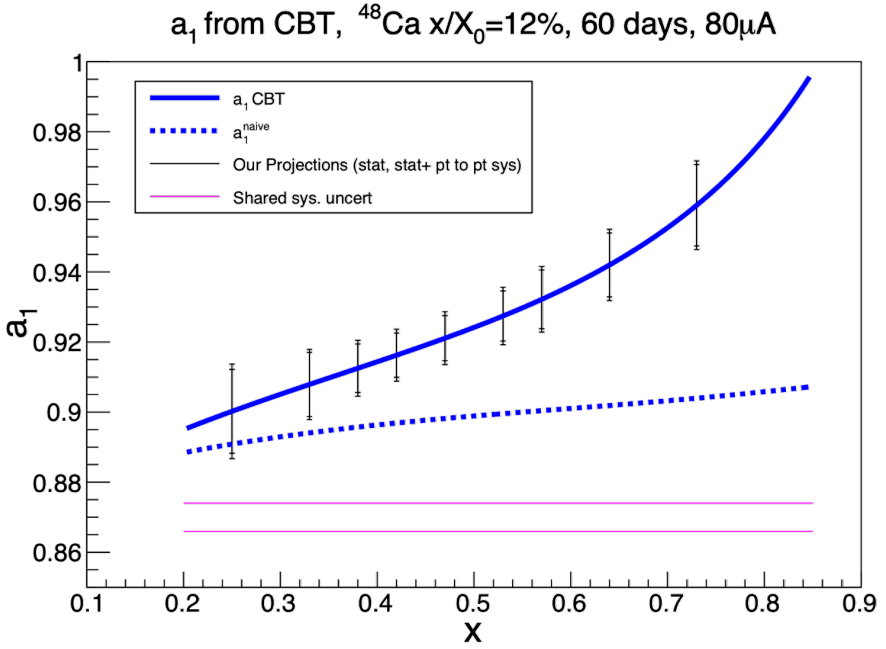
BNSSA and PVEMC Experiments

- Beam Normal Single Spin Asymmetry
  - Approved proposal
  - Investigate the effect of two-photon exchange in DIS
  - Q2 dependence of the asymmetry



- Flavor Dependent EMC effect
  - Conditionally approved proposal
  - Measure PVDIS on ^{48}Ca
  - A_{pv} directly sensitive to flavor dependence of EMC

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



7

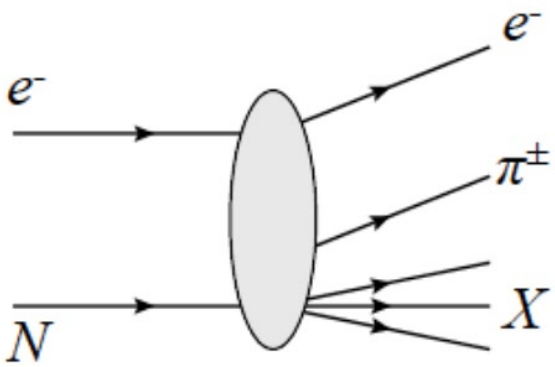
SIDIS Experiments

E12-10-006: Single Spin Asymmetry in SIDIS on Transversely Polarized ^{3}He (90 days)

E12-11-007: Single and Double Spin Asymmetries in SIDIS on Longitudinally Polarized ^{3}He (35 days)

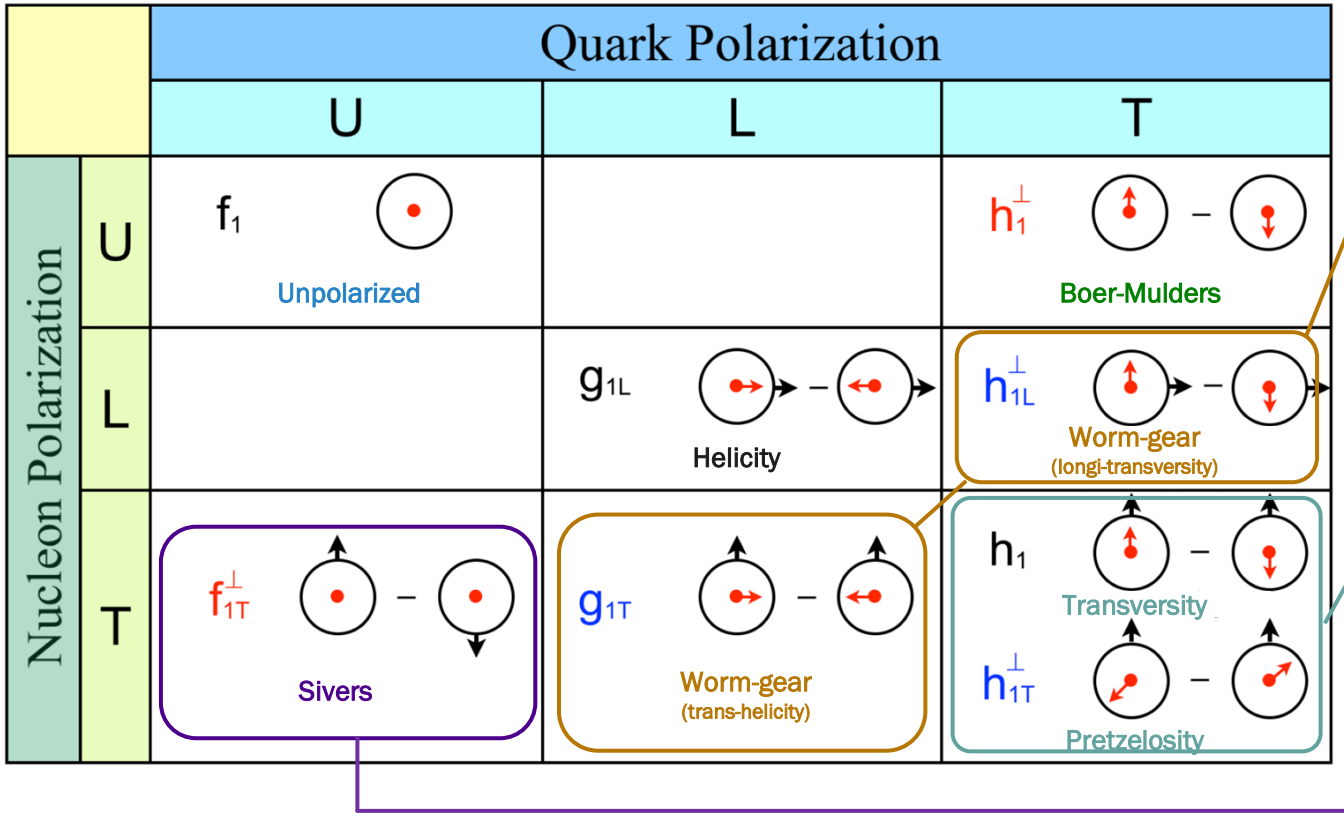
E12-11-108: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)

- Pion Semi Inclusive DIS experiments
- Highly rated
- 4D precision mapping of asymmetries
- Physics impact on TMDs, tensor charge, …



Access the Leading Twist TMDs

Extract the leading twist terms of TMD through SIDIS-π differential cross section measurement



Worm-gear TMDs:

E12-11-007 Longitudinally Polarized ^{3}He

$$A_{UL}^{sin2\phi_h} \propto h_{1L}^\perp \otimes H_1^\perp$$

$$A_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T} \otimes D_1$$

(combined with E12-10-006 data)

Sivers, Transversity, and Pretz. TMDS:

E12-10-006 Transversely Polarized ^{3}He

E12-11-108 Transversely polarized NH_3

$$A_{UT} = \frac{1}{P}\frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow}$$

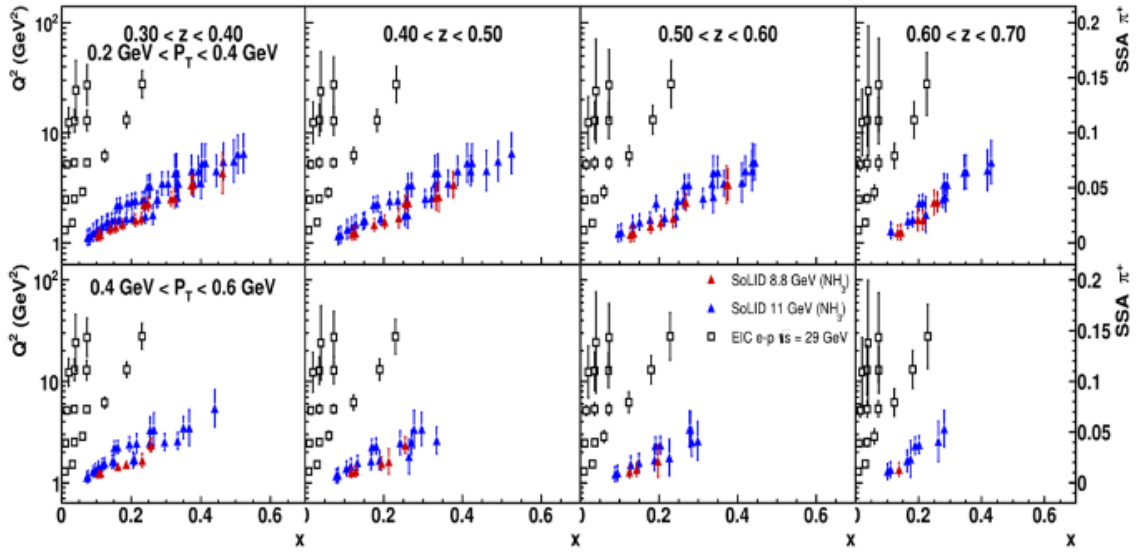
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) \propto h_{1T} \otimes H_1^\perp$$

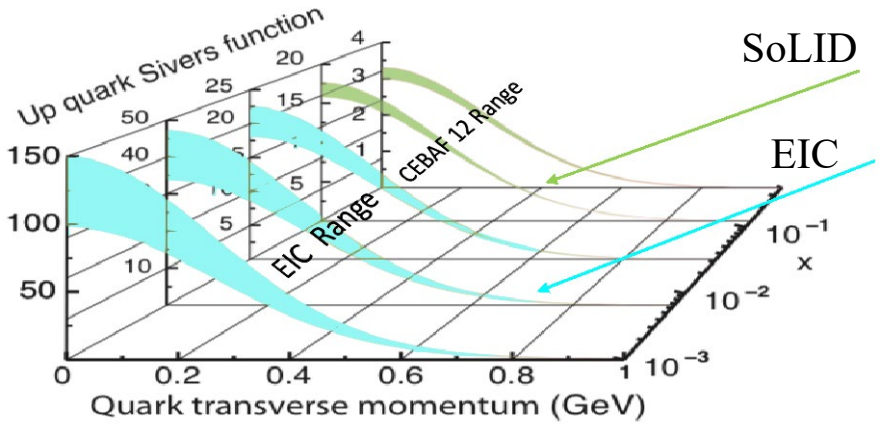
$$+ A_{UT}^{Sivers} \sin(\phi_h - \phi_S) \propto f_1^\perp \otimes D_1$$

$$+ A_{UT}^{Pretz.} \sin(3\phi_h - \phi_S) \propto h_{1T}^\perp \otimes H_1^\perp$$

Large acceptance and precision measurement of asymmetries in 4D phase space is essential for extraction

SSA Projections – Complementary to EIC

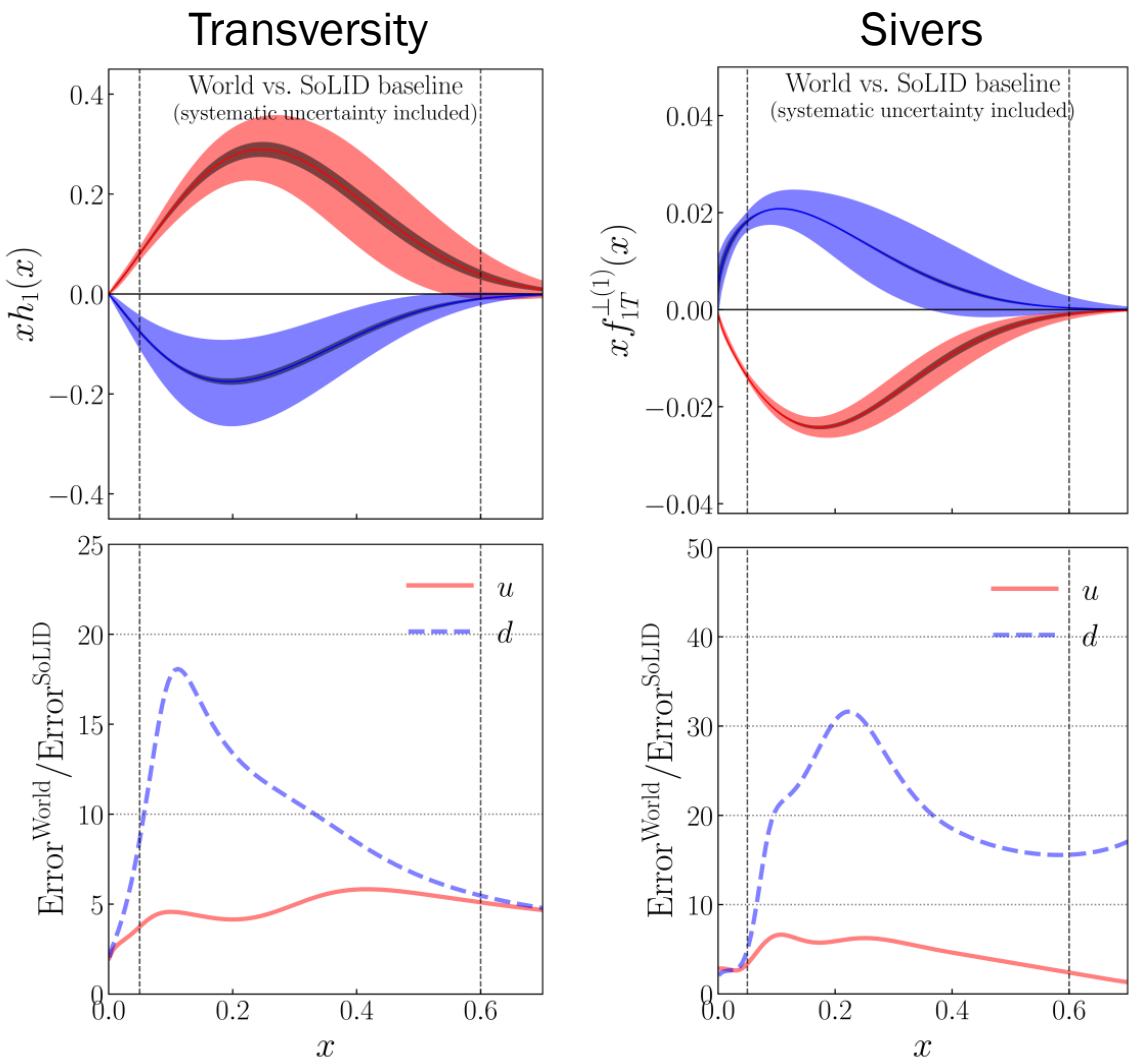




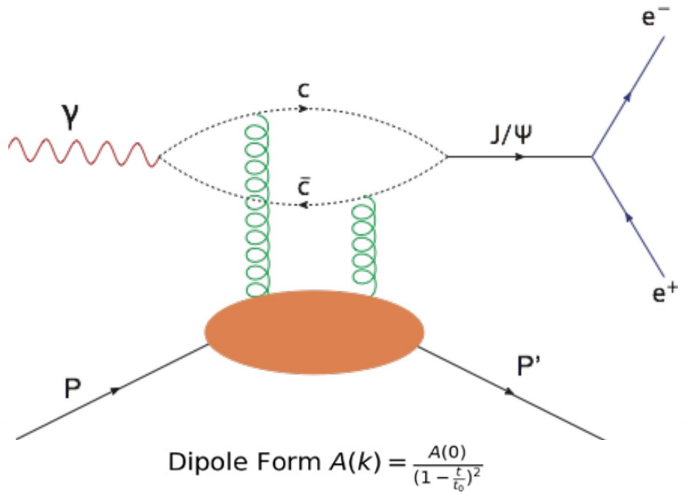
- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- The scale of the SSA and uncertainties shown on the right-side axis of the figures
- SoLID and EIC projections synergistic towards each other, covering different x and Q^2 ranges

SoLID Impact on TMDs

- World: SIDIS data from the COMPASS / HERMES, e+e- annihilation data from the BELLE / BABAR / BESIII
- Top : impact on the *u* and *d* quarks' TMD extractions by the SoLID SIDIS program
- Bottom: ratios between the World and SoLID projected uncertainties shown in the top figures
- Projections from Monte-Carlo simulation at $Q^2 = 2.4\ GeV^2$



Near-threshold J/ψ Production



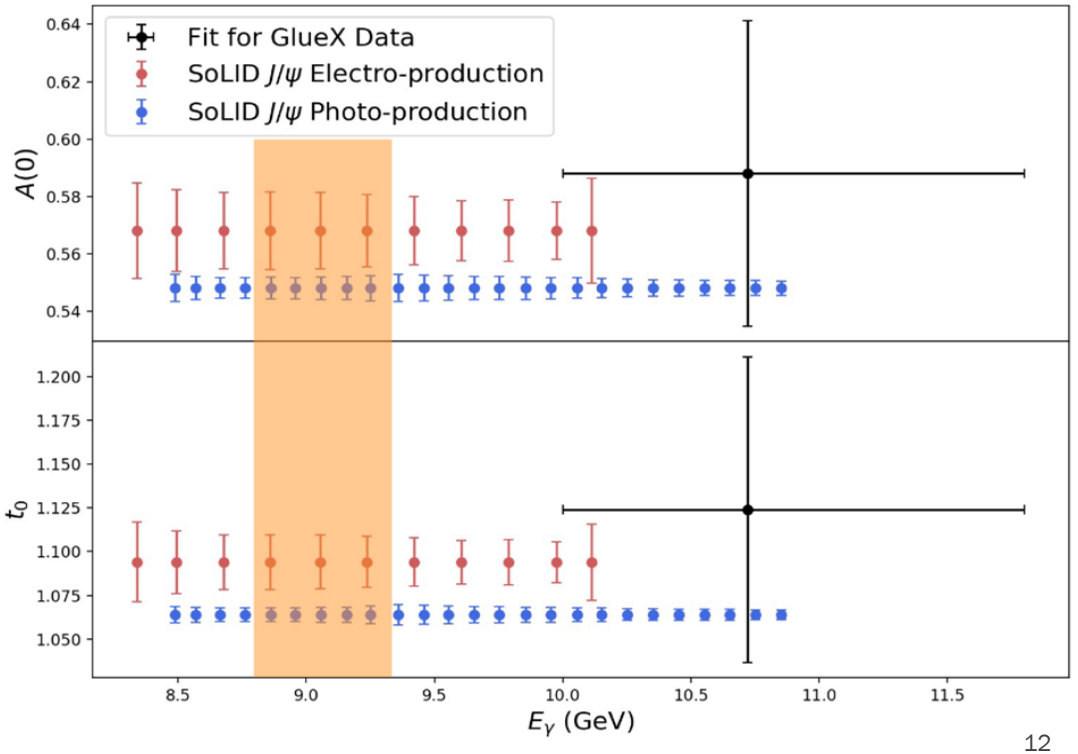
- Electro- and photo-production of Charmonium near threshold

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

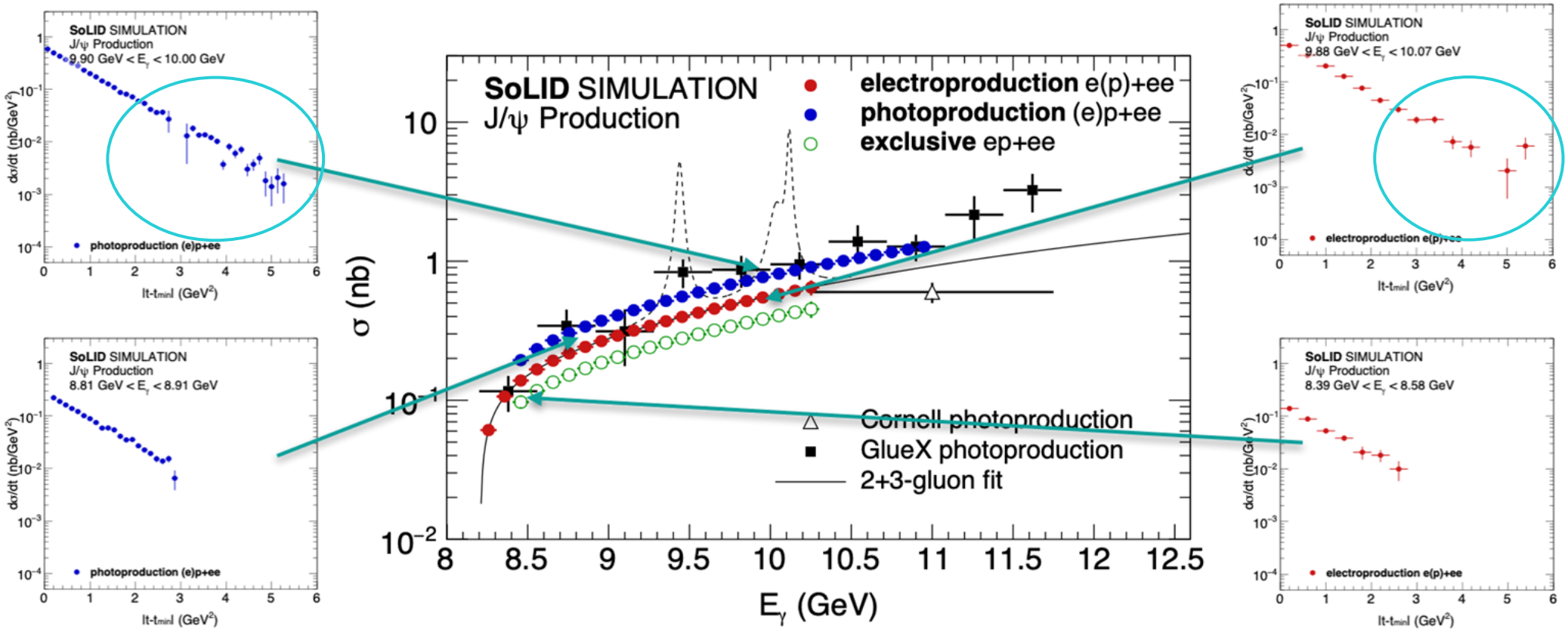
$$\gamma p \rightarrow p'\mathrm{J}/\psi(e^-e^+)$$

- Precision study of the proton's mechanical properties
  - Measurement of wide t-distributions of J/ψ production near-threshold

- Probing strong color field in the nucleon
  - Color Van der Waals force?
  - Pentaquarks existence?
  - Bound states of charmonium-nuclei?



The Ultimate Near-threshold J/ψ Factory



- SoLID will precisely map out the near-threshold region in photo- and electroproduction, with higher statistics than any other experiment.
- The high statistical precision with SoLID is crucial to minimize theoretical uncertainties.

Recent Activities in Pre-R&D

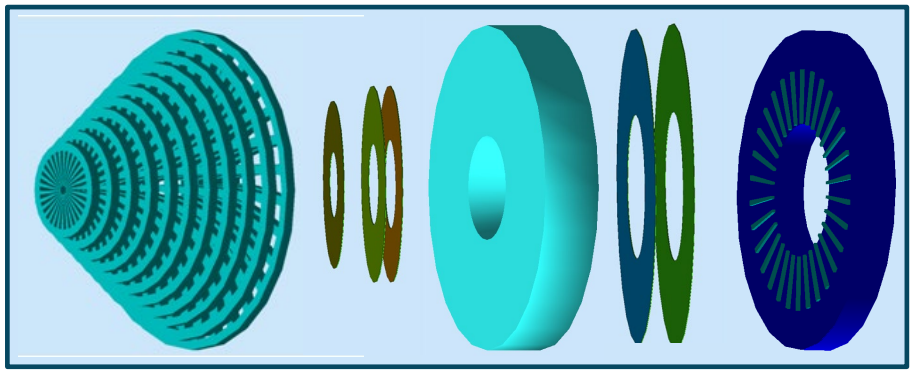
- Design for GEM Trackers
- Design for Scintillator Pad Detector
- Cold Test for CLEO-II Magnet
- Software, simulation, and DAQ development
- **Beam tests for Cherenkov Prototype and Shashlik ECal**

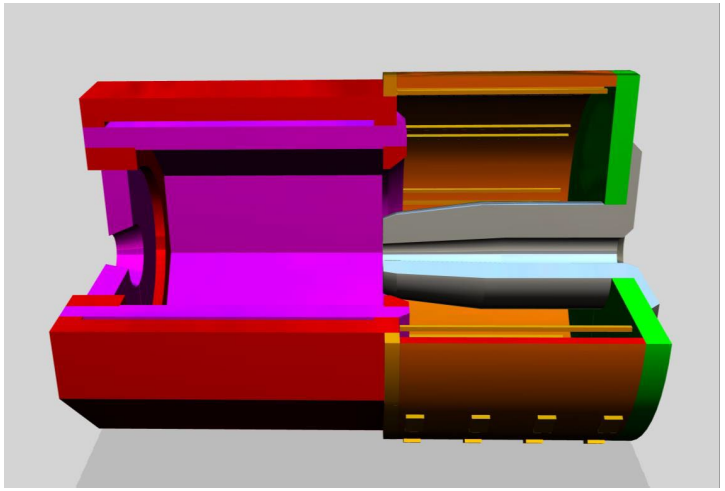
SoLID Detector Subsystems

Uses full capability of JLab electronics

PVDIS

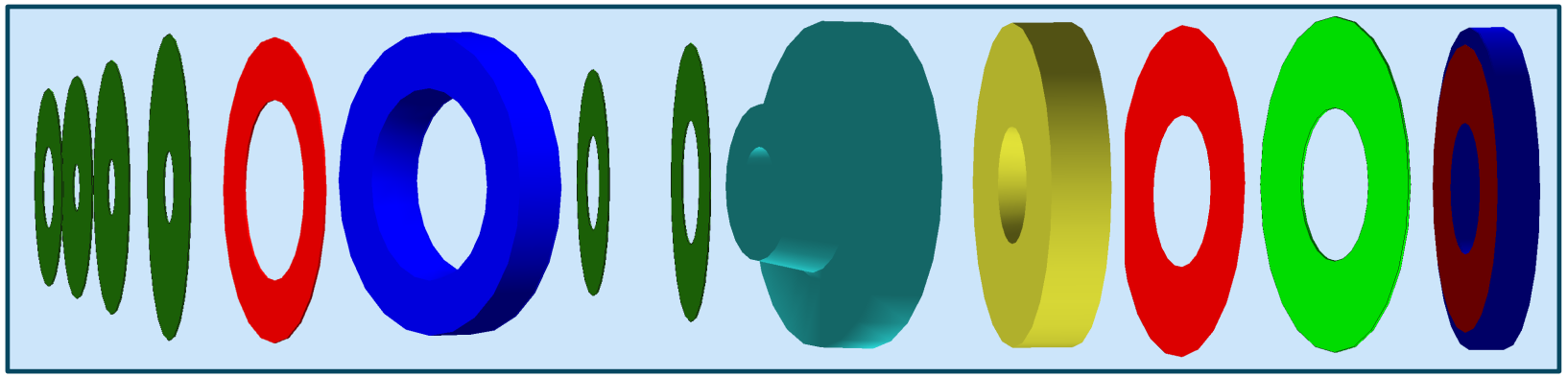
Baffle 3xGEMS LGC 2xGEMs EC





SIDIS-J/ψ

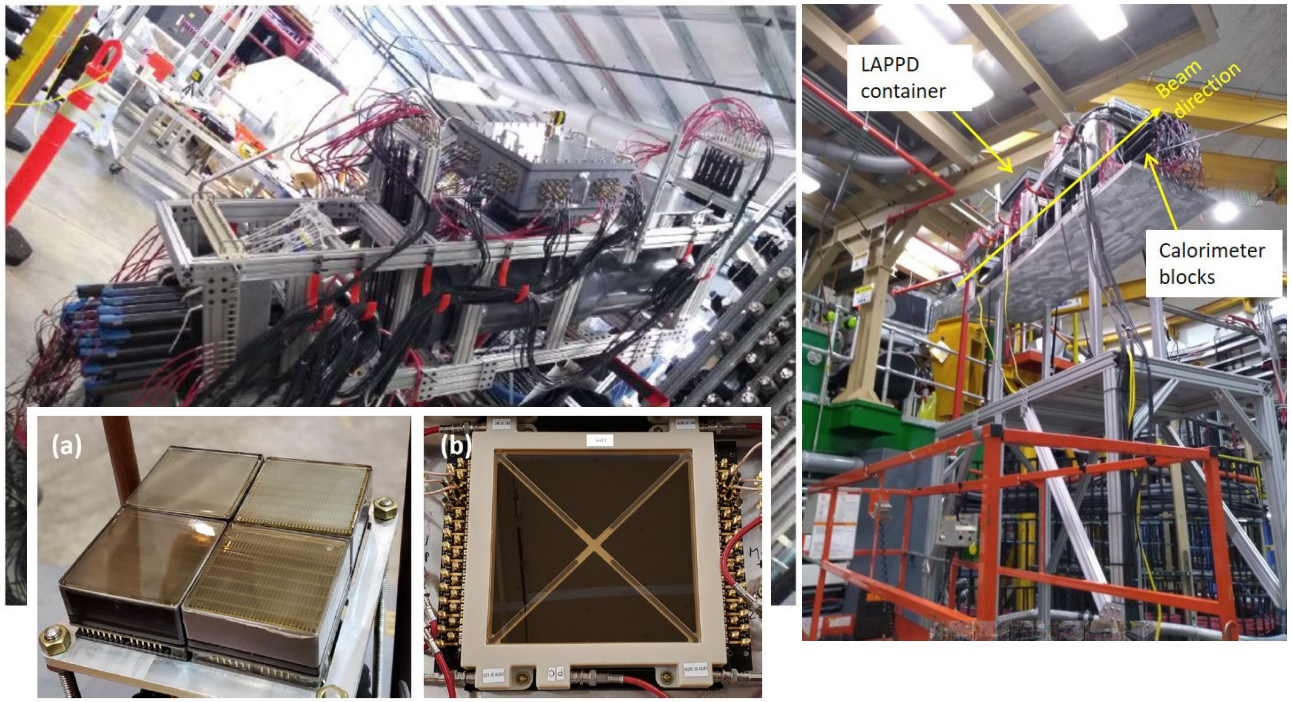
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC

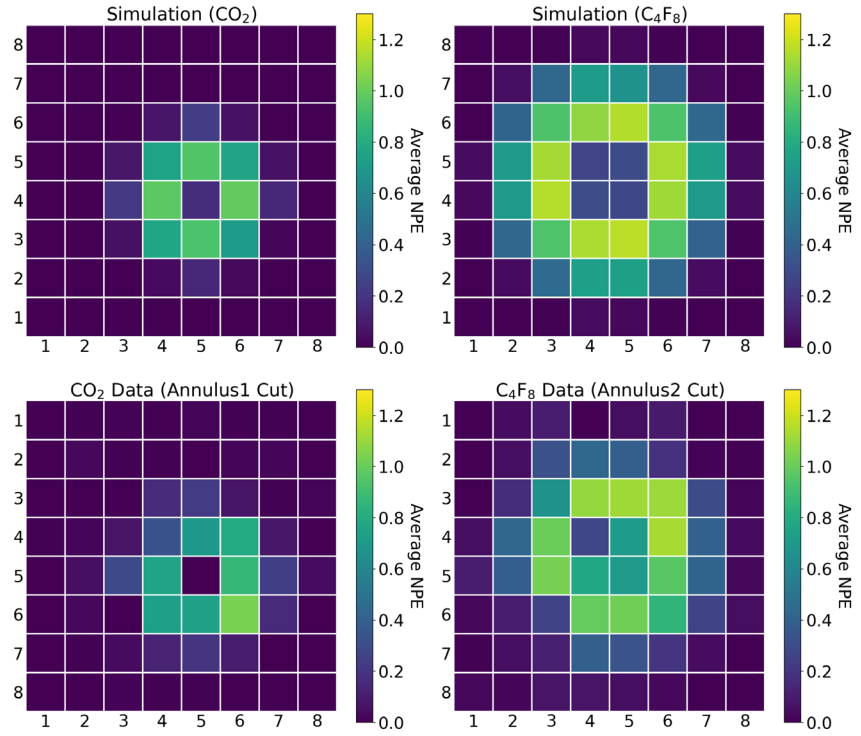


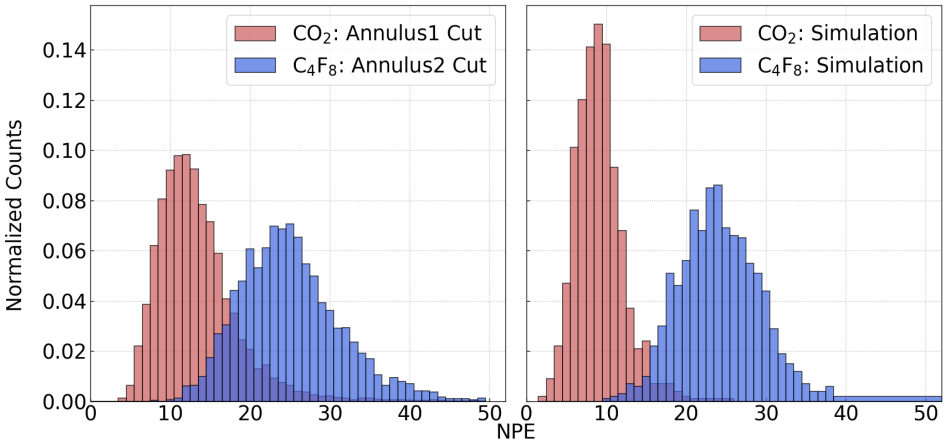
Pre-R&D items: LGC, HGC, GEM's, EC, DAQ/Electronics, Magnet

Beam Tests for Cherenkov Prototype

- 2 beam tests for MaPMT/LAPPD in high-rate background
- SoLID expected rates achieved (> 5 MHz/PMT)
- 1st test *C. Peng et al., JINST 17 (2022), P08022*
- 2nd test *J. Xie et al., accepted by JINST*

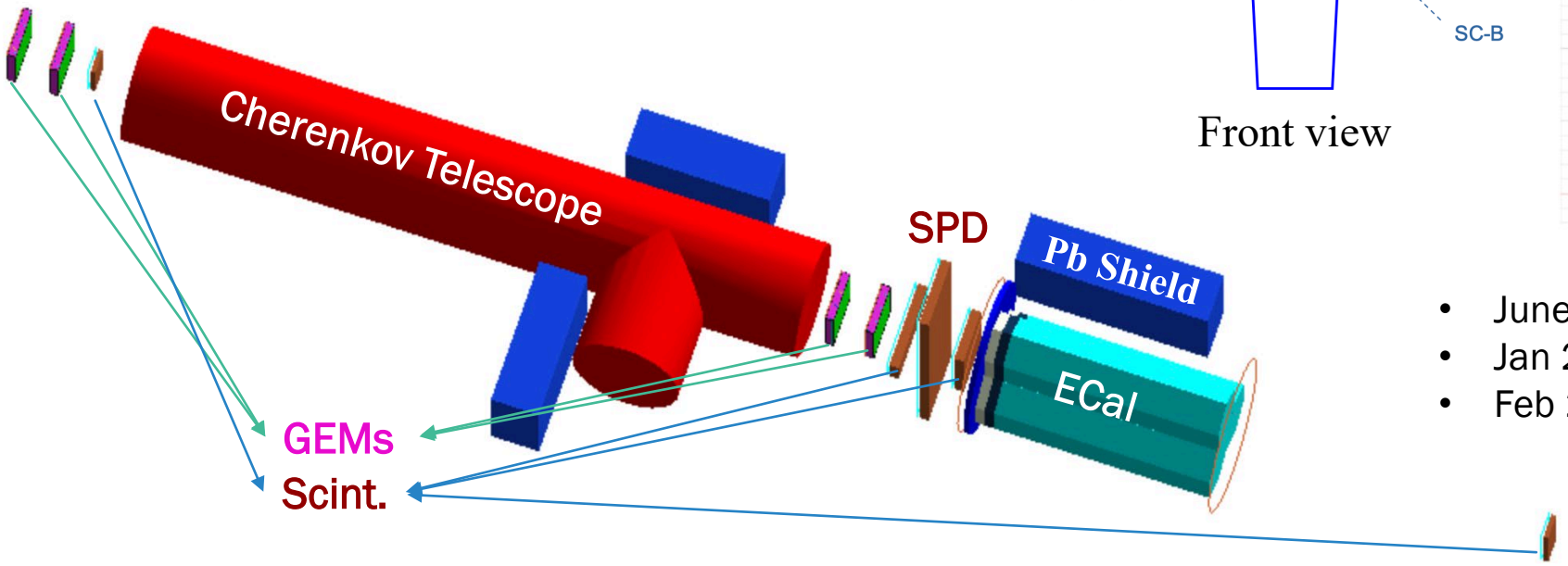


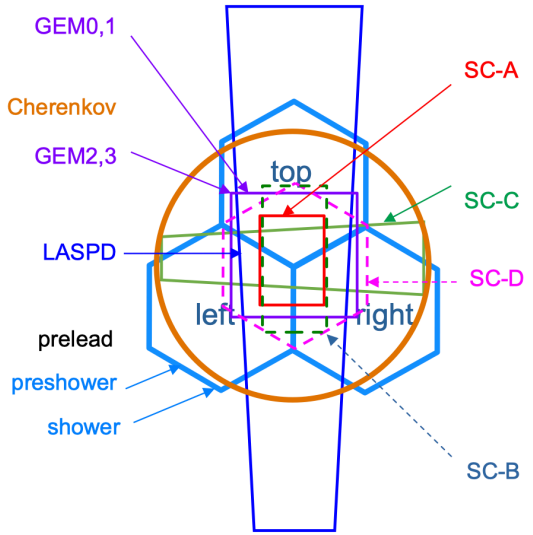




Beam Tests for ECal

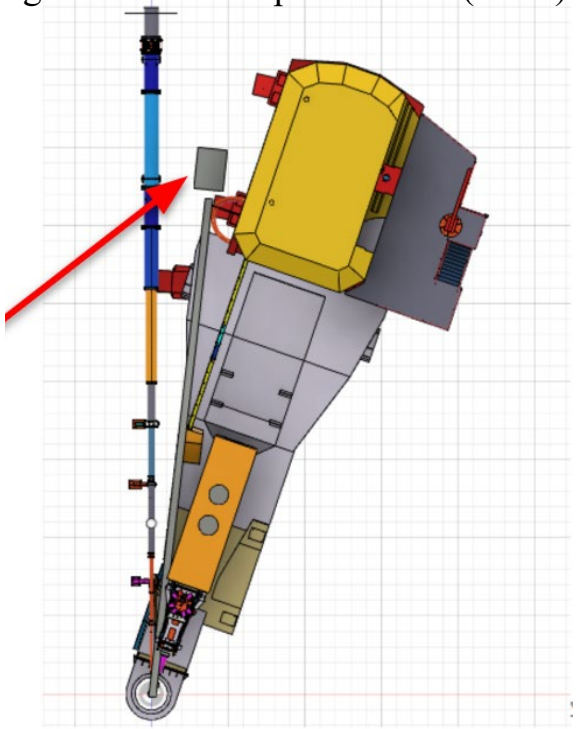
- Similar setup to SoLID detector (no magnet)
- $\sim 10^2$ krad
- 3-stages test in Hall C at JLab





Front view

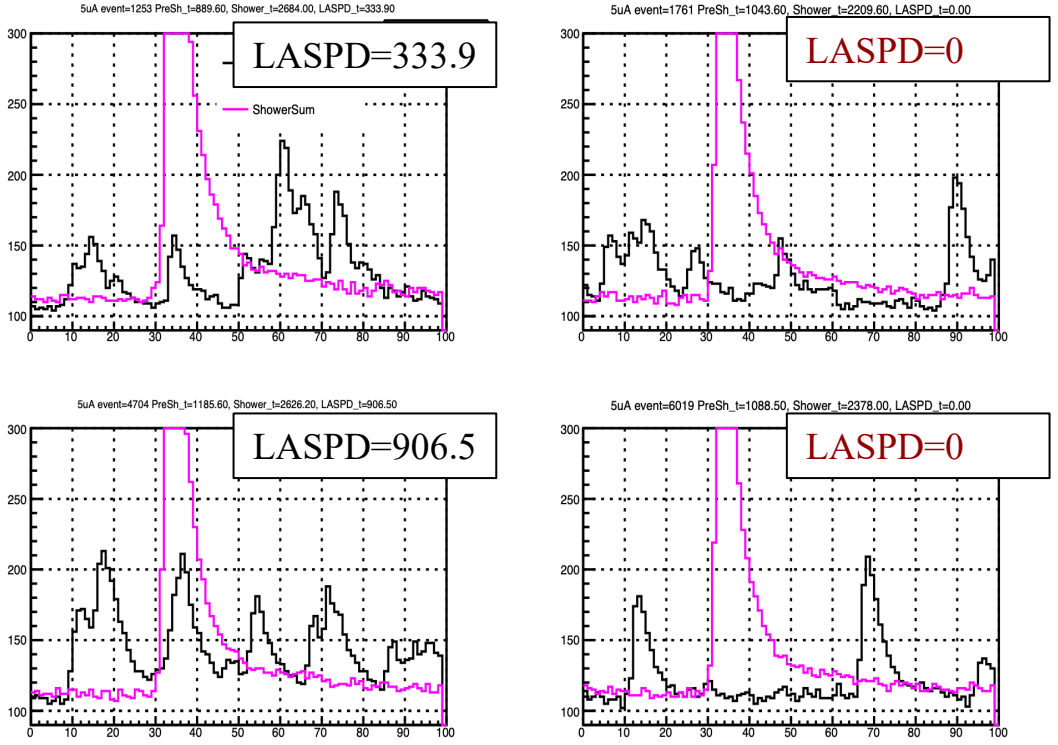
High Momentum Spectrometer (HMS)



- June 2022: install at (L) 82°
- Jan 2023: moved to (R) 7°
- Feb 2023: moved to (R) 18°

Preliminary Results for ECal Test

- LASPD Photon Rejection Study at 18 deg



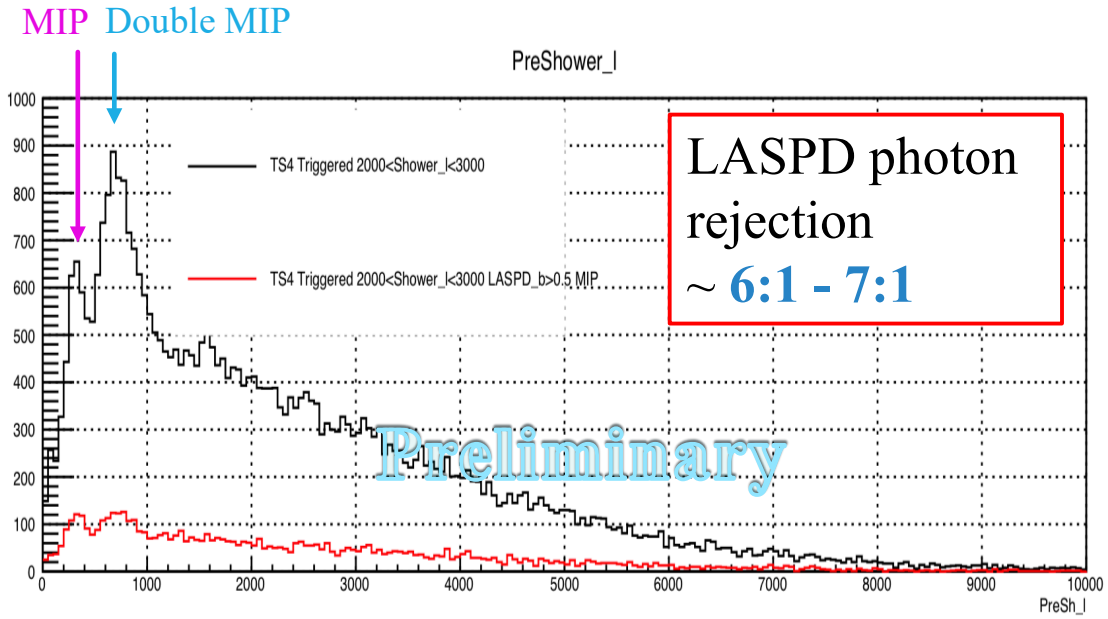
❖ LASPD waveforms with Shower trigger

Photon rejection:

N_{raw}/N_{cut} (LASPD>0.5 MIP)

Important to PVDIS for reducing DAQ rate

Wanted ~**10:1 rejection**



- Cut on shower to select photon dominant events to study the photon rejection.

Potential SoLID Experiments @JLab20+

- SIDIS Measurements
- J/ψ and ψ' Productions
- PVDIS Measurements
- GPD Studies
  - DVCS, TCS, and more – Marie Boer
  - Deep-Exclusive Meson Production (DEMP) – Garth Huber
  - DDVCS – Alexandre Camsonne

SoLID-SIDIS @JLab20+

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

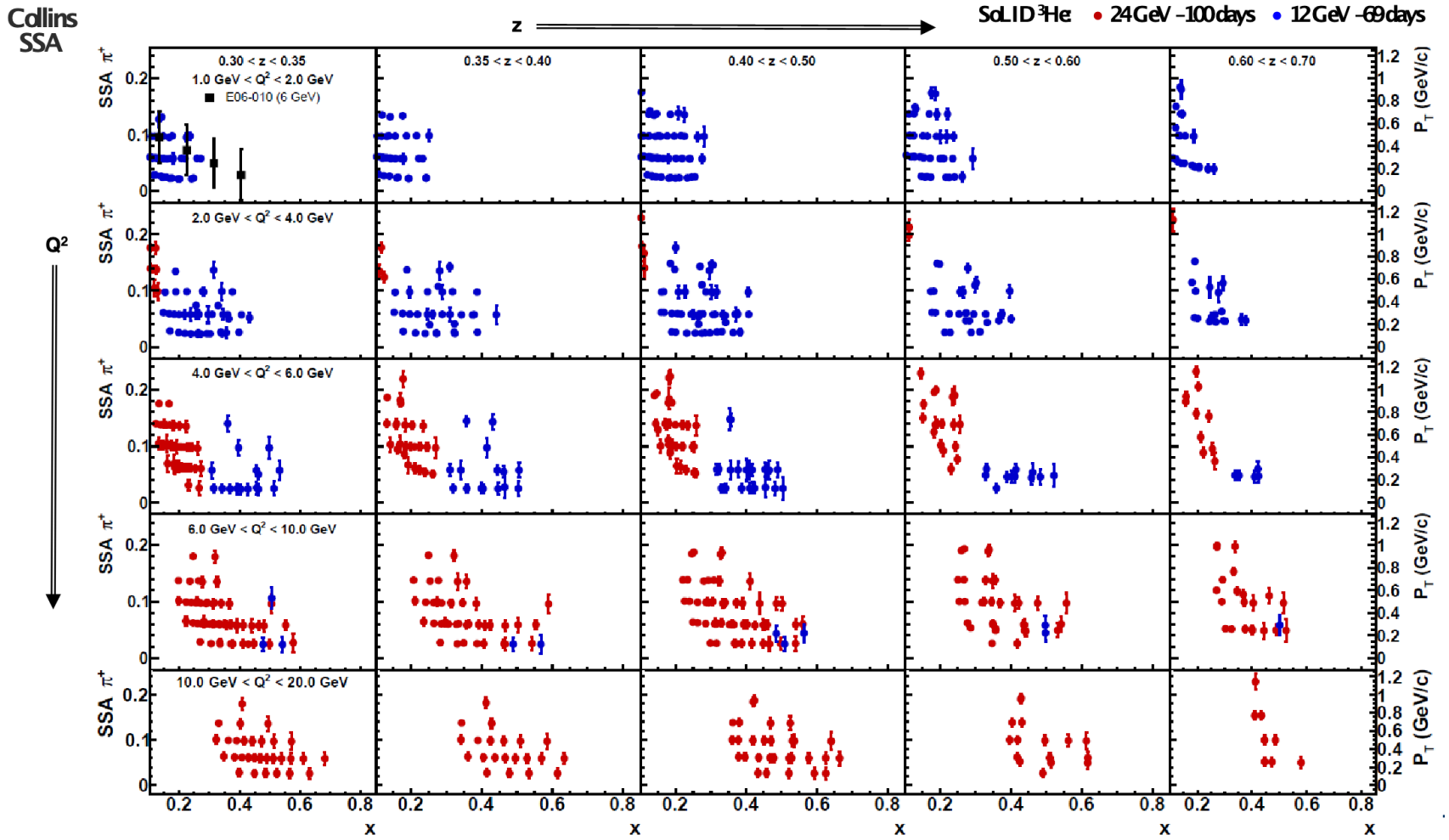


Fig. from Vlad Khachatryan

SoLID-SIDIS @JLab20+

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

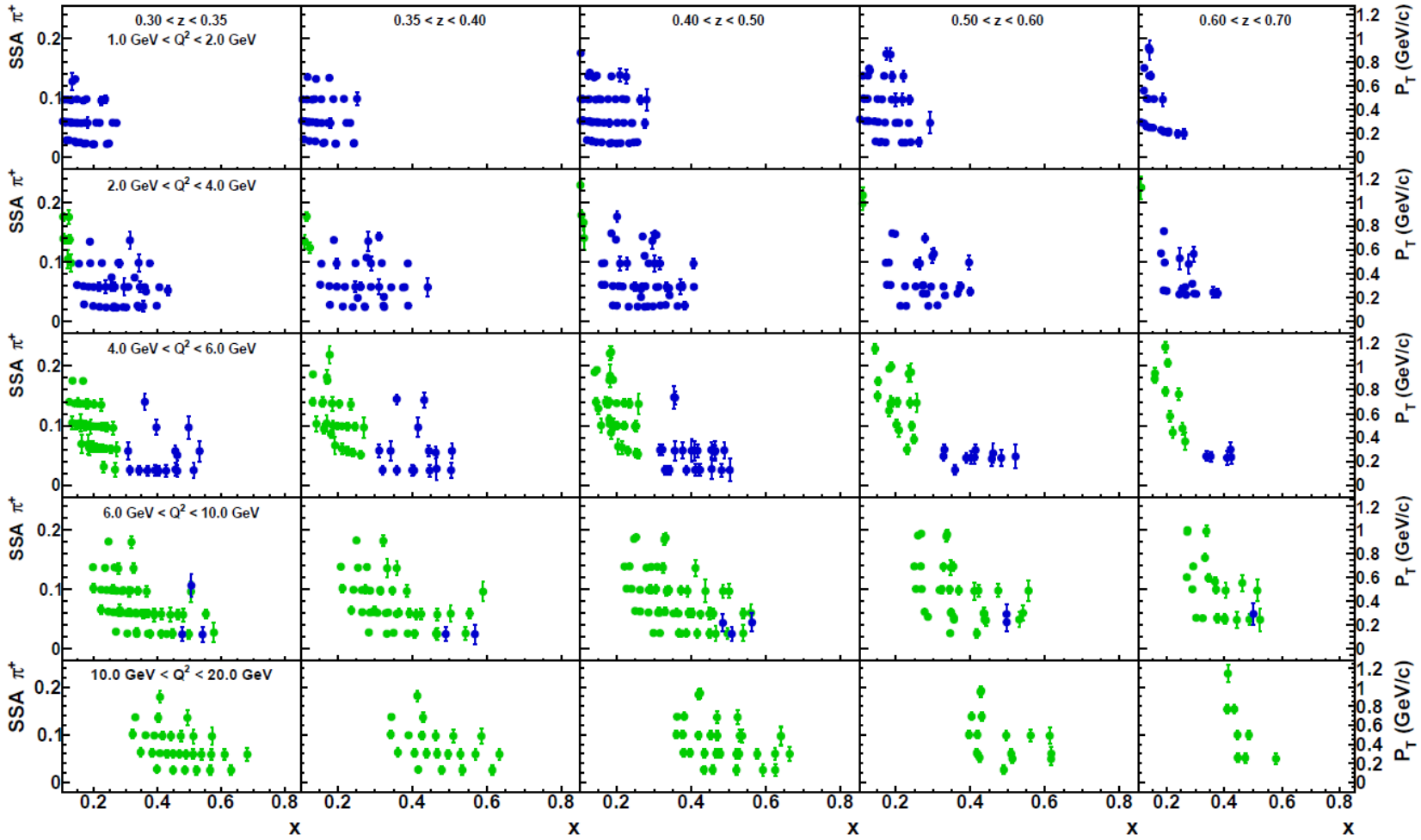


Fig. from Vlad Khachatryan

SoLID ψ' Production @JLab20+

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

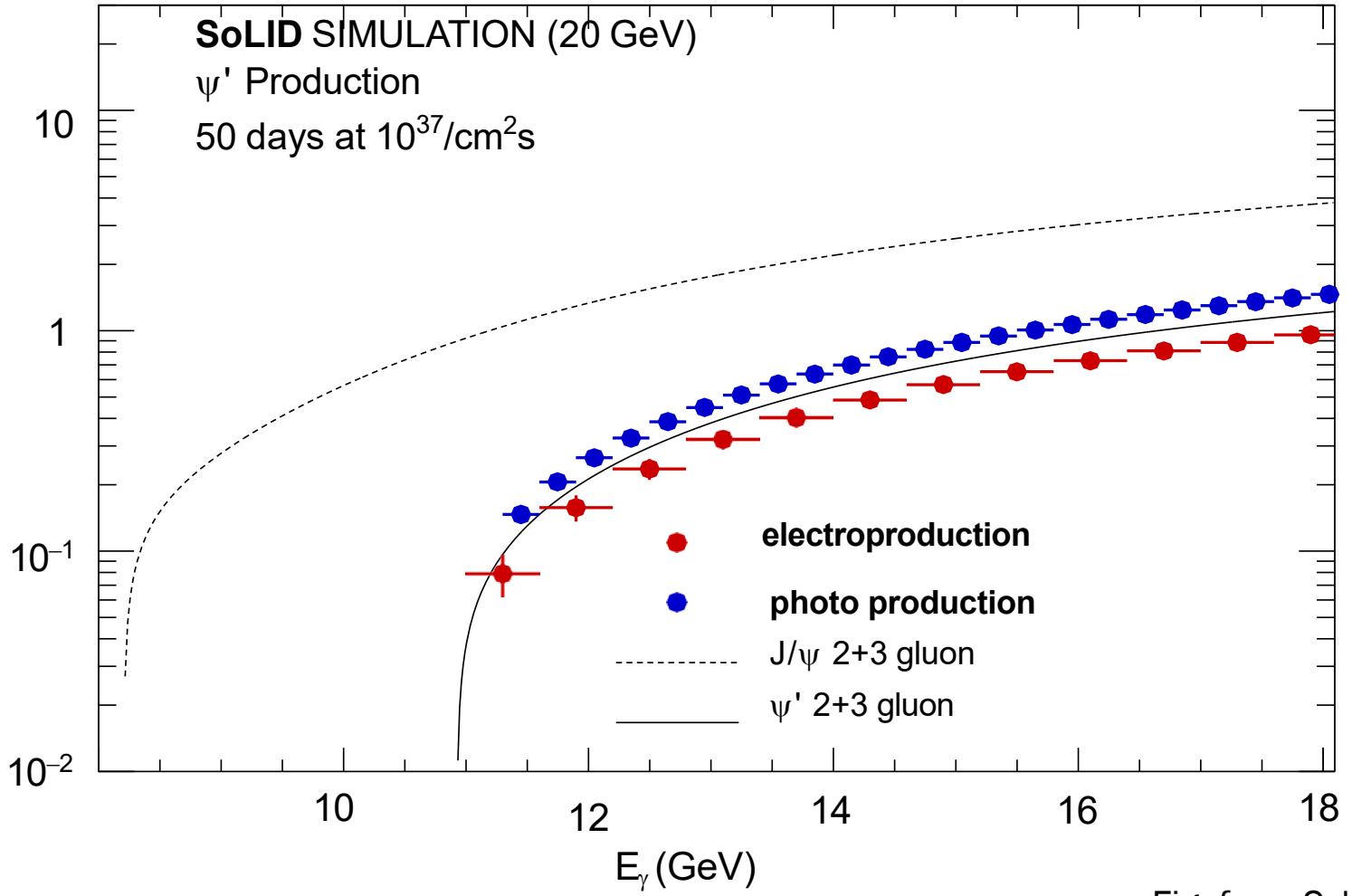


Fig. from Sylvester Joosten

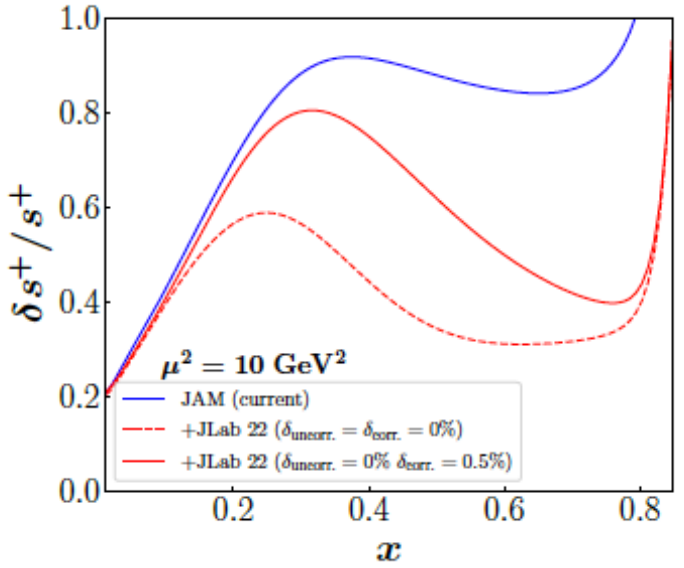
SoLID-PVDIS @JLab20+

- Improvement From 11 GeV to 22 GeV in Uncertainties for
  - Standard Model Test
  - Search for Charge Symmetry Violation
  - Study of Higher-Twist Effect

Table from Alex Emmert and Xiaochao Zheng

	11 GeV		22 GeV	
	Stat.	Syst.	Stat.	Syst.
sin2(θW)	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

Unambiguously isolate strangeness with SoLID-PVDIS @JLab20+



~100 days, 40 μA beam split between 40 cm D and H targets

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

Summary

- SoLID is at the intensity frontier with JLab 12 GeV upgrade
  - Rich and highly rated physics programs
  - Address important questions in Nuclear Physics
  - Complementary and synergistic to the EIC science programs
- Potential measurements at JLab20+
  - PVDIS, SIDIS, J/ψ, GPDs, …
- Active pre-R&D with the support from DOE and JLab
  - Demonstrated the feasibility of key detector subsystems in a high-rate environment
  - Analysis for pre-R&D is ongoing

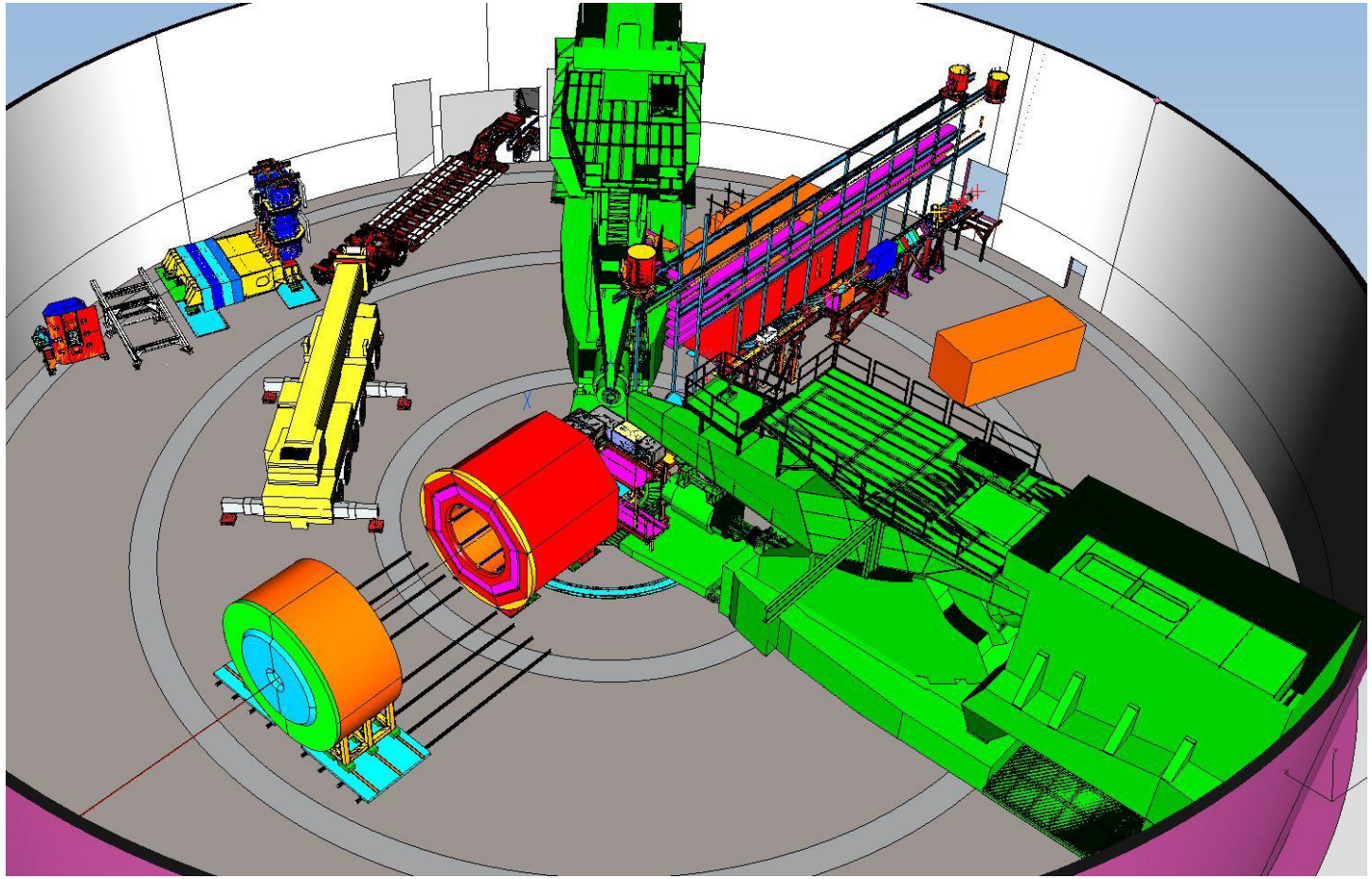
THANK YOU

BACK UP SLIDES

Pre-conceptual Design of SoLID

Key parameters for SoLID

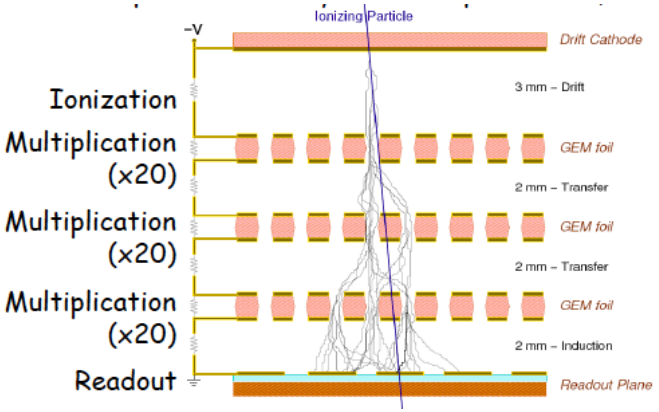
- Unpolarized luminosity 10^{39}
- Polarized luminosity $10^{36\text{-}37}$
- Full 2π azimuthal coverage
  - $\delta\varphi = 6$ mrad
- θ and p coverage
  - PVDIS: 22°-35° (1 mrad); 2.3-5 GeV/c (2%)
  - SIDIS-J/ψ : 8°-24° (2-3 mrad); 1-7 GeV/c (2-3%)
- Precision PID e/π and e/π/K (SIDIS)

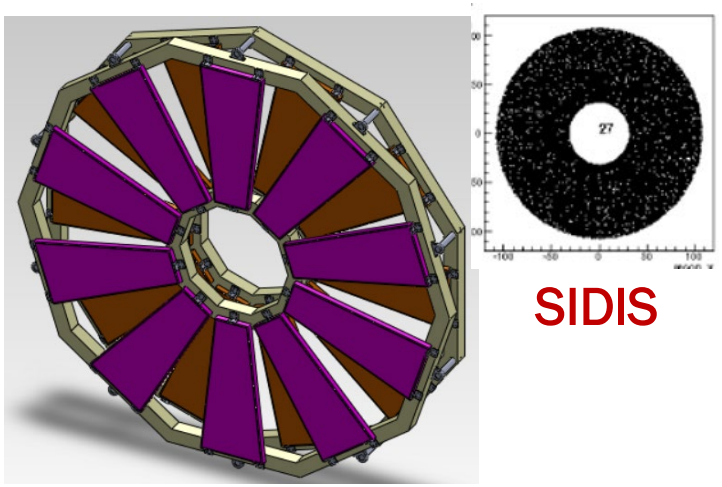


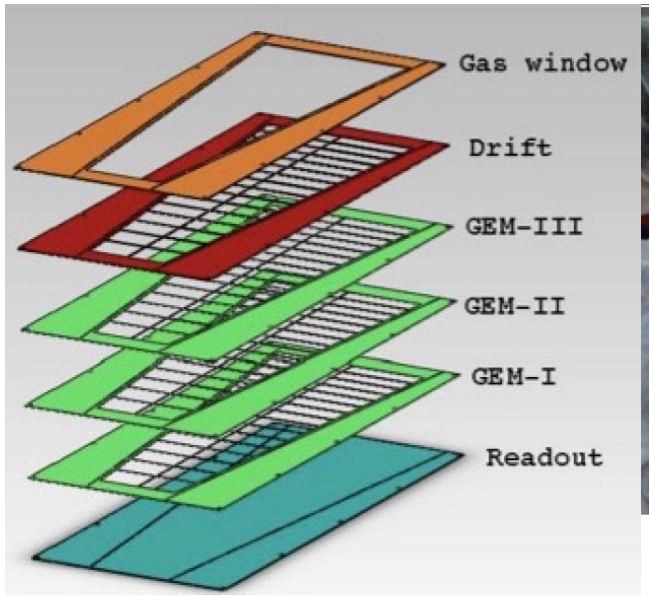
Plan for installing SoLID in Hall A

GEM Trackers

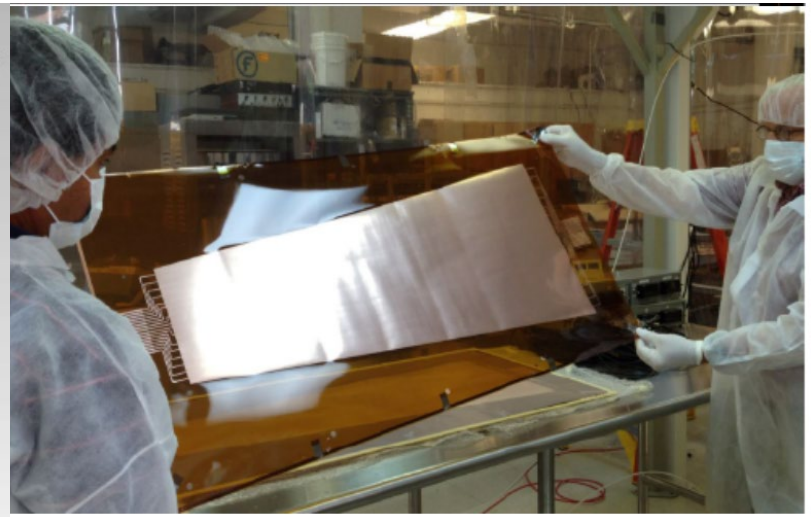
- Rate capabilities > many MHz/cm^2
- High position resolution
- Cover large areas at reasonable cost
- Low thickness (~0.5 radiation length)
- Used in many experiments, and planned for more
  - COMPASS, STAR, ALICE, PRad@JLab, SBS@JLab, CMS upgrade, EIC…







Proposed SoLID GEM Module



UVa EIC GEM Prototype: similar to SoLID design

Scintillator Pad Detector: Requirements and Design

LASPD: photon rejection 5:1;

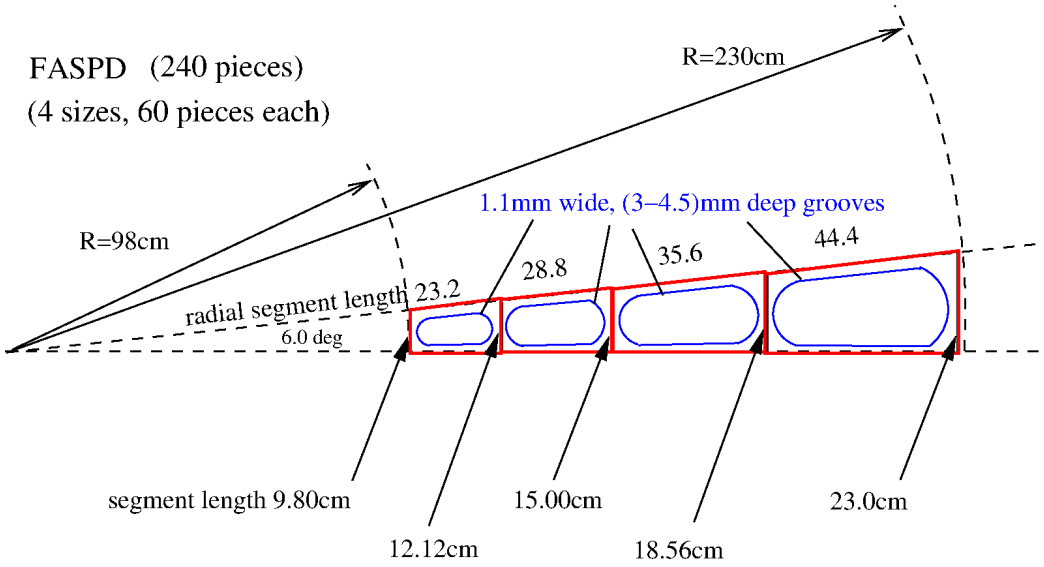
coincidence TOF (150ps)

→ design: 20 mm-thick,

60 azimuthal segments,

direct coupling to fine-mesh PMT (NIMA 827 (2016) 137-144)

a LASPD prototype (regular PMT)



FASPD: **photon rejection 5:1**

→ design: 5-10 mm-thick

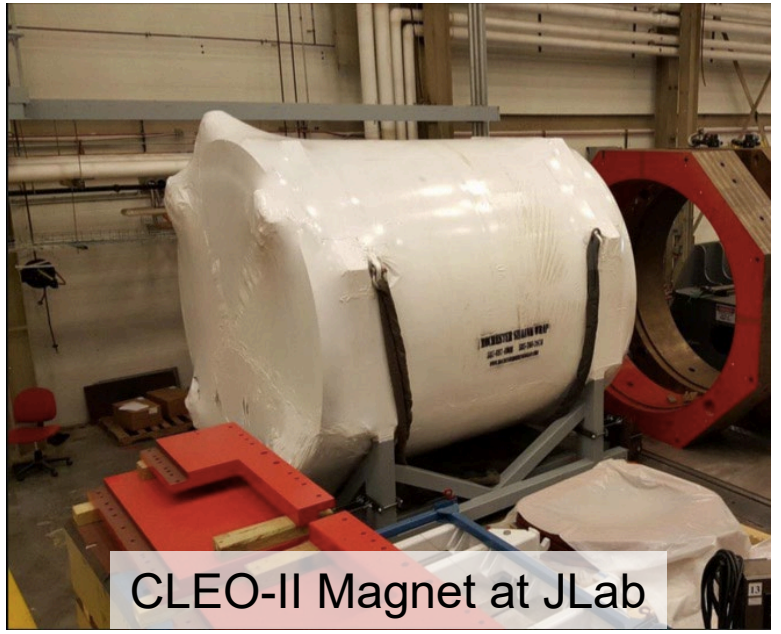
240 segments (60 X 4)

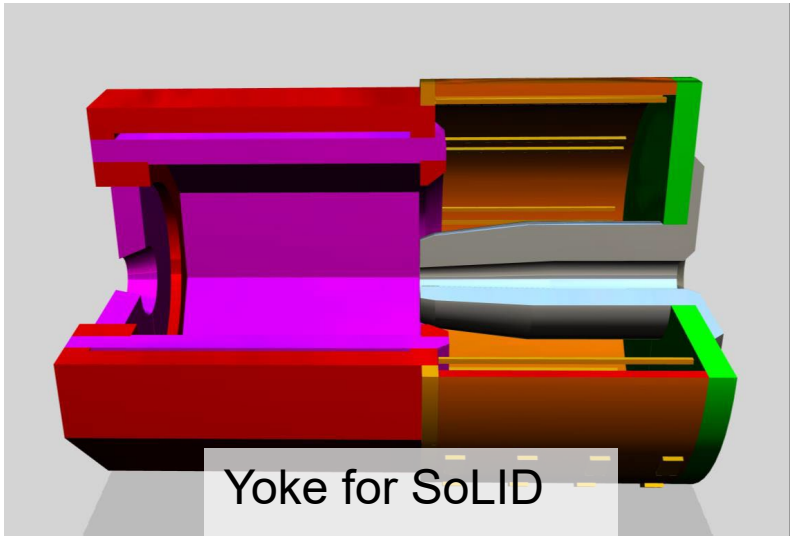
WLS fiber embedding,

MAPMT (outside magnet)

Magnet – Built on the CLEO-II Solenoid

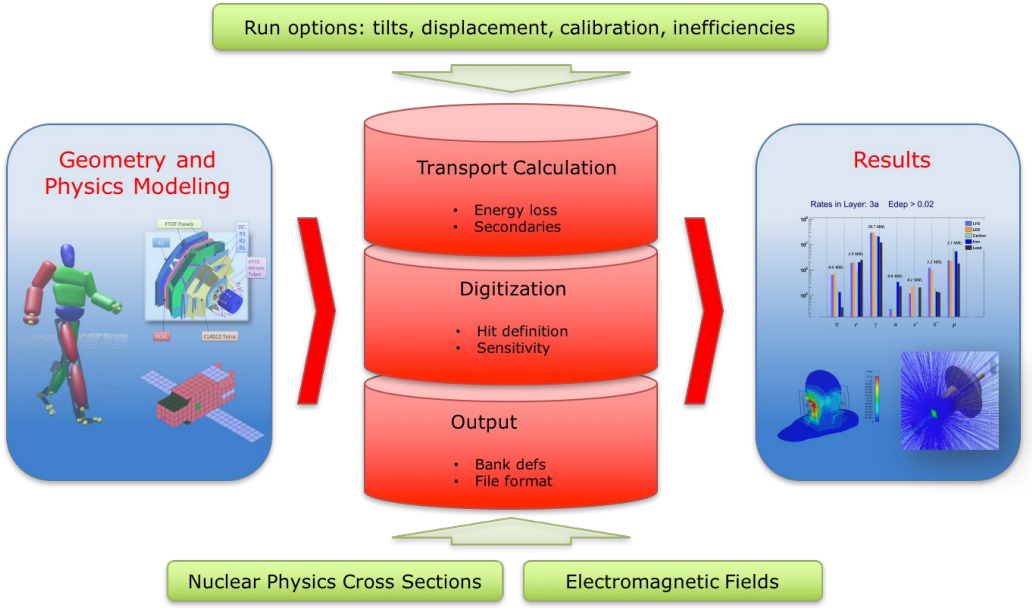
- Requirements:
  - Acceptance:
    p @ 1.0 – 7.0 GeV/c,
    ϕ @ 2π,
    θ @ 8°-24° (SIDIS), 22°-35° (PVDIS)
  - Resolution: $\delta p \sim 2\%$ (0.1 mm tracking resolution)
  - Fringe field at the ^{3}He target < 5 Gauss
- Modifications:
  - Use 2 out of 3 layers of return yoke
  - Thicken the front endcap
  - Add the extended endcap (housing many sub-detectors)
- Two-phase Refurbishment Test Plan:
  - Low current cold test (JLab funded)
  - Full current test with installation (with funded project)


CLEO-II Magnet at JLab

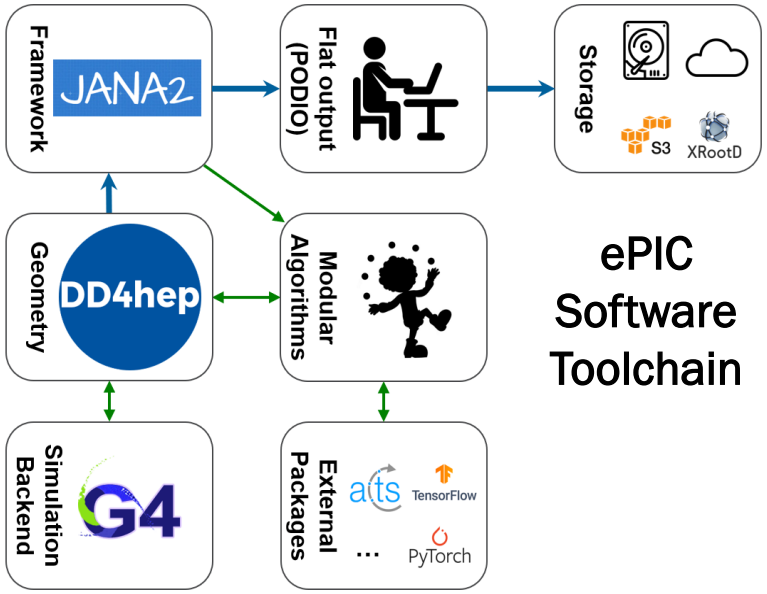

Yoke for SoLID

Simulation Software Development

- Existing simulation: SoLID_GEMC
  - GEANT4-based simulation package used by CLAS12
  - Added SoLID detector description and digitization
  - Used extensively for SoLID pre-cdr and in current pre-R&D studies
  - Variety of physics generators implemented



The architecture of gemc

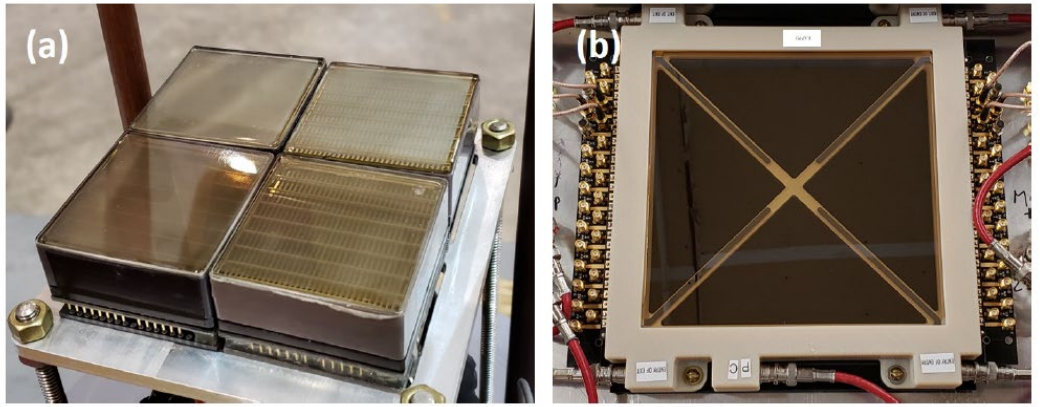


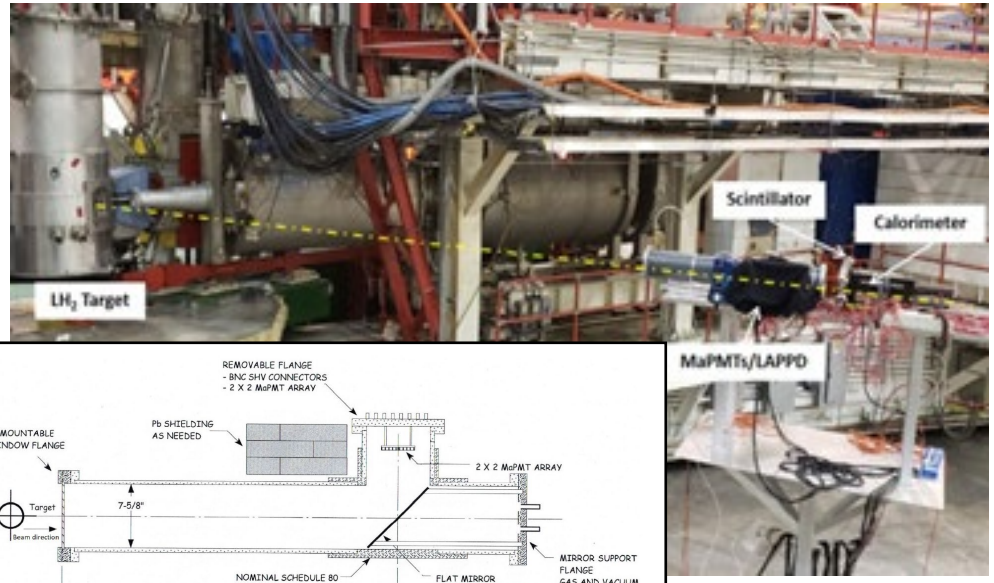
ePIC Software Toolchain

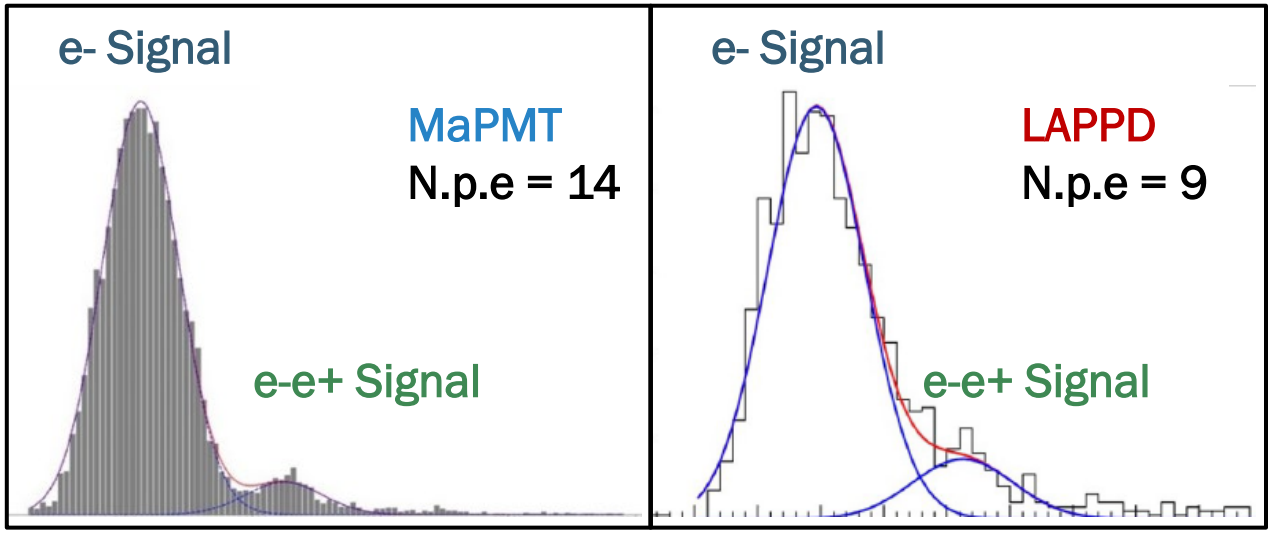
- Long-term Development: SoLID in EIC Software
  - Simulation software toolchain used by ePIC
  - Detector description in DD4Hep, digitization/reconstruction in EICRecon (JLab JANA2 based)
  - Modern, multi-threaded software/framework widely used in HEP/NP
  - Share the development/maintenance effort with the EIC community

Beam Tests for Cherenkov Prototype

- 1st beam test with MaPMT/LAPPD (stripline readout)
- A Cherenkov telescope prototype
- Promising results from MaPMT/LAPPD in a high-rate environment



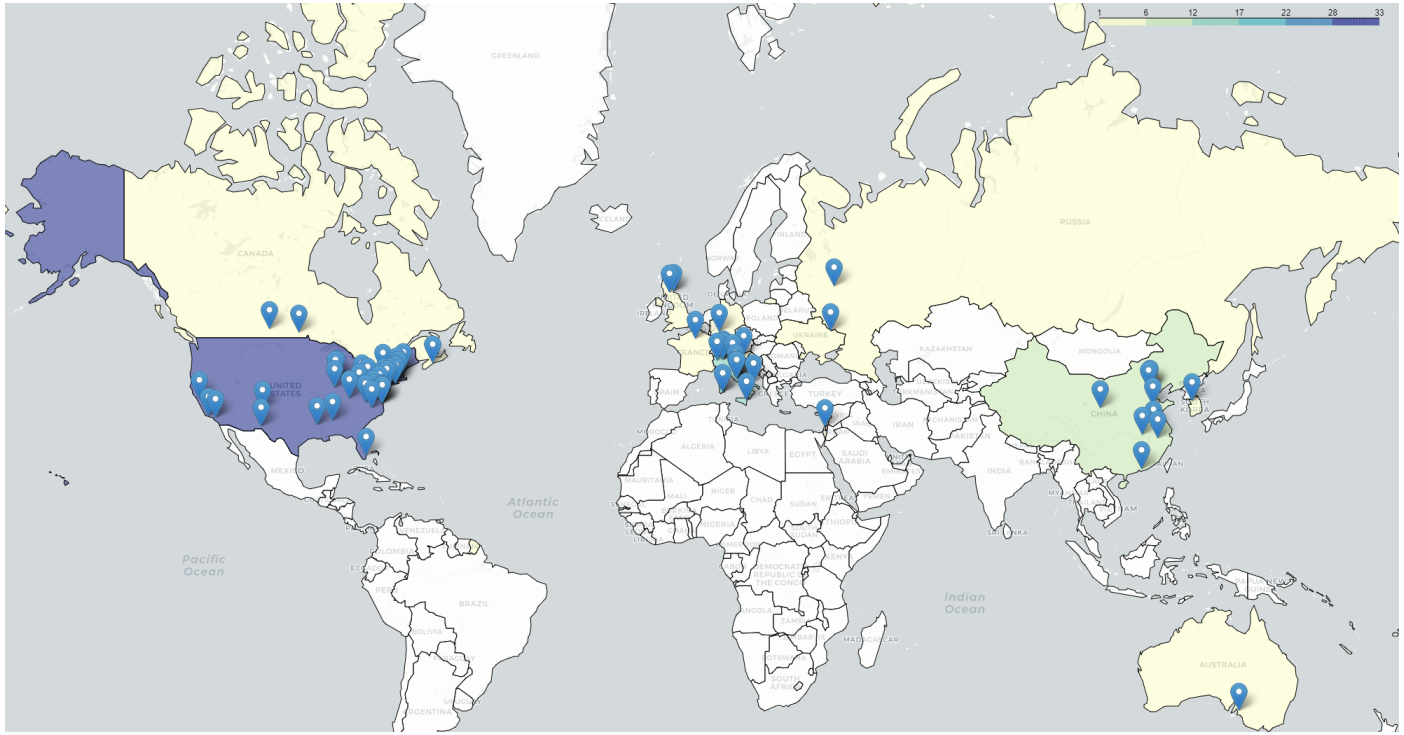




C. Peng et al., JINST 17 (2022), P08022

Strong Collaboration

- 270+ collaborators, 70+ institutions from 13 countries
  - Strong theory support
  - Active development for pre-R&D and physics programs



Nucleon Tensor Charge

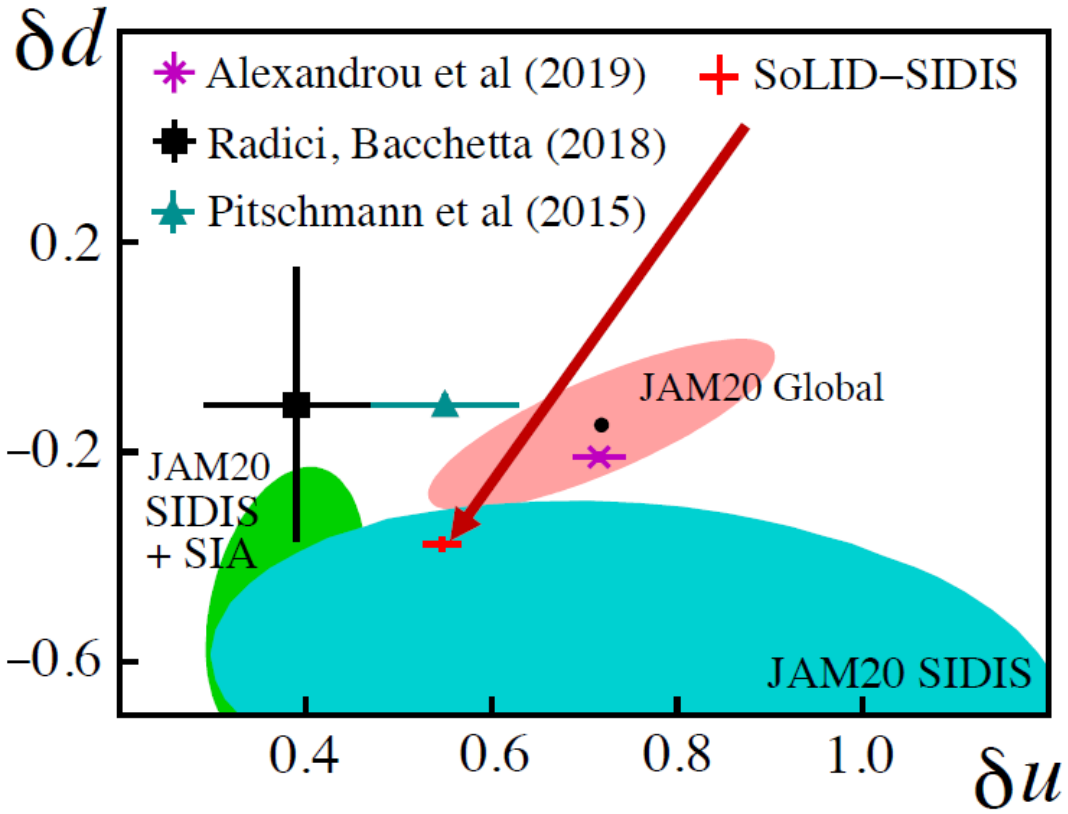
- A fundamental QCD quantity
  - Matrix element of tensor current

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

  - Lowest moment of transversity

$$\delta_T^q = \int_0^1 \left(h_1^q(x) - h_1^{\bar{q}}(x)\right) dx$$

  - Can be tested in Lattice QCD



Combining E12-10-006 & E12-11-108