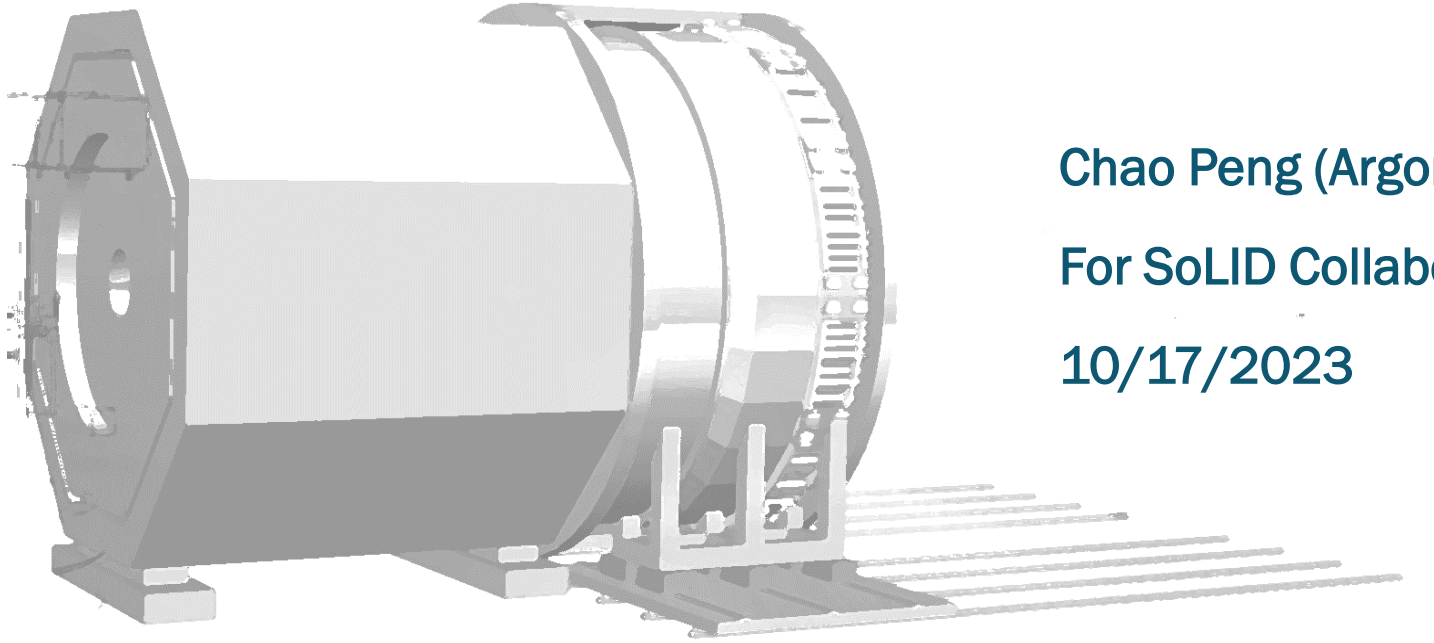
XXXI International Conference on Meson-Nucleon Physics and the Structure of the Nucleon

SoLID: Nucleon 3D Structure at the Luminosity Frontier



Chao Peng (Argonne National Laboratory)

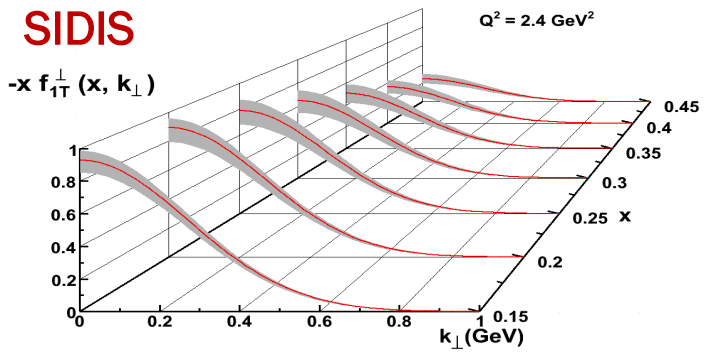
For SoLID Collaboration

10/17/2023

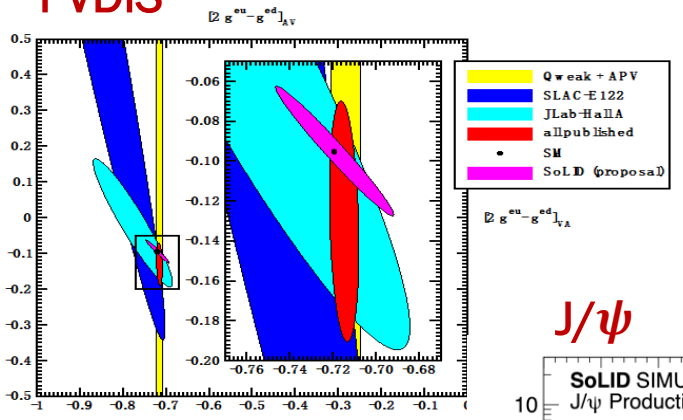
Solenoidal Large Intensity Device (SoLID)

- 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

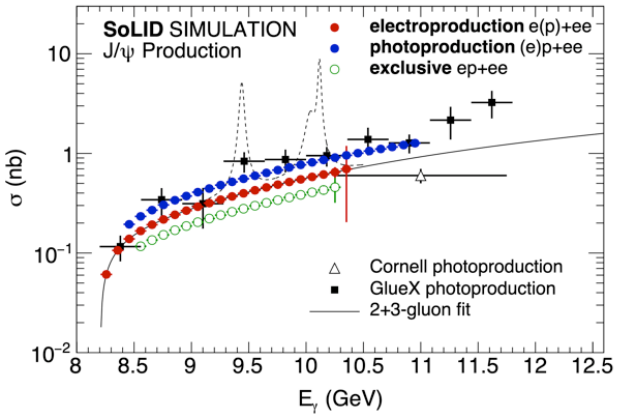
SIDIS



PVDIS

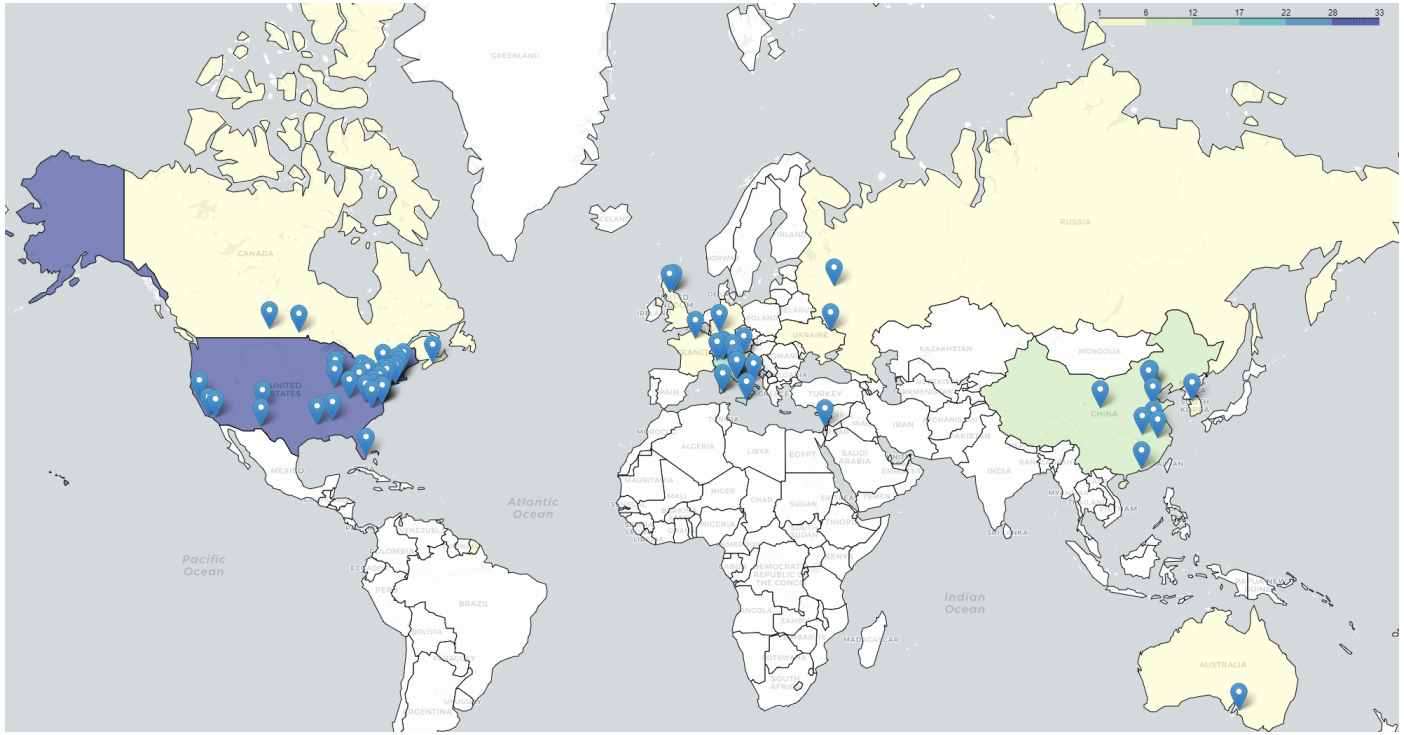


J/ψ



Strong Collaboration

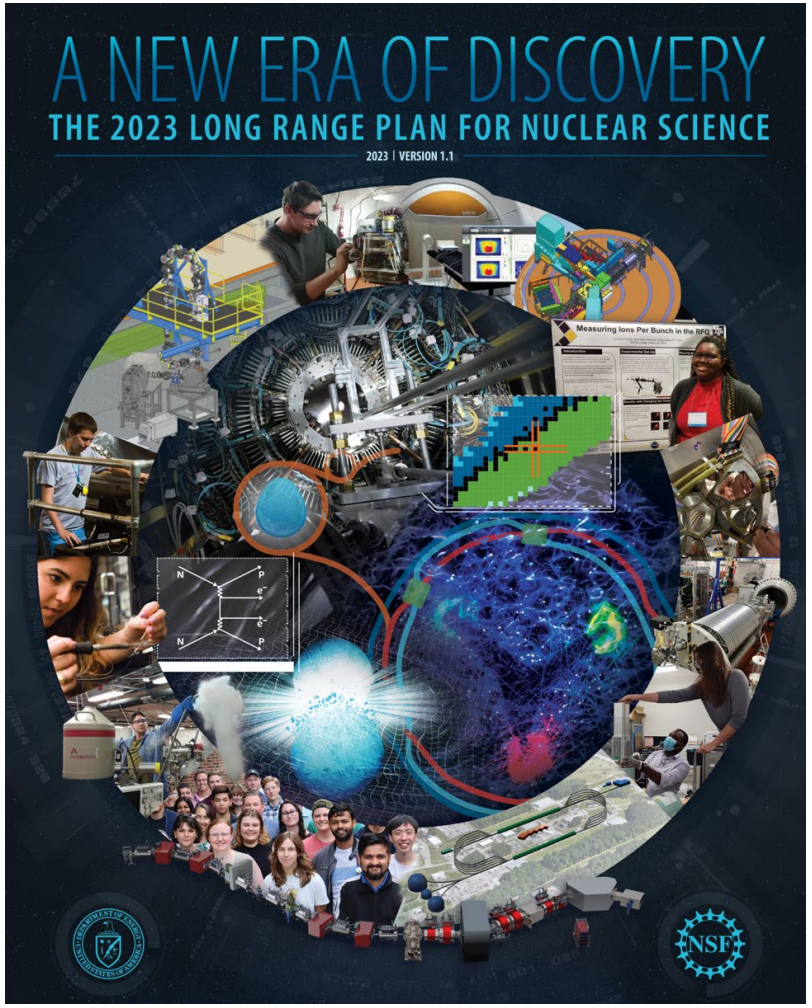
- 270+ collaborators, 70+ institutions from 13 countries
  - Strong theory support
  - Active development for pre-R&D and physics programs



Progresses Since the First Approvals of SoLID Experiments

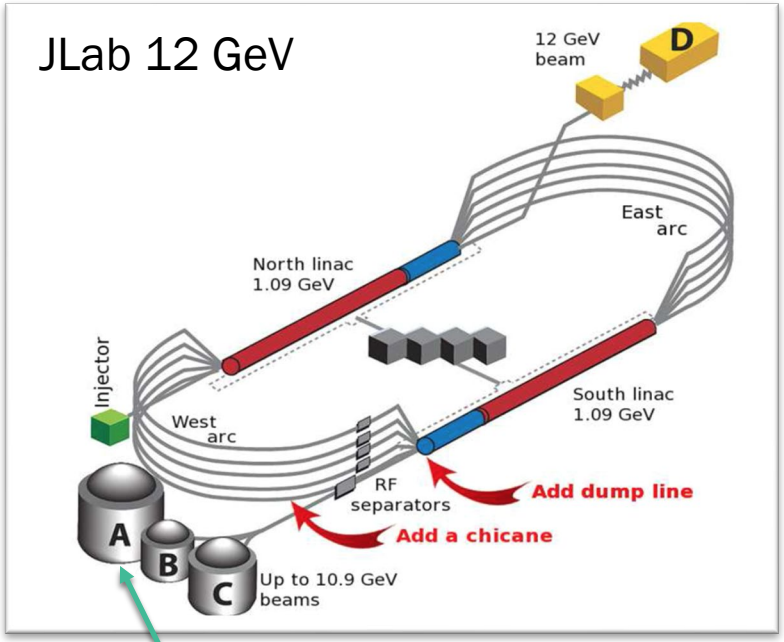
- 2010-2012: Five SoLID experiments approved by JLab PAC with high rating
  - 3 SIDIS, 1 PVDIS, 1 threshold J/ψ
- 2014: pCDR submitted to JLab with cost estimation, updated in 2017, 2019
- Director's Reviews in 2015, 2019 and 2021
- 02/2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE

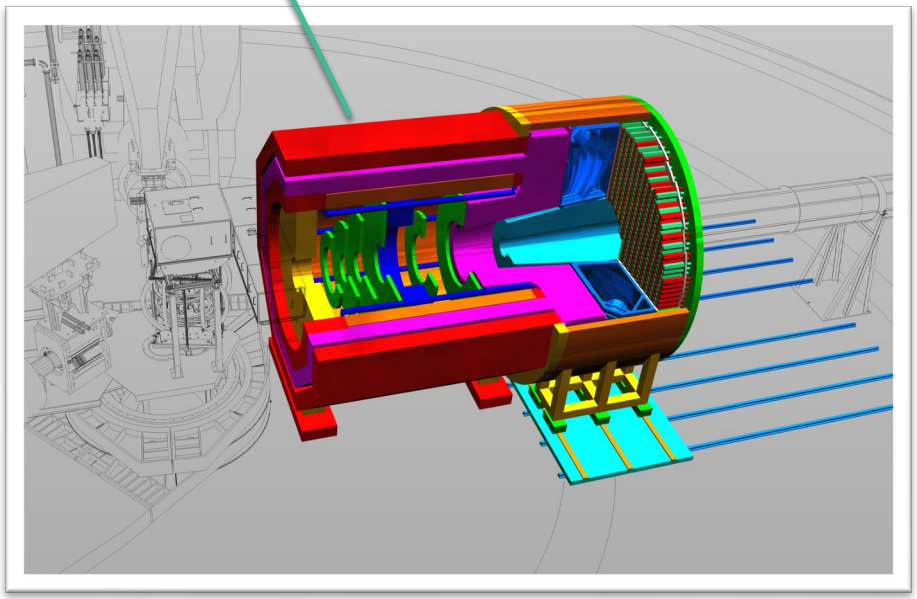
  DOE funded Pre-R&D started and mostly completed
- 03/2021: SoLID Science Review
- 10/2023: "Opportunities to Advance Discovery" in Recommendation 4 of "A New Era of Discovery: The 2023 Long Range Plan for Nuclear Science"
- Continuous efforts in the development of SoLID
  - Pre-conceptual design and pre-R&D with the support of JLab and DOE
  - More SoLID experiments are approved or in development



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

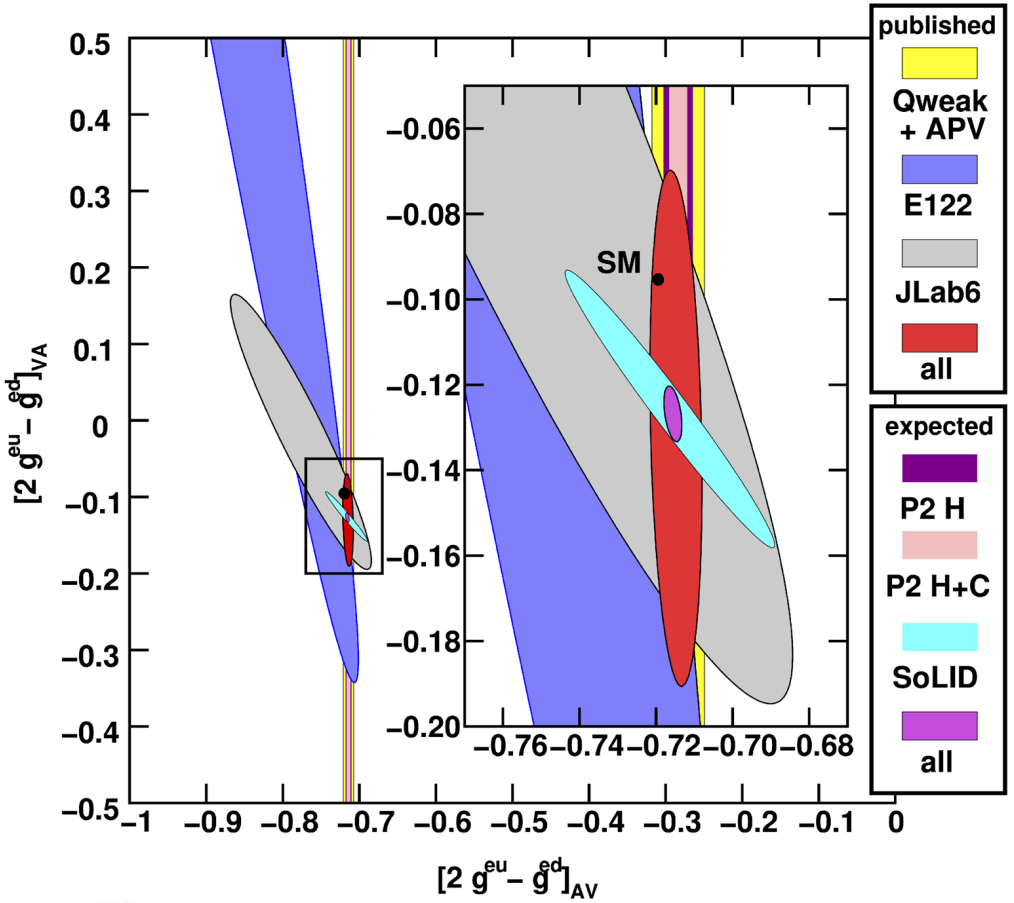
SoLID White Paper

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



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

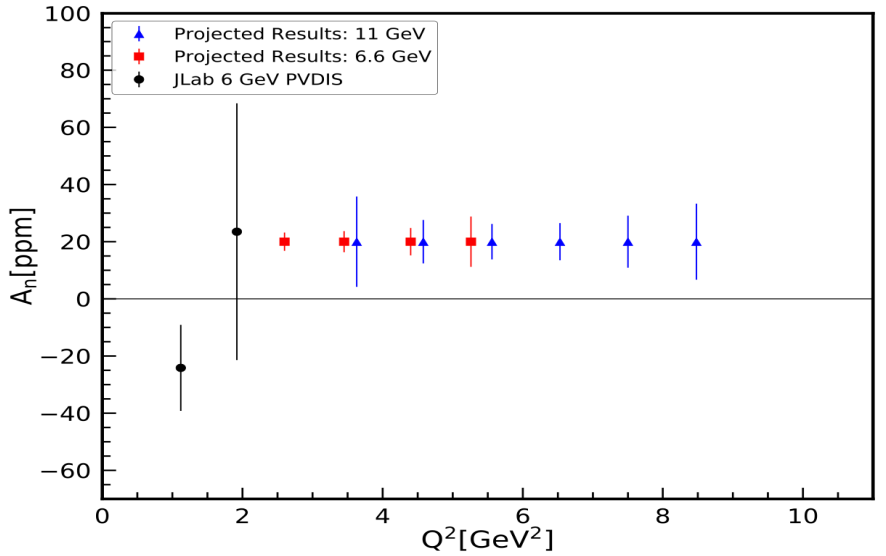
$$\approx \frac{\mathcal{M}^l_{weak,BSM} - \mathcal{M}^r_{weak,BSM}}{\mathcal{M}_{EM}}$$

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

$$\sigma = \left| \gamma + Z + ? \right|^2$$

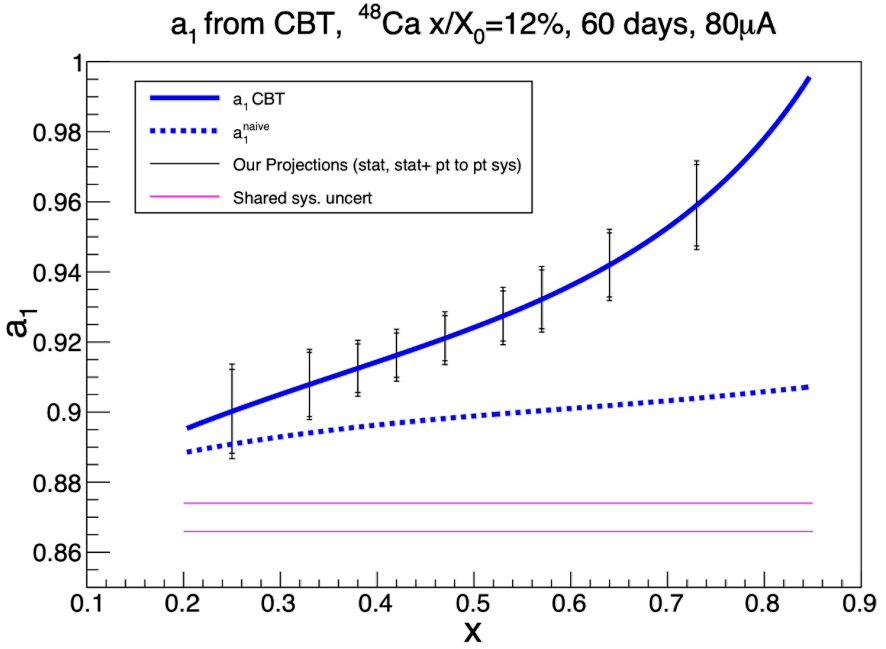
BNSSA and PVEMC Experiments

- 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

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



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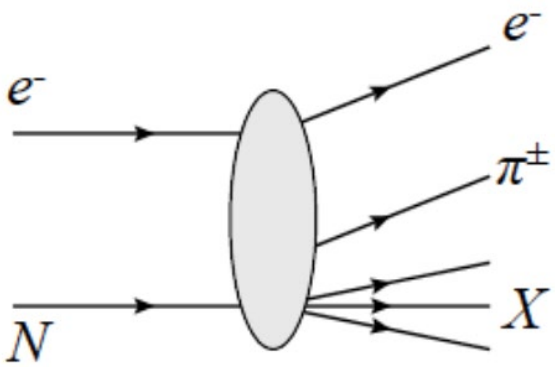
SIDIS Experiments

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)

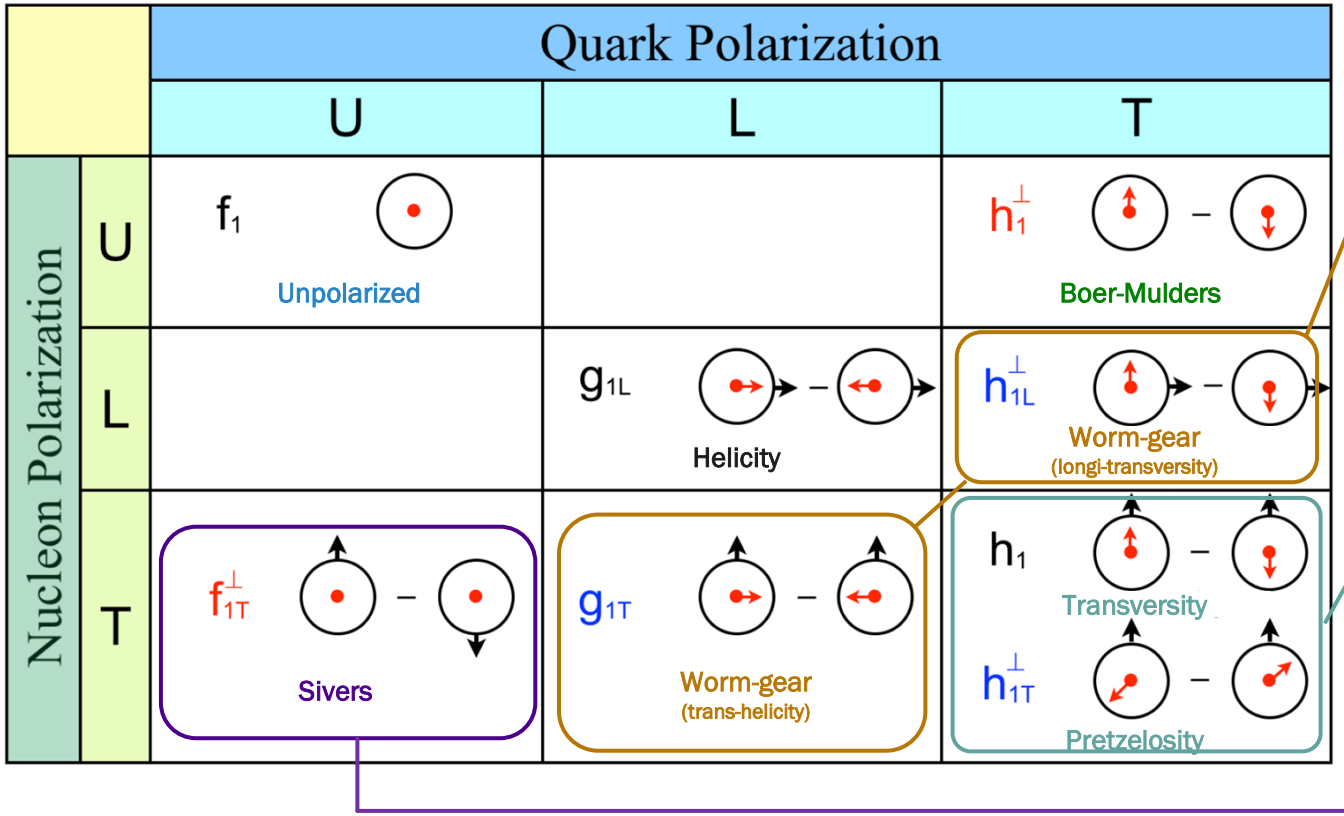
E12-11-108: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)

- 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

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

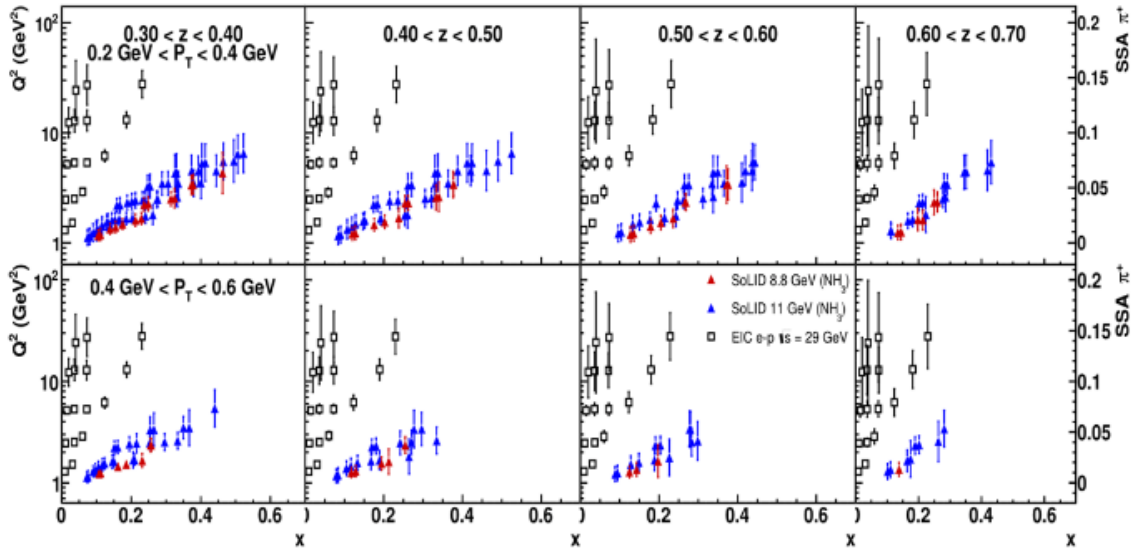
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) \propto h_{1T} \otimes H_1^\perp$$

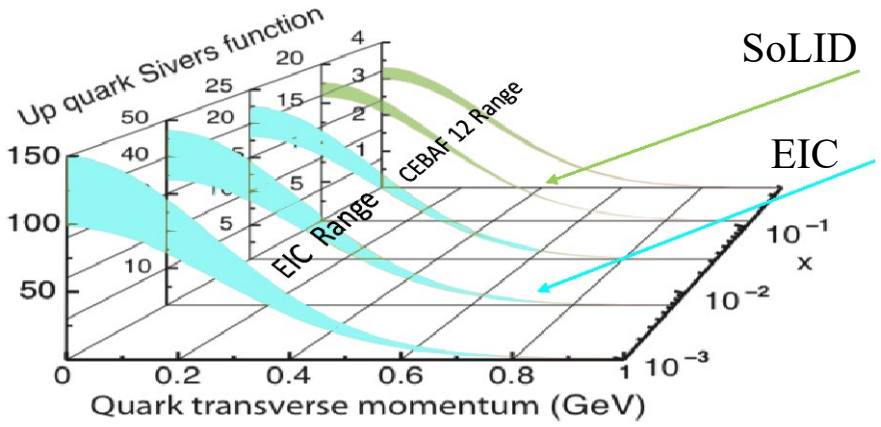
$$+ A_{UT}^{Sivers} \sin(\phi_h - \phi_S) \propto f_1^\perp \otimes D_1$$

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

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

SSA Projections – Complementary to EIC

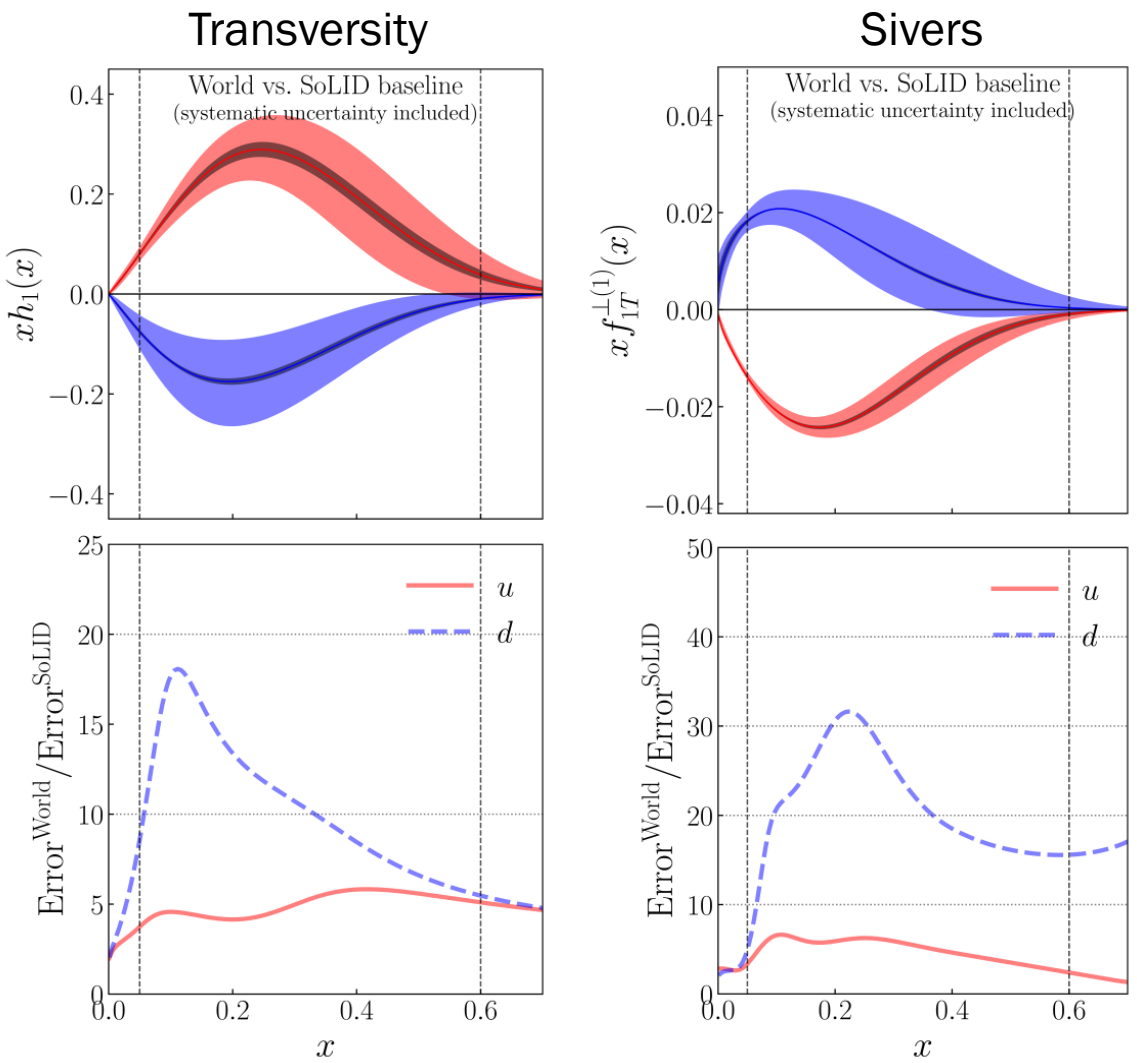




- SoLID SIDIS projections of A_{UT} in various 4-D bins at 11/8.8 GeV
- Projections at EIC kinematics for the same observable at 29 GeV center-of-mass energy
- The scale of the SSA and uncertainties shown on the right-side axis of the figures
- SoLID and EIC projections synergistic towards each other, 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 $Q^2 = 2.4\ GeV^2$



Nucleon Tensor Charge

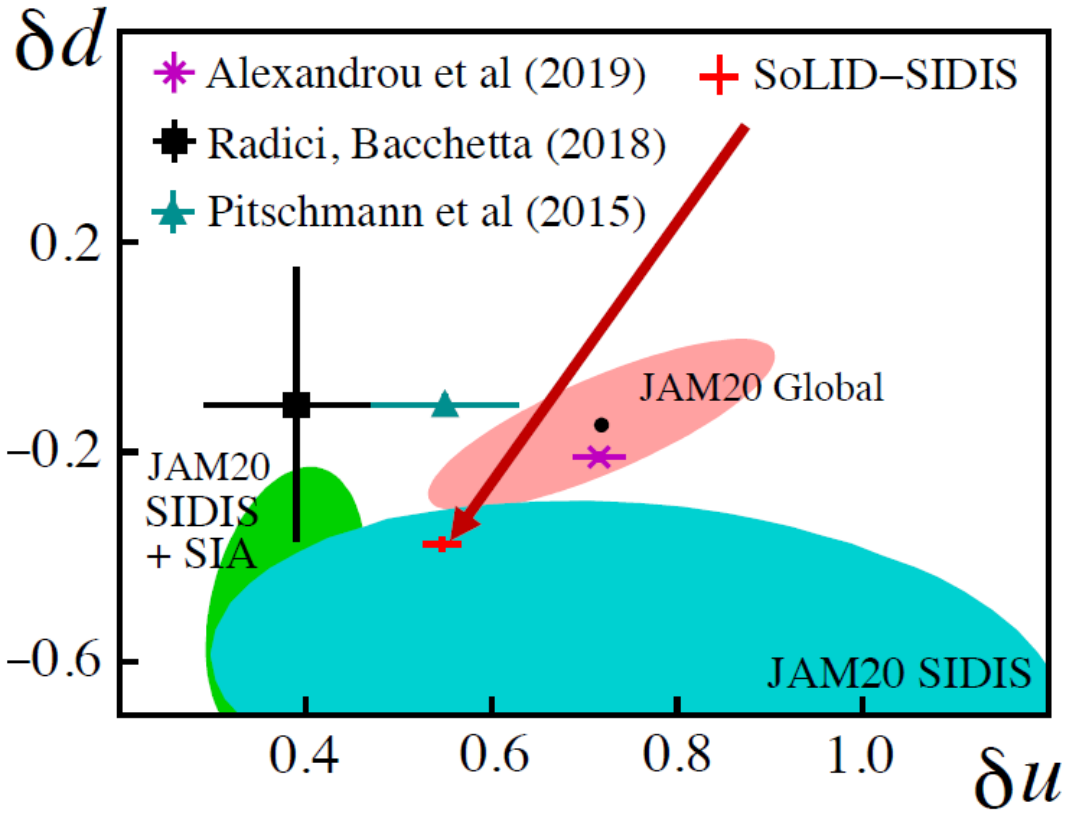
- A fundamental QCD quantity
  - Matrix element of tensor current

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

  - Lowest moment of transversity

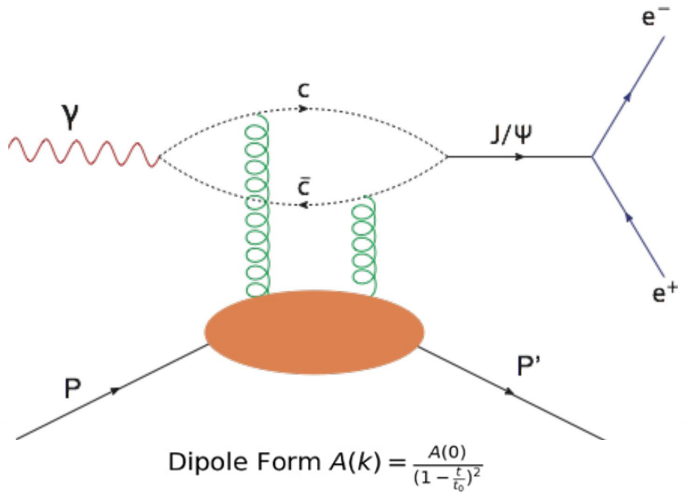
$$\delta_T^q = \int_0^1 \left(h_1^q(x) - h_1^{\bar{q}}(x)\right) dx$$

  - Can be tested in Lattice QCD



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

Near-threshold J/ψ Production



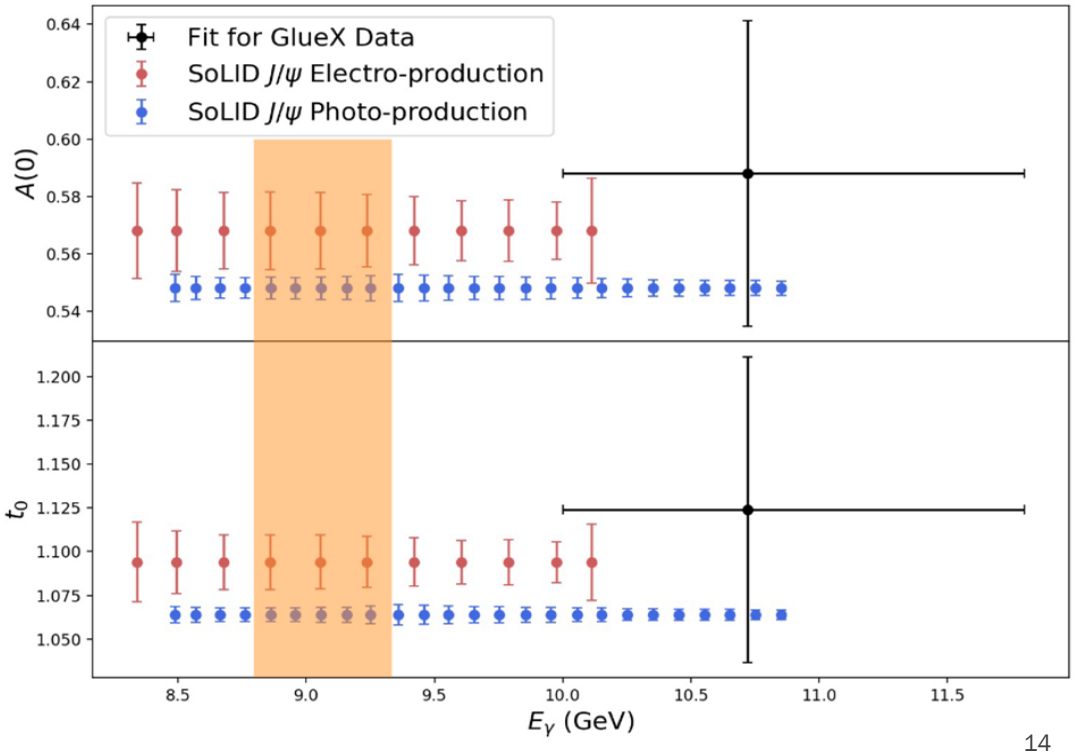
- Electro- and photo-production of Charmonium near threshold

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

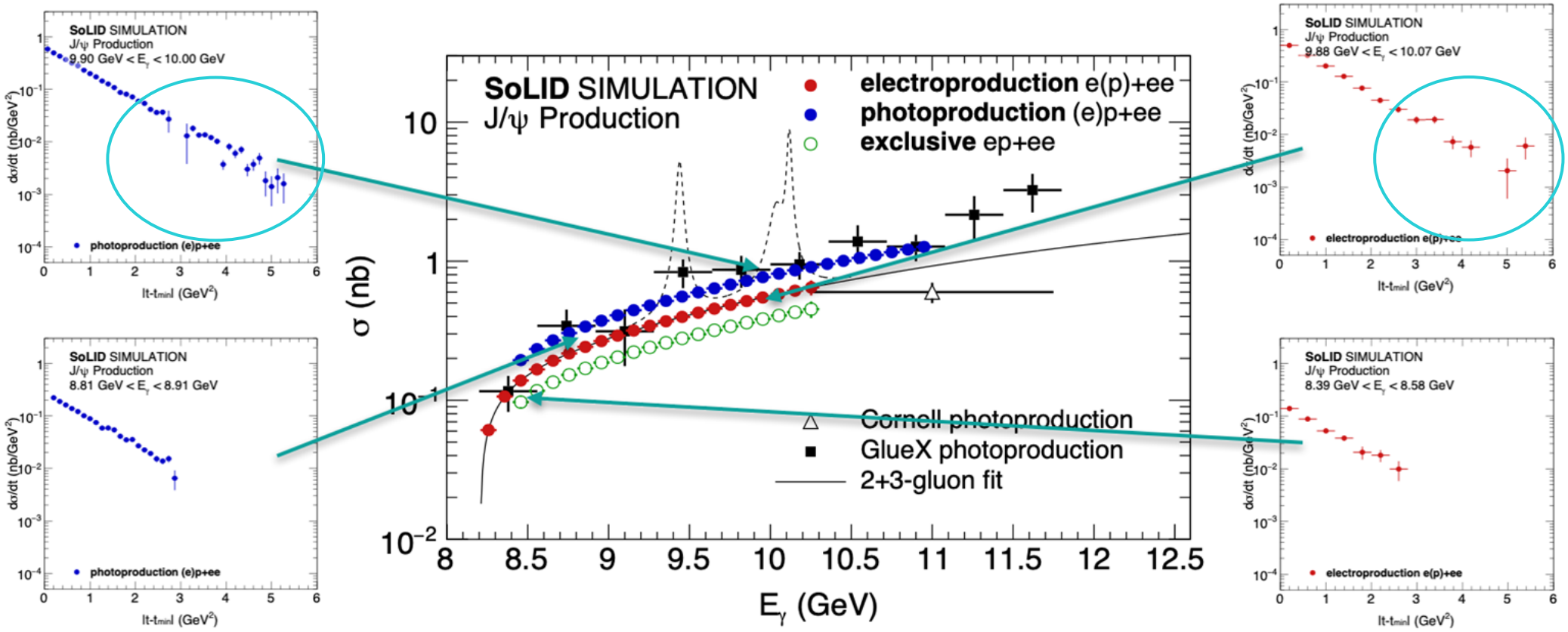
$$\gamma p \rightarrow p'\mathrm{J}/\psi(e^-e^+)$$

- 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

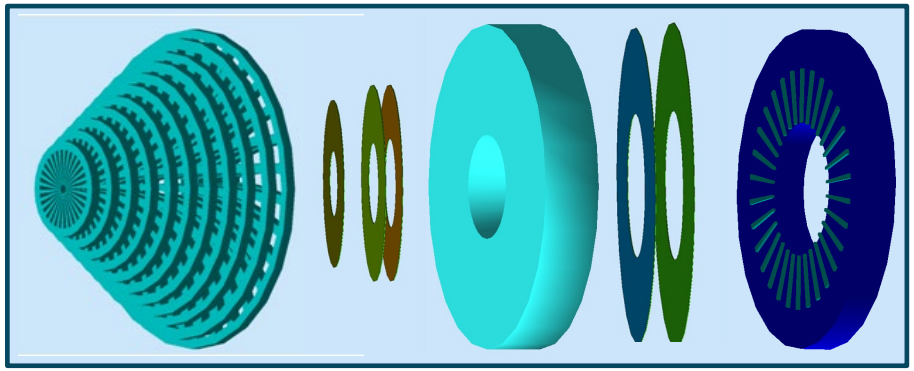
- Design for GEM Trackers
- Design for Scintillator Pad Detector
- Cold Test for CLEO-II Magnet
- Software, simulation, and DAQ development
- **Beam tests for Cherenkov Prototype**
- **Beam tests for Shashlik ECal**

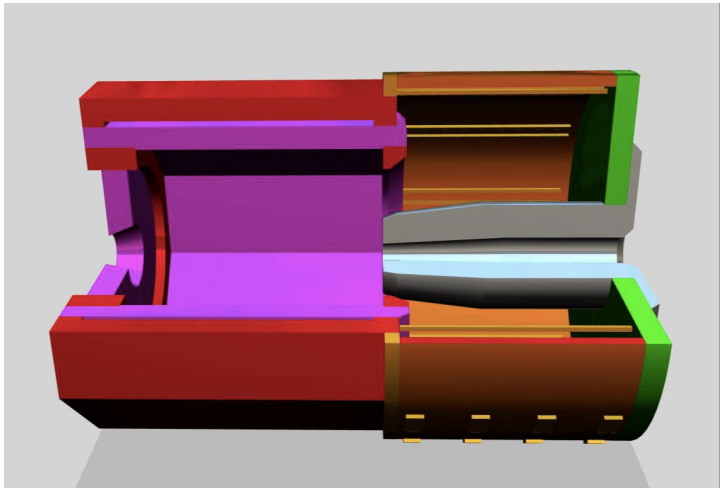
SoLID Detector Subsystems

Uses full capability of JLab electronics

PVDIS

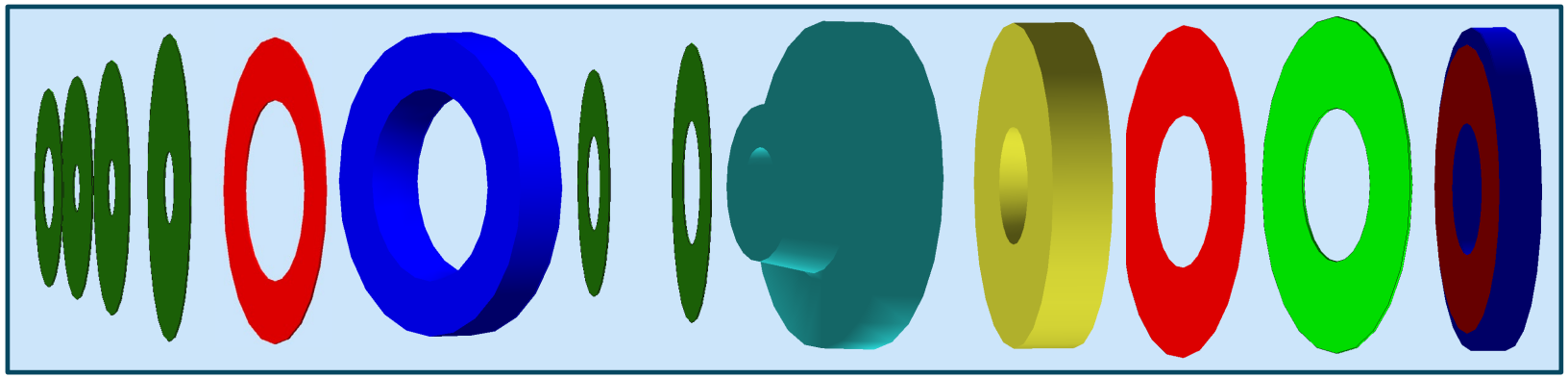
Baffle 3xGEMS LGC 2xGEMs EC





SIDIS-J/ψ

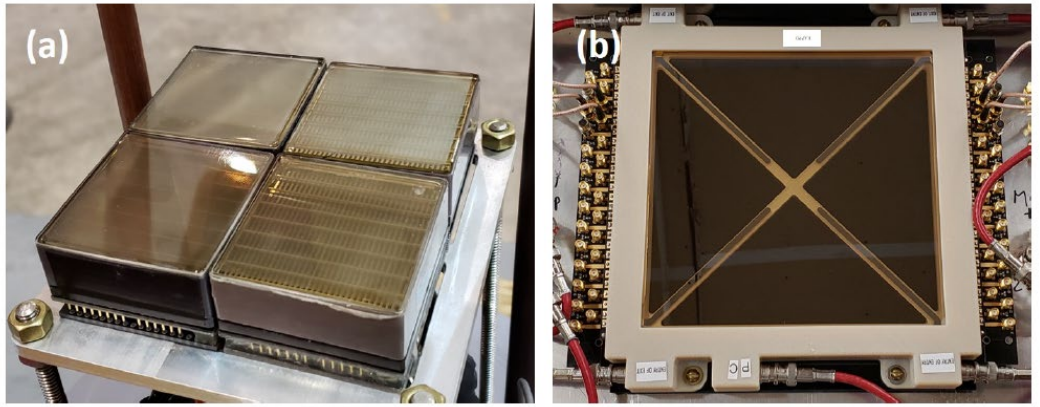
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC

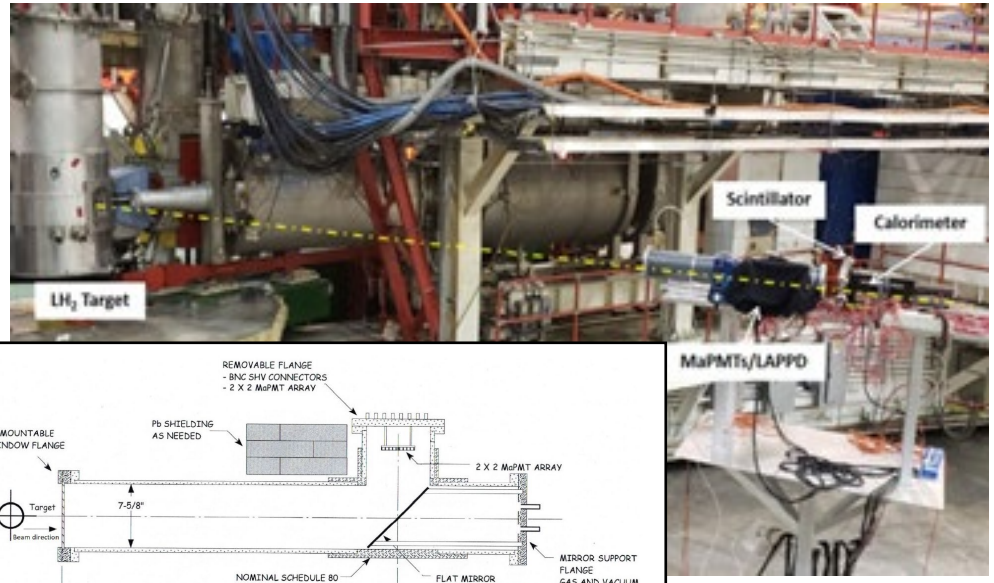


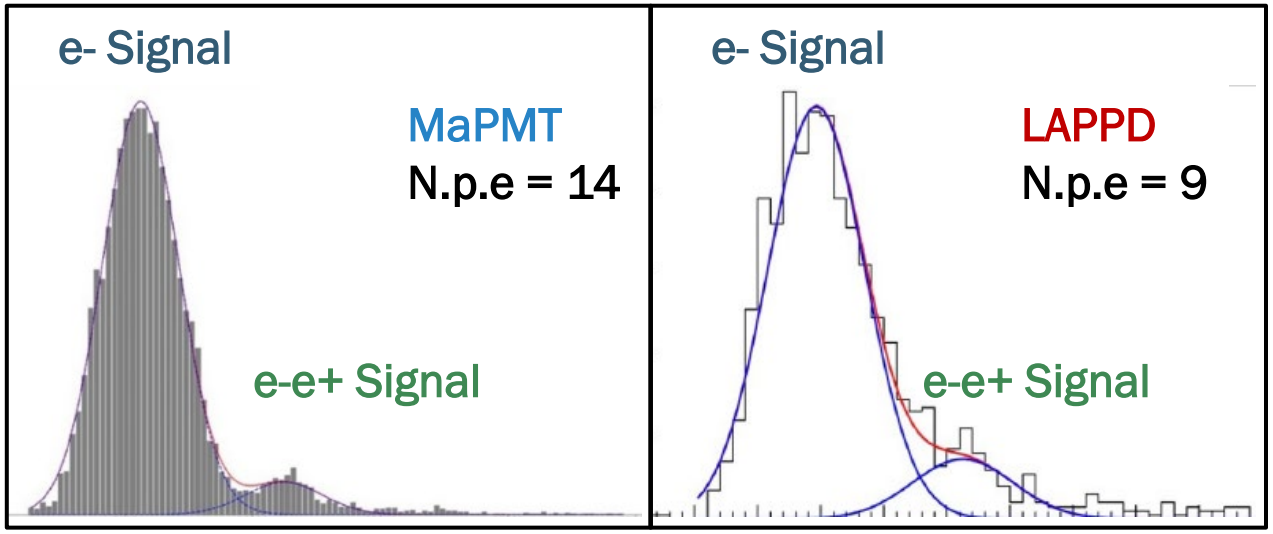
Pre-R&D items: LGC, HGC, GEM's, EC, DAQ/Electronics, Magnet

Beam Tests for Cherenkov Prototype

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



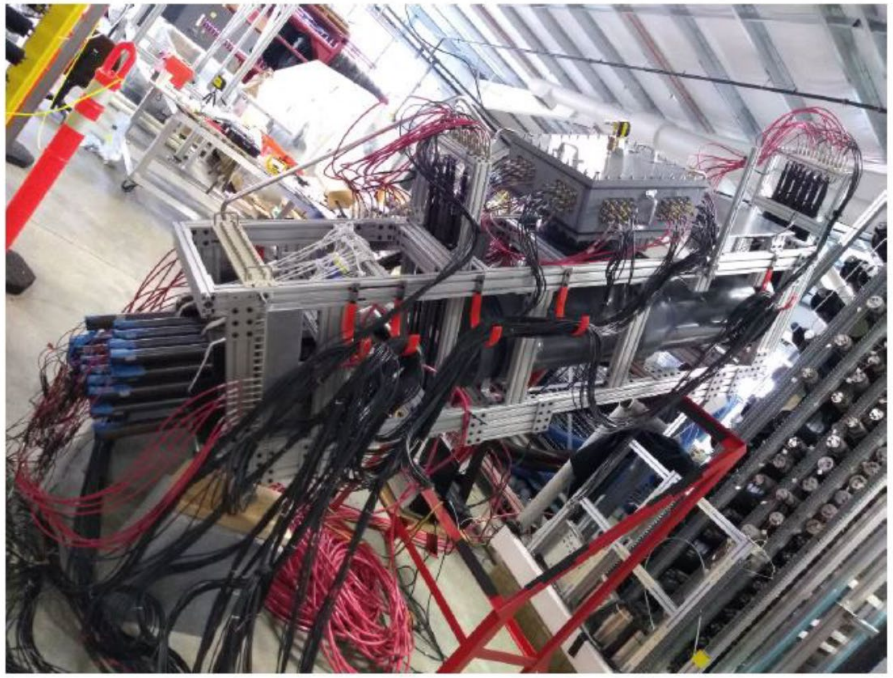


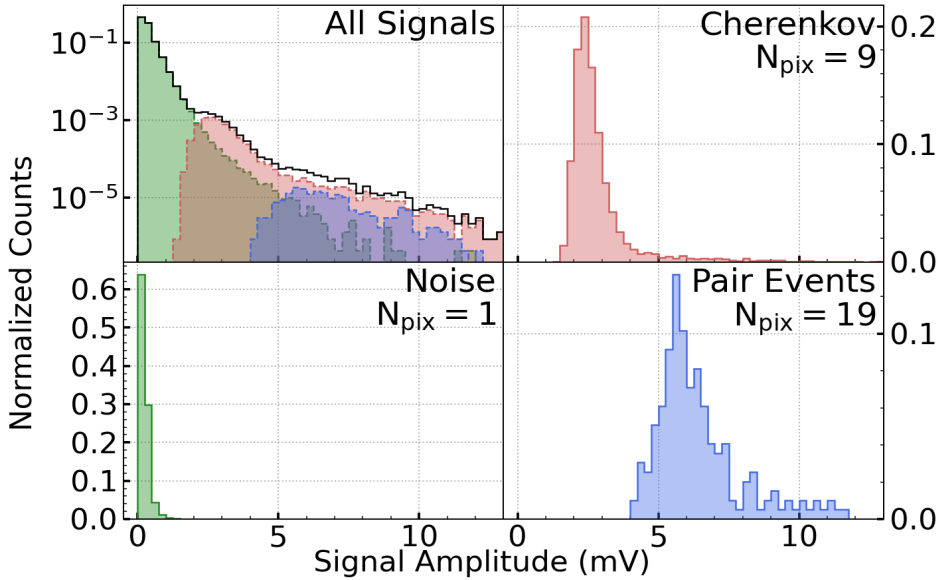


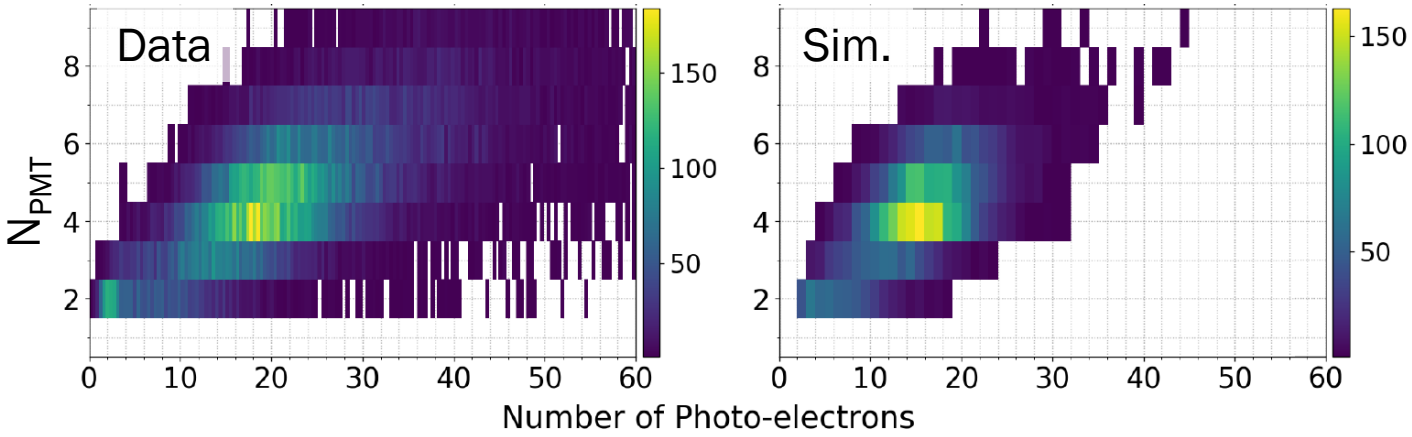
C. Peng et al., JINST 17 (2022), P08022

Beam Tests for Cherenkov Prototype

- 2nd beam test for MaPMT/LAPPD in high-rate background
- SoLID expected rates achieved (> 5 MHz/PMT)
  - Demonstrates the prototype works well in high-rate
  - Separation of different types of signals, initial study for triggers
- Validation of simulations

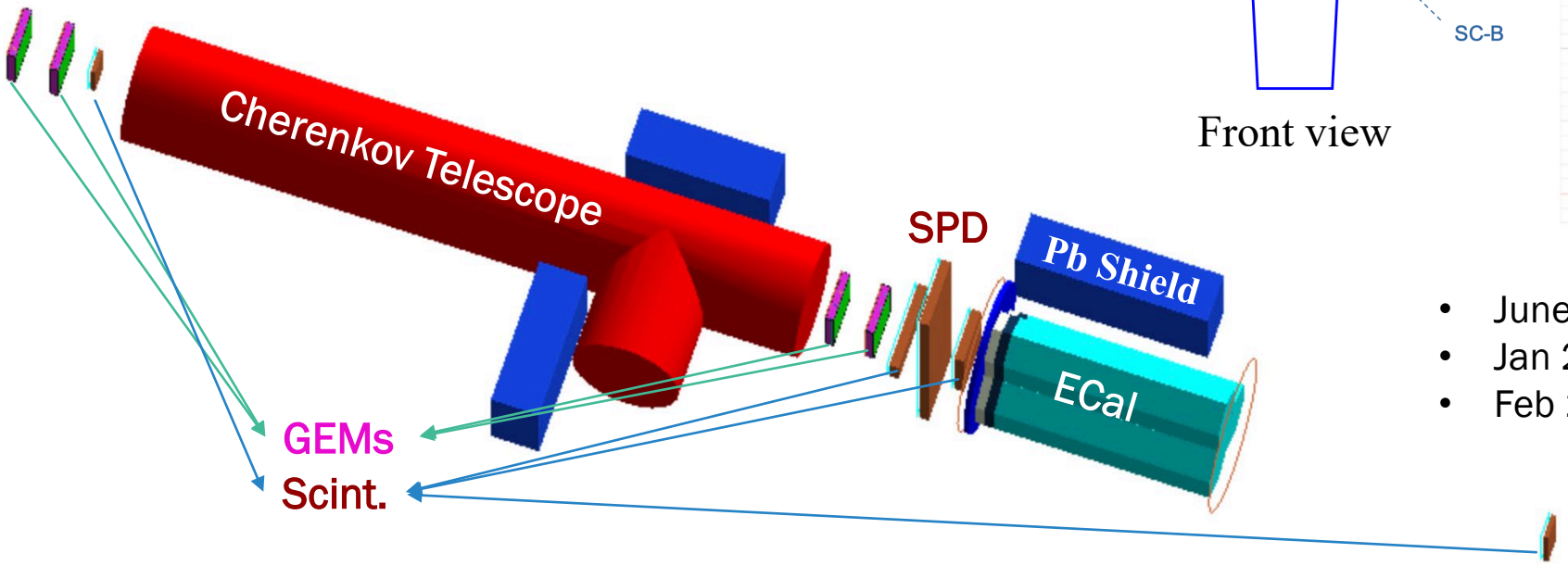


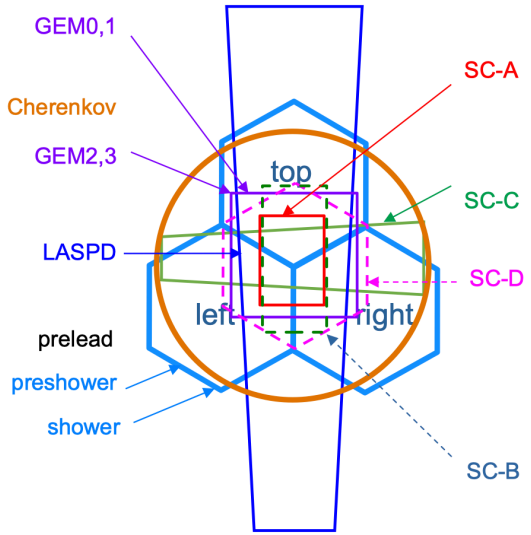




Beam Tests for ECal

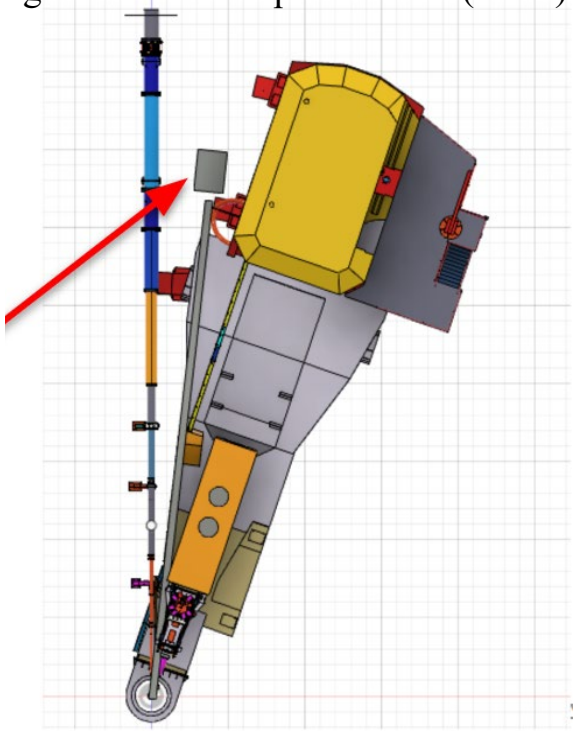
- Similar setup to SoLID detector (no magnet)
- ~10^2 krad
- 3-stages test in Hall C at JLab





Front view

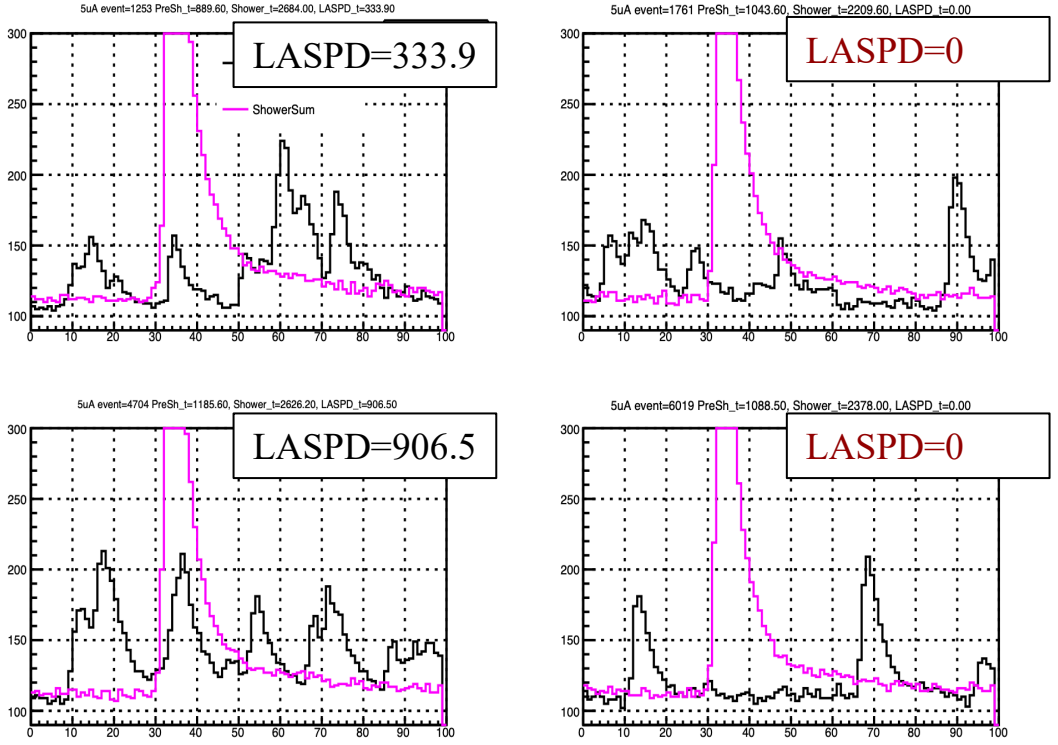
High Momentum Spectrometer (HMS)



- 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



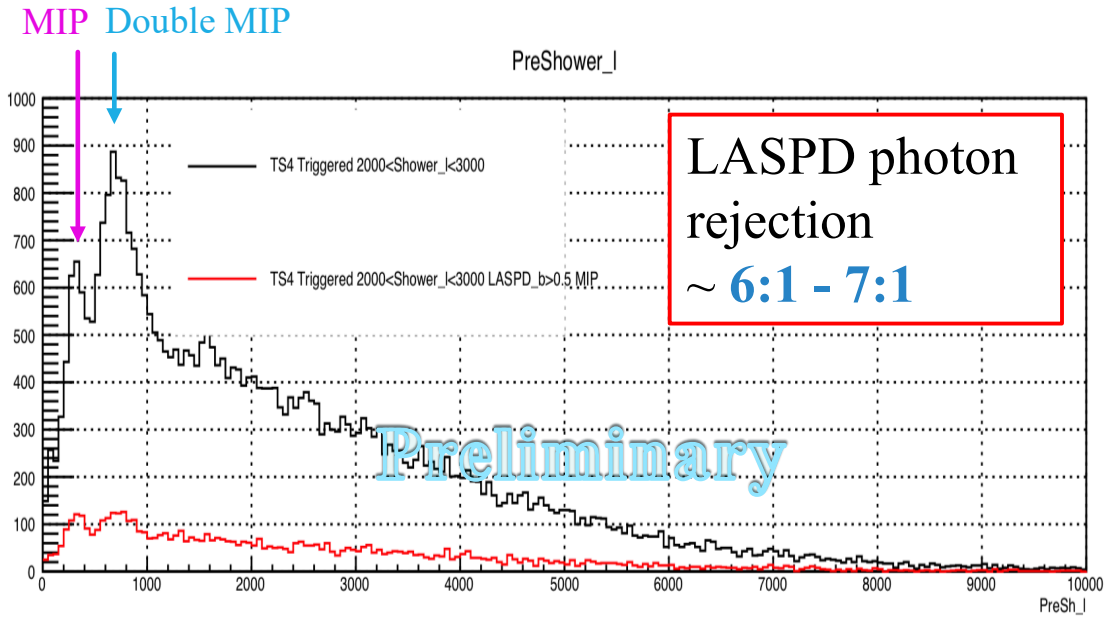
❖ LASPD waveforms with Shower trigger

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.

Summary

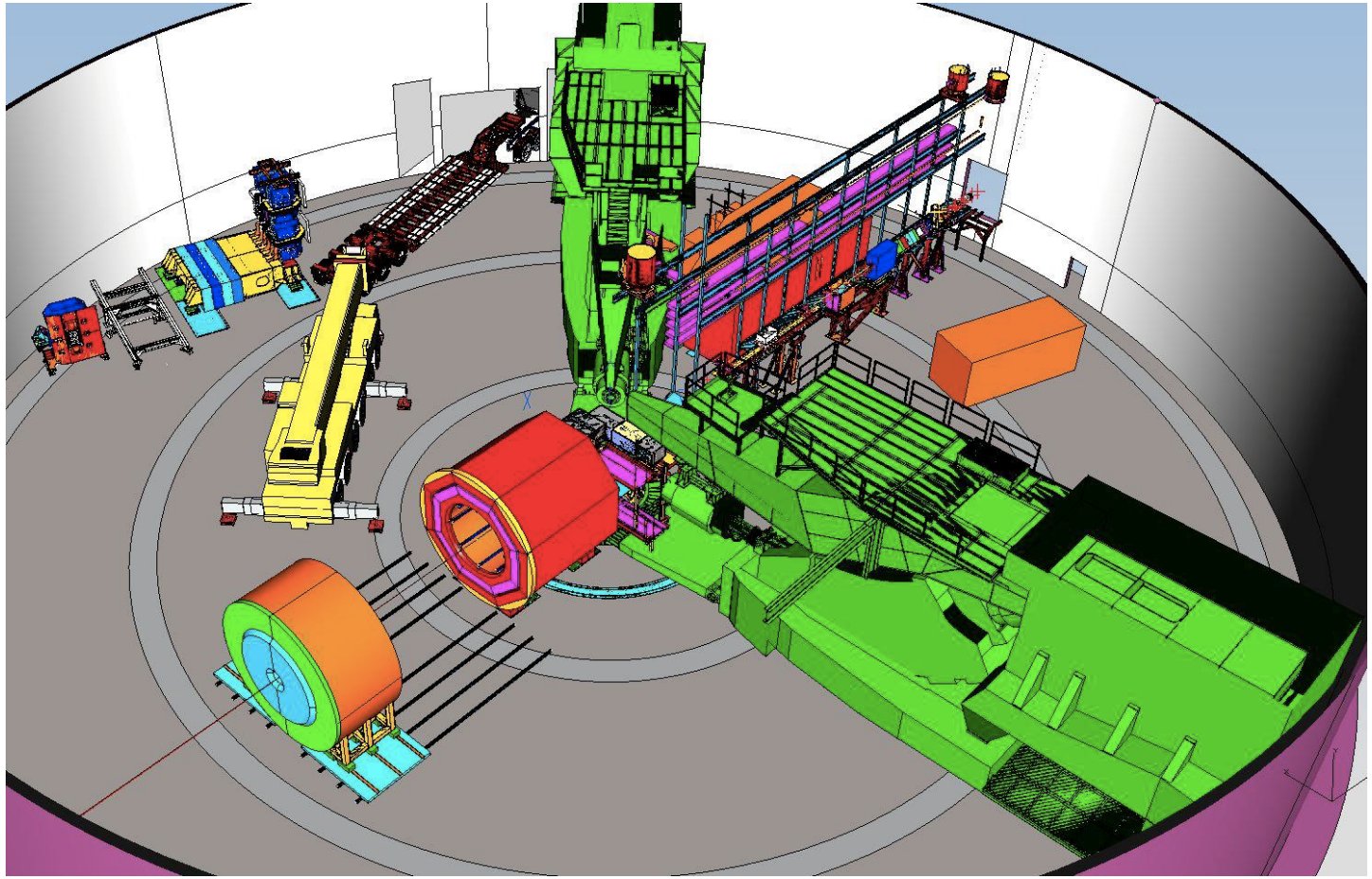
- SoLID is at the intensity frontier with JLab 12 GeV upgrade
  - Rich and highly rated physics programs
  - Address important questions in Nuclear Physics
  - Complementary and synergistic to the EIC science programs
- Three pillars in the SoLID science program
  - PVDIS, SIDIS, near-threshold J/ψ
  - Many other experiments in development
- 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

Pre-conceptual Design of SoLID

Key parameters for SoLID

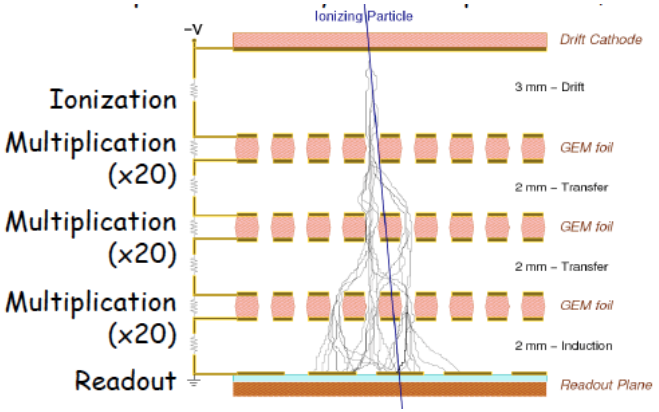
- Unpolarized luminosity 10^{39}
- Polarized luminosity $10^{36\text{-}37}$
- Full 2π azimuthal coverage
  - $\delta\varphi = 6$ mrad
- θ and p coverage
  - PVDIS: 22°-35° (1 mrad); 2.3-5 GeV/c (2%)
  - SIDIS-J/ψ : 8°-24° (2-3 mrad); 1-7 GeV/c (2-3%)
- Precision PID e/π and e/π/K (SIDIS)

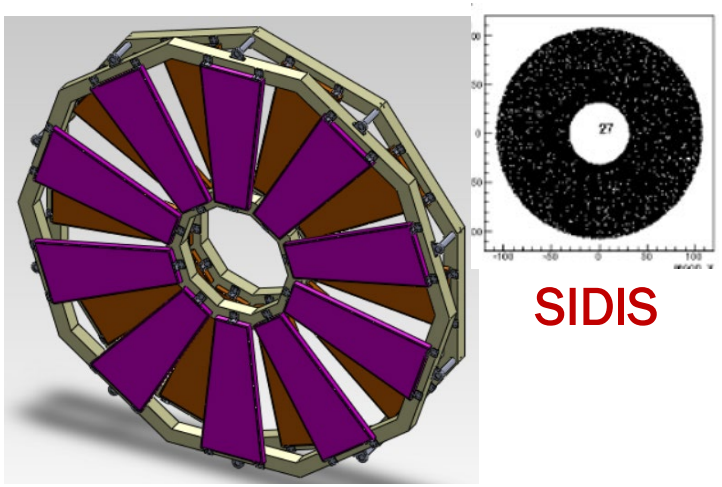


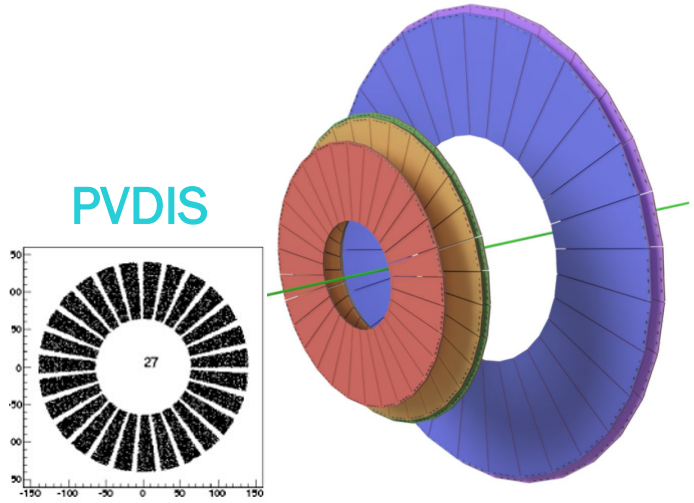
Plan for installing SoLID in Hall A

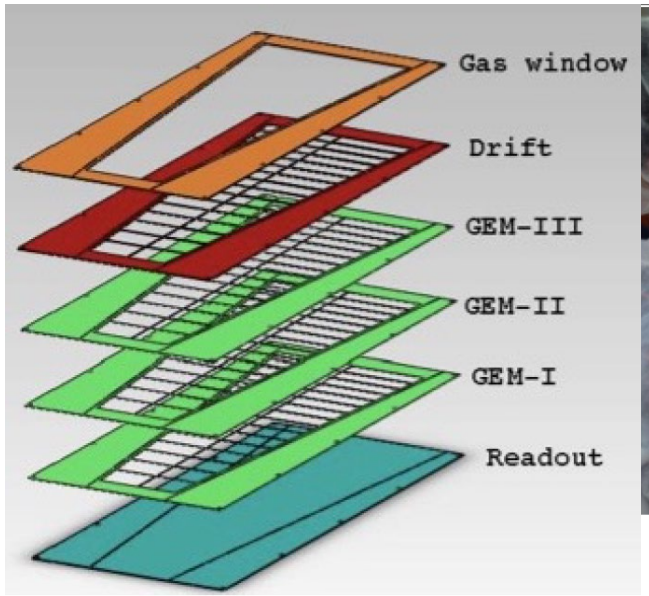
GEM Trackers

- 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…

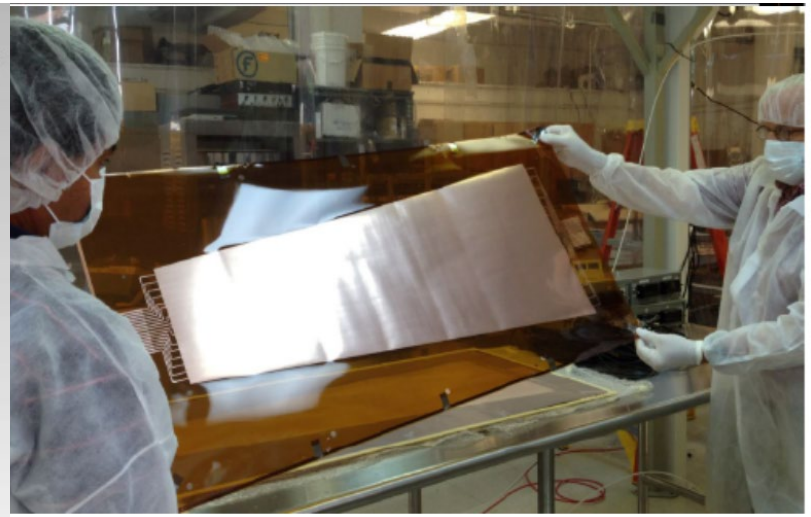








Proposed SoLID GEM Module



UVa EIC GEM Prototype: similar to SoLID design

Scintillator Pad Detector: Requirements and Design

LASPD: photon rejection 5:1;

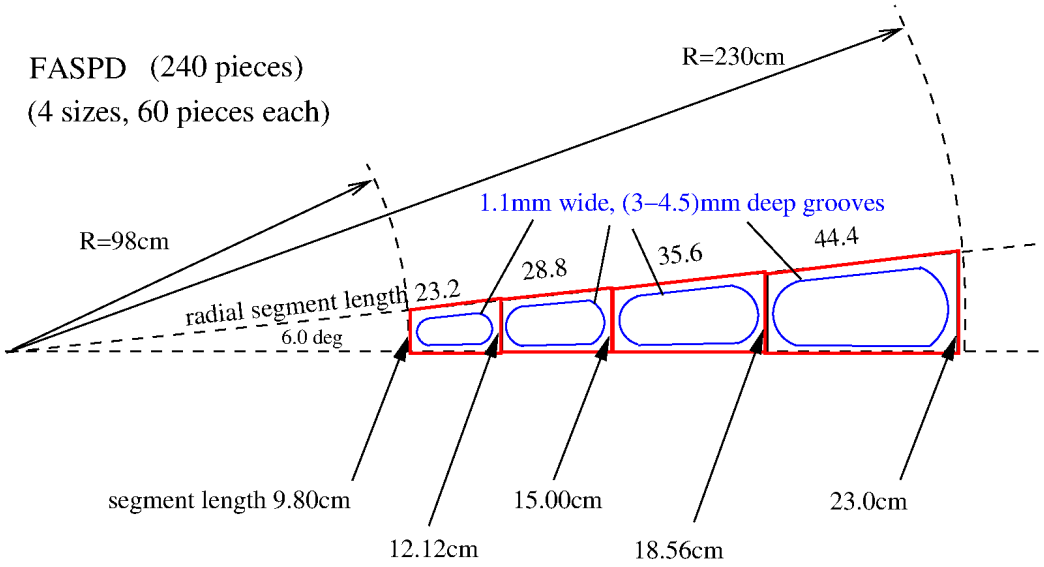
coincidence TOF (150ps)

→ 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

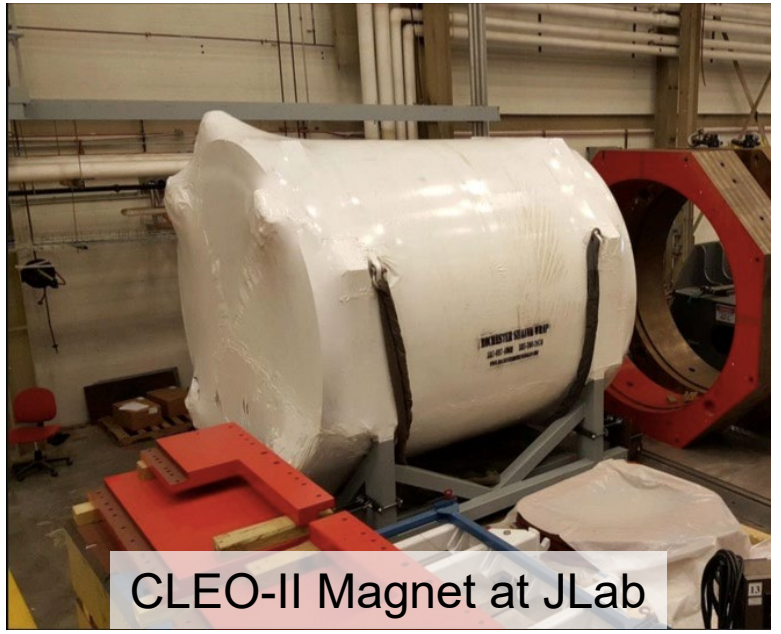
240 segments (60 X 4)

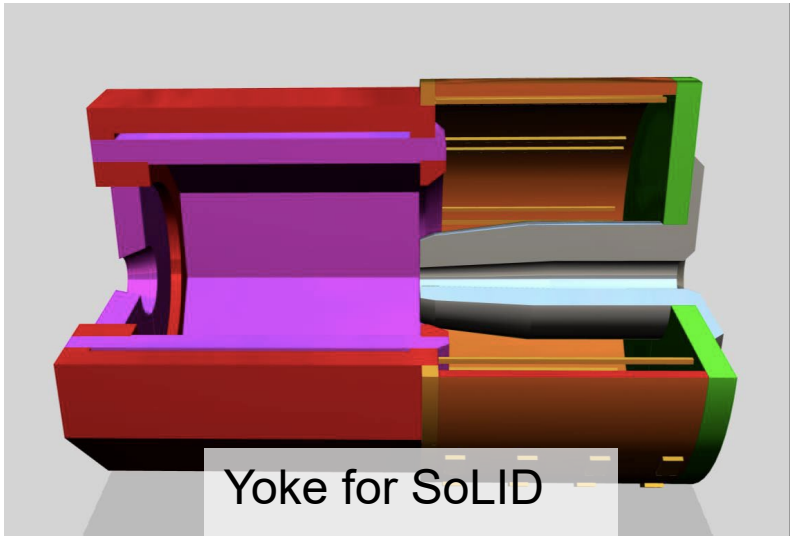
WLS fiber embedding,

MAPMT (outside magnet)

Magnet – Built on the CLEO-II Solenoid

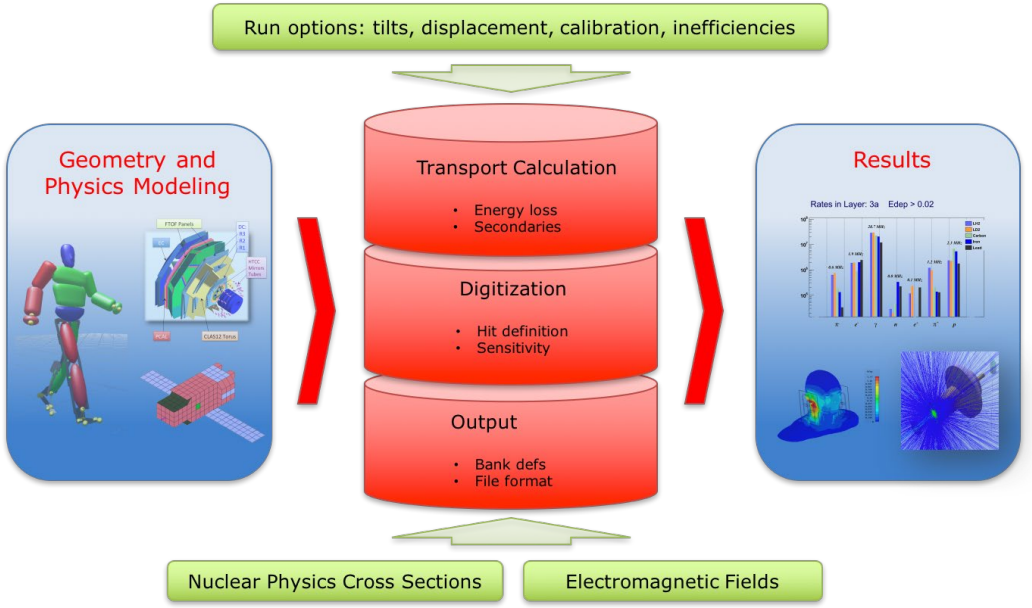
- Requirements:
  - Acceptance:
    p @ 1.0 – 7.0 GeV/c,
    ϕ @ 2π,
    θ @ 8°-24° (SIDIS), 22°-35° (PVDIS)
  - Resolution: $\delta p \sim 2\%$ (0.1 mm tracking resolution)
  - Fringe field at the ^{3}He target < 5 Gauss
- Modifications:
  - Use 2 out of 3 layers of return yoke
  - Thicken the front 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

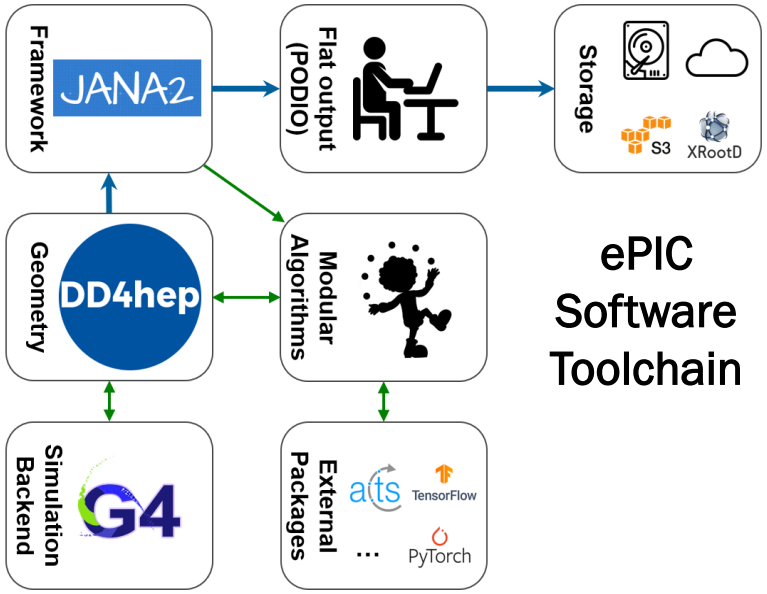

Yoke for SoLID

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