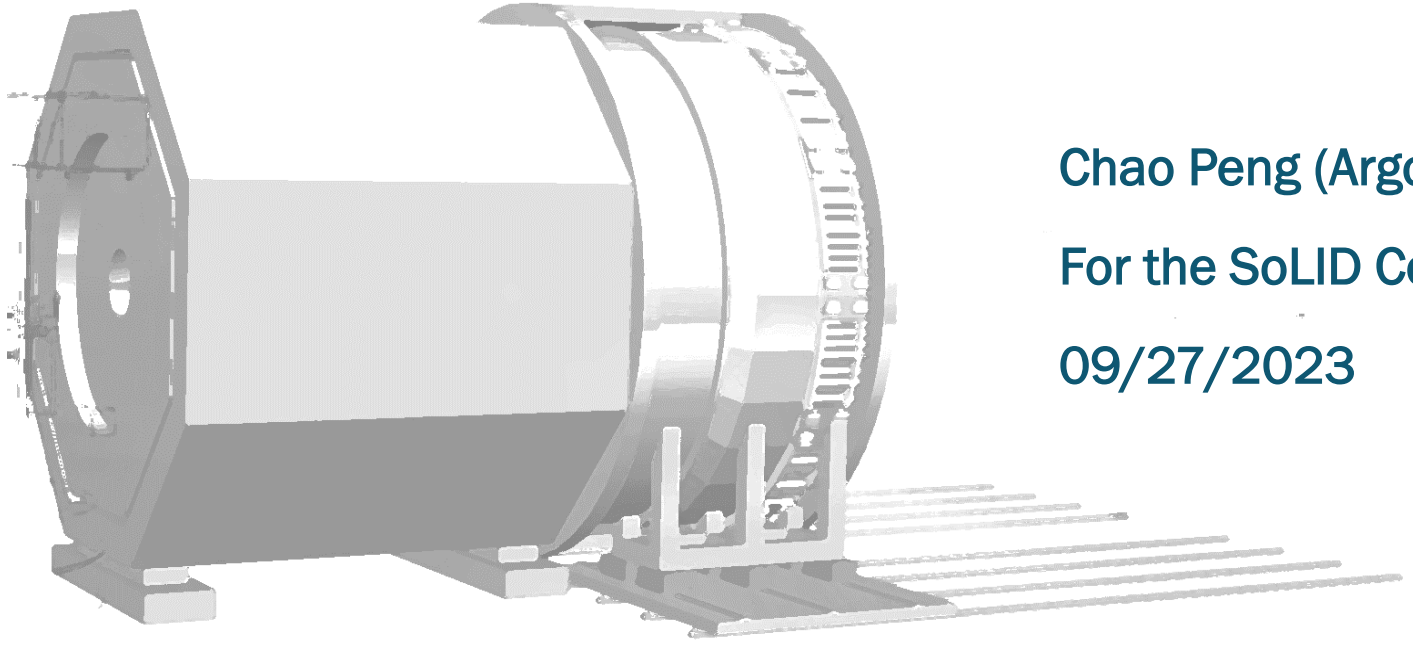
25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM
24-29 September 2023, Durham, NC

SoLID: Investigate the Nucleon at the Luminosity Frontier



Chao Peng (Argonne National Laboratory)

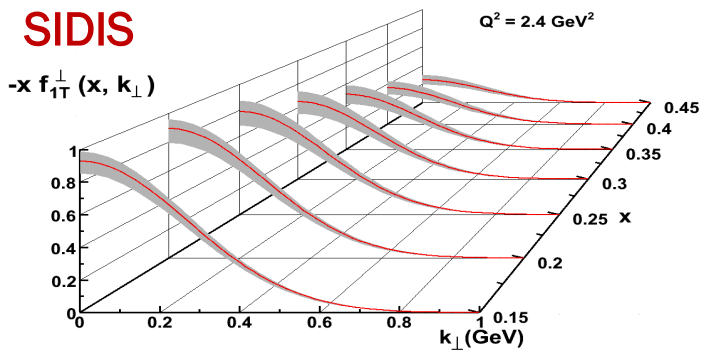
For the SoLID Collaboration

09/27/2023

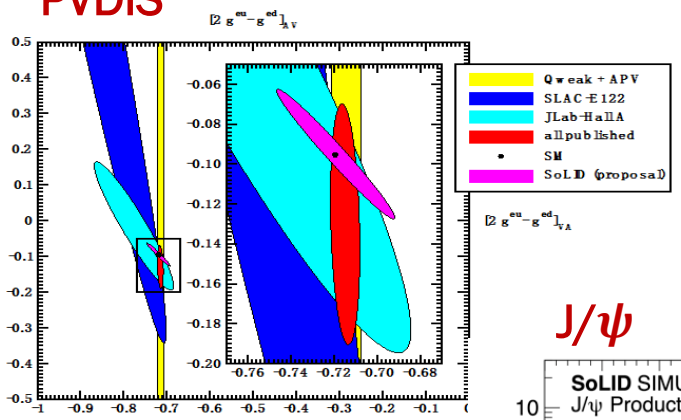
Solenoidal Large Intensity Device (SoLID)

- Maximize scientific outcome of JLab 12 GeV upgrade
  - QCD Intensity frontier (high luminosity $10^{37\text{-}39}/\text{cm}^2/\text{s}$)
  - 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

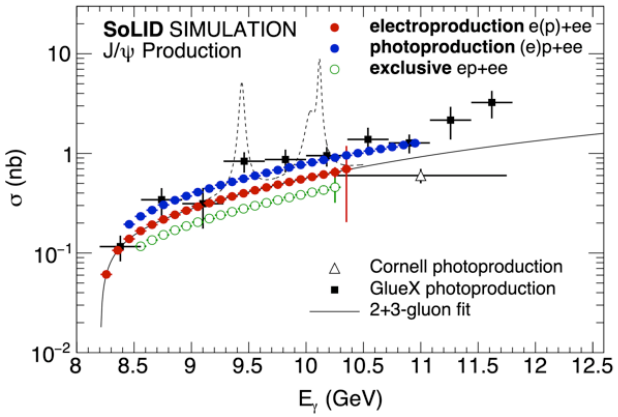
SIDIS



PVDIS

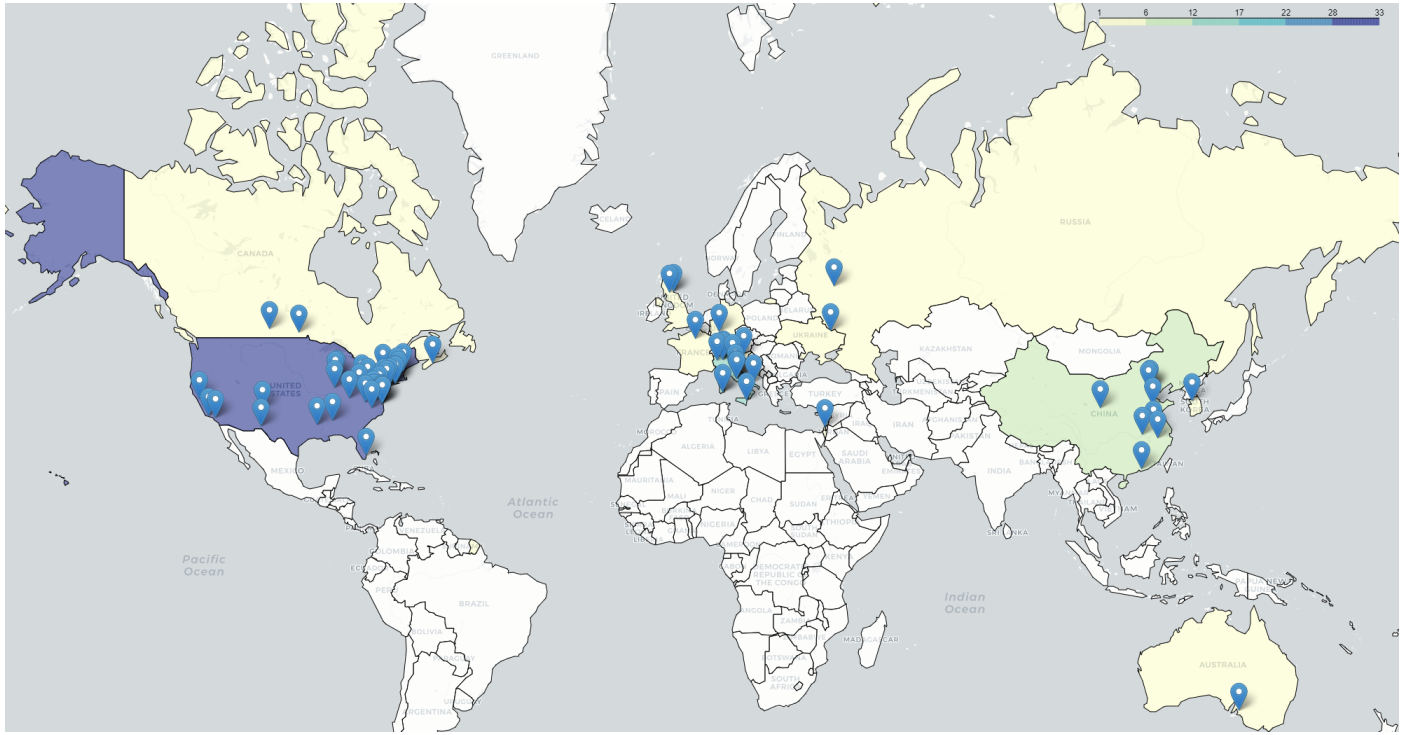


J/ψ



Strong Collaboration

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



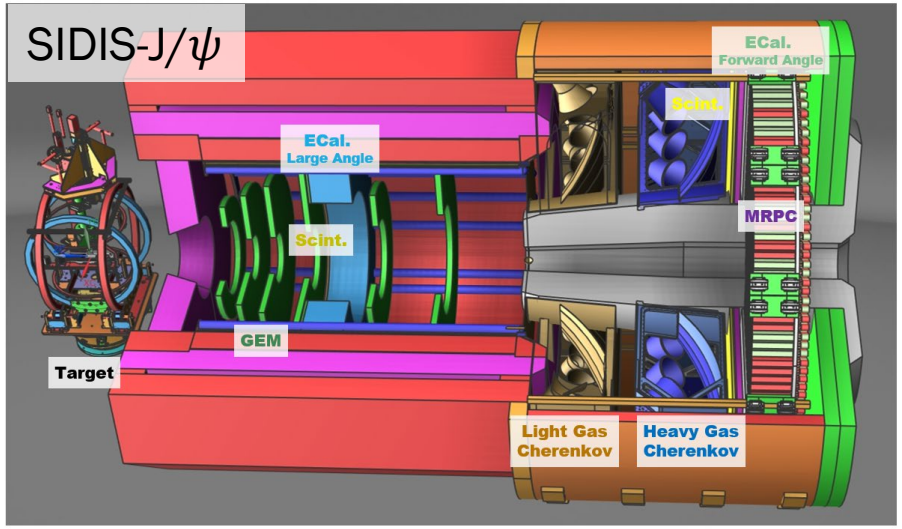
Progresses Since the First Approvals of SoLID Experiments

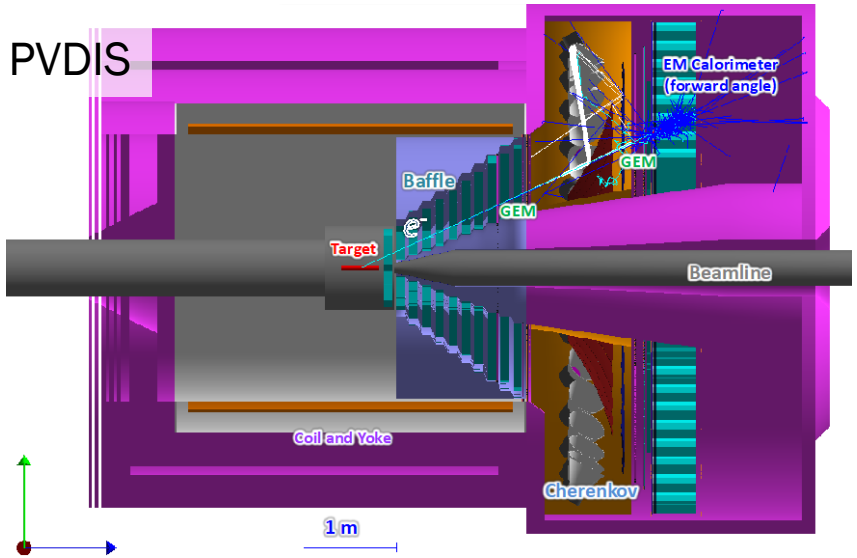
- 2010-2012: Five SoLID experiments approved by JLab PAC with high rating
  - 3 SIDIS, 1 PVDIS, 1 threshold J/ψ
- 2014: pCDR submitted to JLab with cost estimation, updated in 2017 and 2019
- Director's Reviews in 2015, 2019 and 2021
- CLEO-II magnet arrived at JLab in 2016, cold test on-going
- 02/2020: SoLID MIE (with updated pCDR/estimated cost) submitted to DOE

  DOE funded Pre-R&D started and mostly completed
- 03/2021: SoLID Science Review
- Continuous efforts in the development of SoLID
  - Pre-conceptual design and pre-R&D with the support of JLab and DOE
  - Beam tests to validate key detector and DAQ subsystems of SoLID
  - More SoLID experiments are approved, conditionally approved, or in development

SoLID Detector Configurations

- SIDIS-J/ψ and PVDIS Configurations
- 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

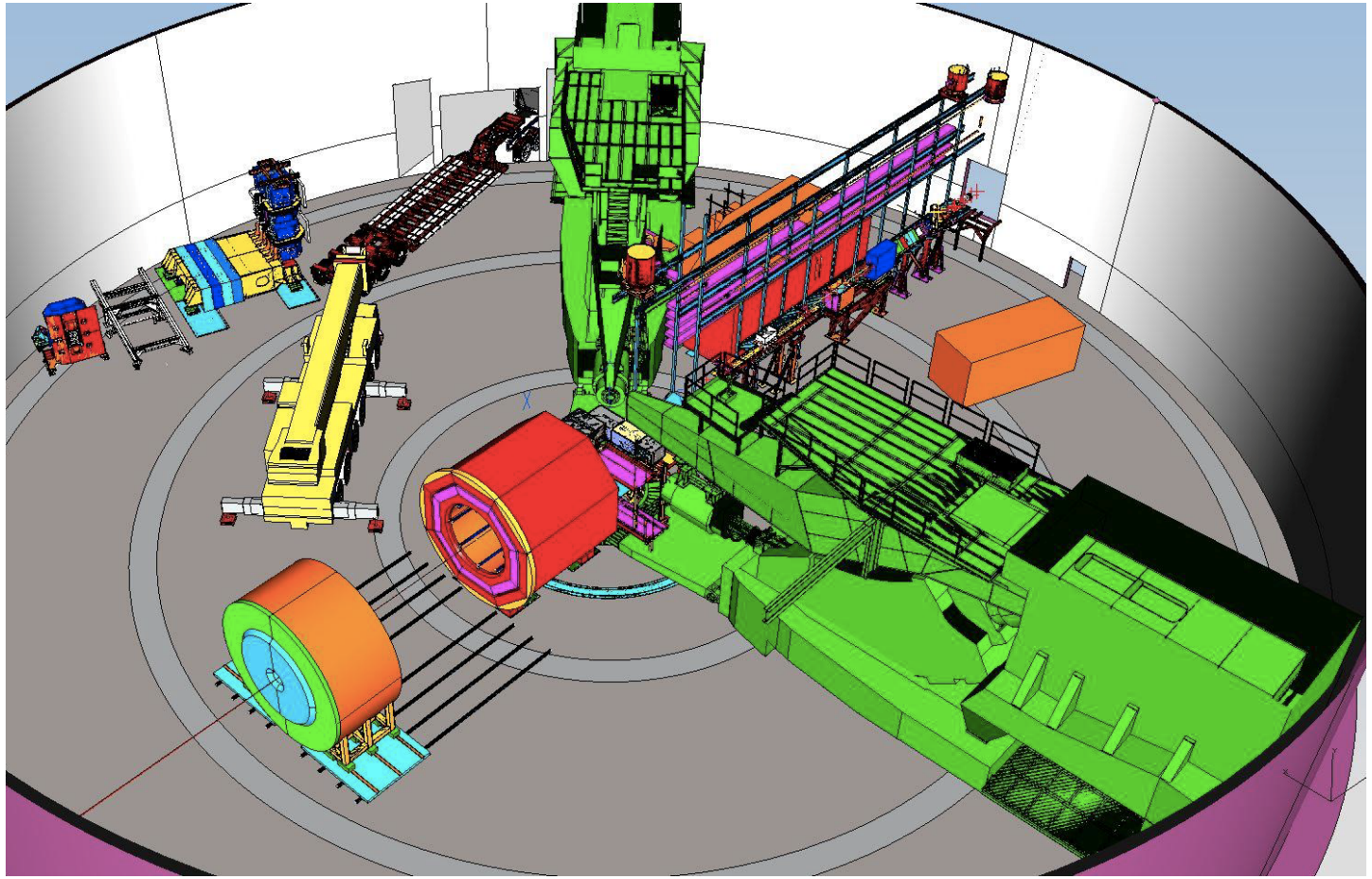




Pre-conceptual Design of SoLID

<u>Key parameters for SoLID</u>

- 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

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

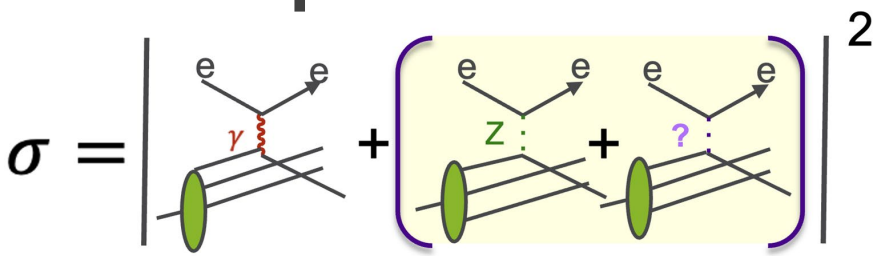
SoLID White Paper

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

:arXiv:2209.13357

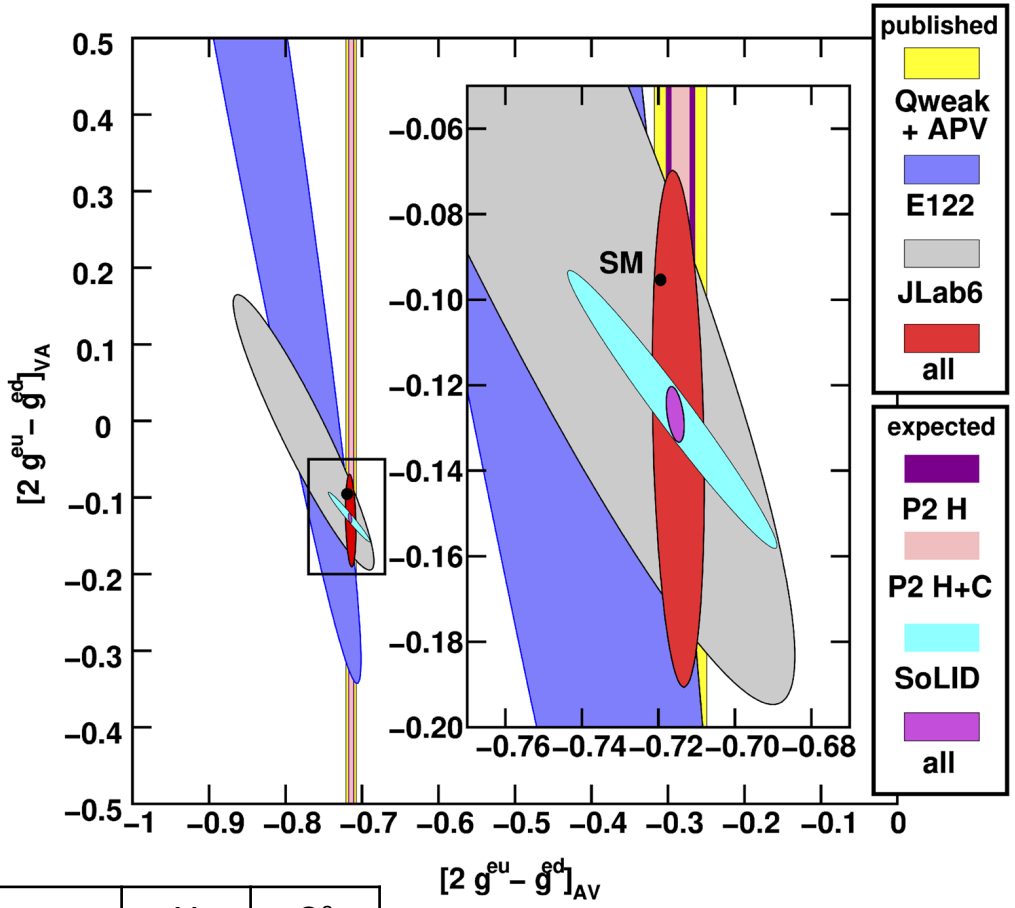
Tian Ye's talk @ 10:00 am

PVDIS Experiment



- $\sin^2\theta_W$ is a Standard Model parameter
- Search for BSM Physics looks directly at **couplings**
- Sensitive to QCD effects through parton distributions in R_s and R_v

$$A_{PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{\mathcal{M}^l_{weak,BSM} - \mathcal{M}^r_{weak,BSM}}{\mathcal{M}_{EM}} \propto \frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$



	x	Y	Q^2
New Physics	none	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

$$A_{\text{Meas.}} = A_{\text{SM}}\left[1 + \frac{\beta_{\text{HT}}}{(1-x)^3 Q^2} + \beta_{\text{CSV}} x^2\right]$$

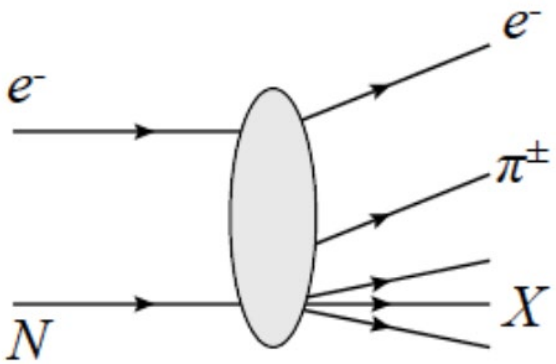
SIDIS Experiments

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)

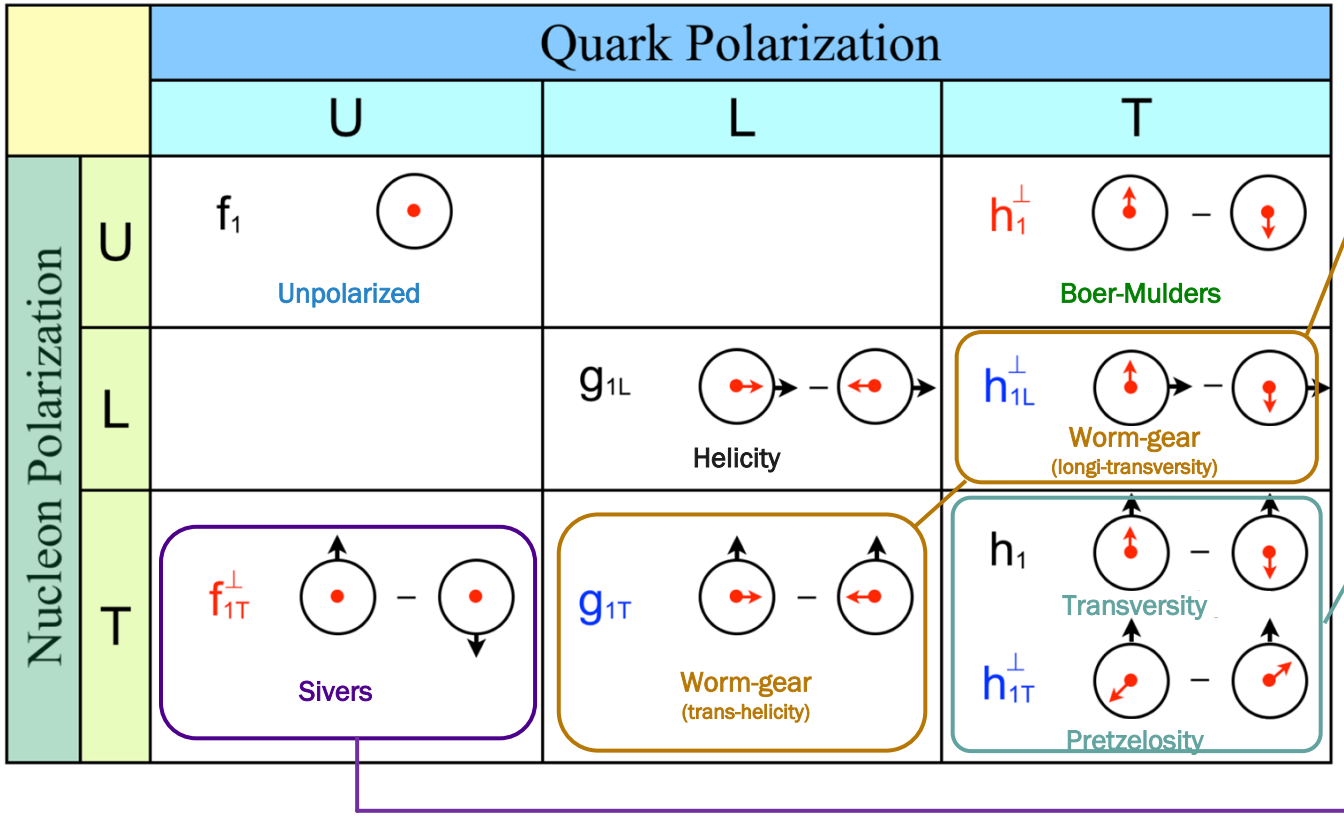
E12-11-108: Single Spin Asymmetry in SIDIS on Transversely Polarized Proton (120 days)

- 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

$$A_{UL}^{\sin 2\phi_h} \propto h_{1L}^\perp \otimes H_1^\perp$$

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

(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

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

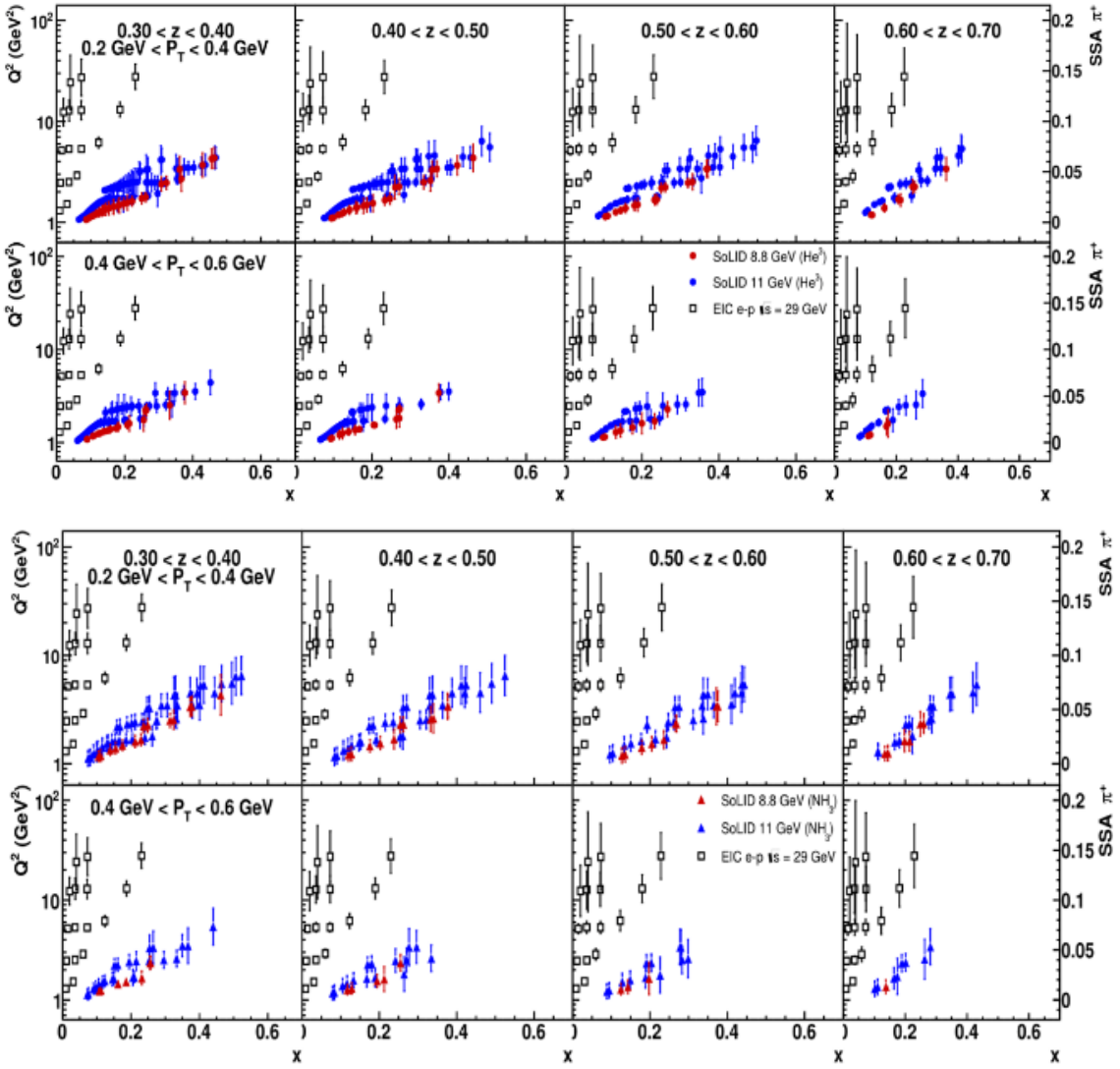
$$= A_{UT}^{Collins} \sin(\phi_h + \phi_S) \quad \propto h_{1T} \otimes H_1^\perp$$

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

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

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

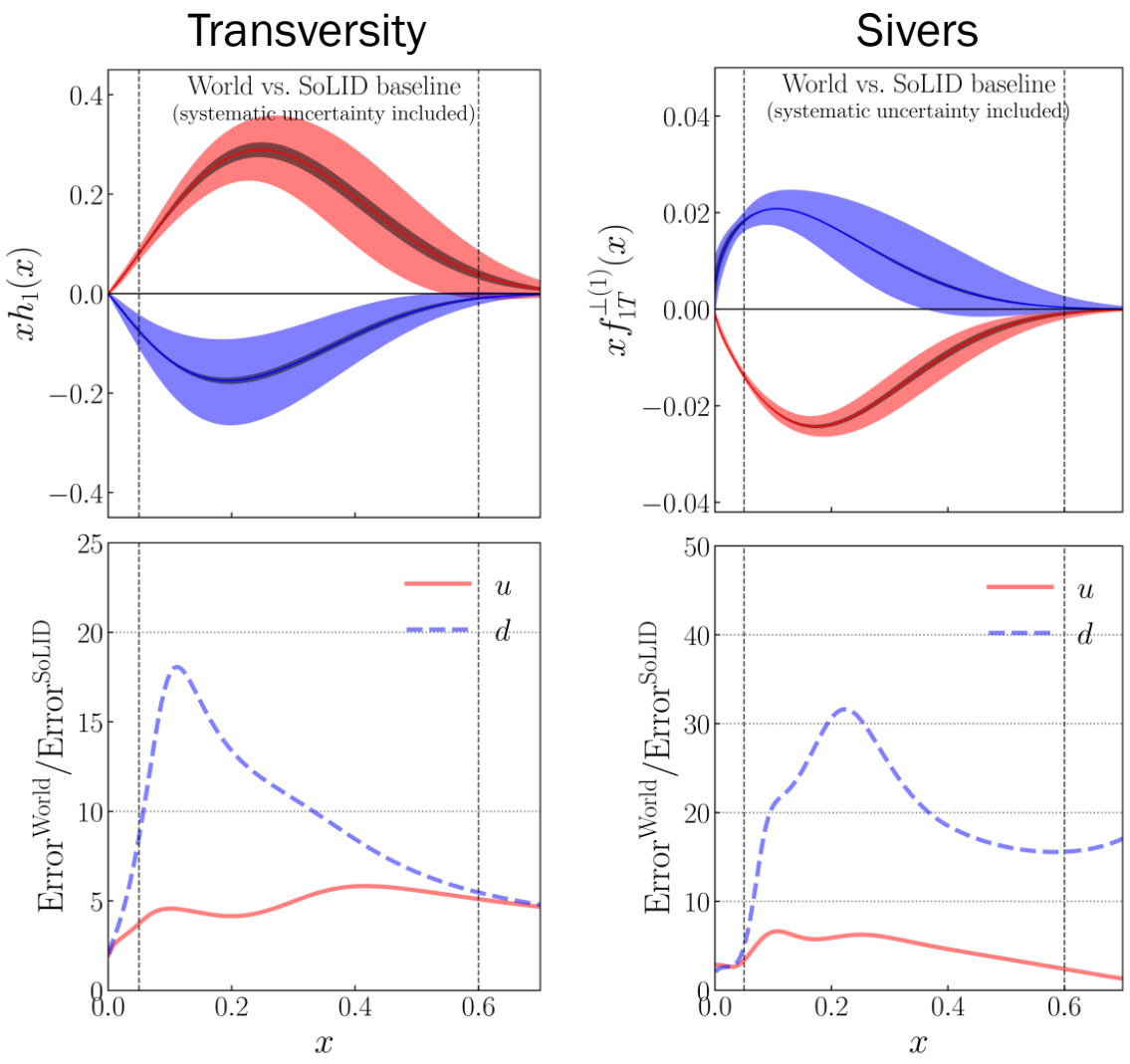
SSA Projections – Complementary to EIC



- 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 $Q^2 = 2.4\ \mathrm{GeV}^2$



Nucleon Tensor Charge

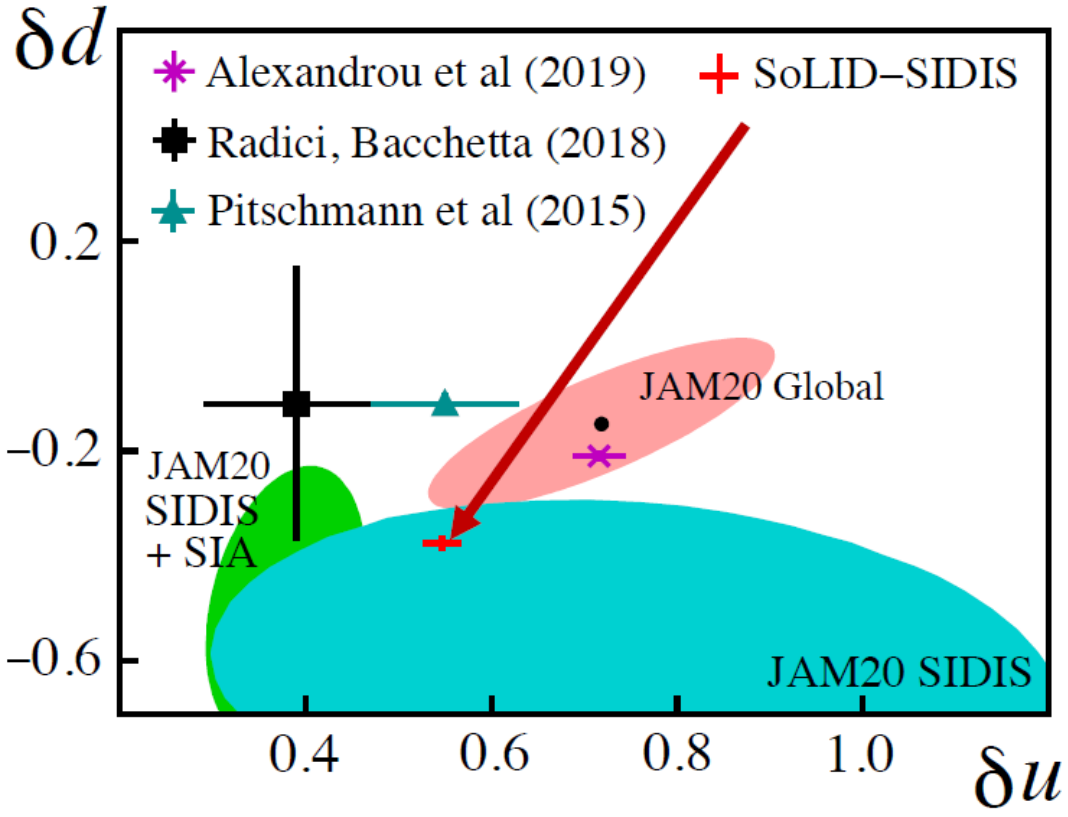
- A fundamental QCD quantity
  - Matrix element of tensor current

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

  - Lowest moment of transversity

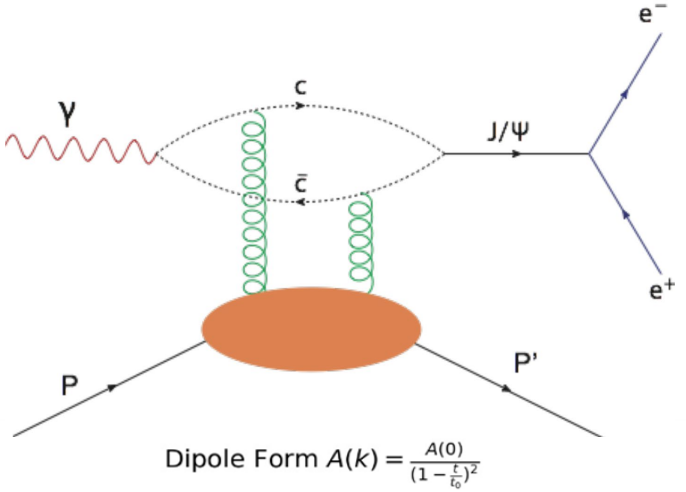
$$\delta_T^q = \int_0^1 \left(h_1^q(x) - h_1^{\bar{q}}(x)\right) dx$$

  - Can be tested in Lattice QCD



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

Near-threshold J/ψ Production

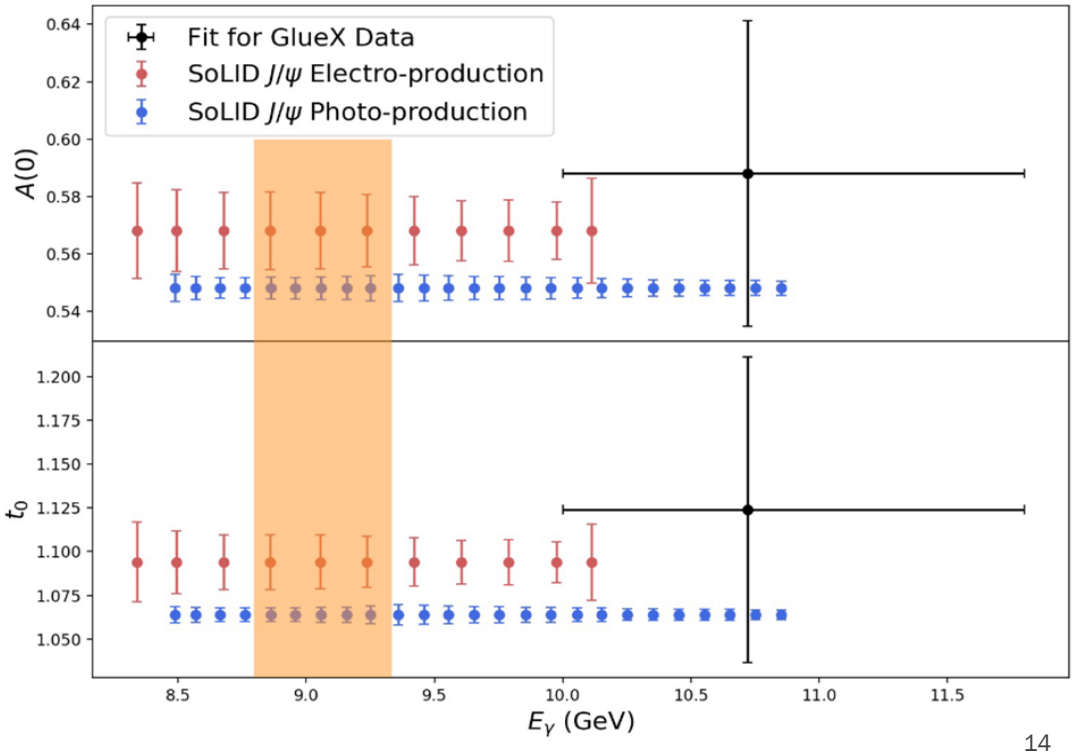


- Electro- and photo-production of Charmonium near threshold

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

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

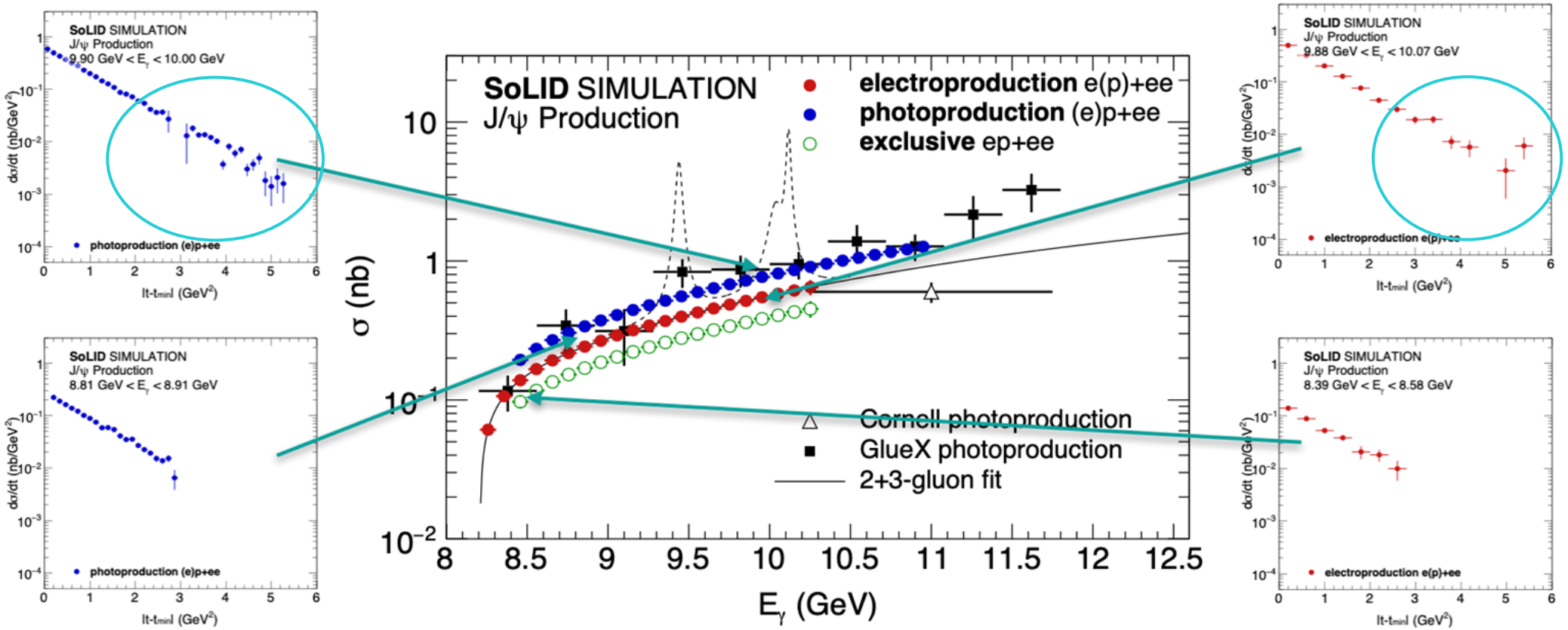
- Precision study of the proton's mechanical properties
  - Measurement of wide t-distributions of J/ψ production near-threshold



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

Z.E. Meziani's Plenary Talk @ 9:30 am Monday

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

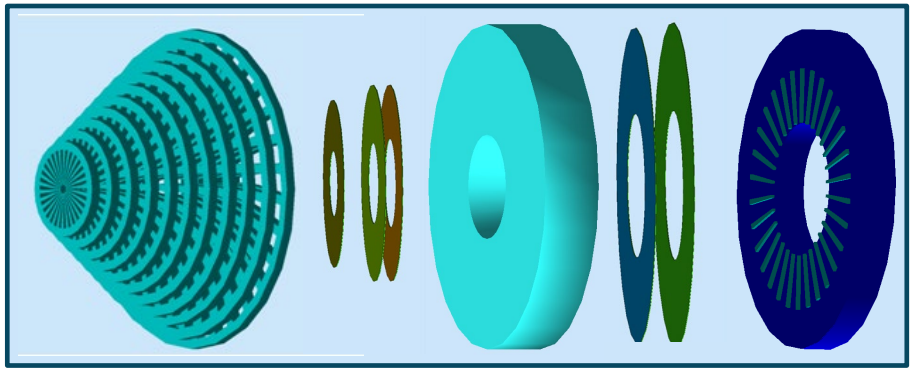
- Beam tests for Shashlik ECal – Tian Ye's talk
- Beam tests for Cherenkov Prototype
- Design for GEM Trackers
- Design for Scintillator Pad Detector
- Cold Test for CLEO-II Magnet
- Software, simulation, DAQ, …

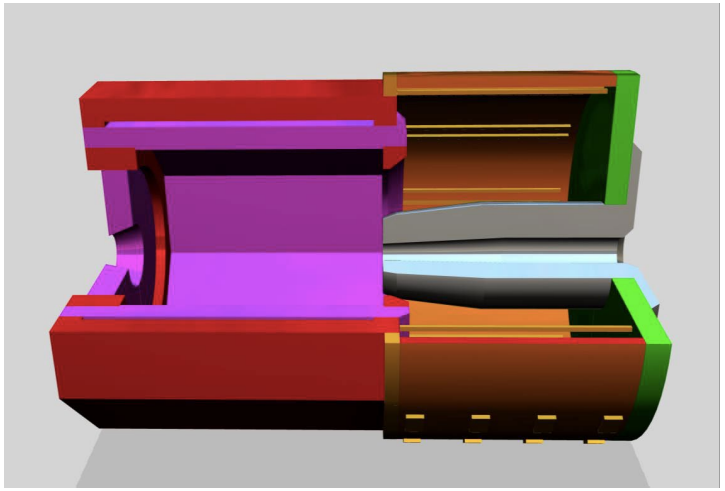
SoLID Detector Subsystems

Uses full capability of JLab electronics

PVDIS

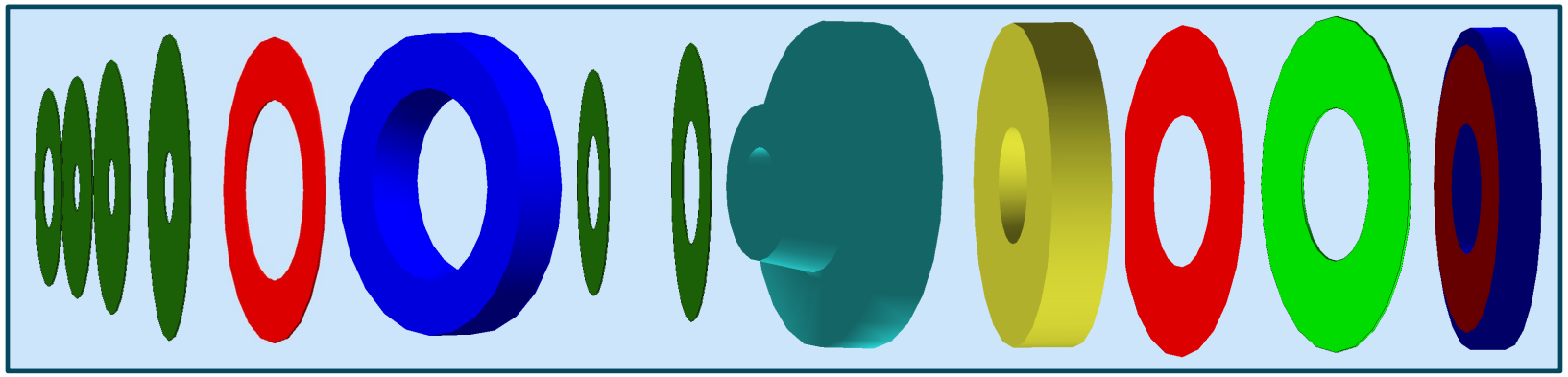
Baffle 3xGEMS LGC 2xGEMs EC





SIDIS-J/ψ

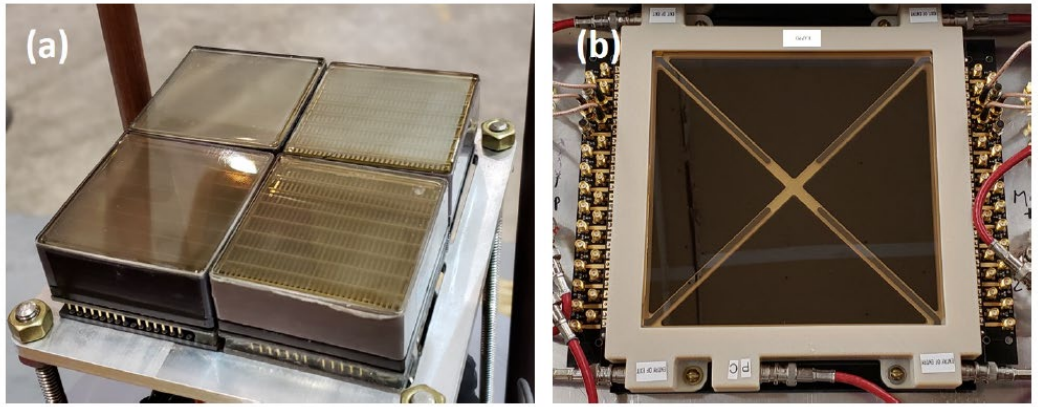
4xGEMs LASPD LAEC 2xGEMs LGC HGC FASPD (MRPC) FAEC

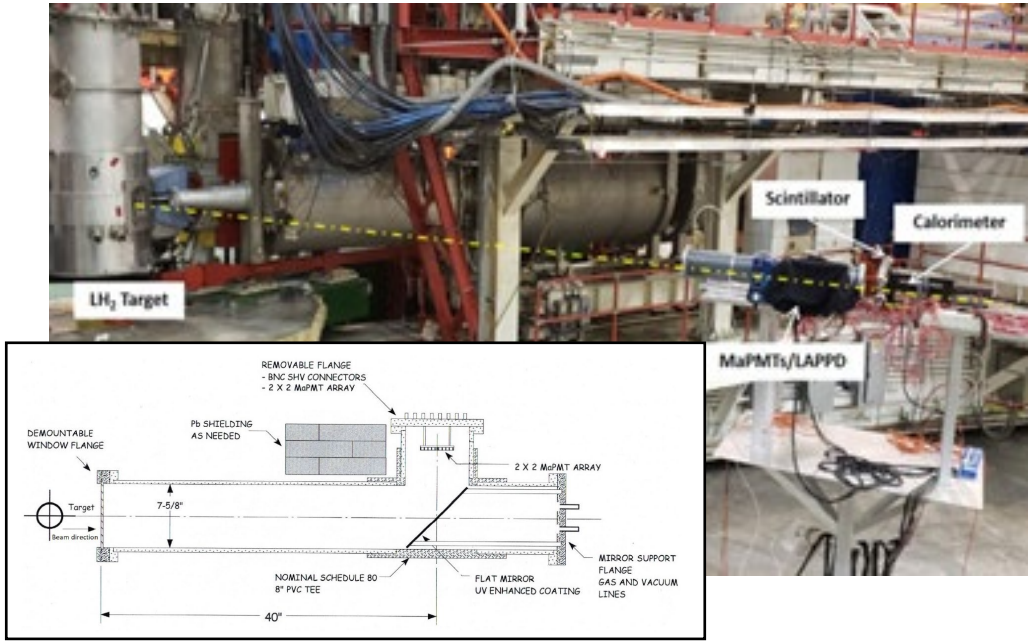


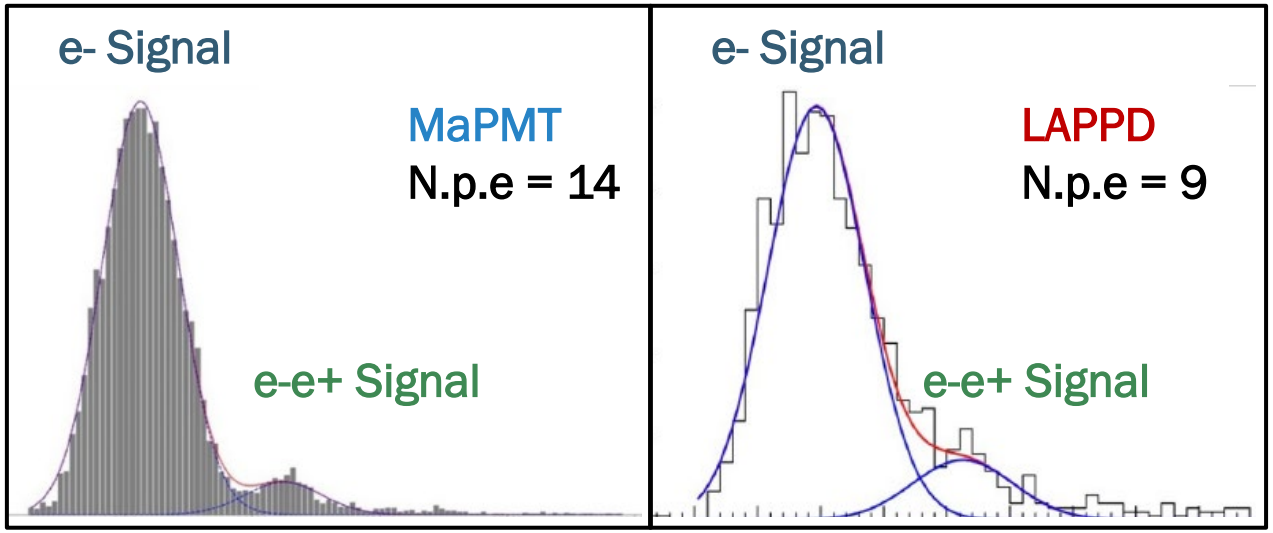
Pre-R&D items: LGC, HGC, GEM's, EC, DAQ/Electronics, Magnet

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



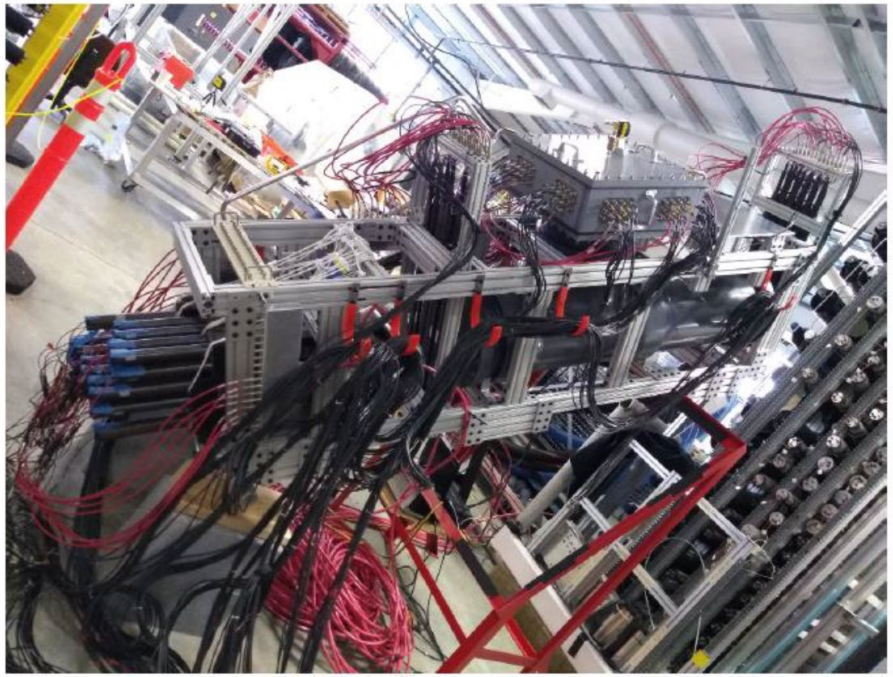


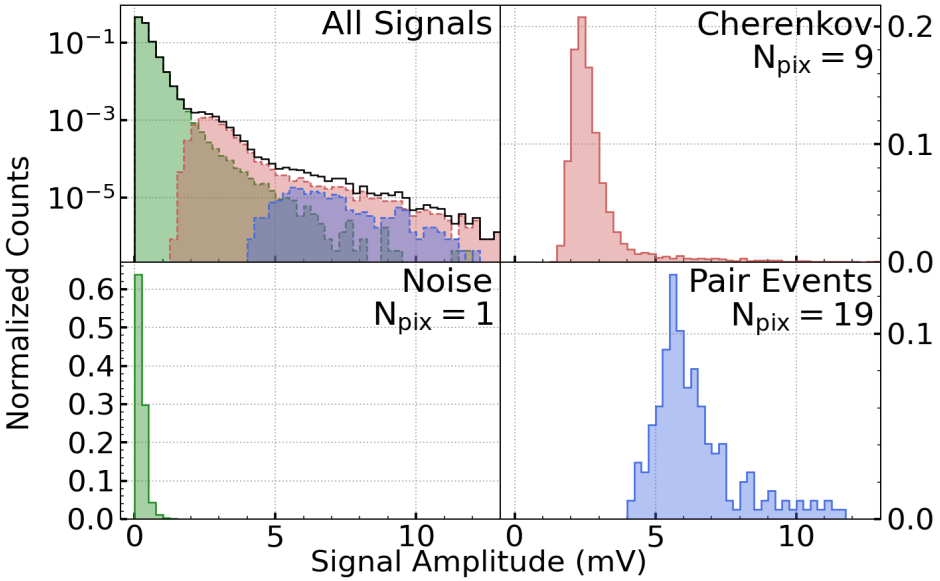


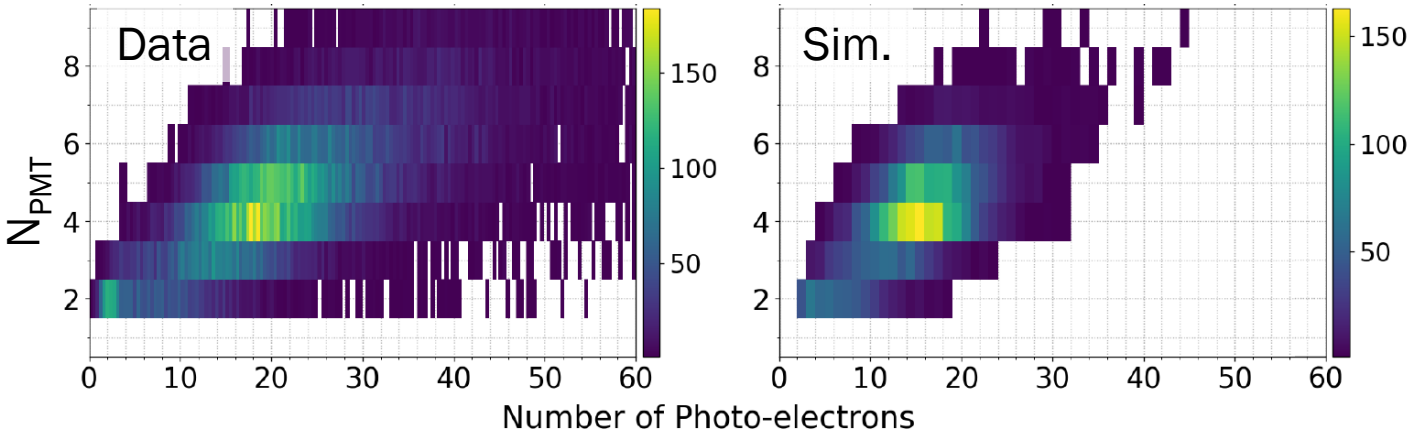
C. Peng et al., JINST 17 (2022), P08022

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

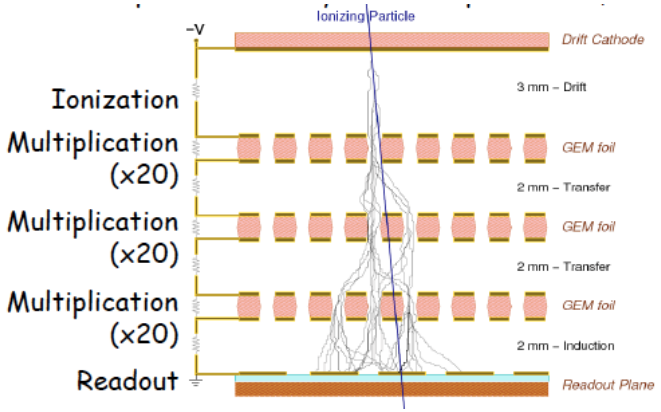


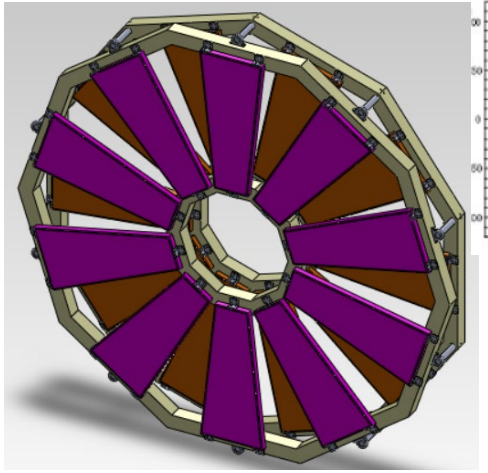


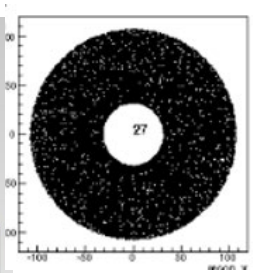


GEM Trackers

- 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…

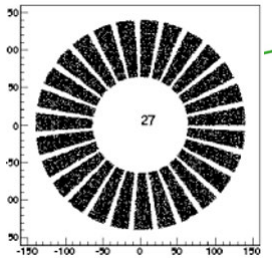


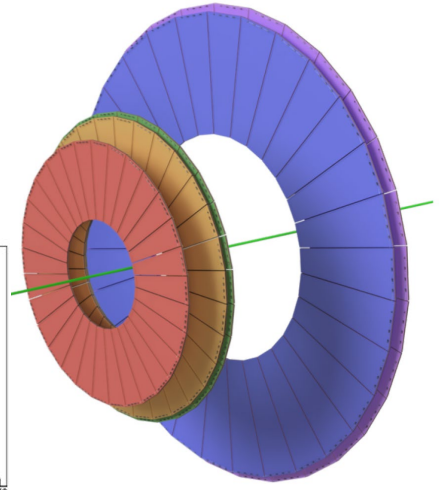


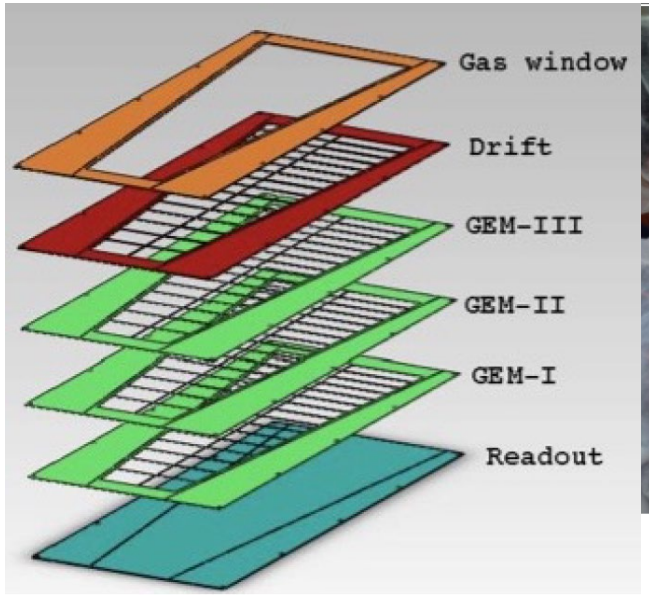


SIDIS

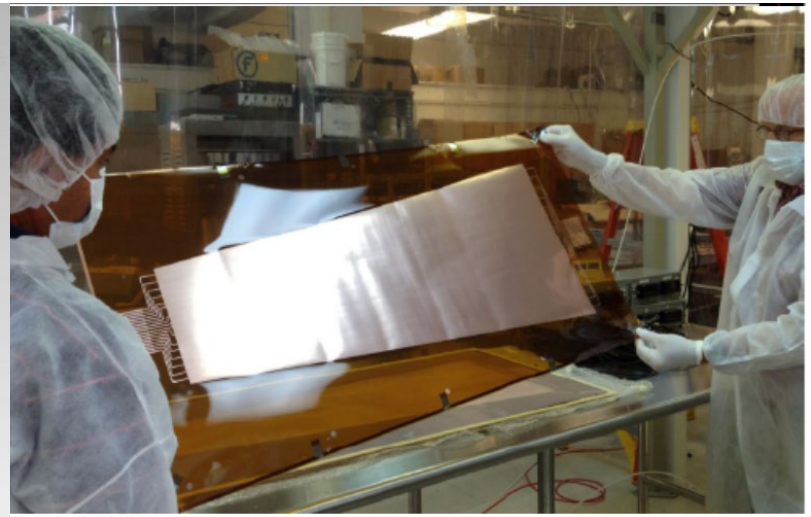
PVDIS







Proposed SoLID GEM Module



UVa EIC GEM Prototype: similar to SoLID design

Scintillator Pad Detector: Requirements and Design

LASPD: photon rejection 5:1;

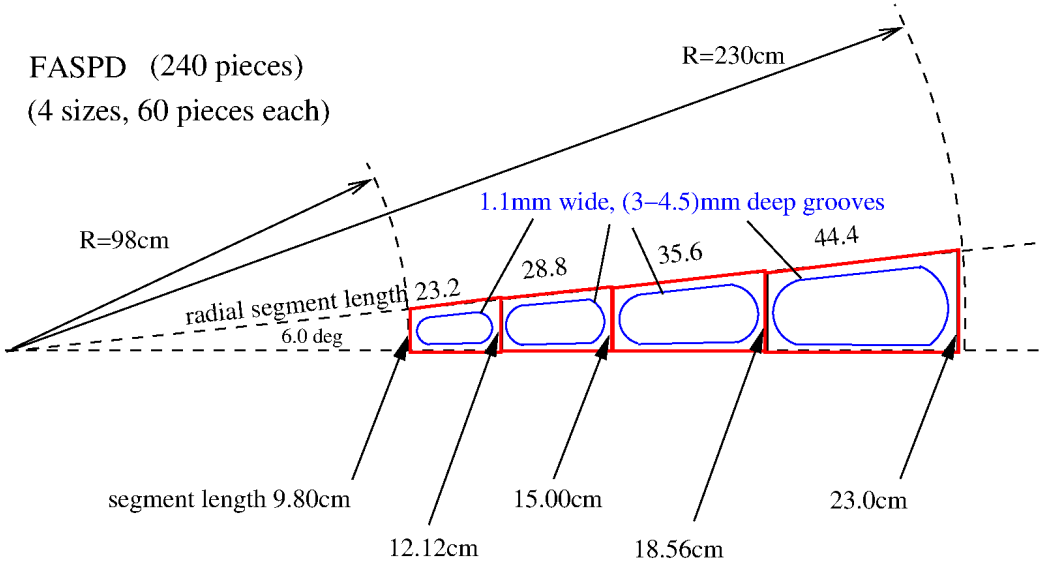
coincidence TOF (150ps)

→ 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

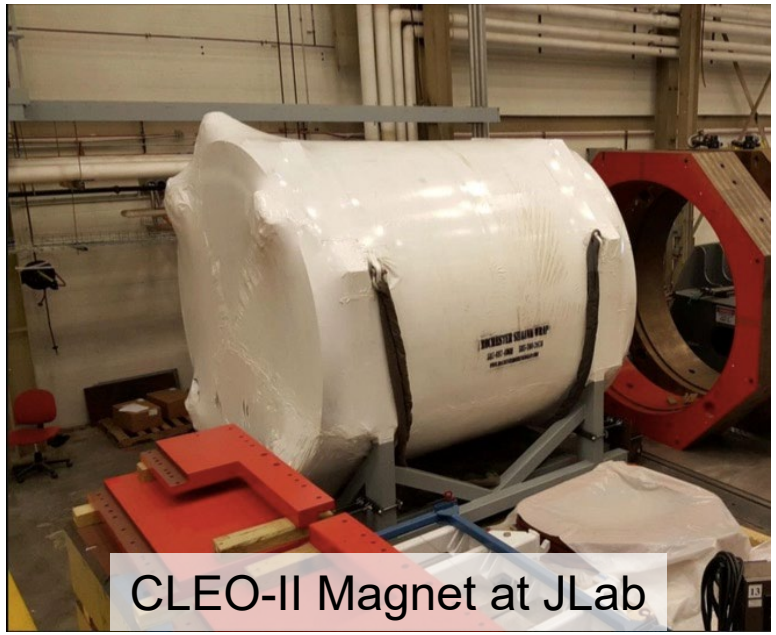
240 segments (60 X 4)

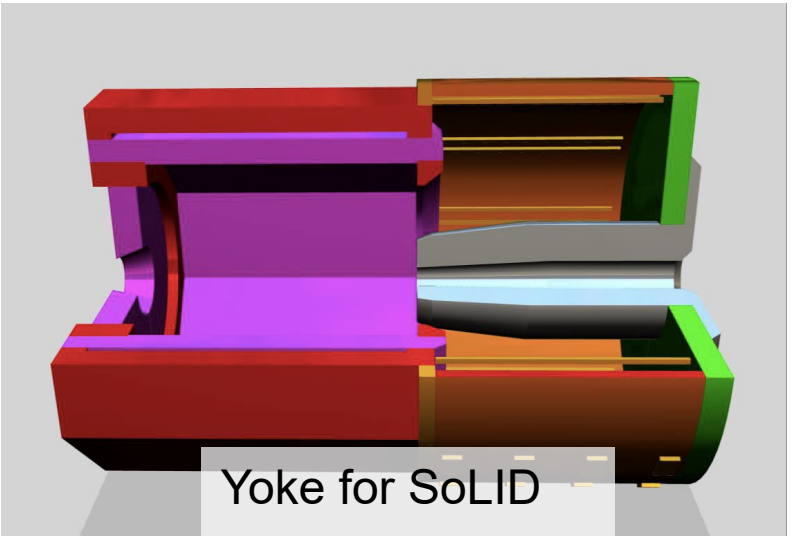
WLS fiber embedding,

MAPMT (outside magnet)

Magnet – Built on the CLEO-II Solenoid

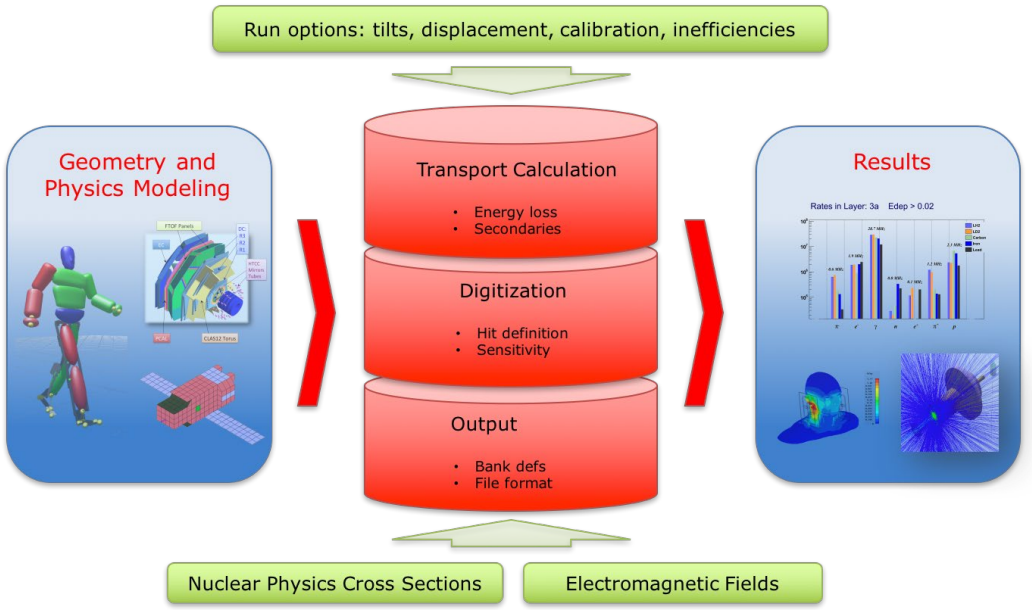
- Requirements:
  - Acceptance:
    p @ 1.0 – 7.0 GeV/c,
    ϕ @ 2π,
    θ @ 8°-24° (SIDIS), 22°-35° (PVDIS)
  - Resolution: $\delta p \sim 2\%$ (0.1 mm tracking resolution)
  - Fringe field at the ^{3}He target < 5 Gauss
- Modifications:
  - Use 2 out of 3 layers of return yoke
  - Thicken the front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

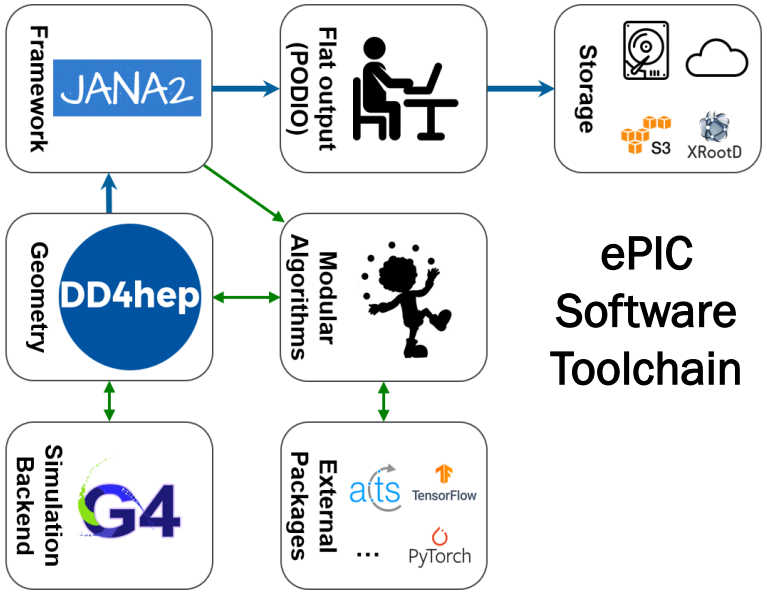

Yoke for SoLID

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

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
  - Cherenkov, ECal, GEM, SPD, Magnet, Software, DAQ, …

THANK YOU