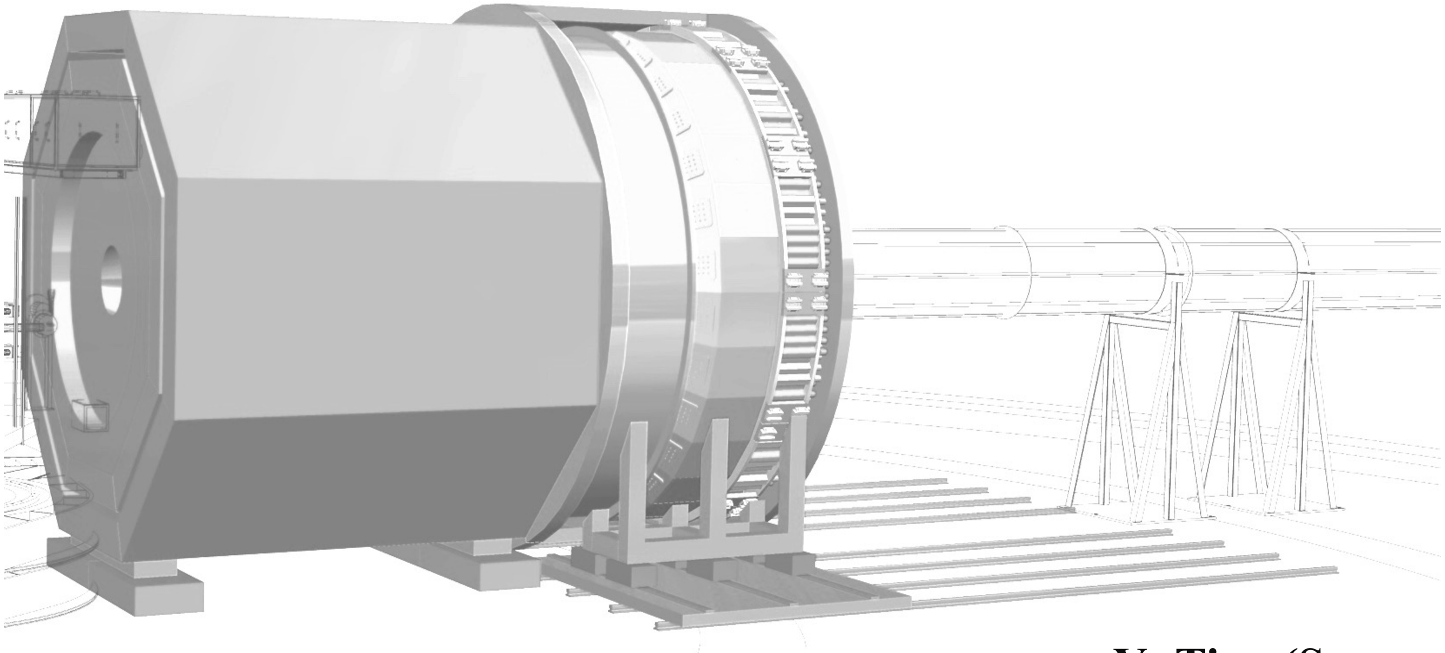
SoLID Overview and PVDIS



Ye Tian (Syracuse University)

For SoLID Collaboration

1/17/2024

Syracuse University

JSA U.S. DEPARTMENT OF ENERGY Office of Science SoLID Jefferson Lab

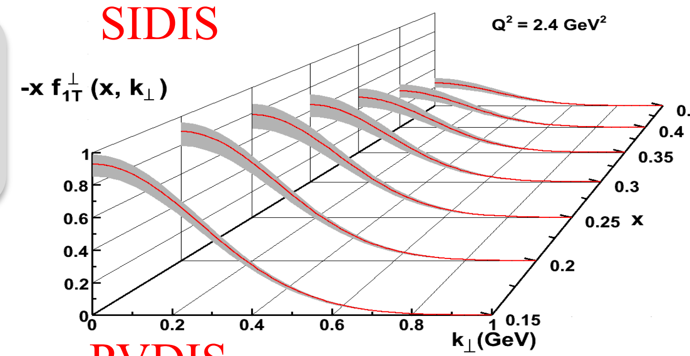
Future SoLID Experiments

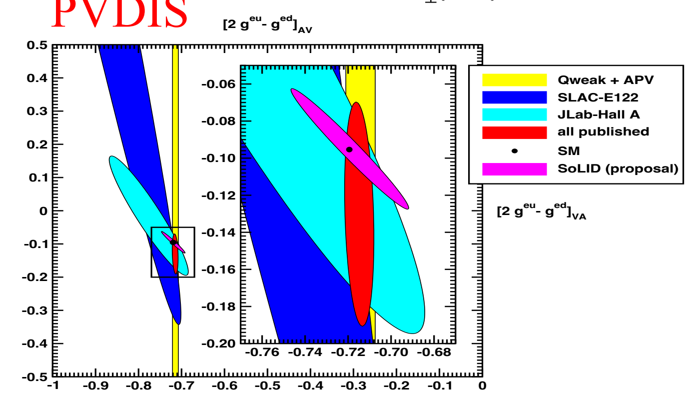
SoLID will maximize the science return of the 12-GeV CEBAF upgrade by combining…

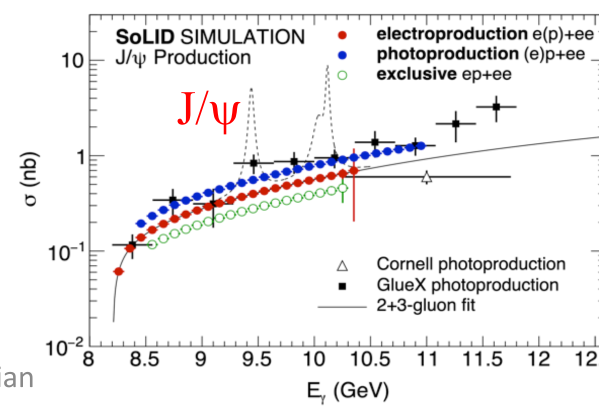
High Luminosity
$10^{37\text{-}39}/\text{cm}^2/\text{s}$

+

Large Acceptance
Full azimuthal ϕ coverage







- ❑ **How does the spin of the nucleon arise?**
  - SIDIS: reaching ultimate precision for tomography of the nucleon
- ❑ **New physics beyond Standard Model?**
  - PVDIS in high-x region: providing sensitivity to new physics at 10-20 TeV
- ❑ **How does the mass of the nucleon arise?**
  - Precision threshold J/ψ probing strong color fields in the nucleon and the origin of its mass (trace anomaly)

SoLID Overview

- Website https://solid.jlab.org
- PreCDR 2019 https://solid.jlab.org/DocDB/0002/000282/001/solid-precdr-2019Nov.pdf
- Whitepaper 2022 https://arxiv.org/abs/2209.13357 *J. Phys. G: Nucl. Part. Phys.* **50** 110501 (2023)

☑ Semi-Inclusive Deep Inelastic Scattering (SIDIS) Program:

- E12-10-006(A): Single Spin Asymmetry on Transversely Polarized ^{3}He (90 days)
- E12-11-007(A): Single and Double Spin Asymmetry on Longitudinally Polarized ^{3}He (35 days)
- E12-11-108(A): Single Spin Asymmetry 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)

☑ Parity Violation Deep Inelastic Scattering (PVDIS) Program:

- E12-10-007 (A): Parity Violating Asymmetry in DIS with LH_2 and LD_2 (169 days)
- E12-22-004 (A^-): Beam Normal Single Spin Asymmetry in DIS with LH_2 (38 days)
- PR12-22-002 (C2 approved): Flavor Dependence of Nuclear PDF Modification Using PVDIS with ^{48}Ca

☑ J/ψ Program: --- Sylvester Joosten's talk

- E12-12-006 (A) Near Threshold Electroproduction of J/ψ at 11 GeV (60 days)

• Generalized Parton Distributions (GPDs) Programs:---Xinzhan Bai's talk

- E12-12-006A: Time-Like Compton Scattering (Run group).
- E12-10-006B: Deep Exclusive π^- production (DEMP) with polarized ^{3}He target and SIDIS configuration
- Under development: Other polarized-proton/neutron DVCS and Doubly DVCS on proton , etc.

SoLID Timeline and Progresses

from X. Zheng, JLUO2023 talk

E12-10-007 PVDIS (169 days, A) — 2010

E12-10-006 SIDIS (90 days, A) — 2010

E12-11-007 SIDIS (35 days, A) — 2011

E12-11-008 SIDIS (120 days, A) — 2011

E12-12-006 J/Psi (60 days, A) — 2012

SIDIS dihadron, Ay — 2014

TCS — 2015

DEMP — 2017

SIDIS kaon production — 2018

g2n, d2n — 2020

PR12-22-002 PVEMC (C2), **E12-22-004** BNSSA (38 days, A-) — 2022

LRP2023 — 2023

Recommendation #4

2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024

2015: Director's Review + **2015 white paper**

2019: Director's Review **preCDR (to DOE)**

2021: Director's+ **Science Review**

2022: **2022 white paper** (J. Phys. G)

2024:

- 12/2023 Cost sharing plan and update (addendum) to preCDR
- 1/2024 JLab management visit DOE, discuss the new plan/feedback
- 2/2024 February lab budget briefing
- 5/2024 Review for the Office Science Charge

- Physics: Rich Vibrant Programs, new development continues

SIDIS and TMDs

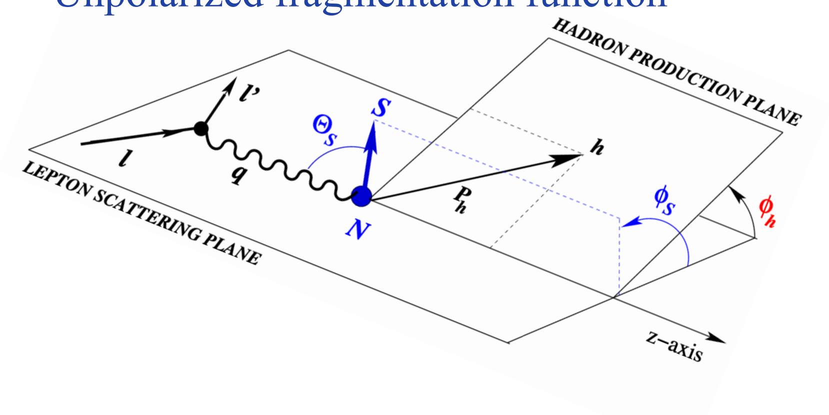
Extract the leading twist terms of TMD through SIDIS-π differential cross section measurement
– hadron in final state "tags" transverse motion of quarks inside the proton/neutron

Target single-spin asymmetries (SSAs)

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

$$A_{UT}^{Collins}\sin(\phi_h+\phi_S) \propto h_{1T}\otimes H_1^{\perp}$$
$$+ A_{UT}^{Pretz.}\sin(3\phi_h-\phi_S) \propto h_{1T}^{\perp}\otimes H_1^{\perp}$$
$$+ A_{UT}^{Sivers}\sin(\phi_h-\phi_S) \propto f_1^{\perp}\otimes D_1$$

- Collins fragmentation function from e^+e^- collisions
- Unpolarized fragmentation function



8 Quark-TMDs (leading twist)   : Nucleon Spin   : Quark Spin

Nucleon Polarization		Quark polarization: Un-Polarized (U)	Quark polarization: Longitudinally Polarized (L)	Quark polarization: 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 $h_{1T}^{\perp}$ = −

Key Features of TMDs:

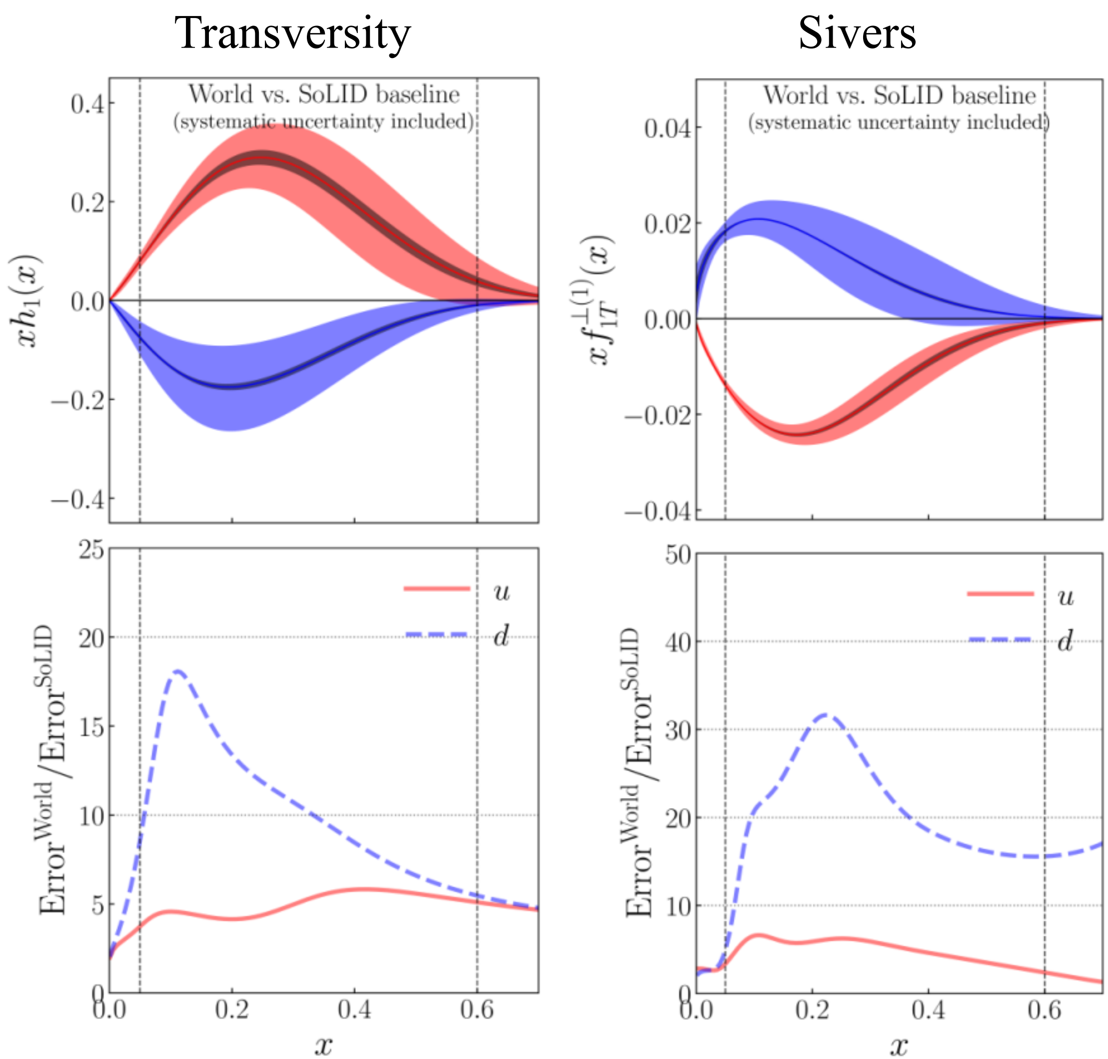
✓ Represent the intrinsic confined motion of quark & gluons

✓ Off-Diagonal TMDs vanish if no orbital angular momentum

✓ Most of TMDs are due to the spin-orbit correlations

- Separation of Collins, Sivers and pretzelocity effects through angular dependence
- Good momentum and angular resolutions in 4-D binning over the kinematic variables (x, z, Q^2, P_T)
- Large acceptance and precision measurement of asymmetries in 4D phase space is essential

SoLID Impact on TMDs

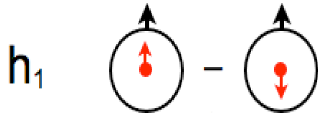


- World: SIDIS data from the COMPASS / HERMES, e^+e^- annihilation data from the BELLE / BABAR / BESIII
- Top : impact on the *u* and *d* quarks' TMD extractions by the SoLID SIDIS program
- Bottom: ratios between the World and SoLID projected uncertainties shown in the top figures
- Projections from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

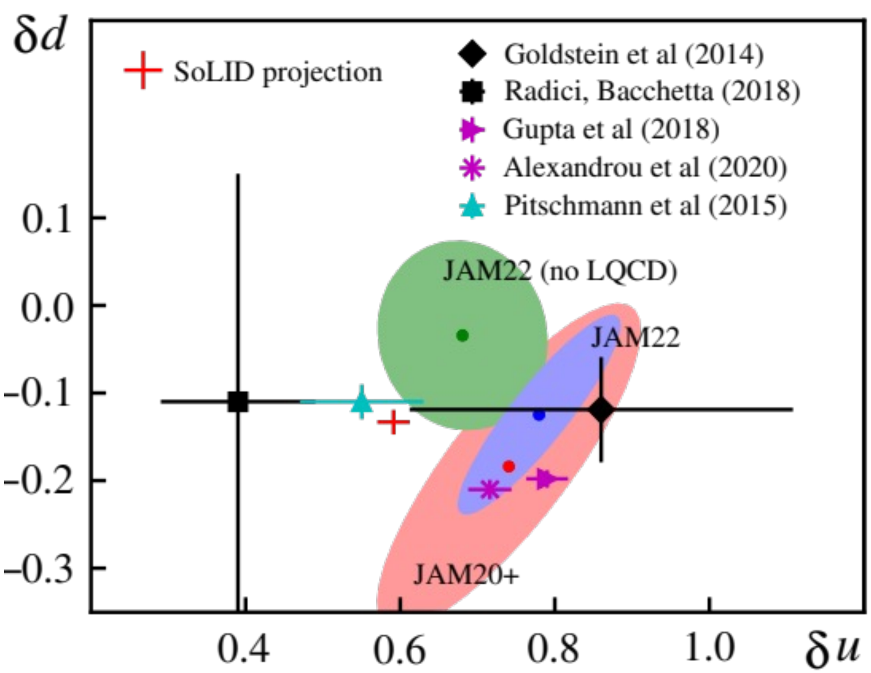
Slide from P. Chao, MENU2023 talk

SoLID for JLab Hall A – SIDIS and TMDs

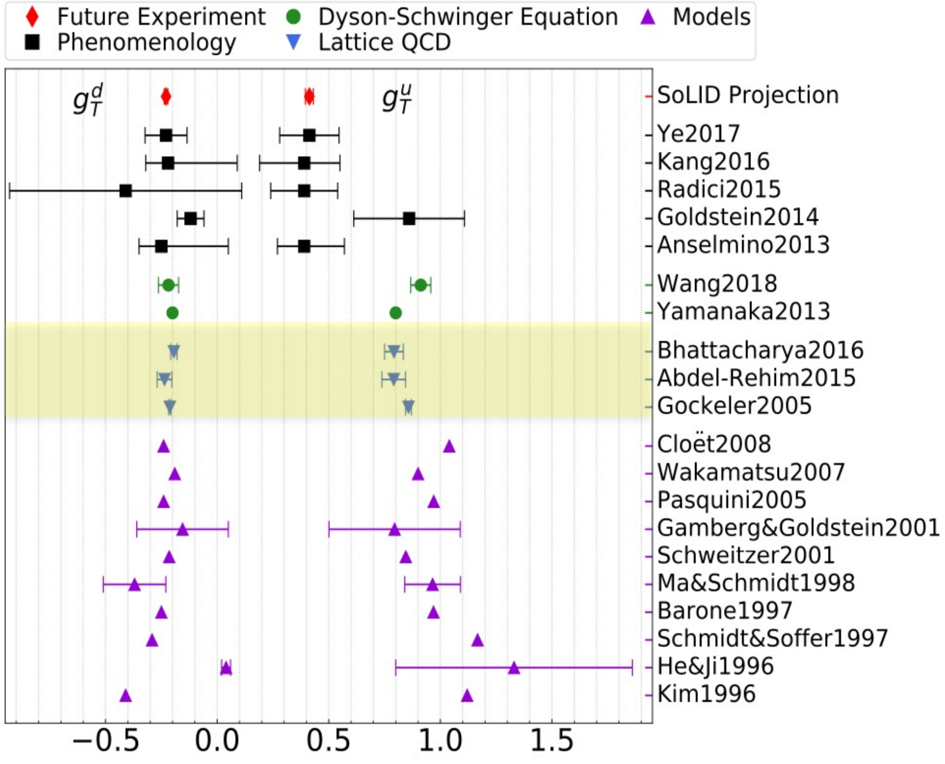
- Nucleon tensor charge as important as its other static properties – electric charge, mass, spin



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



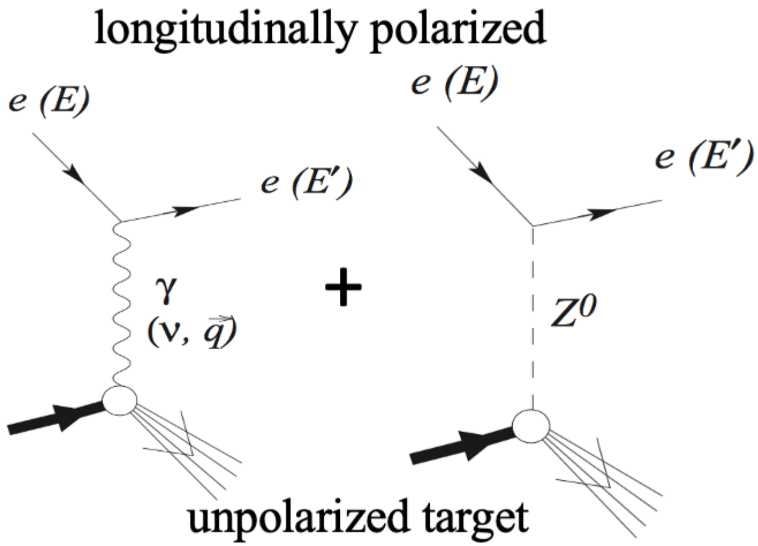
J. Cammarota et al, PRD 102, 054002 (JAM20+)
L. Gamberg et al., PRD 106, 034014 (JAM22)



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

Slide from H. Gao, PAC50 talk

PVDIS with SoLID



$$\sigma^r \propto |M_{em} + M^r_{weak}|^2$$
$$\sigma^l \propto |M_{em} + M^l_{weak}|^2$$
$$\approx |M_{em}|^2 + 2M_{em}M^l_{weak} + |M^l_{weak}|^2$$

$$A_{PV} = \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \approx \frac{M^l_{weak} - M^r_{weak}}{M_{em}}$$

Measure A_{pv} in Deep Inelastic Scattering:

A_{pv} with deuterium:

- Measure electroweak parameters
- Search for BSM physics
- Search for CSV at the quark level
- Search for quark-quark higher twist effects

Apv with proton:

- Help determine d/u PDF's
- Insight into nuclear effects at high x

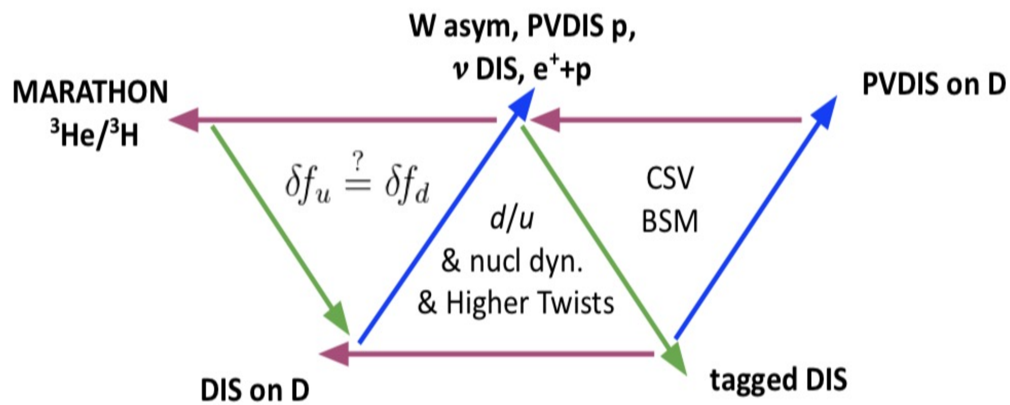
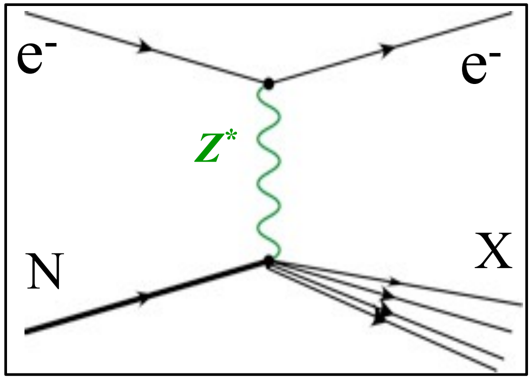


Figure courtesy of A. Accardi [INT workshop on PVDIS at JLab 12 GeV (2022)]

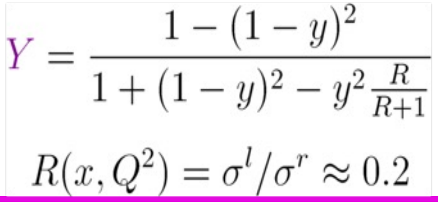
Parity Violating DIS on Deuteron



- Scattering off the simplest isoscalar nucleus and at high x

$$A_{LR}^{DIS} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + a_3(x)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$x \equiv x_{Bjorken} = \frac{Q^2}{2M\nu}, y = 1 - \frac{E'}{E}$$



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

$$= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5 + R_s}$$

At high x, A_{iso} becomes independent of PDFs, x & W, with well-defined SM prediction for Q^2 and y

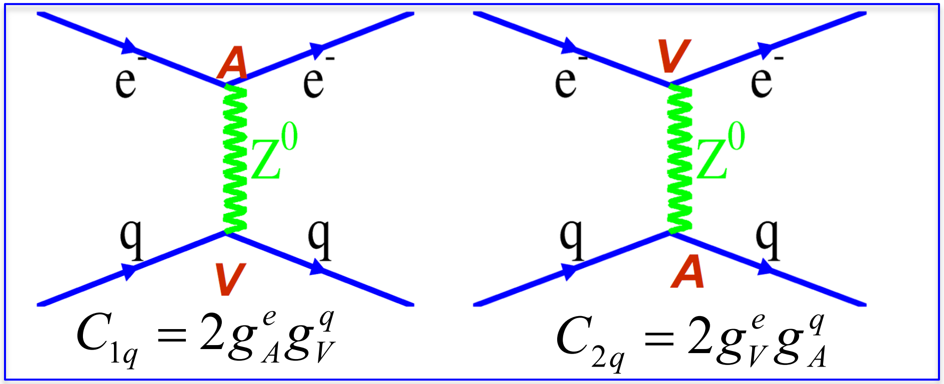
$$C_{1u} = 2g_A^e g_V^u \approx -\frac{1}{2} + \frac{4}{3}sin^2\theta_W \approx -0.19$$

$$C_{1d} = 2g_A^e g_V^d \approx \frac{1}{2} - \frac{2}{3}sin^2\theta_W \approx 0.34$$

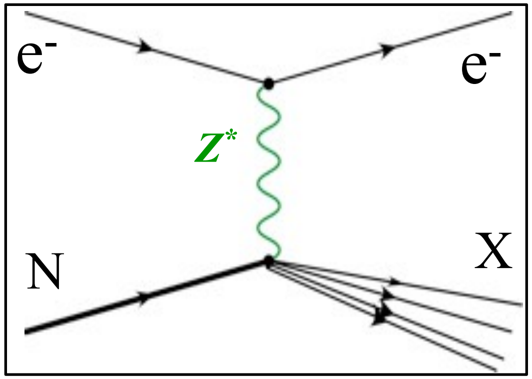
$$C_{2u} = 2g_V^e g_A^u \approx -\frac{1}{2} + 2sin^2\theta_W \approx -0.030$$

$$C_{2d} = 2g_V^e g_A^d \approx \frac{1}{2} - 2sin^2\theta_W \approx 0.025$$

EW neutral current interaction



Parity Violating DIS on Deuteron



- Scattering off the simplest isoscalar nucleus and at high x

$$A_{LR}^{DIS} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + a_3(x)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

$$x \equiv x_{Bjorken} = \frac{Q^2}{2M\nu}, y = 1 - \frac{E'}{E}$$

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x,Q^2) = \sigma^l/\sigma^r \approx 0.2$$

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

At high x, A_{iso} becomes independent of PDFs, x & W, with well-defined SM prediction for Q^2 and y

$$= -\left(\frac{3G_F Q^2}{\pi\alpha 2\sqrt{2}}\right)\frac{2C_{1u} - C_{1d}(1+R_s) + Y(2C_{2u} - C_{2d})R_v}{5+R_s}$$

$$R_s(x) = \frac{2S(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 0$$

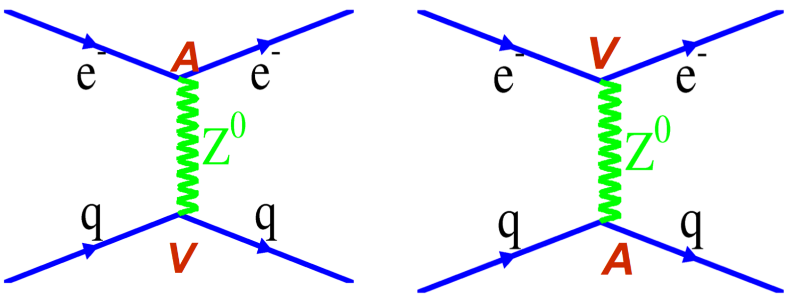
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

QCD
- Parton distributions (u, d, s, c)
- Charge Symmetry (CSV)
- Higher Twist (HT)
- Nuclear Effects (EMC)

Parity Violating DIS on Deuteron

PVDIS on Deuteron:

- Unique feature: sensitivity to C_2's
- Searching for new physics



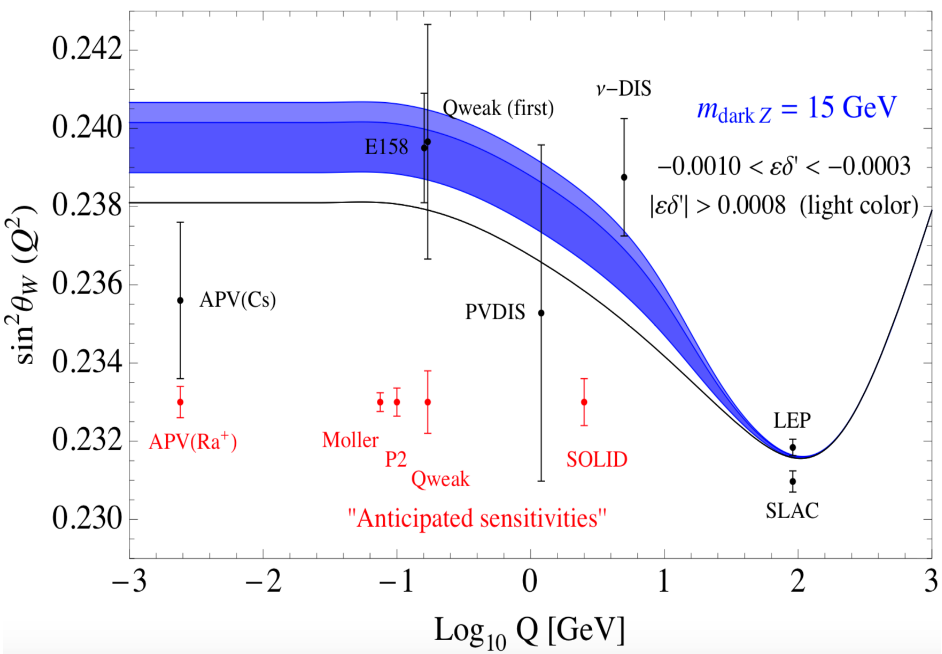
$$C_{1q} = 2g_A^e g_V^q \qquad C_{2q} = 2g_V^e g_A^q$$

C_{ij}=C_{ij}_SM+C_{ij}_BSM

- Search for BSM Physics looks directly at **couplings**
- Measure each C_{ij} as precisely as possible
  (Nobody really knows where the new physics is.)

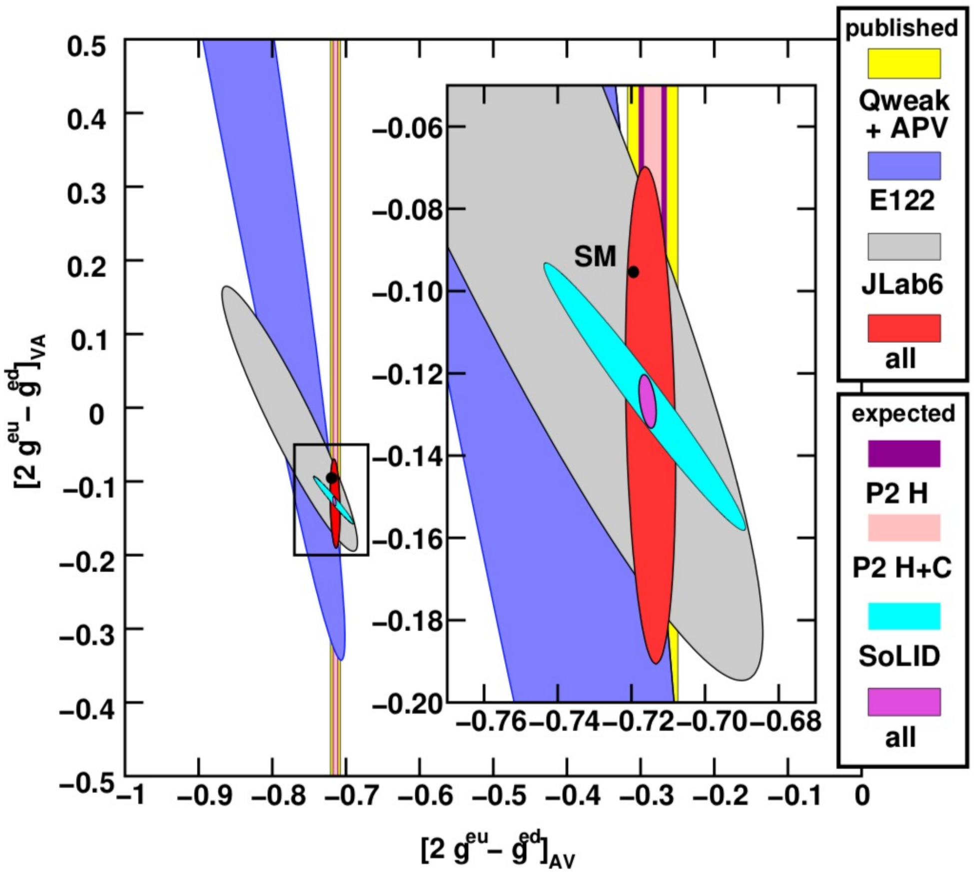
- Running of $\sin^2\theta_W$ with Q^2

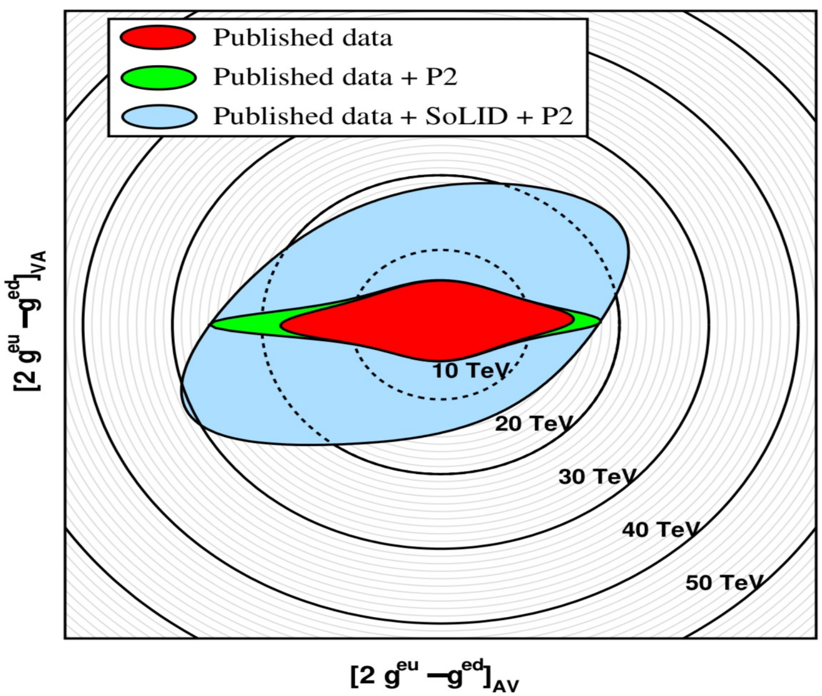
From HD, Lee, Marciano, Phys. Rev. D **92**, no. 5, 055005 (2015)



- $\sin^2\theta_W$ is a Standard Model Parameter
- Treat Ci's as function of $\sin^2\theta_W$
- Fit to one parameter

New Physics





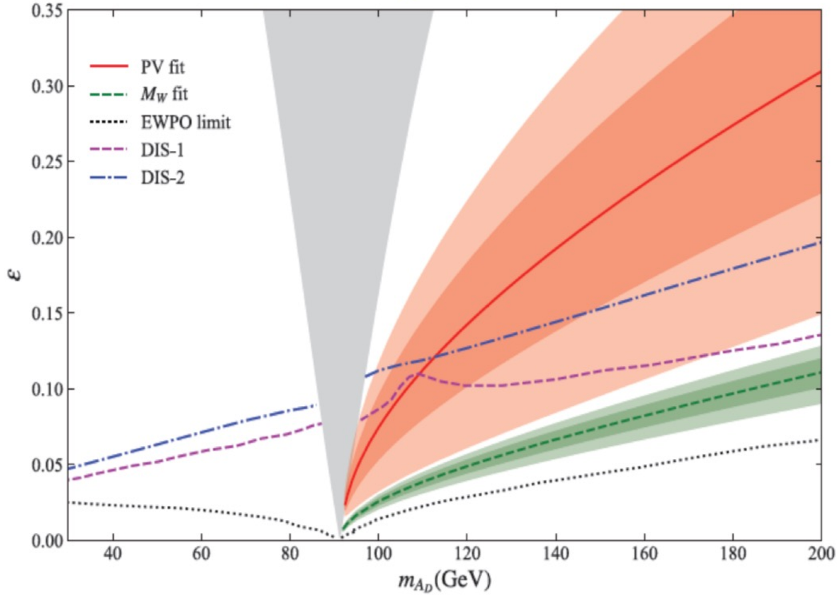
- The phase-space of the linear combinations of axial-vector and vector-axial electron-quark effective coupling constants

- Improvement in energy reach for electron-nucleon couplings.

New Physics Beyond Stand Model

Constraints of new W mass versus PV

Thomas and Wang, arXiv: 2205.01911

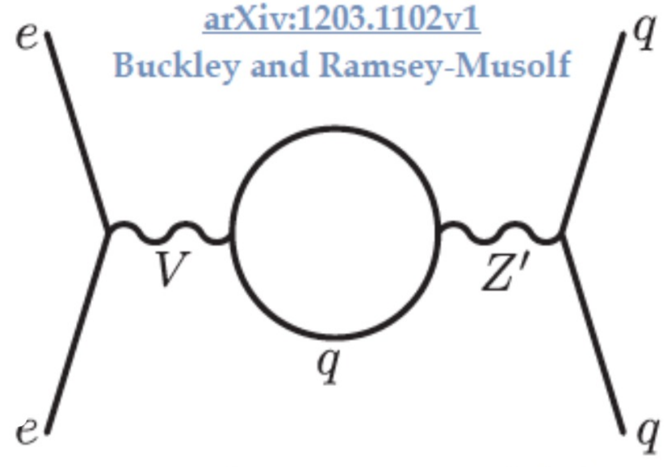


- Constraints on the dark photon from parity violation and the W mass: https://arxiv.org/abs/2205.01911
- Sensitivity of Parity-violating Electron Scattering to a Dark Photon https://arxiv.org/pdf/2201.06760.pdf

Leptophobic Z'

arXiv:1203.1102v1

Buckley and Ramsey-Musolf



- Since electron vertex must be vector, the Z' cannot couple to the C_{1q}'s if there is no electron coupling: can only affect C_{2q}'s

Hadron Physics with PVDIS

- Precision tool to study Hadron Physics
- Sensitive to Partonic Charge Symmetry Violation at large X
- Clean probe to study Higher-Twist effects from q-q correlations
- Broad kinematic coverage allows clean separation of different Physics

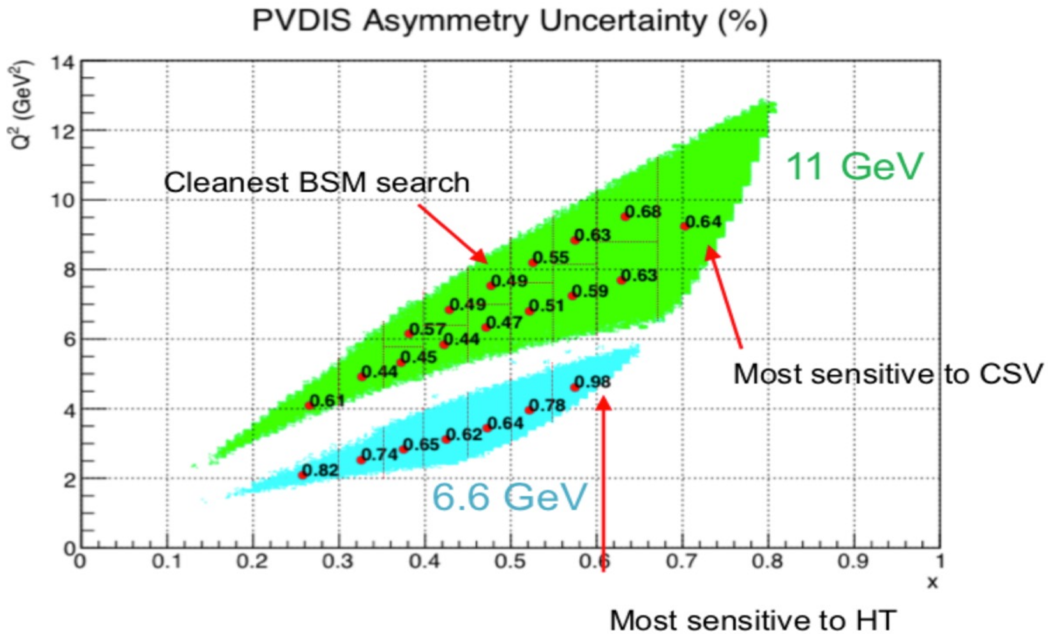
$$A_{DIS}^{D} = A_{SM}\left[1 + \frac{\beta_{HT}}{(1-x)^3} Q^2 + \beta_{CSV} x^2\right]$$

Kinematic dependence of physics topics

	x	Y	Q^2
New Physics	no	yes	small
CSV	yes	small	small
Higher Twist	large?	no	large

$$Y = \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\frac{R}{R+1}}$$

$$R(x, Q^2) = \sigma^l/\sigma^r \approx 0.2$$



Parity Violating DIS on Proton

$$A_{LR}^{P} \sim -\frac{1}{4\pi\alpha}\frac{Q^2}{\upsilon^2}\left[\frac{6C_{1u} - 3C_{1d}\, d(x)/u(x)}{4 + d(x)/u(x)}\right]$$

- Measurement of d(x)/u(x) ratio for the proton at high x
- The d/u extraction is made directly from PVDIS on proton: no nuclear corrections

❖ PVDIS is complementary to the rest of the JLab d/u program

❖ The MARATHON Data on d/u has different interpretations. Hence as many targets as possible should be studied: PVDIS, BoNus (D), and MARATHON

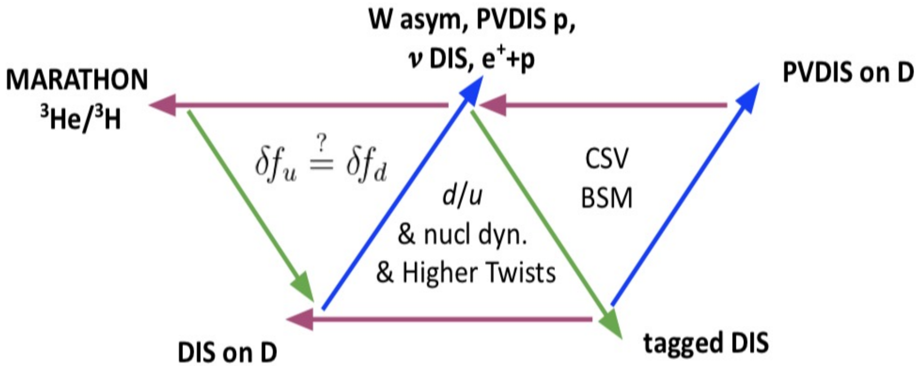
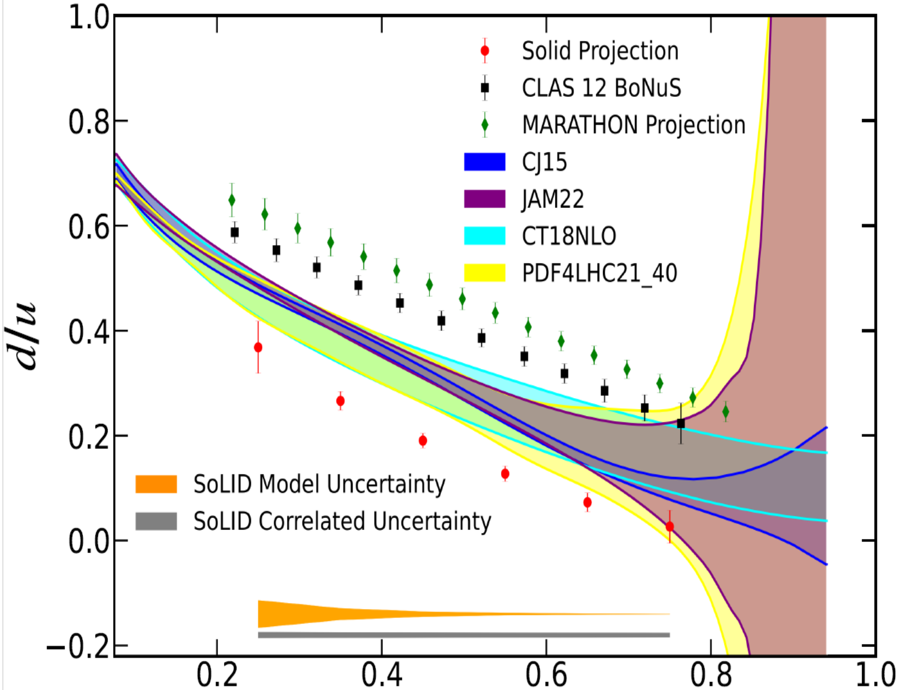


Figure courtesy of A. Accardi

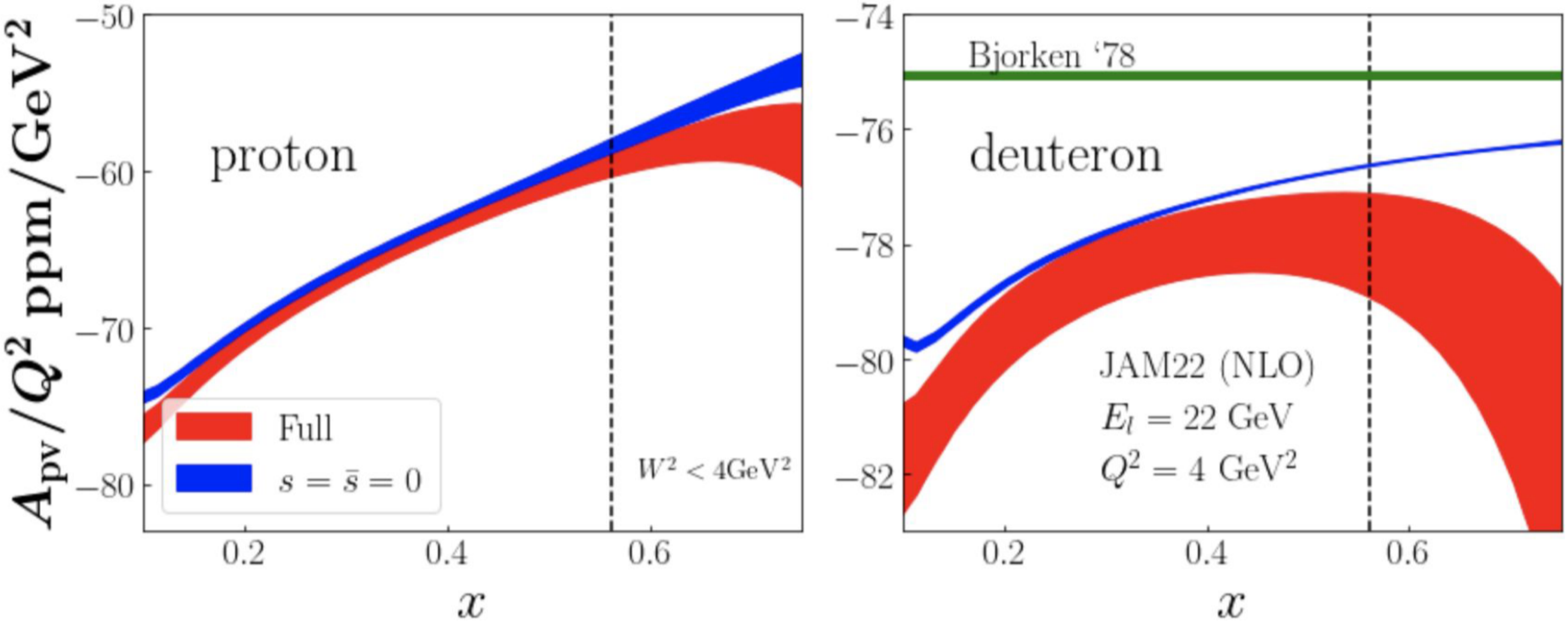


- Global analysis of d/u differ significantly in uncertainty and shape at high x

Apv has the potential to pin down the strangeness

Simulation at SoLID **22 GeV**

Apv with full QCD theory @ NLO

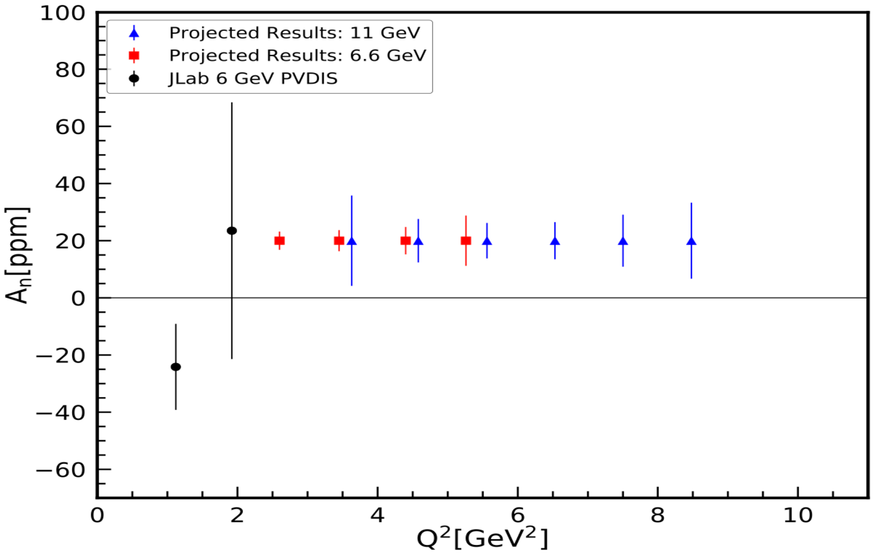


Bottom line: Apvd uncertainties correlates significantly from strangeness

N. Sato, 2023 Hall A collaboration talk

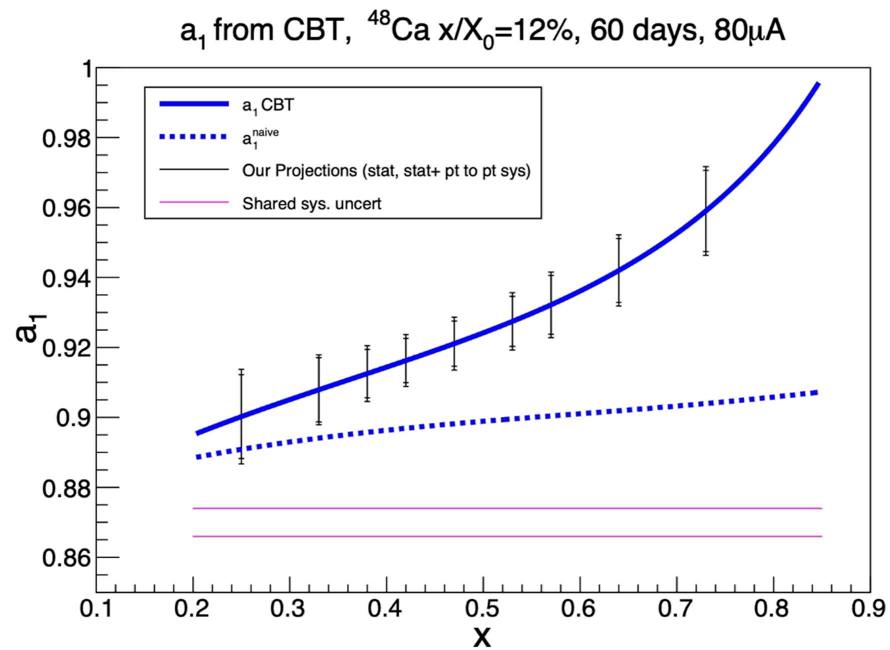
More Physics Programs using SoLID PVDIS configuration

- Beam Normal Single Spin Asymmetry: (Approved proposal)
- Investigate the effect of two-photon exchange in DIS.
- Q^2 dependence of the asymmetry empirically.



- Flavor Dependent EMC effect: (Conditionally approved proposal)
- Measure PVDIS on ^{48}Ca
- Apv directly sensitive to flavor dependence of EMC

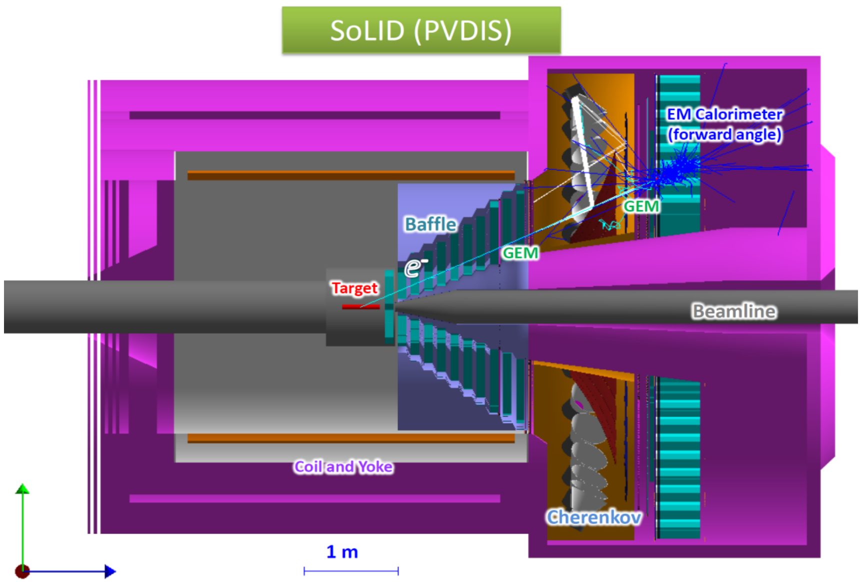
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$

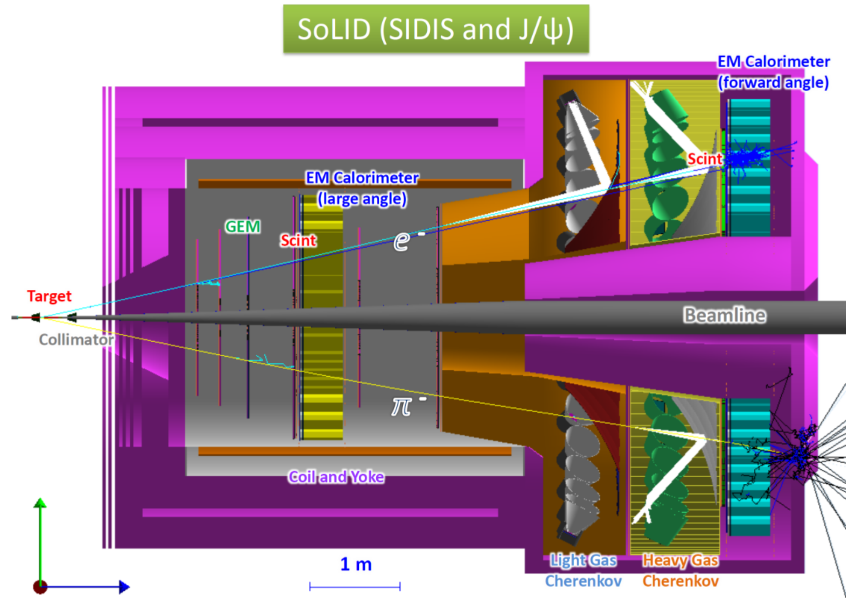


https://solid.jlab.org/experiments.html

SoLID (Solenoidal Large Intensity Device)

High Luminosity + Large Acceptance



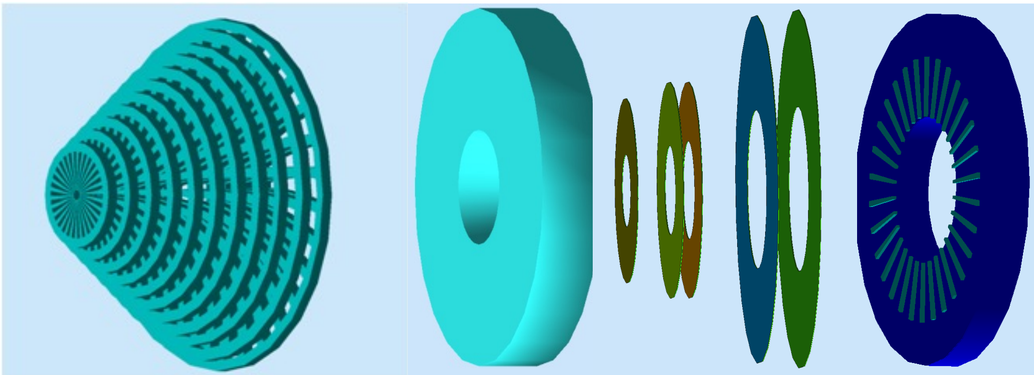


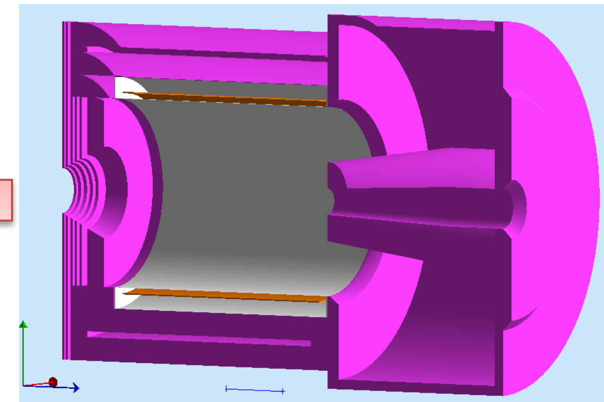
- High Luminosity: 10^{39} $cm^{-2}s^{-1}$
- Large scattering angles ~22° < θ < ~35° (for high x & y).
- Momentum resolution: ~2%
- W^2> 4 GeV^2: Isolate DIS events.
- Polar angle resolution ~ 1mrad

- High luminosity (polarized) ~ 10^{37} cm^{-2} s^{-1}
- Detection e^- : $8^o < \theta < 24^o$, full azimuthal $0.8 < P < 7.0$ GeV
- Detection of π^+/π^- : $8^o < \theta < 15^o$, full azimuthal $2.5 < P < 7.5$GeV (baseline)
- SPD: photon rejection 10:1
- Momentum resolution: 2%

SoLID Detector Overview

PVDIS: Baffle LGC 5xGEMs EC

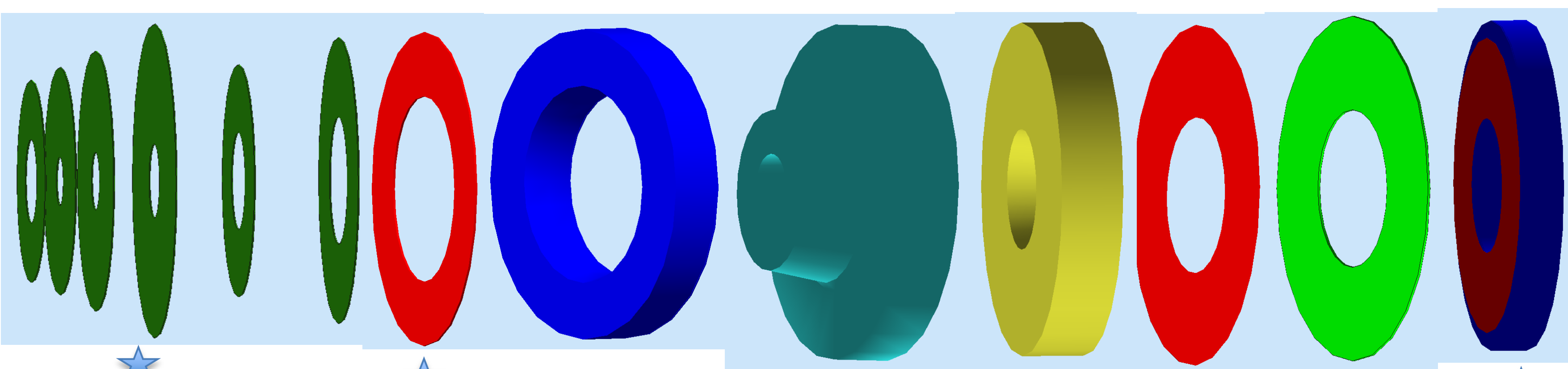




- **Baffle:** ~40% azimuthal coverage with baffles which provide curved channels that block positive and neutral background particles.

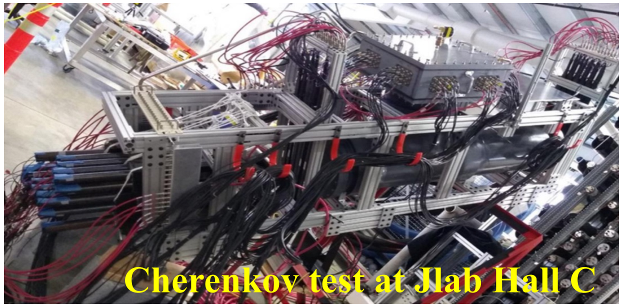
SIDIS&J/Psi:

6xGEMs LASPD LAEC LGC HGC FASPD MRPC FAEC



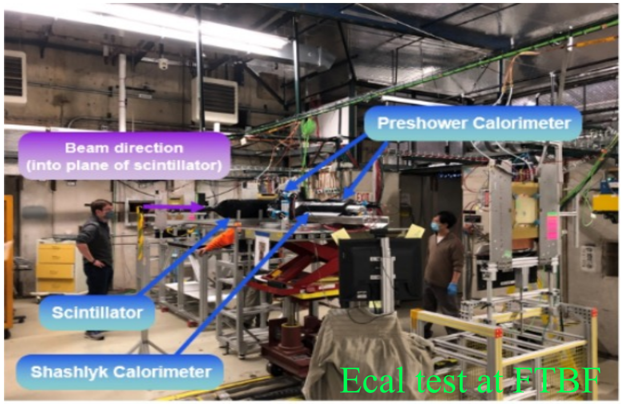
SoLID Detector Beam Test

➢ Beam test of Cherenkov (pre-R&D in 2020) at Jlab Hall C
✓ Low-rate beam test of maPMTs: 3/2020
✓ High-rate beam test of maPMTs: 6-8/2020
- MaPMT works well in a high-rate environment of 300 kHz per cm2
- LAPPD exhibits a similar performance
✓ Low-rate beam test of LAPPD: 8-9/2020



➢ Beam test of Ecal at Fermilab Test Beam Facility (1/2021)
✓ energy resolution $\frac{\sigma_E}{E} = 4.6\% \bigoplus \frac{10.4\%}{\sqrt{E}}$

✓ position resolution dX = 0.67 cm dY = 0.56 cm



Beam test of a full set of SoLID detector prototypes – GEM, LGC, LASPD, ECal, DAQ and associated electronics: (6/2022-3/2023)

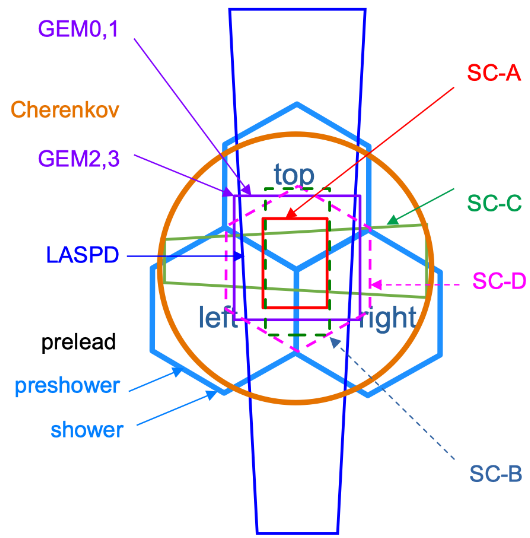
- Benchmarking simulation of rate and background
- Study **ECal** and **LASPD** performance under high rate, high radiation, high background condition
- Study ECal and LASPD PID

Latest pre-R&D – Detector Beam Test

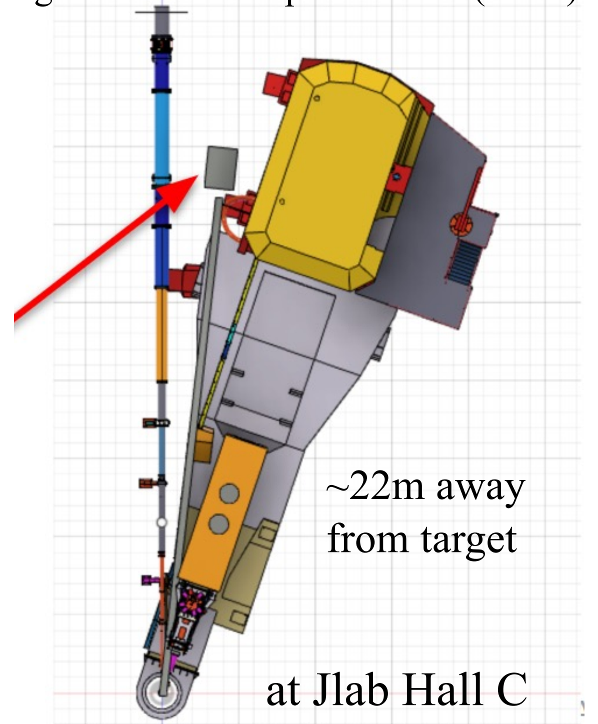
Three stages:

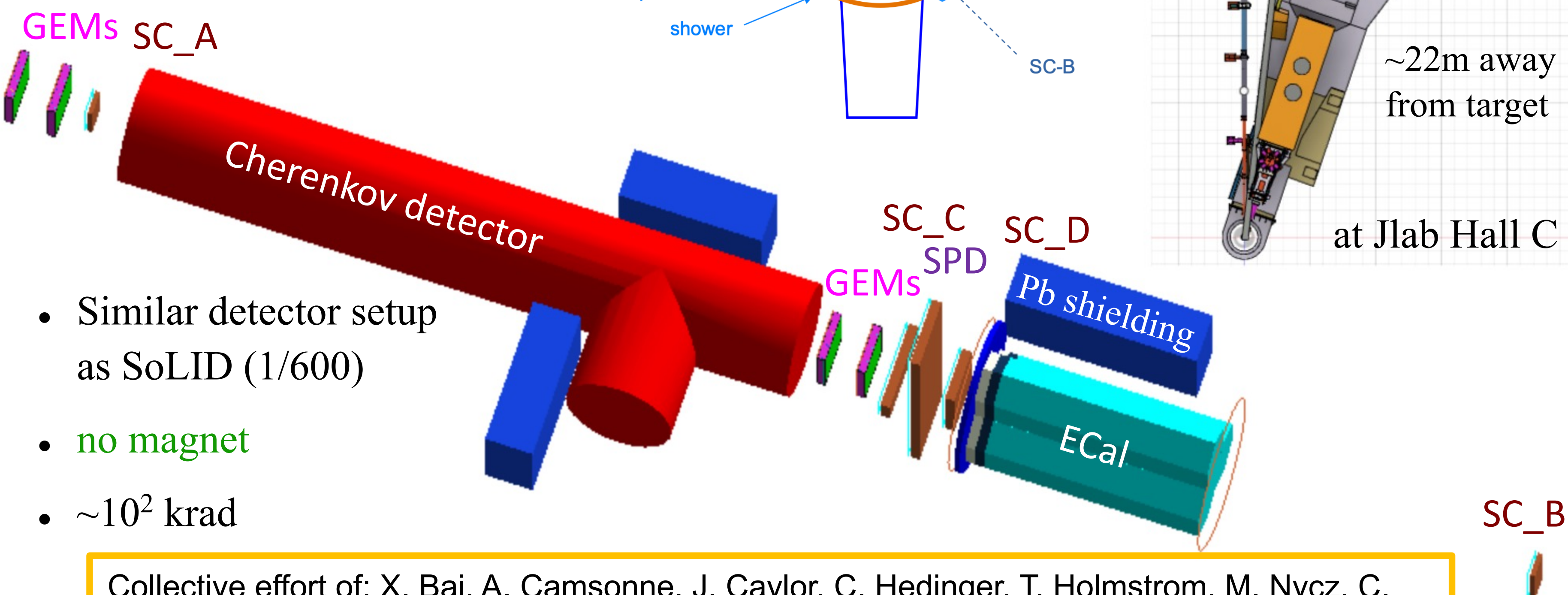
- June 2022: install at (L) 82°
- Jan 2023: moved to (R) 7°
- Feb 2023: moved to (R) 18°

Front view



High Momentum Spectrometer (HMS)



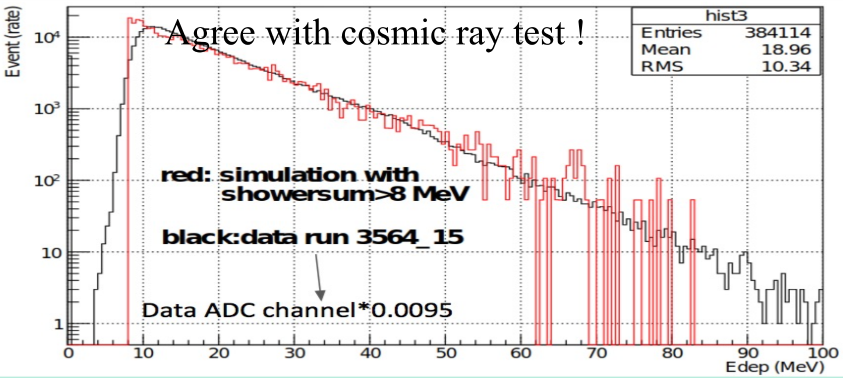


- Similar detector setup as SoLID (1/600)
- no magnet
- ~10^2 krad

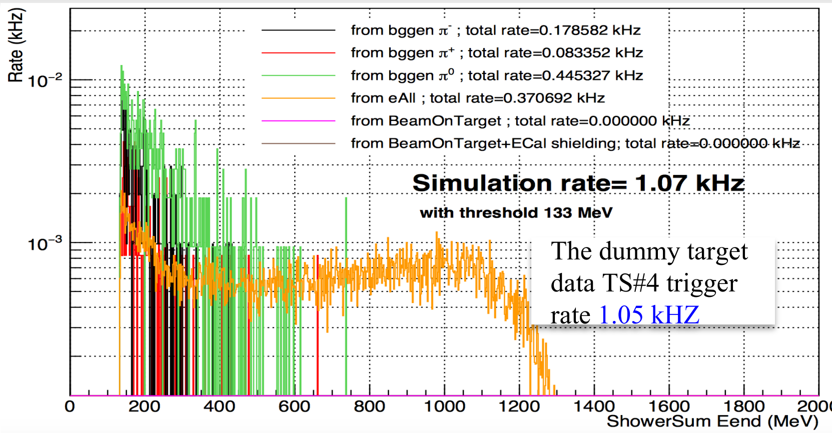
Collective effort of: X. Bai, A. Camsonne, J. Caylor, C. Hedinger, T. Holmstrom, M. Nycz, C. Peng, Y. Tian, D. Upton, Z. Ye, J. Zhang, Z. Zhao, JLab DAQ group, and Hall C(A) tech/staff

Latest pre-R&D – Detector Beam Test

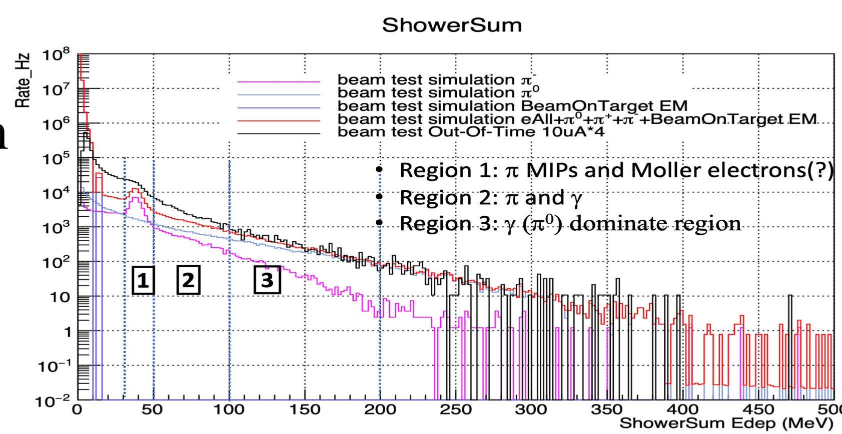
➢ 82 deg:
- dominant by pi0
- charged pion energy is not large enough to see the MIP at shower
- calibrate sim/data using spectrum slope



➢ 7 deg:
- 60 MeV Moller electron from the target
- photons from beam line (high energy photons covered the MIP at shower)
- Simulation rate is consistent with the 7 deg data (<10%)

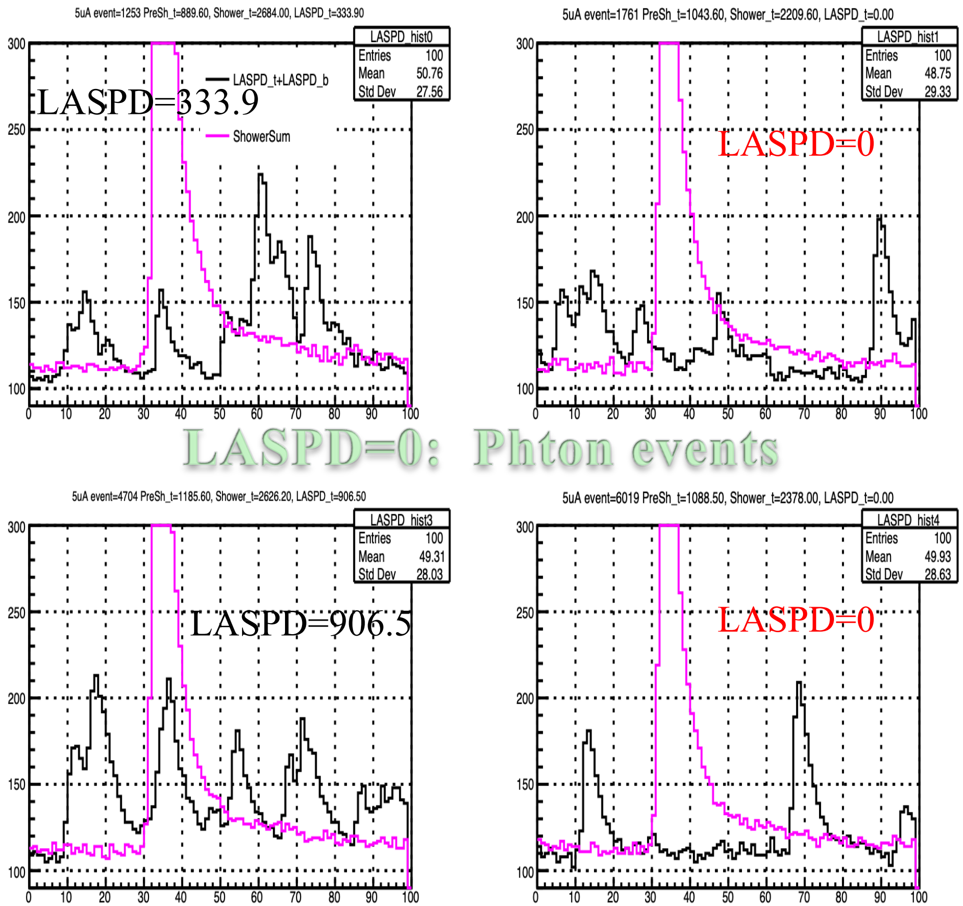


➢ 18 deg:
- large shower pulses are dominant by photon
- It is easy to see the MIP at shower



LASPD Photon Rejection Study at 18 deg

❖ LASPD waveforms with Shower trigger



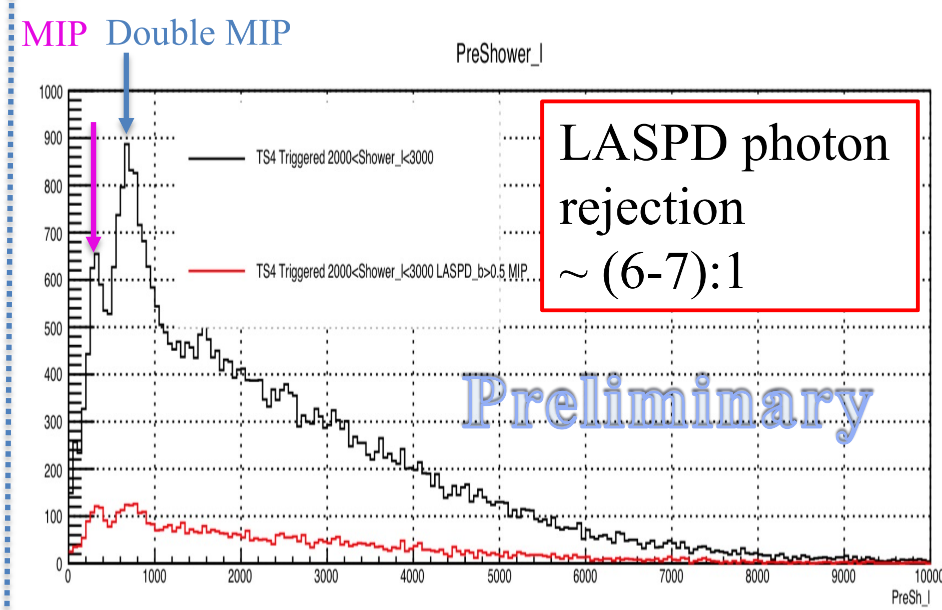
– LASPD_t+LASPD_b

– ShowerSum

- **5uA** on LD2
- 2200<Shower_t<2800
- 800<PreSh_t<1200

LASPD: Large Angle SPD
(---SoLID SIDIS detector)

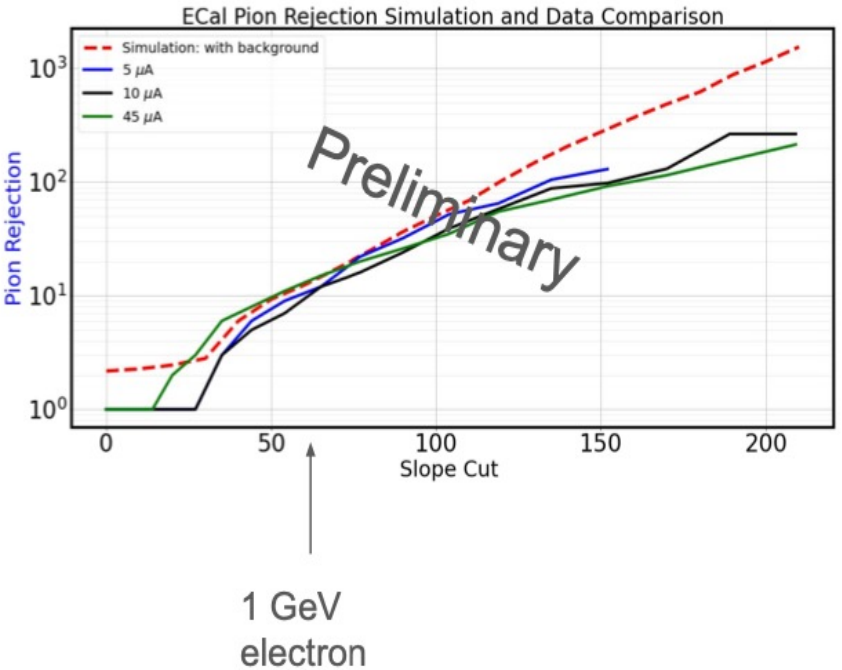
Photon rejection:
N/N(LASPD>0.5 MIP)



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

Summary and Status of PID

- Apply same cuts to simulation
  - Trigger, Scintillator, Cherenkov, etc…
- Provides a baseline for comparison with data



Next Steps

1. Simulation
   - Did not use true PID in simulation
   - Better mixing of background
2. Data
   - Further refinements to Cherenkov SPE from recent bench test
   - Improvement with updates from GEM tracking

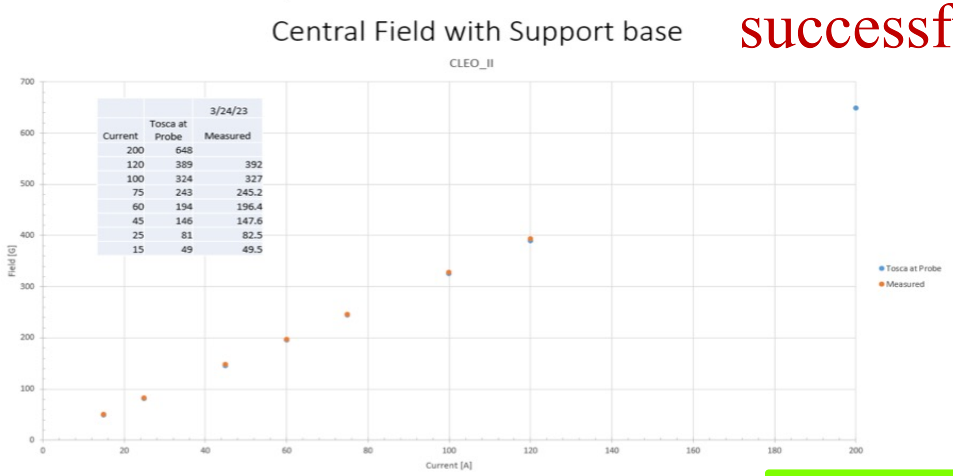
Slide from M. Nycz, 2023 SoLID collaboration talk

CLEO-II Magnet Cold Test at JLab

Magnet – Low Current Test – Preliminary Data

- A low current test was conducted on March 21st up to 75A. Test was cut short due to another heat excursion.
- March 21st test indicated connectors for voltage taps wired incorrectly – corrected on March 24th.
- A 2nd low current test was conducted on March 24th while LHe temps were stable. The current for this tests was ramped up to 120A and was held for 30 mins.
- PSU output voltage was approx 1.15V during ramp up at 0.5A/s.
- No increase in coil voltages observed during ramp up or while at 120A for 30 mins.
- Coil believed to be superconducting with flat lined nature of temp curves during test.
- 5 Gauss boundary was monitored with the help of ES&H to ensure the field remained within limits at the established boundaries.
- A 3 axis Hall probe was installed in the bore of the magnet for each of the tests.

successful first magnet cold test at JLab



		3/24/23
Current	Tosca at Probe	Measured
200	648	
120	389	392
100	324	327
75	243	245.2
60	194	196.4
45	146	147.6
25	81	82.5
15	49	49.5

Slide from W. Seay, 2023 SoLID collaboration meeting

Summary

SoLID is at the intensity frontier with JLab 12 GeV upgrade

- Rich and highly rated physics programs: PVDIS, SIDIS, near-threshold J/ψ
- Many other experiments in development
- Great potentials for JLab 20+ GeV
- Address important questions in Nuclear Physics
- Complementary and synergistic to the EIC science programs

Active pre-R&D with the support from DOE and JLab

- Demonstrated the feasibility of key detector subsystems in a high-rate environment
- To reduce risk/cost for SoLID
- **Cherenkov, GEM readout, and detector beam tests recently completed or well underway**
- Analysis for pre-R&D is ongoing

SoLID Project Status

- Science Review Feedback**: positive report, recommend to move to next step**
- LRP: **SoLID In Recommendation #4**, prominently featured in the report.
- DOE 2024: keep cost down (JLab re-direct) and find a funding path forward.
- Working on a new budget plan with JLab cost sharing
- Preparing the review for the Office-Science-Charge

SoLID PVDIS Collaboration

- 247+ collaborators, 62+ institutions from 13 countries
- Large international participations and anticipate contributions
- Strong theory support

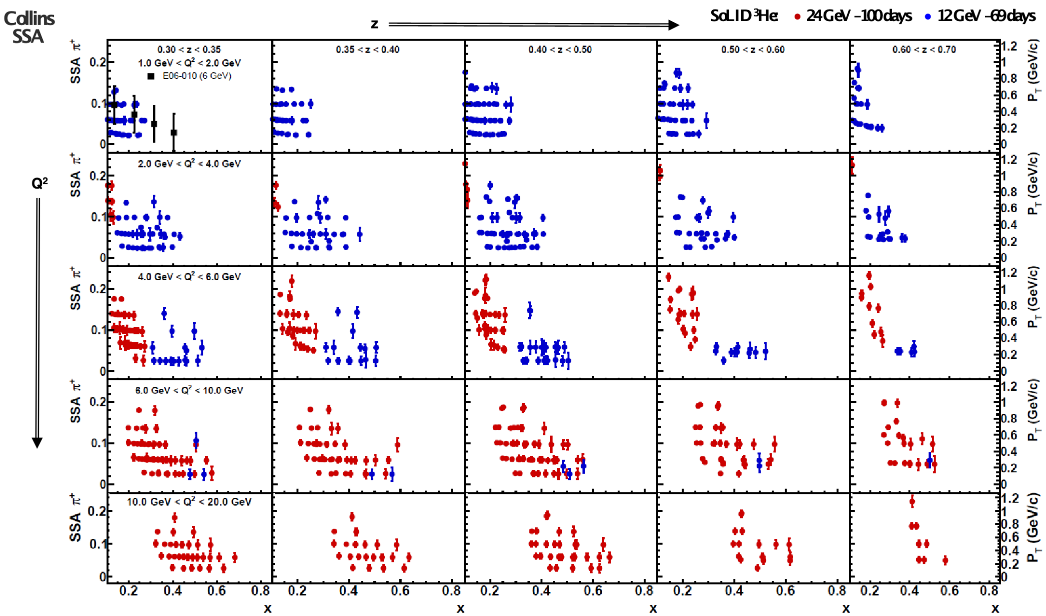
Thank you !

Backup

Great Potentials: SoLID with JLab20+

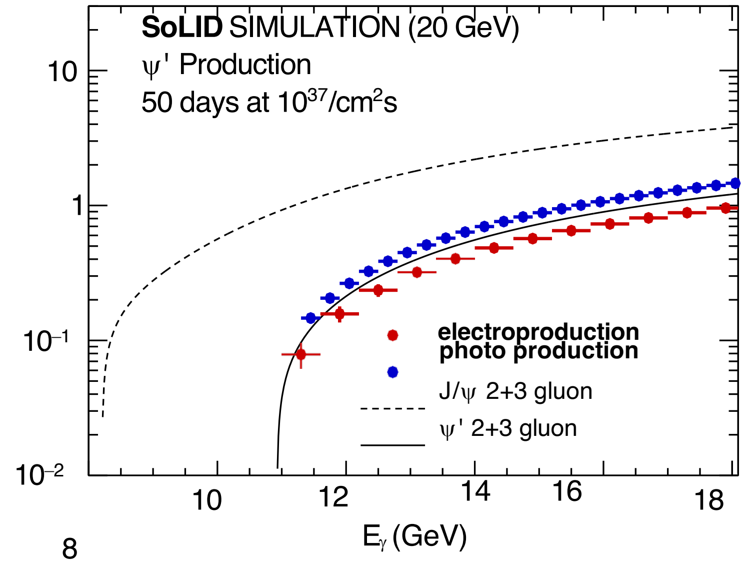
1) SIDIS: Collins Asymmetry: 20 GeV and 12GeV

Vlad Khachatrya



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

Sylvester Joosten



3) PVDIS@JLab20+:

a) Standard Model test with deuterium, Alex Emmert/Xiaochao Zheng

b) Precision study of strange sea, Mark/Dalton

4) Electron weak coupling C_3 with e+ and e-

LOI by Xiaochao Zheng

5) DDVCS, Alexandre Camsonne

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Slide from Jianping Chen, SoLID collaboration talk