Parity Violation in DIS Region with SoLID at 12 GeV JLab

Ye Tian

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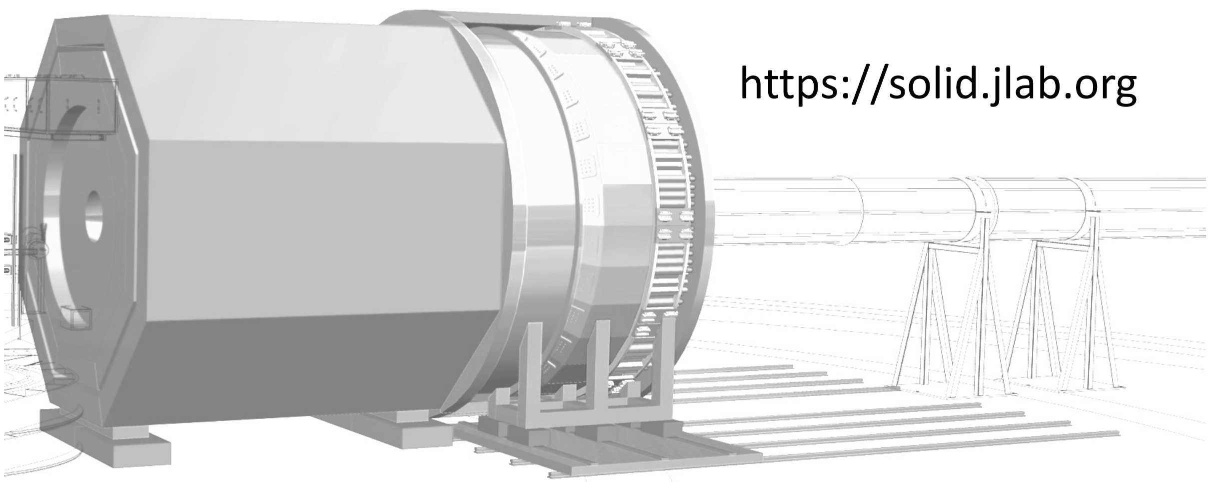
For the SoLID Collaboration

https://solid.jlab.org



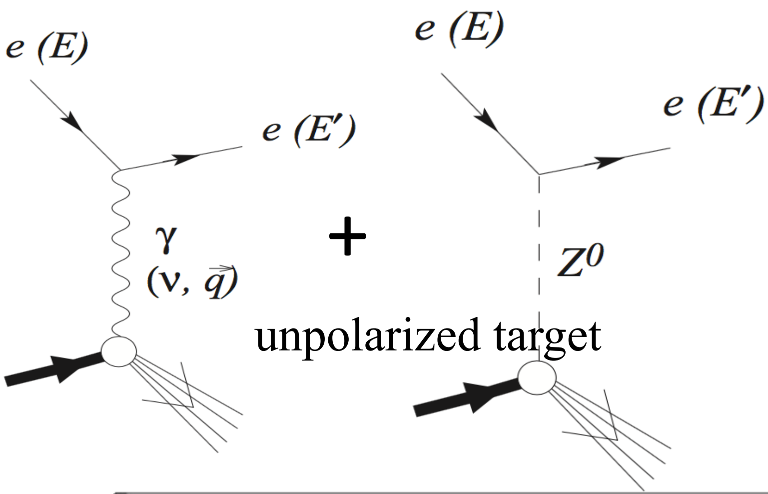
Supported by the U.S. Department of Energy under Grant : DE-FG02-84ER40146

Outline

- Physics Motivation
- SoLID Detector for PVDIS
- SoLID Detector Beam test
- Summary

Parity Violation in Electron Scattering

longitudinally polarized

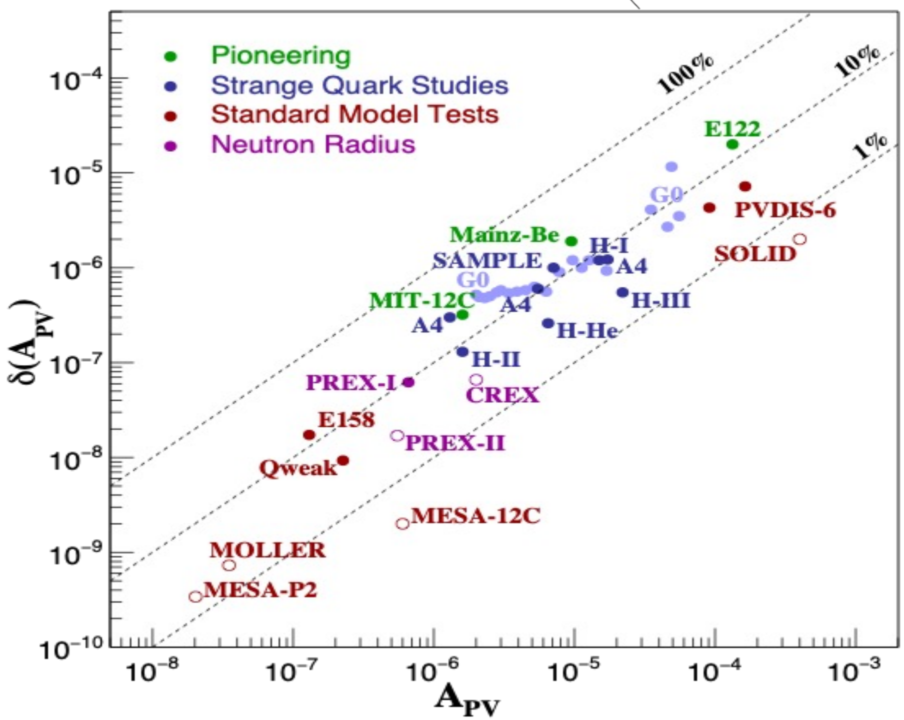


$$\sigma^r \propto |M_{em} + M^r_{weak}|^2$$

$$\sigma^l \propto \left|M_{em} + M^l_{weak}\right|^2$$

$$\approx |M_{em}|^2 + 2M_{em}M^l_{weak} + \left|M^l_{weak}\right|^2$$

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



	A ppm	δA ppm	δA/A(%)
SoLID	500	3	0.6
MOLLER	0.035	0.0008	2.2
P2	0.020	0.0004	2.0

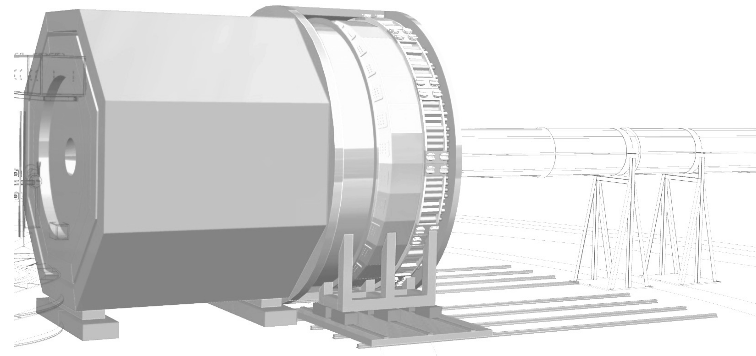
- SoLID, MOLLER, and P2 all improve precision

PVDIS with SoLID

Measure A_{pv} in Deep Inelastic Scattering:

A_{pv} with deuterium:

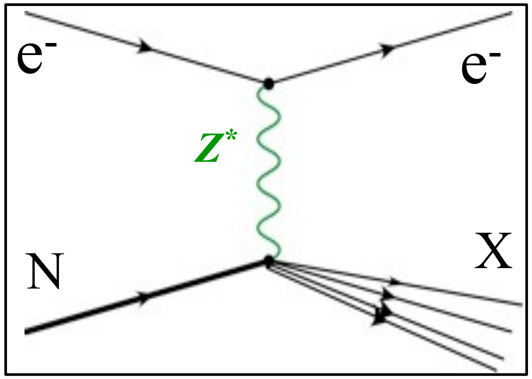
- Measure electroweak parameters
- Search for BSM physics
- Search for CSV at the quark level
- Search for quark-quark higher twist effects



Apv with proton:

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

Parity Violating DIS on Deuteron



- Scattering off the simplest isoscalar nucleus and at high x

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

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

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

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

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

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

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

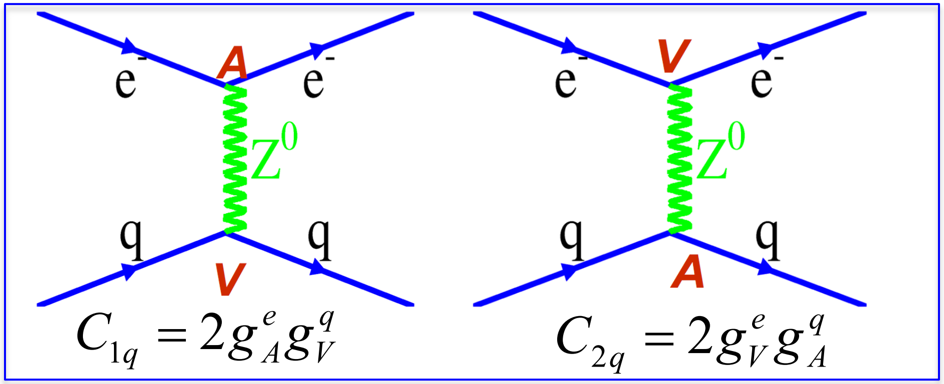
$$C_{1u} = 2g_A^e g_V^u \approx -\frac{1}{2} + \frac{4}{3}sin^2\theta_W \approx -0.19$$

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

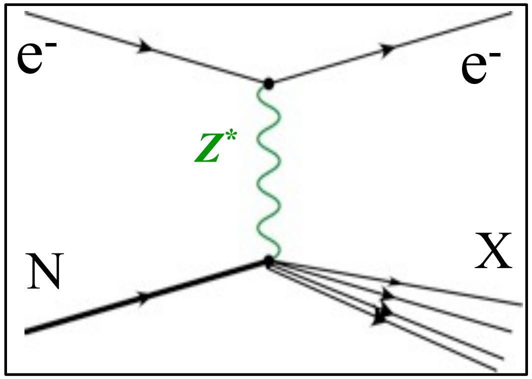
$$C_{2u} = 2g_V^e g_A^u \approx -\frac{1}{2} + 2sin^2\theta_W \approx -0.030$$

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

EW neutral current interaction



Parity Violating DIS on Deuteron



- Scattering off the simplest isoscalar nucleus and at high x

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

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

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

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

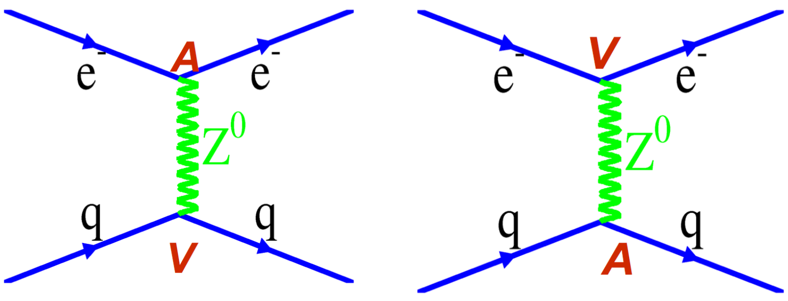
$$R_v(x) = \frac{u_v(x)+d_v(x)}{U(x)+D(x)} \xrightarrow{\text{Large } x} 1$$

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



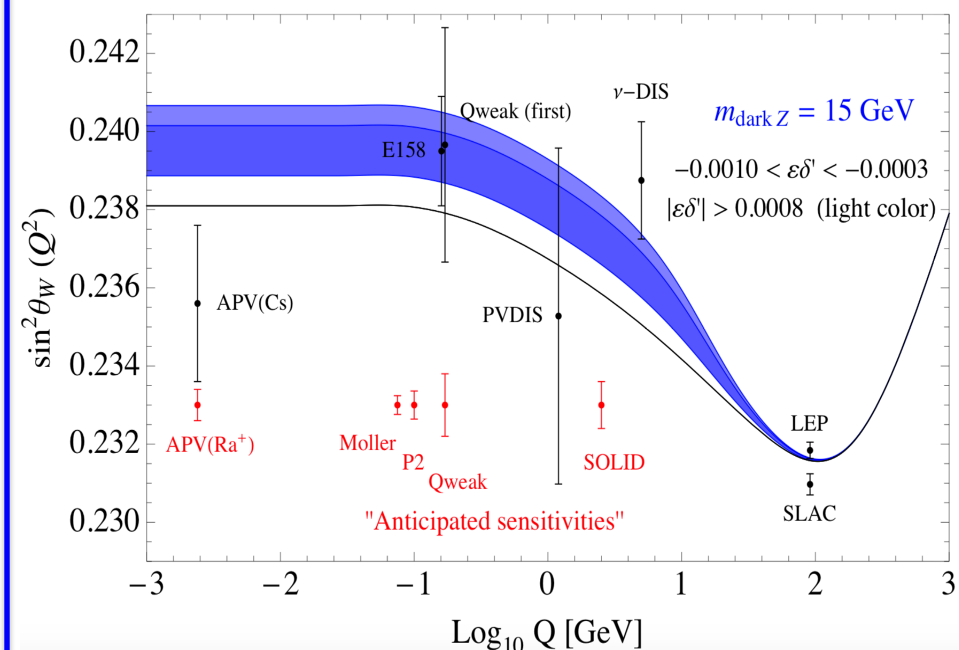
$$C_{1q} = 2g_A^e g_V^q \qquad C_{2q} = 2g_V^e g_A^q$$

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.)

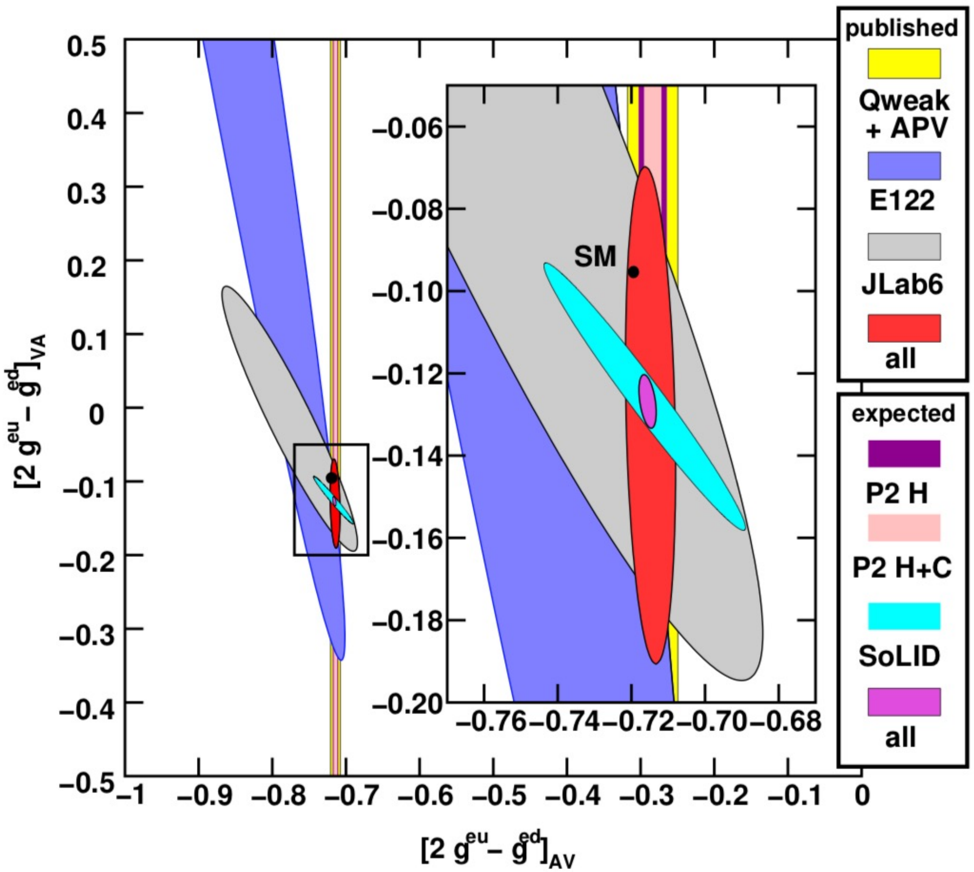
- Running of $\sin^2\theta_W$ with Q^2

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

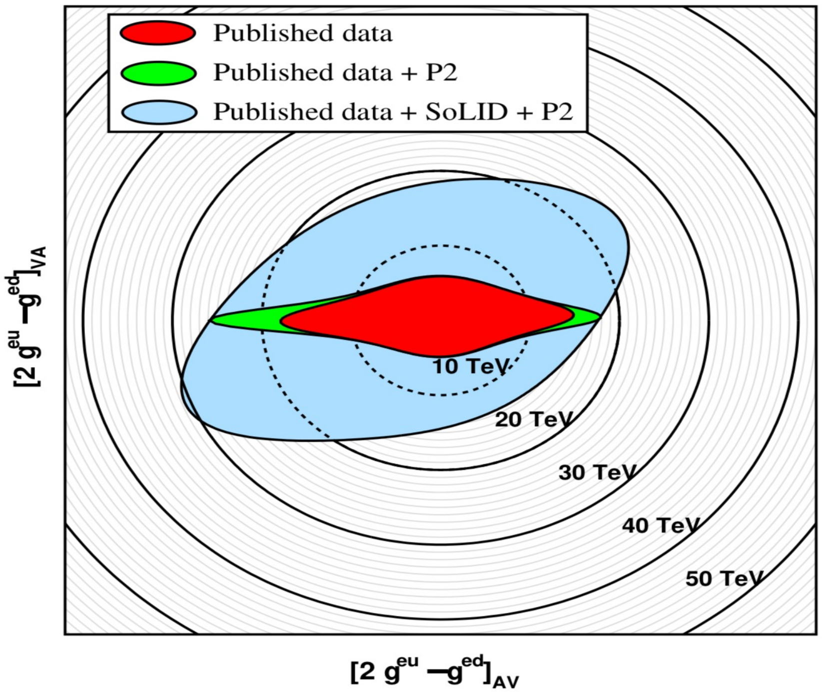


- $\sin^2\theta_W$ is a Standard Model Parameter
- Treat Ci's as function of $\sin^2\theta_W$
- Fit to one parameter

New Physics



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

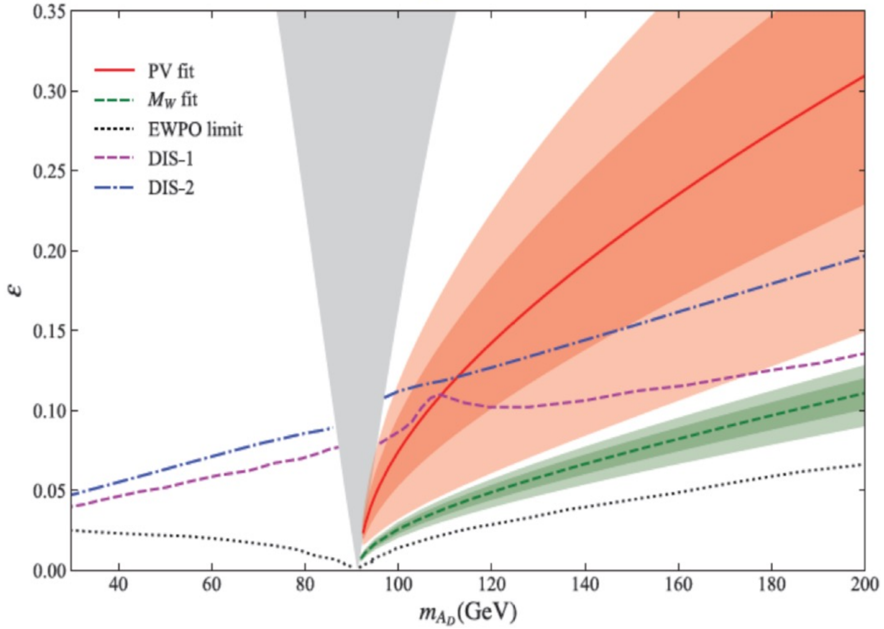


- Improvement in energy reach for electron-nucleon couplings.

New Physics Beyond Stand Model

Constraints of new W mass versus PV

Thomas and Wang, arXiv: 2205.01911

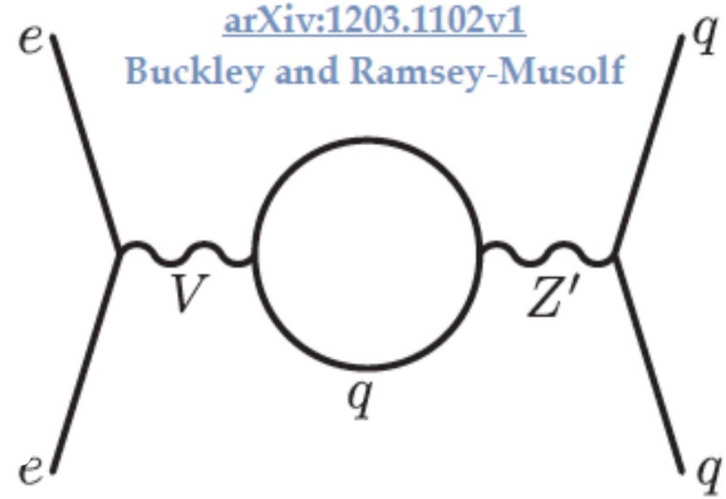


- Constraints on the dark photon from parity violation and the W mass: https://arxiv.org/abs/2205.01911
- Sensitivity of Parity-violating Electron Scattering to a Dark Photon https://arxiv.org/pdf/2201.06760.pdf

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

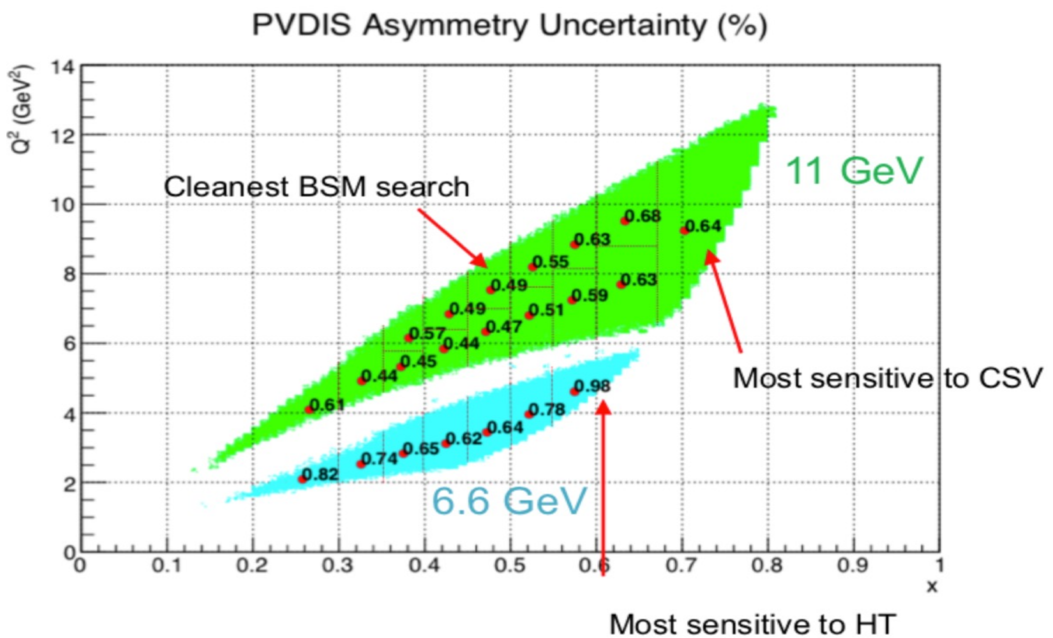
$$A_{DIS}^{D} = A_{SM}\left[1 + \frac{\beta_{HT}}{(1-x)^3 Q^2} + \beta_{CSV} x^2\right]$$

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

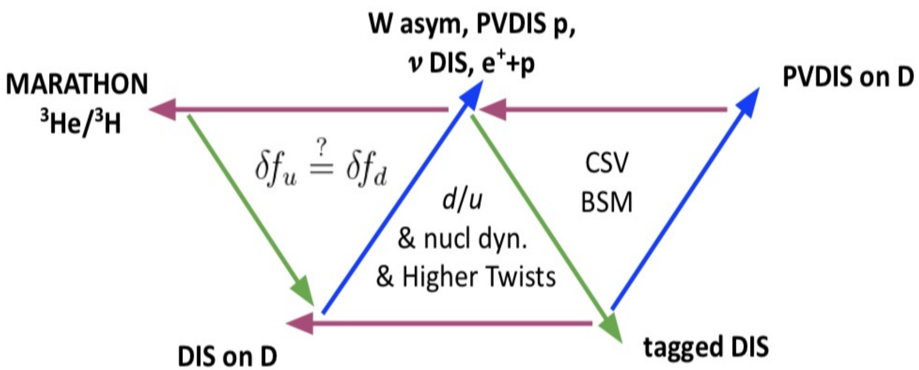
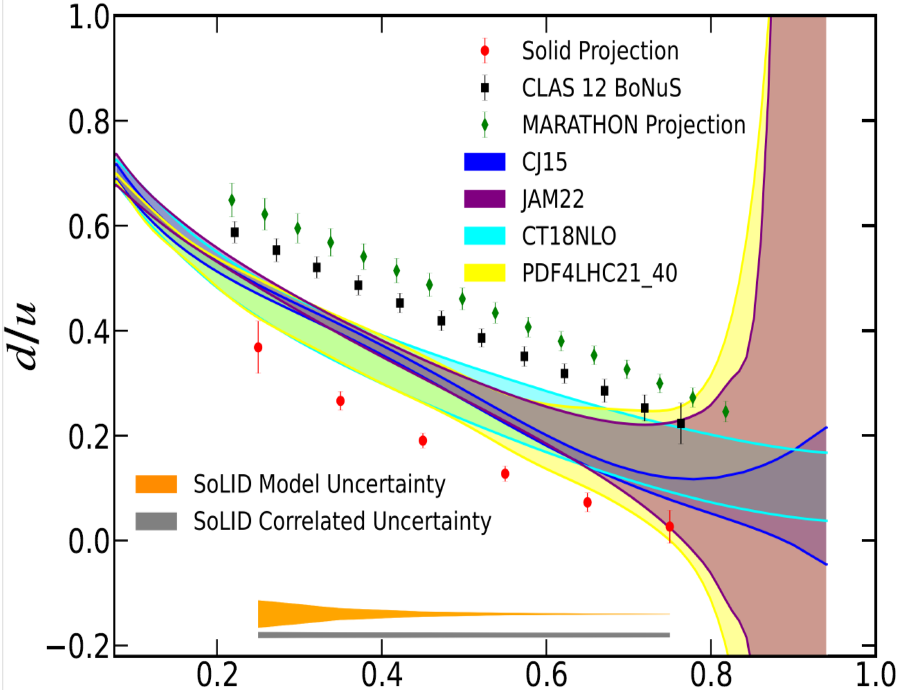


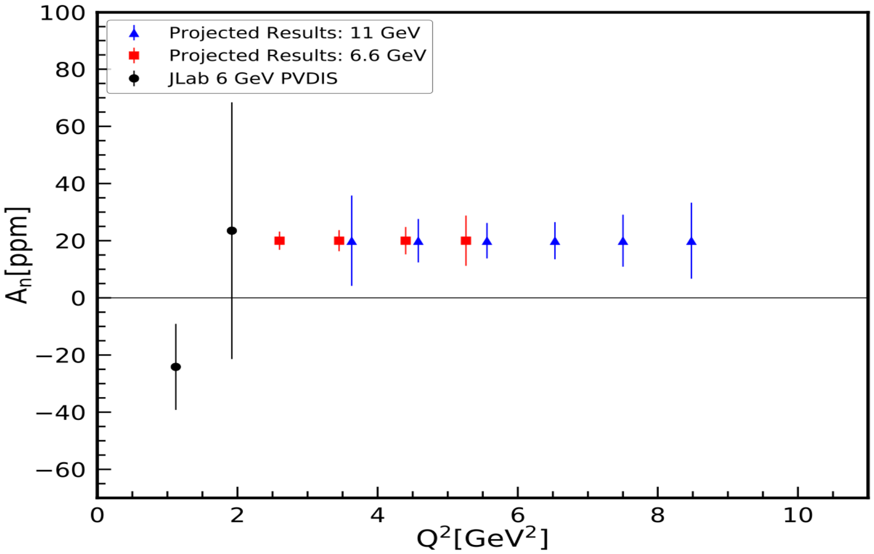
Figure courtesy of A. Accardi



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

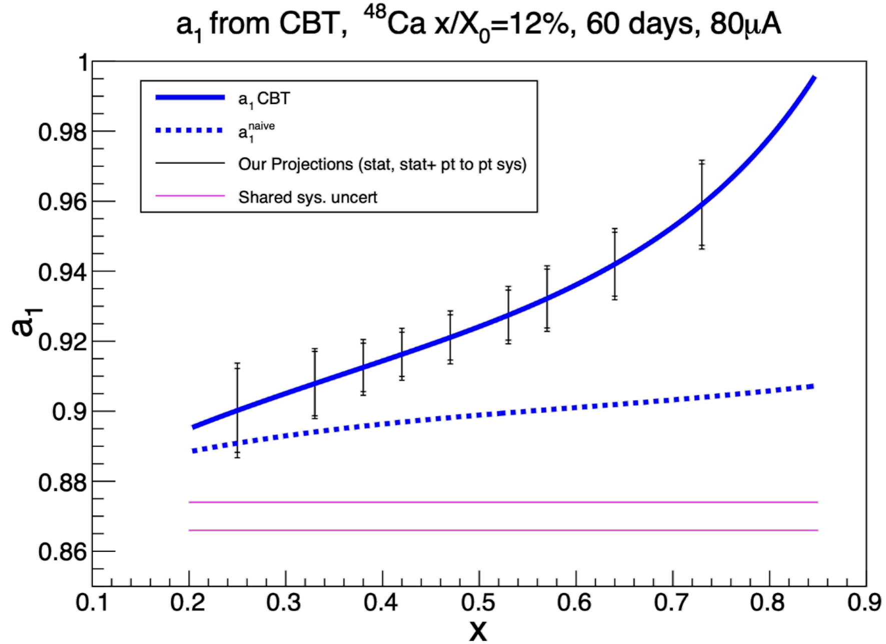
More Physics Programs using SoLID PVDIS configuration

➢ 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

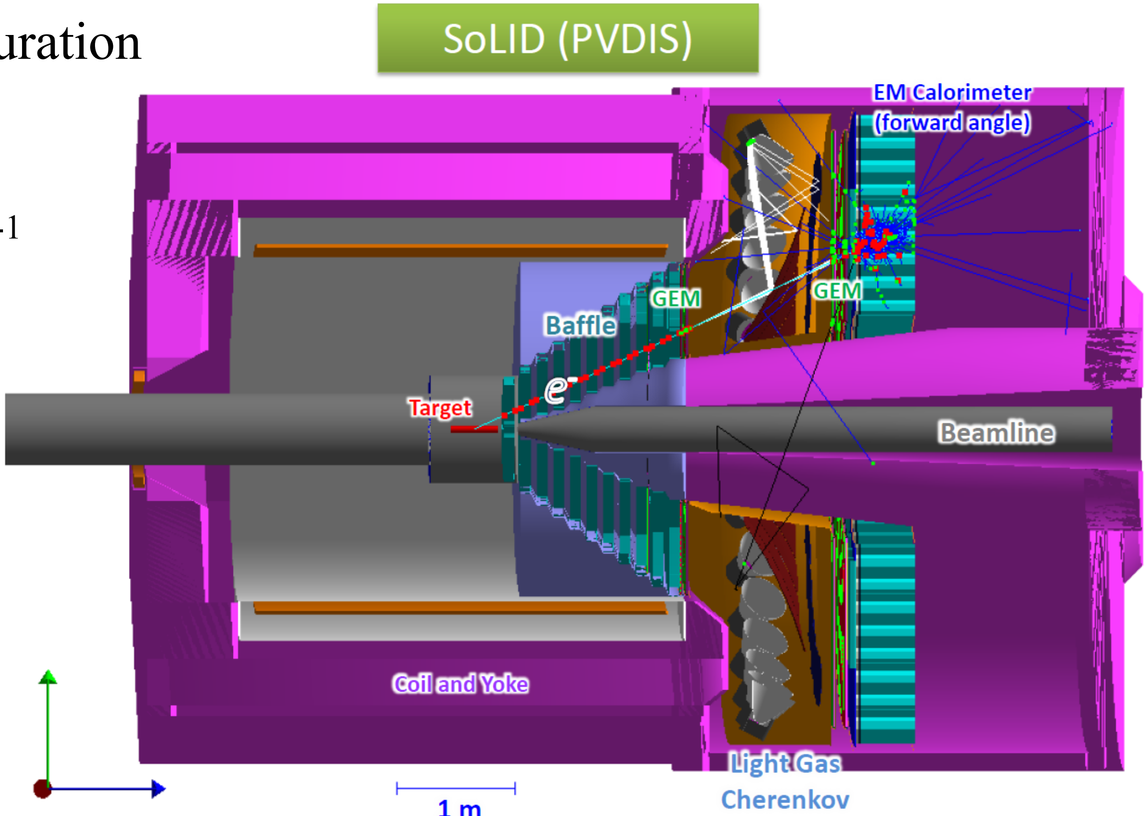
$$a_1 \simeq \frac{9}{5} - 4\sin^2\theta_W - \frac{12}{25}\frac{u_A^+ - d_A^+}{u_A^+ + d_A^+}$$



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

SoLID PVDIS Proposed Setup

- Solenoidal Large Intensity Device – Hall A at Jlab
- SoLID-PVDIS detector configuration



- High Luminosity: 10^{39} cm^{-2}s^{-1}
- Large azimuthal acceptance.
- Large scattering angles
  $\sim 22° < \theta < \sim 35°$
  (for high x & y).

Kinematic Requirements

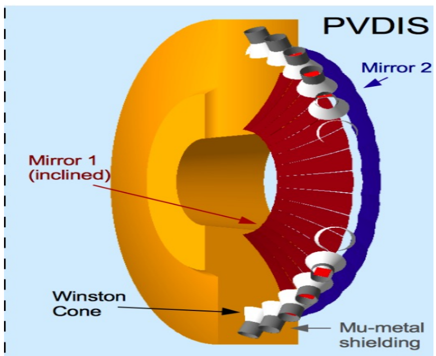
- 2 GeV < E'< 6 GeV: Low background
- $2\text{GeV}^2 < Q^2 < 10\text{GeV}^2$
- Wide x-range: 0.25-0.75
- Momentum resolution: ~2%
- $W^2 > 4$ GeV^2: Isolate DIS events.
- Polar angle resolution ~ 1mrad

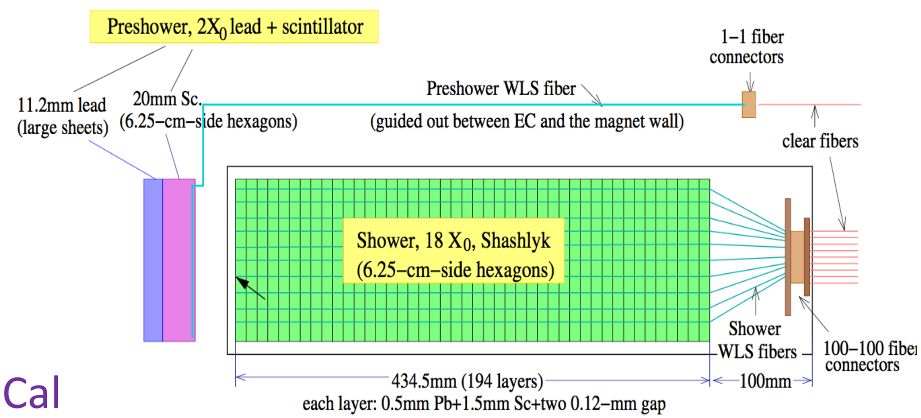
- CLEO magnet with the 40 cm LD_2 or 40 cm LH_2 target in the center provides the desired acceptance.

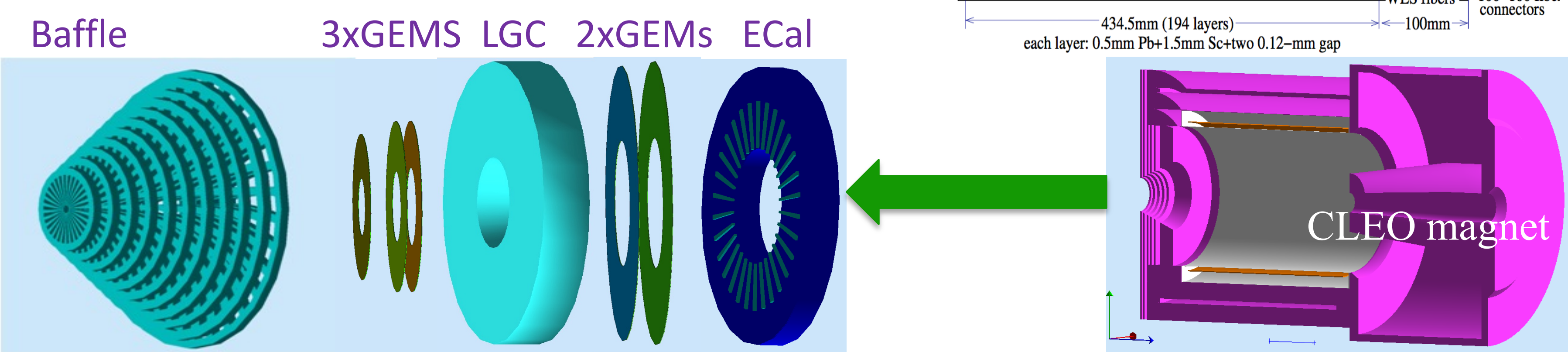
SoLID PVDIS Detector Subsystems

Requirements for Particle Identification and Trigger

- Light Gas Cherenkov (LGC): identify electrons for trigger; reject pions.
- Shashlyk electromagnetic calorimeter (ECal) : coincident trigger with LGC and further particle identification.
- With tracking, tight E/p cuts reduce pion backgrounds.



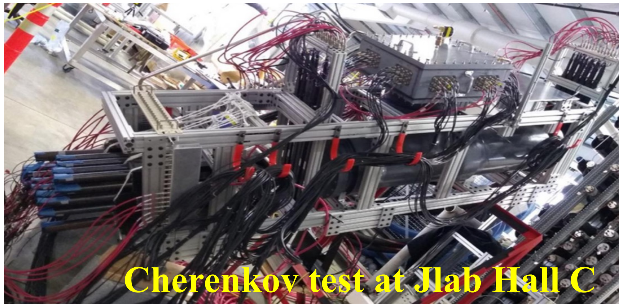




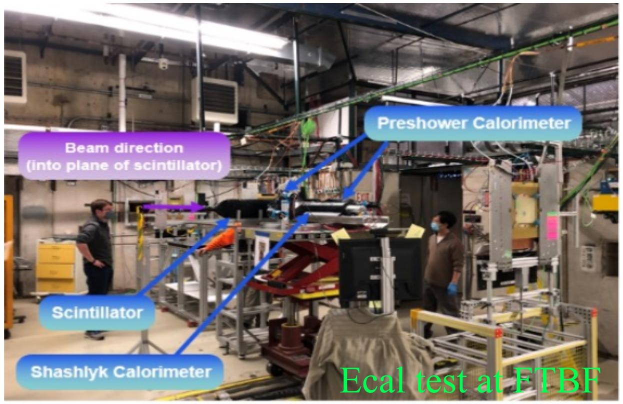
- **Baffle:** ~40% azimuthal coverage with baffles which provide curved channels that block positive and neutral background particles

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)

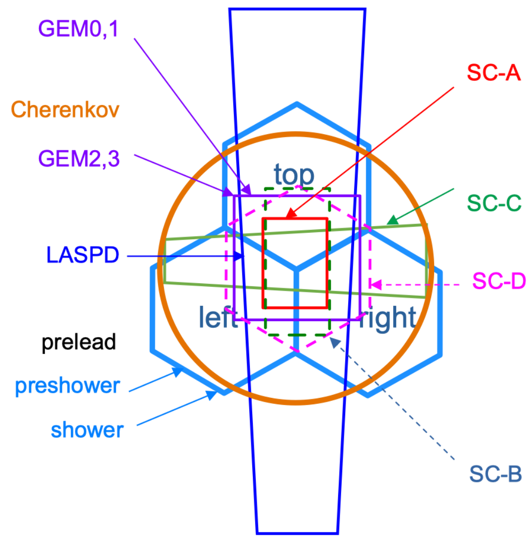
- Benchmarking simulation of rate and background
- Study ECal and LASPD performance under high rate, high radiation, high background condition
- Study ECal and LASPD PID

Latest pre-R&D – Detector Beam Test

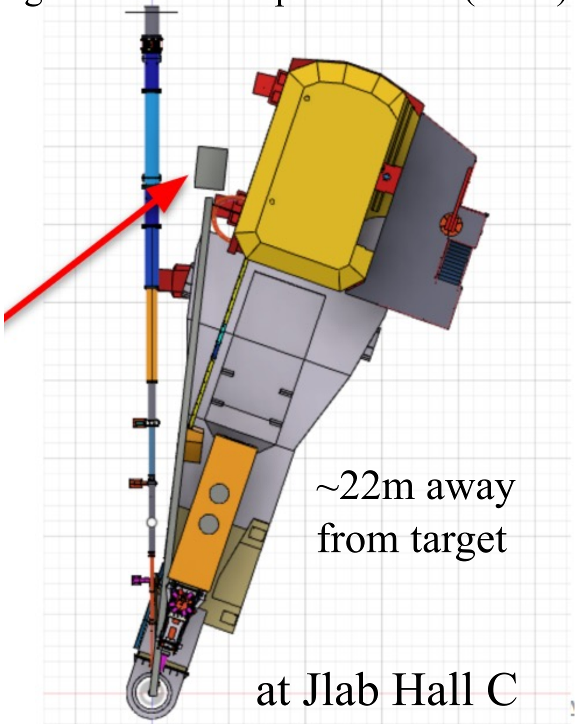
Three stages:

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

Front view

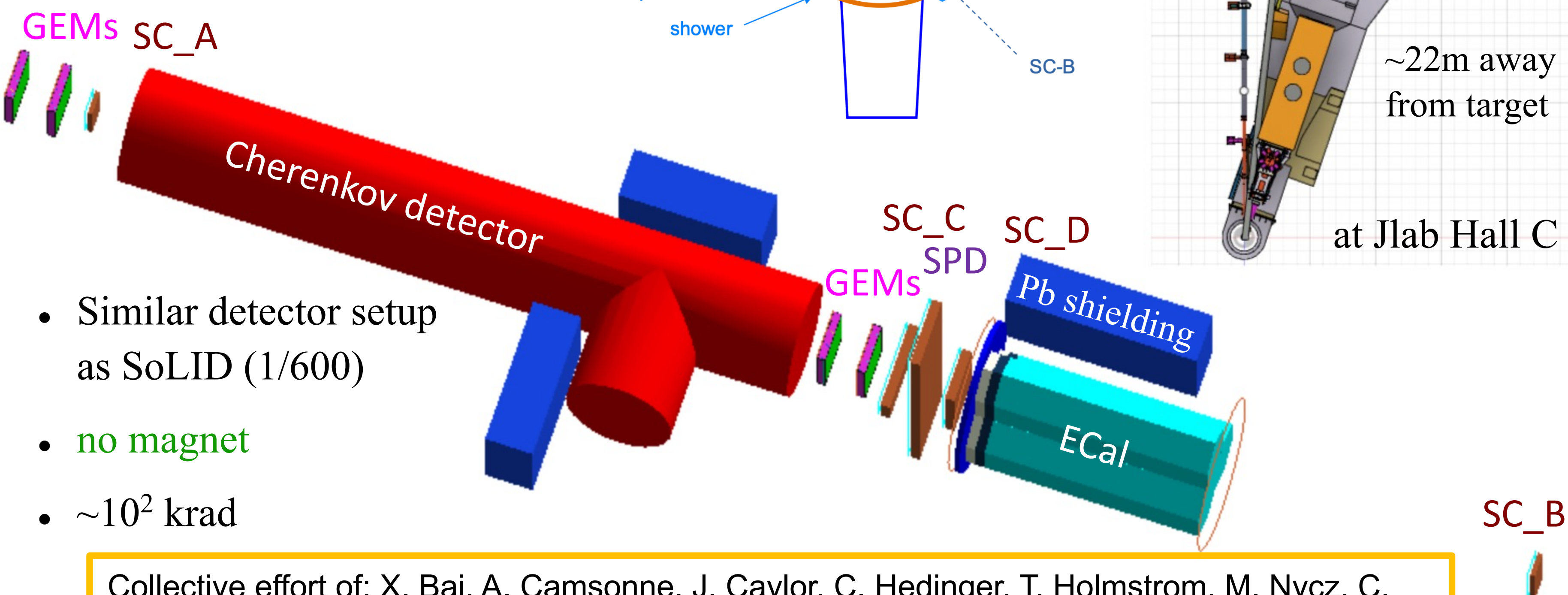


High Momentum Spectrometer (HMS)



~22m away from target

at Jlab Hall C

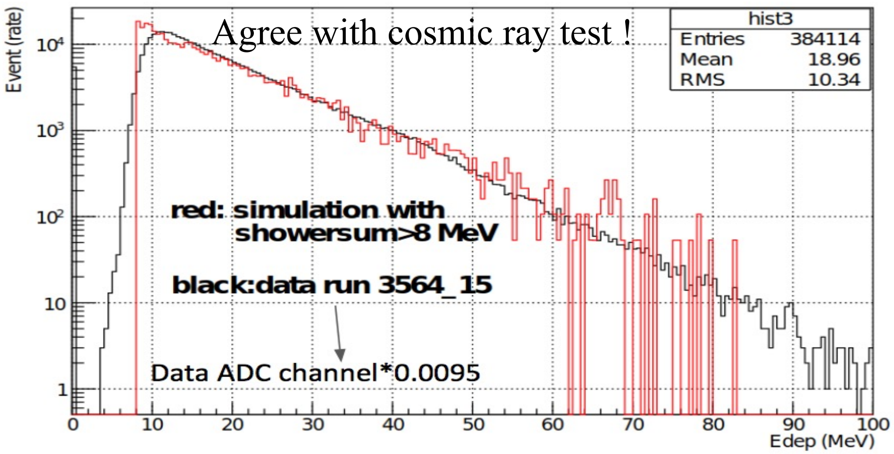


- Similar detector setup as SoLID (1/600)
- no magnet
- ~10^2 krad

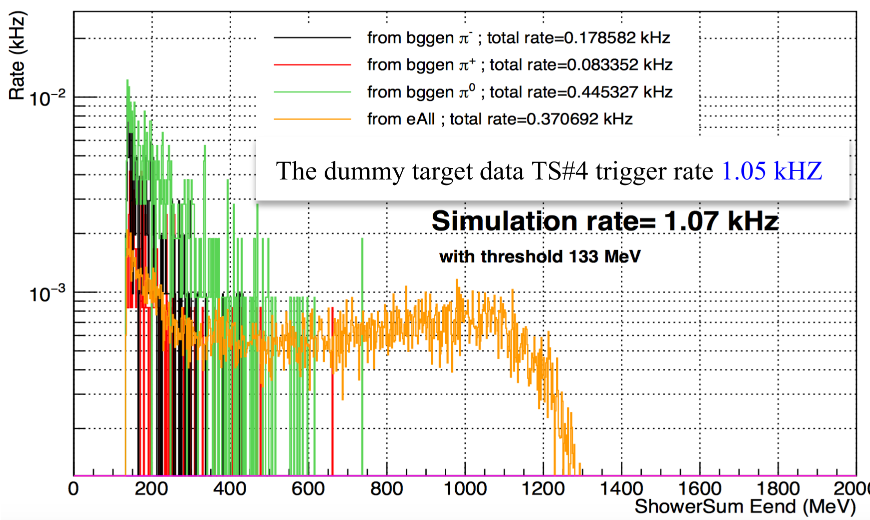
Collective effort of: X. Bai, A. Camsonne, J. Caylor, C. Hedinger, T. Holmstrom, M. Nycz, C. Peng, Y. Tian, D. Upton, Z. Ye, J. Zhang, Z. Zhao, JLab DAQ group, and Hall C(A) tech/staff

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

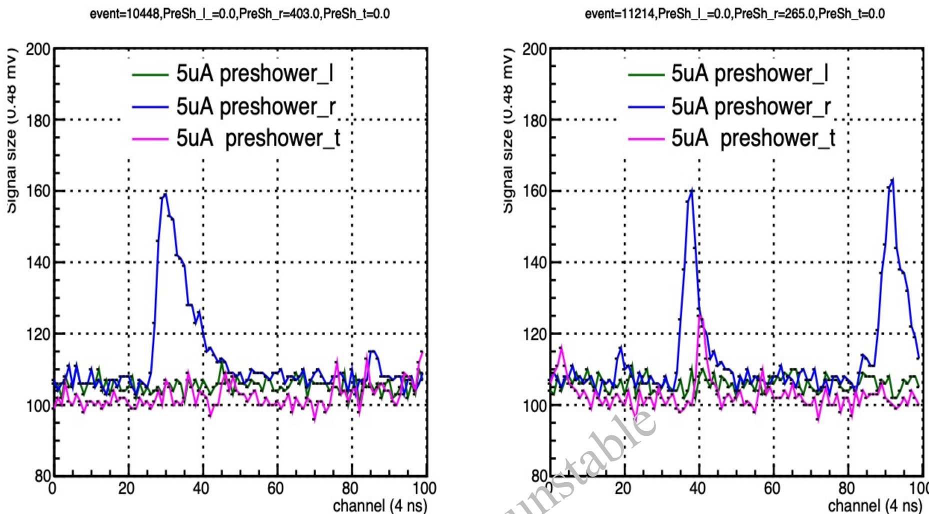


- 7 deg:
  - 60 MeV Moller electron from the target
  - photons from beam line (high energy photons covered the MIP at shower)
  - Simulation rate is consistent with the 7 deg data (<10%)

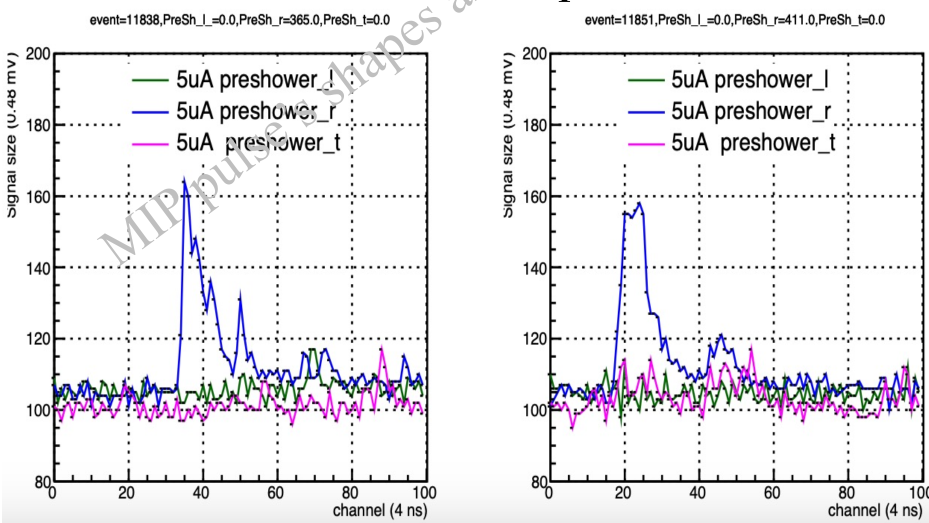


- 18 deg:
  - large shower pulses are dominant by photon
  - It is easy to see the MIP at shower

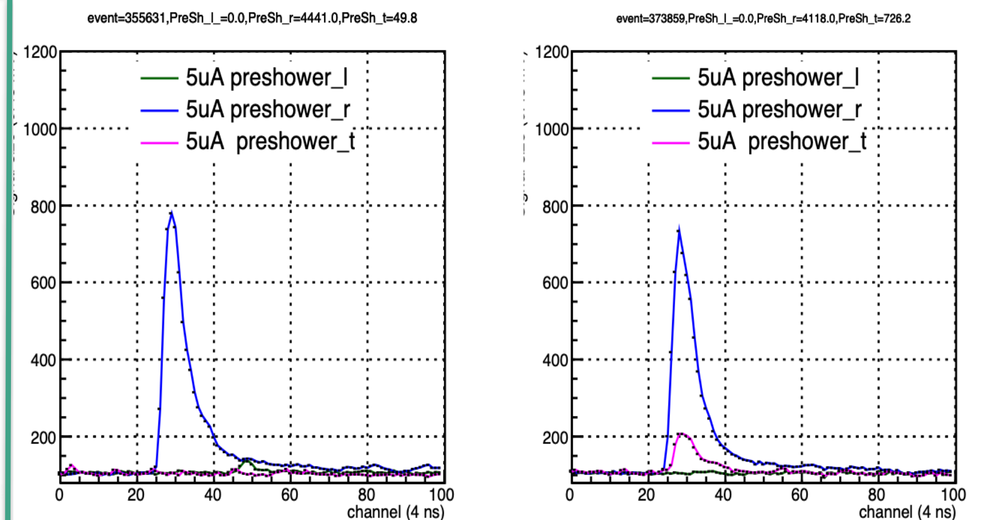
18 Deg Data Analysis is Ongoing



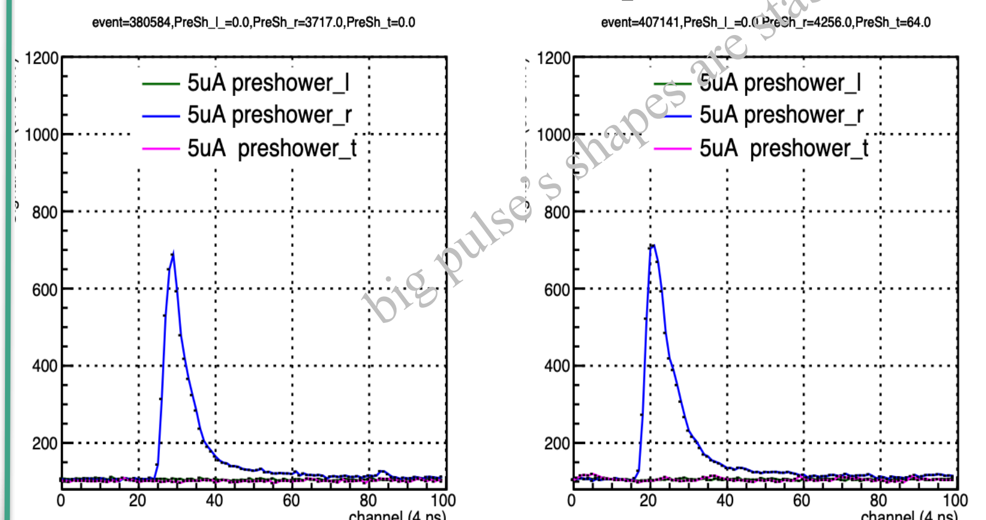
PreShower MIP pulses



MIP pulse's shapes are unstable



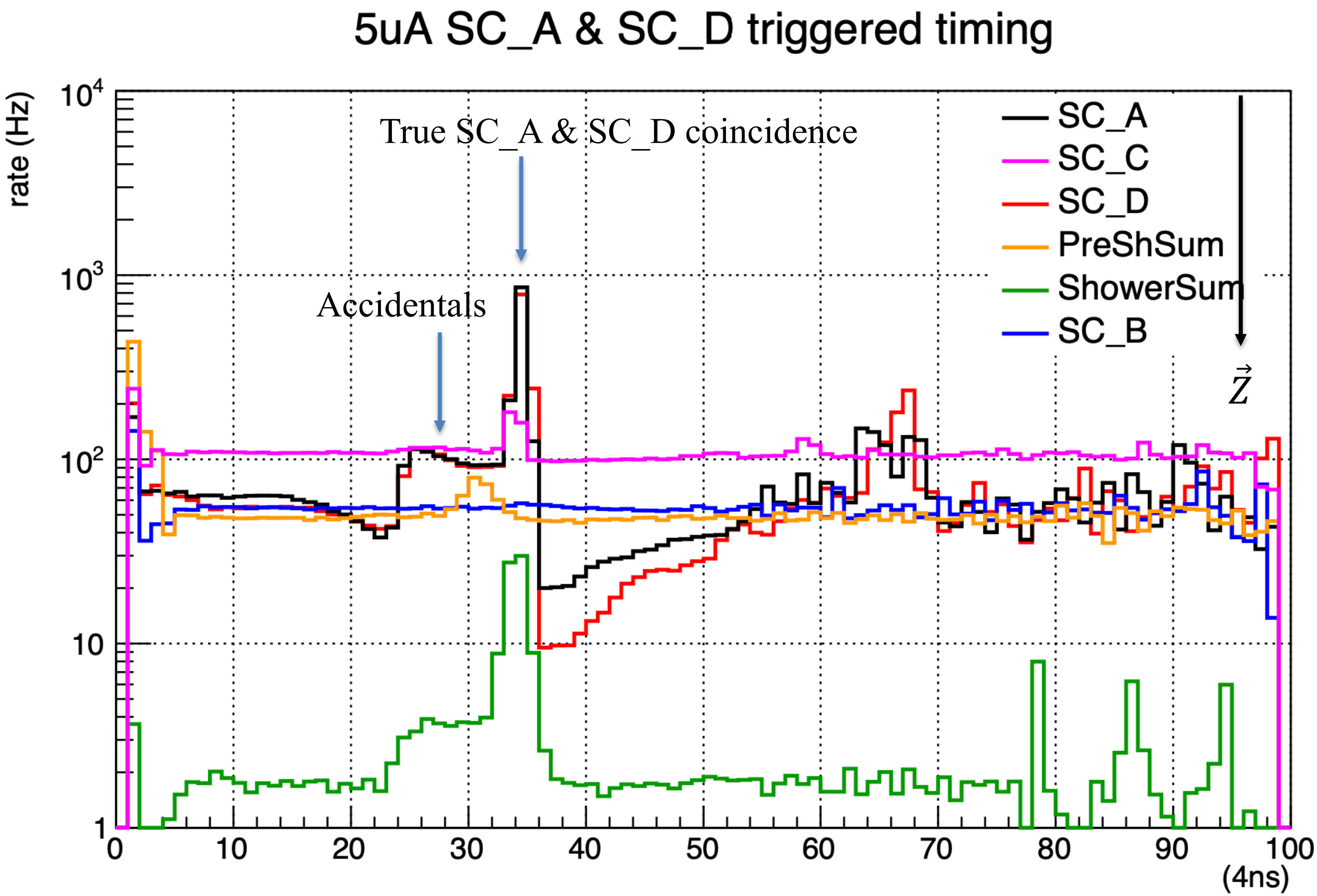
PreShower 10*MIP pulses



big pulse's shapes are stable

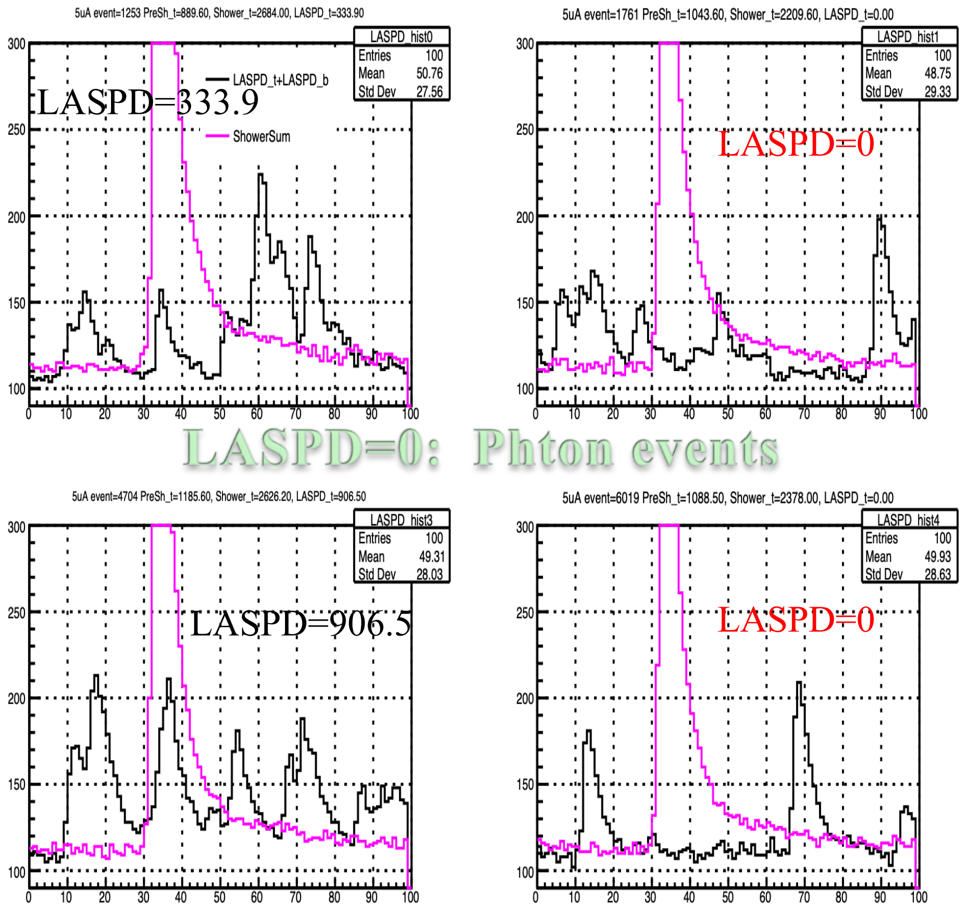
- Analog signals are digitized by the JLab FADC250, a 16-channel 12-bit FADC sampling at 250 MHz.
- We plan to record the entire waveform for PVDIS (pile up is going to be significant)
- 40ns integral window

18 Deg Data Analysis is Ongoing



LASPD Photon Rejection Study at 18 deg

❖ LASPD waveforms with Shower trigger

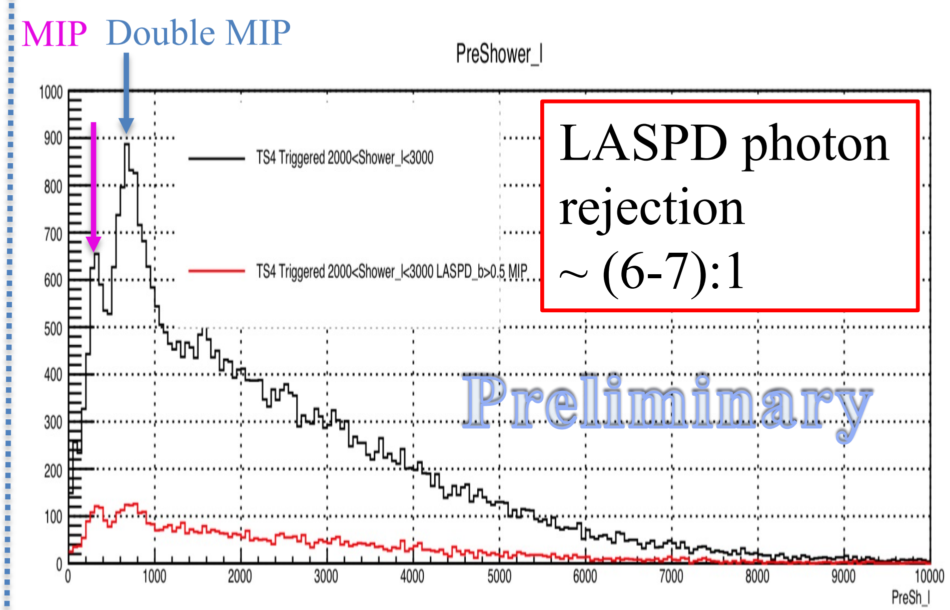


– LASPD_t+LASPD_b
– ShowerSum

- **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

- PVDIS on deuteron: sensitive to C_{2q} weak couplings, precision test of SM, precision study of charge symmetry violation and higher-twist.
- PVDIS on proton: clean measurement of d/u at high-x without nuclear correction.
- Completed the DOE science review (March 2021).
- DOE-funded pre-R&D activities on Cherenkov, GEM readout, and detector beam tests recently completed.
- Technical risks are assessed and addressed in the pre-R&D activities.
- 2022 SoLID white paper: https://arxiv.org/abs/2209.13357 (accepted by J. Phys. G)
- SoLID is explicit mentioned in the proposed recommendations from the town hall meeting for both Hot/Cold QCD and Fundamental Symmetries Long Range Plan Workshops.

SoLID PVDIS Collaboration

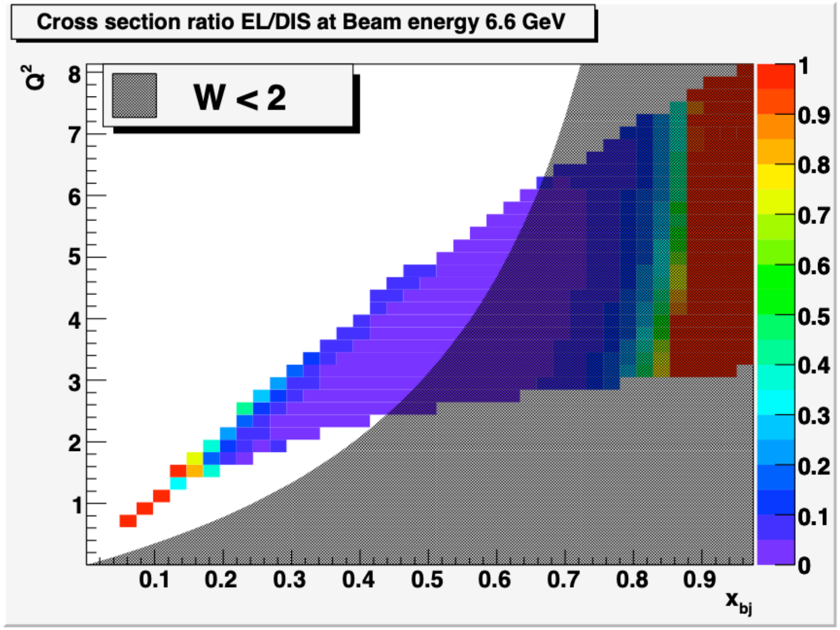
- 247+ collaborators, 62+ institutions from 13 countries
- Large international participations and anticipate contributions
- Strong theory support

Thank you !

Backup

7 Radiative Corrections

We have started estimating the sensitivity of the experiment to radiative corrections. One important contribution is elastic scattering. The elastic events due to initial state radiation have significantly smaller Q^2, resulting in a dilution of the asymmetry. Hence we would like the fraction of elastic events to be below 10%. In Figures 7, we see that this criteria is satisfied for both 6.6 and 11 GeV data.



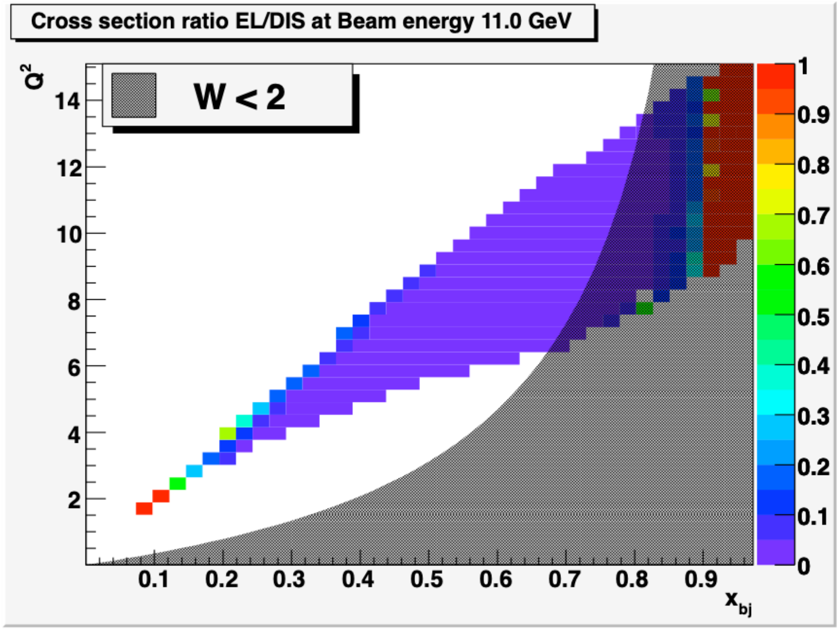


Figure 9: Ratio of elastic tail to DIS data for 6.6 GeV (left) and 11 GeV (right.

Summary of Uncertainties and Beam Request

Experimental Uncertainty Budget

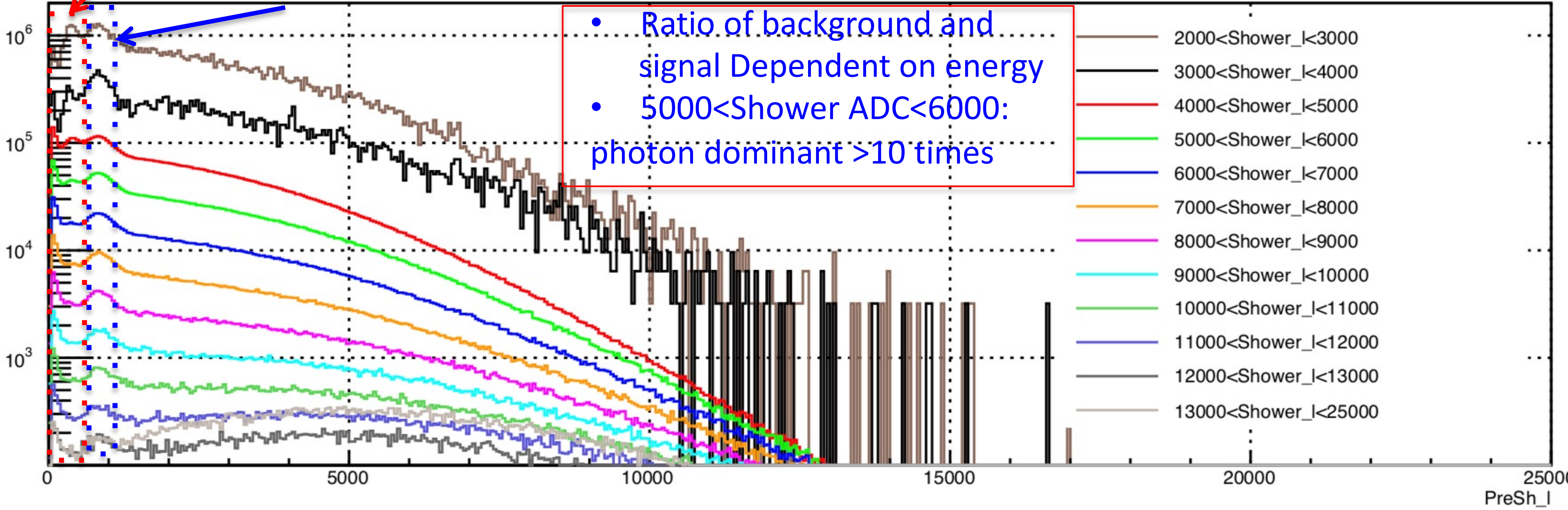
Total	**0.6**
Polarimetry	0.4
Q^2	0.2
Radiative Corrections	0.2
Event reconstruction	0.2
Statistics	0.3

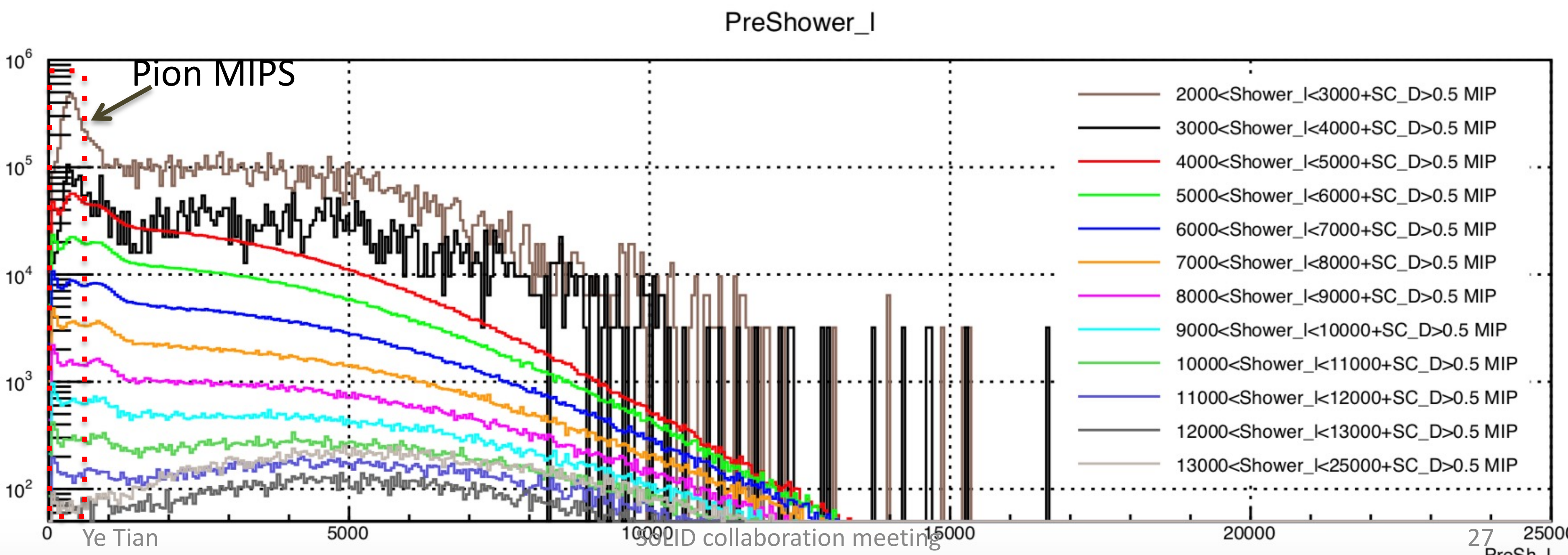
Energy(GeV)	4.4	6.6	11	Test
Days(LD2)	18	60	120	27
Days(LH2)	9	-	90	14

The size (both transverse and thickness) of each detector and their readout information

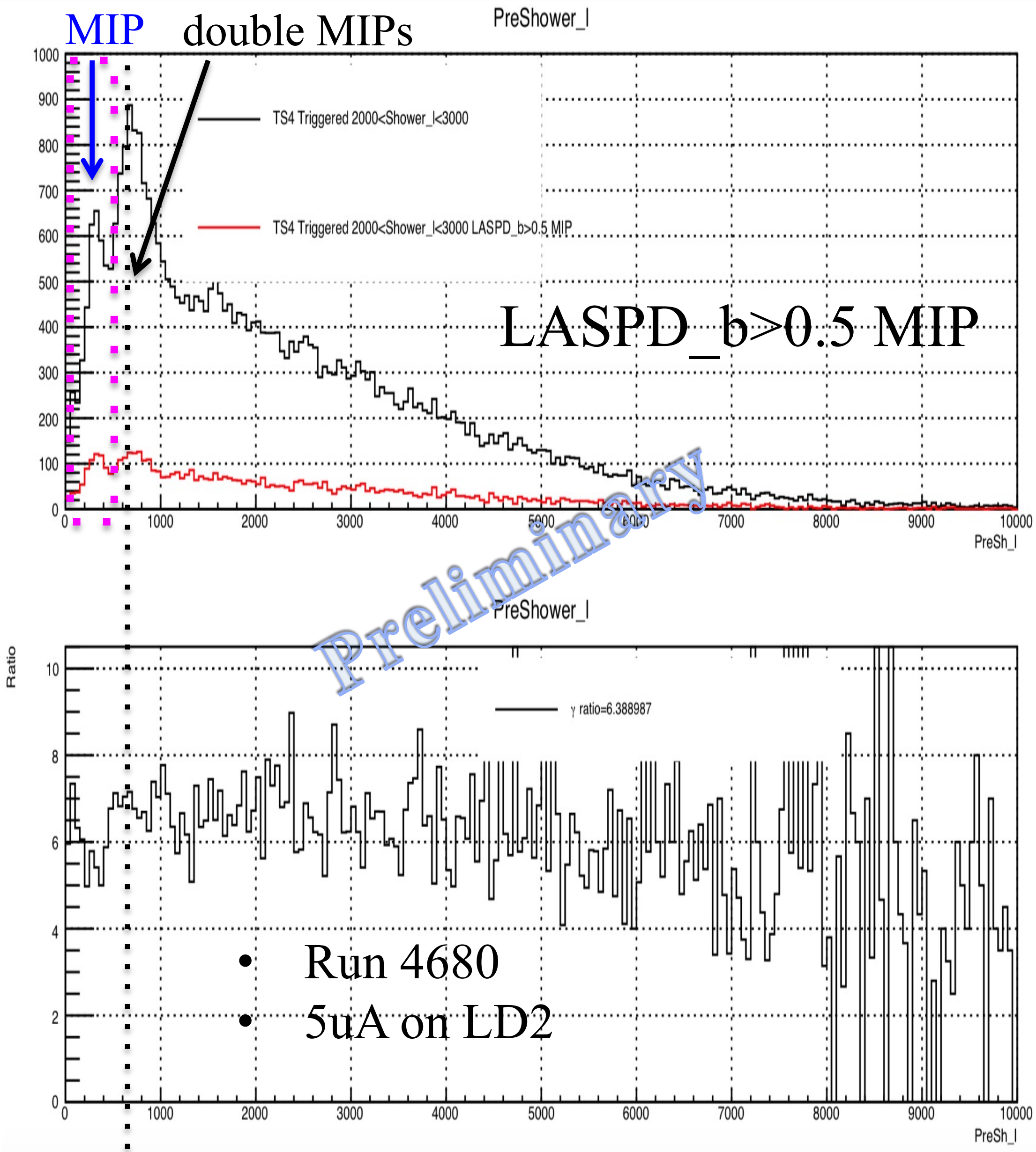
Detector	Size (cm)	thickness (cm)	Readout
GEM0	10×10	1.5	APV/mpd
GEM1	10×10	1.5	APV/mpd
SC-A	5.0(W) $\times$ 7.5(H)	1.0	PMT
Cherenkov	circular Φ???		4 MAPMTs
GEM2	10×10	1.5	APV/mpd
GEM3	10×10	1.5	APV/mpd
SC-C	18.0(W) $\times$ [3.5(L), 4.5(R)](H) trapezoid	2.0	LG+PMT (R)
LASPD	[8.3 (B), 14 (T)](W) $\times$ 57(H) trapezoid		LG+PMT (T,B)
SC-D	6.25-side hexagon	2.0	LG+PMT
pre-lead			$--$
Preshower	6.25-side hexagon	2.0	WLS fiber, PMT
Shower	6.25-side hexagon	45	WLS fiber, PMT
SC-B	5.0(H)$\times$ 10.0(W)	1.0	PMT

PreShower feature





LASPD Photon Rejection Study



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

PreCDR LASPD photon rejection 10:1

- 30-ns timing window
- 60 segmentation
- (π^0 γ+low energy e^- + γ bkg)

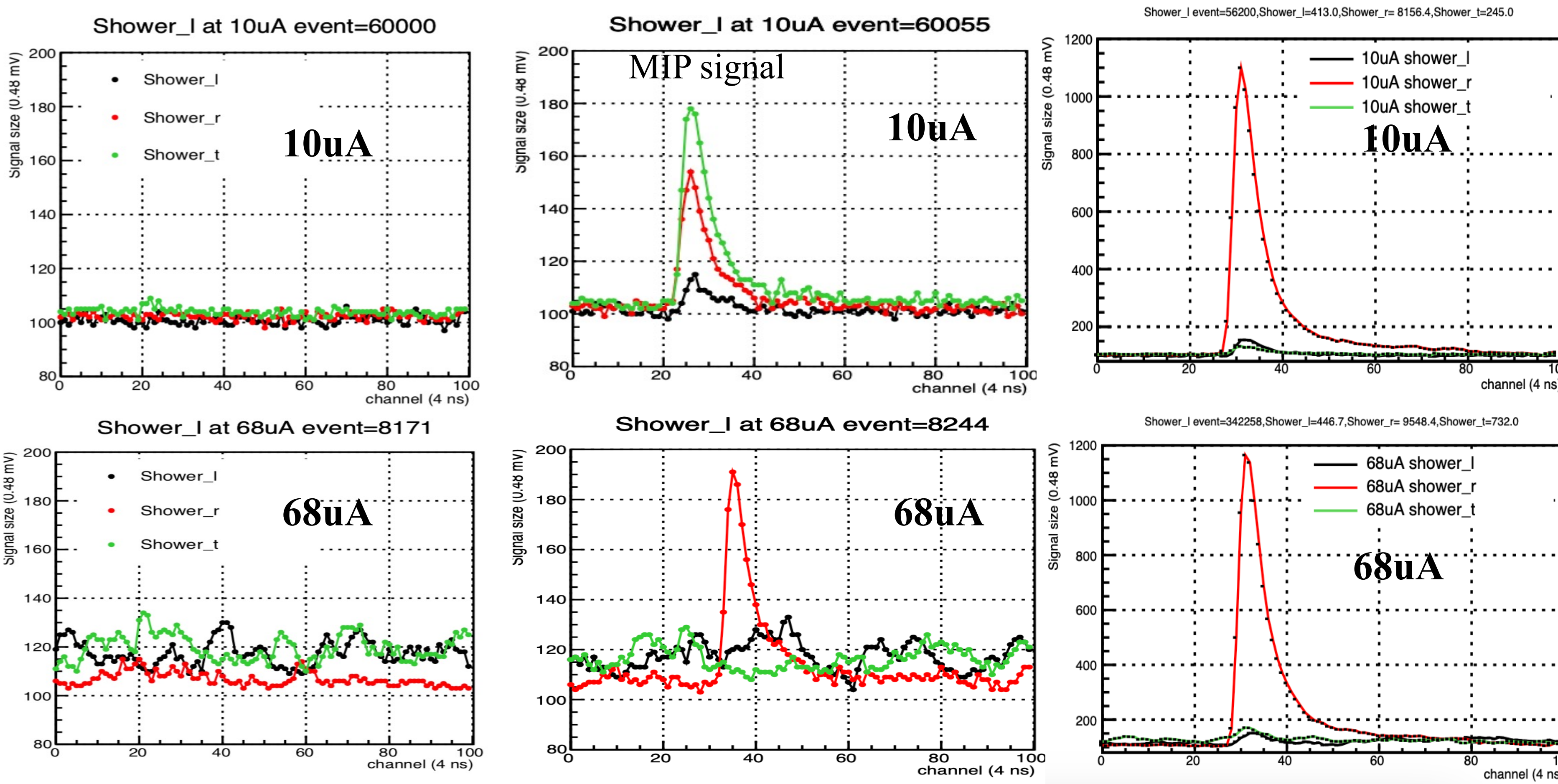
Beam test photon rejection factor ~ 7:1 at double MIPs

- LASPD_b>0.5 MIP cut

Latest pre-R&D – Data Analysis (ongoing)

18 deg data: luminosity ~ $3.2e^{37}$-$4.3e^{38}$, 10cm-LD_2 target

- All components of the detector setup can operate in SoLID-like running conditions?



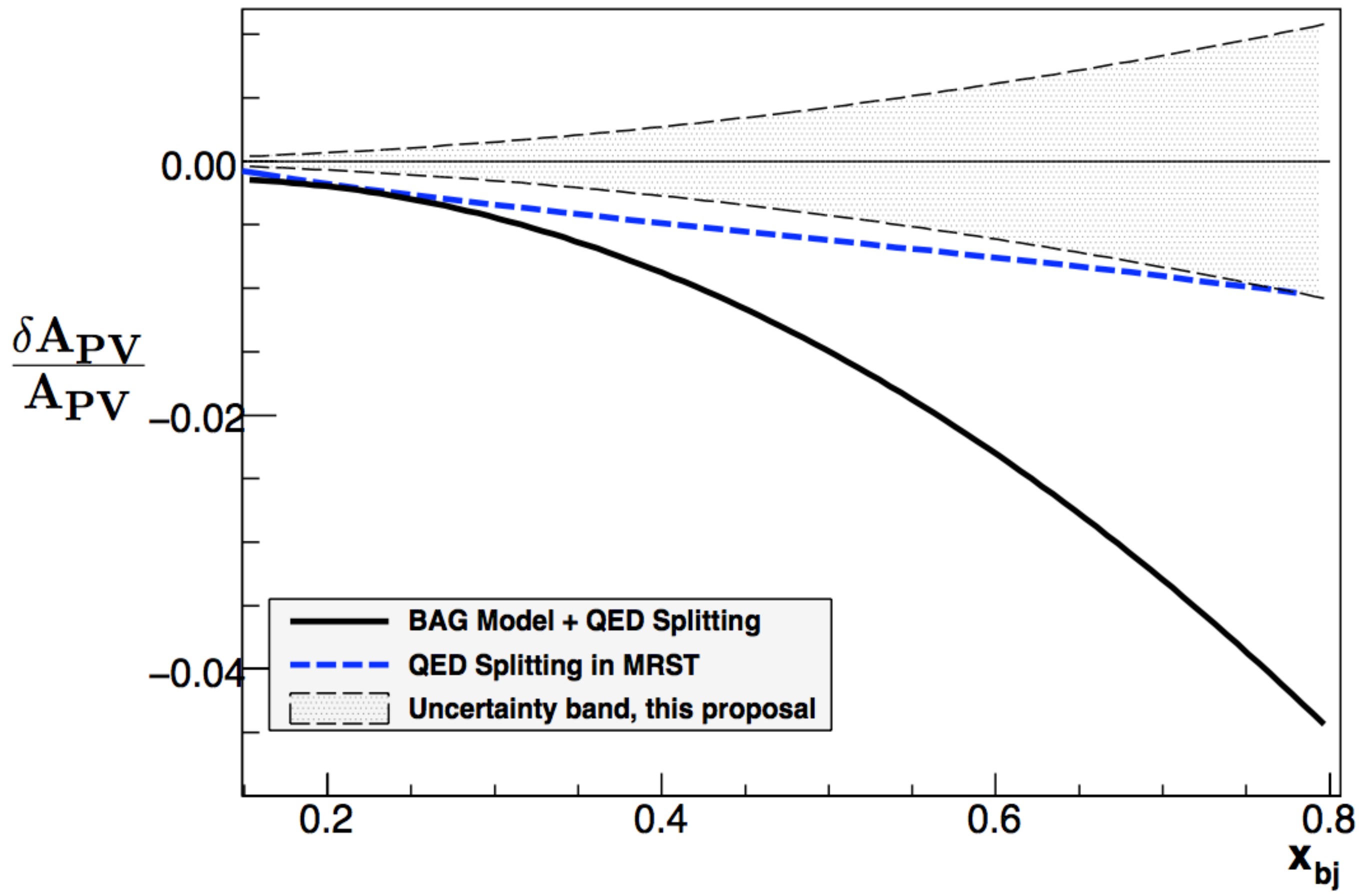


Figure 2.5: CSV predictions as a function of x. The vertical axis is the fractional change in A_{PV} due to CSV. The uncertainty band is the result of the fit discussed in Section 2.4.2. The MRST results shown here account for QED splitting in the Q^2 evolution only, and do not include non-pertubative QCD effects [24].

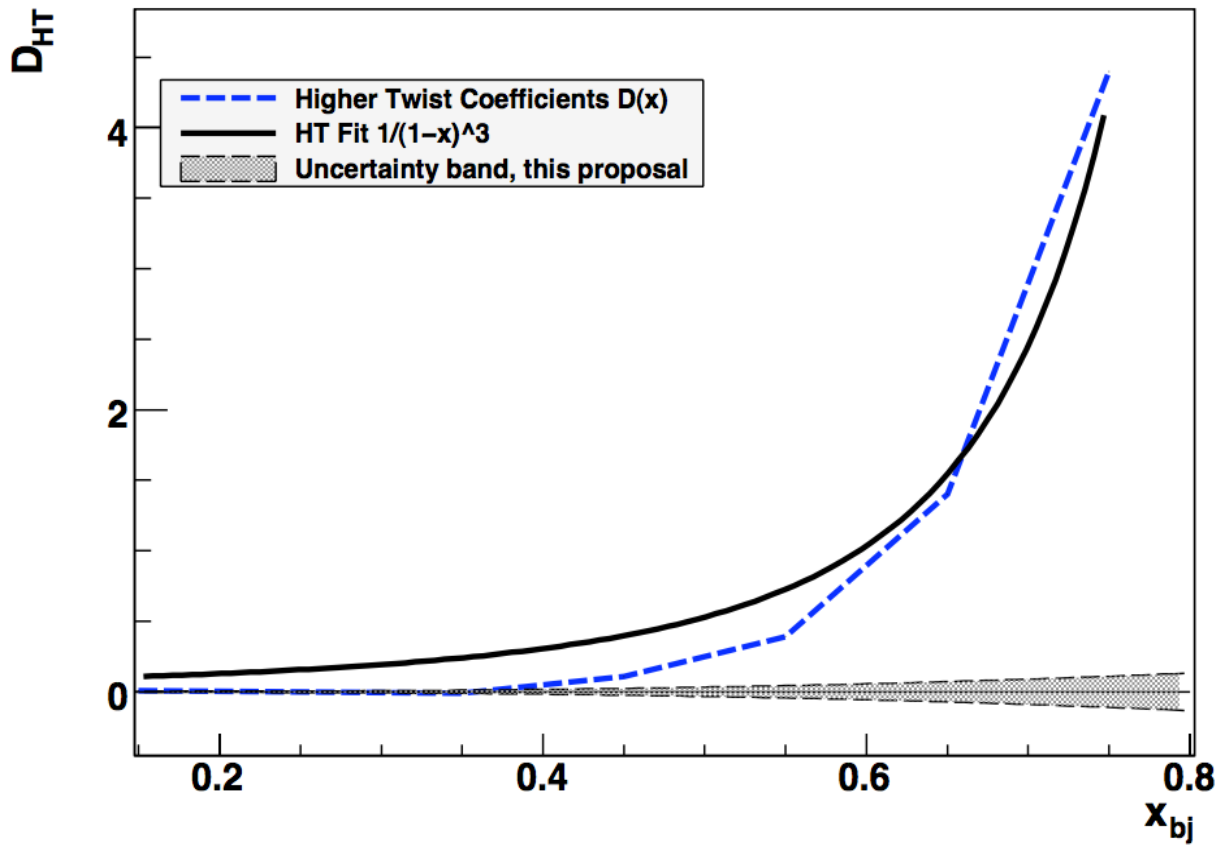
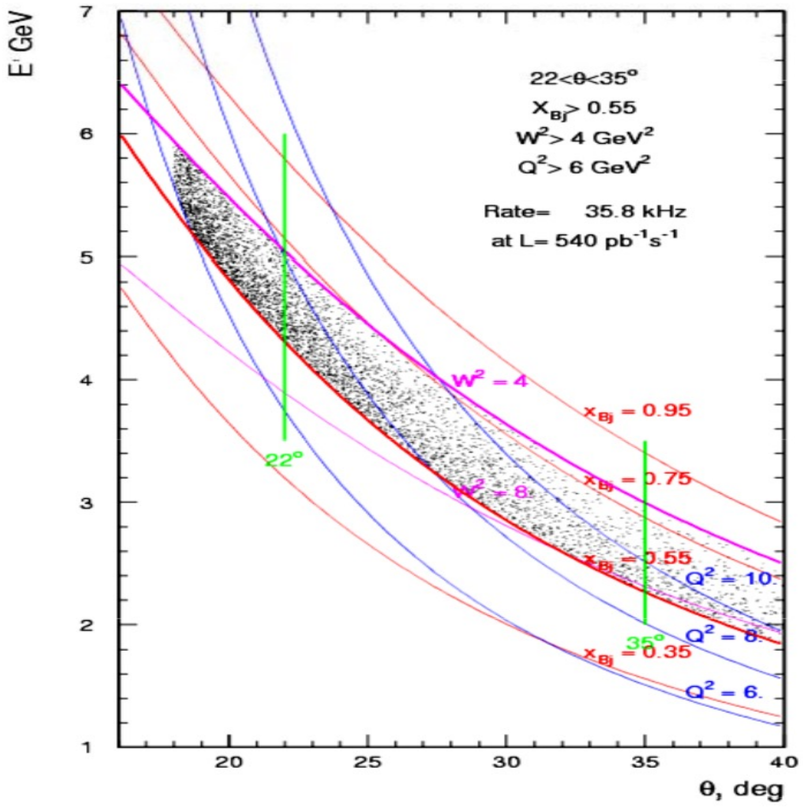
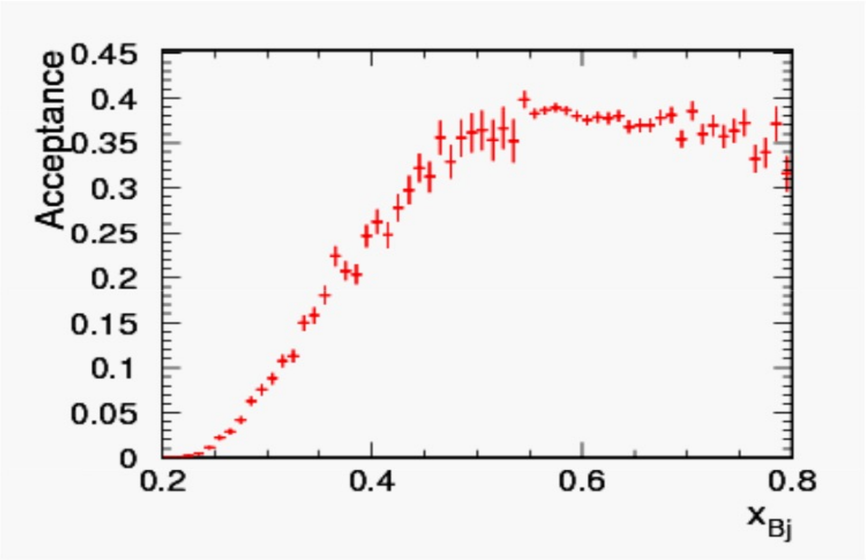


Figure 2.7: Demonstration of sensitivity to Q^2-dependent effects. Plotted are the higher-twist coefficients $D(x)$ from Ref. [21], listed in Table 2.1. Also shown is a fit to these coefficients using the form $(1-x)^{-3}$. The uncertainty band is the result of the fit discussed in Section 2.4.2.

Kinematics at large x





Parity Violation in Deep Inelastic Scattering

$$A_{LR}^{DIS} \approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + a_3(x)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$ $x \equiv x_{Bjorken} = \frac{Q^2}{2M\nu}, y = 1 - \frac{E'}{E}$

In valence quark region:

at high x

$$a_1(x) = \frac{6}{5}(2C_{1u} - C_{1d})\left(1 + \underbrace{\cancel{\frac{0.6s^+}{u^+ + d^+}}}_{0}\right), \quad a_3(x) = \frac{6}{5}(2C_{2u} - C_{2d})\left(\underbrace{\cancel{\frac{u^+ - d^+}{u^+ + d^+}}}_{1}\right) + \ldots$$

SM at tree level:

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

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

PV elastic e-p scattering, Atomic parity violation

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

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

PV deep inelastic scattering (PVDIS)