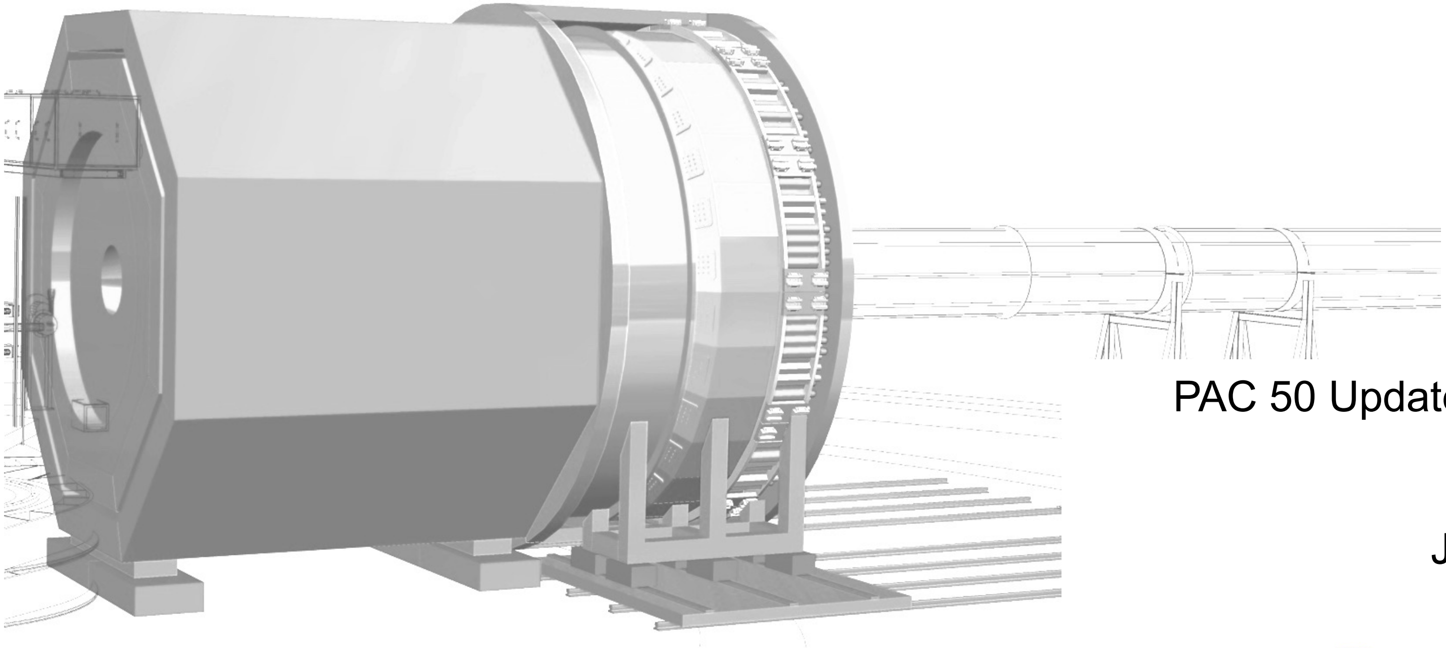
PVDIS Jeopardy Update



PAC 50 Update on PVDIS with SoLID

July 2022

SOLENOIDAL LARGE INTENSITY DEVICE

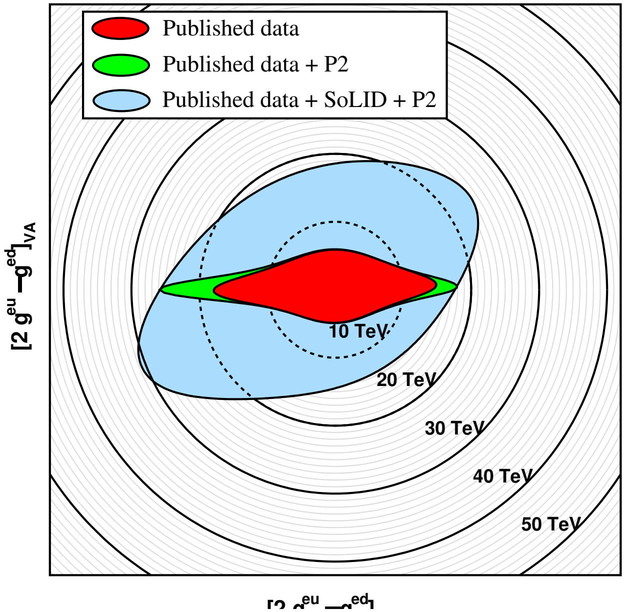
Paul Souder

Syracuse University

Goals of PVDIS with SoLID

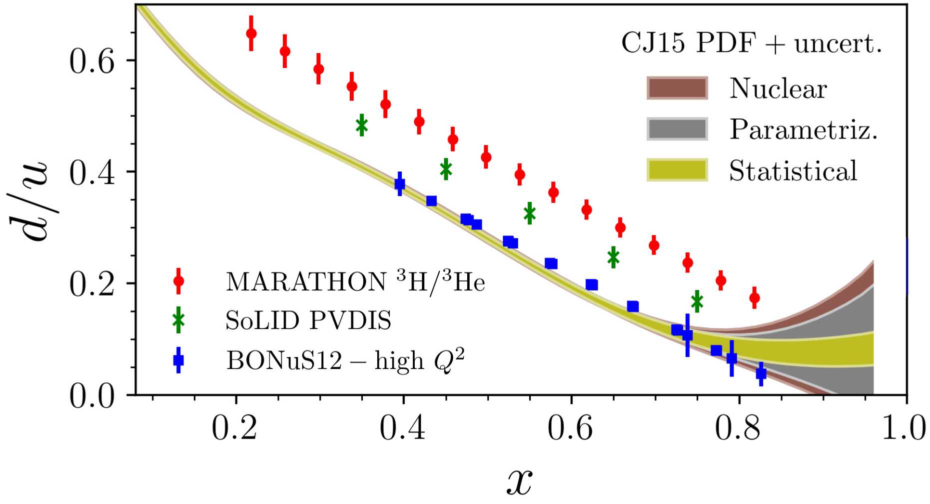
A_{PV} with deuterium

1. Search for BSM physics at a high energy scale.
2. Search for CSV at the quark level
3. Search for quark-quark higher twist effects

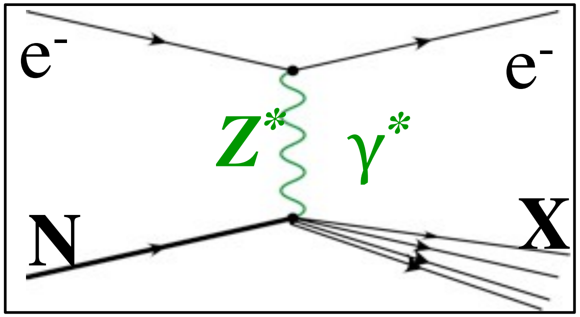


A_{PV} with the Proton

1. Help determine d/u PDF's
2. Insight into nuclear effects at high x



PVDIS for eD Scattering



$$A_{PV} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\left[g_A \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V \frac{f(y)}{2}\frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

$$x \equiv x_{Bjorken}$$
$$y \equiv 1 - E'/E$$

$Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y) b(x)\right]$$

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

Unique feature: sensitivity to C_2's

$$R_s(x) = \frac{2S(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 0$$
$$R_v(x) = \frac{u_v(x) + d_v(x)}{U(x) + D(x)} \xrightarrow{\text{Large } x} 1$$

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

SM Effective Field Theory (SMEFT) and LHC Data

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{d-4}} \mathcal{O}_d^{ij}$$

$$\mathcal{O}_d^{ij} = \bar{e}_i \gamma_\mu e_i \overline{f}_j \gamma^\mu f_j$$

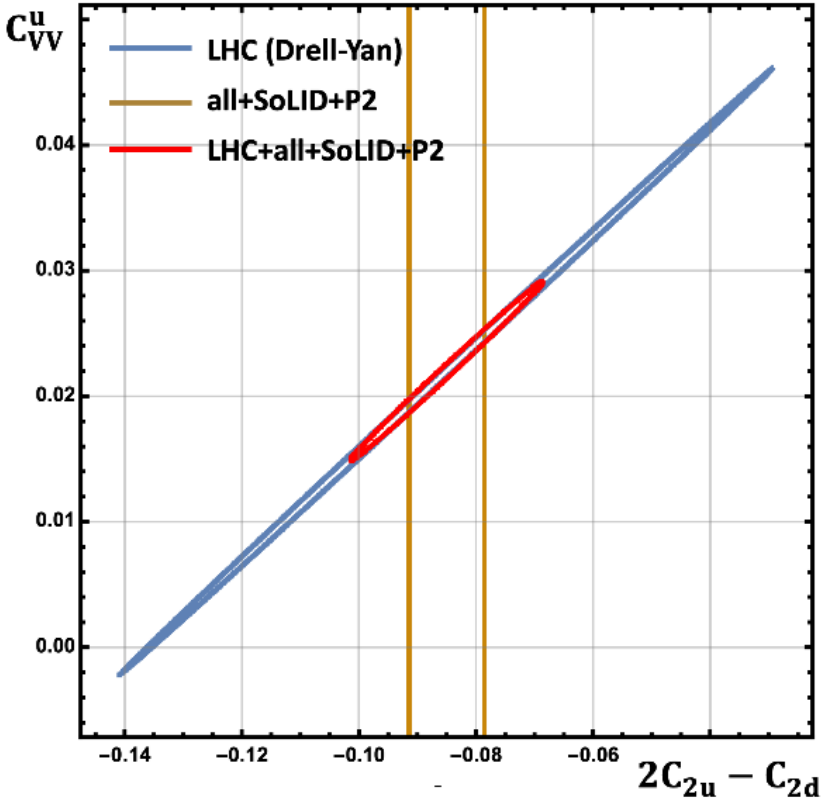
$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

New Drell-Yan LHC data measures a combination of parity conserving and parity violating couplings.

Goal: Measure each C_d^{ij} as precisely as possible (Nobody really knows where the new physics is.)

Figure courtesy of Frank Petriello…

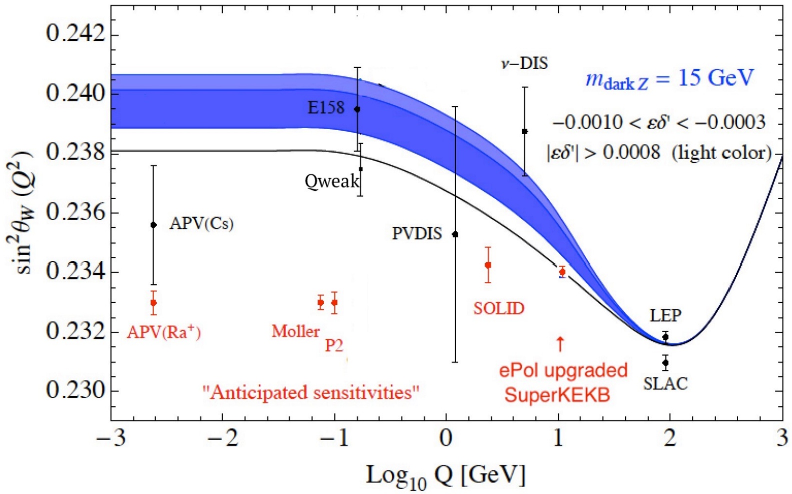


SoLID and LHC data are complementary

Dark Boson Z_d and other Sub-TeV BSM Models

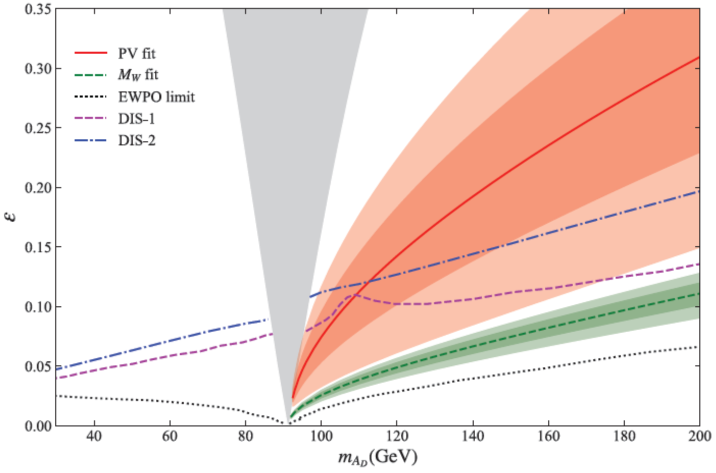
- *Davoudiasl, et al. Phys.Rev.D* 92
- (2015) 5, 055005

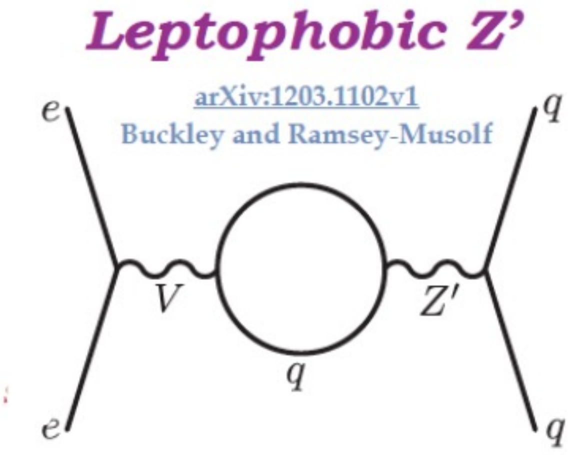
Thomas, A. W. and Wang, X. G.
arXiv hep-ph ADP-22-19/T1190 (2022),
author = Thomas, A. W. and Wang, X. G.
and Williams, A. G. arXiv
hep-ph ADP-22-4/T1175 (2022)



Constraints of new W mass versus PV

Thomas and Wang, arXiv: 2205.01911



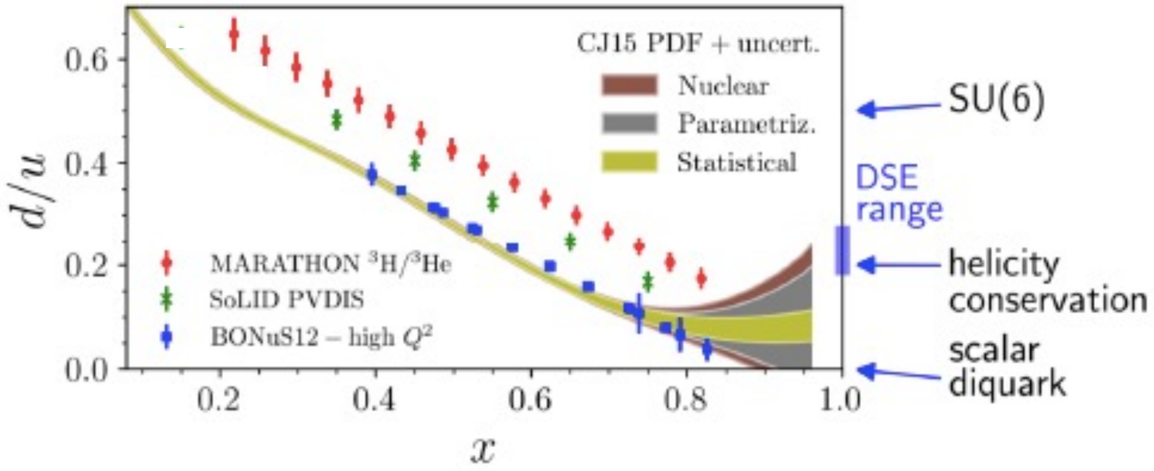

Leptophobic Z'

arXiv:1203.1102v1

Buckley and Ramsey-Musolf

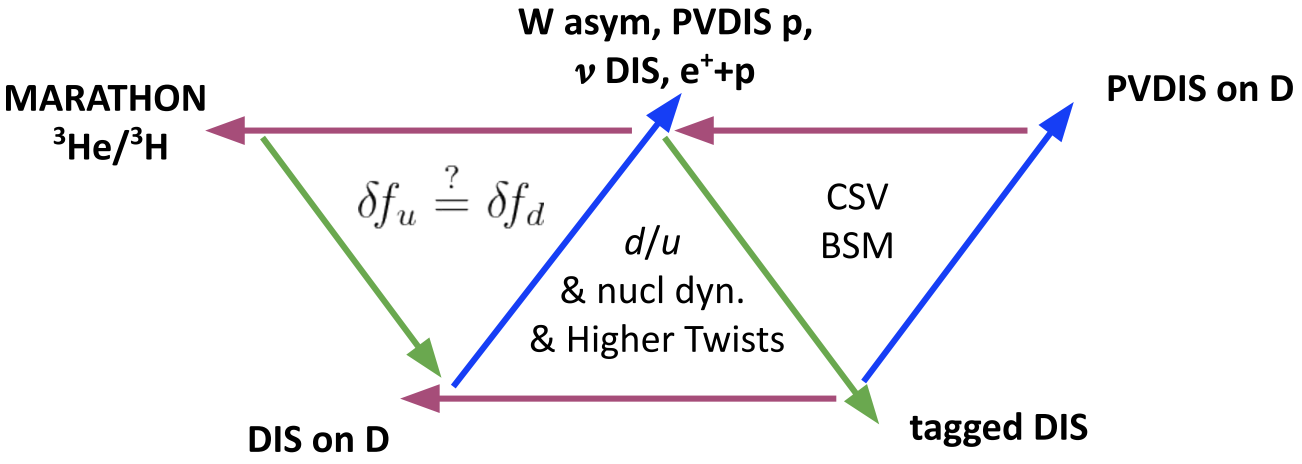
PVDIS with the Proton

PVDIS is complementary to
the rest of the Jlab d/u program.
Only PVDIS has no nuclear effects



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

Phys.Rev.Lett. 127 (2021) 24, 242001
Phys.Rev.Lett. 128 (2022) 13, 132003



W asym, PVDIS p,
ν DIS, e$^+$+p

MARATHON
^{3}He/^{3}H

PVDIS on D

$\delta f_u \overset{?}{=} \delta f_d$

d/u
& nucl dyn.
& Higher Twists

CSV
BSM

DIS on D

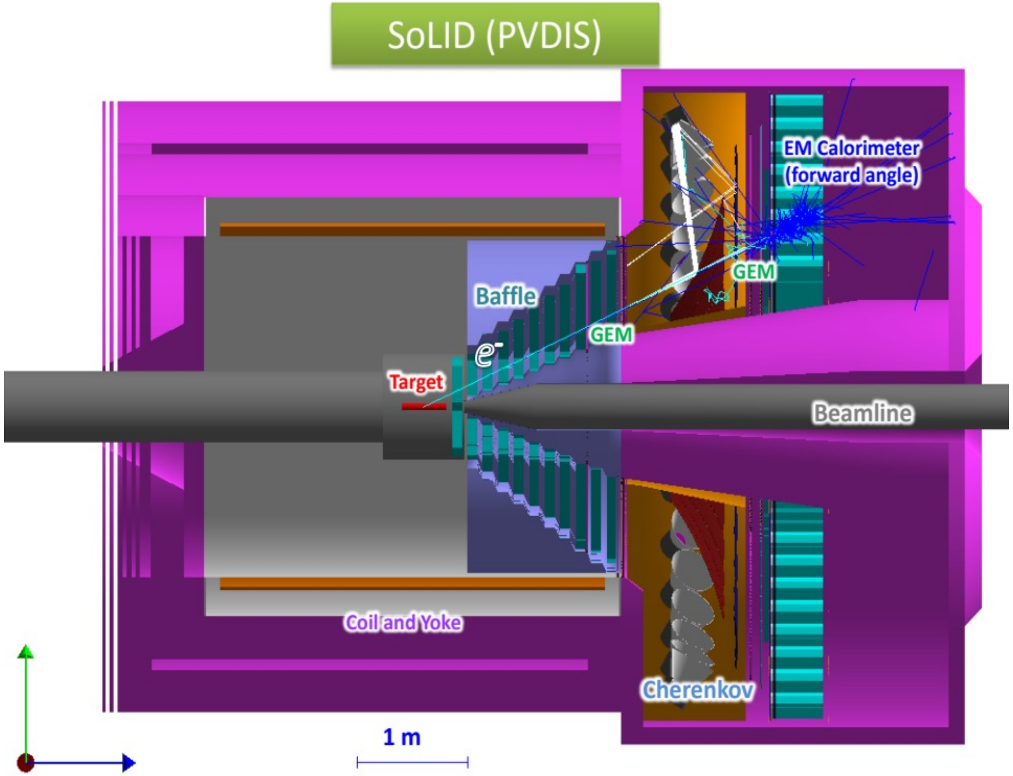
tagged DIS

Figure courtesy of A. Accardi

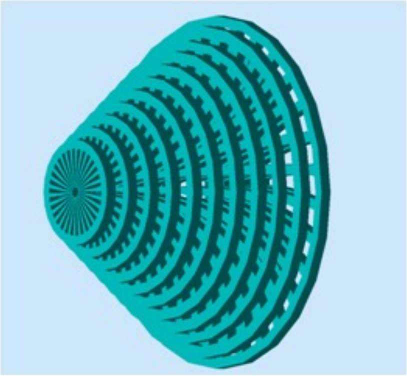
SoLID PVDIS Apparatus Described in Pre-CDR

Achieving High Luminosity

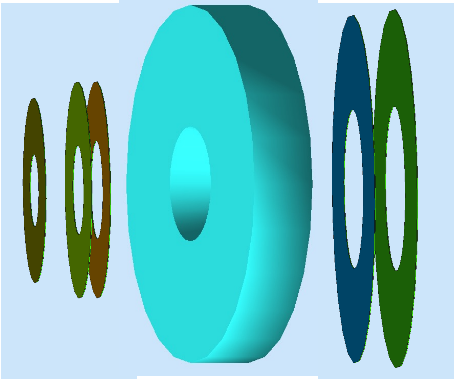
- 50 μA beam current.
- 40 cm LD_2 target
- ~40% azimuthal coverage with baffles which provide curved channels that block positive and neutral background particles
- Azimuthally symmetric.
- High-rate GEM tracking Chambers



Baffles



GEM Chambers



Magnet from CLEO experiment at Cornell is at JLab. Cold test is expected to be completed by October.

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

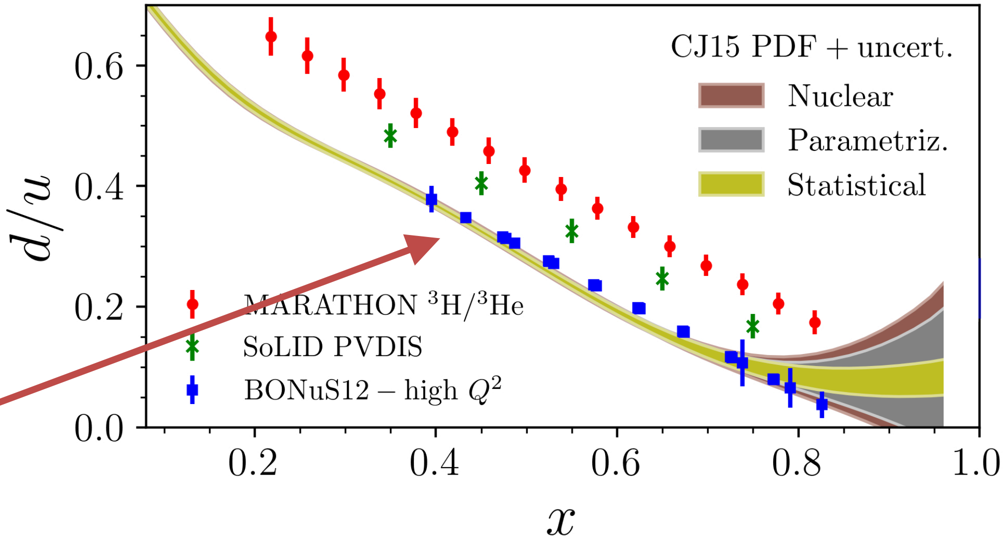
169 Days were Approved. Based on the urgency of the science and successful Pre-CDR design, we now request the full 338 days.

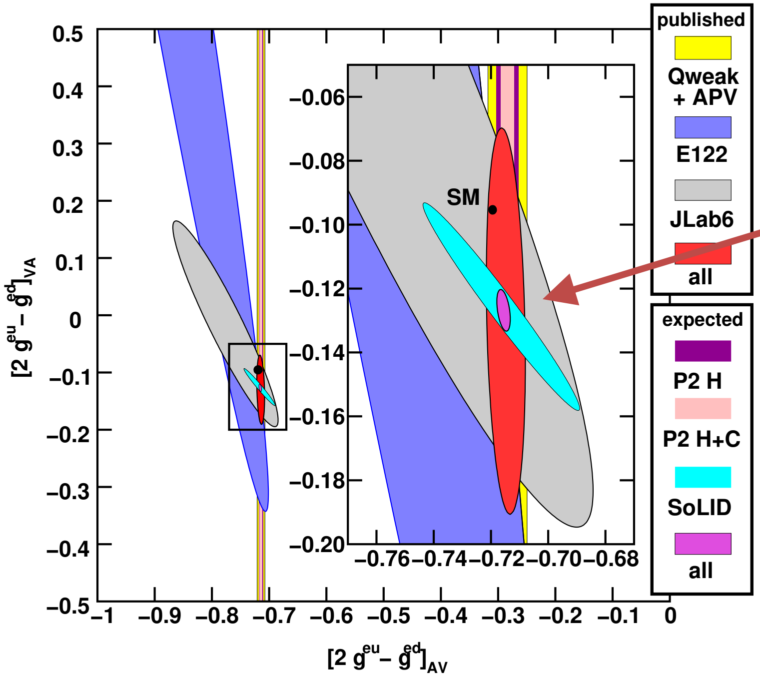
Fine points

The formula

$$a^P(x) \approx \frac{u(x)+0.91d(x)}{u(x)+0.25d(x)}$$

is at leading order (LO) in QCD. Extracting d/u requires higher order corrections, which are performed by PDF groups. Comparisons of relative errors between BONUS, Marathon, and SoLID is done at LO.





Qweak, APV, and P2 do not provide constraints in the vertical direction. Only PVDIS experiments (SLAC, Jlab 6 GeV, and Solid) constrain the C_2's

SoLID PVDIS Collaboration

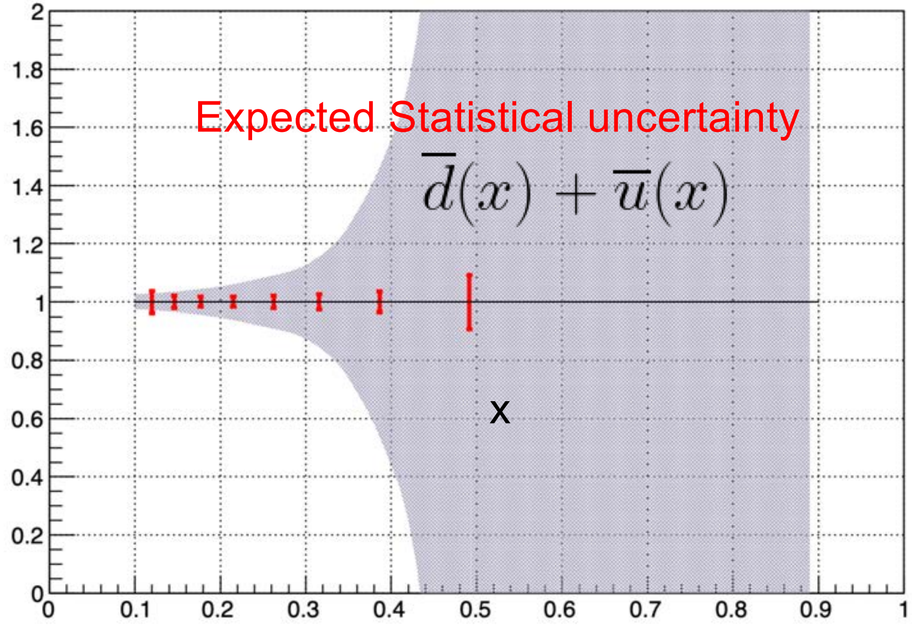
247 Members
62 Institutions
13 countries

P. A. Souder: Contact
X. Zheng: Co-spokesperson
P. Reimer: Co-spokesperson

Backup

PDF contributions

Limited data for x>0.25
New SeaQuest data for x<0.5 coming soon
If strange sea < light quark sea, strange contribution is small
PDF fits less useful because of extrapolation errors
PDF contribution may be < 0.3%



Anticipated improvements on light antiquarks from SeaQuest

Impact of PDF Errors for Various Fits

Red lines are seq quark uncertainties:
At x~0.25, fits similar
At x=0.7, fits differ by more than two orders of magnitude!

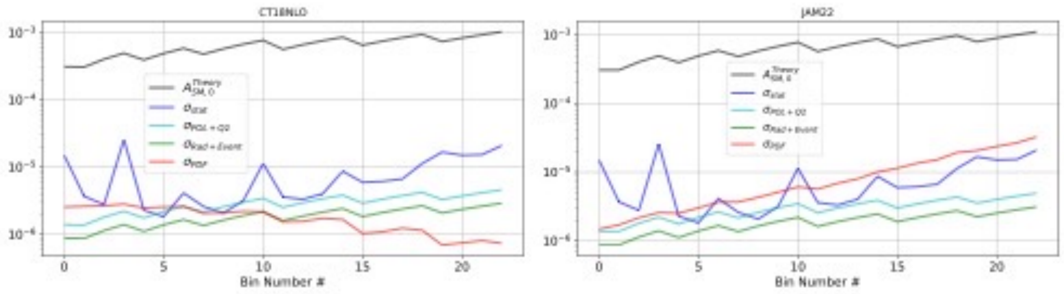


FIG. 6. A comparison of the theoretical asymmetry vs. all uncertainties. All Uncertainties consists of statistical, systematic, and PDF errors. The x-axis is the bin labels in Number. Bin number is a geometrical coordinate of kinematic variables (x, Q^2). The PDF uncertainties were obtained with CT18NLO (90% C.L., left) and JAM22 (right) PDF sets.

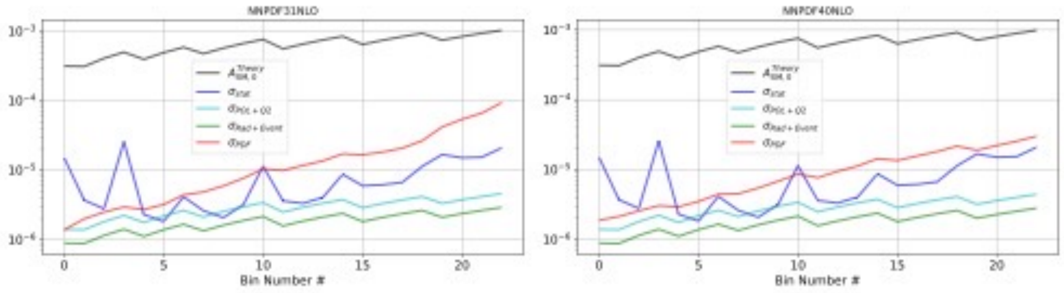
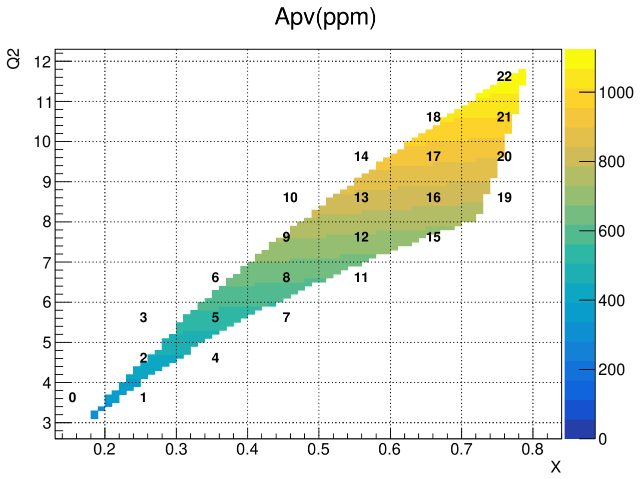
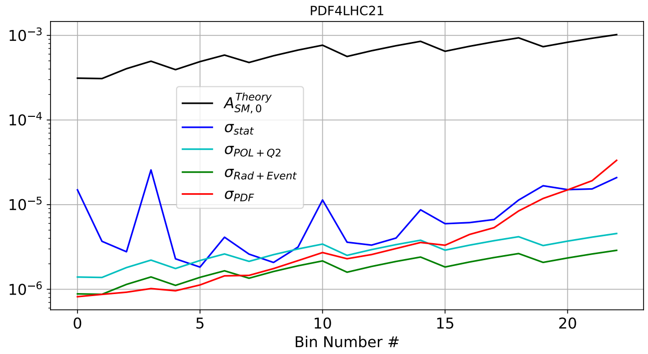


FIG. 7. Comparison of the theoretical asymmetry vs. all uncertainties. PDF uncertainties from NNPDF31NLO (left) and NNPDF40NLO (right).



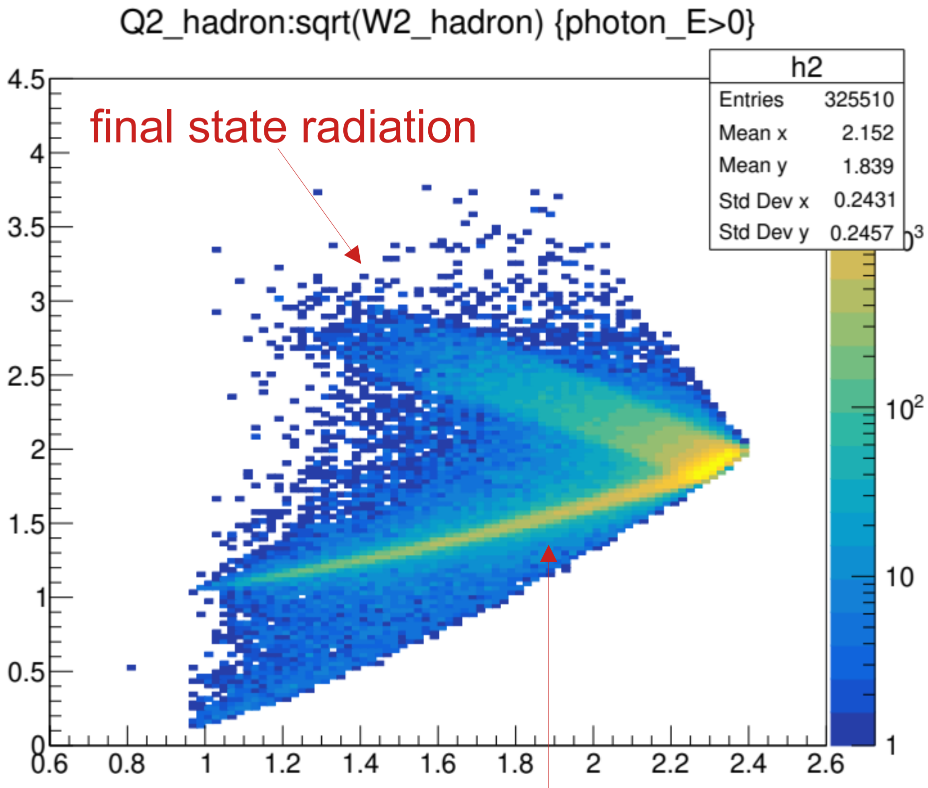
Definition of bins



Radiative Corrections

Formula for internal corrections

$$d\sigma^{\mathrm{obs}}(P,q)=\int\frac{d^3k}{2k^0}\sum_n R_n(l,l',k)\,d\hat{\sigma}_n^{(0)}(P,q-k)$$



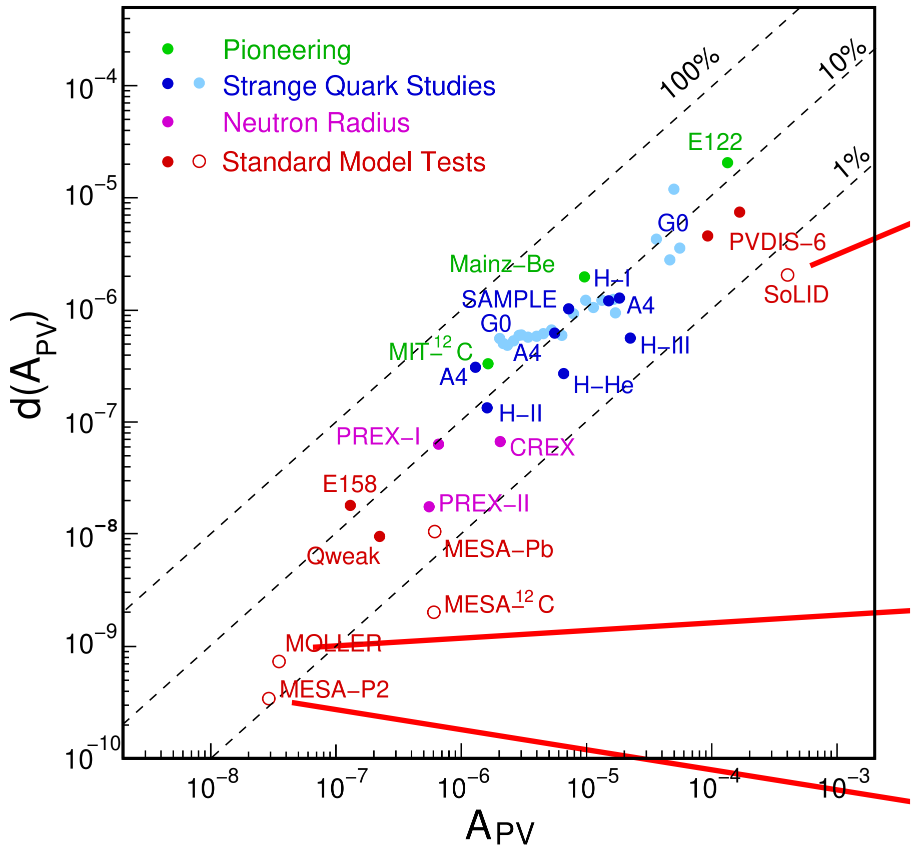
R_n from Djangoh

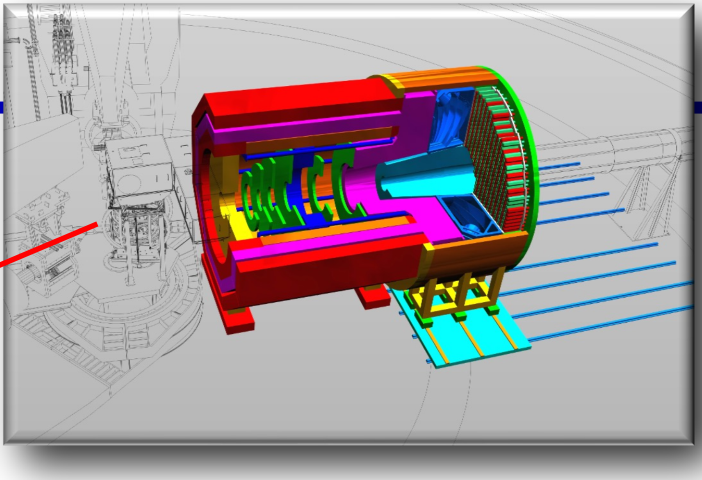
initial state radiation

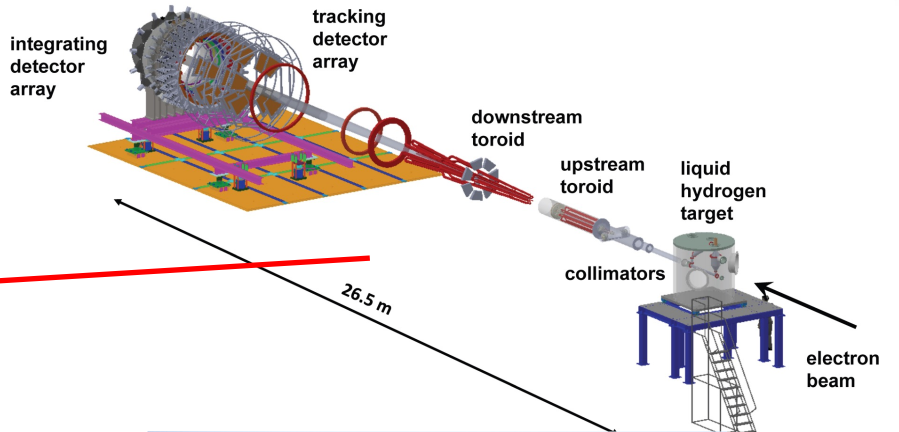
Uncertainties for internal and external radiative corrections are being calculated from known cross sections and projected asymmetries that SoLID will measure in the resonance region.

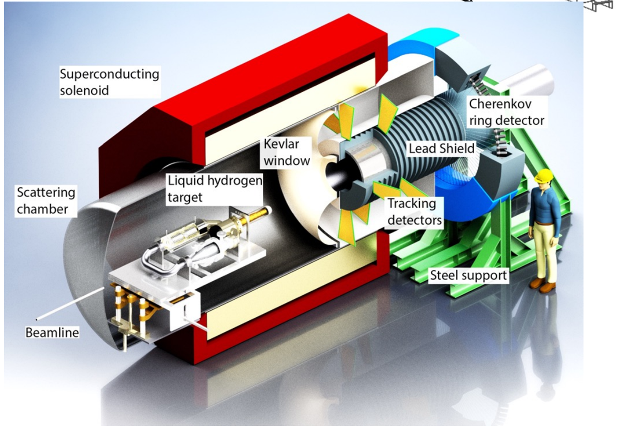
Box diagrams and other higher order corrections can be calculated with the desired precision.

BSM PVES Experiments









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

MOLLER, SoLID, and P2 all improve precision

Hadronic Physics: Charge Symmetry Violation

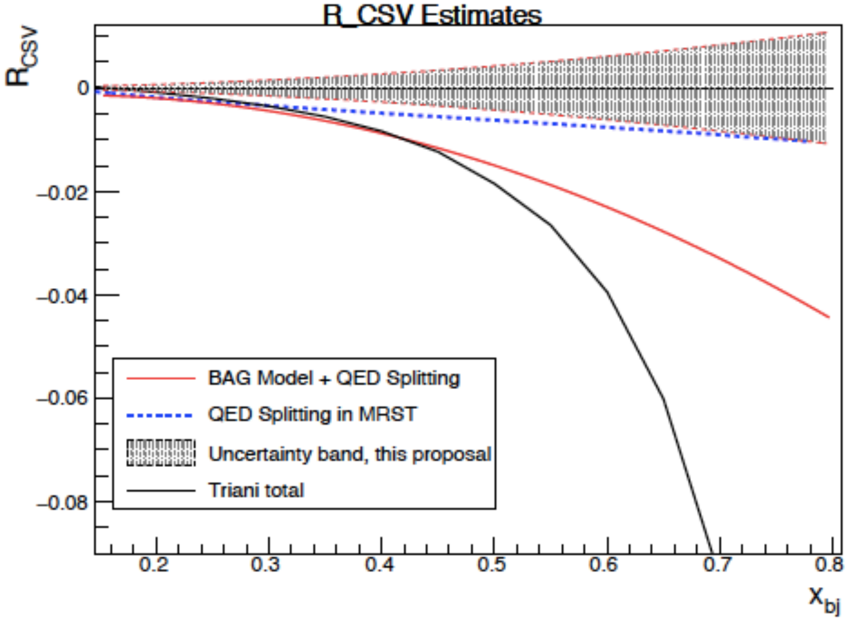
$$u^p(x) \overset{?}{=} d^n(x) \quad \Rightarrow \quad \delta u(x) \equiv u^p(x) - d^n(x)$$

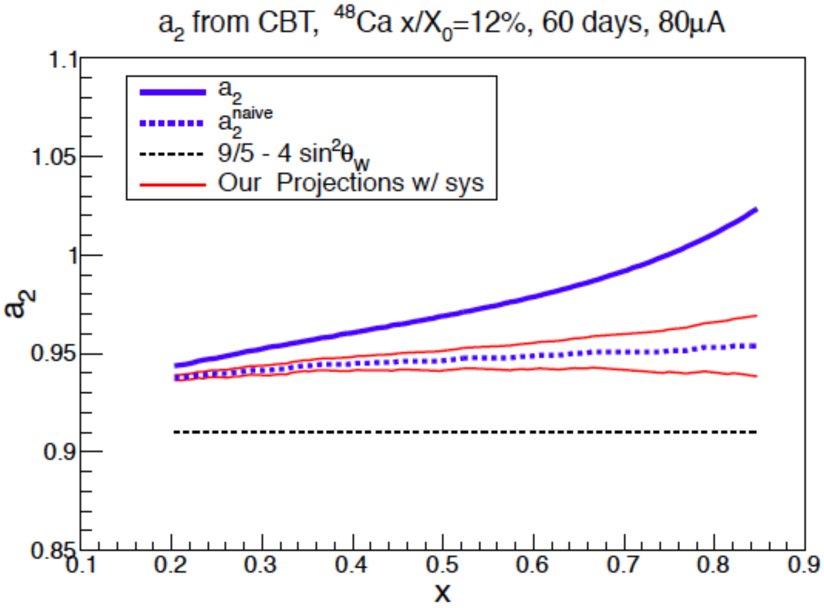
$$d^p(x) \overset{?}{=} u^n(x) \quad \Rightarrow \quad \delta d(x) \equiv d^p(x) - u^n(x)$$

$$R_{CSV} = \frac{\delta A_{PV}}{A_{PV}} \approx 0.28 \frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

For A_{PV} in electron-^{2}H DIS

Additional contribution to NuTeV anomaly?





"The paper on PVDIS and the EMC effect highlights a way -- perhaps the best way -- to access the flavor dependence of the EMC effect using PVDIS." Ian Cloet

Unique Higher Twist Contribution

The observation of Higher Twist in PV-DIS would be exciting direct evidence for diquarks

following the approach of
Bjorken, PRD 18, 3239 (78),
Wolfenstein, NPB146, 477 (78)

$$V_\mu = (\bar{u}\gamma_\mu u - \bar{d}\gamma_\mu d) \Leftrightarrow S_\mu = (\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d)$$

$$\langle VV\rangle = l_{\mu\nu}\int \langle D|V_\mu(x)V_\nu(0)|D\rangle e^{iqx}d^4x$$

Isospin decomposition
before using PDF's

$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}\left[a(x) + f(y)b(x)\right]$$

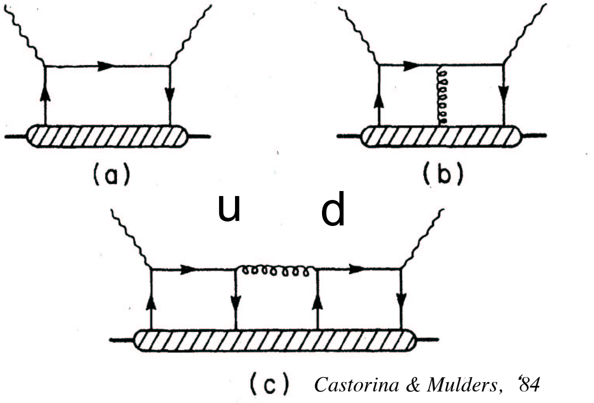
$$\delta = \frac{\langle VV\rangle - \langle SS\rangle}{\langle VV\rangle + \langle SS\rangle}$$

$$a(x) \propto \frac{F_1^{\gamma Z}}{F_1^{\gamma}} \propto 1 - 0.3\delta$$

Higher-Twist valence quark-quark correlation

Zero in quark-parton model

$$< VV > - < SS > = < (V - S)(V + S) > \propto l_{\nu\mu}\int < D|\bar{u}(x)\gamma_\mu u(x)\bar{d}(0)\gamma_\nu d(0)|D > eiqxd^4x$$



Castorina & Mulders, '84

(c) type diagram is the only operator that can contribute to a(x) higher twist: theoretically very interesting!

σ_L contributions cancel

See Mantry et al., PRC **82** 065205 (2010),
Belitski et al., PRD (2011) **84** 014010

Untangling the Physics

Kinematic dependence of physics topics:

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

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

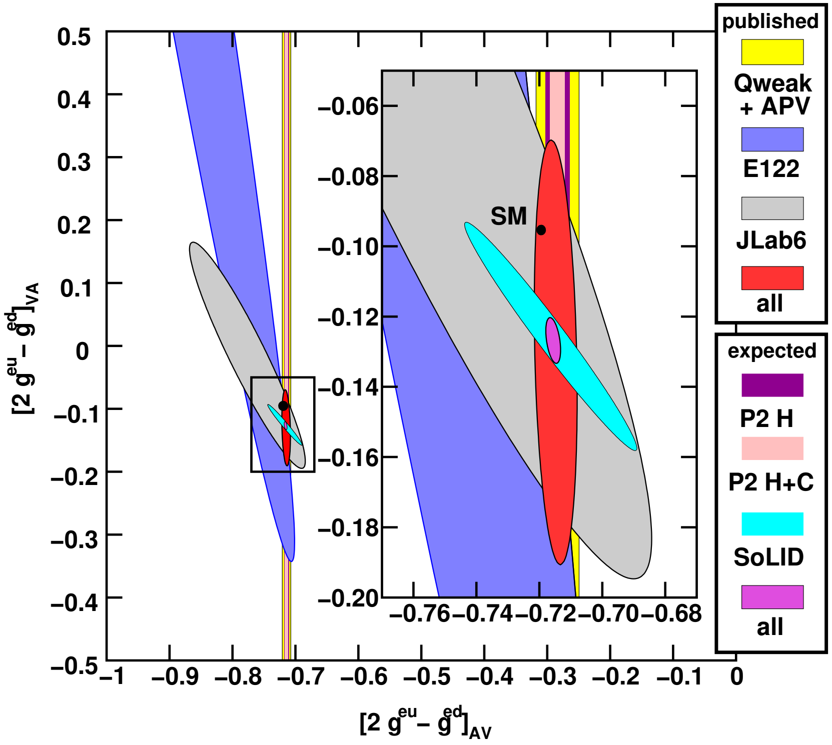
	A_{SM}	β_{HT}	β_{CSV}
A_{SM}	1	0.18	-0.67
β_{HT}	0.18	1	-0.81
β_{CSV}	-0.67	-0.81	1

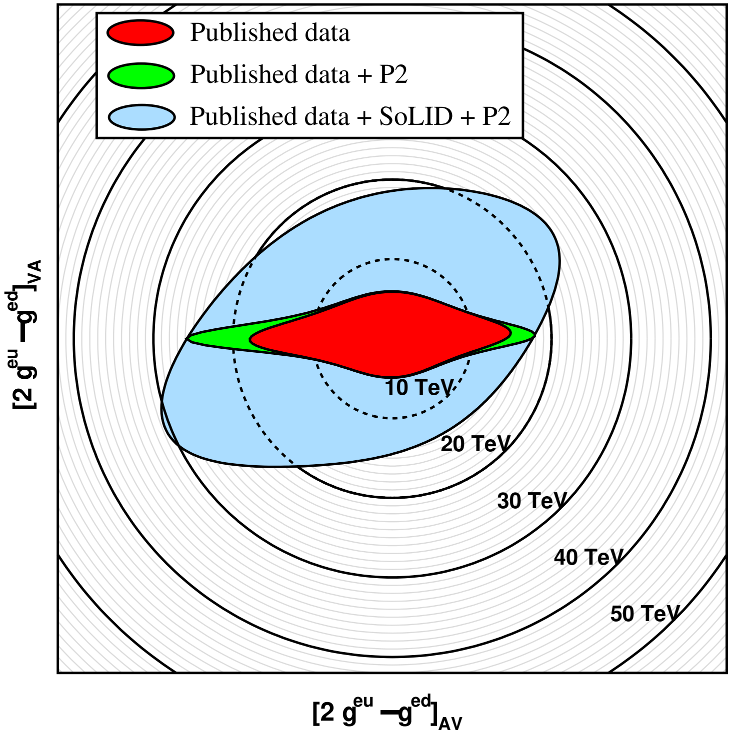
Projected Results

With this precision,
SoLID makes a unique contribution
to the SMEFT program.

Improvement in
couplings

Improvement in
energy reach for
electron-nucleon couplings





PVES Lagrangian and **PVDIS for eD Scattering**

$$\mathcal{L}_{\rm NC}^{ef} = \frac{1}{2v^2}\left(\bar{e}\gamma^\mu\gamma^5 e \sum_{q=u,d} g_{AV}^{eq}\bar{q}\gamma_\mu q + \bar{e}\gamma^\mu e \sum_{q=u,d} g_{VA}^{eq}\bar{q}\gamma_\mu\gamma^5 q\right)$$

$$g_{AV}^{eu} = C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W; \quad g_{AV}^{ed} = C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W$$

$$g_{VA}^{eu} = C_{2u} = g_{VA}^{ed} = -C_{2d} = \frac{1}{2} - 2\sin^2\theta_W$$

Tree only

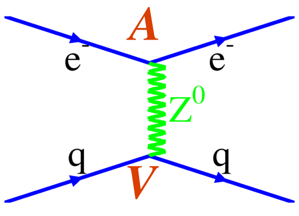
$C_{ij}=C_{ij}^{SM}+C_{ij}^{BSM}$

Renormalized

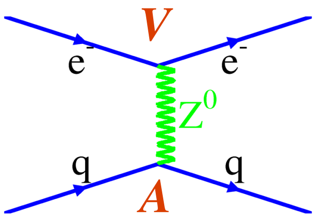
$$A_{LR}^{\rm DIS} \approx -\frac{3}{20\pi\alpha(Q)}\frac{Q^2}{v^2}\left[(2g_{AV}^{eu} - g_{AV}^{ed}) + (2g_{VA}^{eu} - g_{VA}^{ed})\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

At high x, A^{DIS} becomes approximately independent of pdfs, x & W, with well-defined SM prediction for Q^2 and y

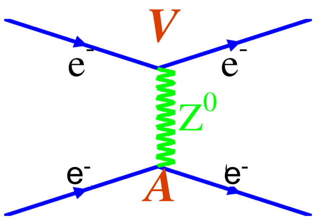
PVES Lagrangian



$C_{1i} \equiv 2 g_A^e g_V^i$



$C_{2i} \equiv 2 g_V^e g_A^i$



$C_{ee} = 2 g_V^e g_A^e$

SMEFT: C_{ij}^{BSM}: are linear combinations of the C^{ij}_6

$$\mathcal{L}^{PV} = \frac{G_F}{\sqrt{2}}[\bar{e}\gamma^\mu\gamma_5 e(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d) + \bar{e}\gamma^\mu e(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$

$$\mathcal{L} = \sum_d \sum_{ij} \frac{C_d^{ij}}{\Lambda^{4-d}} \mathcal{O}_d^{ij}$$

$$\begin{aligned} C_{1u} &= -\tfrac{1}{2}+\tfrac{4}{3}\sin^2\theta_W \approx -0.19 \\ C_{1d} &= \tfrac{1}{2}-\tfrac{2}{3}\sin^2\theta_W \approx 0.35 \\ C_{2u} &= -\tfrac{1}{2}+2\sin^2\theta_W \approx -0.04 \\ C_{2d} &= \tfrac{1}{2}-2\sin^2\theta_W \approx 0.04 \end{aligned}$$

$$\mathcal{O}_d^{ij} = \bar{e}_i\gamma_\mu e_i \bar{f}_j\gamma^\mu f_j$$

$$e_{L/R} = \frac{1}{2}(1 \mp \gamma^5)\psi_e$$

$$\mathcal{O}_d^{ij} = LL_f,\ LR_f,\ RL_f,\ RR_f$$

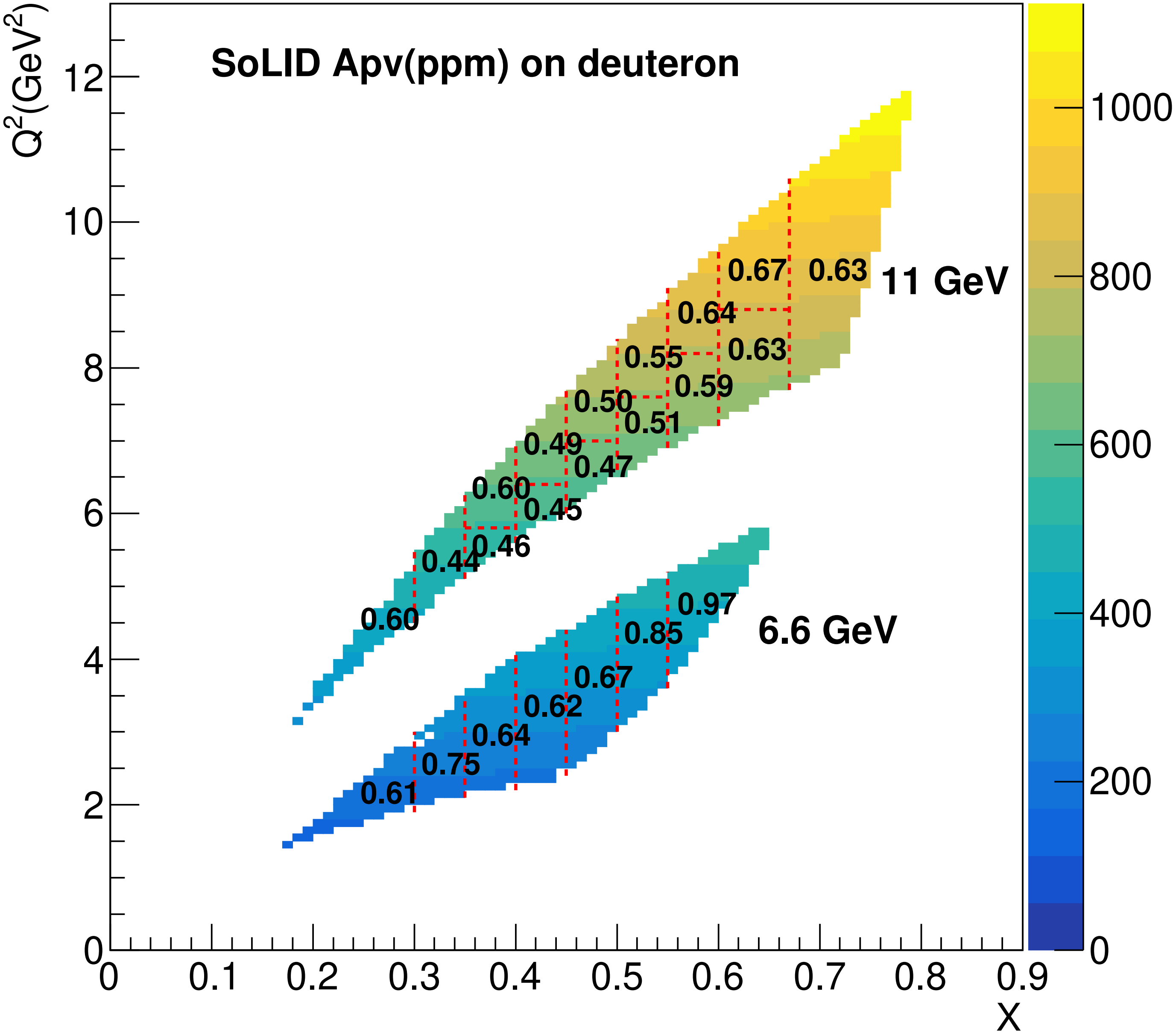
$$\boxed{C_{ij} = C_{ij}^{SM} + C_{ij}^{BSM}}$$

Tree only

Renormalized

SMEFT: Useful for Global analysis.

Projected statistics

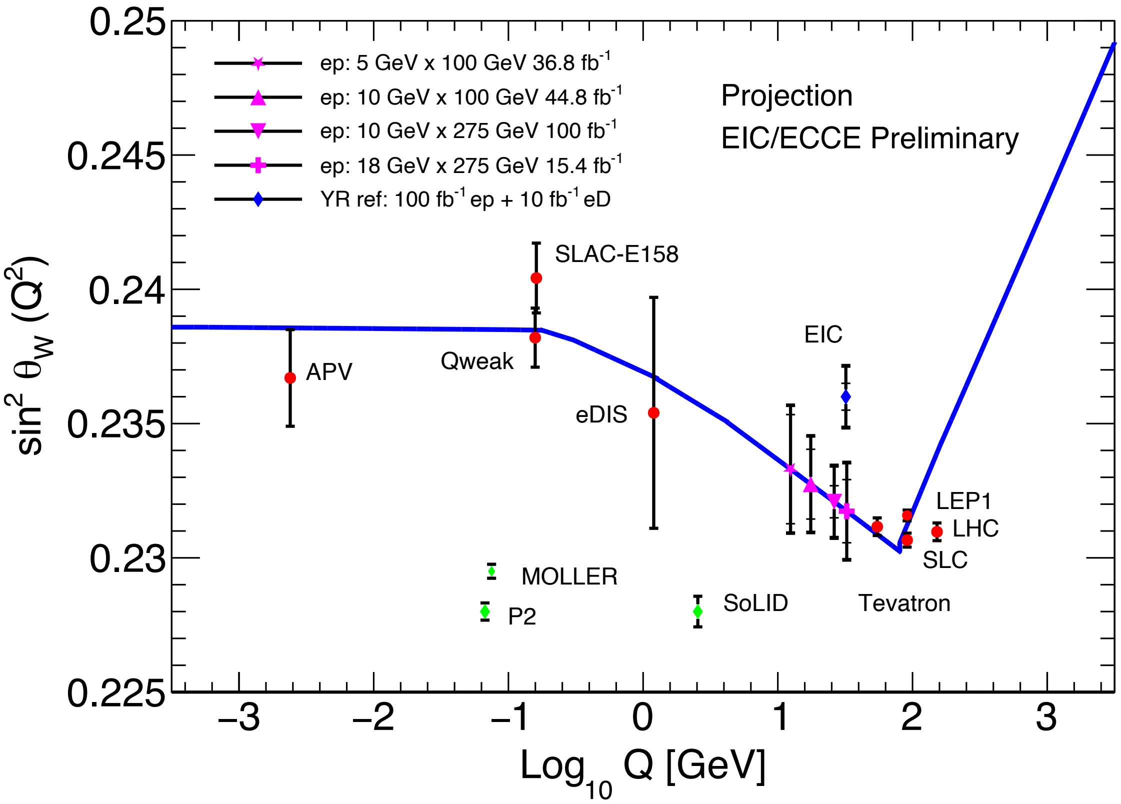


Precision Polarimetry: $\delta Pb/P_b$~0.4%

- Method I: Compton Polarimeter:
  - Operates at full beam intensity.
  - Operates simultaneously with the PVES experiment.
- Method II: Moller Polarimeter:
  - Independent systematics.
  - Operates at low beam current.
  - Invasive measurement.
- Built on extensive experience with PVES experiments in both Hall A and Hall C.
- Compton capital upgrade (lasers, new electron detector).
- Commissioning will occur during the MOLLER experiment.
- An upgrade for the Moller polarimeter is part of the MOLLER MIE.

BSM Physics and the EIC

Very large range in x, particularly low x. Little data above x=0.4. No CSV test



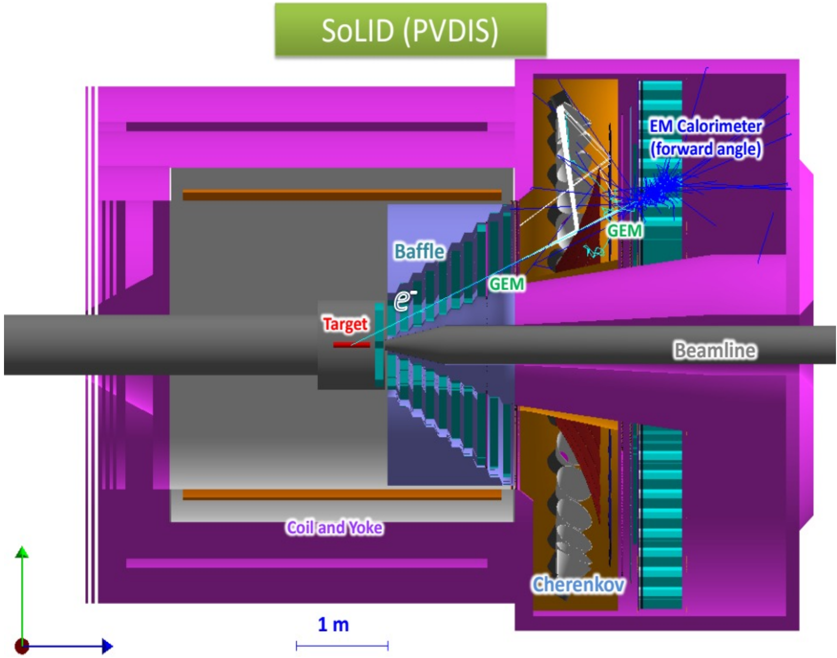
https://arxiv.org/abs/2204.07557)

All of the SoLID data is at large y and sensitive to C_2;
about 25% of the EIC data is at large y.
EIC emphasizes new structure functions for P and D data.

SoLID Apparatus for PVDIS

Kinematic Requirements

- High Luminosity with E ~ 11 GeV
- Only electron is detected.
- Wide x-range: 0.25-0.75: untangle physics.
- $W^2 > 4$ GeV: Isolate DIS events.
- Large scattering angles $\sim 22^\circ < \theta < \sim 35^\circ$: (for high x & y).
- Large azimuthal acceptance.
- Better than 1% statistical errors for small bins
- Q^2 range a factor of 2 for each x bin: Measure Higher Twist.
    - (Except at very high x)
- 2 GeV < E′< 6 GeV: Low background
- ~2% Momentum resolution



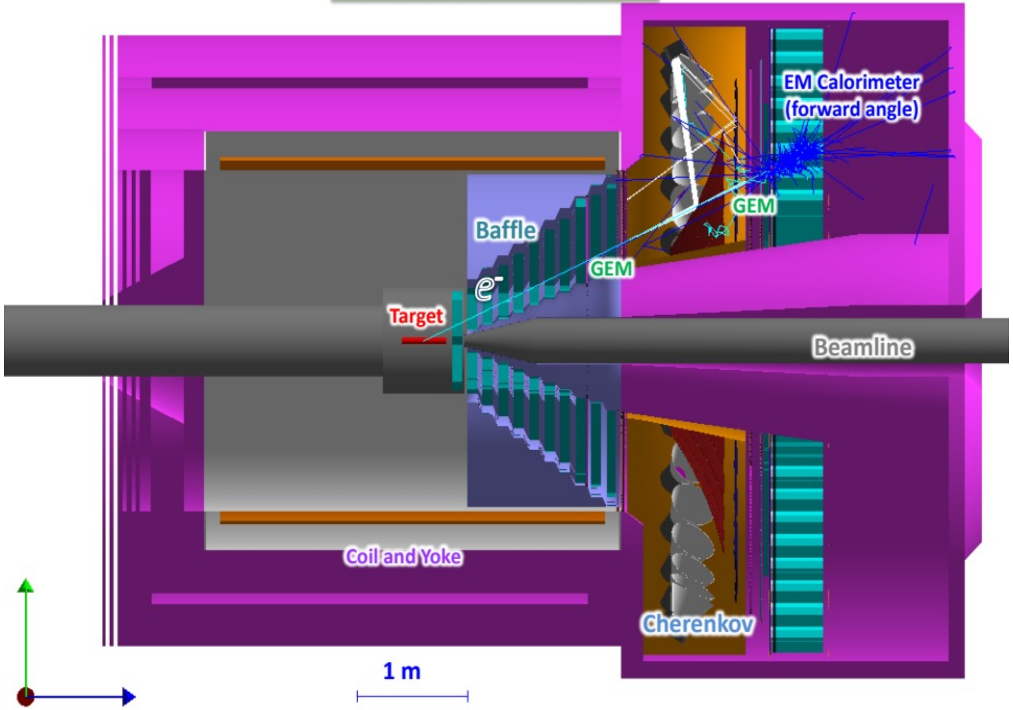
CLEO magnet with the LD_2 or LH_2 target in the center provides the desired acceptance.

SoLID Apparatus

Achieving High Luminosity

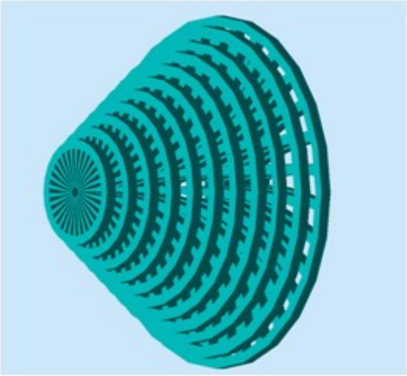
- 50 μA beam current.
- 40 cm LD_2 target
- ~40% azimuthal coverage with baffles which provide curved channels that block positive and neutral background particles
- Azimuthally symmetric.
- High-rate GEM tracking Chambers

SoLID (PVDIS)

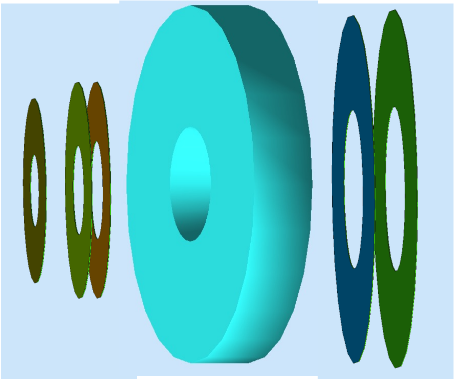


Magnet from CLEO experiment at Cornell is at JLab. Cold test is expected to be completed by October.

Baffles



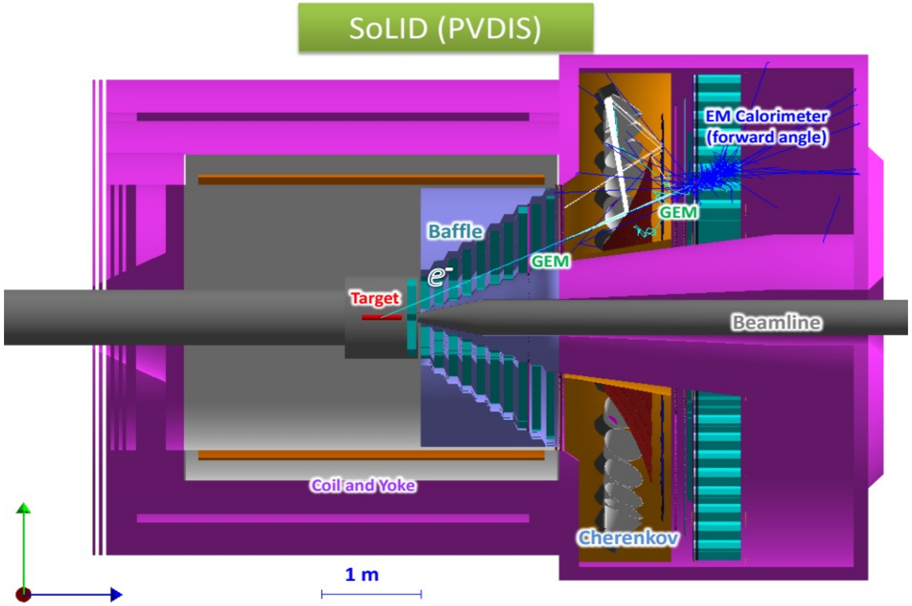
GEM Chambers

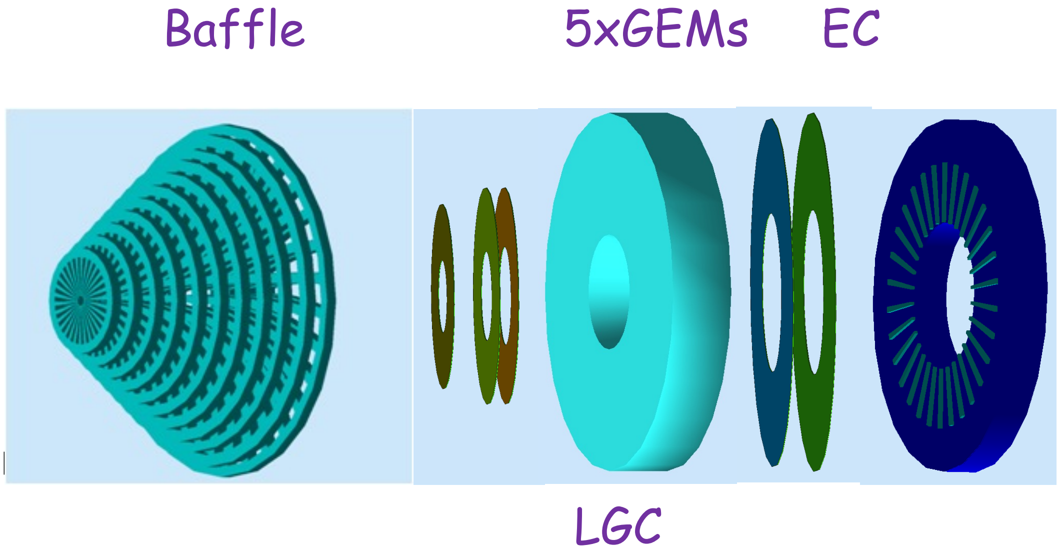


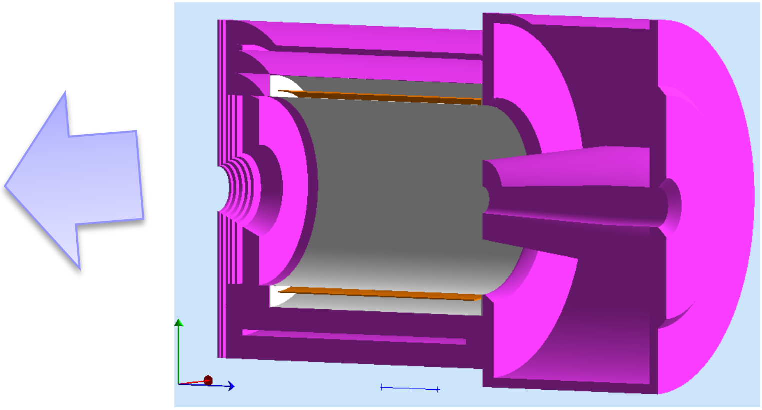
SoLID Apparatus

Requirements for Particle Identification and Trigger

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







Goals of SoLID, MOLLER, and P2

$$A_{PV} = Q_W^e \frac{Q^2 G_F}{\sqrt{2}\pi} \left(\frac{1-y}{1+y^4+(1-y)^4} \right)$$

Moller (Simple formula)

$$A_{PV} = \frac{G_F Q^2}{\pi \sqrt{2}} (Q_W^p \cancel{+ A_M + A_s + A_A})$$

P2: eP (Simple formula at low E and θ)

$$A^{PV} = \left(\frac{G_F Q^2}{4\sqrt{2}\pi} \right) (Y_1 a_1 + Y_3 a_3)$$

SoLID PVDIS (Simple for d at large E and θ, only way to get C_2's)

$$a_1^d = \frac{6}{5}(2C_{1u} - C_{1d}); \quad a_3^d = \frac{6}{5}(2\underline{C_{2u}} - \underline{C_{2d}})$$

$$Q_W(Z,N) = -2[\underline{C_{1u}}(2Z+N) + \underline{C_{1d}}(Z+2N)] \qquad Q_W(e) = -2\underline{C_{2e}}$$

Measure all the C's as precisely as possible

Normalization Systematics:

$$\frac{A_{PV}^{phys}}{Q^2} = \frac{1}{P_b}\frac{A_{PV}^{measured} - fA_{PV}^{\pi}}{1-f}$$

- Beam Polarimetry
- Average Q^2
- Event reconstruction (f)