

# The Parity-Violating Deep Inelastic Scattering (PVDIS) Program with SoLID

Zhongling Ji

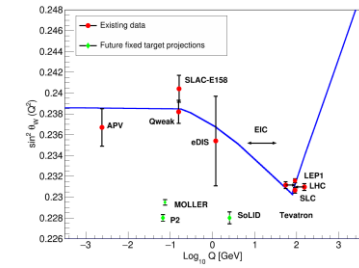
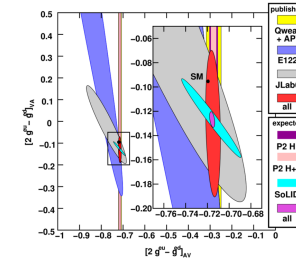
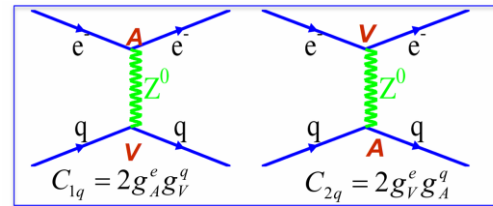
Hall A/C Collaboration Meeting

June 17, 2026

# Physics Motivations

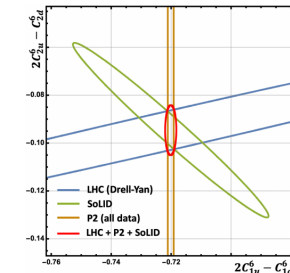
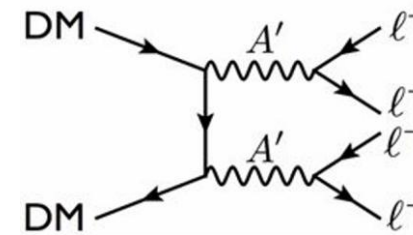
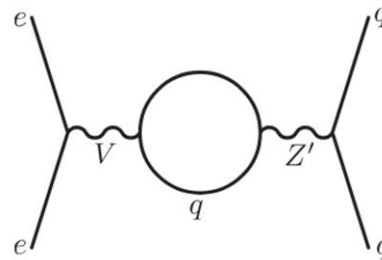
- Precision Electroweak Physics

- Electron-quark couplings  $C_{iq}$ 's
- Weak mixing angle  $\sin^2 \theta_W$



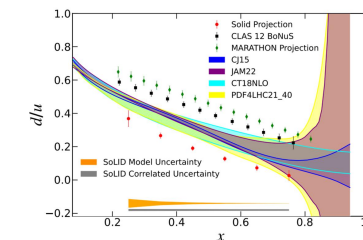
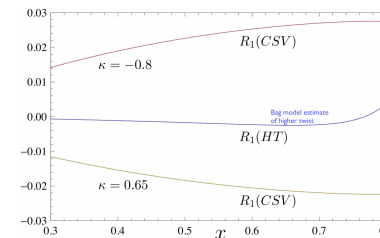
- Probing Beyond the Standard Model (BSM)

- BSM reach  $\Lambda_{BSM} \sim 10 - 20$  TeV
- Unique sensitivity to
  - Leptophobic  $Z'$
  - Dark photons
  - Dark-Z boson
- SMEFT analysis, lift flat directions



- Hadronic Structure

- Charge Symmetry Violation (CSV)
- Higher Twist (HT) Effects
- d/u proton PDF ratio, free of nuclear effects



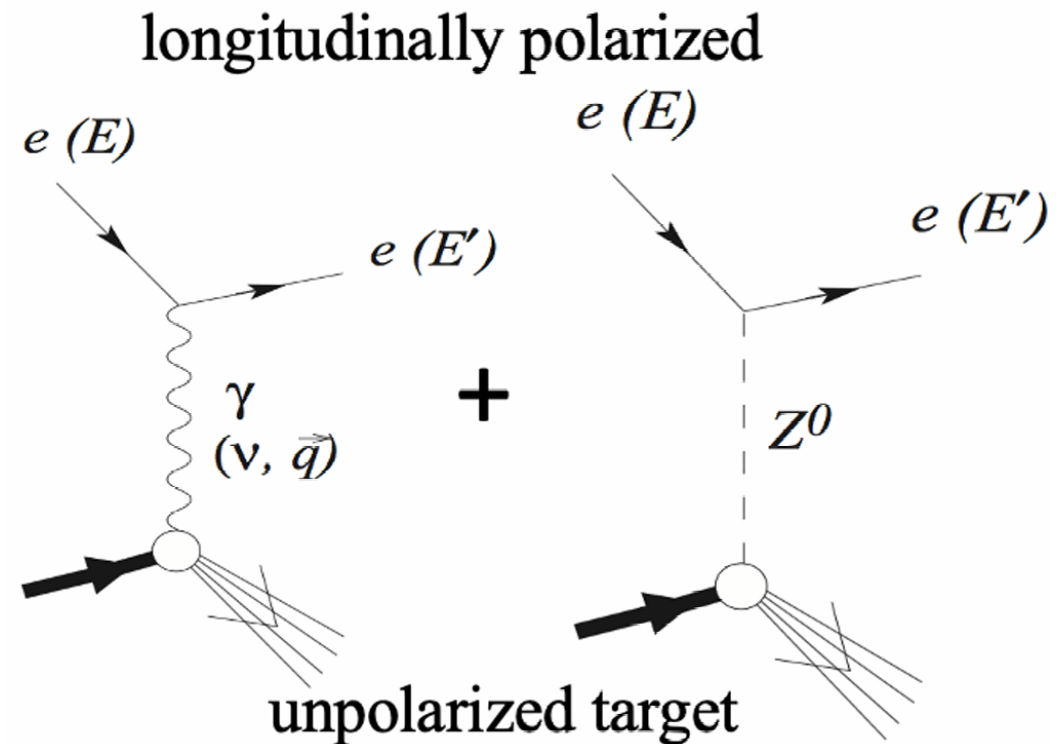
# Theoretical Framework: Parity-Violating Asymmetry

- The Origin of  $A_{PV}$ 
  - $\gamma - Z^0$  interference
- Cross Sections

$$\begin{aligned} \sigma^r &\propto |M_{em} + M_{weak}^r|^2 \\ \sigma^l &\propto |M_{em} + M_{weak}^l|^2 \\ &= |M_{em}|^2 + 2M_{em}M_{weak}^l + |M_{weak}^l|^2 \end{aligned}$$

- The Asymmetry Equation

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



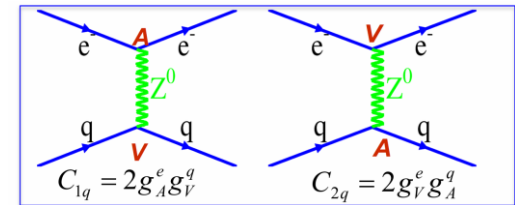
# Neutral-Current Electron-Quark Couplings

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

- Physical Meaning

- $C_{1q}$  Terms: Axial-vector electron to vector quark ( $g_A^e g_V^q$ )

- $C_{2q}$  Terms: Vector electron to axial-vector quark ( $g_V^e g_A^q$ )



- Standard Model Tree-Level Expectations:  $C_{1u} = 2g_A^e g_V^u \approx -\frac{1}{2} + \frac{4}{3} \sin^2 \theta_W \approx -0.19$

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

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

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

Note: The  $C_{2q}$  couplings are exceptionally small and traditionally difficult to isolate due to suppression factor  $1 - 4 \sin^2 \theta_W$  at the electron vertex.

# Experimental Channels: Deuteron and Proton Targets

- Parity-Violating DIS on a Deuteron Target ( $A_{iso}$ )

- For a symmetric isoscalar target ( $u \approx d$ ), PDF mostly cancel out at high  $x$

$$\begin{aligned}
 A_{iso} &= \frac{\sigma^l - \sigma^r}{\sigma^l + \sigma^r} \quad \text{At high } x, A_{iso} \text{ becomes independent of PDFs, } x \text{ \& } W, \text{ with well-defined SM prediction for } Q^2 \text{ and } y \\
 &= - \left( \frac{3G_F Q^2}{\pi \alpha 2\sqrt{2}} \right) \frac{2C_{1u} - C_{1d} (1 + R_s) + Y (2C_{2u} - C_{2d}) R_v}{5 + R_s}
 \end{aligned}$$

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

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

- Unique sensitivity to  $C_{2q}$  via the kinematic Y-factor
- Isolating partonic CSV and higher-twist effects

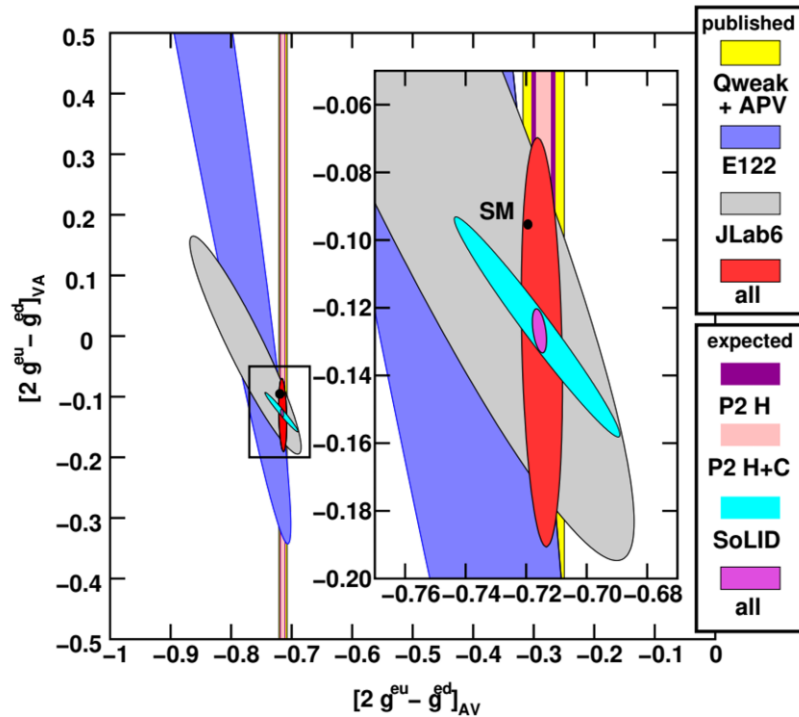
$$Y = \frac{1 - (1 - y)^2}{1 + (1 - y)^2 - y^2 \frac{R}{R+1}}$$

- Parity-Violating DIS on a Proton Target

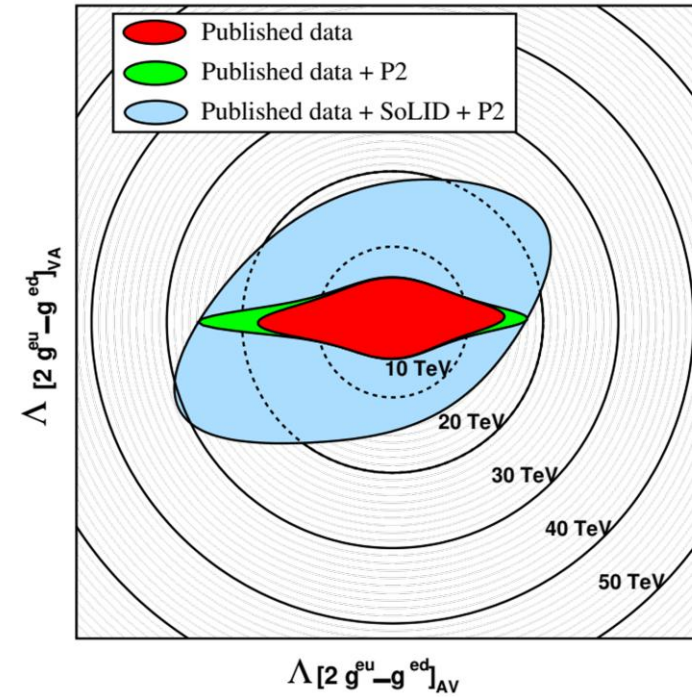
- Clean, model-independent anchor to pin down the d/u PDF ratio at high  $x$
- Removing nuclear correction dependencies



# The Uniqueness of SoLID PVDIS



The Power of SoLID: While complementary programs (like Qweak, MOLLER, and Mainz-P2) intensely measure the  $C_{1q}$  via elastic electron scattering, SoLID PVDIS is the only viable experimental path to isolate the  $C_{2q}$  with high precision



Improvement in energy reach for electron-nucleon couplings.

arXiv: 2209.13357, SoLID white paper

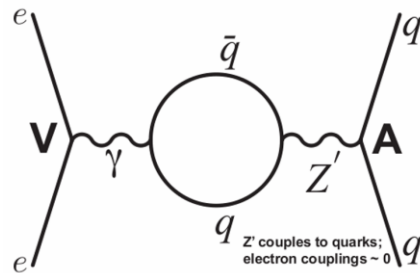
# BSM Physics Sensitivities

- **Leptophobic Z' Bosons:** Because the photon is a vector, any parity-violating Z' must manifest as an axial-vector coupling. Consequently, it alters only the VA ( $C_{2q}$ ) terms in  $A_{PV}$ , making SoLID a pristine discovery channel.
- **Dark Photons & Light Dark-Z Portals:** Induces structural radiative correction shifts across both  $C_{1q}$  and  $C_{2q}$  parameter spaces.
- **SMEFT Integration:** Low-energy PVES breaks parameter degeneracies (flat directions) between dim-6 and dim-8 operators that are typically entangled at high-energy colliders like the LHC.

# Leptophobic $Z'$

- Since the photon is a vector, to violate parity,  $Z'$  needs to be an axial vector, thus only affect the VA ( $C_{2q}$ ) term in  $A_{pv}$

- Babu, Kolda and March-Russell, Phys.Rev. D 54 (1996) 4635–4647, [hep-ph/9603212].
- Gonzalez-Alonso, Ramsey-Musolf, Phys. Rev. D 87 (2013) 5, 055013 [arXiv:1211.4581].
- Buckley, Ramsey-Musolf, Phys. Lett. B 712 (2012)261-265 [ arXiv:1203.1102].



[M.Alonso-Gonzalez, M.Ramsey-Musolf;  
M.Buckley,M.Ramsey-Musolf]

Leptophobic  $Z'$   
contributes only to  
the  $C_{2q}$  couplings!

$$a_1 = \frac{2 \sum_q e_q C_{1q} (q + \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

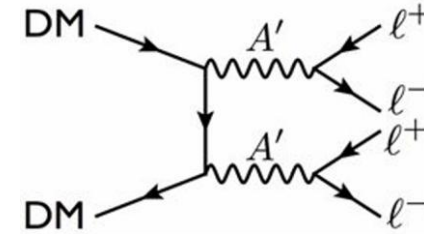
$$a_3 = \frac{2 \sum_q e_q C_{2q} (q - \bar{q})}{\sum_q e_q^2 (q + \bar{q})}$$

$$A_{PV}^{\text{DIS}} = \frac{G_F Q^2}{4\sqrt{2}(1 + Q^2/M_Z^2)\pi\alpha} \left[ a_1 + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} a_3 \right]$$

# Dark Photons

- Shift both  $C_{1q}$  and  $C_{2q}$

- Thomas, Wang, Williams, Phys. Rev. Lett. 129 (2022) 1, 011807 [arXiv:2201.06760]



$$\mathcal{L} \supset -\frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} + \frac{m_{A'}^2}{2} A'_\mu A'^\mu + \frac{\epsilon}{2 \cos \theta_W} F'_{\mu\nu} B^{\mu\nu}$$

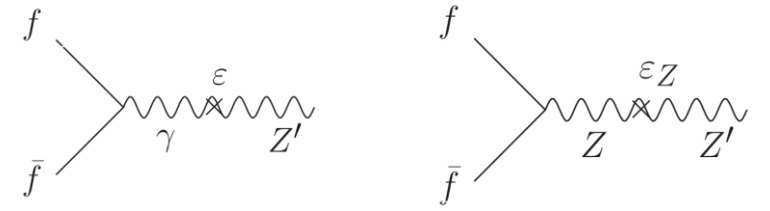
$$\mathcal{L}_{int} = -e\epsilon J_{em}^\mu A'_\mu$$

$$A_{PV} = \frac{Q^2}{2 \sin^2 2\theta_W (Q^2 + M_Z^2)} \left[ a_1^{\gamma Z} + \frac{1 - (1-y)^2}{1 + (1-y)^2} a_3^{\gamma Z} \right. \\ \left. + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} (a_1^{\gamma A_D} + \frac{1 - (1-y)^2}{1 + (1-y)^2} a_3^{\gamma A_D}) \right],$$

$$C_{1q} = C_{1q}^Z + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{1q}^{A_D} = C_{1q}^{SM} (1 + R_{1q})$$

$$C_{2q} = C_{2q}^Z + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{2q}^{A_D} = C_{2q}^{SM} (1 + R_{2q})$$

# Light Dark-Z Parity Violation

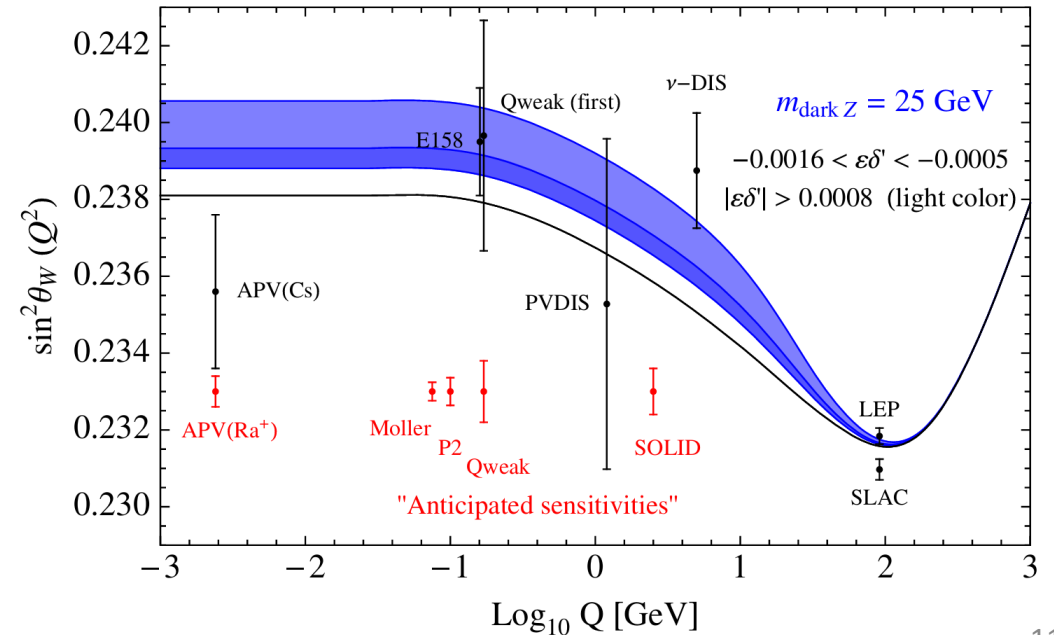
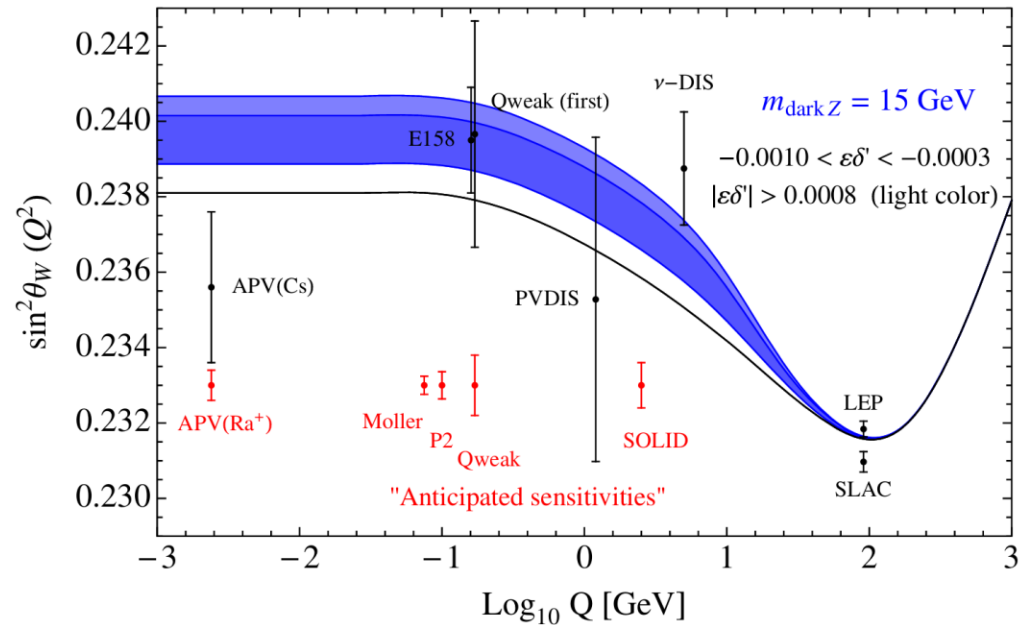


$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$

$$\mathcal{L}_{\text{int}} = \left( -e\varepsilon J_\mu^{\text{em}} - \frac{g}{2\cos\theta_W}\varepsilon_Z J_\mu^{\text{NC}} \right) Z_d^\mu$$

[Davoudiasl, Lee, Marciano, PRD 92, 055005 (2015)]

$$M_0^2 = m_Z^2 \begin{pmatrix} 1 & -\varepsilon_Z \\ -\varepsilon_Z & m_{Z_d}^2/m_Z^2 \end{pmatrix} \quad \varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$$

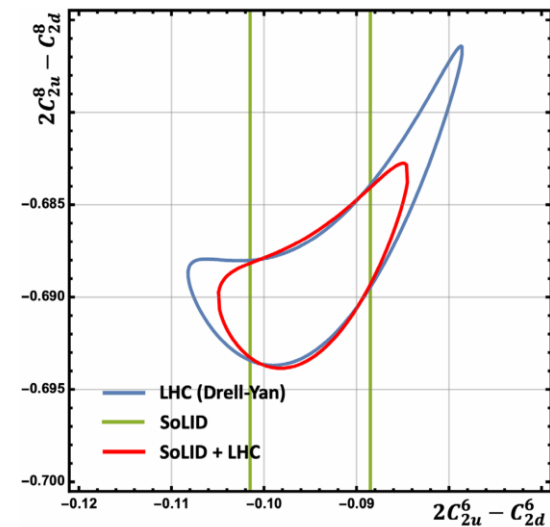
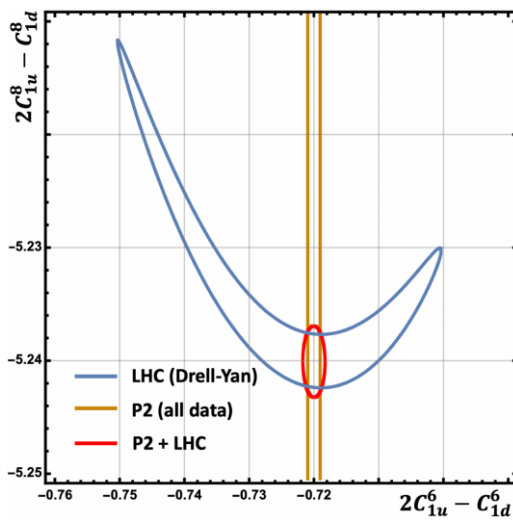
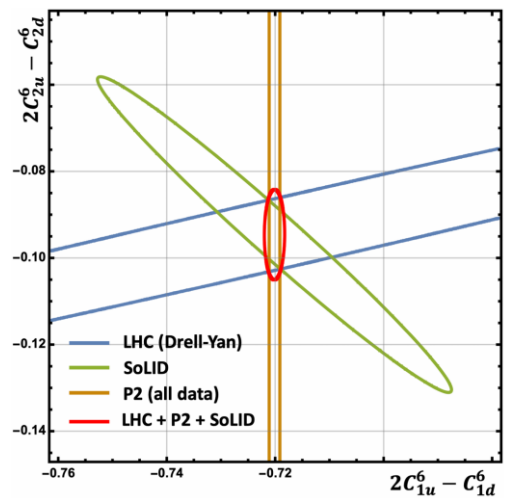


# New Physics from PVDIS – SMEFT

- New physics with Standard Model Effective Field Theory beyond the electroweak scale:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2} \sum_i C_i^6 \mathcal{O}_{6,i} + \frac{1}{\Lambda^4} \sum_i C_i^8 \mathcal{O}_{8,i} + \dots,$$

- PVES and Drell-Yan at LHC are sensitive to different combinations of the SMEFT Wilson coefficients
  - The high energy of the LHC makes it difficult to separate dim-6 and dim-8 operators
  - Low-energy PVES breaks parameter degeneracies (flat directions) between dim-6 and dim-8 operators



# Hadronic & Core QCD Physics Impacts

- **Charge Symmetry Violation (CSV):** PVDIS allows us to look for small, fundamental masses/u-d differences at the quark level without heavy nuclear contamination.
- **Higher-Twist (HT) Operator Effects:** Isolate dynamic, non-perturbative multi-quark (quark-quark) correlation effects as a function of  $x$  and  $Q^2$ .
- **Flavor Structure (d/u PDF ratio):** Directly constrains the PDF extraction at high valence-region  $x$ , helping settle discrepancies among global fits.

# Hadronic Effects

$$A_{RL} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{9}{10} \left[ \tilde{a}_1 + \tilde{a}_2 \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right]$$

$$\tilde{a}_j = -\frac{2}{3} (2C_{ju} - C_{jd}) [1 + R_j(\text{new}) + R_j(\text{sea}) + R_j(\text{CSV}) + R_j(\text{TMC}) + R_j(\text{HT})]$$

↑  
New physics

↑  
Sea quarks

↑  
Charge symmetry  
violation

↑  
Target mass

↑  
Higher  
twist

# Charge Symmetry Violation

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

$$\delta u = u^p - d^n$$

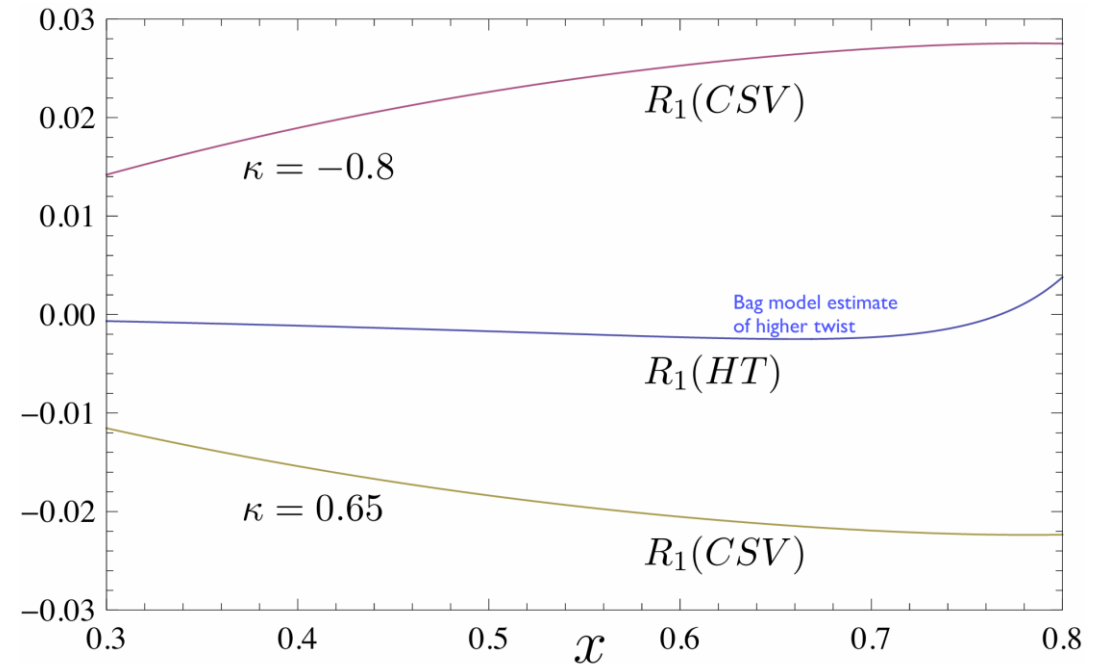
$$\delta d = d^p - u^n$$

$$R_1(\text{CSV}) = \left[ \frac{1}{2} \left( \frac{2C_{1u} + C_{1d}}{2C_{1u} - C_{1d}} \right) - \frac{3}{10} \right] \left( \frac{\delta u - \delta d}{u + d} \right)$$

$$\delta u - \delta d = 2\kappa f(x)$$

$$f(x) = x^{-1/2}(1-x)^4(x-0.0909)$$

Mantry, Ramsey-Musolf, Sacco  
PRC 82, 065205 (2010)

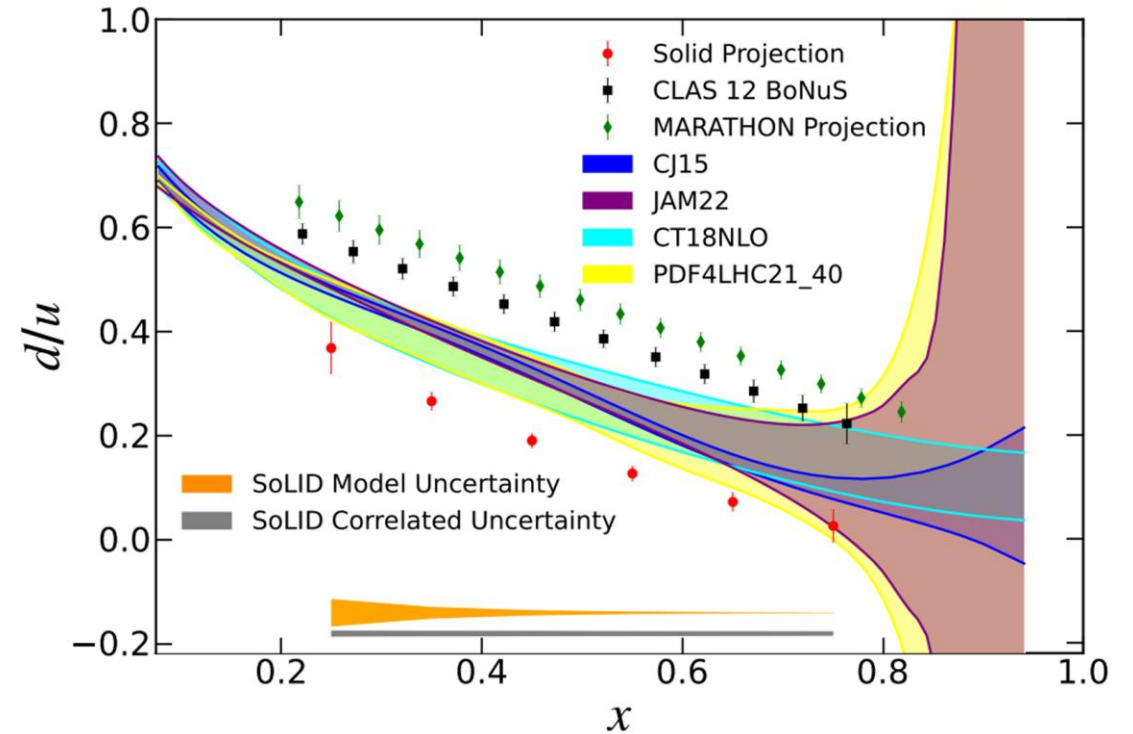


# PVDIS on d/u PDF

- PVDIS proton measurement access PDF d/u at high x, without the need of nuclear model

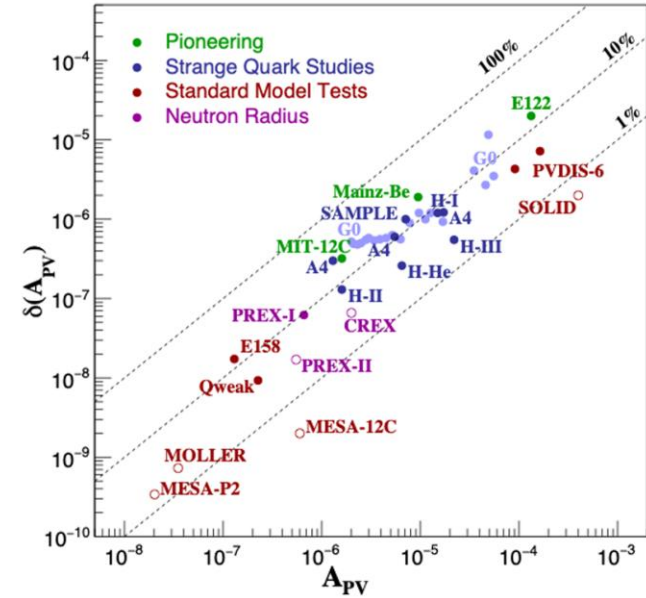
$$A_{RL}^p = \frac{3G_F Q^2}{2\sqrt{2}\pi\alpha} \frac{(2C_{1u} - d/u C_{1d}) + Y(2C_{2u} - d/u C_{2d})}{4 + d/u}$$

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

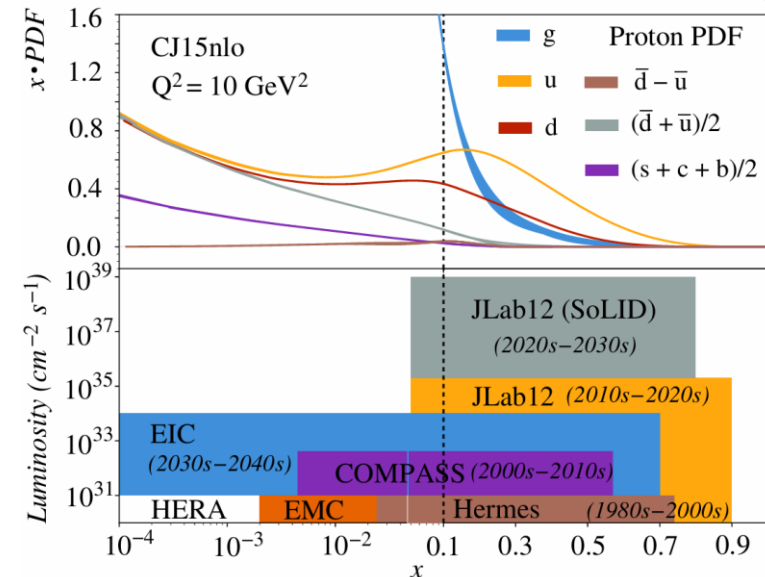


# SoLID Landscape

- High Luminosity ( $10^{37} - 10^{39}$ )
- High data rate
- High background
- Low systematics
- High Radiation
- Large scale (Like RHIC)
- New Technologies
  - GEM's
  - Shashlyk Ecal
  - Pipeline DAQ



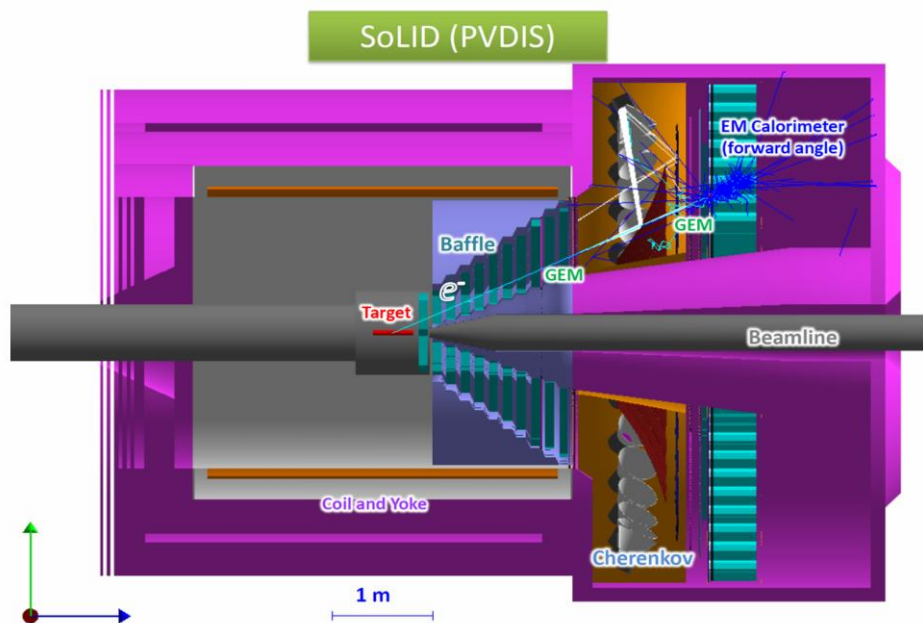
arXiv:2209.13357, SoLID White Paper



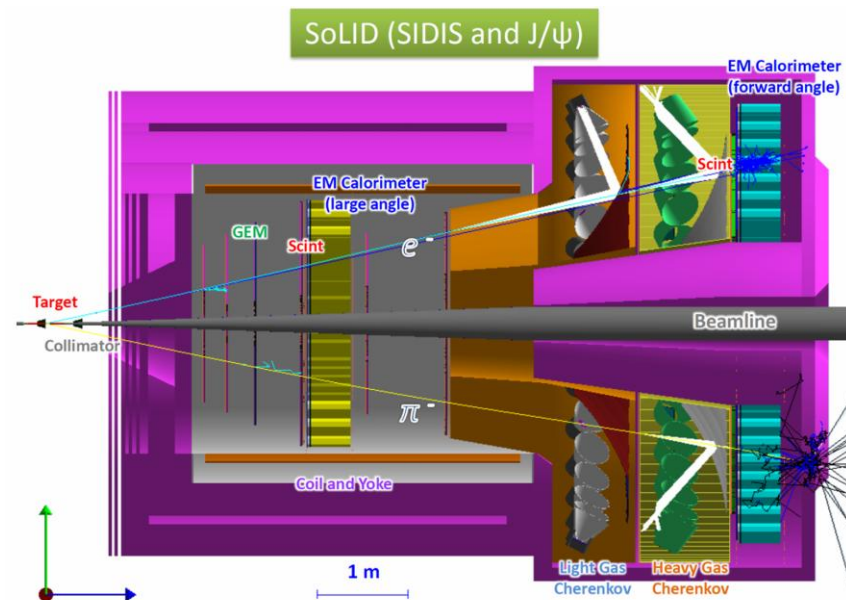
# SoLID Landscape

- The Operational Environment
  - Ultra-high luminosity configurations ( $\mathcal{L} \sim 10^{37} - 10^{39} \text{cm}^{-2} \text{s}^{-1}$ ).
  - Demands exceptional tolerance against massive data rates, high backgrounds, and intense radiation environments.
- Cutting-Edge Subsystems
  - **Tracking:** Large-area Gas Electron Multipliers (GEMs).
  - **Calorimetry:** Shashlyk Electromagnetic Calorimeter (ECal) for high-rate electron identification.
  - **Electronics:** Advanced Pipeline DAQ to process high-throughput events without dead-time constraints.

# SoLID Detector



- High Luminosity:  $10^{39} \text{ cm}^{-2} \text{ s}^{-1}$
- Large scattering angles  $\sim 22^\circ < \theta < \sim 35^\circ$
- Momentum resolution:  $\sim 2\%$
- $W^2 > 4 \text{ GeV}^2$ : Isolate DIS events
- Polar angle resolution  $\sim 1 \text{ mrad}$



- High luminosity  $\sim 10^{37} \text{ cm}^{-2} \text{ s}^{-1}$
- Detection  $e^-$ :  $8^\circ < \theta < 24^\circ$ , full azimuthal  
 $0.8 < P < 7.0 \text{ GeV}$
- Detection of  $\pi^\pm$ :  $8^\circ < \theta < 15^\circ$ , full azimuthal  
 $2.5 < P < 7.5 \text{ GeV}$  (baseline)
- SPD: photon rejection 10:1
- Momentum resolution: 2%

# SoLID Detector

- PVDIS Specific Configuration
  - Employs an optimized heavy-metal **Baffle System** to systematically block high-rate low-energy backgrounds (pions/photons) while directing DIS electrons cleanly into detectors.
  - Acceptance profile: Large scattering angles ( $\sim 22^\circ < \theta < \sim 35^\circ$ ) with  $\sim 2\%$  momentum resolution to completely isolate the DIS regime  $W^2 > 4 \text{ GeV}^2$ .
- SIDIS /  $J/\psi$  Versatility
  - Open geometry without the baffle layer to maximize multiparticle tracking capabilities over a wide forward angular range.

# Summary & Conclusions

- PVDIS at SoLID is sensitive to coupling  $C_{2q}$ 's
- Unique and complementary constraints on new physics
- Allows for precision extractions of the weak mixing angle
- Provides input for the global SMEFT analysis
- Constrains Leptophobic  $Z'$ , Dark photon/ $Z$
- Explores hadronic effects such as charge symmetry violation, higher-twist correlations, and d/u PDF ratio
- *Moving Forward*: The technical designs of the high-rate subcomponents (GEMs, Shashlyk ECal, Pipeline DAQ) are strategically progressing to meet the requirements of this high-luminosity frontier.
- *New strategy*: Starting with one experiment with minimum cost, possibly reduced detector configuration.