PVDIS at SoLID: Physics Overview

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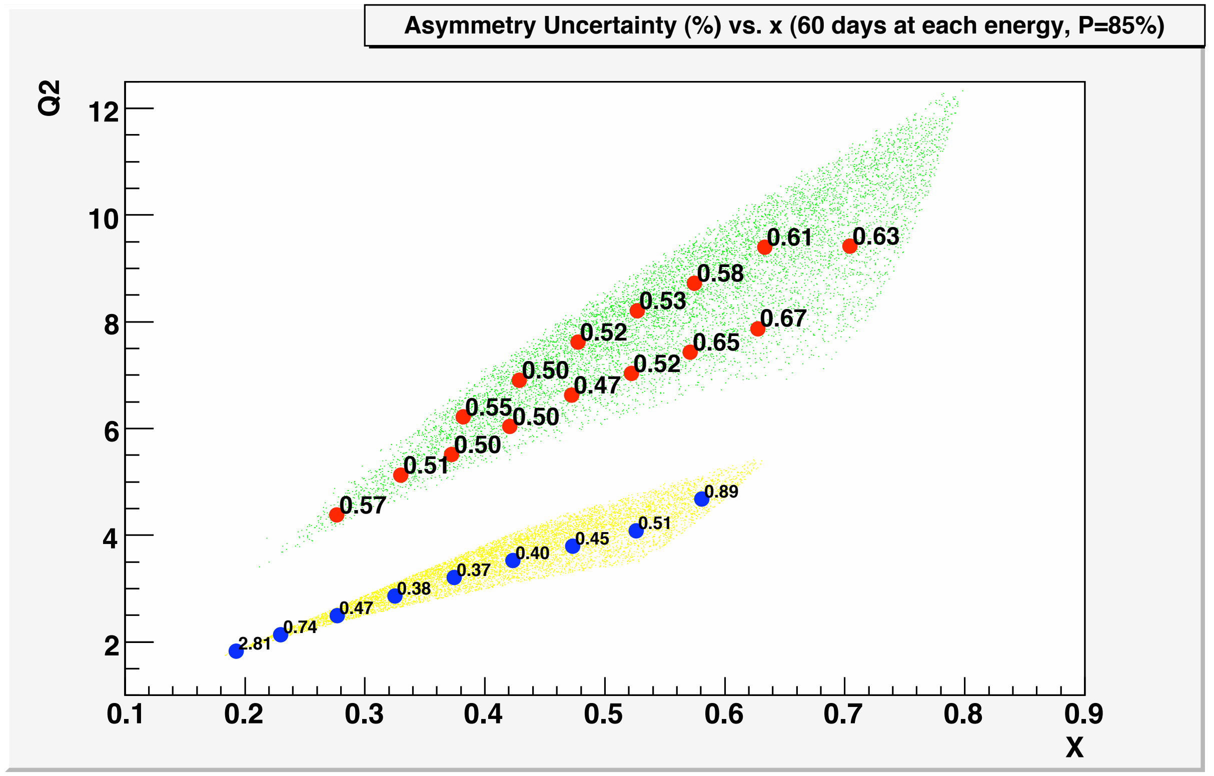
SoLID Opportunities and Challenges of Nuclear Physics at the Luminosity Frontier

June 17th-22nd, 2024

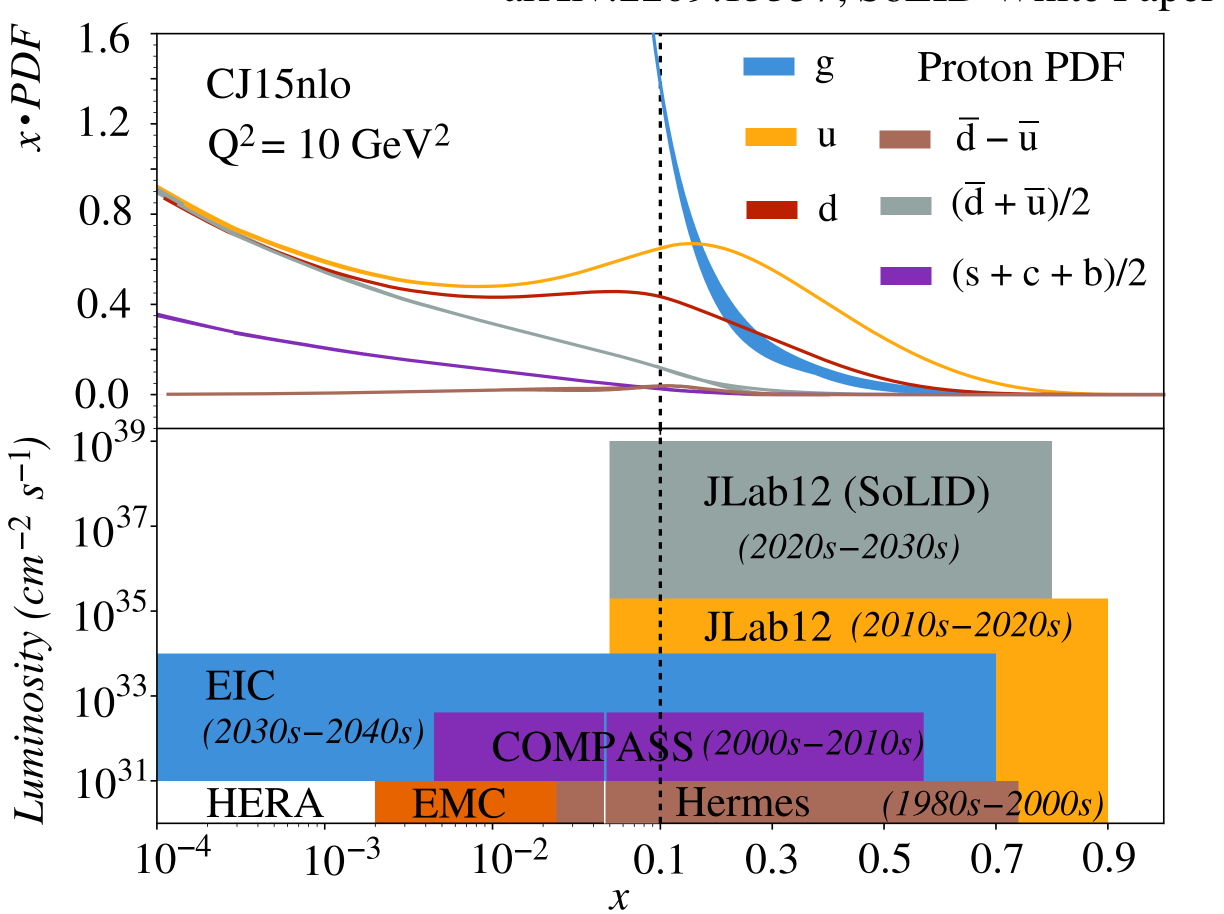
Parity-Violating DIS (PVDIS) at SoLID

- PVDIS at SoLID:
  - High Luminosity ($\mathscr{L} \sim 10^{39} cm^{-2} s^{-1}$)
  - High data processing rate
  - Kinematics:
    $2\ \mathrm{GeV}^2 \lesssim Q^2 \lesssim 10\ \mathrm{GeV}^2,\ x \gtrsim 0.2$
  - Access to high-x region ($x \gtrsim 0.2$), sea quark effects suppressed
  - Polarized electron beams ($85\ \%$ polarization)
  - Proton and Deuteron Targets (possibly ^{48}Ca)
  - Deuteron is an isoscalar target, many hadronic effects cancel
  - Extracted physics will be complementary to other low energy experiments (MOLLER, PS, etc), the EIC, and the LHC

Taken from P. Souder talk



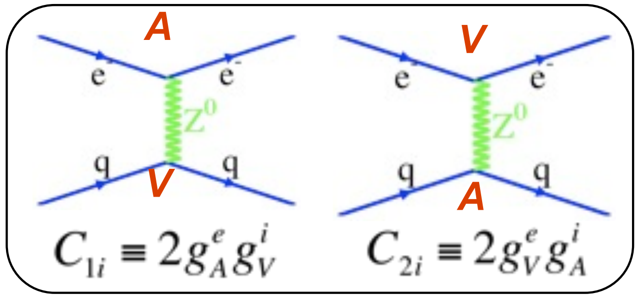
arXiv:2209.13357, SoLID White Paper

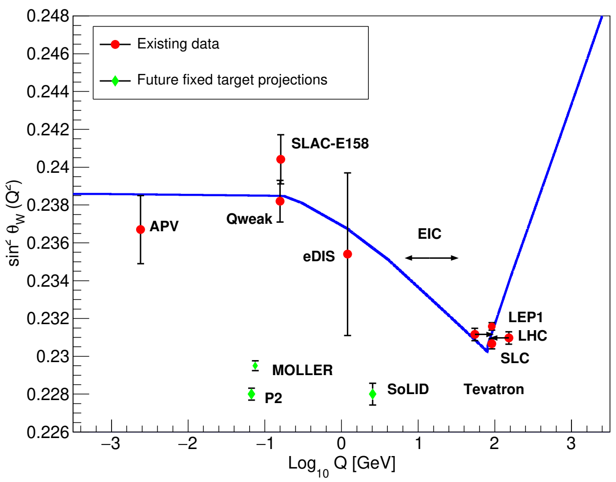


Parity-Violating DIS (PVDIS) at SoLID

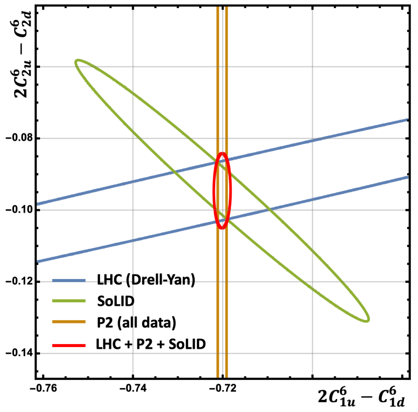
arXiv:2209.13357, SoLID White Paper

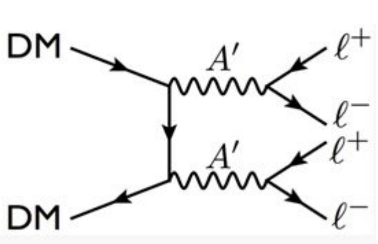
- Precision physics
  - Measure electroweak parameters:
    - C_{iq} couplings
    - Weak Mixing Angle (θ_W)

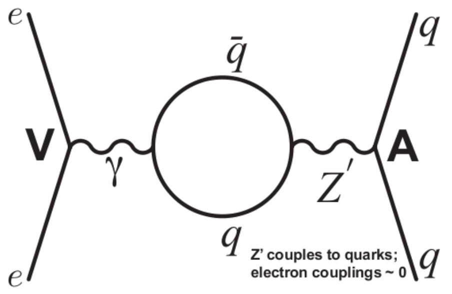




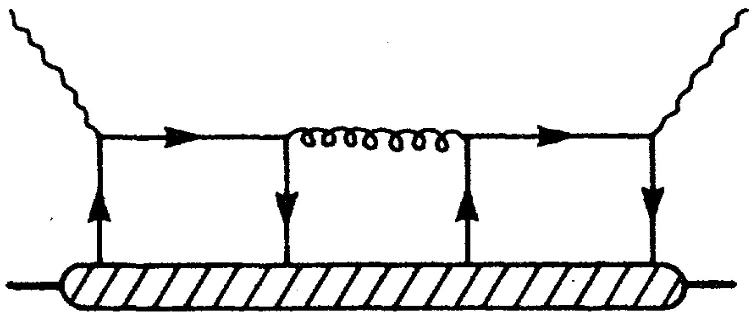
  - Constrain BSM physics:
    - BSM reach $\Lambda_{\mathrm{BSM}} \sim 10$ - 20 TeV
    - Leptophobic Z'
    - Dark Photons
    - Dark-Z
    - SMEFT Analysis, lift flat directions



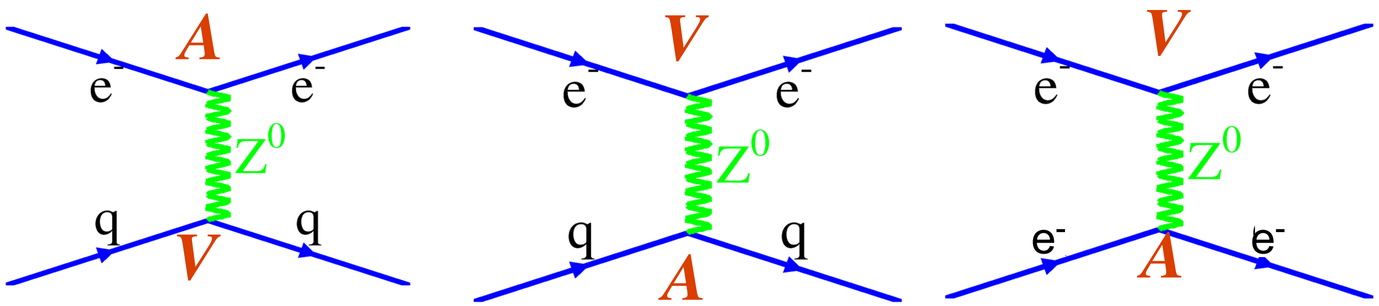




- Hadronic Physics
  - Charge Symmetry Violation (CSV)
  - Higher Twist (HT) Effects
  - d/u proton PDF ratio, free of nuclear effects



Contact Interactions



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

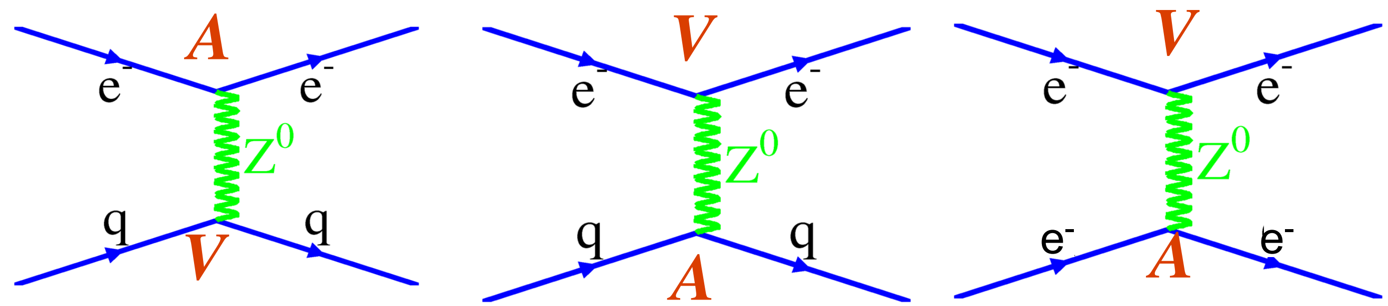
- For $Q^2 << (M_Z)^2$ limit, the effective Lagrangian relevant for PVES scattering is given by:

$$\mathscr{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{e}\gamma^\mu\gamma_5 e\, \bar{q}\gamma_\mu q + C_{2q}\, \bar{e}\gamma^\mu e\, \bar{q}\gamma_\mu\gamma_5 q + C_{2e}\, \bar{e}\gamma^\mu\gamma_5 e\, \bar{e}\gamma_\mu e \right]$$

- Tree-level Standard Model values:

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

Contact Interactions



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- Tree-level Standard Model values:

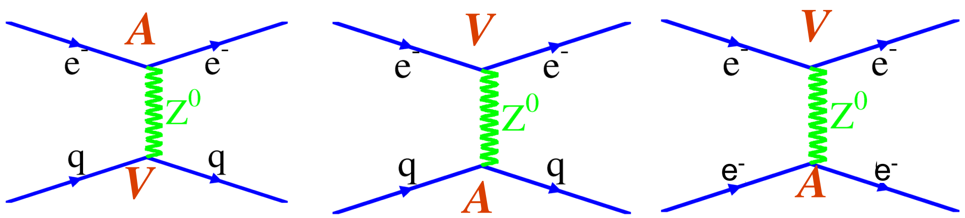
$$C_{1q} = 2g_A^e g_V^q \qquad C_{2q} = 2g_V^e g_A^q \qquad C_{2e} = 2g_A^e g_V^e$$

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W \qquad C_{2u} = -\frac{1}{2} + 2\sin^2\theta_W$$

$$C_{2e} = \frac{1}{2} - 2\sin^2\theta_W$$

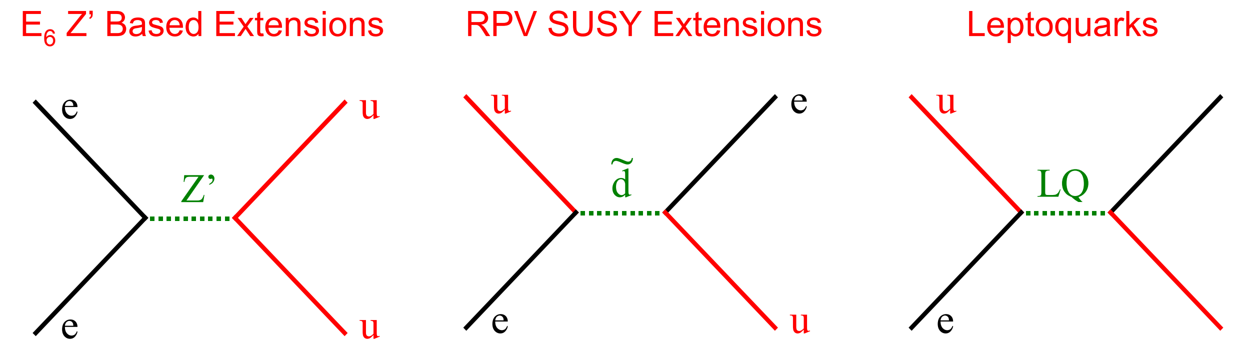
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W \qquad C_{2d} = \frac{1}{2} - 2\sin^2\theta_W$$

New Physics Effects



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

+



- In the $Q^2 \ll M_Z^2$ limit, electron-quark interactions via the weak neutral current can be parameterized by contact interactions:

$$\mathscr{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{e}\gamma^\mu\gamma_5 e\, \bar{q}\gamma_\mu q + C_{2q}\, \bar{e}\gamma^\mu e\, \bar{q}\gamma_\mu\gamma_5 q + C_{2e}\, \bar{e}\gamma^\mu\gamma_5 e\, \bar{e}\gamma_\mu e \right]$$

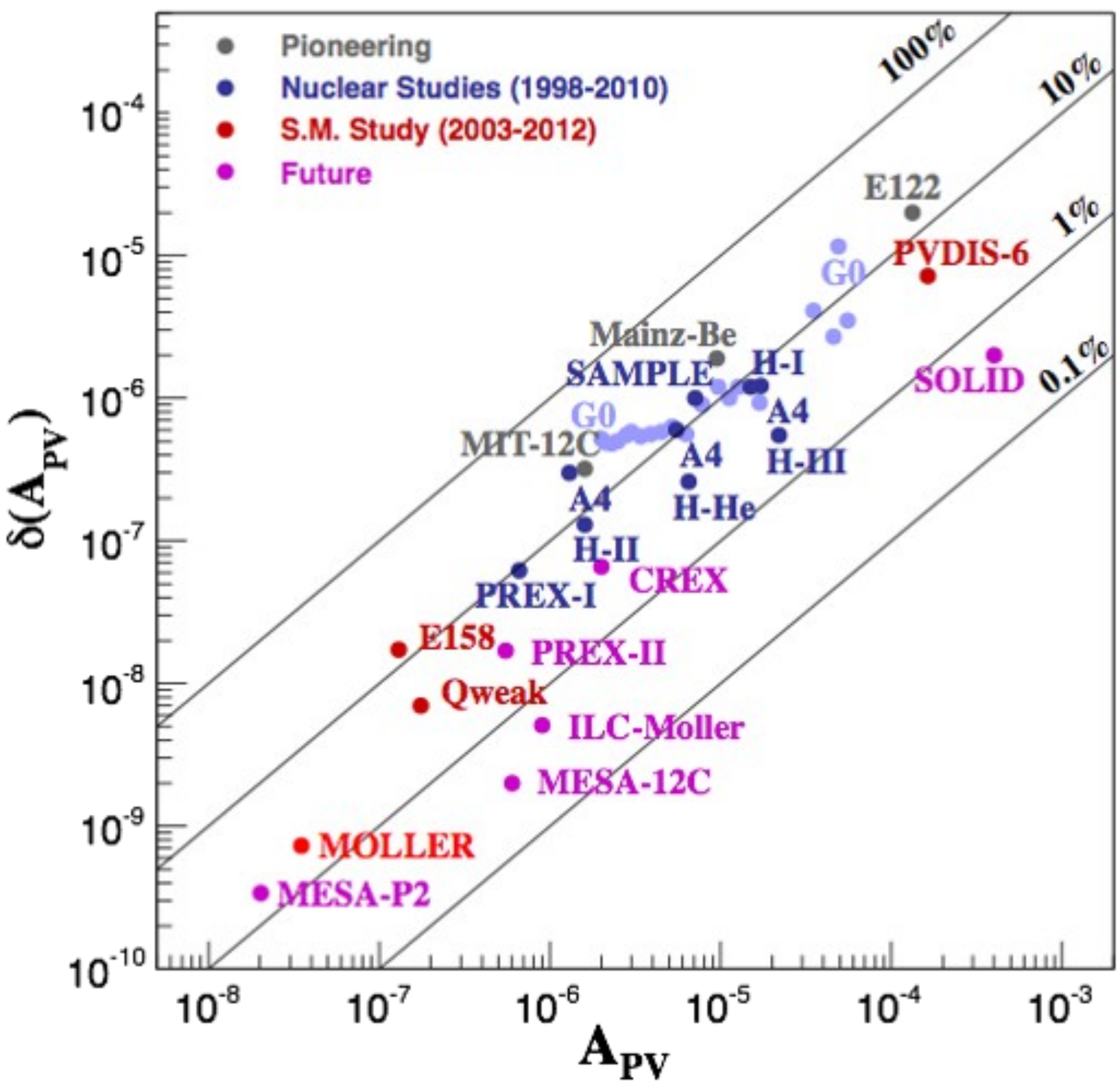
- New physics contact interactions arise as a shift in the WNC couplings compared to the SM prediction:

$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

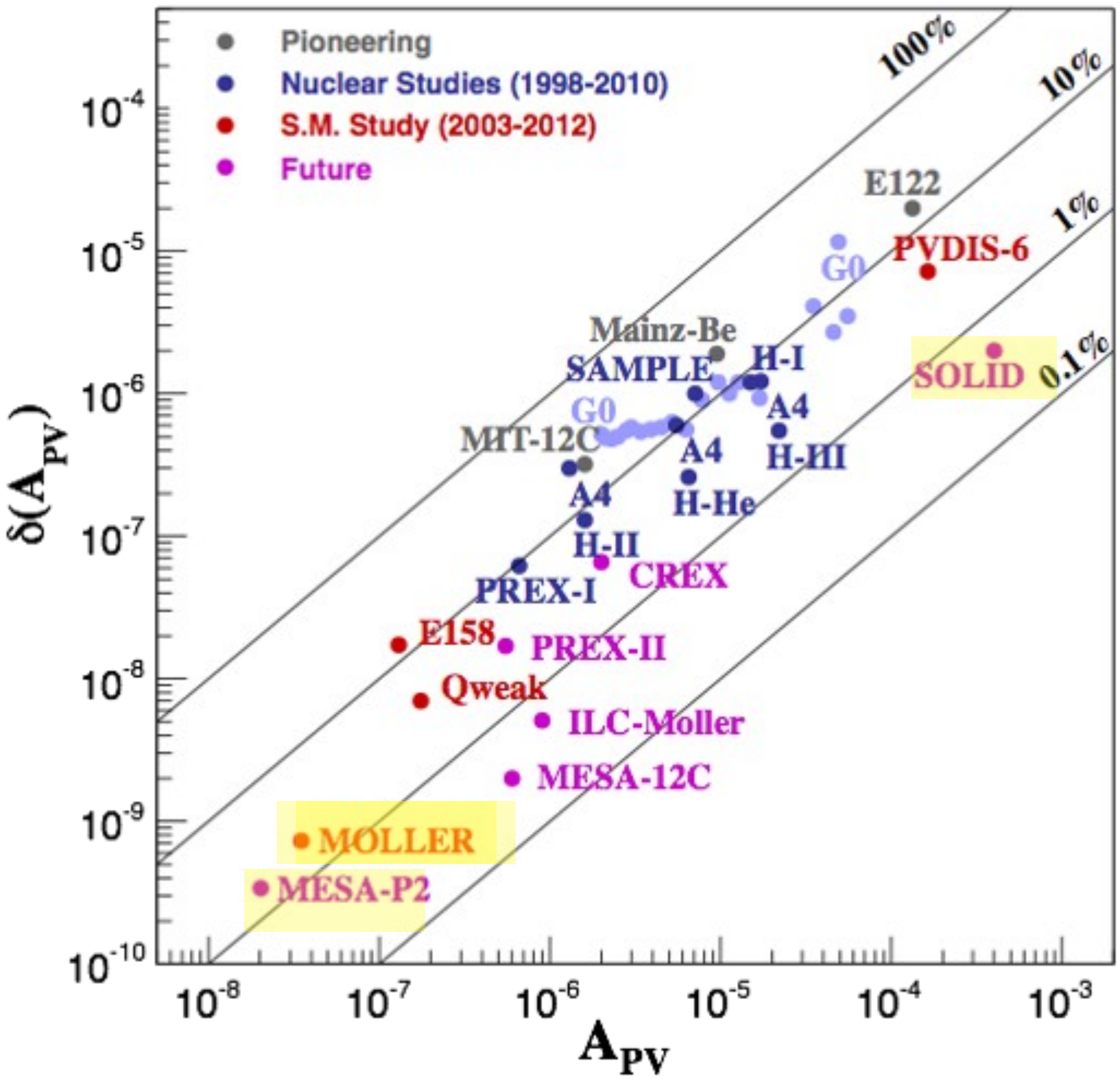
SM contribution $\quad$ New Physics contribution

- Deviations from the SM prediction of the WNC couplings will lead to corresponding deviations in the extracted value of the weak mixing angle.

Accessing C_{iq}, C_{2e} via Parity-Violating Observables



Accessing C_{iq}, C_{2e} via Parity-Violating Observables



	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

Taken from P. Souder talk

- SoLID, MOLLER, and P2 are all expected to improve precision

C_{iq}, C_{2e} via Parity-Violating Electron Scattering (PVES)

- Parity-Violating asymmetry using longitudinally polarized electron beams, can probe C_{iq} and C_{2e}:

$$A_{RL} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

Elastic Electron-Proton Scattering Asymmetry

- Low Energy and forward ($E \to 0, Q^2 \to 0$), elastic electron-proton scattering asymmetry is sensitive to the proton weak charge:

$$A_{RL} = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left[Q_W^p - F(E, Q^2)\right]$$

proton weak charge ↗ Proton structure ↖

- At tree-level, the SM value of the proton weak charge is (receives radiative corrections + box diagram corrections):

$$Q_W^p = -2\left[2C_{1u} + C_{1d}\right] = 1 - 4\sin^2\theta_W$$

	$Q^2(\mathrm{GeV}^2/\mathrm{c}^2)$	E	δQ_W^p	$\delta \sin^2\theta_W$
$Q_{\rm weak}$	0.025	1.155 GeV	$\sim 4\,\%$	$\sim 0.3\,\%$
P2 (MESA)	0.006	155 MeV	$\sim 2\,\%$	$\sim 0.15\,\%$

Moller Scattering Asymmetry

- Low Energy and forward ($E \to 0, Q^2 \to 0$), elastic electron-electron scattering asymmetry is sensitive to the proton weak charge:

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

electron weak charge

- At tree-level, the SM value of the proton weak charge is (receives radiative corrections + box diagram corrections):

$$Q_W^e = -\,2C_{2e} = -\,1 + 4\sin^2\theta_W$$

	$Q^2(\mathrm{GeV}^2/\mathrm{c}^2)$	E	δQ_W^e	$\delta\sin^2\theta_W$
E158	0.026	50 GeV	$\sim 4\,\%$	0.3 %
MOLLER	0.0056	11 GeV	$\sim 2.4\,\%$	0.1 %

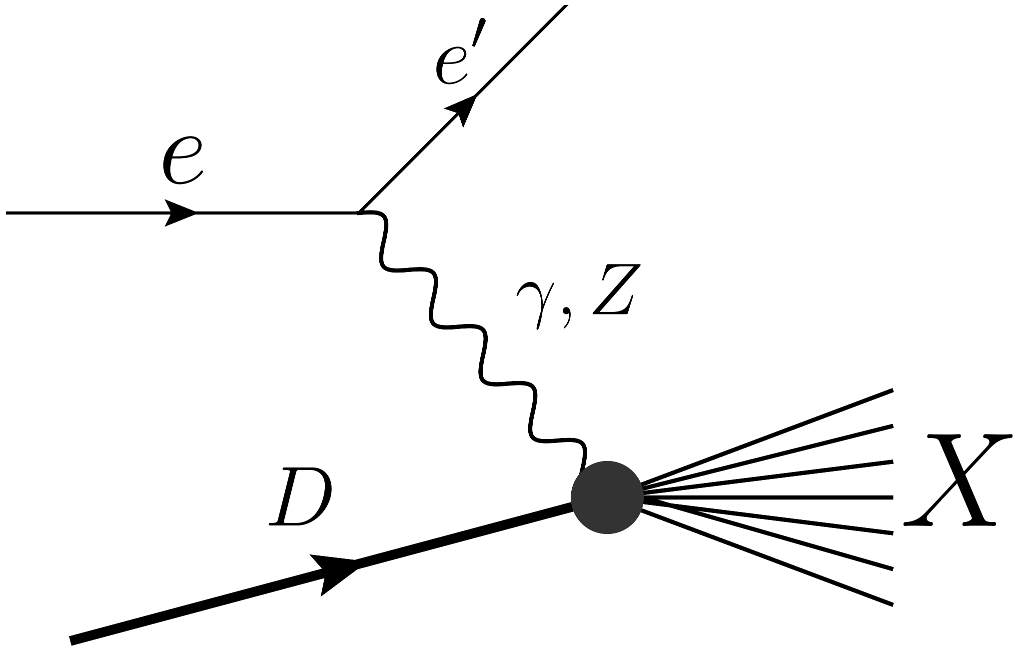
PVDIS Asymmetry

- Parity Violating DIS (E122, PVDIS-6, SOLID):
  Sensitive to C_{1q} and C_{2q}

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

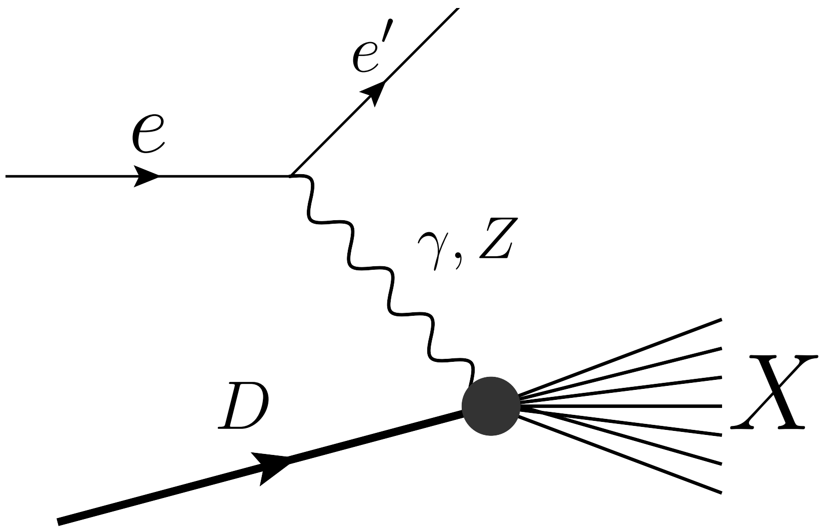
$$a_1 = \frac{2\sum_q e_q C_{1q}(q+\bar{q})}{\sum_q e_q^2(q+\bar{q})}$$

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



Parity-Violating e-D Asymmetry

- Parity-violating e-D asymmetry is a powerful probe of the WNC couplings:



$$A_{\mathrm{PV}} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \simeq \frac{|A_Z|}{|A_\gamma|} \simeq \frac{G_F Q^2}{4\pi\alpha} \simeq 10^{-4} \frac{Q^2}{\mathrm{GeV}^2}$$

- Due to the isoscalar nature of the Deuteron target, the dependence of the asymmetry on the structure functions largely cancels (Cahn-Gilman formula).

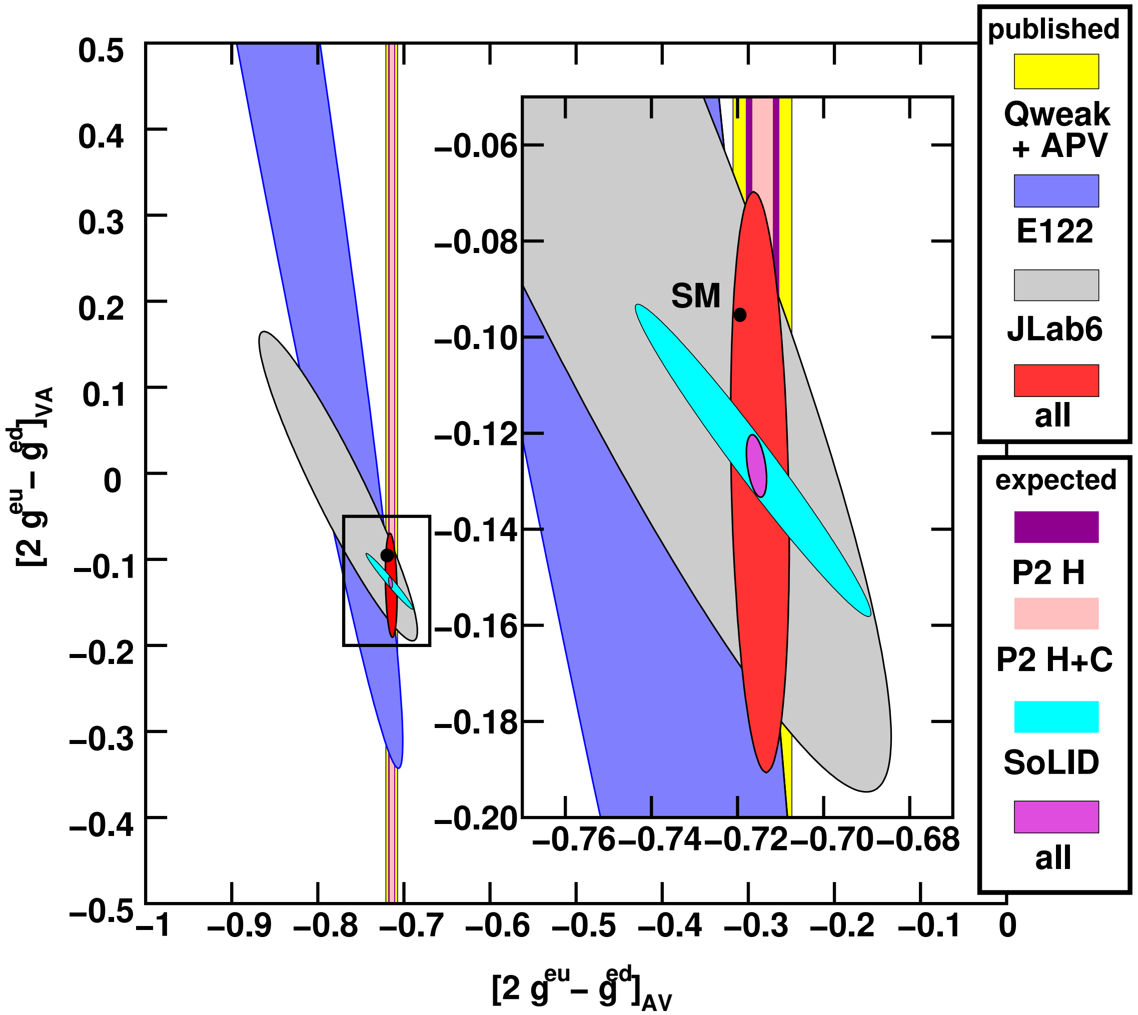
$$A^{RL}_{\mathrm{CG}} = -\frac{G_F Q^2}{2\sqrt{2}\pi\alpha}\frac{9}{10}\left[\left(1 - \frac{20}{9}\sin^2\theta_W\right) + \left(1 - 4\sin^2\theta_W\right)\frac{1-(1-y)^2}{1+(1-y)^2}\right]$$

All hadronic effects cancel!

Clean probe of WNC

- e-D asymmetry allows a precision measurement of the weak mixing angle.

Status of WNC Couplings



arXiv:2209.13357, SoLID White Paper

FIG. 13. Adapted from Ref. [63]: Current experimental knowledge of the couplings g_{VA}^{eq} (vertical axis). The latest world data constraint (red ellipse) is provided by combining the 6 GeV Qweak [51] on g_{AV}^{eq} (yellow vertical band) and the JLab 6 GeV PVDIS [53, 54] experiments (grey ellipse). The SoLID projected result is shown as the cyan ellipse. Also shown are expected results from P2 (purple and pink vertical bands) and the combined projection using SoLID, P2, and all existing world data (magenta ellipse), centered at the current best fit values.

- The combination $2C_{1u} - C_{1d}$ is severely constrained by Qweak and Atomic Parity violation.
- The combination $2C_{2u} - C_{2d}$ is known to within ~50% from the JLAB 6 GeV experiment:

$$2C_{2u} - C_{2d} = -0.145 \pm 0.068$$

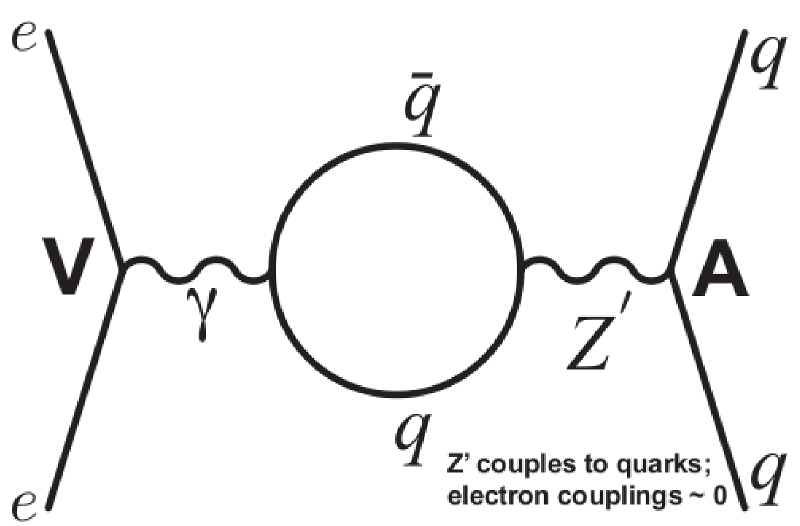
- SOLID is expected significantly improve on this result.

BSM Physics Scenarios

Leptophobic Z'

- Leptophobic Z's are an interesting BSM scenario since they only shifts the C_{2q} couplings in A_{PV}

- Leptophobic Z's only affect the b(x) term or the C_{2q} coefficients in A_{PV}:



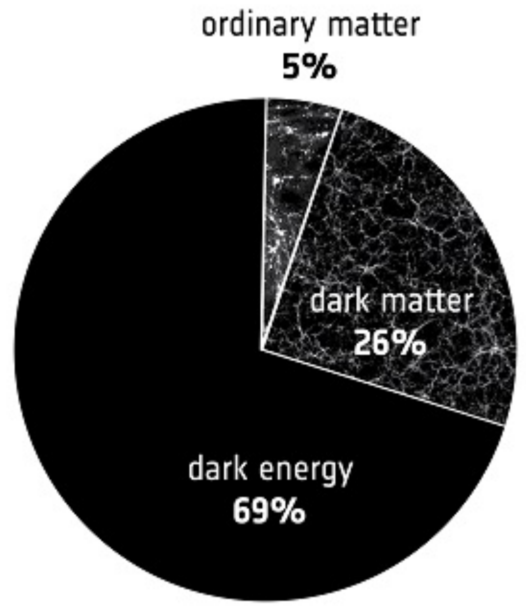
Leptophobic Z' contributes only to the C_{2q} couplings!

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

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

Probing the Dark Sector

- Strong evidence for dark matter through gravitational effects:
  - Galactic Rotation Curves
  - Gravitational Lensing
  - Cosmic Microwave Background
  - Large Scale Structure Surveys



- WIMP dark matter paradigm
  - Mass ~ TeV
  - Weak interaction strength couplings
  - Gives the required relic abundance

- However, so far no direct evidence for WIMP dark matter

- Perhaps dark sector has a rich structure including different species and gauge forces, just like the visible sector

Dark Photon Scenario

- Dark $U(1)_d$ gauge group
- Interacts with SM via kinetic mixing (and mass mixing)

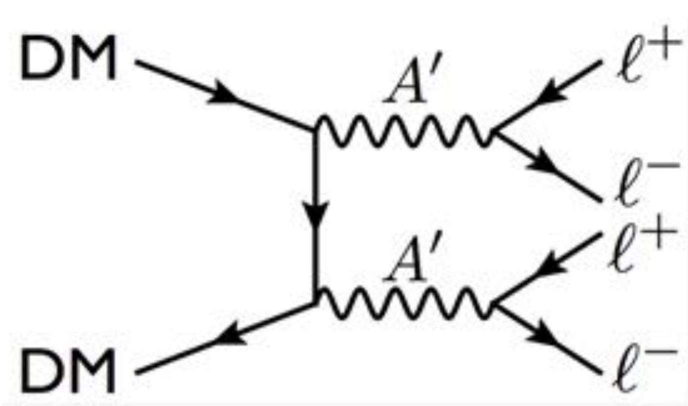
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m^2_{A'}}{2}A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$

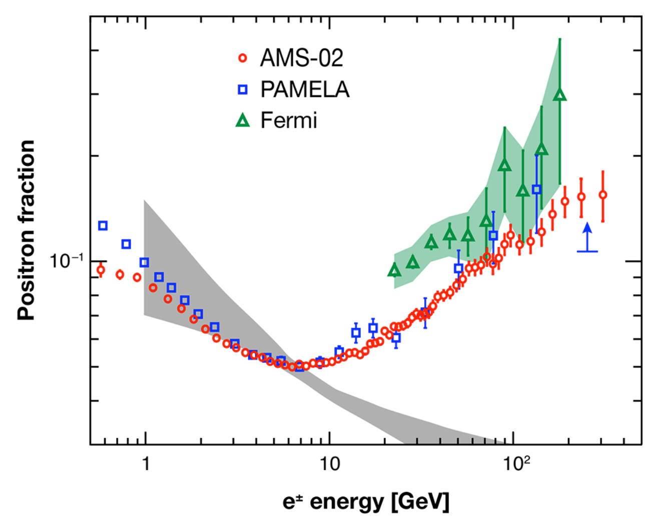
- The mixing induces a coupling of the dark photon to the electromagnetic and weak neutral currents.

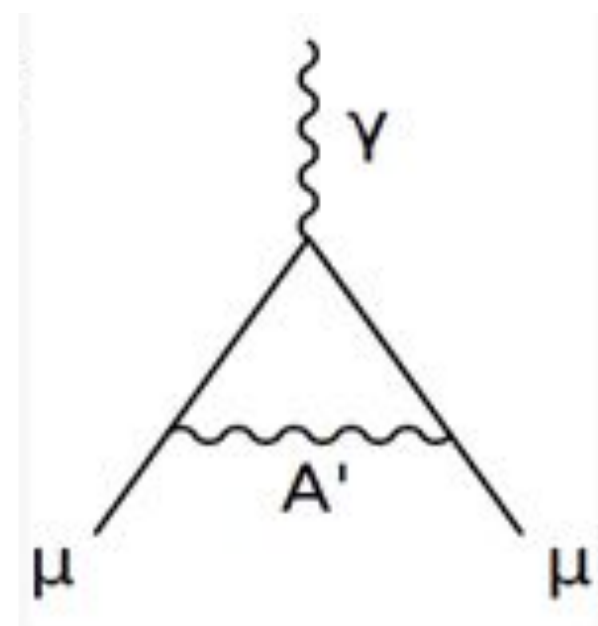
$$\mathscr{L}_{int} = -e\epsilon J^\mu_{em} A'_\mu$$

- Could help explain astrophysical data and anomalies

[Arkani-Hamed, Finkbeiner, Slatyer, Wiener, …]

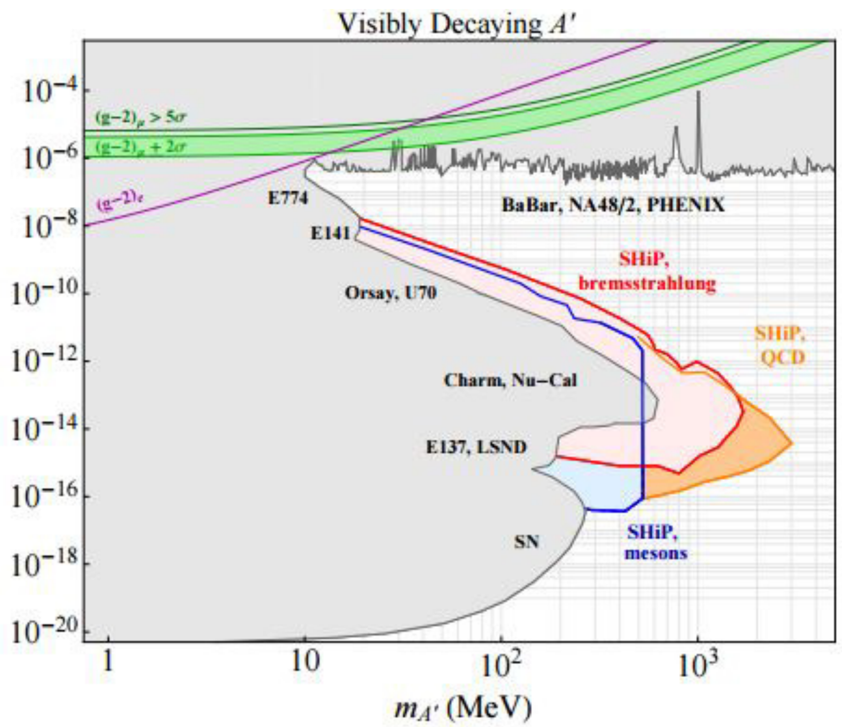




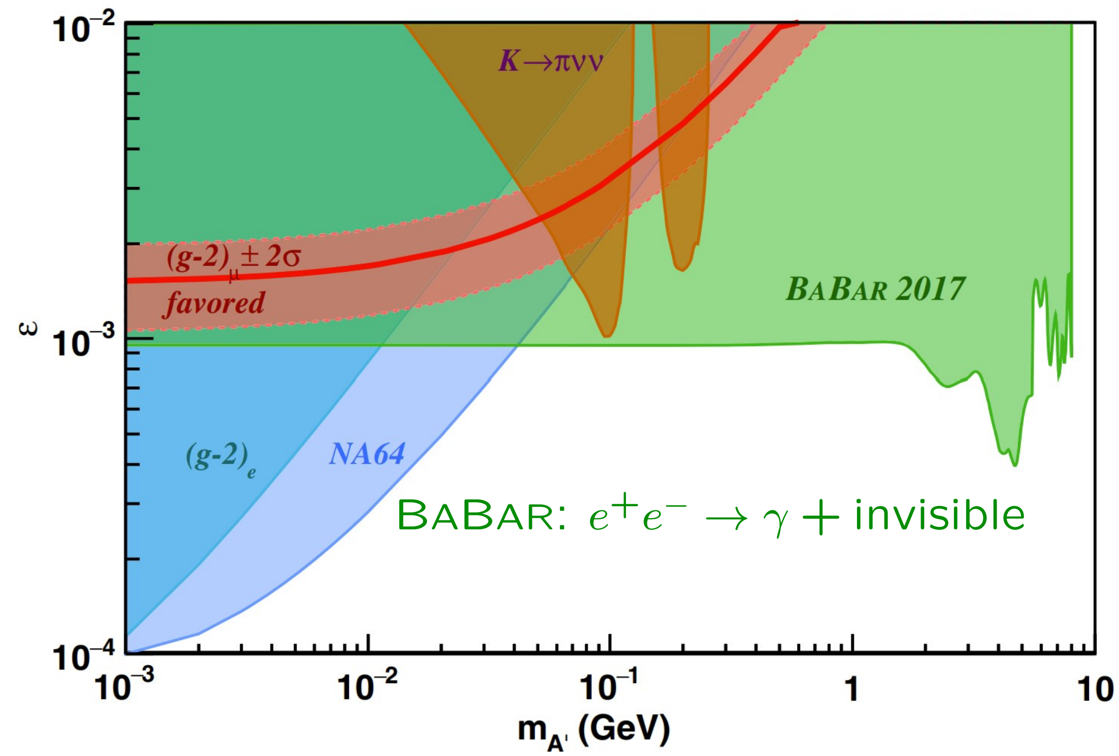


Dark Photon Scenario

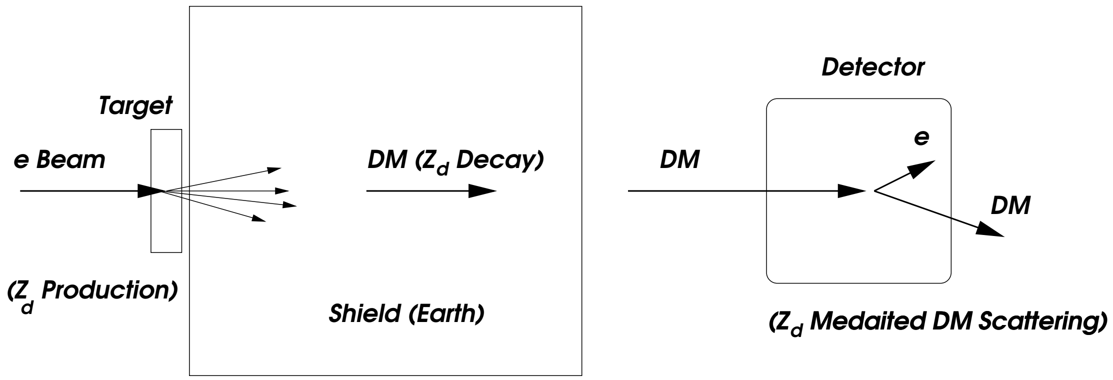
- Active experimental program to search for dark photons
[Bjorken, Essig, Schuster, Toro; Baten, Pospelov, Ritz; Izaguirre Krnjaic, Schuster, Toro]



S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]



- Beam Dump Experiments:



[Bjorken, Essig, Schuster, Toro]

Dark Photon Scenario: Impact on PVES

[Thomas, Wang, Williams]

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

- Constraints on Dark Photon parameter space will be independent of the details of the decay branching fractions of the dark photon

- For a light dark photon, the induced coupling to the weak neutral coupling is suppressed (due to a cancellation between the kinetic and mass mixing induced couplings). [Gopalakrishna, Jung, Wells; Davoudiasl, Lee, Marciano]

- Thus, we consider a heavier dark photon for a sizable coupling to the weak neutral current and a correspondingly sizable effect in PVES. [Thomas, Wang, Williams]

Dark Photon Scenario: Impact on PVES

[Thomas, Wang, Williams]

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

- Constraints on Dark Photon parameter space will be independent of the details of the decay branching fractions of the dark photon

- The usual PVDIS asymmetry has the form:

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

- Including the effects of a dark photon, we get additional terms:

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

Dark Photon Scenario: Impact on PVES

- Equivalent to working with the usual PVDIS formula:

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

- But with shifted C_{iq} couplings:

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

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

[Thomas, Wang, Williams]

Dark Photon Scenario: Shift in C_{1q} (PREX)

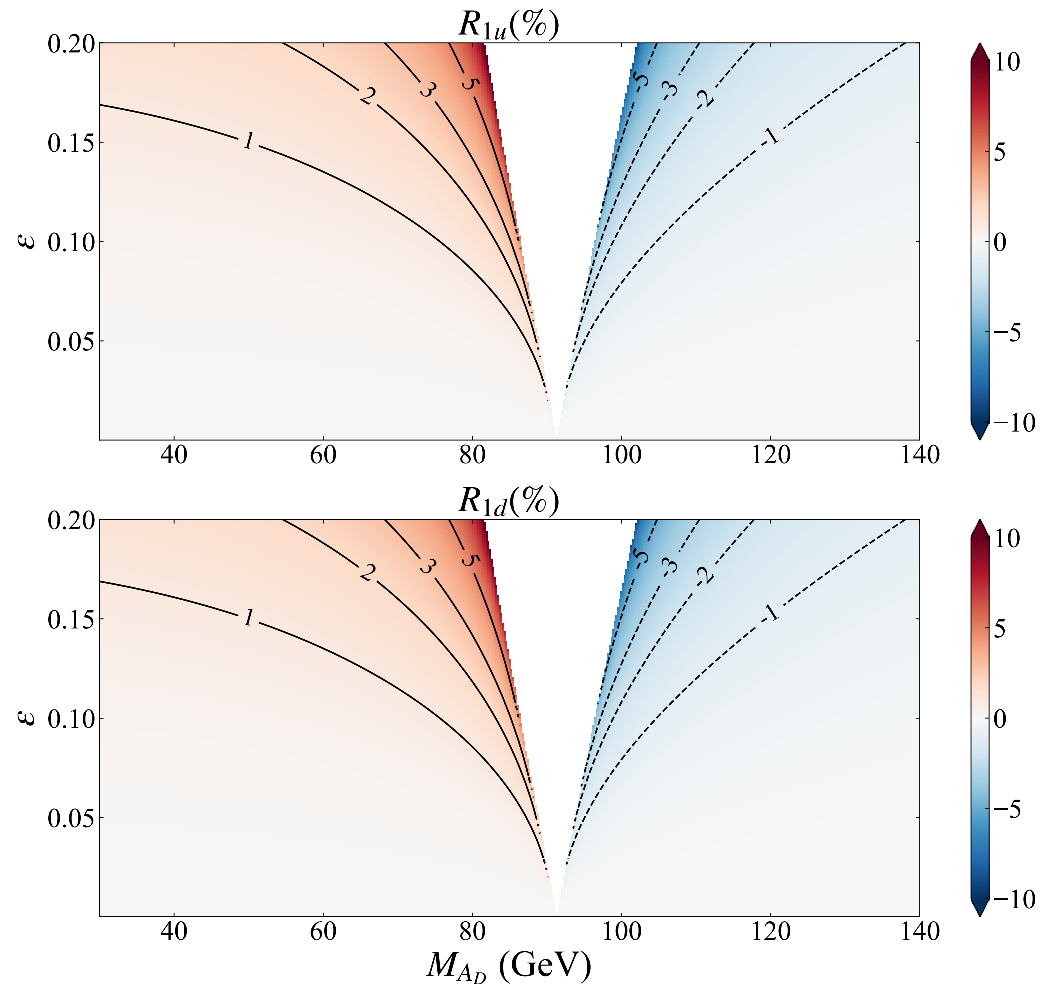


FIG. 1. The correction factors R_{1u} and R_{1d} at $Q^2 = 0.00616\ \mathrm{GeV}^2$, appropriate to the PREX-II experiment. The gap on the $\epsilon - M$ plane is not accessible because of "eigenmass repulsion" associated with the Z mass.

$$Q_W^p = -2\left[C_{1u}(2Z+N) + C_{1d}(Z+2N)\right]$$

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

[Thomas, Wang, Williams]

Dark Photon Scenario: Shift in C_{iq} (PVDIS, HERA)

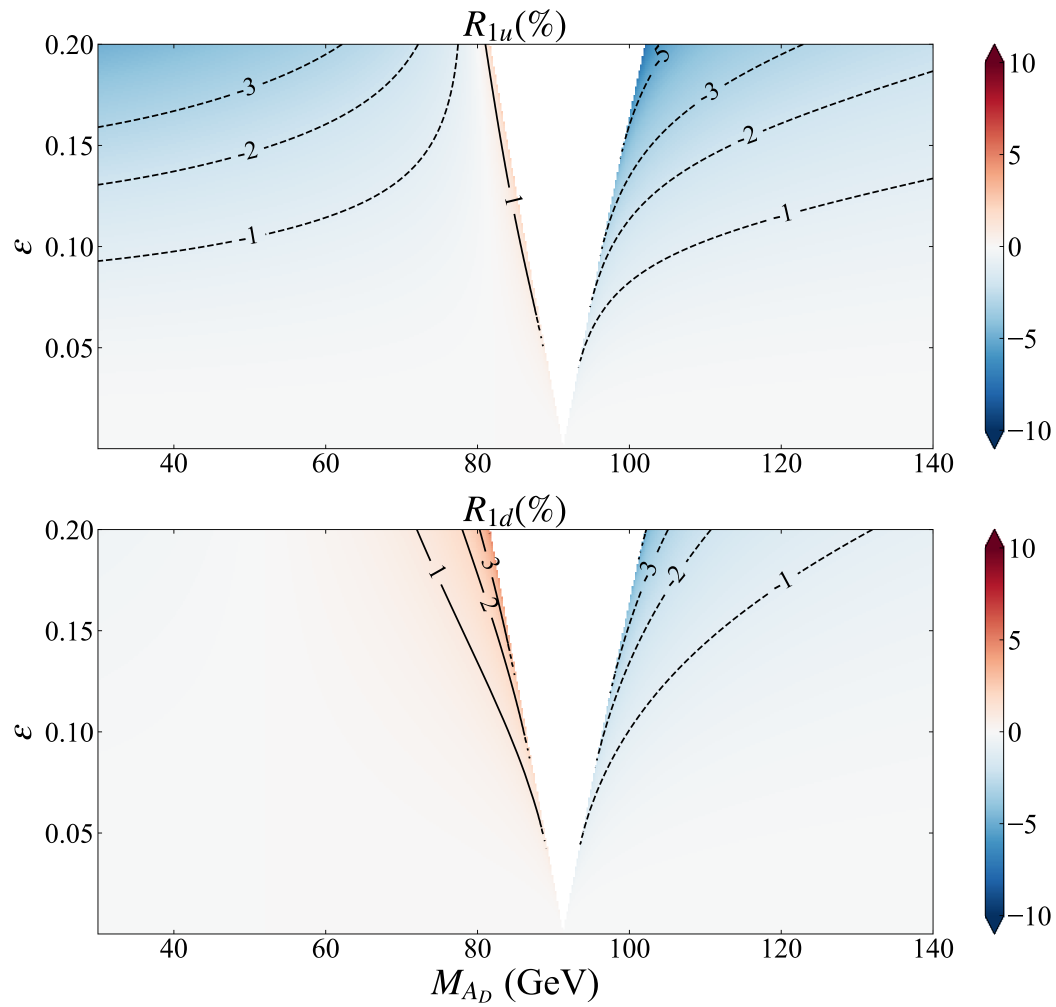


FIG. 2. The correction factors R_{1u} and R_{1d} at $Q^2 = M_Z^2$.

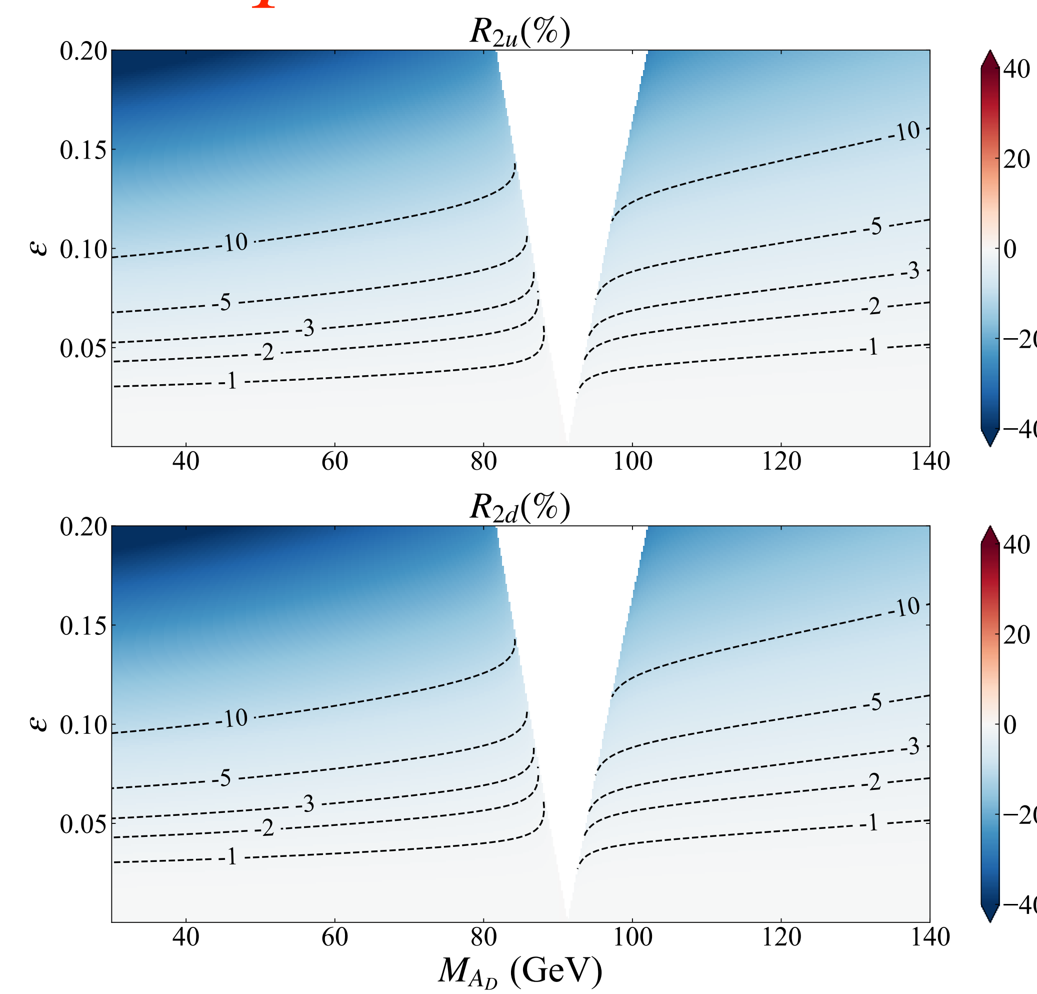


FIG. 3. The correction factors R_{2u} and R_{2d} at $Q^2 = M_Z^2$.

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

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

Dark Photon Scenario: Shift in C_{iq} (PVDIS)

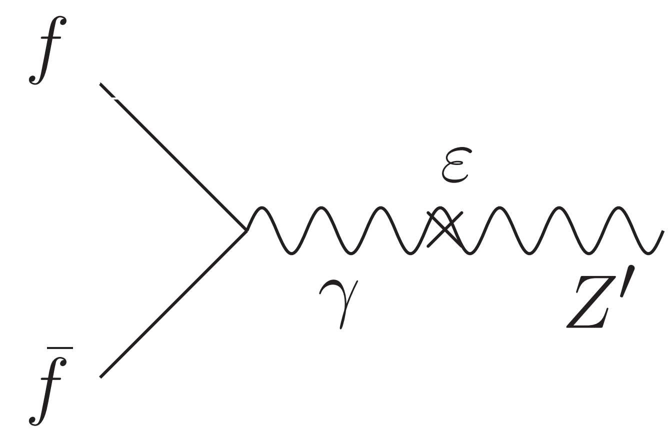
Qualitatively different behavior in shifts to C_{iq} for different Q^2

Useful to explore dark-photon space over a wide range of Q^2

Light Dark-Z Parity Violation

[Davoudiasl, Lee, Marciano]

- An interesting scenario is that of a "light" Dark-Z.



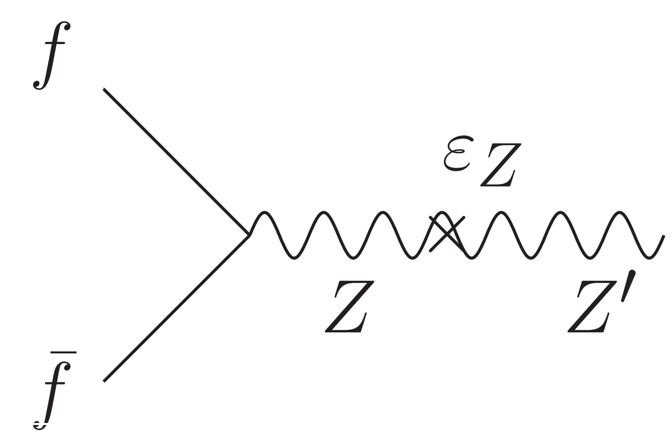
- The standard kinetic mixing scenario:

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

- And additional mass mixing (for example, from extended Higgs sector) to induce sizable dark-Z coupling to the weak neutral current:

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

$$\varepsilon_Z = \frac{m_{Z_d}}{m_Z}\delta$$



- Dark-Z couples to the electromagnetic and neutral current coupling:

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

Light Dark-Z Parity Violation

[Davoudiasl, Lee, Marciano]

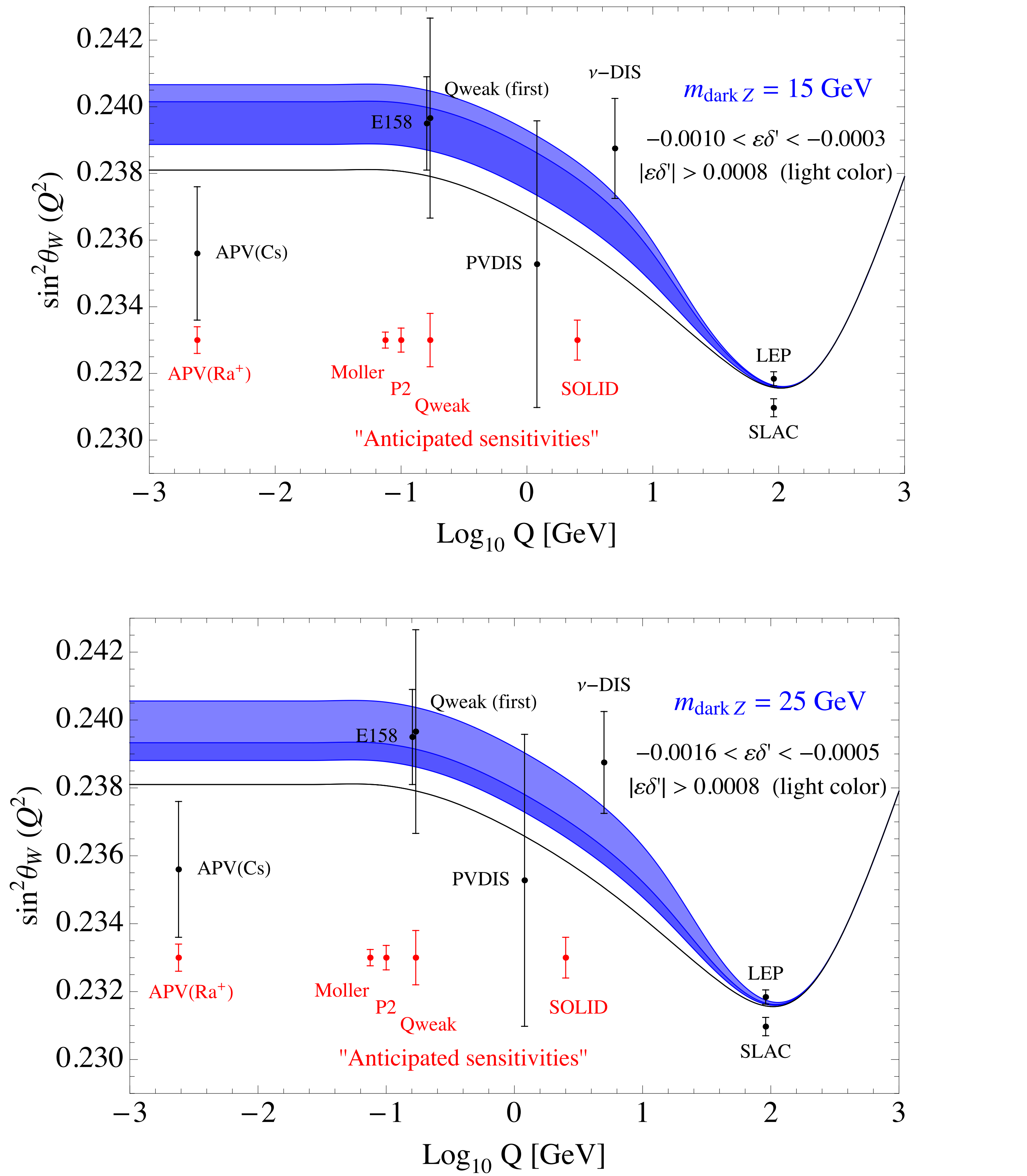
- Effective change in presence of dark-Z for parity violating asymmetries:

$$G_F \to \rho_d G_F$$

$$\sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

$$\rho_d = 1 + \delta^2 \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$

$$\kappa_d = 1 - \frac{\varepsilon}{\varepsilon_Z}\delta^2 \frac{\cos\theta_W}{\sin\theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$



SMEFT Analysis

Standard Model Effective Theory (SMEFT) Operator Basis

[Boughezal, Petriello, Wiegand]

- The SMEFT basis often used in global fit analysis to constrain new physics beyond the electroweak scale:

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

- Relevant SMEFT operators for DIS processes at dim-6 and dim-8

Dimension 6		Dimension 8	
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)\,(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{l^2q^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{q}\gamma_\mu q)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^i l)\,(\bar{q}\gamma_\mu \tau^i q)$	$\mathcal{O}_{l^2q^2D^2}^{(3)}$	$D^\nu\,(\bar{l}\gamma^\mu \tau^i l)\,D_\nu\,(\bar{q}\gamma_\mu \tau^i q)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)\,(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{e^2u^2D^2}^{(1)}$	$D^\nu\,(\bar{e}\gamma^\mu e)\,D_\nu\,(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)\,(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{e^2d^2D^2}^{(1)}$	$D^\nu\,(\bar{e}\gamma^\mu e)\,D_\nu\,(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{lu}$	$(\bar{l}\gamma^\mu l)\,(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{l^2u^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{ld}$	$(\bar{l}\gamma^\mu l)\,(\bar{d}\gamma_\mu d)$	$\mathcal{O}_{l^2d^2D^2}^{(1)}$	$D^\nu\,(\bar{l}\gamma^\mu l)\,D_\nu\,(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)\,(\bar{e}\gamma_\mu e)$	$\mathcal{O}_{q^2e^2D^2}^{(1)}$	$D^\nu\,(\bar{q}\gamma^\mu q)\,D_\nu\,(\bar{e}\gamma_\mu e)$

SMEFT vs C_{iq} Basis

[Boughezal, Petriello, Wiegand]

- For low energy experiments, typically the C_{iq} basis of operators based on V-A structure after EWSB is used:

$$\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}}\Big[(\bar{e}\gamma^\mu\gamma_5 e)(C^6_{1u}\bar{u}\gamma_\mu u + C^6_{1d}\bar{d}\gamma_\mu d) + (\bar{e}\gamma^\mu e)(C^6_{2u}\bar{u}\gamma_\mu\gamma_5 u + C^6_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$
$$+ (\bar{e}\gamma^\mu e)(C^6_{Vu}\bar{u}\gamma_\mu u + C^6_{Vd}\bar{d}\gamma_\mu d) + (\bar{e}\gamma^\mu\gamma_5 e)(C^6_{Au}\bar{u}\gamma_\mu\gamma_5 u)$$
$$+ D^\nu\left(\bar{e}\gamma^\mu\gamma_5 e\right)D_\nu\left(\frac{C^8_{1u}}{v^2}\bar{u}\gamma_\mu u + \frac{C^8_{1d}}{v^2}\bar{d}\gamma_\mu d\right) + D^\nu\left(\bar{e}\gamma^\mu e\right)D_\nu\left(\frac{C^8_{2u}}{v^2}\bar{u}\gamma_\mu\gamma_5 u + \frac{C^8_{2d}}{v^2}\bar{d}\gamma_\mu\gamma_5 d\right)$$
$$+ D^\nu\left(\bar{e}\gamma^\mu e\right)D_\nu\left(\frac{C^8_{Vu}}{v^2}\bar{u}\gamma_\mu u + \frac{C^8_{Vd}}{v^2}\bar{d}\gamma_\mu d\right) + D^\nu\left(\bar{e}\gamma^\mu\gamma_5 e\right)D_\nu\left(\frac{C^8_{Au}}{v^2}\bar{u}\gamma_\mu\gamma_5 u\right)\Big].$$

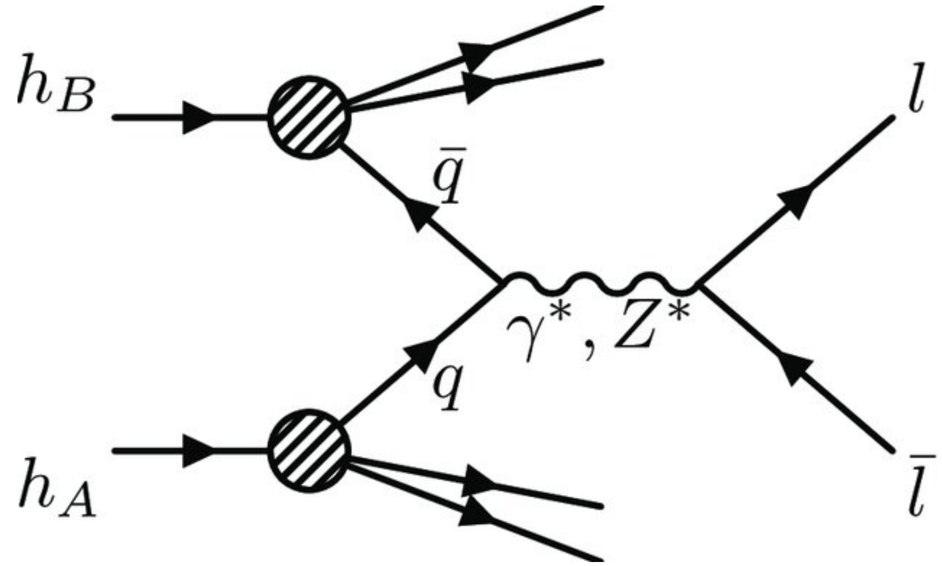
- One can find relations between the two bases:

$$C^6_{1u} = 2(g^e_R - g^e_L)(g^u_R + g^u_L) + \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} + C_{qe} - C_{lu}\right\}$$
$$C^6_{2u} = 2(g^e_R + g^e_L)(g^u_R - g^u_L) + \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} - C_{qe} + C_{lu}\right\}$$
$$C^6_{1d} = 2(g^e_R - g^e_L)(g^d_R + g^d_L) + \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} + C_{qe} - C_{ld}\right\}$$
$$C^6_{2d} = 2(g^e_R + g^e_L)(g^d_R - g^d_L) + \frac{v^2}{2\Lambda^2}\left\{-\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} - C_{qe} + C_{ld}\right\}$$
$$C^6_{Vu} = 2(g^e_R + g^e_L)(g^u_R + g^u_L) + \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} + C_{qe} + C_{lu}\right\}$$
$$C^6_{Au} = 2(g^e_R - g^e_L)(g^u_R - g^u_L) + \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} - C^{(3)}_{lq}\right) + C_{eu} - C_{qe} - C_{lu}\right\}$$
$$C^6_{Vd} = 2(g^e_R + g^e_L)(g^d_R + g^d_L) + \frac{v^2}{2\Lambda^2}\left\{\left(C^{(1)}_{lq} + C^{(3)}_{lq}\right) + C_{ed} + C_{qe} + C_{ld}\right\}.$$

SMEFT Constraints from Drell-Yan at LHC

[Boughezal, Petriello, Wiegand]

- The SMEFT Wilson coefficients that affect PVES also contribute to the Drell-Yan process at the LHC

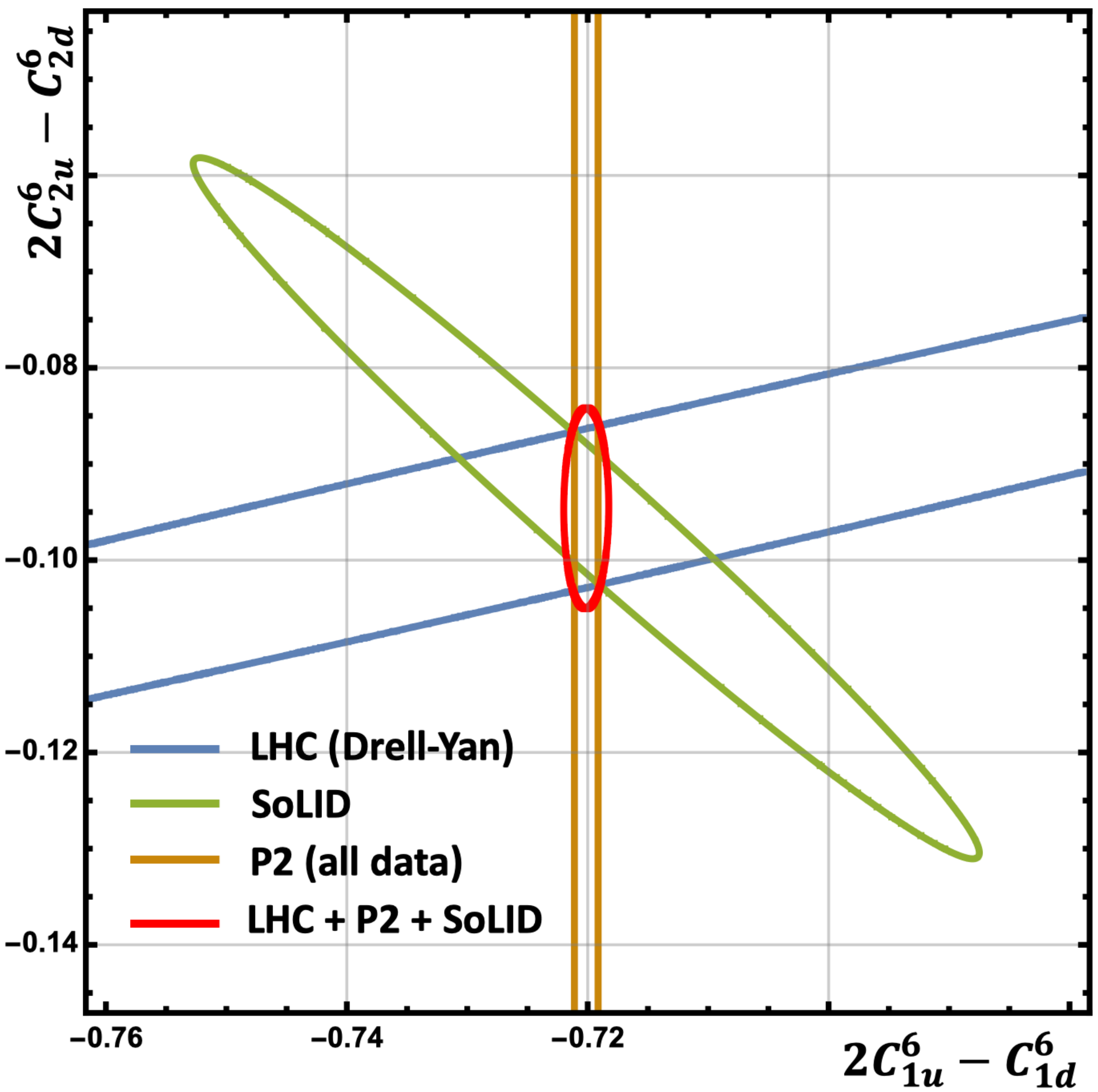


$$\frac{d\sigma_{q\bar{q}}}{dm_{ll}^2 dY dc_\theta} = \frac{1}{32\pi m_{ll}^2 \hat{s}} f_q(x_1) f_{\bar{q}}(x_2) \left\{ \frac{d\hat{\sigma}_{q\bar{q}}^{\gamma\gamma}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{\gamma Z}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{ZZ}}{dm_{ll}^2 dY dc_\theta} \right.$$
$$\left. + \frac{d\hat{\sigma}_{q\bar{q}}^{\gamma SMEFT6}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{ZSMEFT6}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{\gamma SMEFT8}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{ZSMEFT8}}{dm_{ll}^2 dY dc_\theta} + \frac{d\hat{\sigma}_{q\bar{q}}^{SMEFT6^2}}{dm_{ll}^2 dY dc_\theta} \right\}$$

- PVES and the LHC can be complementary to each other in constraining new physics

Lifting Flat Directions

[Boughezal, Petriello, Wiegand]

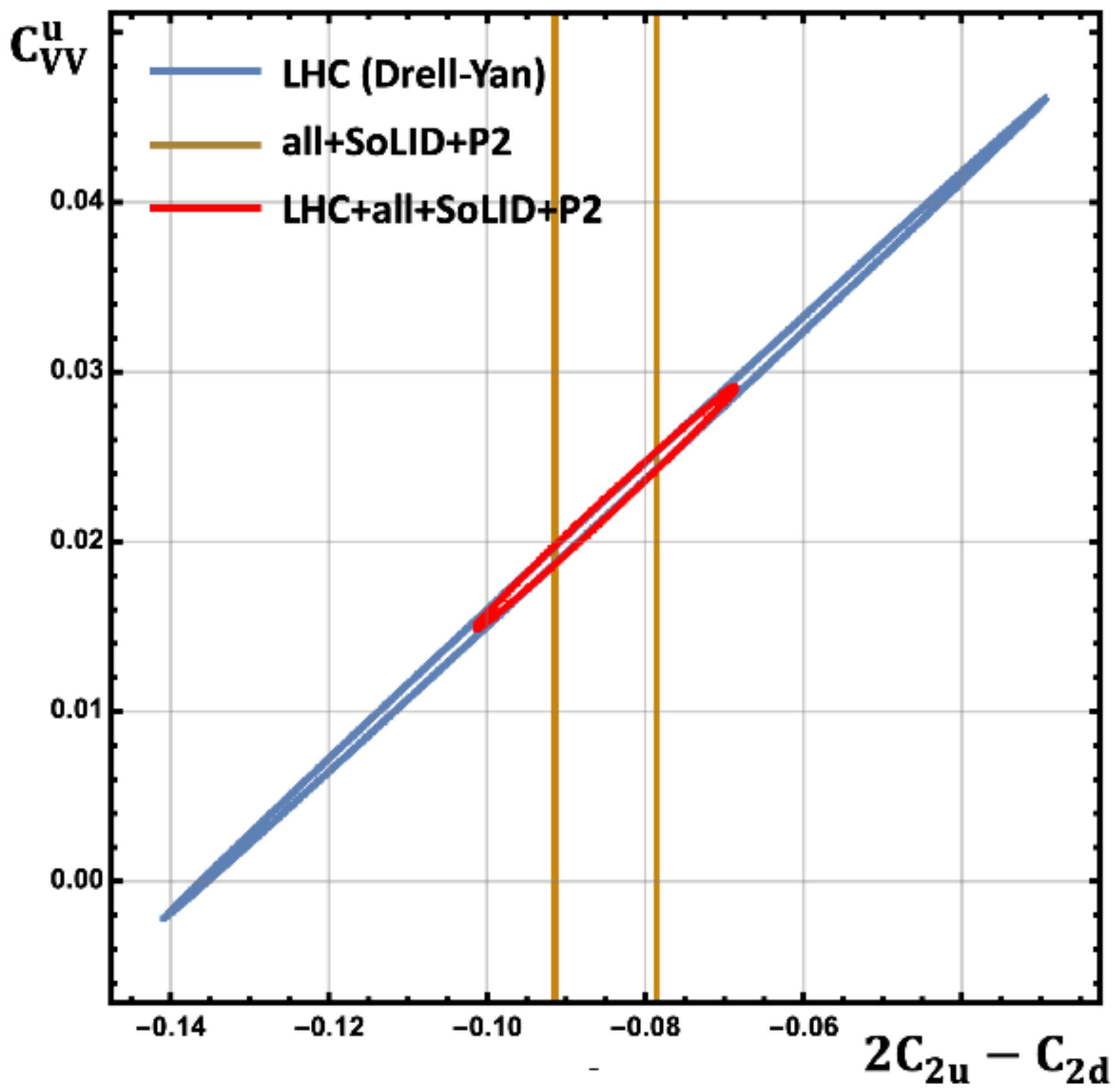


- PVES and Drell-Yan at the LHC are sensitive to different combinations of the SMEFT Wilson coefficients.

- PVES can lift "flat directions" by probing orthogonal directions in the SMEFT parameter space compared to the LHC

Lifting Flat Directions

[Boughezal, Petriello, Wiegand]

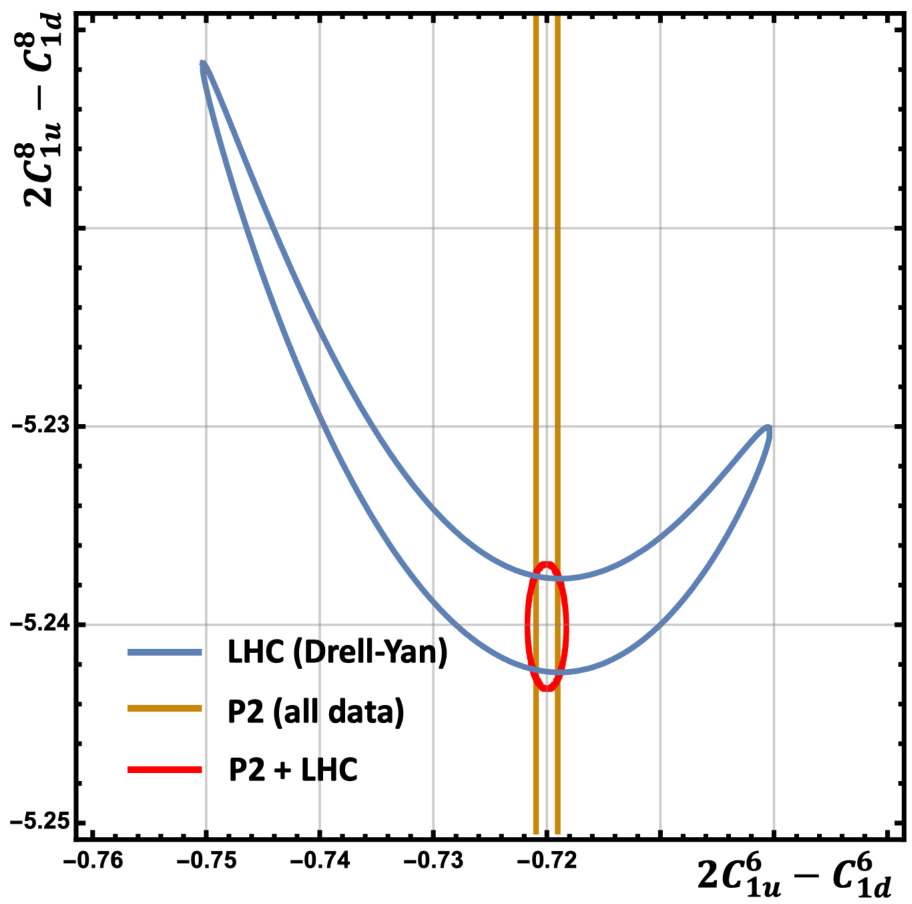


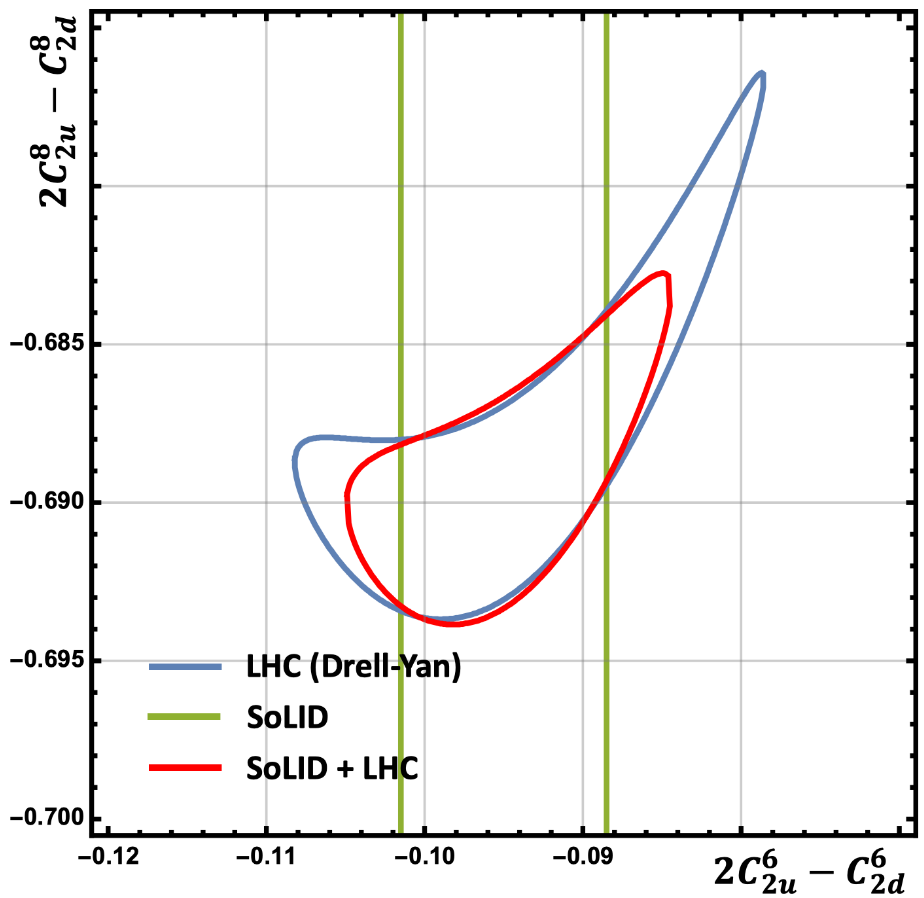
- An example of SOLID probing a unique direction in parameter space. Neither the LHC, Qweak, P2, or APV have sensitivity in this region

- This requires that $2C_{1u} - C_{1d}$ is assumed to be know from the P2 experiment so that the SOLID then directly measures $2C_{2u} - C_{2d}$

Disentangling Dim-6 and Dim-8 SMEFT Operators

[Boughezal, Petriello, Wiegand]





- Another advantage of low energy PVES experiments:

The large energy of the LHC can make it difficult to disentangle the effects of dim-6 or dim-8 (and dim-6 squared) operators.

Low energy PVES will only have sensitivity to dim-6 operators providing valuable input to disentangle dim-6 vs dim-8.

Hadronic Effects

Corrections to Cahn-Gilman

- Hadronic effects appear as corrections to the Cahn-Gilman formula:

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

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

New physics

Sea quarks

Charge symmetry violation

Target mass

Higher twist

- Hadronic effects must be well understood before any claim for evidence of new physics can be made.

[Bjorken, Wolfenstein; Hobbs, Melnitchouk;
SM, Ramsey-Musolf, Sacco;
Belitsky, Mashanov, Schafer;
Seng, Ramsey-Musolf, ….]

Some Definitions and Notation

- Asymmetry can be brought into the form:

$$A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

- The Y_1 factor has the form:

$$Y_1 = \left(\frac{1+R^{\gamma Z}}{1+R^{\gamma}}\right) \frac{1+(1-y)^2 - y^2\left[1 - r^2/(1+R^{\gamma Z})\right] - 2xyM/E}{1+(1-y)^2 - y^2\left[1 - r^2/(1+R^{\gamma})\right] - 2xyM/E}$$

- The Y_3 factor has the form:

$$Y_3 = \left(\frac{r^2}{1+R^{\gamma}}\right) \frac{1-(1-y)^2}{1+(1-y)^2 - y^2\left[1 - r^2/(1+R^{\gamma})\right] - 2xyM/E}$$

- We have used the definitions:

$$R^{\gamma(\gamma Z)} \equiv \frac{\sigma_L^{\gamma(\gamma Z)}}{\sigma_T^{\gamma(\gamma Z)}} = r^2 \frac{F_2^{\gamma(\gamma Z)}}{2xF_1^{\gamma(\gamma Z)}} - 1, \qquad r^2 = 1 + \frac{4M^2x^2}{Q^2}$$

Key features of the Asymmetry Terms

- Asymmetry can be brought into the form:

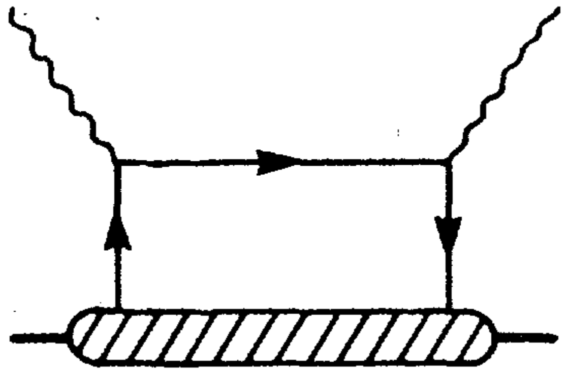
$$A_{RL} = -\left(\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\right)\left[g_A^e Y_1 \frac{F_1^{\gamma Z}}{F_1^{\gamma}} + g_V^e Y_3 \frac{F_3^{\gamma Z}}{F_1^{\gamma}}\right]$$

- Dominant term in asymmetry
- Can in principle be kinematically distinguished from second term (independent of y)
- Can be sensitive to only quark-quark correlations
- A single twist-4 matrix element determines quark-quark correlations.

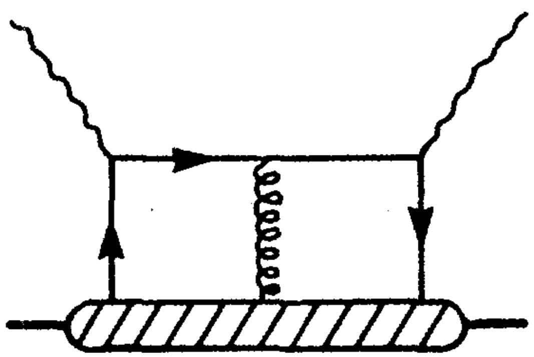
[Bjorken, Wolfenstein; SM, Ramsey-Musolf, Sacco]

- suppressed by small electron vector coupling
- Can be kinematically distinguished from second term(dependent on y)
- Can be sensitive to quark-quark and quark-gluon correlations
- Multiple twist-4 matrix elements determine correlations
- Can be extracted from neutrino scattering data

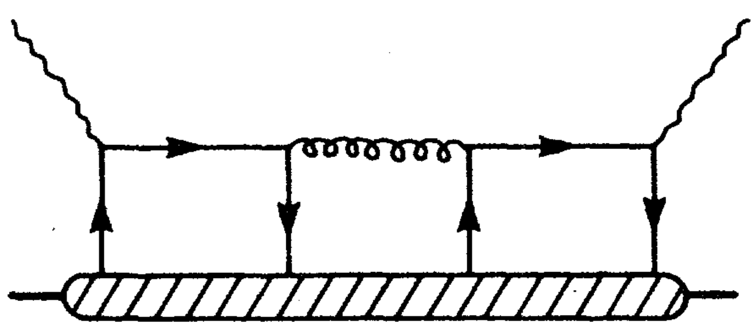
Operator Product Expansion



Twist-2



Quark-gluon correlation (Twist-2 + Twist-4)

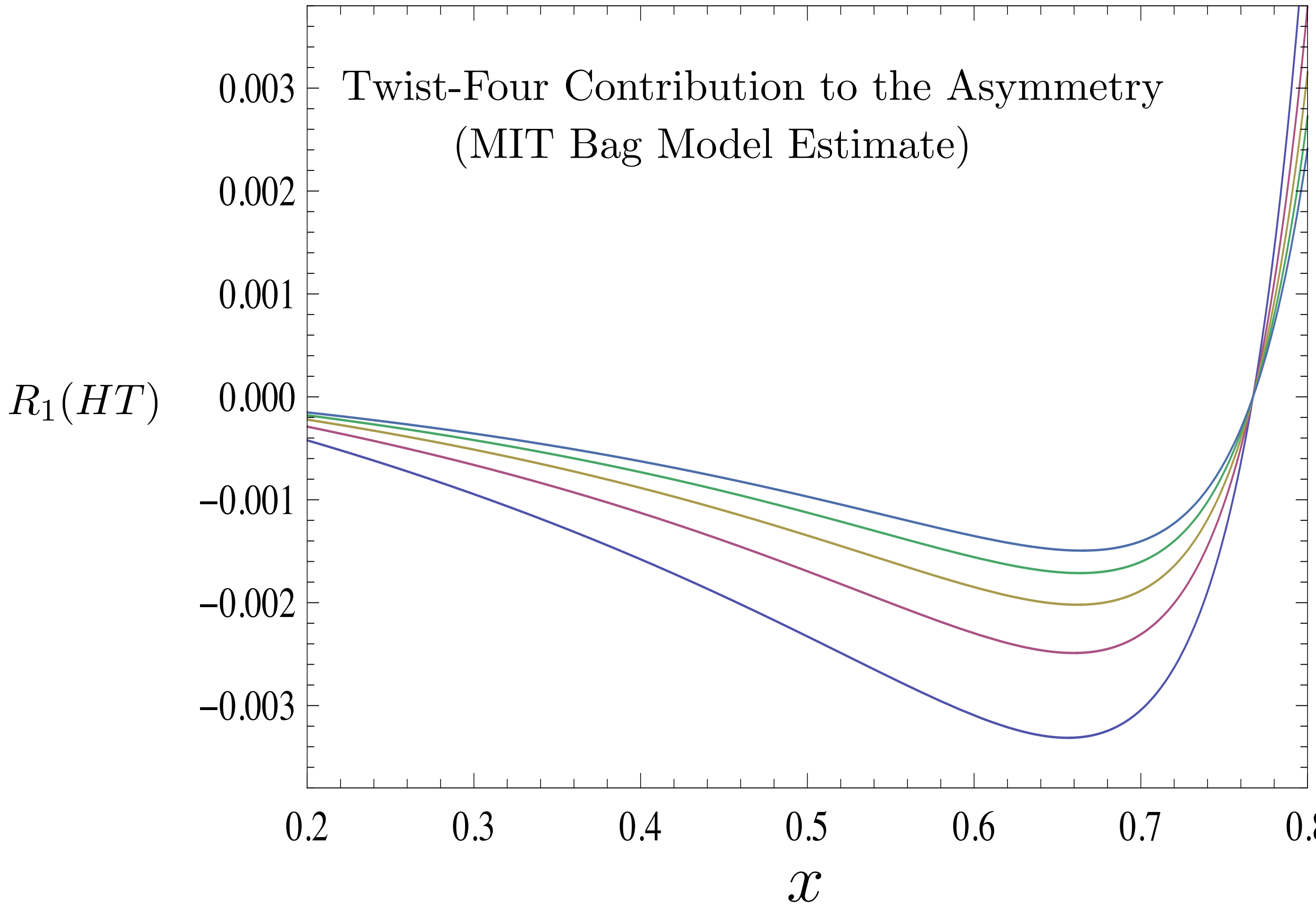


Quark-quark correlation(Twist-4)

$$\mathcal{O}^{\mu\nu}_{ud}(x) = \frac{1}{2}[\bar{u}(x)\gamma^{\mu}u(x)d(0)\gamma^{\nu}d(0) + (u \leftrightarrow d)]$$

Form of twist-4 correction

[SM, Ramsey-Musolf, Sacco]



$$R_1(\mathrm{HT}) \; = \left[\frac{-4}{5(1-\frac{20}{9}\sin^2\theta_W)}\right]\frac{F_1^{du}}{u_p(x)+d_p(x)}.$$

- Bag model estimate of quark-quark correlation is below the half-percent level.

- If the Bag Model estimate is accurate, then higher twist effect is small and becomes difficult to extract.

Charge Symmetry Violation (CSV)

[Hobbs,Melnitchouk]

- Parameterization of CSV effects:

$$\begin{aligned} u_p &= u + \frac{\delta u}{2} \\ d_p &= d + \frac{\delta d}{2} \\ u_n &= d - \frac{\delta d}{2} \\ d_n &= u - \frac{\delta u}{2} \end{aligned}$$

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

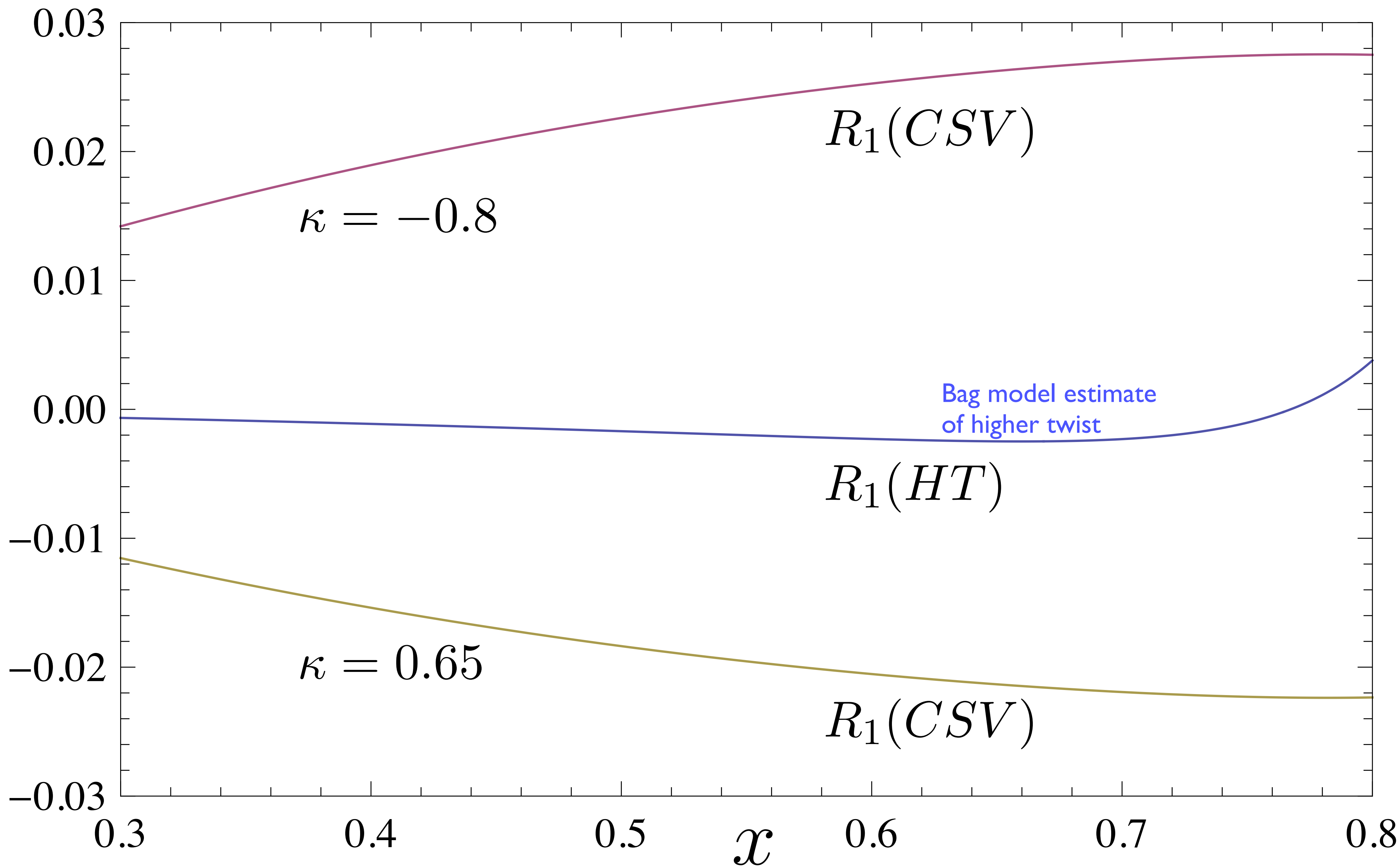
- Phenomenological model of CSV effects:

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

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

CSV vs Higher Twist

[SM, Ramsey-Musolf, Sacco]



- These estimates indicate that HT effects may be small compared to CSV effects.

SoLID Projection Analysis $\sin^2\theta_W$ Extraction

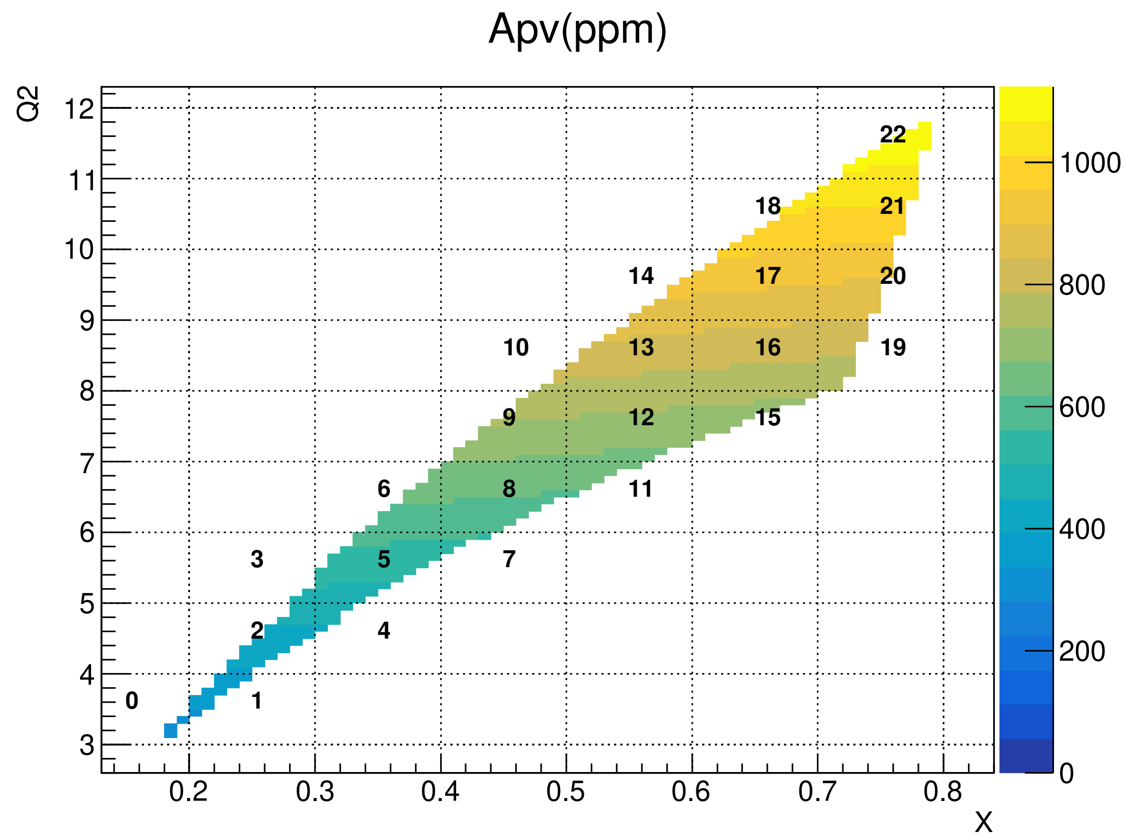


FIG. 11. Illustration of PVDIS asymmetry on a deuteron target in ppm on the (x, Q^2) plane. The data are divided into evenly spaced grid with the bin number shown. The expected statistical uncertainty is less than 1% in most of the bins.

arXiv:2209.13357, SoLID White Paper

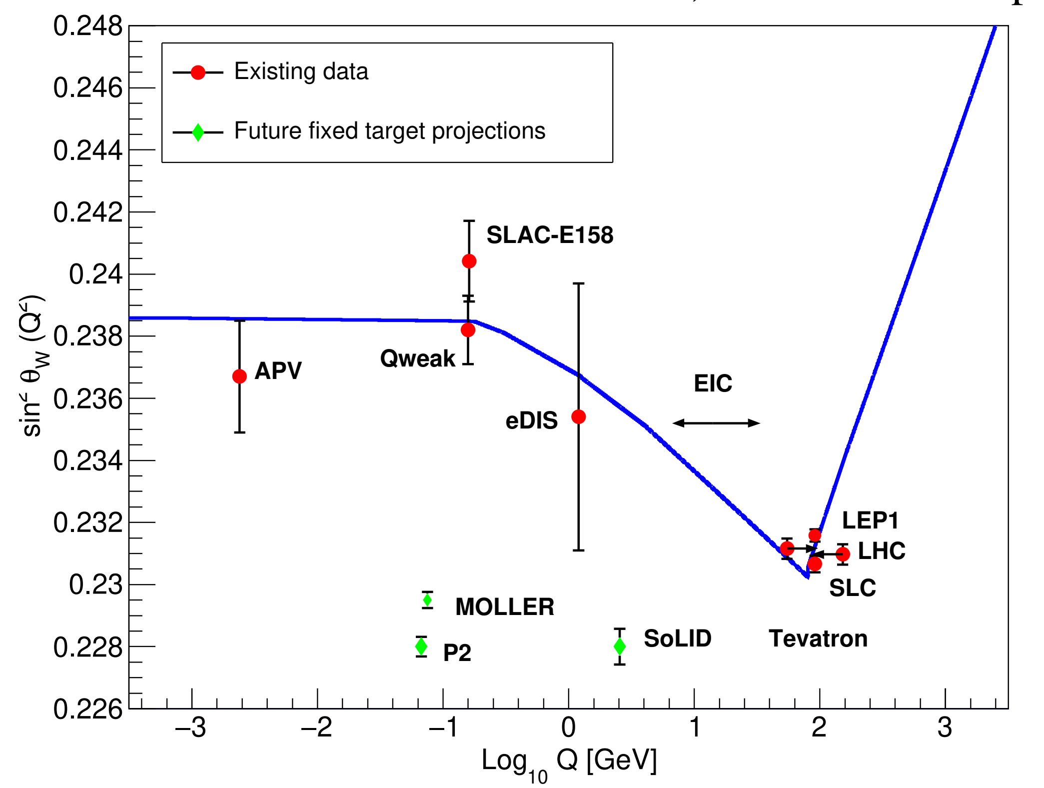


FIG. 12. Experimental determination of the weak mixing angle $\sin^2\theta_W$. Data points for Tevatron and LHC are shifted horizontally for clarity.

$$A_{PV}^{\mathrm{data}} = A_{PV,(d)}^{\mathrm{SM}}\left(1 + \frac{\beta_{\mathrm{HT}}}{(1-x)^3 Q^2} + \beta_{\mathrm{CSV}} x^2\right)$$

[Emmert, Nycz, Zheng]

Uncertainty Contributions to A_{PV}

- Statistical uncertainty

$$dA_{PV}^{\mathrm{stat}} = \frac{1}{P_e\sqrt{n_b}} = \sigma_{\mathrm{stat},b}$$

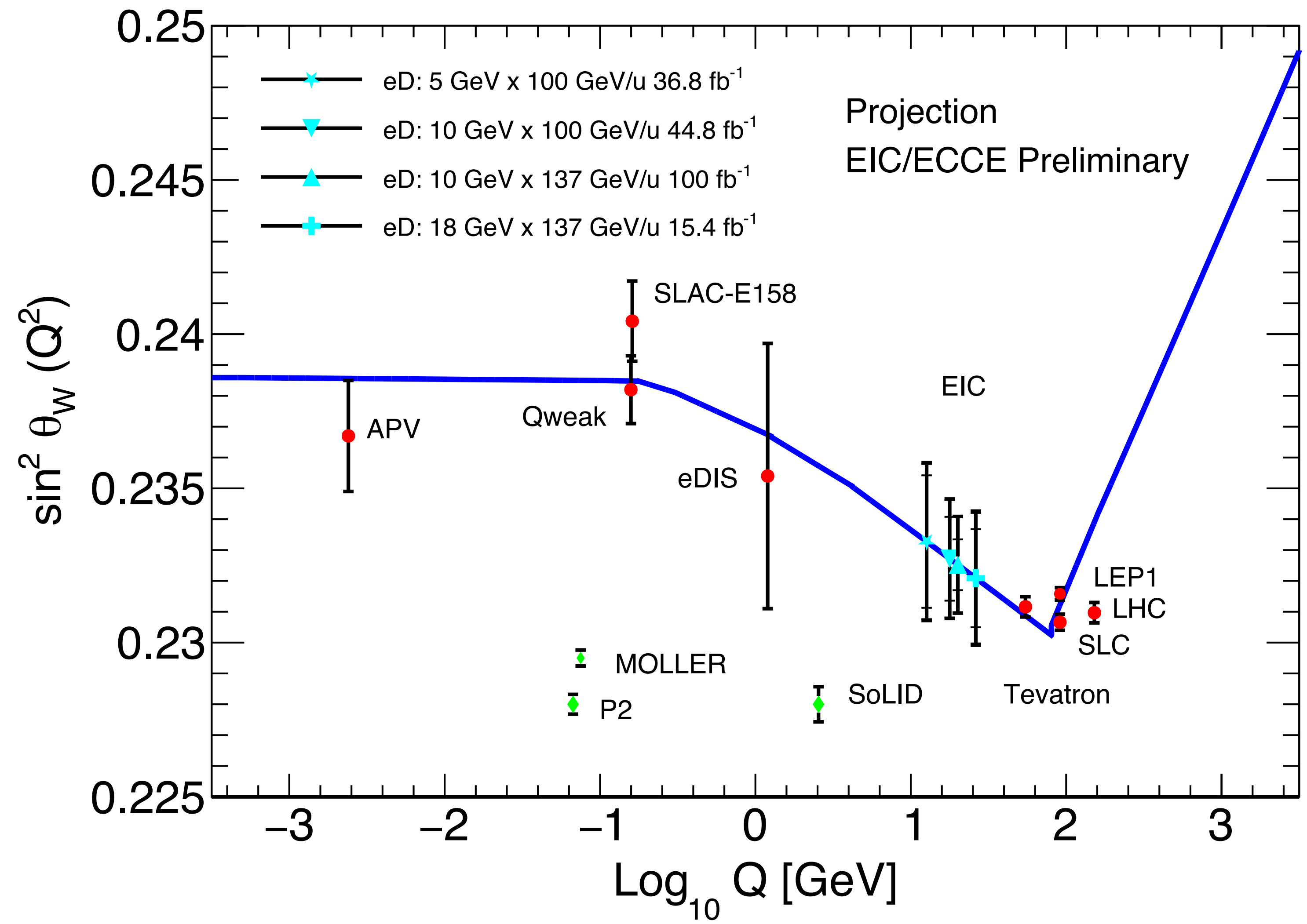
with $P_e = 0.8$ and bin event count n_b computed from rates for **120 days** of run time

- Experimental systematic uncertainties

Source	Relative Uncertainty dA/A
Beam polarization	0.4%
Q^2 determination	0.2%
Event reconstruction	0.2%
Radiative correction	0.2%

Completely correlated ($\sigma_{\mathrm{corr}}/A = 0.45\%$)
Uncorrelated ($\sigma_{\mathrm{uncorr}}/A = 0.28\%$)

Extraction of the Weak Mixing Angle



[Boughezal, Emmert, Kutz, SM, Nycz,Petriello, Simsek,Wiegand, Zheng]

- SoLID can extract the weak mixing angle with higher precision than the EIC.

Extraction of the Weak Mixing Angle

- PVDIS asymmetry with a proton target (ignoring sea quarks):

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

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

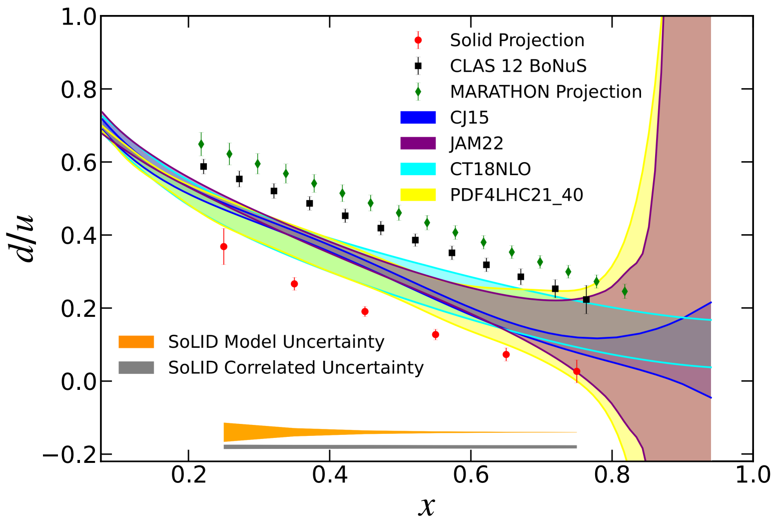


FIG. 14. Projected results on the PDF ratio d/u from the PVDIS proton measurement (red points) compared with the current world fits from a number of PDF groups and their uncertainties. The error bars of the SoLID projection indicate the uncertainty in the extracted d/u from statistical uncertainties, while uncorrelated systematic uncertainties are negligible. The two horizontal shaded bands show the uncertainty in d/u due to omitting sea quarks in Eq. (25) (model uncertainty, orange-colored band), and from correlated systematic uncertainties (dark grey band). Projections on MARATHON and CLAS12 BoNuS are from their respective experimental proposals [72, 73].

- Typically d/u is extracted from a comparison of fully inclusive DIS on proton vs deuteron targets. However, nuclear effects in the deuteron need to be modeled well to extract d/u.

- The PVDIS asymmetry allows for an extraction of proton PDF ratio d/u in the valence quark region, free of nuclear effects.

- Complementary other experiments (BoNuS, MARATHON) that use different nuclear targets to extract d/u.

Conclusions

- PVDIS with SoLID at JLAB can provide unique and complementary information to constrain new physics

- Allows for precision extractions of the weak mixing angle

- It can provide input for the global SMEFT analysis by lifting flat directions and disentangling dim-6 and dim-8 operators

- Can constrain the parameter space of Dark photons/Z and Leptophobic Z-primes

- Could provide a way to explore hadronic effects such as higher twist quark-quark correlations, charge symmetry violation, and d/u PDF ratios