Constraining New Physics with PVDIS

Sonny Mantry
University of North Georgia (UNG)

Physics Beyond the Standard Model
High Energy Workshop Series

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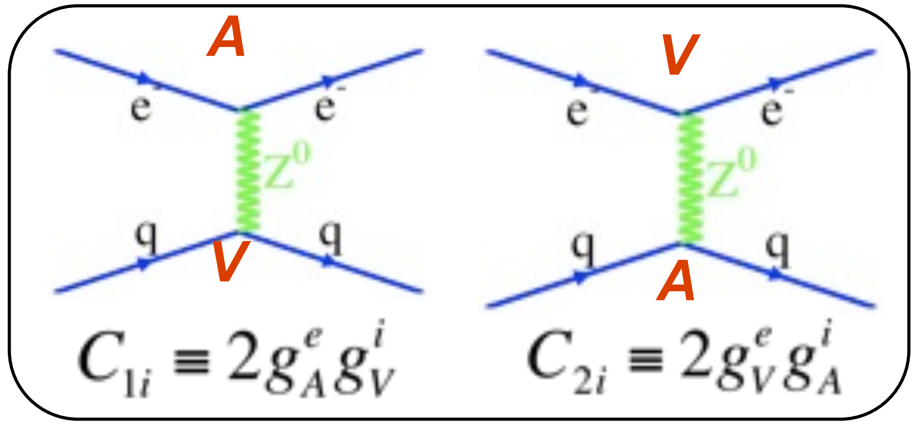
Outline

- The C_{iq} couplings
- SMEFT Analysis
- Dark Photons
- Dark-Z
- Charged Lepton Violation ($e \to \mu$)

Contact Interactions



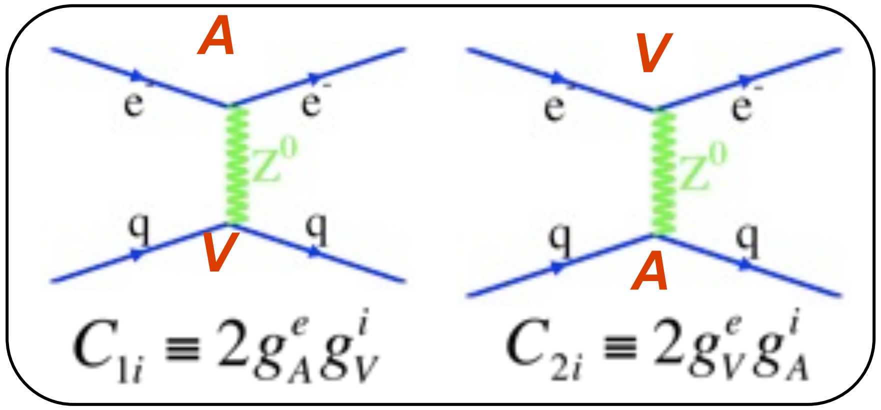
- For $Q^2 << (M_Z)^2$ limit, electron-quark scattering via the weak neutral current is mediated by contact interactions:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$

- Tree-level Standard Model values:

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W)\,, \quad C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W)\,, \qquad C_{3u} = \frac{1}{2}\,,$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W)\,, \qquad C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W)\,, \qquad C_{3d} = -\frac{1}{2}$$

New Physics Effects



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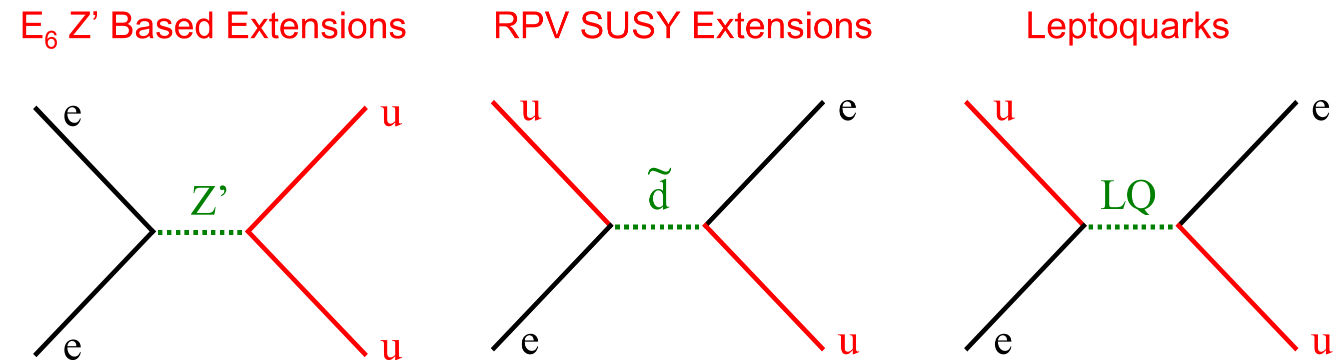


- In the $Q^2 \ll M_Z^2$ limit, electron-quark interactions via the weak neutral current can be parameterized by contact interactions:

$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$

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

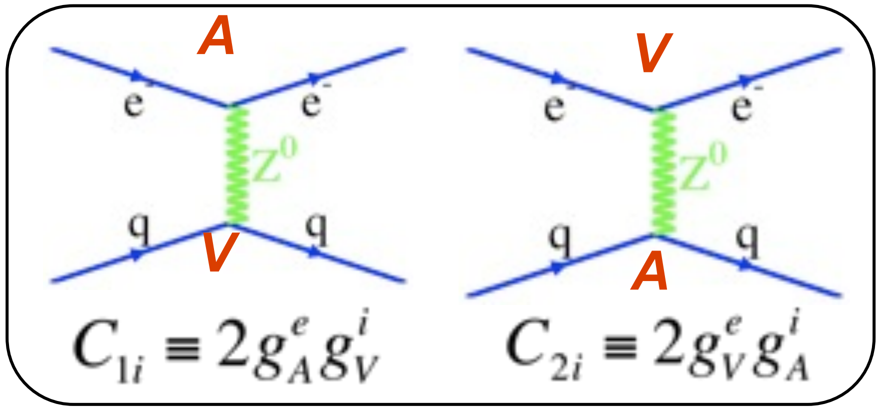
$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

SM contribution

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.

New Physics Effects



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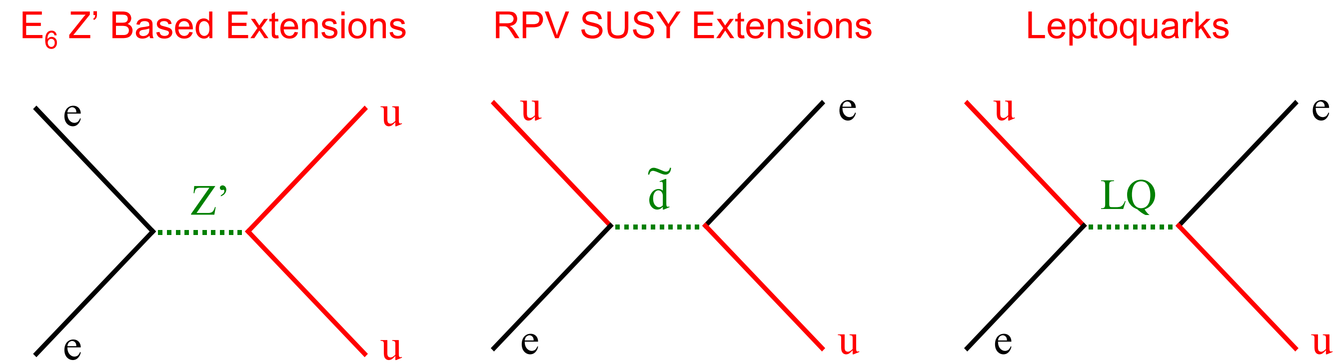


$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

- Effective Lagrangian for New Physics Contributions can be parameterized as:

$$\delta\mathcal{L} = \frac{g^2}{\Lambda^2}\sum_{\ell,q}\left\{\eta_{LL}^{\ell q}\,\bar{\ell}_L\gamma_\mu\ell_L\bar{q}_L\gamma_\mu q_L + \eta_{LR}^{\ell q}\,\bar{\ell}_L\gamma_\mu\ell_L\bar{q}_R\gamma_\mu q_R + \eta_{RL}^{\ell q}\,\bar{\ell}_R\gamma_\mu\ell_R\bar{q}_L\gamma_\mu q_L + \eta_{RR}^{\ell q}\,\bar{\ell}_R\gamma_\mu\ell_R\bar{q}_R\gamma_\mu q_R\right\}$$

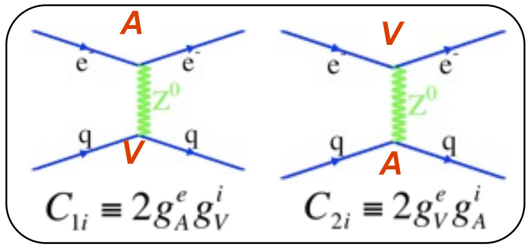
- Shift in the WNC couplings due to new physics contact interactions:

$$\Delta C_{1q} = \frac{g^2}{\Lambda^2}\frac{\eta_{LL}^{\ell q} + \eta_{LR}^{\ell q} - \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q}}{2\sqrt{2}G_F},$$

$$\Delta C_{2q} = \frac{g^2}{\Lambda^2}\frac{\eta_{LL}^{\ell q} - \eta_{LR}^{\ell q} + \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q}}{2\sqrt{2}G_F},$$

Each of the WNC couplings probe a unique combination of chiral structures thereby complementing constraints arising from other low energy experiments or colliders.

Contact Interactions



$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_q \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$

- Precision measurements of the electroweak couplings can also be translated into constraints in specific models.

- For example, for the different LQ states only particular chiral structures arise which leads to a corresponding pattern of shifts in the WNC couplings:

ZEUS (prel.) 1994-2000 $e^\pm p$									
	Coupling structure								95% CL [TeV]
Model	a^{ed}_{LL}	a^{ed}_{LR}	a^{ed}_{RL}	a^{ed}_{RR}	a^{eu}_{LL}	a^{eu}_{LR}	a^{eu}_{RL}	a^{eu}_{RR}	M_{LQ}/λ_{LQ}
$S^L_\circ$					$+\frac{1}{2}$				0.75
$S^R_\circ$								$+\frac{1}{2}$	0.69
$\tilde{S}^R_\circ$				$+\frac{1}{2}$					0.31
$S^L_{1/2}$						$-\frac{1}{2}$			0.91
$S^R_{1/2}$			$-\frac{1}{2}$				$-\frac{1}{2}$		0.69
$\tilde{S}^L_{1/2}$		$-\frac{1}{2}$							0.50
S^L_1	$+1$				$+\frac{1}{2}$				0.55
$V^L_\circ$	-1								0.69
$V^R_\circ$				-1					0.58
$\tilde{V}^R_\circ$								-1	1.03
$V^L_{1/2}$		$+1$							0.49
$V^R_{1/2}$			$+1$				$+1$		1.15
$\tilde{V}^L_{1/2}$						$+1$			1.26
V^L_1	-1				-2				1.42

$$\Delta C_{1q} = \frac{g^2}{\Lambda^2} \frac{\eta^{\ell q}_{LL} + \eta^{\ell q}_{LR} - \eta^{\ell q}_{RL} - \eta^{\ell q}_{RR}}{2\sqrt{2}G_F},$$

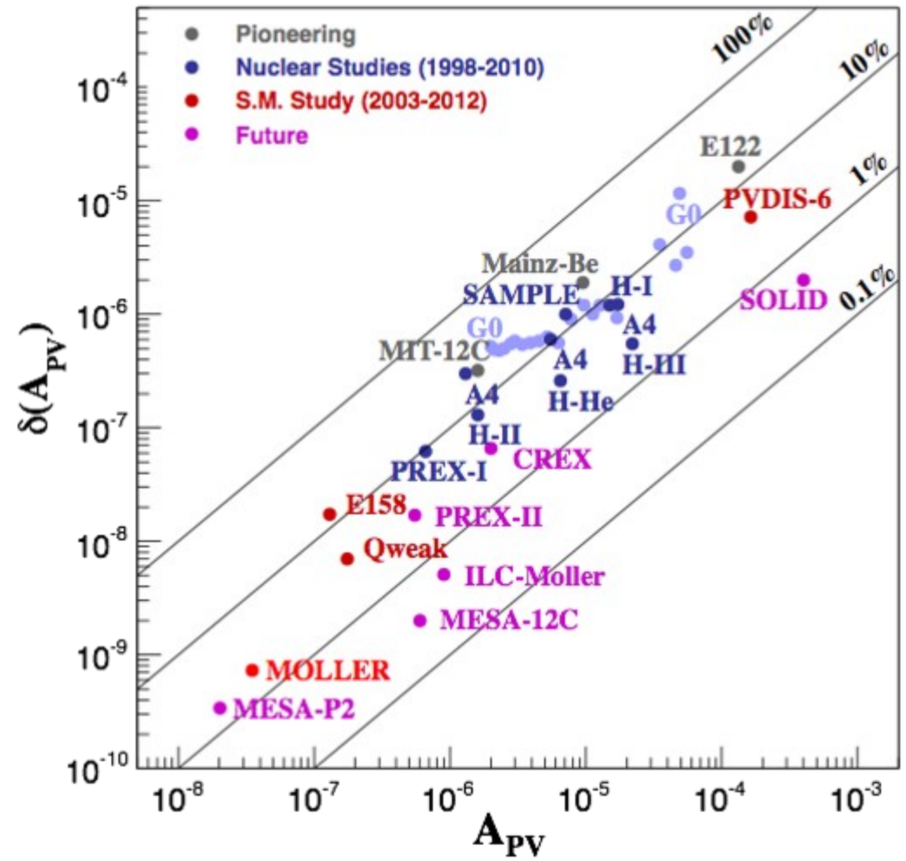
$$\Delta C_{2q} = \frac{g^2}{\Lambda^2} \frac{\eta^{\ell q}_{LL} - \eta^{\ell q}_{LR} + \eta^{\ell q}_{RL} - \eta^{\ell q}_{RR}}{2\sqrt{2}G_F},$$

Accessing C_{iq} via Parity-Violating Observables

- Atomic Parity Violation (APV):
  Sensitive to C_{1q} couplings via $Q_W(Z,N)$

- Parity Violating Elastic Scattering (Qweak, P2):
  Sensitive to C_{1q} couplings through $Q_W(Z=1, N=0)$

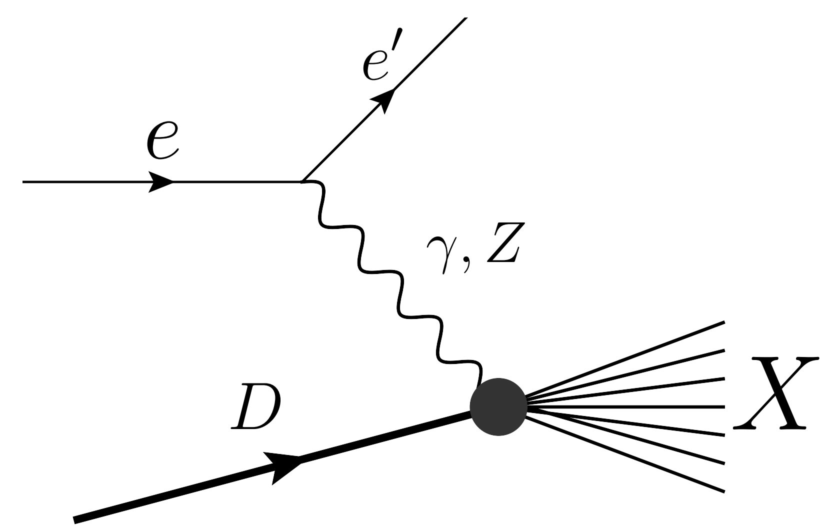
$$Q_W(Z,N) = -2[C_{1u}(2Z+N) + C_{1d}(Z+2N)]$$



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

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

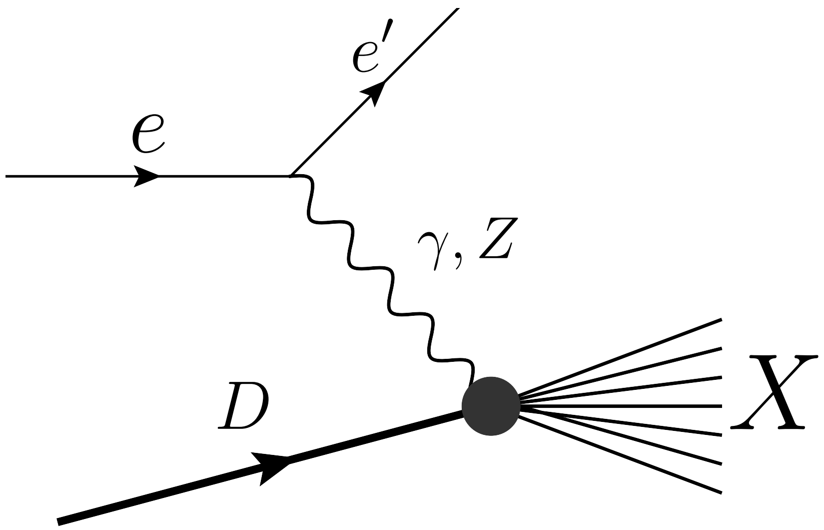
$$a_1 = \frac{2\sum_q e_q C_{1q}(q+\bar{q})}{\sum_q e_q^2(q+\bar{q})} \qquad a_3 = \frac{2\sum_q e_q C_{2q}(q-\bar{q})}{\sum_q e_q^2(q+\bar{q})}$$



For the isocalar deuteron target,
structure function effects largely cancel

Parity-Violating e-D Asymmetry

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



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

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

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

All hadronic effects cancel!

Clean probe of WNC

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

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

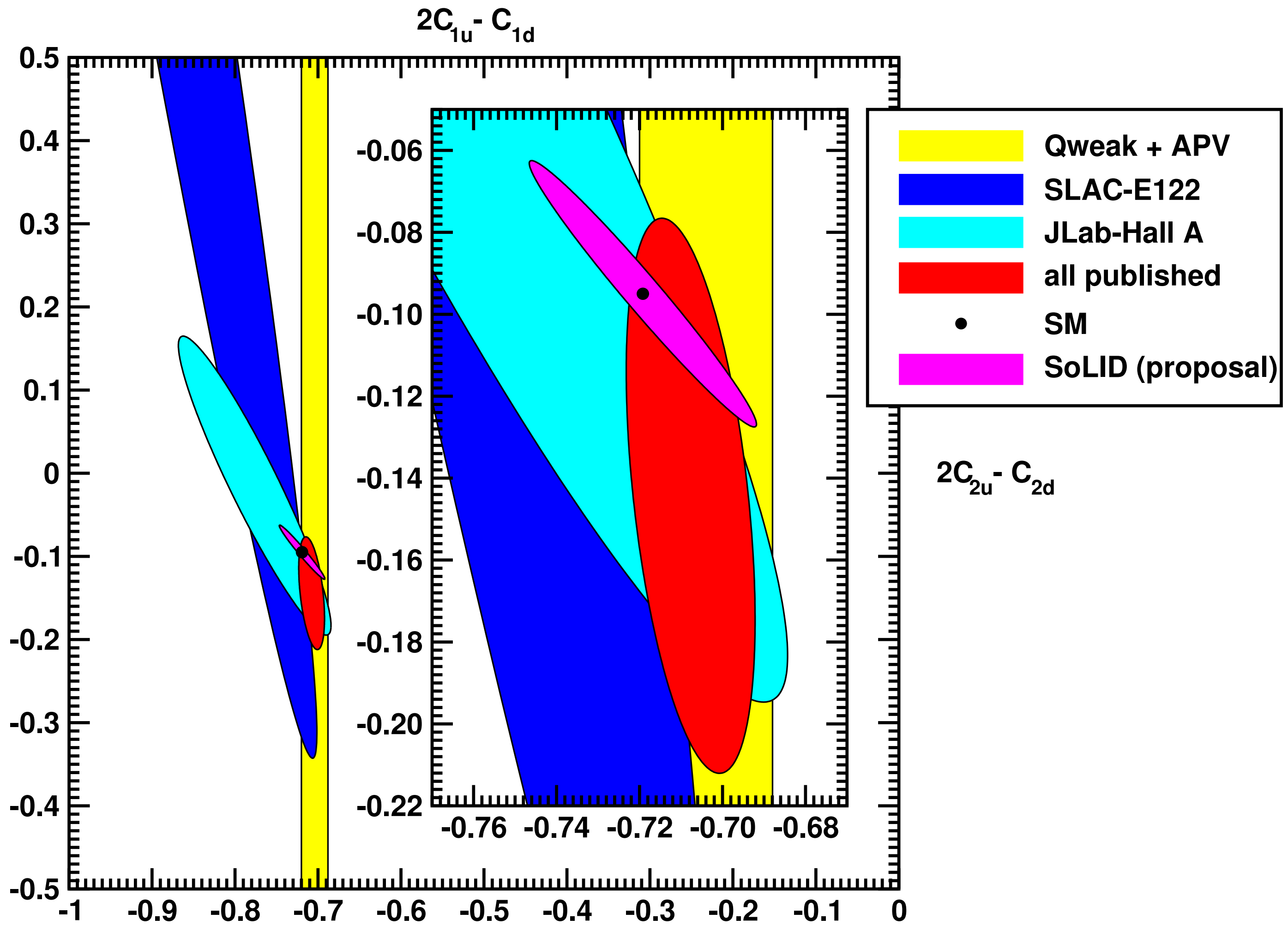
Target mass

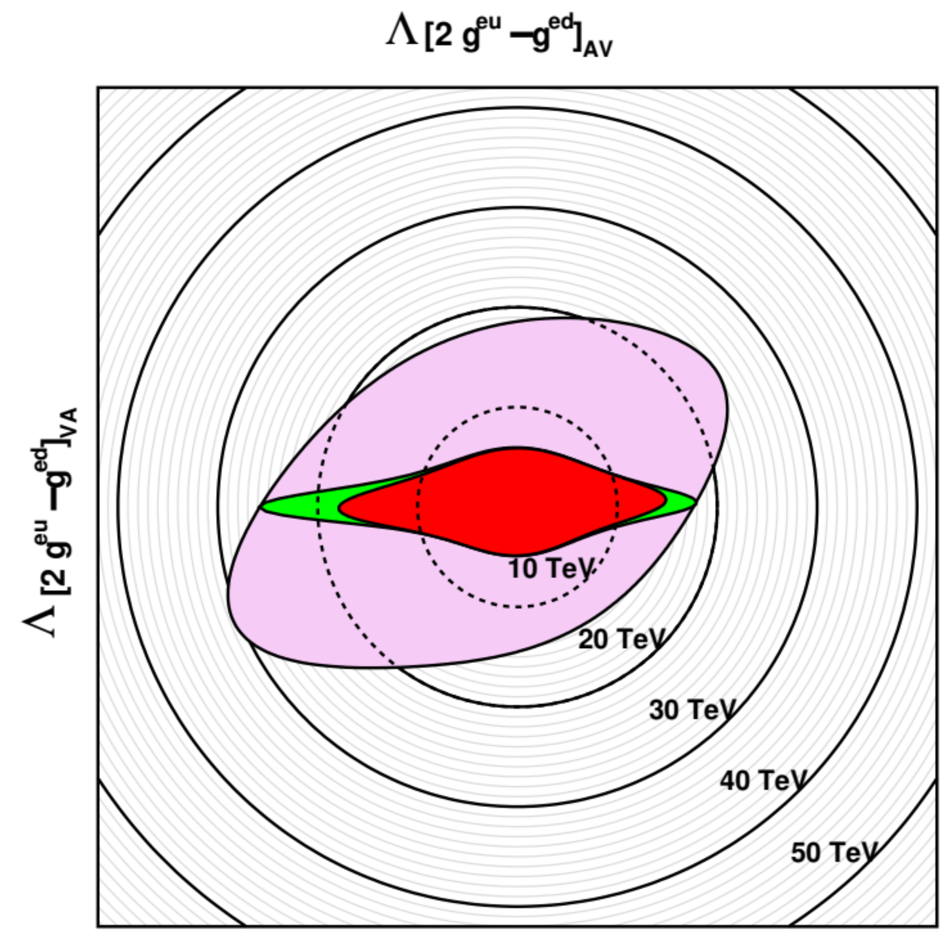
Higher twist

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

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

Status of WNC Couplings





- 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:

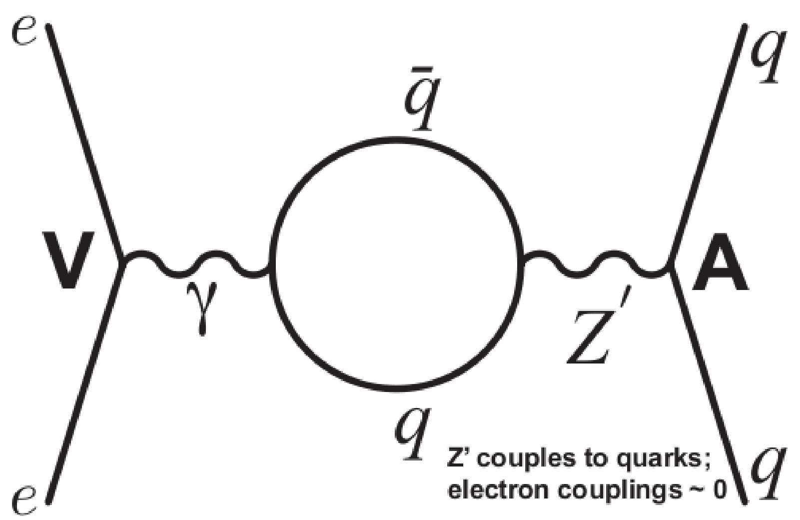
$$2C_{2u} - C_{2d} = -0.145 \pm 0.068$$

- SOLID is expected significantly improve on this result.

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}:

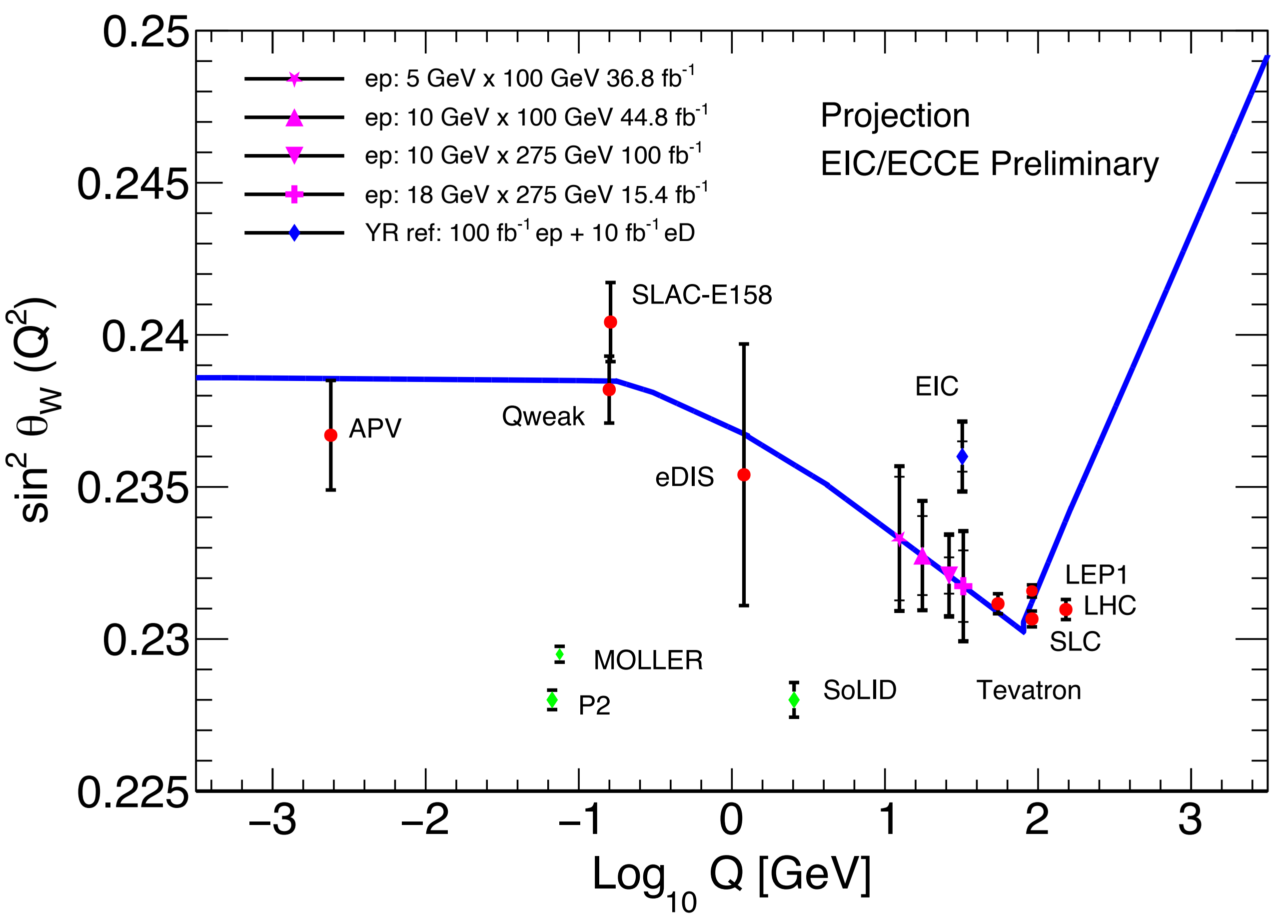


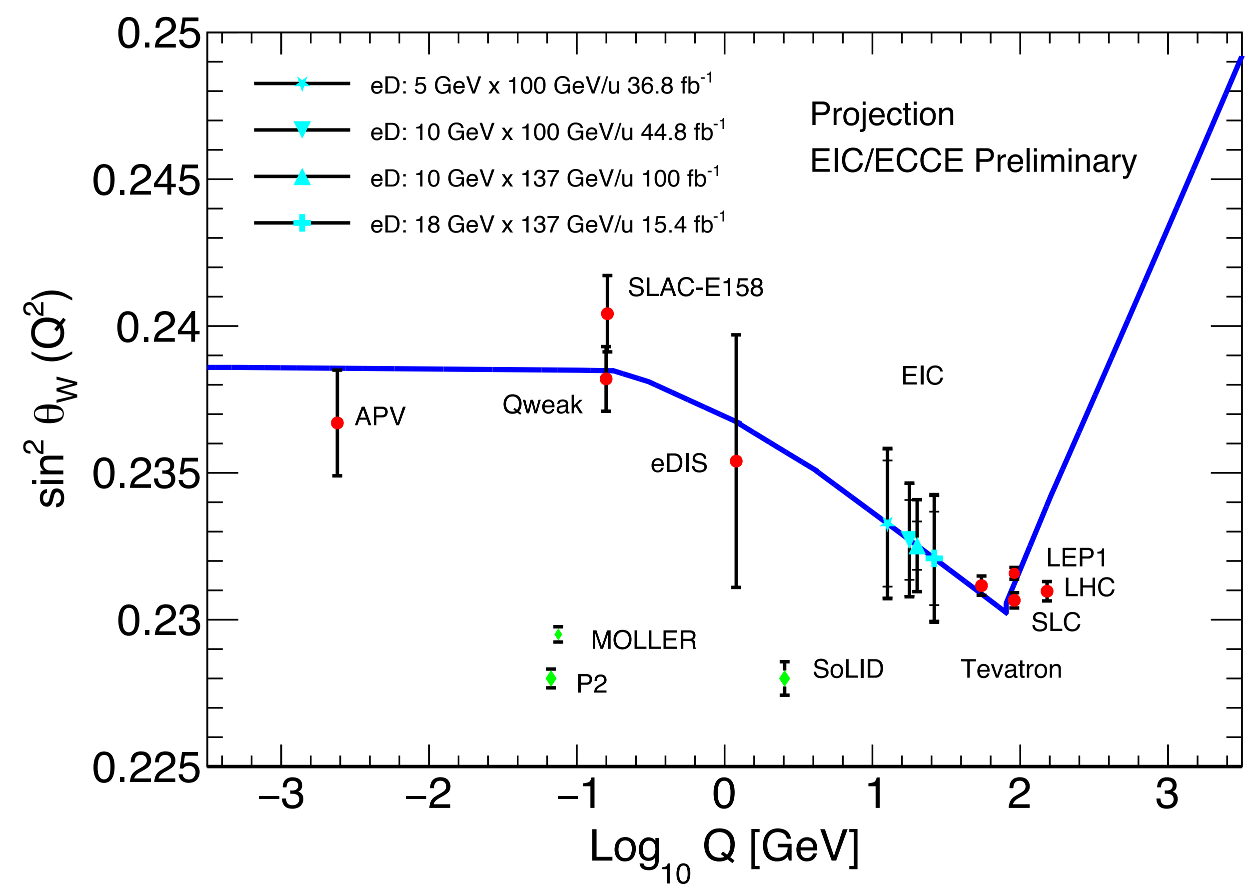
Leptophobic Z' contributes only to the C_{2q} couplings!

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

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

Extraction of the Weak Mixing Angle





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

- SOLID is extract the weak mixing angle with higher precision than the EIC.
- How does SOLID measurement contribute in the global fit that includes data from APV, Qweak, P2, and LHC?

Standard Model Effective Theory (SMEFT) Operator Basis

[Boughazel, 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

[Boughazel, Petriello, Wiegand]

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

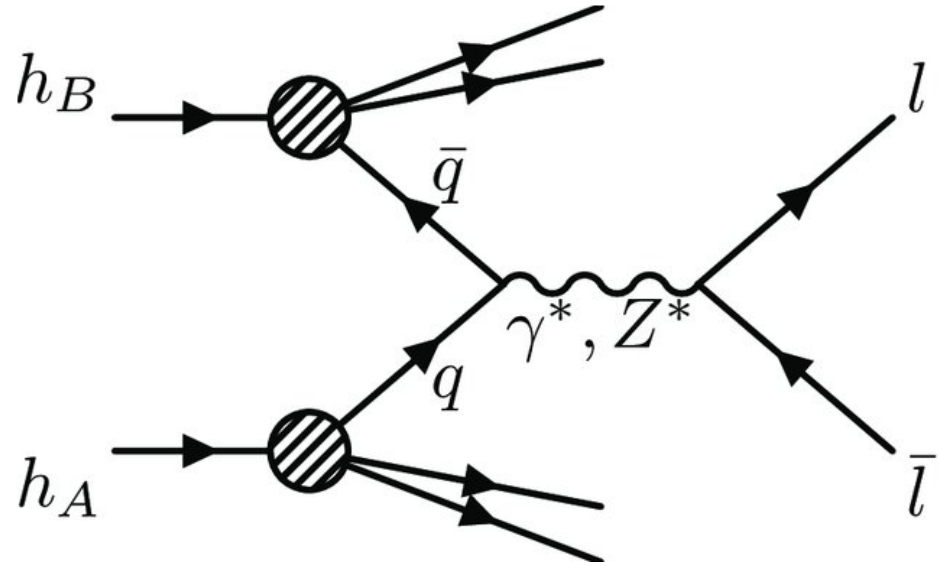
$$\mathcal{L}_{PV} = \frac{G_F}{\sqrt{2}}\Big[(\bar{e}\gamma^\mu\gamma_5 e)(C^6_{1u}\bar{u}\gamma_\mu u + C^6_{1d}\bar{d}\gamma_\mu d) + (\bar{e}\gamma^\mu e)(C^6_{2u}\bar{u}\gamma_\mu\gamma_5 u + C^6_{2d}\bar{d}\gamma_\mu\gamma_5 d)$$
$$+ (\bar{e}\gamma^\mu e)(C^6_{Vu}\bar{u}\gamma_\mu u + C^6_{Vd}\bar{d}\gamma_\mu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

- 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

[Boughazel, Petriello, Wiegand]



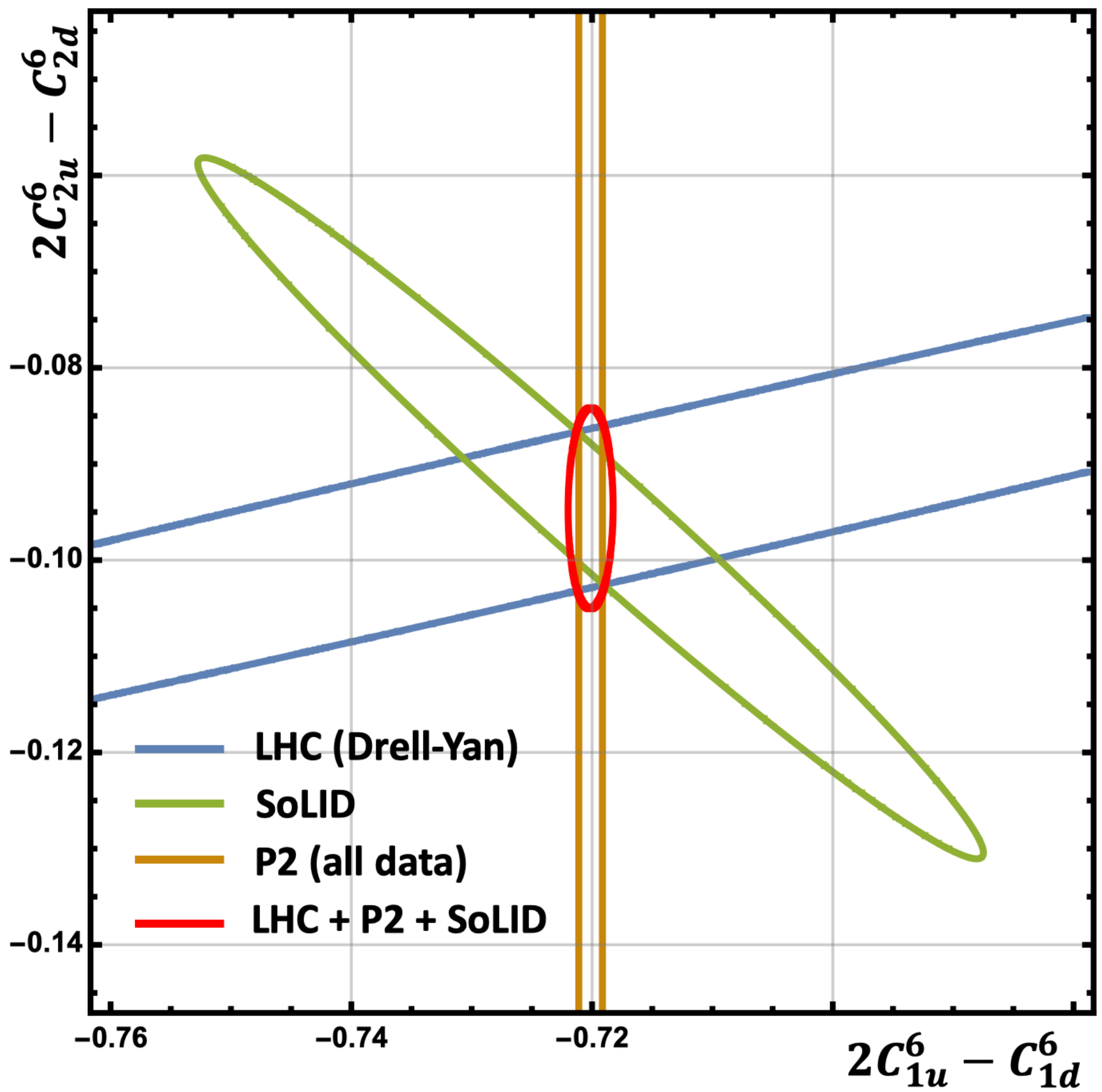
- The SMEFT Wilson coefficients that affect PVES also contribute to the Drell-Yan process at the LHC

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

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

Lifting Flat Directions

[Boughazel, Petriello, Wiegand]

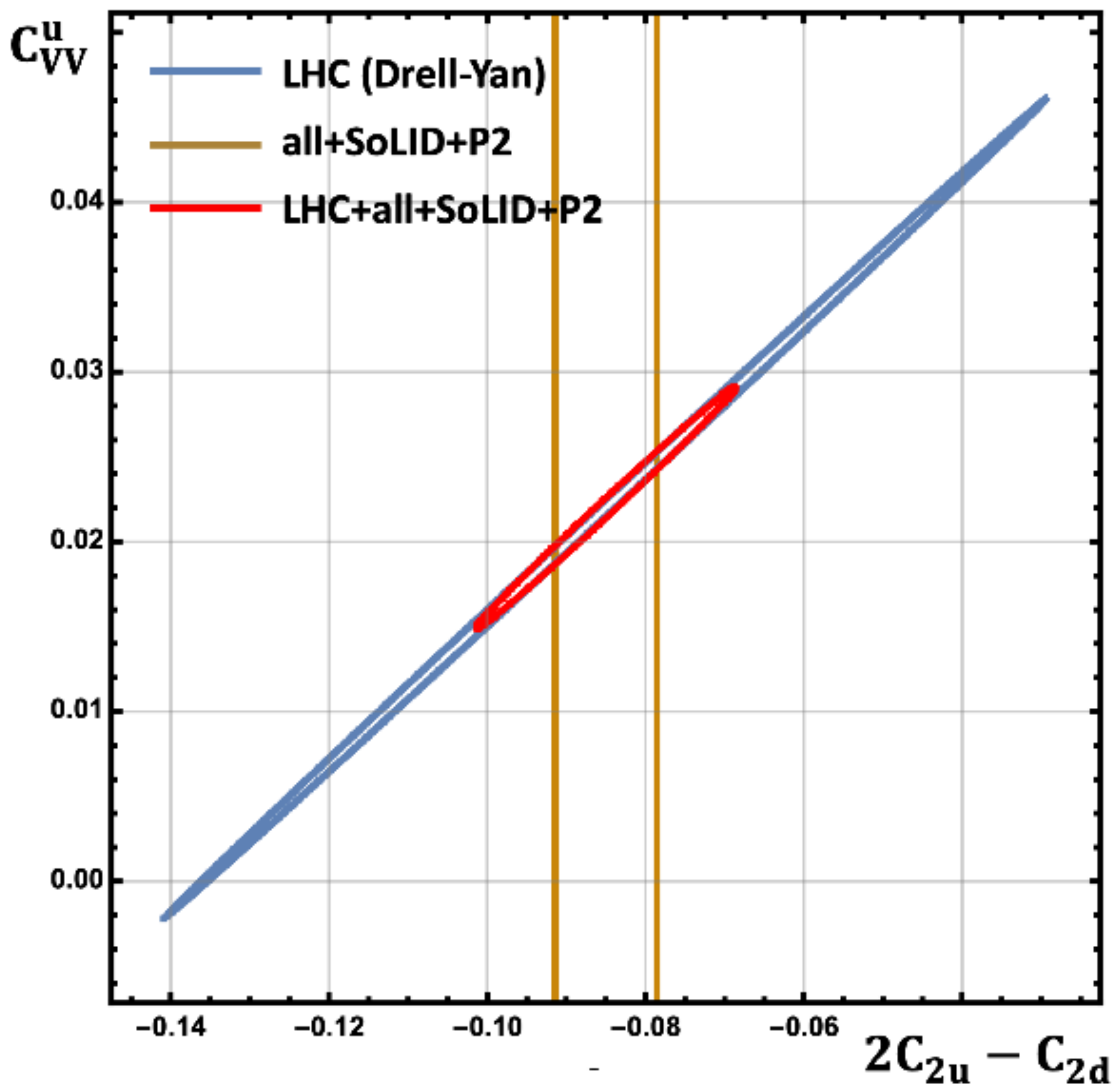


- PVES and Drell-Yan at the LHC are sensitive to different combinations of the SMEFT Wilson coefficients.

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

Lifting Flat Directions

[Boughazel, Petriello, Wiegand]

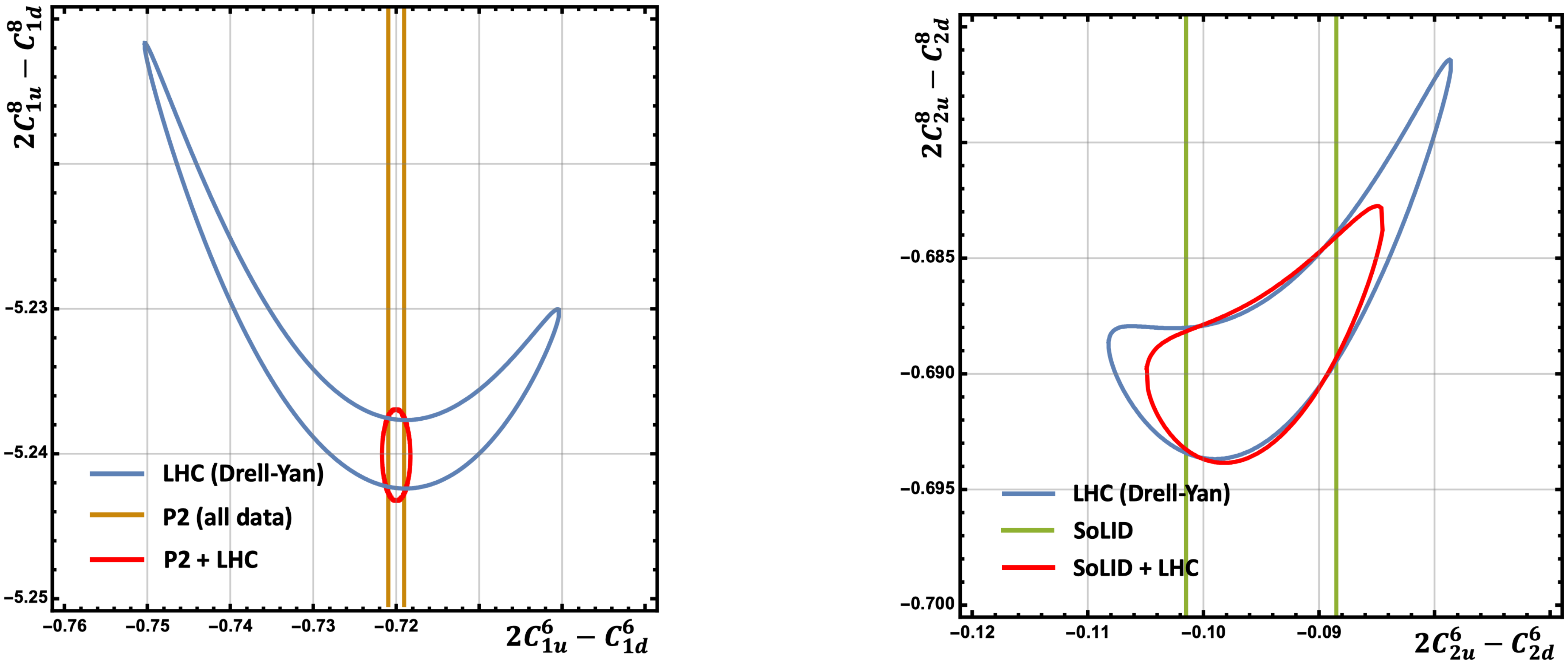


- An example of SOLID probing a unique direction in parameter space. Neither the LHC, Qweak, P2, or APV have sensitivity in this region

- 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

[Boughazel, 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.

Accessing C_{3q} via Parity-Violating Observables

- The C3q couplings are parity conserving but can be accessed by comparing DIS cross sections with unpolarized or polarized leptons and anti-leptons

$$A^{e^+e^-} \equiv \frac{\sigma^{e^+} - \sigma^{e^-}}{\sigma^{e^+} + \sigma^{e^-}} \qquad A_{ij}^{e^+e^-} \equiv \frac{\sigma_i^{e^+} - \sigma_j^{e^-}}{\sigma_i^{e^+} + \sigma_j^{e^-}} \quad (i,j = R,L)$$

- The combination of C3q couplings are poorly known; have only been measured using polarized muon and anti-muon beams incident on a Carbon target:

[Erler, Ramsey-Musolf, Prog. Part. Nucl. Phys. 54, 351, (2005)]

Beam	Process	$\overline{Q^2}$ [GeV^2]	Combination	Result/Status	SM
SLAC	e^--D DIS	1.39	$2C_{1u} - C_{1d}$	-0.90 ± 0.17	-0.7185
SLAC	e^--D DIS	1.39	$2C_{2u} - C_{2d}$	$+0.62 \pm 0.81$	-0.0983
CERN	$\mu^\pm$-C DIS	34	$0.66(2C_{2u} - C_{2d}) + 2C_{3u} - C_{3d}$	$+1.80 \pm 0.83$	$+1.4351$
CERN	$\mu^\pm$-C DIS	66	$0.81(2C_{2u} - C_{2d}) + 2C_{3u} - C_{3d}$	$+1.53 \pm 0.45$	$+1.4204$
Mainz	e^--Be QE	0.20	$2.68C_{1u} - 0.64C_{1d} + 2.16C_{2u} - 2.00C_{2d}$	-0.94 ± 0.21	-0.8544
Bates	e^--C elastic	0.0225	$C_{1u} + C_{1d}$	0.138 ± 0.034	$+0.1528$
Bates	e^--D QE	0.1	$C_{2u} - C_{2d}$	0.015 ± 0.042	-0.0624
JLAB	e^--p elastic	0.03	$2C_{1u} + C_{1d}$	approved	$+0.0357$
SLAC	e^--D DIS	20	$2C_{1u} - C_{1d}$	to be proposed	-0.7185
SLAC	e^--D DIS	20	$2C_{2u} - C_{2d}$	to be proposed	-0.0983
SLAC	$e^\pm$-D DIS	20	$2C_{3u} - C_{3d}$	to be proposed	$+1.5000$
—	^{133}Cs APV	0	$-376C_{1u} - 422C_{1d}$	-72.69 ± 0.48	-73.16
—	^{205}Tl APV	0	$-572C_{1u} - 658C_{1d}$	-116.6 ± 3.7	-116.8

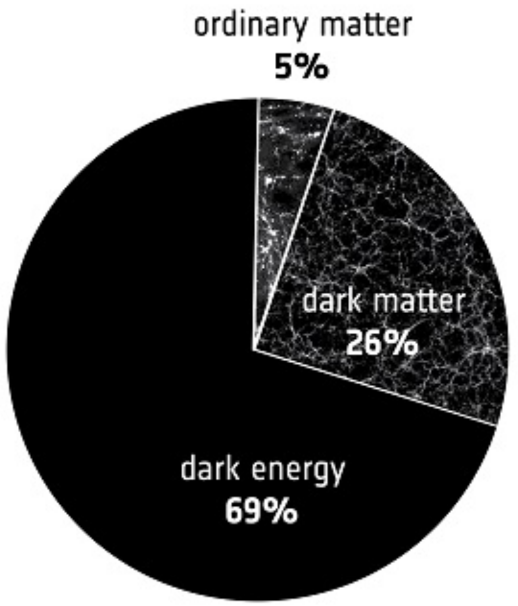
$$2g_{AA}^{\mu u} - g_{AA}^{\mu d} + 0.81\,(2g_{VA}^{\mu u} - g_{VA}^{\mu d}) = 1.45 \pm 0.41$$
$$2g_{AA}^{\mu u} - g_{AA}^{\mu d} + 0.66\,(2g_{VA}^{\mu u} - g_{VA}^{\mu d}) = 1.70 \pm 0.79$$

Using PVDIS 6 GeV

$$2g_{AA}^{\mu u} - g_{AA}^{\mu d} = 1.57 \pm 0.38$$

[Erler, Liu, Spiesberger, Zheng]

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)

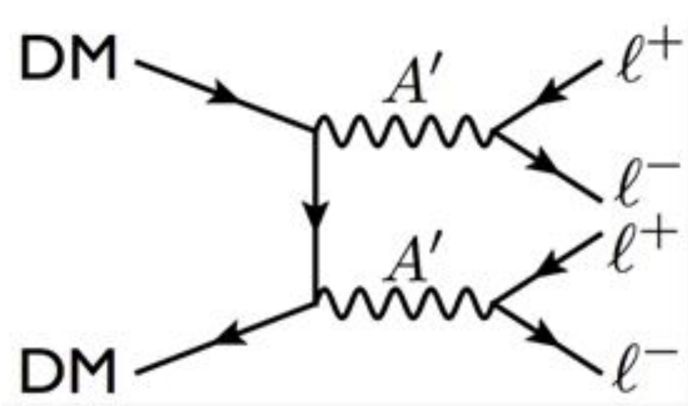
$$\mathcal{L} \supset -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'_\mu A'^\mu + \frac{\epsilon}{2\cos\theta_W}F'_{\mu\nu}B^{\mu\nu}$$

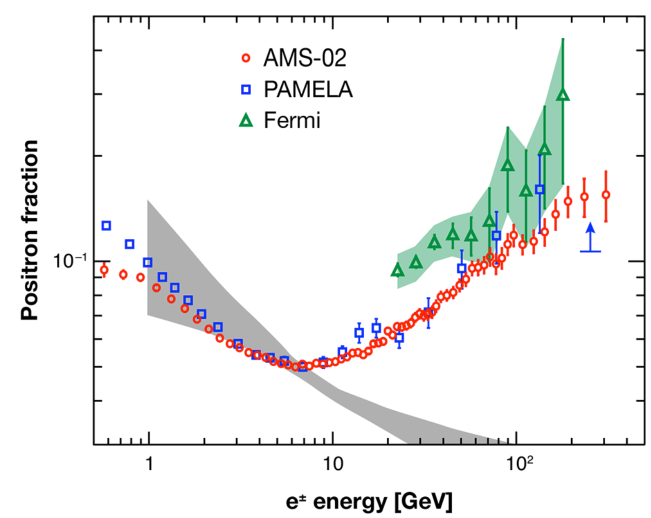
- The mixing induces a coupling of the dark photon to the electromagnetic and weak neutral currents.

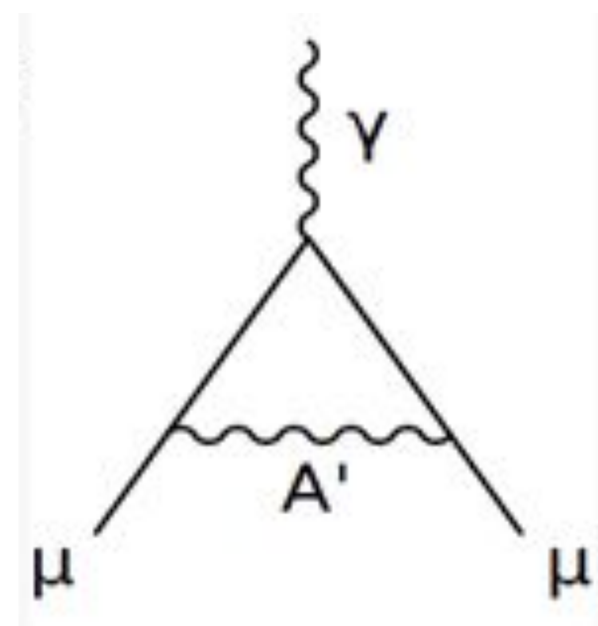
$$\mathscr{L}_{int} = -e\epsilon J^\mu_{em} A'_\mu$$

- Could help explain astrophysical data and anomalies

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



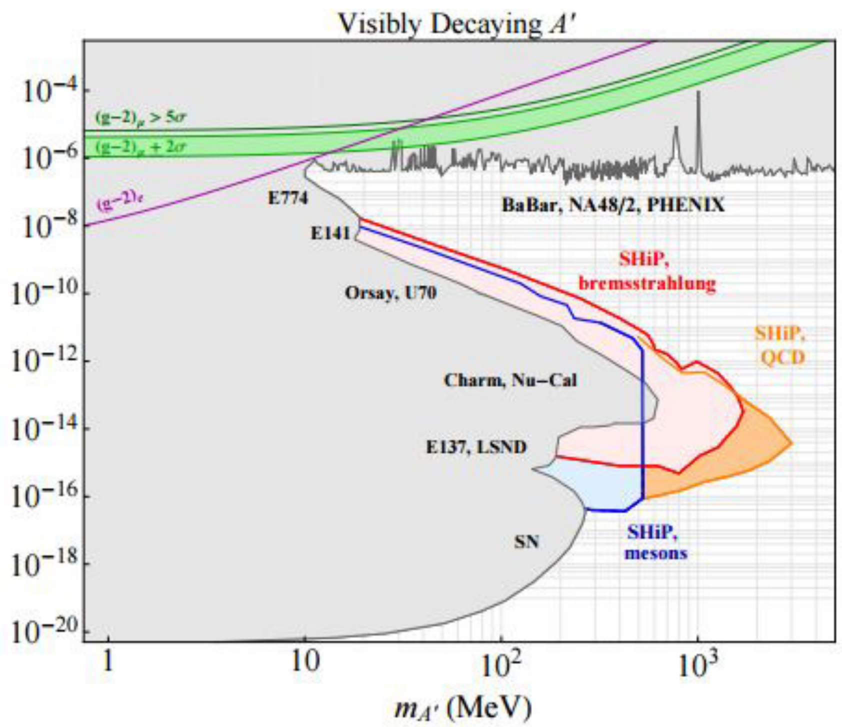




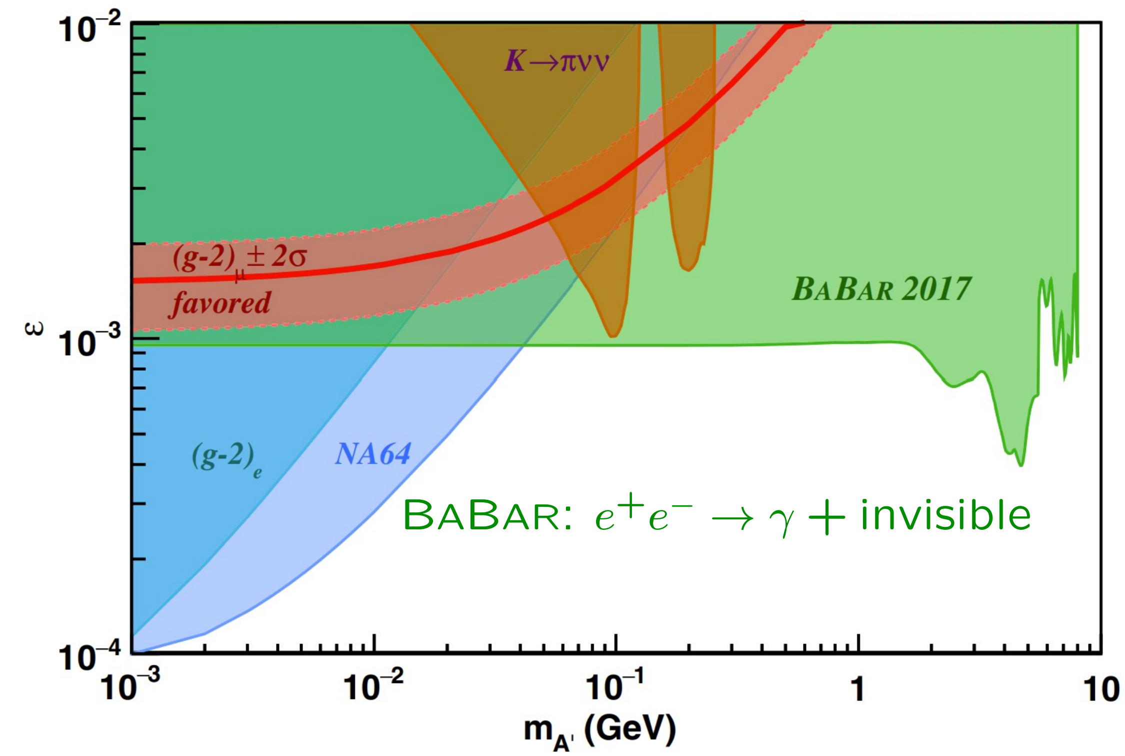
Dark Photon Scenario

- Active experimental program to search for dark photons

[Bjorken, Essig, Schuster, Toro; Baten, Pospelov, Ritz; Izaguirre Krnjaic, Schuster, Toro]

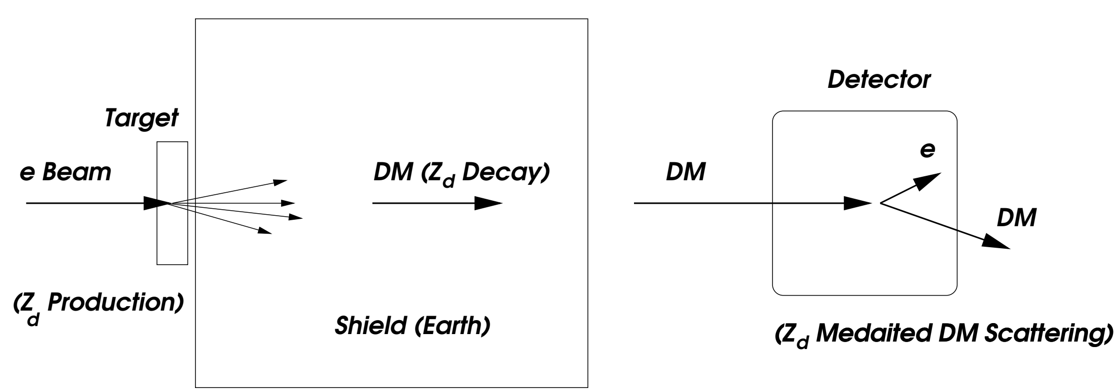


S. Alekhin *et al.*, arXiv:1504.04855 [hep-ph]



- Beam Dump Experiments (see talk by Marco Spreafico)

[Bjorken, Essig, Schuster, Toro]



Dark Photon Scenario: Impact on PVES

[Thomas, Wang, Williams]

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

- Contraints 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]

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

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

- Contraints 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:

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

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

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

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)

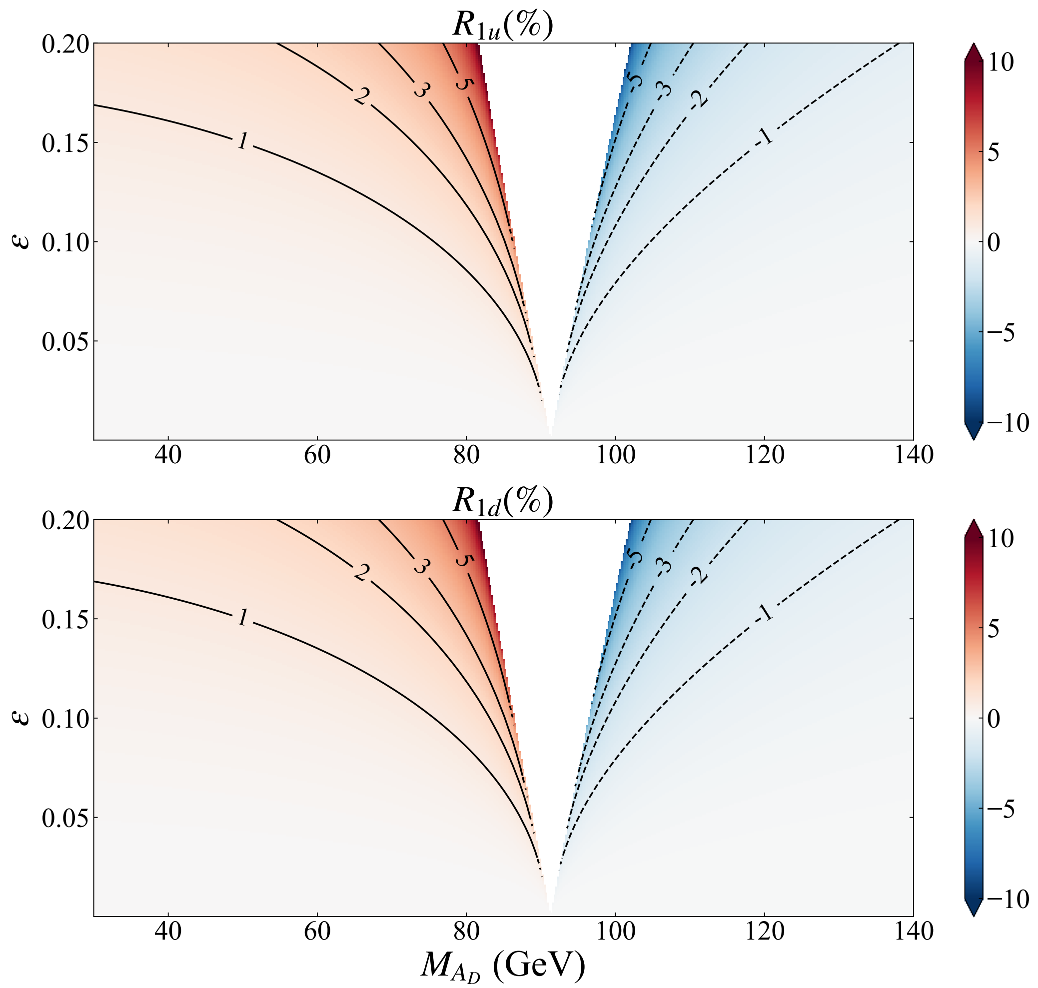


FIG. 1. The correction factors R_{1u} and R_{1d} at $Q^2 = 0.00616\ \mathrm{GeV}^2$, appropriate to the PREX-II experiment. The gap on the $\epsilon - M$ plane is not accessible because of "eigenmass repulsion" associated with the Z mass.

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

[Thomas, Wang, Williams]

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

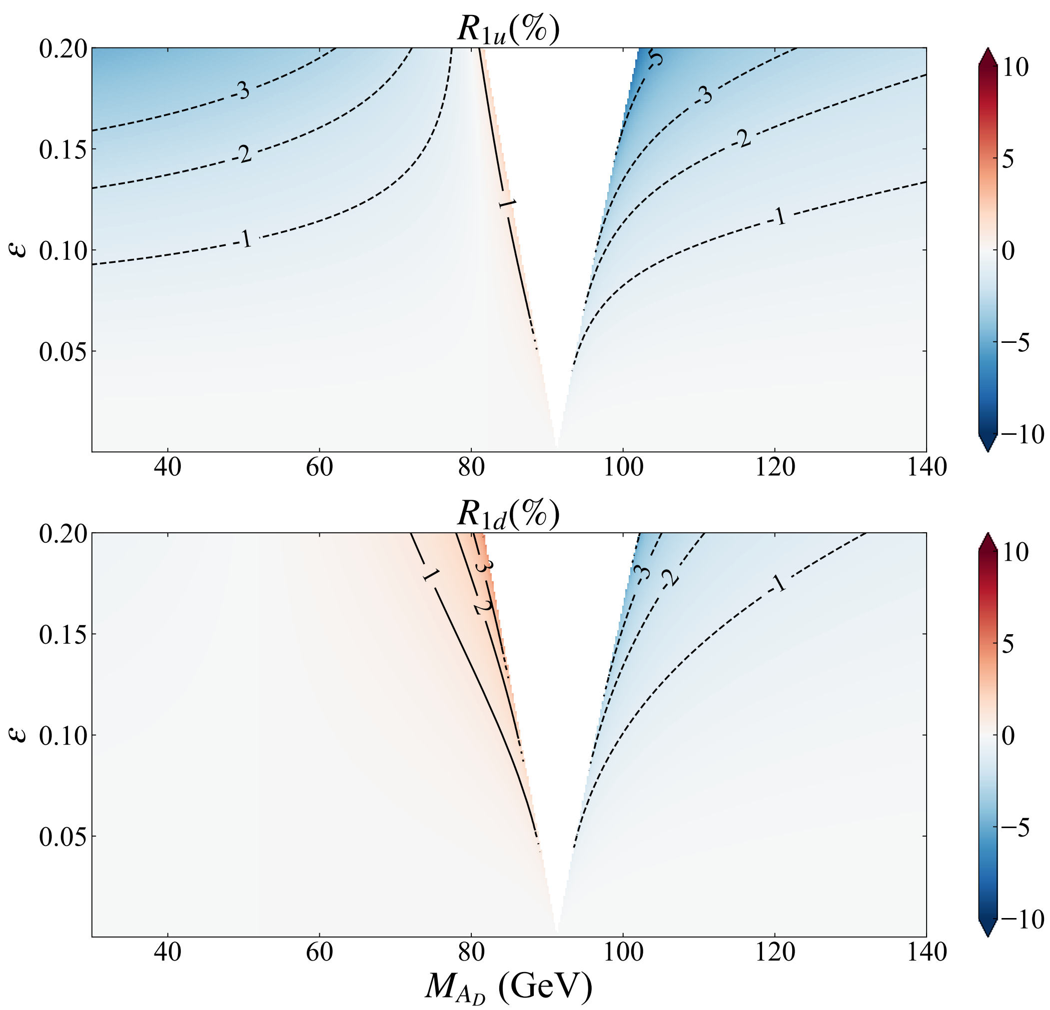


FIG. 2. The correction factors R_{1u} and R_{1d} at $Q^2 = M_Z^2$.

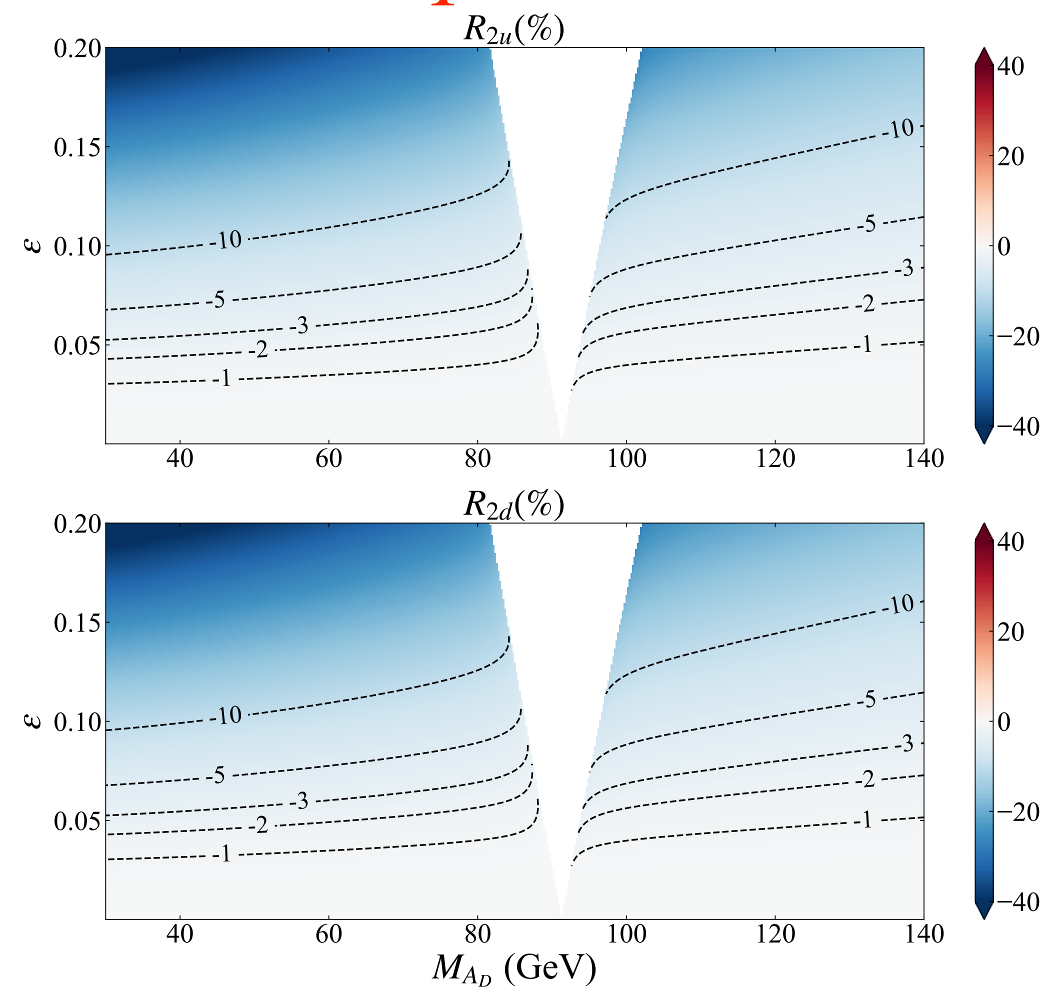


FIG. 3. The correction factors R_{2u} and R_{2d} at $Q^2 = M_Z^2$.

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

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

Dark Photon Scenario: Shift in C_{3q} (PVDIS)

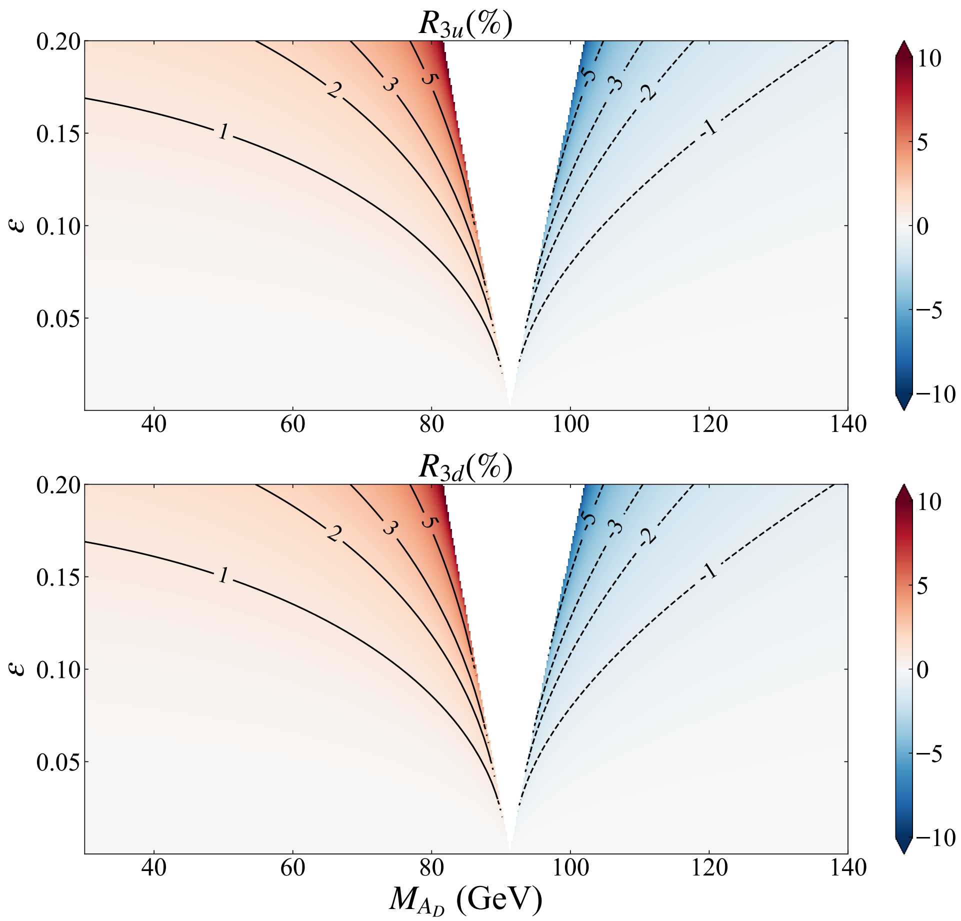


FIG. 4. The correction factors R_{3u} and R_{3d} at $Q^2 = 10$ GeV^2.

[Thomas, Wang, Williams]

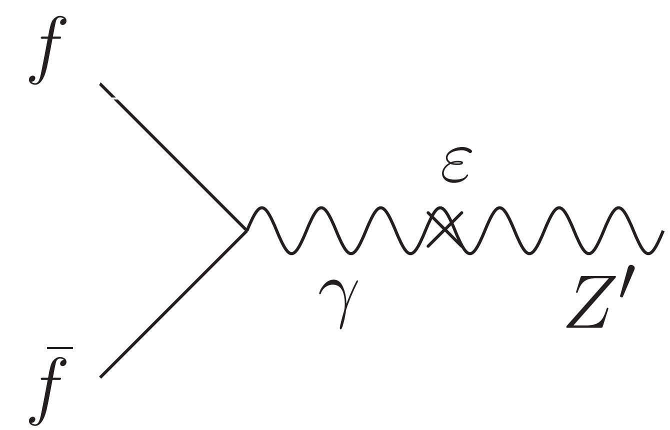
$$A_d^{e^+e^-} = -\frac{3G_F Q^2 Y}{2\sqrt{2}\pi\alpha} \frac{R_V(2g_{AA}^{eu} - g_{AA}^{ed})}{5 + 4R_C + R_S}$$

$$C_{3q} = C_{3q}^{Z} + \frac{Q^2 + M_Z^2}{Q^2 + M_{A_D}^2} C_{3q}^{A_D} = C_{3q}^{\mathrm{SM}}(1 + R_{3q})$$

Light Dark-Z Parity Violation

[Davoudiasl, Lee, Marciano]

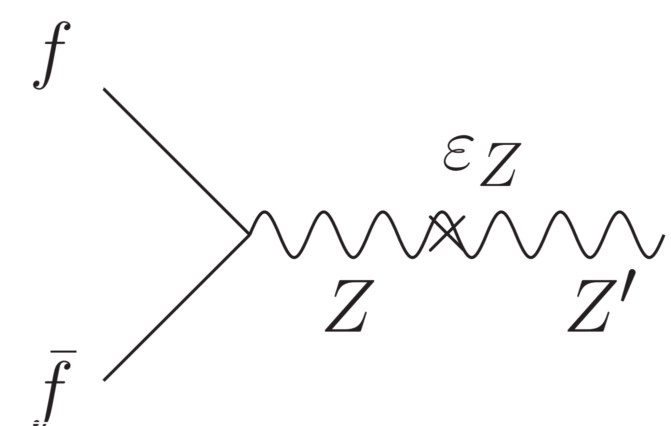
- An interesting scenario is that of a "light" Dark-Z.



- The standard kinetic mixing scenario:

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

- And additional mass mixing (for example, from extended Higgs sector) ton 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:

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

Light Dark-Z Parity Violation

[Davoudiasl, Lee, Marciano]

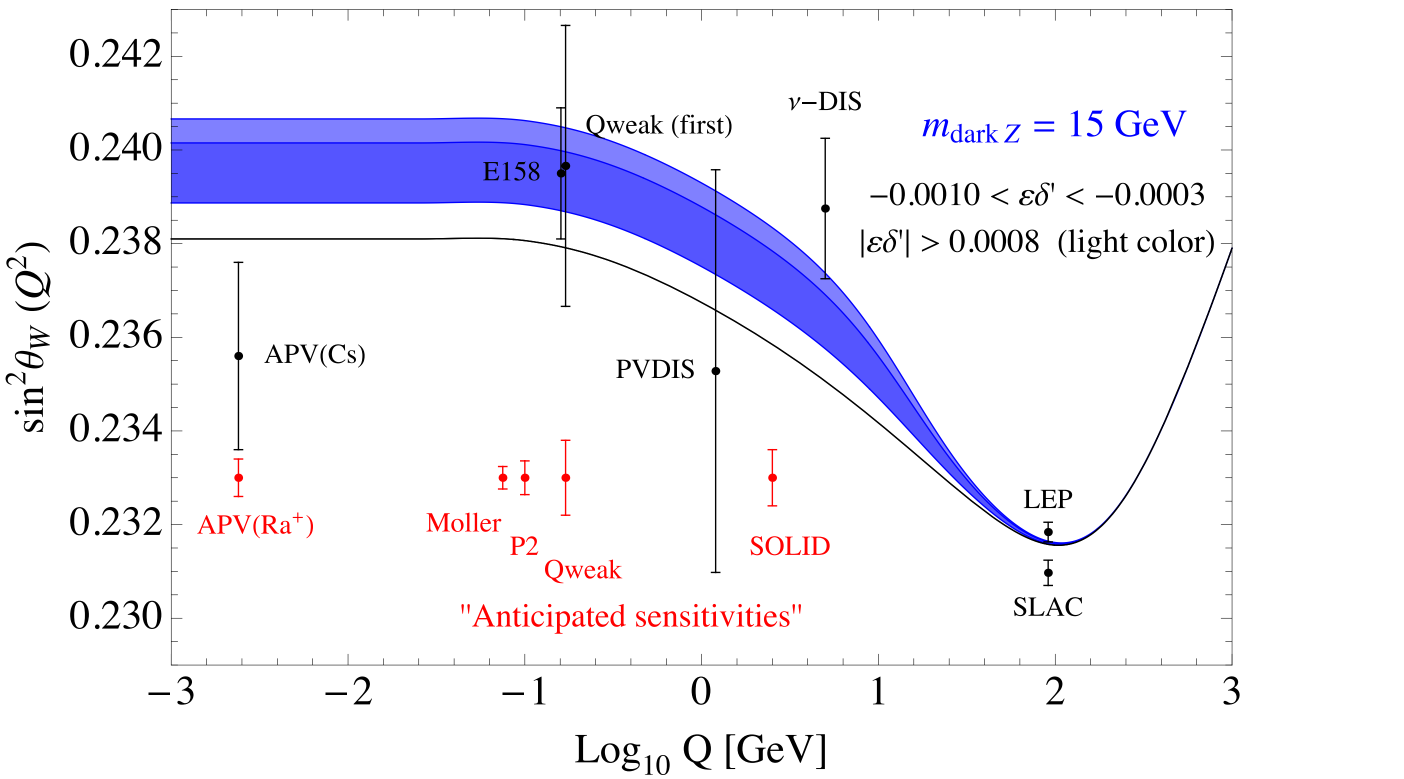
- Effective change in presence of dark-Z for parity violating asymmetries:

$$G_F \to \rho_d G_F$$

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

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

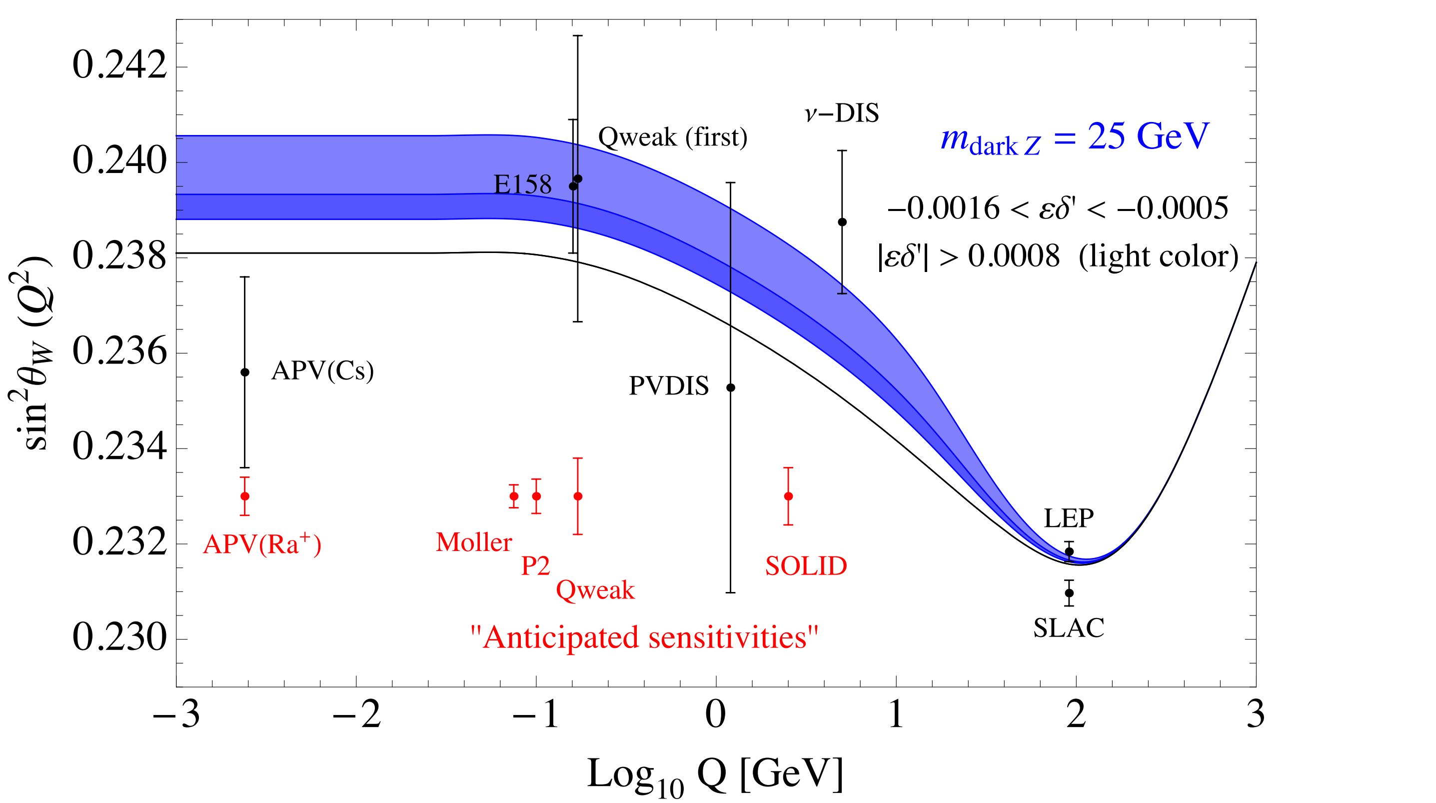
$$\kappa_d = 1 - \frac{\varepsilon}{\varepsilon_Z}\delta^2 \frac{\cos\theta_W}{\sin\theta_W} \frac{m_{Z_d}^2}{Q^2 + m_{Z_d}^2}$$



- Constraints from Higgs Decay:

$$H \to Z Z_d \to \ell_1^+ \ell_1^- \ell_2^+ \ell_2^-$$

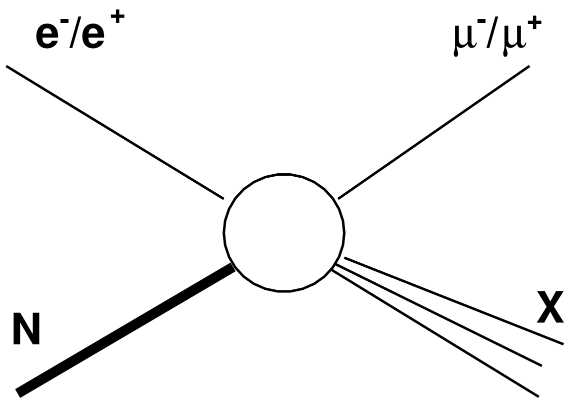
$$|\varepsilon\delta'| \lesssim 0.0008$$



- Note that this constraint will be much weaker if the Dark Z has a larger branching fraction to the dar sector.

Charged Lepton Flavor Violation ($e^+ \to \mu^+$)

[Furletova, SM]



$$e^+ + N \to \mu^+ + X$$

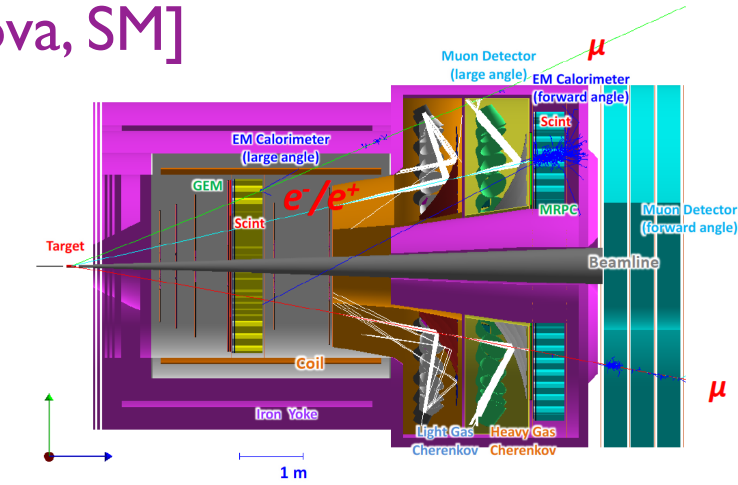


Fig. 3. The SoLID J/Ψ configuration with muon detectors [28]. Other sub-detectors are labeled.

- Low center of mass energy but high luminosity:

$$\sqrt{s} \sim 4.5 \text{ GeV}$$
$$\mathcal{L} \sim 10^{36} \text{ - } 10^{39} \text{ cm}^{-2} \text{ s}^{-1}$$

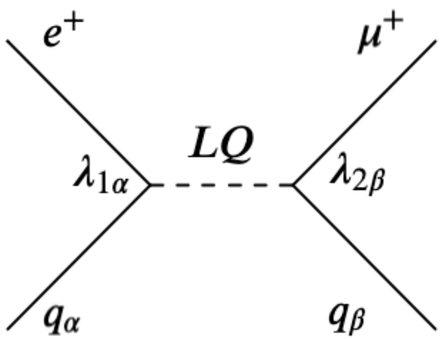
- Detectors should be equipped with muon detectors and a good tracker. Proposed SoLID spectrometer meets these requirements

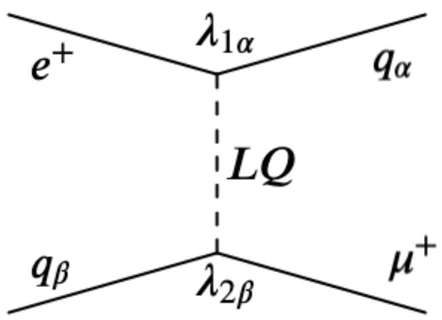
- High luminosity will allow for substantial improvement over HERA limits on CLFV.

- For $\mathcal{L} \sim 10^{38}\ cm^{-2} s^{-1}$ one can expect two to three orders of magnitude improvement over HERA.

Charged Lepton Flavor Violation via Leptoquarks

- Convenient to study CLFV in Leptoquark framework which mediates CLFV at tree-level:





$$\sigma^{e^+p}_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{2\beta}}{M^2_{LQ}}\right]^2 \int dx \int dy \left\{ x q_\alpha(x, xs) f(y) + x\bar{q}_\beta(x, -u) g(y) \right\}$$

$$\sigma^{e^+p}_{|F|=2} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{1\alpha}\lambda_{2\beta}}{M^2_{LQ}}\right]^2 \int dx \int dy \left\{ x\bar{q}_\alpha(x, xs) f(y) + q_\beta(x, -u) g(y) \right\}$$

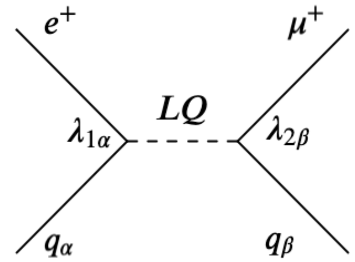
- 14 LQ states. Positron beam can help disentangle F=0 and |F|=2 LQ states. Polarized beams can help distinguish between left-handed and right-handed LQs.

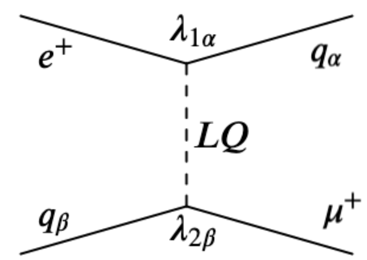
Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e^-_L u_L \rightarrow \ell^- u$	λ_L	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
S_0^R	0	2	$-1/3$	$e^-_R u_R \rightarrow \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e^-_R d_R \rightarrow \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$	$e^-_L u_L \rightarrow \ell^- u$	$-\lambda_L$	1/2
				$\nu_\ell d$	$-\lambda_L$	1/2
			$-4/3$	$e^-_L d_L \rightarrow \ell^- d$	$-\sqrt{2}\lambda_L$	1
$V_{1/2}^L$	1	2	$-4/3$	$e^-_L d_R \rightarrow \ell^- d$	λ_L	1
$V_{1/2}^R$	1	2	$-1/3$	$e^-_R u_L \rightarrow \ell^- u$	λ_R	1
			$-4/3$	$e^-_R d_L \rightarrow \ell^- d$	λ_R	1
$\tilde{V}_{1/2}^L$	1	2	$-1/3$	$e^-_L u_R \rightarrow \ell^- u$	λ_L	1

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
V_0^L	1	0	$+2/3$	$e^+_R d_L \rightarrow \ell^+ d$	λ_L	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
V_0^R	1	0	$+2/3$	$e^+_L d_R \rightarrow \ell^+ d$	λ_R	1
$\tilde{V}_0^R$	1	0	$+5/3$	$e^+_L u_R \rightarrow \ell^+ u$	λ_R	1
V_1^L	1	0	$+2/3$	$e^+_R d_L \rightarrow \ell^+ d$	$-\lambda_L$	1/2
				$\bar{\nu}_\ell u$	λ_L	1/2
			$+5/3$	$e^+_R u_L \rightarrow \ell^+ u$	$\sqrt{2}\lambda_L$	1
$S_{1/2}^L$	0	0	$+5/3$	$e^+_R u_R \rightarrow \ell^+ u$	λ_L	1
$S_{1/2}^R$	0	0	$+2/3$	$e^+_L d_L \rightarrow \ell^+ d$	$-\lambda_R$	1
			$+5/3$	$e^+_L u_L \rightarrow \ell^+ u$	λ_R	1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e^+_R d_R \rightarrow \ell^+ d$	λ_L	1

- HERA put limits on the ratio of the product LQ couplings and the LQ mass squared:

$$\chi_{\alpha\beta} \equiv \frac{\lambda_{1\alpha}\lambda_{2\beta}}{M_{LQ}^2}$$





- Define "z" such that z=1 corresponds to the HERA limit and z< 1 an improvement over the HERA limit:

[Furletova, SM]

$$z \equiv \frac{\chi_{\alpha\beta}}{\chi_{\alpha\beta}^{\mathrm{HERA}}}$$

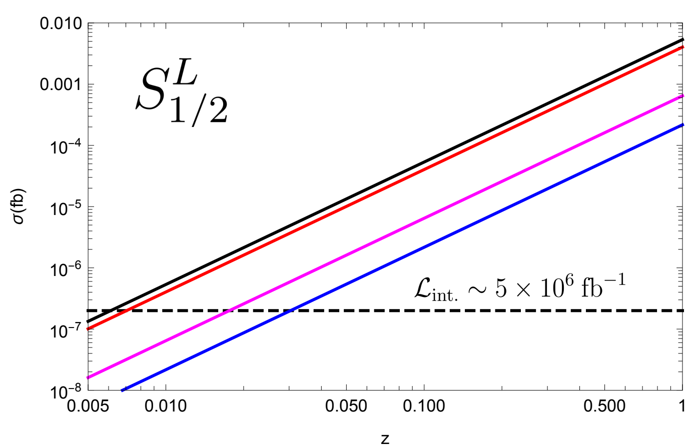


Fig. 5. The cross section for $e^+N \to \mu^+X$ with center of mass energy $\sqrt{s} = 4.5$ GeV, via exchange of the F=0 scalar LQ, $S^L_{1/2}$, as a function of the ratio z defined in Eq. (9). The red, black, magenta, and blue solid lines correspond to the choices $(\alpha, \beta) = \{11, 12, 21, 22\}$ in Eq. (6) with all other terms set to zero. An integrated luminosity of $\mathcal{L} \sim 5 \times 10^6 \mathrm{fb}^{-1}$ will allow sensitivity to cross sections as small as $\sigma \sim 0.2 \times 10^{-6}$ fb (horizontal dashed line).

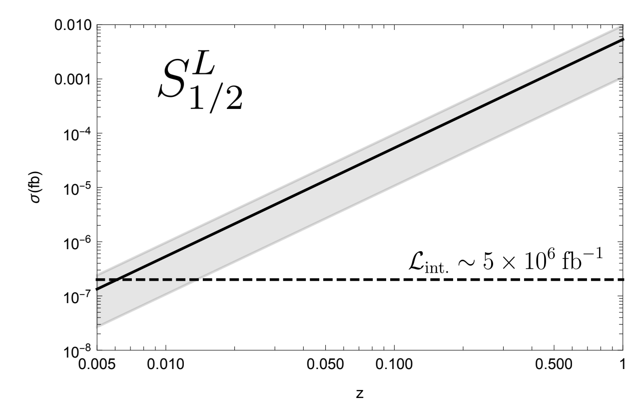


Fig. 6. The positron beam polarization dependence of cross section for $e^+N \to \mu^+X$ with center of mass energy $\sqrt{s} = 4.5$ GeV, via exchange of the F=0 scalar LQ, $S^L_{1/2}$, as a function of the ratio z defined in Eq. (9). The solid black line corresponds to the cross section for an unpolarized positron beam ($P_e = 0$). The gray band corresponds to the linear variation of the cross section with beam polarization, as shown in Eq. (11). The size of the band corresponds to a variation of the beam polarization between [-80%,80%].

Conclusions

- PVDIS at JLAB can provide unique and complementary information to constrain new physics
- 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
- Additionally, could improve on HERA limits for Charged Lepton Violation ($e \to \mu$)