BSM Physics at the EIC Mini Ad-hoc Workshop

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Physics Beyond the Standard Model at the EIC

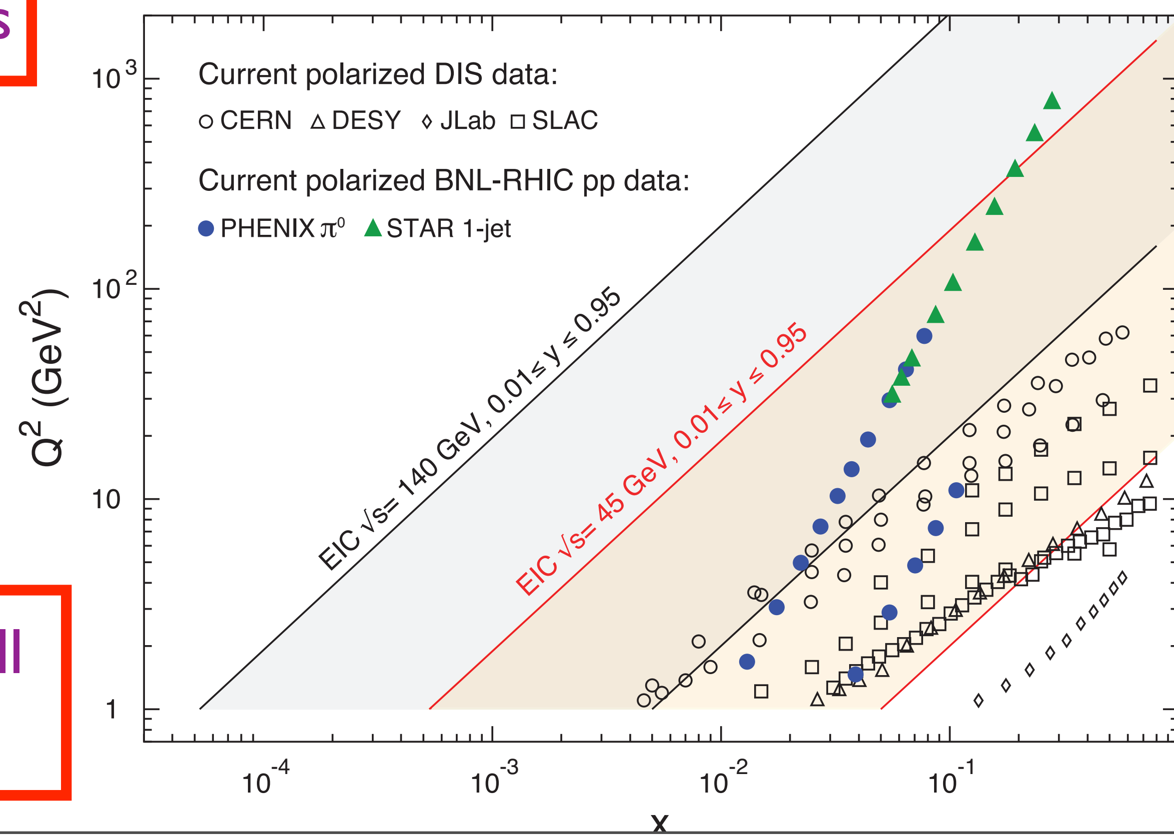
- The EIC is primarily a QCD machine. But it can also provide for a vibrant program to study physics beyond the Standard Model (BSM), complementing efforts at other colliders.

- The EIC can play an important role in searching/constraining various new physics scenarios that include:
  - Leptoquarks
  - R-parity violating Supersymmetry
  - Right-handed W-bosons
  - Excited leptons (compositeness)
  - Dark Photons
  - Charged Lepton Flavor Violation (CLFV)
  - ...

- New physics can be constrained through:
  - Precision measurements of the electroweak parameters

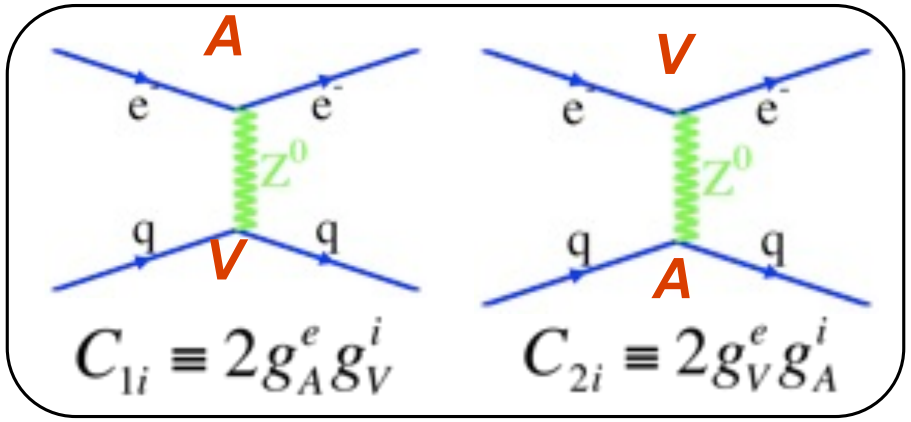
- Such a program physics is facilitated by:
  - high luminosity
  - wide kinematic range
  - range of nuclear targets
  - polarized beams

★ The addition of a polarized positron beam will enhance the BSM program at the EIC.



Precision Measurements of the Weak Neutral Current Couplings

Contact Interactions



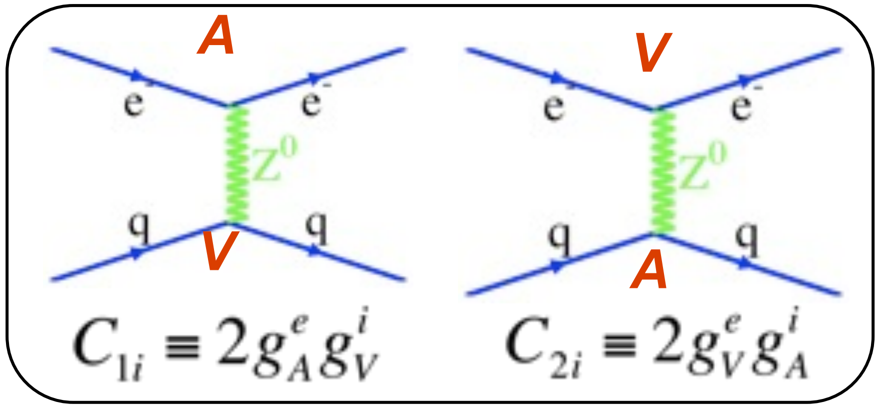
- For $Q^2 << (M_Z)^2$ limit, electron-quark scattering via the weak neutral current is mediated by contact interactions:

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

- 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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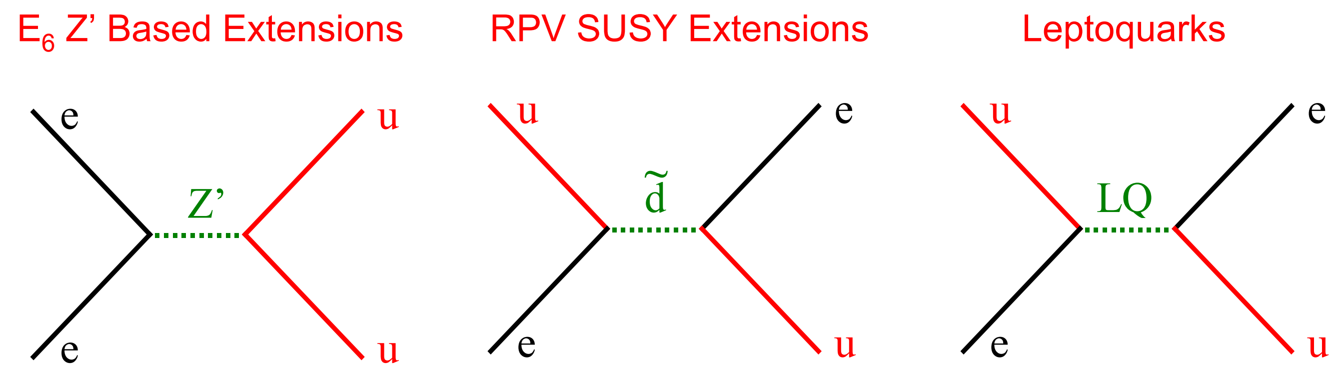


$$\mathcal{L} = \frac{G_F}{\sqrt{2}} \sum_{\ell,q} \left[C_{1q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu q + C_{2q}\, \bar{\ell}\gamma^\mu\ell\bar{q}\gamma_\mu\gamma_5 q + C_{3q}\, \bar{\ell}\gamma^\mu\gamma_5\ell\bar{q}\gamma_\mu\gamma_5 q \right]$$

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

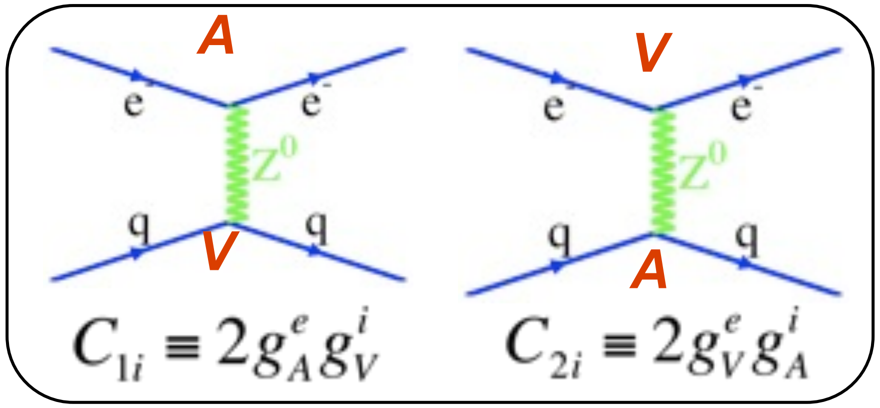
$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

SM contribution

New Physics contribution

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

New Physics Effects



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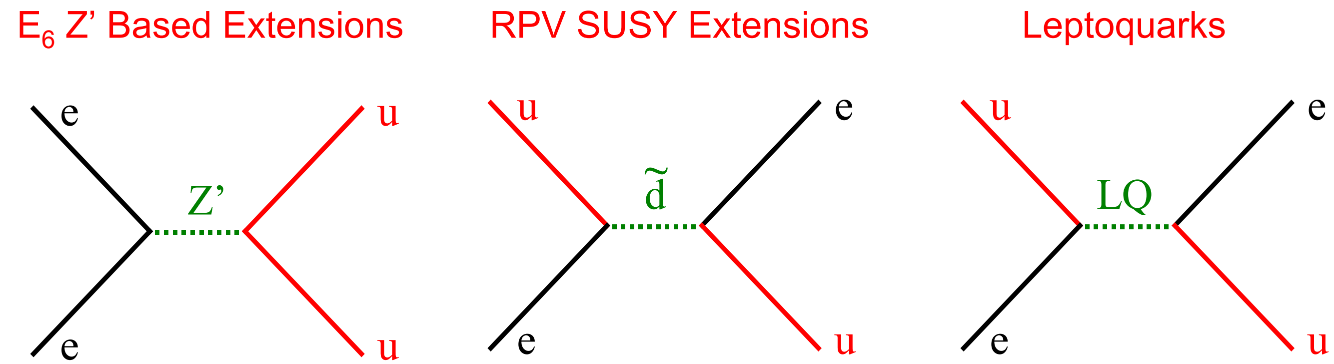


$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

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

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

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

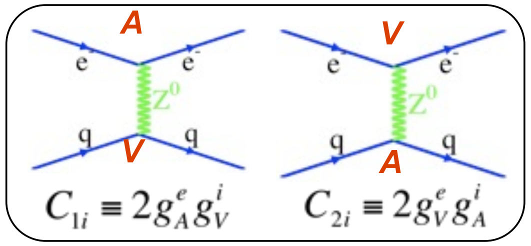
$$\Delta C_{1q} = \frac{g^2}{\Lambda^2}\frac{\eta^{\ell q}_{LL} + \eta^{\ell q}_{LR} - \eta^{\ell q}_{RL} - \eta^{\ell q}_{RR}}{2\sqrt{2}G_F},$$

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

$$\Delta C_{3q} = \frac{g^2}{\Lambda^2}\frac{-\eta^{\ell q}_{LL} + \eta^{\ell q}_{LR} + \eta^{\ell q}_{RL} - \eta^{\ell q}_{RR}}{2\sqrt{2}G_F}.$$

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 $e^\pm p$

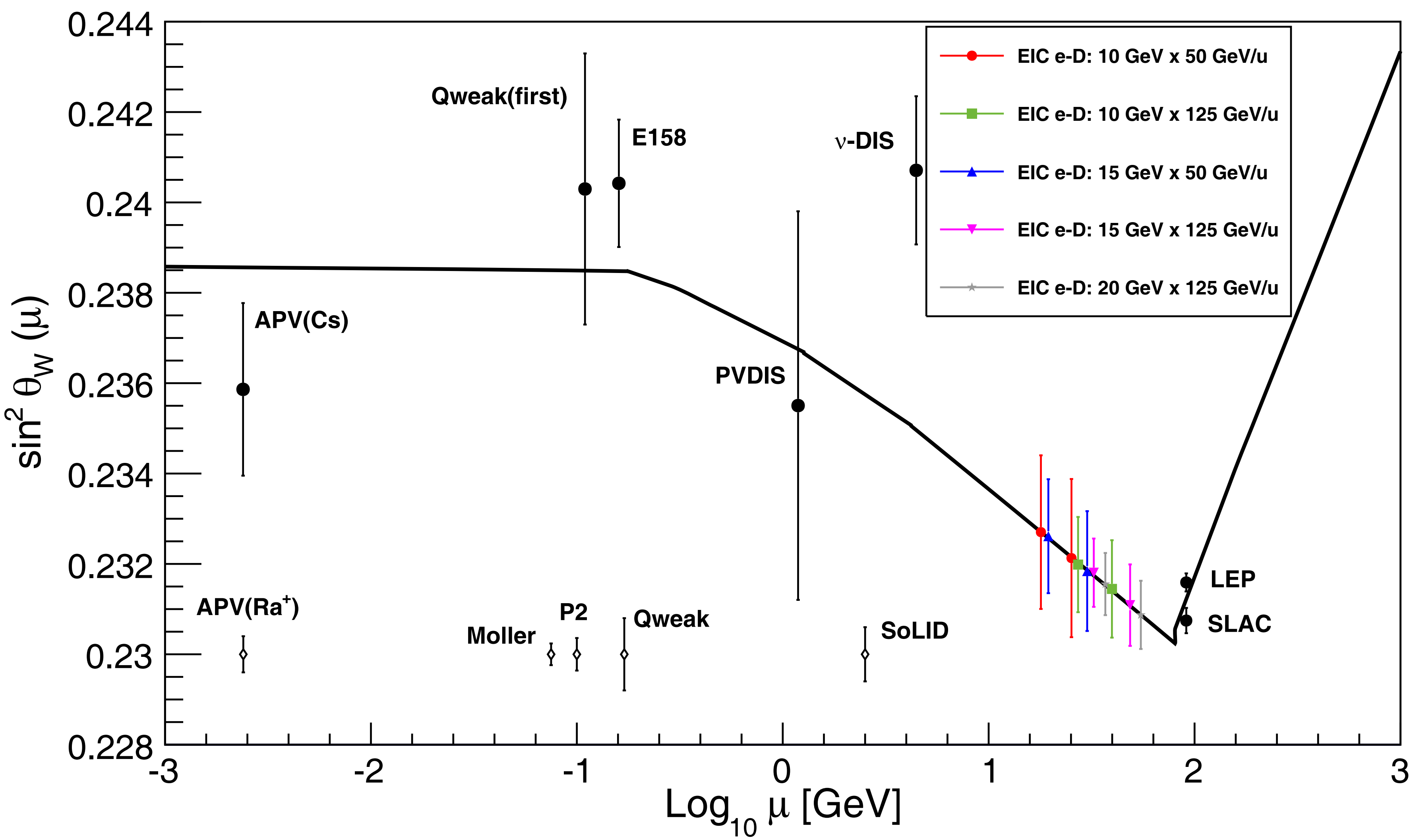
Model	Coupling structure								95% CL [TeV]
	a^{ed}_{LL}	a^{ed}_{LR}	a^{ed}_{RL}	a^{ed}_{RR}	a^{eu}_{LL}	a^{eu}_{LR}	a^{eu}_{RL}	a^{eu}_{RR}	M_{LQ}/λ_{LQ}
$S^L_\circ$					$+\frac{1}{2}$				0.75
$S^R_\circ$								$+\frac{1}{2}$	0.69
$\tilde{S}^R_\circ$				$+\frac{1}{2}$					0.31
$S^L_{1/2}$						$-\frac{1}{2}$			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

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

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

$$\Delta C_{3q} = \frac{g^2}{\Lambda^2}\frac{-\eta^{\ell q}_{LL} + \eta^{\ell q}_{LR} + \eta^{\ell q}_{RL} - \eta^{\ell q}_{RR}}{2\sqrt{2}G_F}.$$

Weak Mixing Angle Measurements at the EIC



Projections based on an integrated luminosity of 267 fb^(-1) per nucleon in electron-deuteron collisions at EIC.

[Y.X.Zhao, A.Despande, J.Huang, K.S. Kumar, S.Riordan]

- Deviations from SM predictions for the WNC couplings will lead to corresponding deviations in the SM behavior of the weak mixing angle.

- Wide kinematic range and high luminosity of the EIC can provide many more measurements of the weak mixing angle along this curve.

Precision Measurements of the Weak Neutral Current Couplings

- New physics reach from various precision experiments and the combination of couplings they constrain:

Experiment	Λ	Coupling
Cesium APV	9.9 TeV	$C_{1u} + C_{1d}$
E-158	8.5 TeV	C_{ee}
Qweak	11 TeV	$2C_{1u} + C_{1d}$
SoLID	8.9 TeV	$2C_{2u} - C_{2d}$
MOLLER	19 TeV	C_{ee}
P2	16 TeV	$2C_{1u} + C_{1d}$

[K.kumar, et.al. Ann.Rev.Nucl.Part.Sci. 63 (2013) 237-267]

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

Asymmetries as a Probe of Electroweak Couplings

$$\mathcal{L}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \sum_{\ell,q} \Big[C_{1q} \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_\mu q + C_{2q} \bar{\ell} \gamma^\mu \ell \bar{q} \gamma_\mu \gamma_5 q + C_{3q} \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_\mu \gamma_5 q \Big]$$

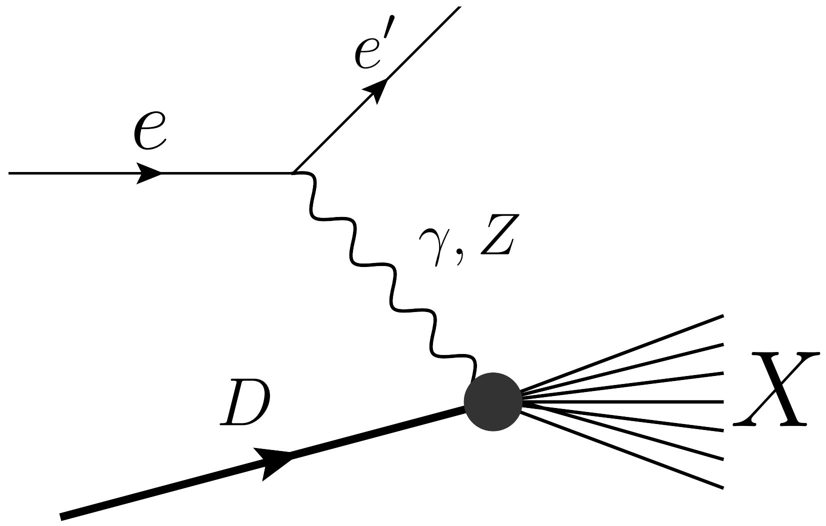
Can be further constrained by
Parity-Violating eD DIS

Can be further constrained by
lepton charge conjugate violating
(positron beams) asymmetry

- Measurement of these asymmetries requires:

-p, D targets
-polarized electron and positron beams

Parity-Violating e-D Asymmetry



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

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

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

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

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:

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

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

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.

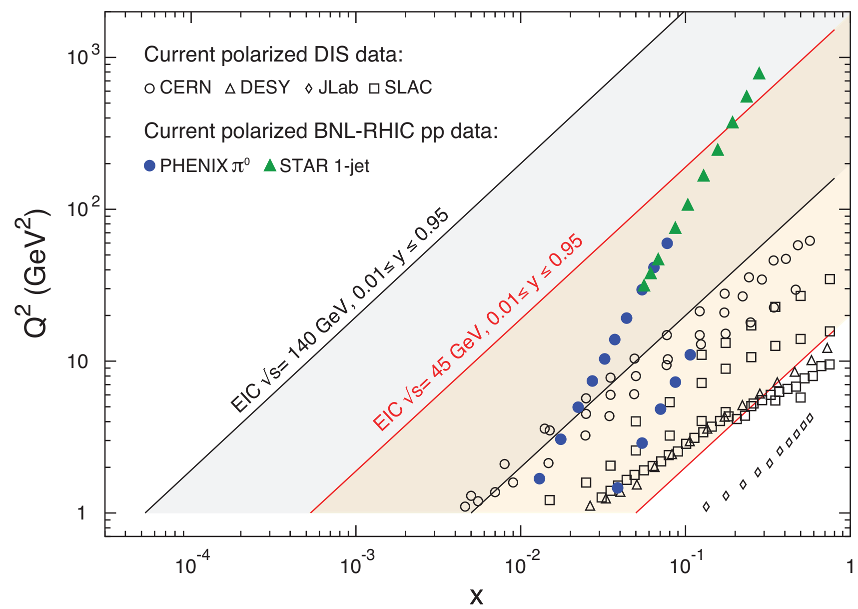
[J.Bjorken, T.Hobbs, W. Melnitchouk; S.Mantry, M.Ramsey-Musolf, G.Sacco; A.V.Belitsky, A.Mashanov, A. Schafer; C.Seng, M.Ramsey-Musolf, ...]

e-D PVDIS at EIC

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

$$a(x) = \frac{6}{5}\left[\left(C_{1u} - \frac{1}{2}C_{1d}\right) + \text{corrections}\right]$$

$$b(x) = \frac{6}{5}\left[\left(C_{2u} - \frac{1}{2}C_{2d}\right)\frac{q(x)-\bar{q}(x)}{q(x)+\bar{q}(x)} + \text{corrections}\right]$$

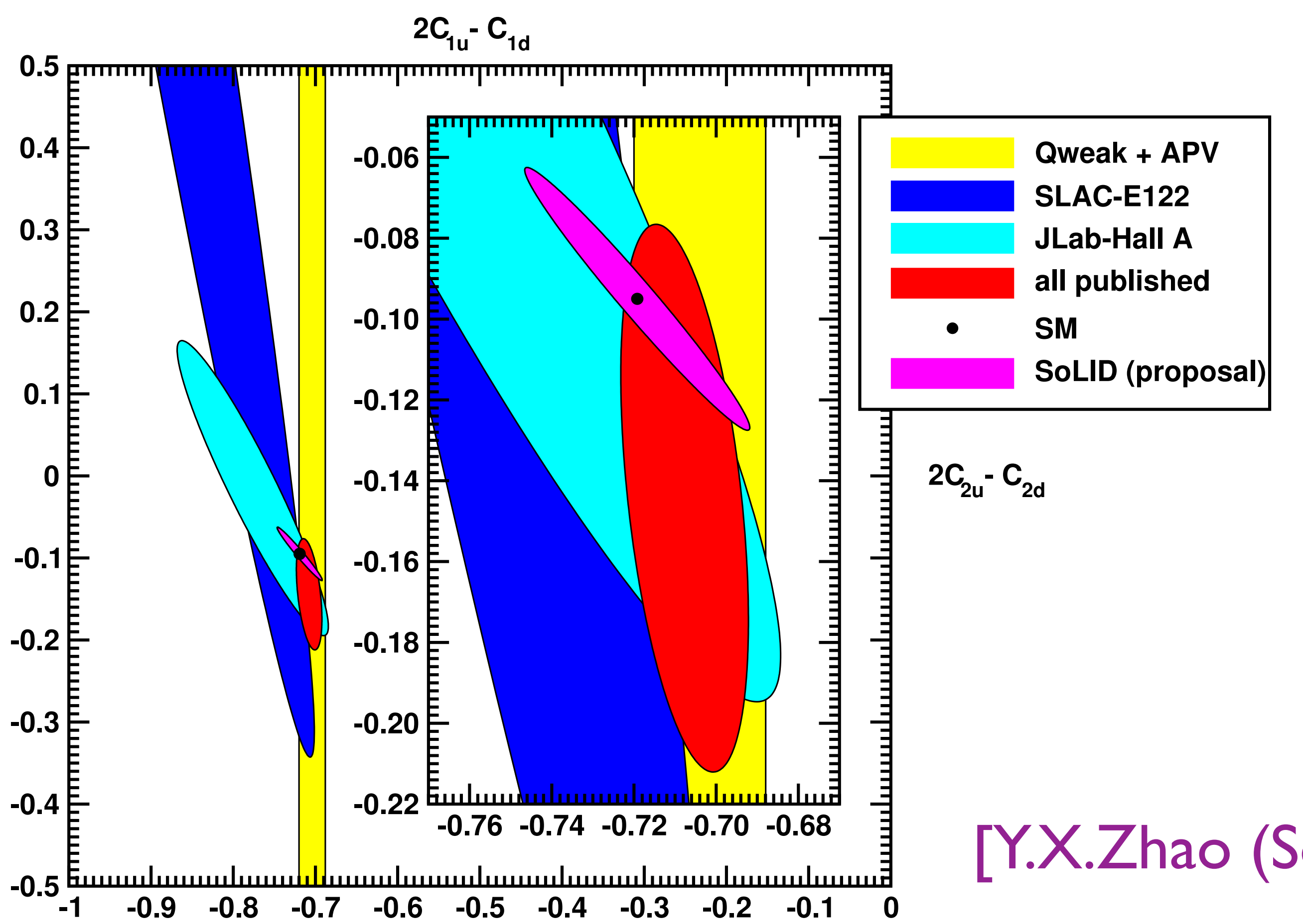


- EIC can make improve on the precision of the WNC couplings.
  - High luminosity:
    - -allows high precision
  - Measurements over wide range of y:
    - -allows clean separation of a(x) and b(x) terms
    - -clean separation of the combinations of WNC couplings:

$$2C_{1u} - C_{1d}, \; 2C_{2u} - C_{2d}$$

  - Region of high Q^2:
    - -larger asymmetry
    - -suppress higher twist effects
  - Region of high Q^2 and restrict range of Bjorken-x $0.2 \lesssim x \lesssim 0.5$
    - -suppress sea quark effects

Status of WNC Couplings



[Y.X.Zhao (SoLID Collaboration)]

- 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:

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

- The JLAB 12 GeV (SoLID) program is expected to measure $2C_{2u} - C_{2d}$ to within 10%.
- The EIC can further improve on the JLAB 12 GeV expected result by a factor of 2 or 3 at 100fb^(-1).

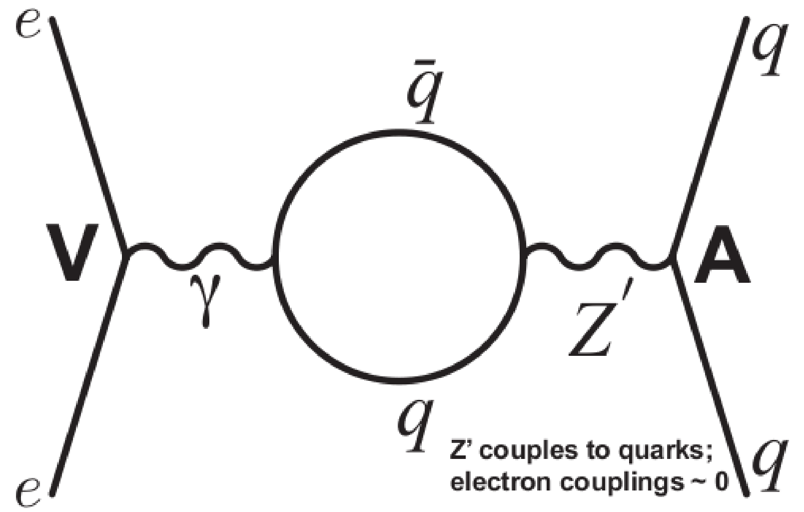
Leptophobic Z'

- Leptophobic Z's are an interesting BSM scenario for a high luminosity EIC to probe.

- Leptophobic Z's couple very weakly to leptons:

  -difficult to constrain at colliders due to large QCD backgrounds

- 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]

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi\alpha}\left[a(x) + \frac{1-(1-y)^2}{1+(1-y)^2} b(x)\right]$$

Mass Reach of 6 and 12 GeV JLAB

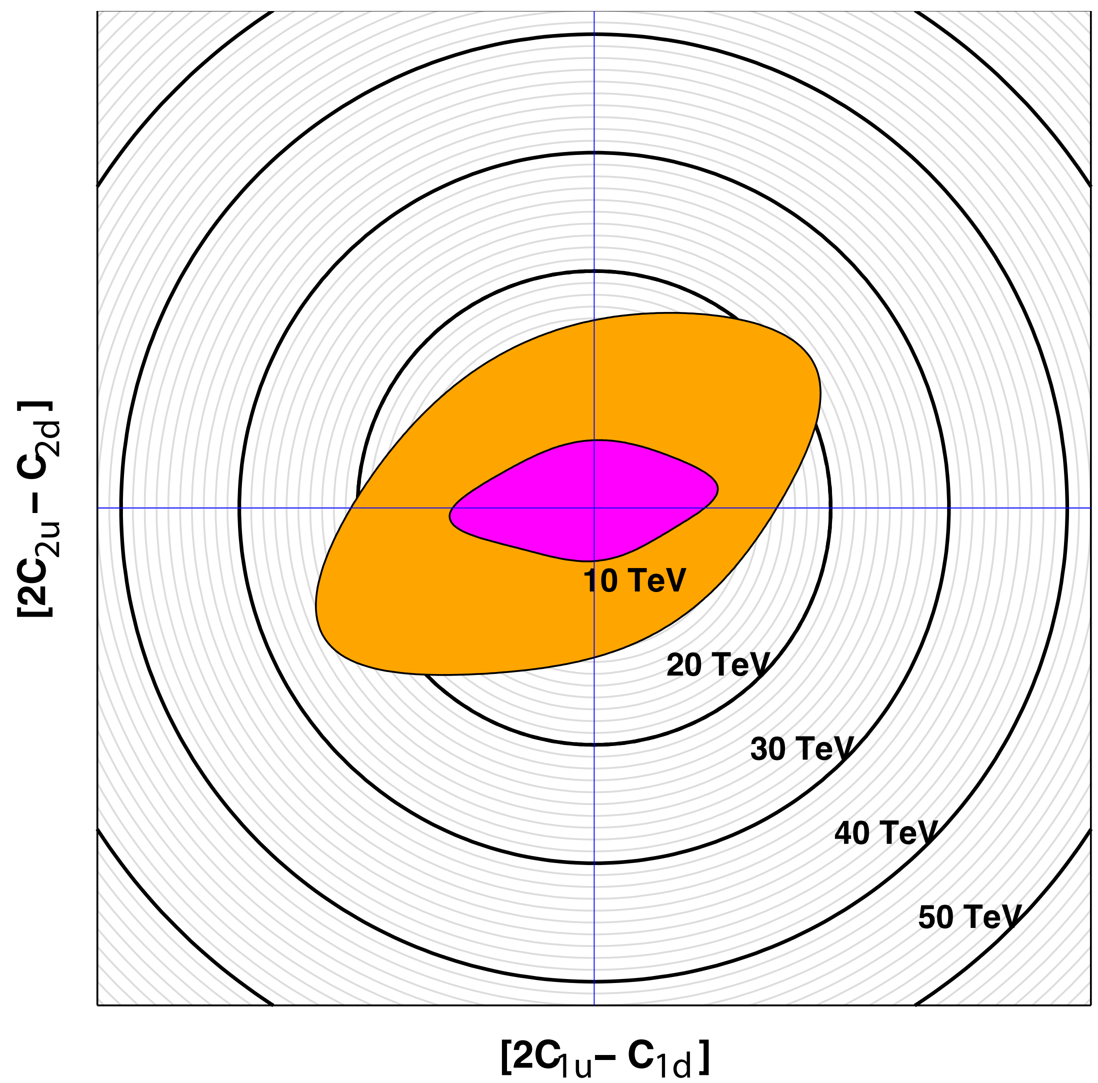
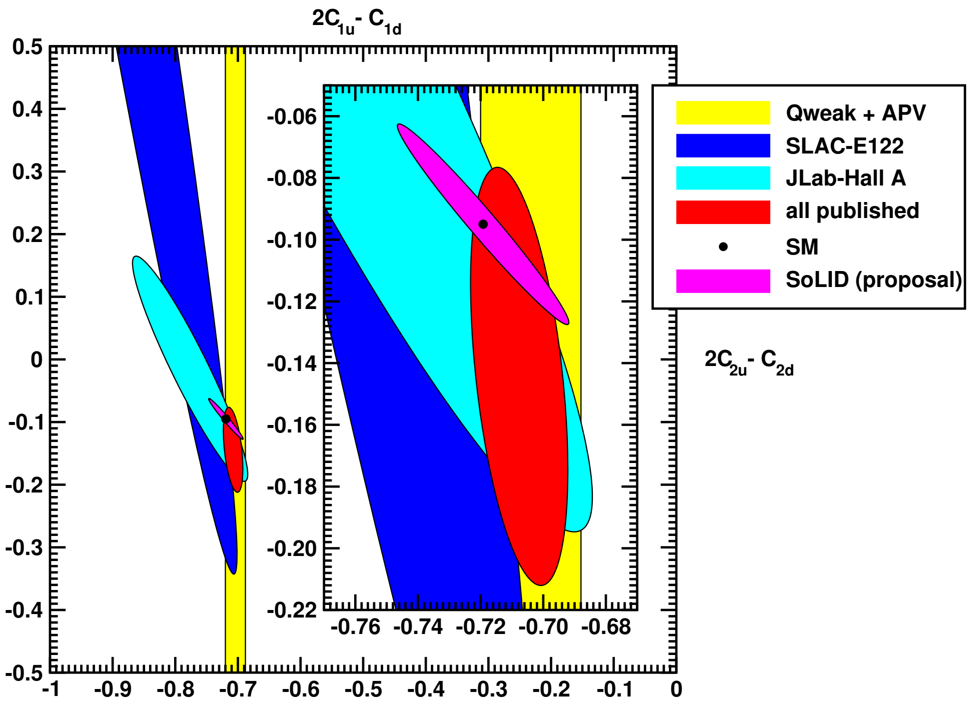


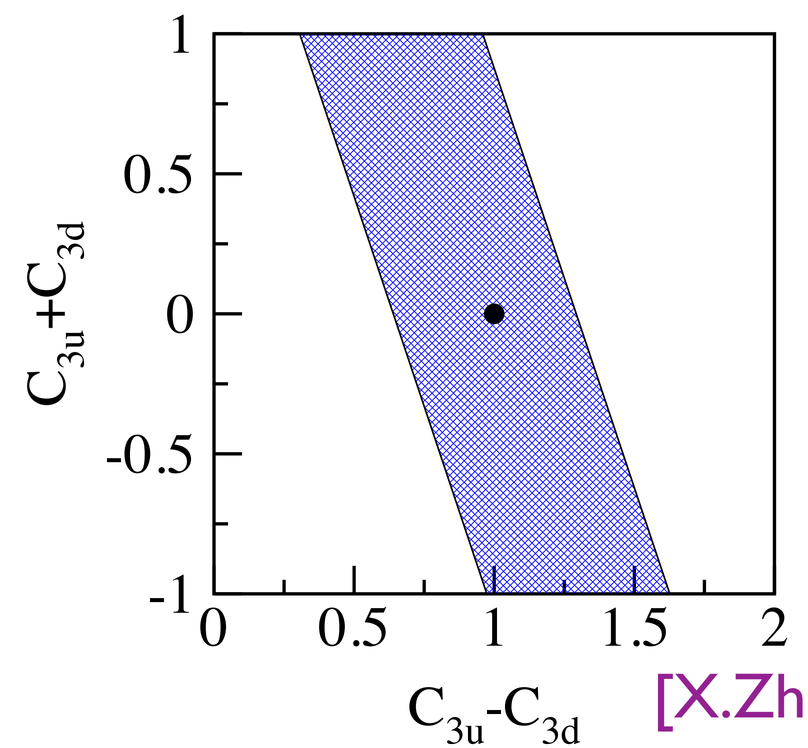
FIG. 4. (Color online) Mass-exclusion plot of the mass scales of new contact interactions assuming a physics coupling strength of $g^2 = 4\pi$. The pink (inner) region illustrates the reach by combining the 6 GeV PVDIS experiment at JLab and other precision experiments [7], the orange (outer) region shows the new reach assuming final precision from Qweak [11] and SoLID PVDIS.

[Y.X.Zhao (SoLID Collaboration)]

- The EIC can further improve on the JLAB 12 GeV expected result.

The C3q Couplings





[X.Zheng Proc. JPOS 2009]

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

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

$$0.81(2C_{2u} - C_{2d}) + 2C_{3u} - C_{3d} = 1.53 \pm 0.45$$

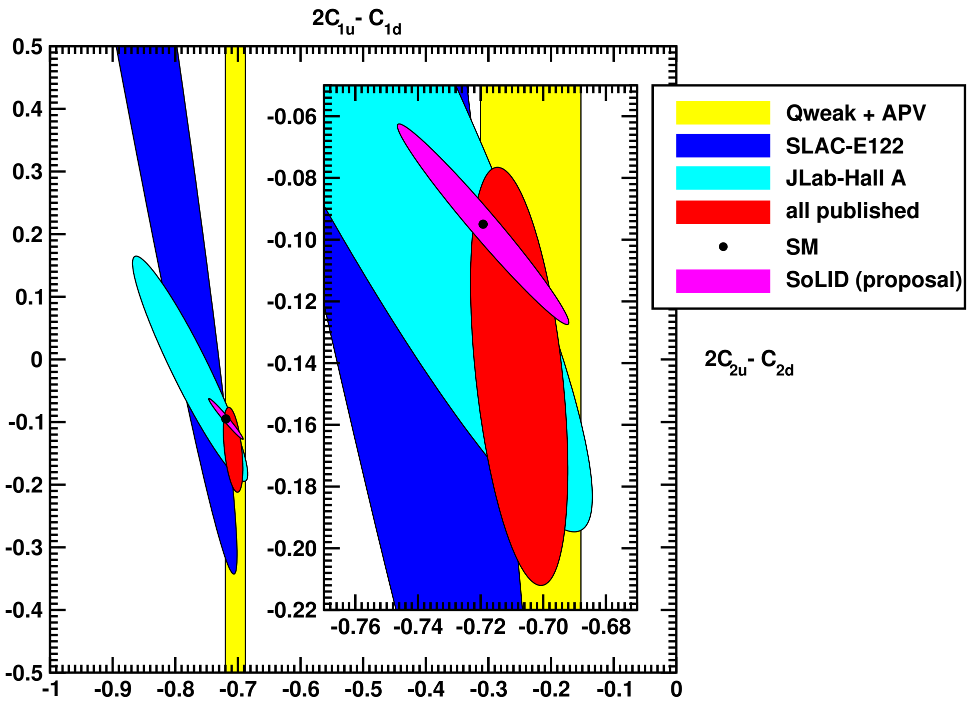
Using 12 GeV JLAB result for the C2q couplings

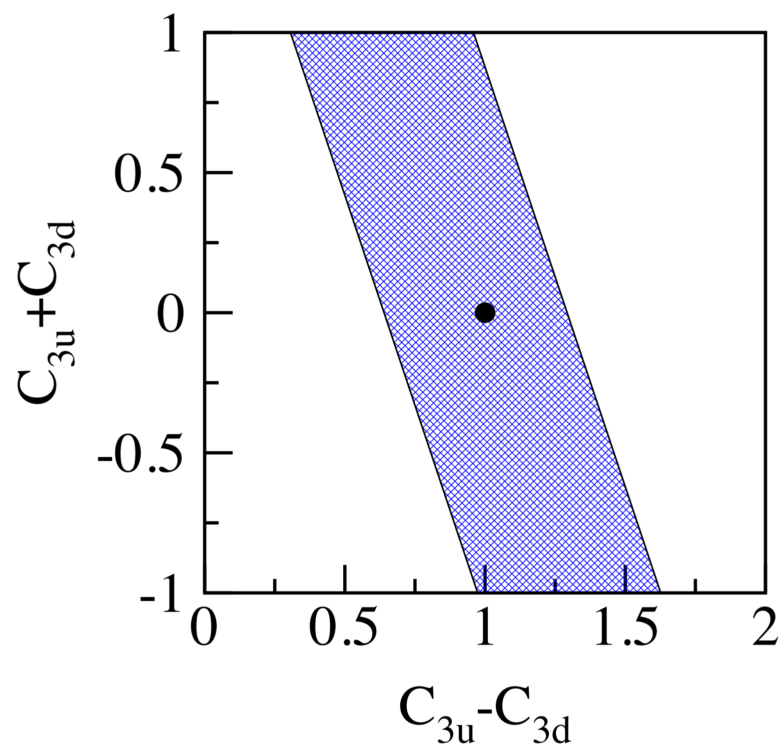
$$2C_{3u} - C_{3d} = 1.65 \pm 0.453$$

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

- The combination of C3q couplings only known to within 30%.

The C3q Couplings





[S.M.Berman, J.R. Primack (1974), X.Zheng Proc. JPOS 2009]

- There is a unique opportunity to use a polarized positron beam at the 12 GeV JLAB program to extract the C3q coupling combination to within ~3%.

- What about at the EIC?

C-Violating Asymmetry using Polarized Electron and Positron Beams

[S.M.Berman, J.R. Primack (1974), X.Zheng Proc. JPOS 2009]

- C-violating asymmetry:

$$A^{l_L^- - l_R^+} = \frac{d\sigma\left(l_L^- + N \to l_L^- + X\right) - d\sigma\left(l_R^+ + N \to l_R^+ + X\right)}{d\sigma\left(l^- + N \to l^- + X\right) + d\sigma\left(l^+ + N \to l^+ + X\right)}$$

- Proton target:

$$A_p^{e_L^- - e_R^+} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right) \frac{y(2-y)}{2} \frac{2C_{2u}u_V - C_{2d}d_V + 2C_{3u}u_V - C_{3d}d_V}{4u+d}$$

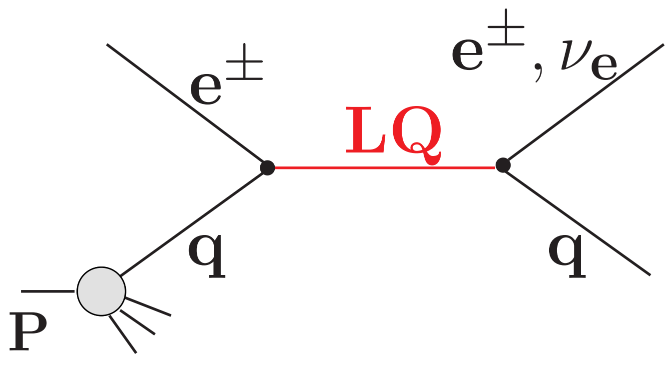
- Isoscalar deuteron target:

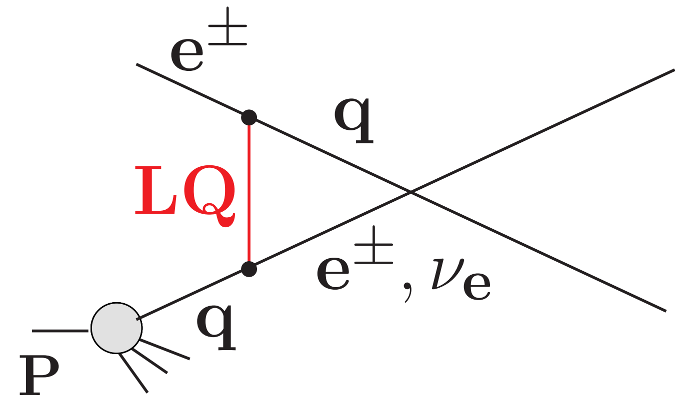
$$A_d^{e_L^- - e_R^+} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right) \frac{y(2-y)}{2} \frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d})R_V}{5}, \qquad R_V \equiv (u_V + d_V)/(u+d)$$

- Corrections will arise from other hadronic effects.

Contact Interactions arising from Leptoquarks

Leptoquarks





- Leptoquarks (LQs) are color triplet bosons that couple leptons to quarks

- LQs arise in many BSM models:
    - Pati-Salam Model
    - GUTs: SU(5), SO(10),...
    - Extended Technicolor

- LQs have a rich phenomenology and come in 14 types, classified according to:
    - Fermion number F=3B+L [|F|=0, 2]
    - Spin [scalar (S) or vector (V)]
    - Chirality of coupling to leptons [L or R]
    - Gauge group quantum numbers [SU(2)_L X U(1)_Y]

Leptoquarks

- Renormalizable and gauge invariant couplings of LQs to quarks and leptons:

$$\begin{aligned}\mathcal{L}_{F=0} &= h^L_{1/2}\overline{u}_R\ell_L S^L_{1/2} + h^R_{1/2}\overline{q}_L\epsilon e_R S^R_{1/2} + \tilde{h}^L_{1/2}\overline{d}_R\ell_L\tilde{S}^L_{1/2} + h^L_0\overline{q}_L\gamma_\mu\ell_L V_0^{L\mu} \\ &\quad + h^R_0\overline{d}_R\gamma_\mu e_R V_0^{R\mu} + \tilde{h}^R_0\overline{u}_R\gamma_\mu e_R\tilde{V}_0^{R\mu} + h^L_1\overline{q}_L\gamma_\mu\vec{\tau}\ell_L\vec{V}_1^{L\mu} + \mathrm{h.c.}\end{aligned}$$

$$\begin{aligned}\mathcal{L}_{|F|=2} &= g^L_0\overline{q}^c_L\epsilon\ell_L S^L_0 + g^R_0\overline{u}^c_R e_R S^R_0 + \tilde{g}^R_0\overline{d}^c_R e_R\tilde{S}^R_0 + g^L_1\overline{q}^c_L\epsilon\vec{\tau}\ell_L\vec{S}^L_1 + g^L_{1/2}\overline{d}^c_R\gamma_\mu\ell_L V^{L\mu}_{1/2} \\ &\quad + g^R_{1/2}\overline{q}^c_L\gamma_\mu e_R V^{R\mu}_{1/2} + \tilde{g}^L_{1/2}\overline{u}^c_R\gamma_\mu\ell_L\tilde{V}^{L\mu}_{1/2} + \mathrm{h.c.}\end{aligned}$$

- Classification of the 14 types of LQs: [Buchmuller, Ruckl, Wyler (BRW)]

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

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

Leptoquarks

[Buchmuller, Ruckl, Wyler (BRW)]

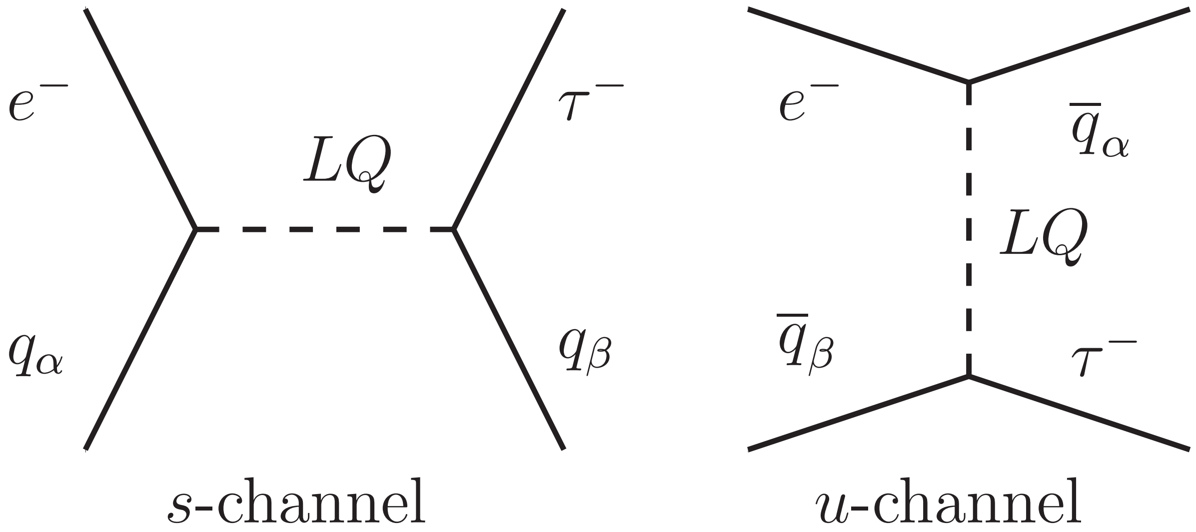
Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \to \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	λ_L $-\lambda_L$	1/2 1/2
S_0^R	0	2	$-1/3$	$e_R^- u_R \to \ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \to \ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$ $-4/3$	$e_L^-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

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

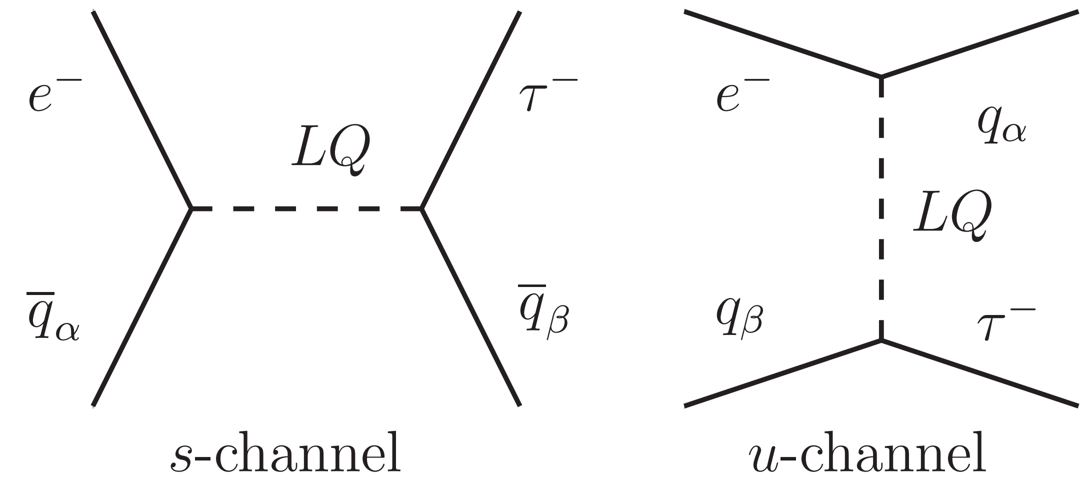
- In order to maximally exploit the phenomenology of LQs and be able to distinguish between different types of LQ states, we need:

  - -electron and positron beams [separate |F|=0 vs |F|=2]
  - -proton and deuteron targets [separate “eu” vs “ed” LQs]
  - -polarized beams [separate L vs R]
  - -wide kinematic range [separate scalar vs vector LQs]

Leptoquarks: Electron vs Positron Beams



$|F| = 2$



$F = 0$

- With electron beams, LQs couple to:

  |F|= 2:
  - -quarks in s-channel
  - -antiquarks in u-channel

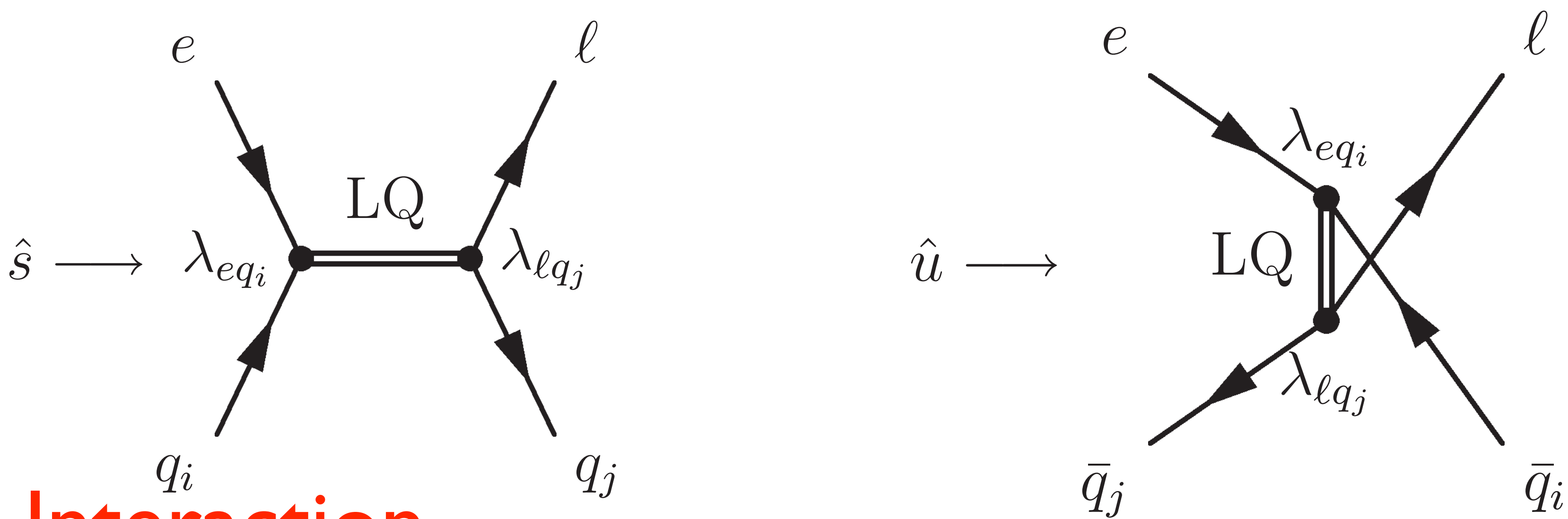
  F= 0:
  - -antiquarks in s-channel
  - -quarks in the u-channel

- With positron beams, LQs couple to:

  |F|= 2:
  - -antiquarks in s-channel
  - -quarks in u-channel

  F= 0:
  - -quarks in s-channel
  - -antiquarks in the u-channel

Leptoquarks: Electron vs Positron Beams



Contact Interaction

- For $M_{\mathrm{LQ}} \gg \sqrt{s}$, the cross section for contact-interaction mediated processes are:

$$\sigma_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{eq_i}\lambda_{\ell q_j}}{M_{LQ}^2} \right]^2 \left\{ \int dxdy\; x\bar{q}_\alpha (x, xs)\, f(y) + \int dxdy\; xq_\beta (x, -u)\, g(y) \right\}$$

$$\sigma_{|F|=2} = \sum_{\alpha,\beta} \frac{s}{32\pi} \left[\frac{\lambda_{eq_i}\lambda_{\ell q_j}}{M_{LQ}^2} \right]^2 \left\{ \int dxdy\; xq_\alpha (x, xs)\, f(y) + \int dxdy\; x\bar{q}_\beta (x, -u)\, g(y) \right\}$$

$$f(y) = \begin{cases} 1/2 & \text{(scalar)} \\ 2(1-y)^2 & \text{(vector)} \end{cases}, \quad g(y) = \begin{cases} (1-y)^2/2 & \text{(scalar)} \\ 2 & \text{(vector)} \end{cases} \longrightarrow$$

y-dependence can distinguish scalar and vector leptoquarks

Leptoquarks: Polarized Lepton and Nuclear (p,D) Beams

Type	J	F	Q	ep dominant process	Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$	λ_L $-\lambda_L$	$1/2$ $1/2$
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	$-1/3$ $-4/3$	$e_L^- u_L \rightarrow \begin{cases} \ell^- u \\ \nu_\ell d \end{cases}$ $e_L^- d_L \rightarrow \ell^- d$	$-\lambda_L$ $-\lambda_L$ $-\sqrt{2}\lambda_L$	$1/2$ $1/2$ 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	$-1/3$ $-4/3$	$e_R^- u_L \rightarrow \ell^- u$ $e_R^- d_L \rightarrow \ell^- d$	λ_R λ_R	1 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	$+2/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$	λ_L λ_L	$1/2$ $1/2$
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	$+2/3$ $+5/3$	$e_R^+ d_L \rightarrow \begin{cases} \ell^+ d \\ \bar{\nu}_\ell u \end{cases}$ $e_R^+ u_L \rightarrow \ell^+ u$	$-\lambda_L$ λ_L $\sqrt{2}\lambda_L$	$1/2$ $1/2$ 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	$+2/3$ $+5/3$	$e_L^+ d_L \rightarrow \ell^+ d$ $e_L^+ u_L \rightarrow \ell^+ u$	$-\lambda_R$ λ_R	1 1
$\tilde{S}_{1/2}^L$	0	0	$+2/3$	$e_R^+ d_R \rightarrow \ell^+ d$	λ_L	1

- Different nuclear targets (p vs D) can help untangle different leptoquark states ("eu" vs "ed" LQs).

- The chiral structure can be further unraveled through asymmetries involving both polarized lepton and nuclear beams.

> We feel that it was important to get an answer to the following question : are both (lepton and proton) polarizations mandatory to completely disentangle the various LQ models present in the BRW lagrangians ? According to our analysis the answer is yes.
>
> -P.Taxil, E.Tugcu, J.M.Virey (Eur.Phys.J. C14 (2000) 165-168)

Leptoquarks: Polarized Lepton and Nuclear (p,D) Beams

- Various asymmetries involving both polarized leptons and e,D beams have been proposed to identify the nature of LQ states.

[P.Taxil, E.Tugcu, J.M.Virey]

$$A_{LL}^{PV}(e^t) = \frac{\sigma_t^{--} - \sigma_t^{++}}{\sigma_t^{--} + \sigma_t^{++}}$$

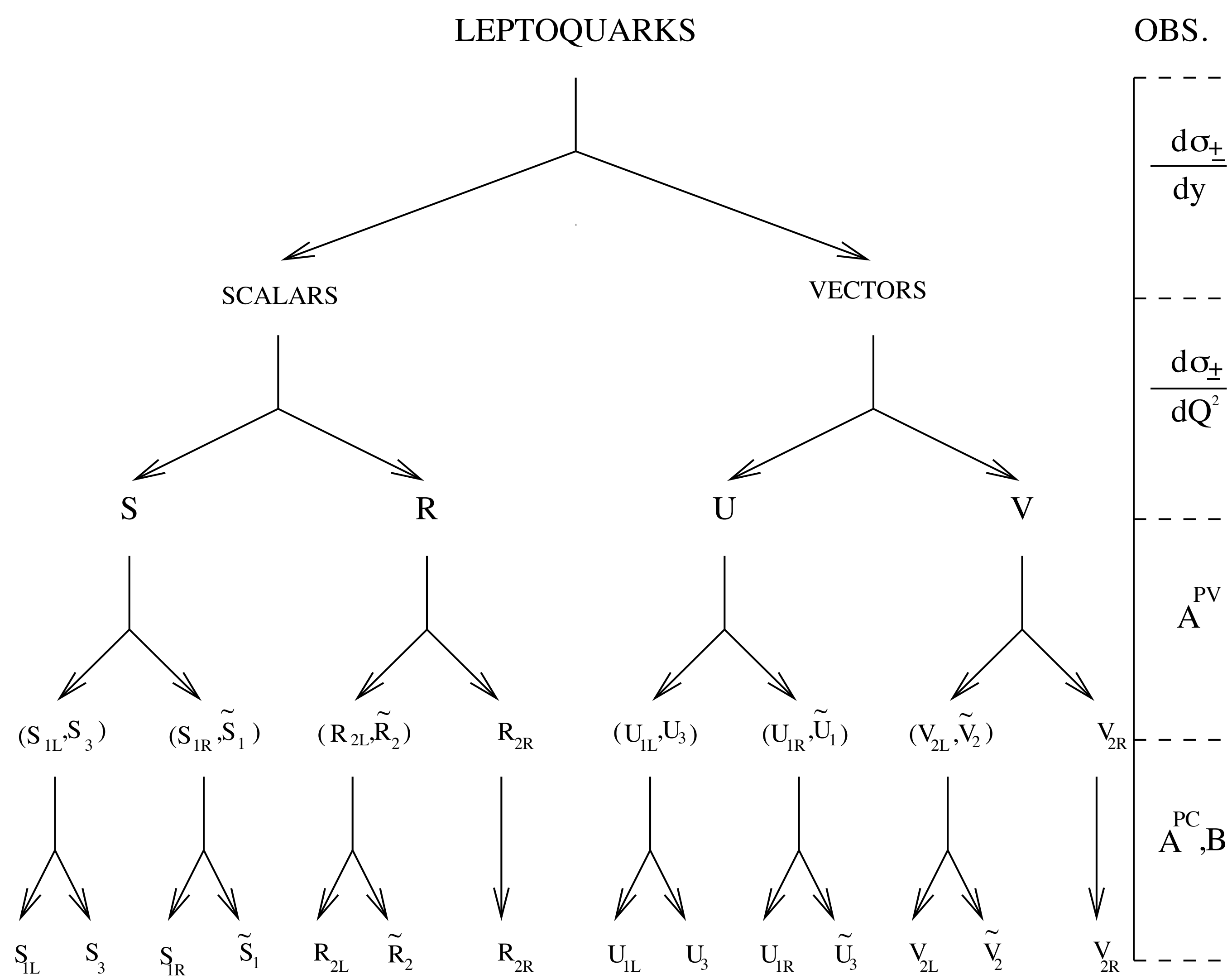
$$A_1^{PC} = \frac{\sigma_-^{--} - \sigma_-^{-+}}{\sigma_-^{--} + \sigma_-^{-+}}$$

$$A_2^{PC} = \frac{\sigma_-^{++} - \sigma_-^{+-}}{\sigma_-^{++} + \sigma_-^{+-}}$$

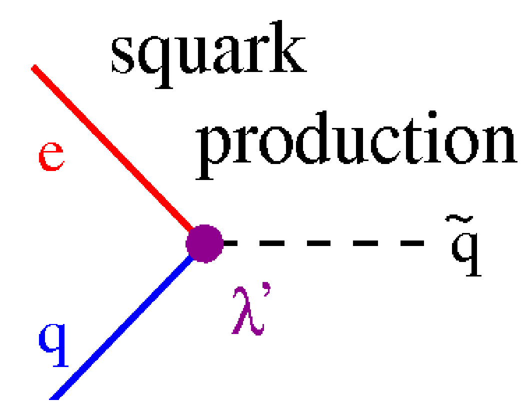
$$A_3^{PC} = \frac{\sigma_+^{++} - \sigma_+^{+-}}{\sigma_+^{++} + \sigma_+^{+-}}$$

$$B_U = \frac{\sigma_-^{--} - \sigma_-^{++} + \sigma_+^{++} - \sigma_+^{--} + \sigma_-^{-+} - \sigma_-^{+-} + \sigma_+^{-+} - \sigma_+^{+-}}{\sigma_-^{--} + \sigma_-^{++} + \sigma_+^{++} + \sigma_+^{--} + \sigma_-^{-+} + \sigma_-^{+-} + \sigma_+^{-+} + \sigma_+^{+-}}$$

$$B_V = \frac{\sigma_-^{--} - \sigma_-^{++} + \sigma_+^{--} - \sigma_+^{++} + \sigma_-^{+-} - \sigma_-^{-+} + \sigma_+^{-+} - \sigma_+^{+-}}{\sigma_-^{--} + \sigma_-^{++} + \sigma_+^{--} + \sigma_+^{++} + \sigma_-^{+-} + \sigma_-^{-+} + \sigma_+^{-+} + \sigma_+^{+-}}$$



R-Parity Violating (RPV) SUSY



- R-parity:

$$R_p = (-1)^{3B+L+2S}$$

- With R-parity violation (RPV), the LSP is no longer stable, and many of the sparticle mass bounds from the LHC can be relaxed.

- SUSY RPV couplings (MSSM):

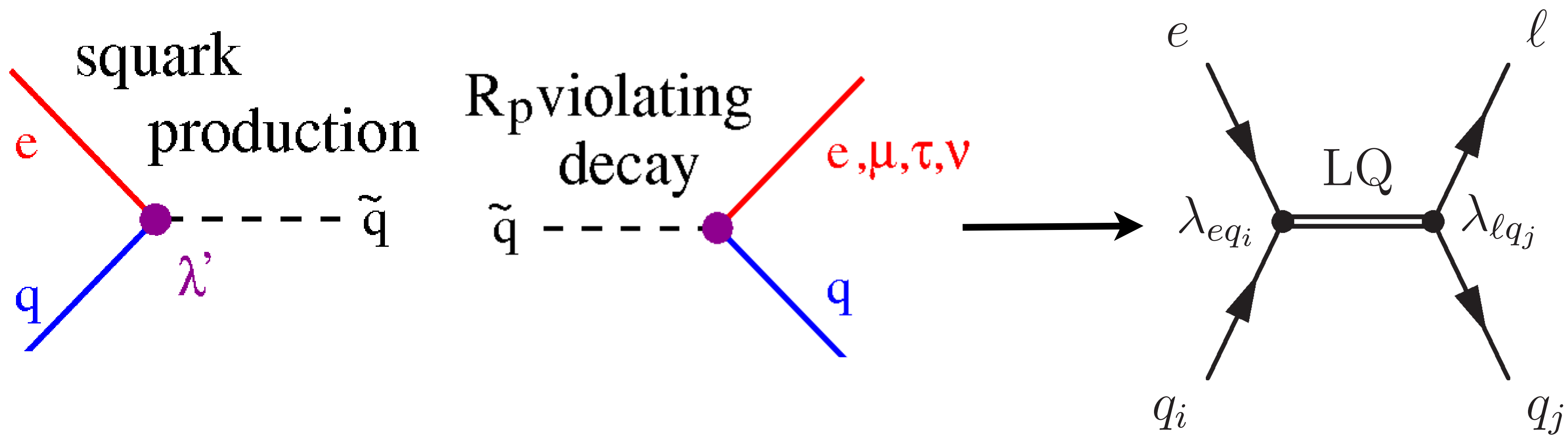
$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \boxed{\lambda'^{ijk} L_i Q_j \bar{d}_k} + \mu'^{i} L_i H_u$$

$$W_{\Delta \mathrm{B}=1} = \frac{1}{2}\lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k$$

Single squark production at HERA, EIC

R-Parity Violating (RPV) SUSY

- For RPV production and RPV decay, the contact interaction generated is the same as through Leptoquarks:

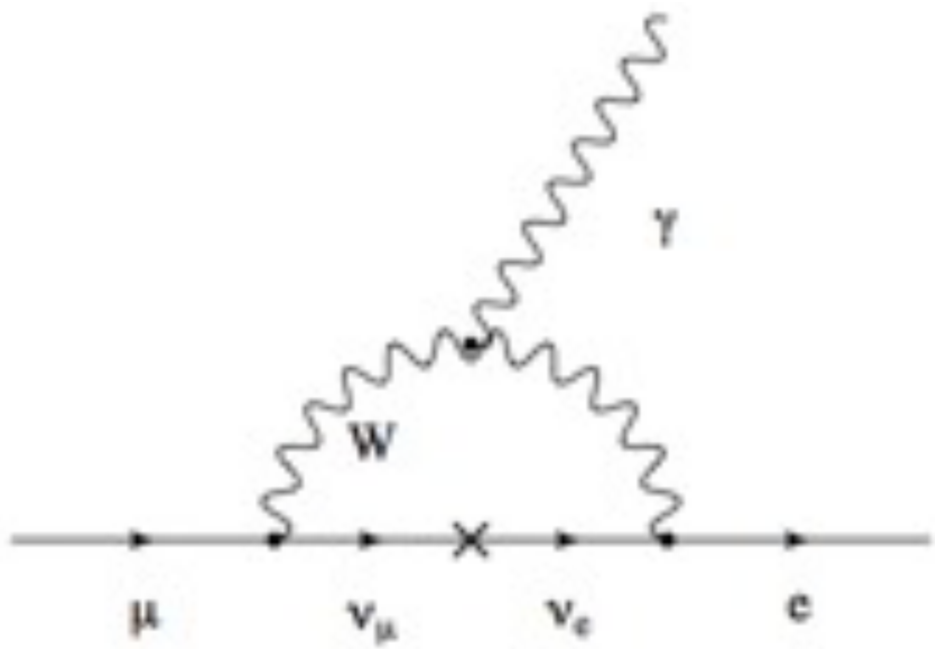


- The bounds on LQs can be applied to squarks if they proceed via RPV decay.

Lepton Flavor Violation

Lepton Flavor Violation

- Discovery of neutrino oscillations indicate that neutrinos have mass!
- Neutrino oscillations imply Lepton Flavor Violation (LFV).
- LFV in the neutrinos also implies Charged Lepton Flavor Violation (CLFV):



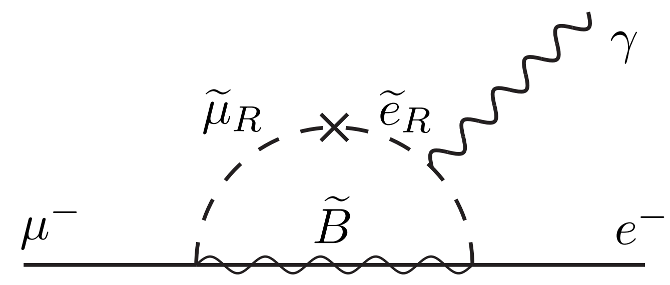
$$\mathrm{BR}(\mu \to e\gamma) < 10^{-54}$$

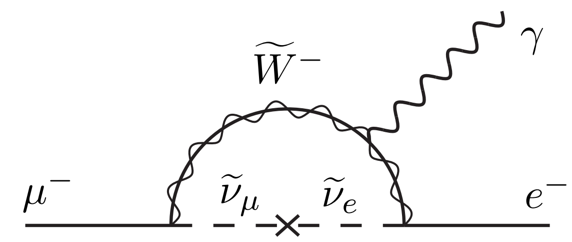
However, SM rate for CLFV is tiny due to small neutrino masses

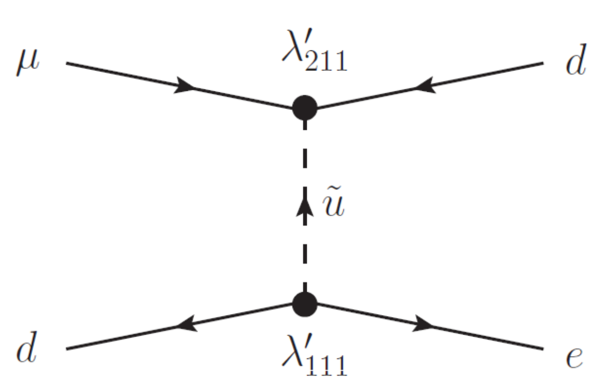
- No hope of detecting such small rates for CLFV at any present or future planned experiments!

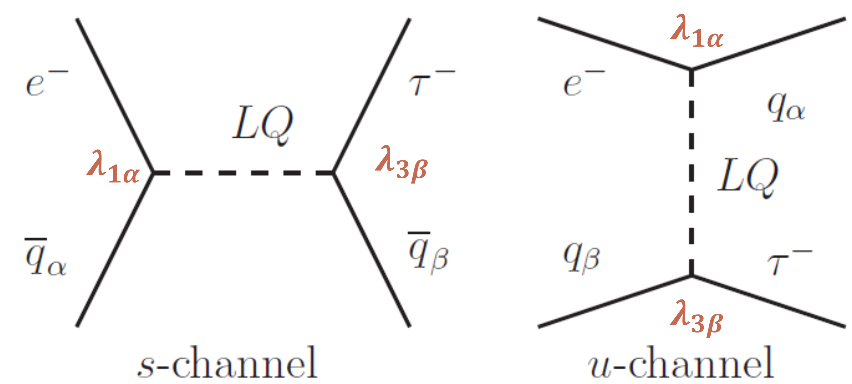
Lepton Flavor Violation in BSM

- However, many BSM scenarios predict enhanced CLFV rates:
  - SUSY (RPV)
  - SU(5), SO(10) GUTS
  - Left-Right symmetric models
  - Randall-Sundrum Models
  - LeptoQuarks
  - ...









- Leptoquarks can generate CLFV at tree level! Likely to produce enhanced CLFV rates compared to loop level processes in other models.

Charged Lepton Flavor Violation Limits

- Present and future limits:

Process	Experiment	Limit $(90\%\ C.L.)$	Year
$\mu \to e\gamma$	MEGA	$Br < 1.2 \times 10^{-11}$	2002
$\mu + Au \to e + Au$	SINDRUM II	$\Gamma_{conv}/\Gamma_{capt} < 7.0 \times 10^{-13}$	2006
$\mu \to 3e$	SINDRUM	$Br < 1.0 \times 10^{-12}$	1988
$\tau \to e\gamma$	BaBar	$Br < 3.3 \times 10^{-8}$	2010
$\tau \to \mu\gamma$	BaBar	$Br < 6.8 \times 10^{-8}$	2005
$\tau \to 3e$	BELLE	$Br < 3.6 \times 10^{-8}$	2008
$\mu + N \to e + N$	Mu2e	$\Gamma_{conv}/\Gamma_{capt} < 6.0 \times 10^{-17}$	2017?
$\mu \to e\gamma$	MEG	$Br \lesssim 10^{-13}$	2011?
$\tau \to e\gamma$	Super-B	$Br \lesssim 10^{-10}$	$>$ 2020?

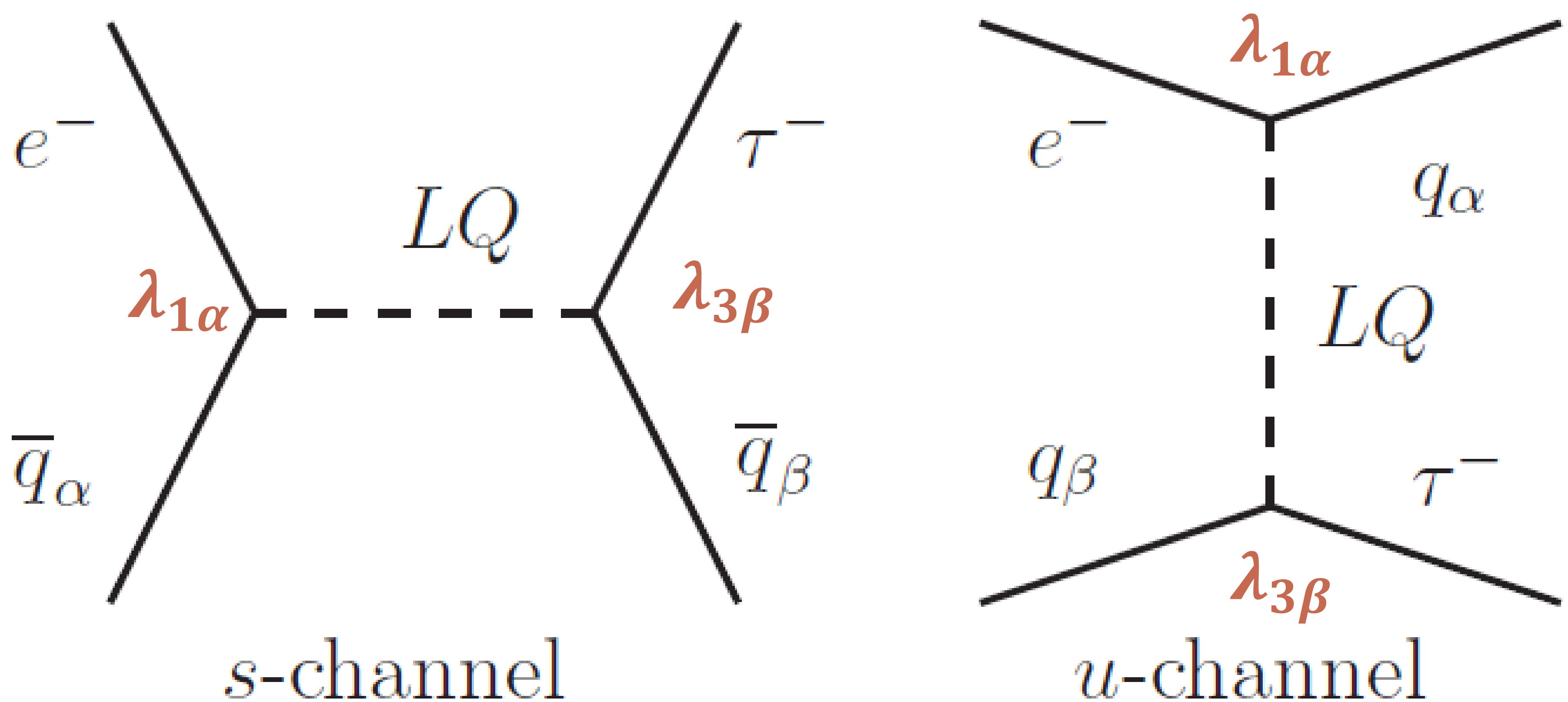
- Note that CLFV(1,2) is severely constrained. Limits on CLFV(1,3) are weaker by several orders of magnitude.
- Limits on CLFV(1,2) are expected to improve even further in future experiments.

CLFV in DIS

- The EIC can search for CLFV(1,3) in the DIS process:

$$ep \to \tau X$$

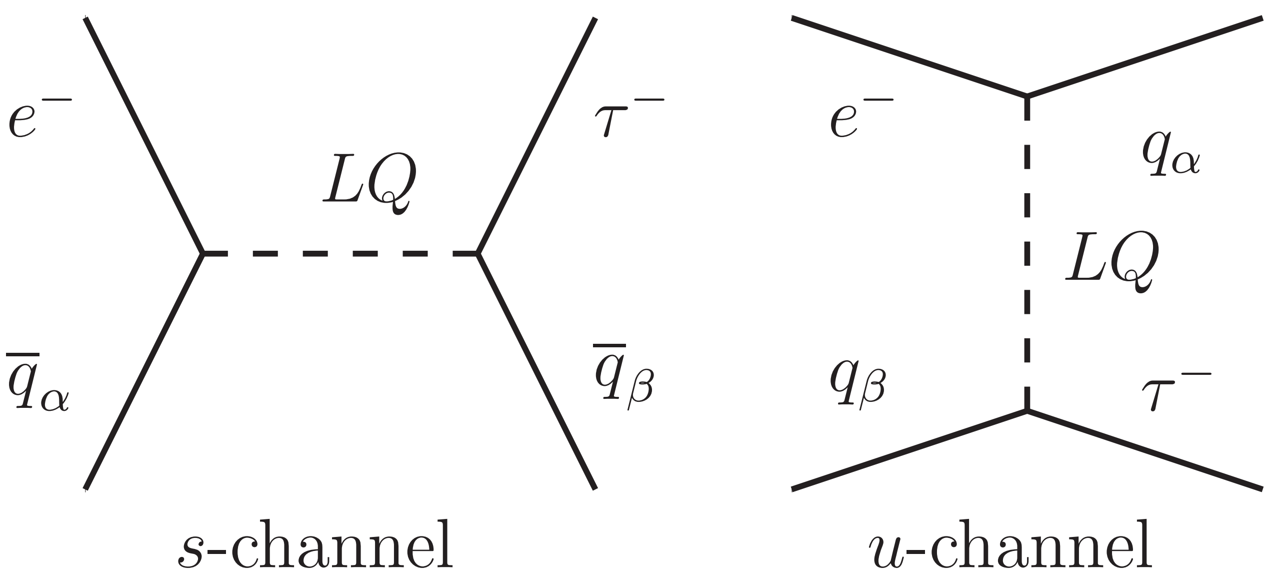
- Such a process could be mediated, for example, by leptoquarks:



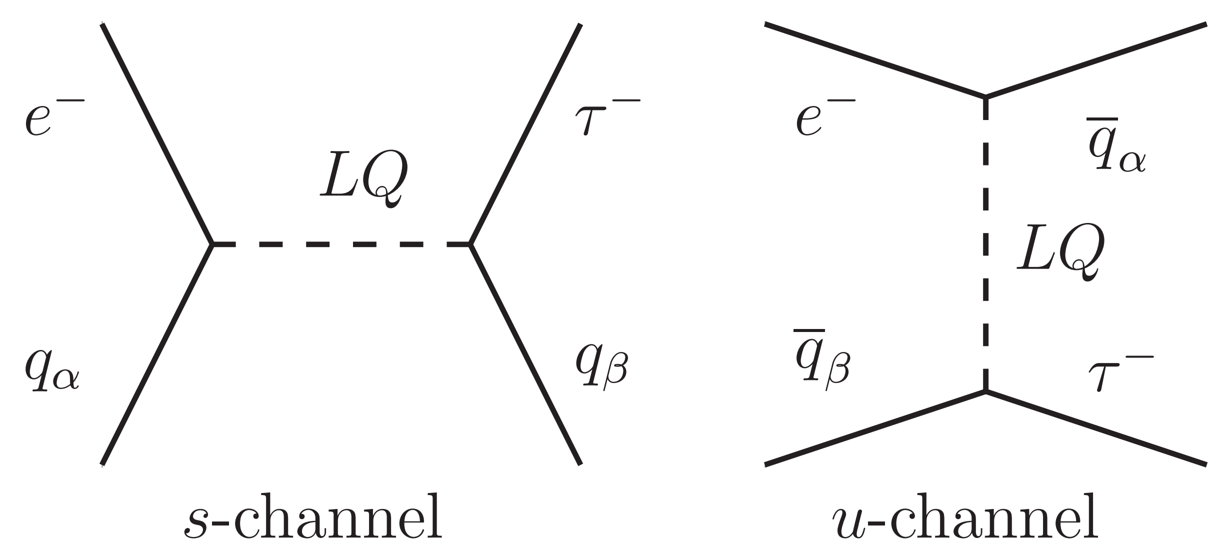
CLFV mediated by Leptoquarks

- Detailed theoretical study of $ep \to \tau X$ has been performed in the Leptoquark framework [M.Gonderinger, M.Ramsey-Musolf]

$$\mathcal{L}_{scalar} = \lambda_0^L \overline{q}_L^C \epsilon l_L S_0^L + \lambda_0^R \overline{u}_R^C e_R S_0^R + \tilde{\lambda}_0^R \overline{d}_R^C e_R \tilde{S}_0^R + \lambda_1^L \overline{q}_L^C \epsilon \vec{\sigma} l_L \vec{S}_1^L$$
$$+ \lambda_{1/2}^L \overline{u}_R l_L S_{1/2}^L + \lambda_{1/2}^R \overline{q}_L \epsilon e_R S_{1/2}^R + \tilde{\lambda}_{1/2}^L \overline{d}_R l_L \tilde{S}_{1/2}^L + h.c.$$



$F = 0$



$|F| = 2$

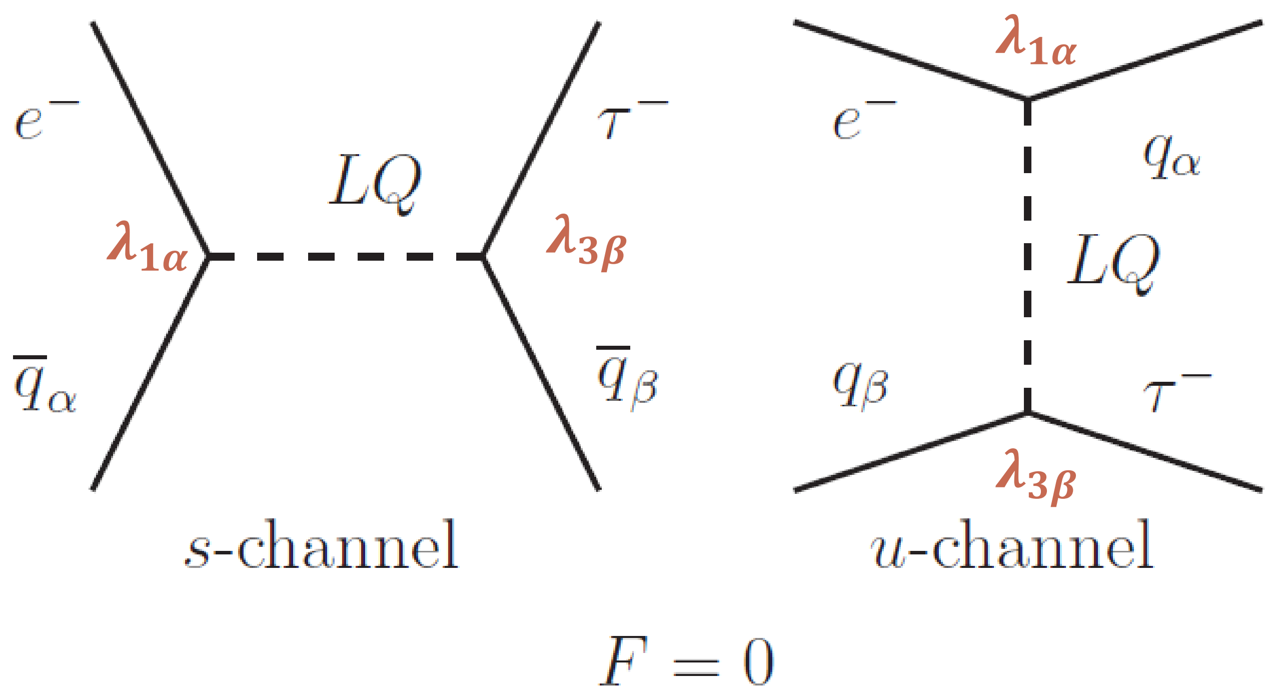
$$F = 3B + L$$

CLFV mediated by Leptoquarks

- Cross-section for $ep \to \tau X$ takes the form:

$$\sigma_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}\right]^2 \left\{\int dxdy\ x\bar{q}_\alpha(x,xs)\, f(y) + \int dxdy\ xq_\beta(x,-u)\, g(y)\right\}$$

$$f(y) = \begin{cases} 1/2 & (\text{scalar}) \\ 2(1-y)^2 & (\text{vector}) \end{cases}, \quad g(y) = \begin{cases} (1-y)^2/2 & (\text{scalar}) \\ 2 & (\text{vector}) \end{cases}$$



- HERA set limits on the ratios $\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$.
  - all LQs
  - all combinations of quark generations (no top quarks)
  - degenerate masses assumed for LQ multiplets

[S. Chekanov et.al (ZEUS), A.Atkas et.al (H1)]

- Comparison of HERA limits with limits from other rare CLFV processes:

[S.Davidson, D.C. Bailey, B.A.Campbell]

- HERA limits that are stronger are highlighted in yellow.

- HERA limits are generally better for couplings with second and third generations.

$\alpha\beta$	$S^L_{1/2}$ $e^-\bar{u}$ e^+u	$S^R_{1/2}$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}^L_{1/2}$ $e^-\bar{d}$ e^+d
1 1	$\tau \to \pi e$ 0.4 **1.8**	$\tau \to \pi e$ 0.2 **1.5**	$\tau \to \pi e$ 0.4 **2.7**
1 2	**1.9**	$\tau \to K e$ 6.3 **1.6**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.9**
1 3	*	$B \to \tau\bar{e}$ 0.3 **3.2**	$B \to \tau\bar{e}$ 0.3 **3.3**
2 1	**6.0**	$\tau \to K e$ 6.3 **4.1**	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **5.2**
2 2	$\tau \to 3e$ 5 **10**	$\tau \to 3e$ 8 **5.6**	$\tau \to 3e$ 17 **6.5**
2 3	*	$B \to \tau\bar{e}X$ 14 **8.1**	$B \to \tau\bar{e}X$ 14 **7.8**

EIC Sensitivity

- How much can the EIC improve upon HERA limits?

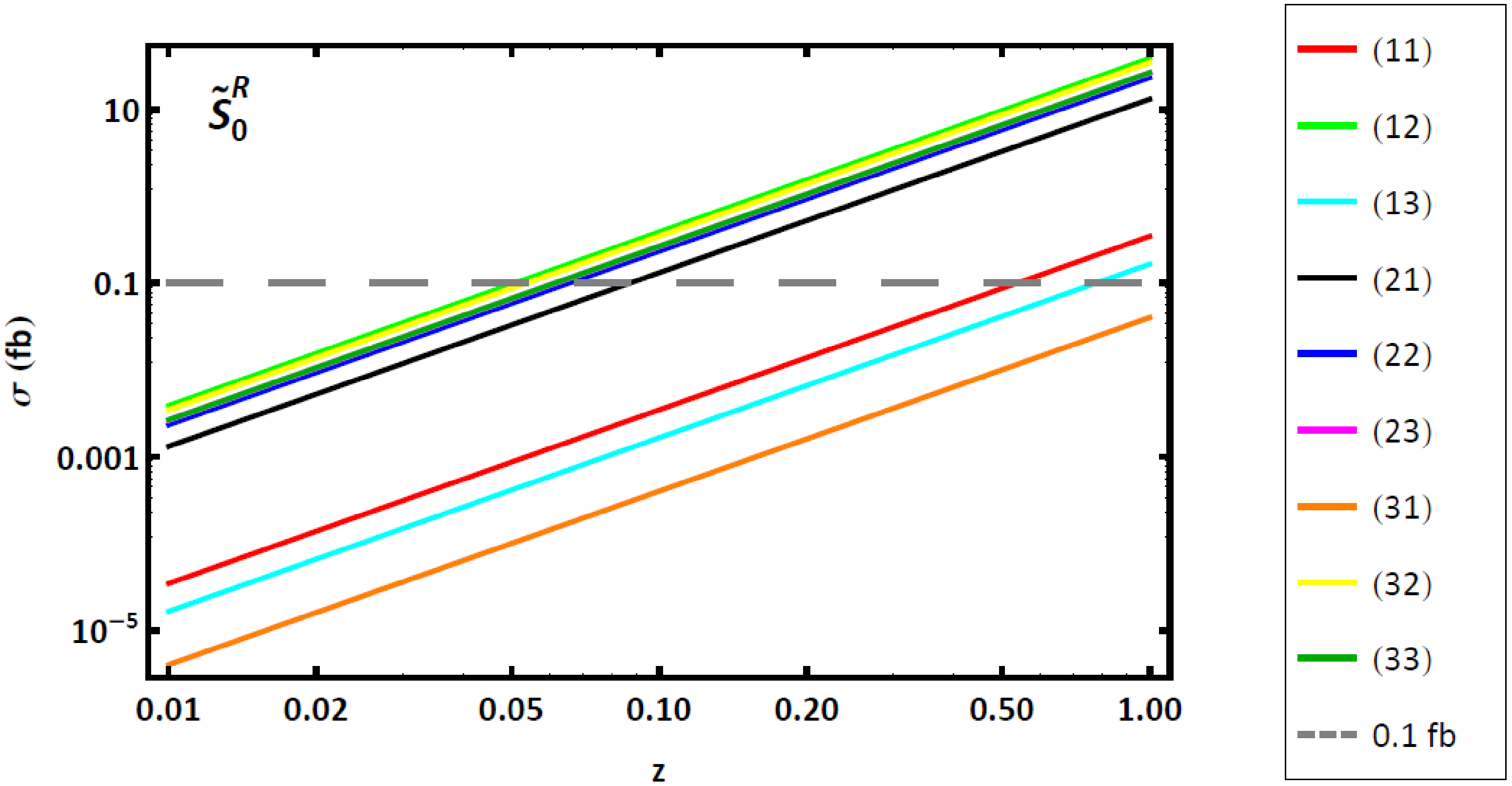
- Study was done for EIC at a center of mass energy of 90 GeV

[M.Gonderinger, M.Ramsey-Musolf]

- At 10 fb^{-1} of luminosity, a cross-section of 0.1 fb yields order one events.

- This cross-section of 0.1 fb corresponds to a typical size of $\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$ that is about a factor of 2 to almost 2 orders of magnitude smaller, compared to the HERA limits.

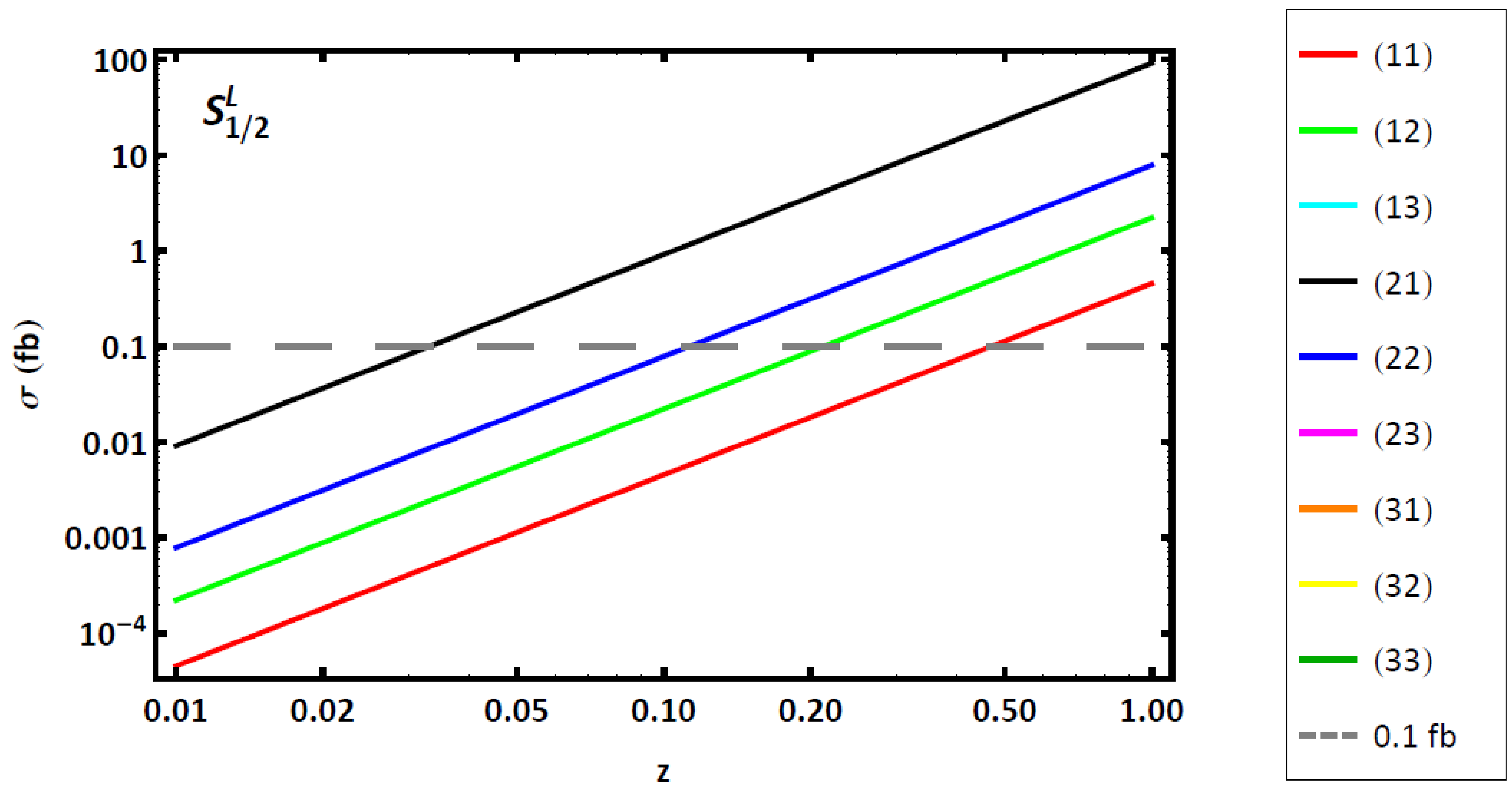
EIC Sensitivity



$$z = \frac{(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)}{[(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)]_{\mathrm{HERAlimit}}}$$

[M.Gonderinger, M.Ramsey-Musolf]

- Present limits involving first generation quarks are harder to improve upon.
- Limits can be improved upon for couplings involving higher generation quarks.
- Larger center of mass energy will increase the cross-section, giving better limits.

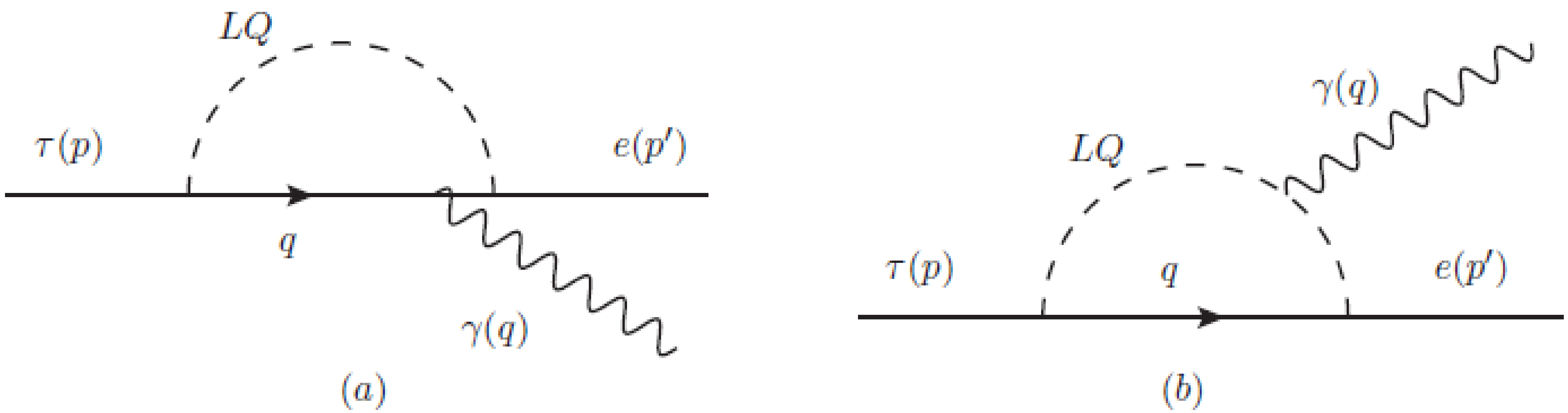


- Of course, higher luminosity will also give better limits.

Leptoquark Mediated CLFV(1,3) Decays

- Leptoquarks can also mediate the rare decay:

$$\tau \to e\gamma$$



- These diagrams are also proportional to the combination:

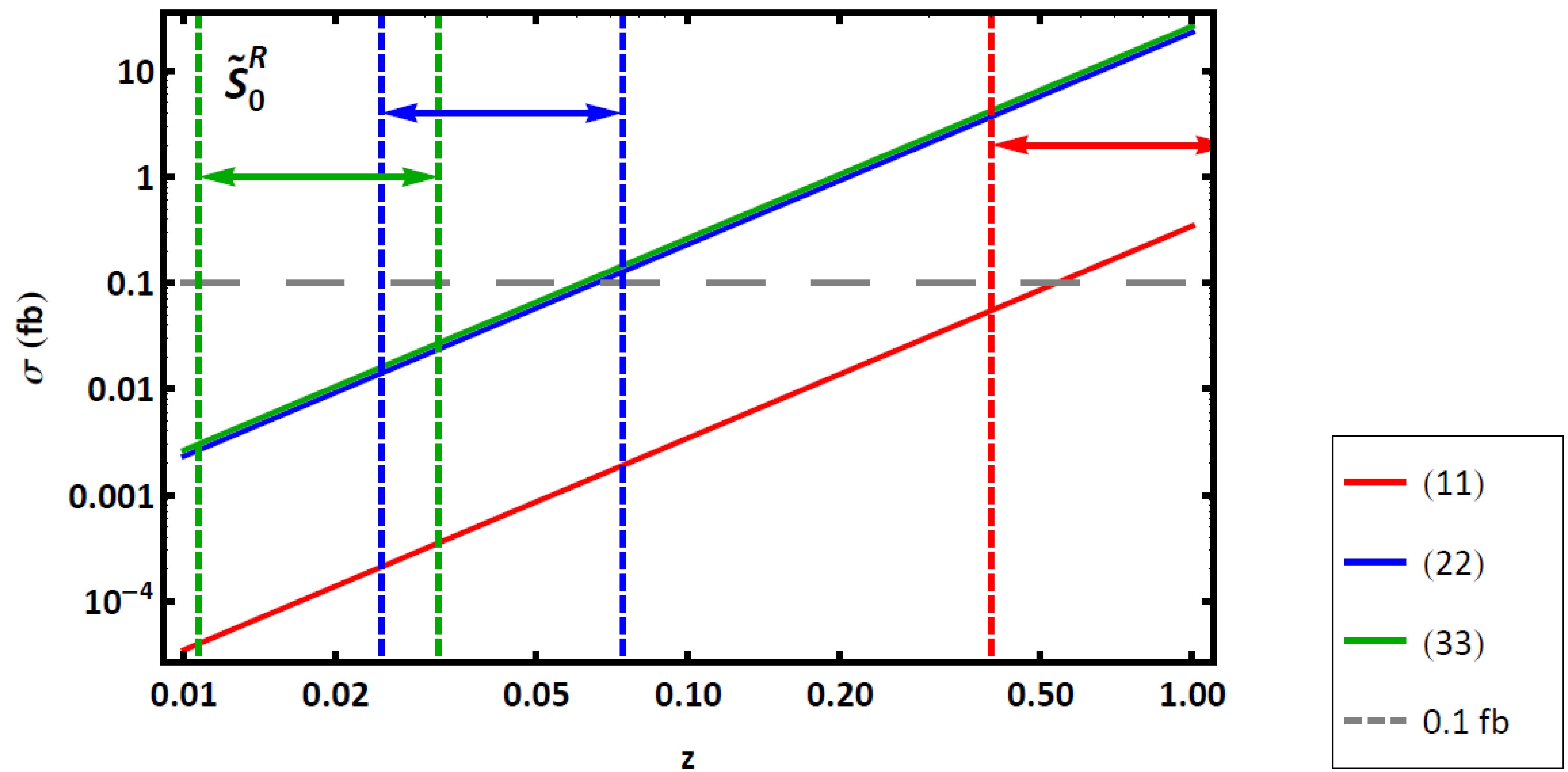
$$\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$$ but only for $\alpha = \beta$

(quark flavor-diagonal case)

EIC Sensitivity

- How does the EIC sensitivity compare to limits from rare decays?

[M.Gonderinger, M.Ramsey-Musolf]



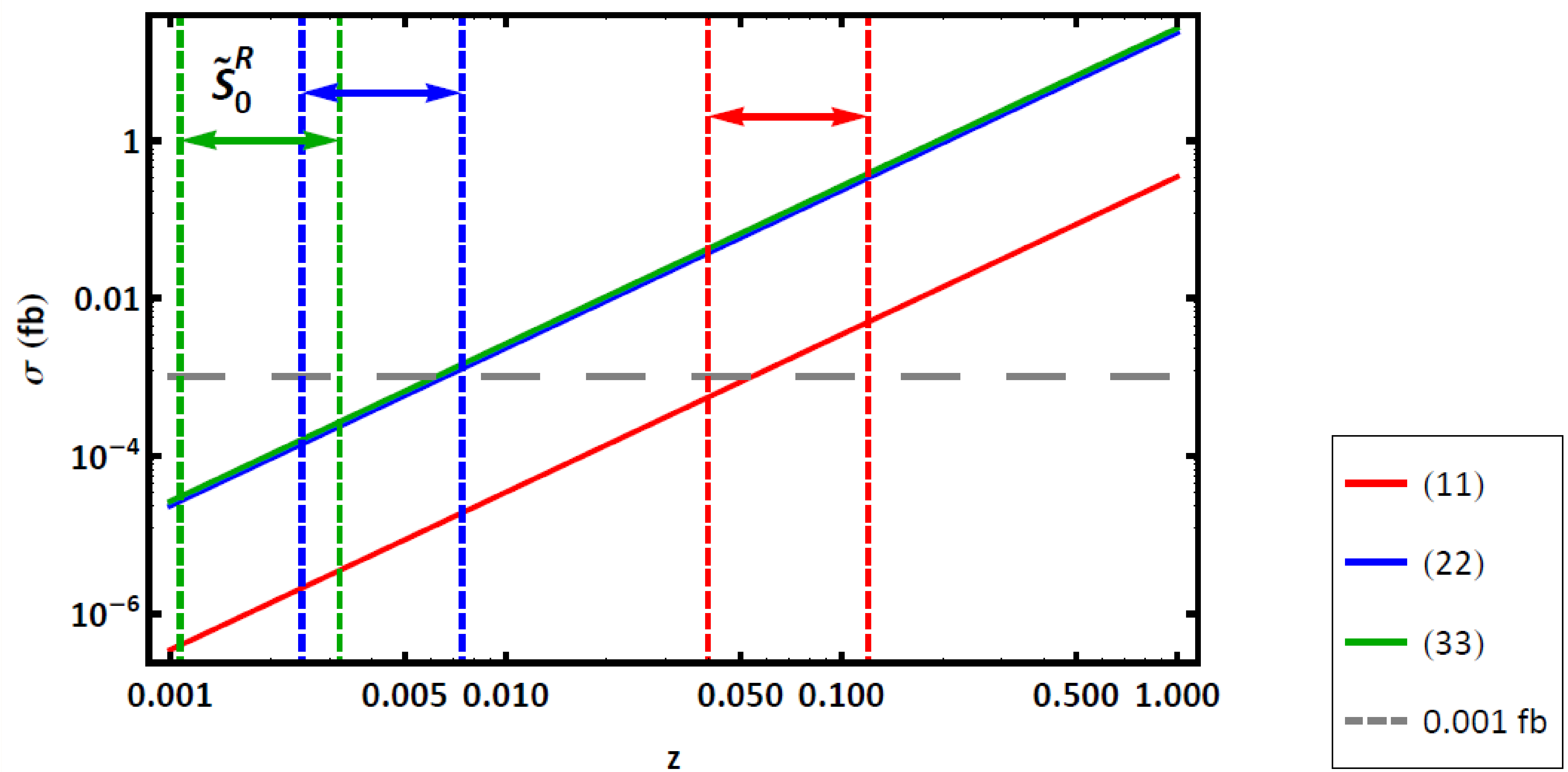
- Vertical dashed lines and horizontal arrows indicate the range of limits from rare decays ("Totalitarian" vs "Democratic" scenarios).

- At 10^{-1}fb, the EIC cannot compete with limits from rare decays.

EIC Sensitivity vs Super-B

- How does the EIC sensitivity compare to limits from rare decays?

[M.Gonderinger, M.Ramsey-Musolf]

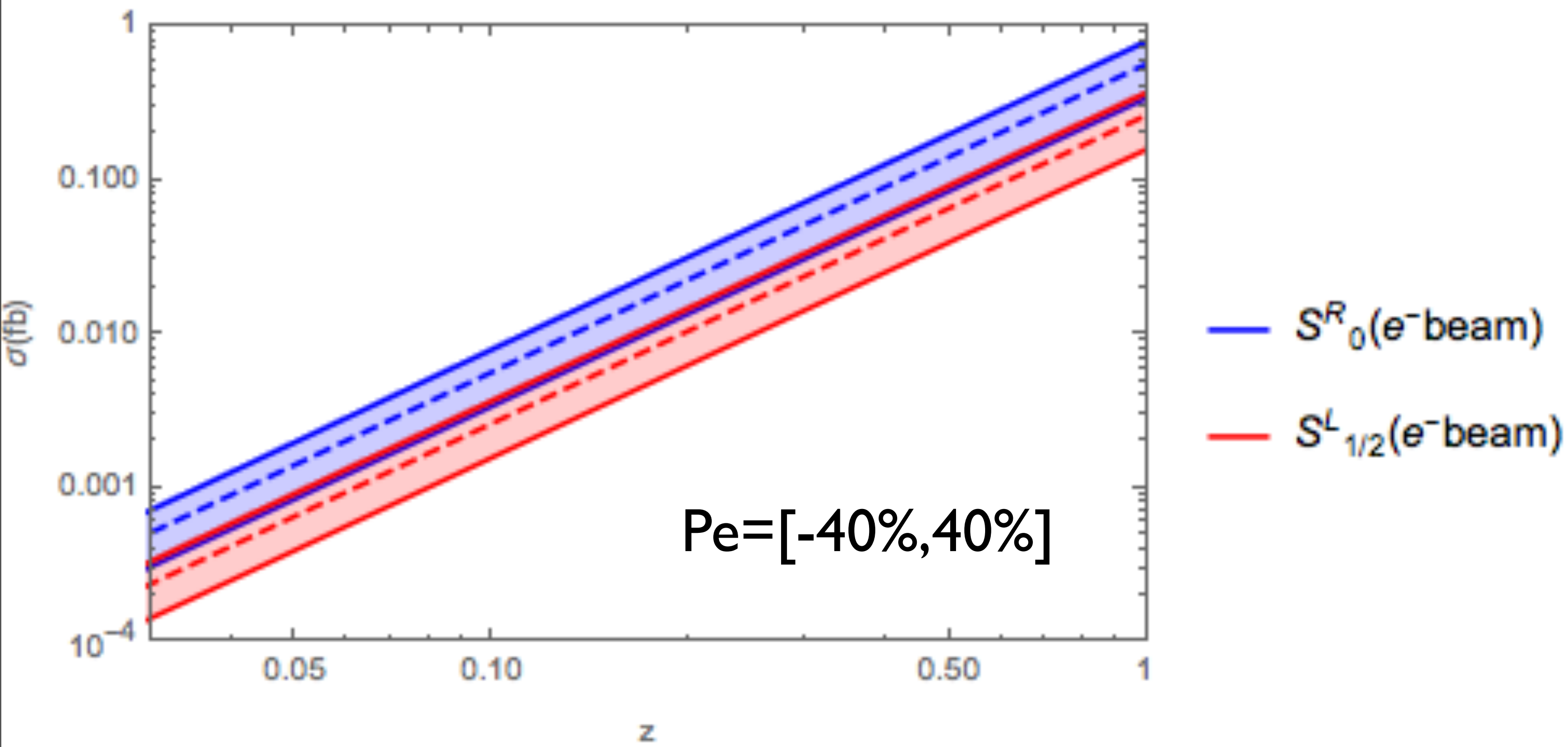


- Vertical dashed lines and horizontal arrows indicate the range of limits from rare decays ("Totalitarian" vs "Democratic" scenarios).

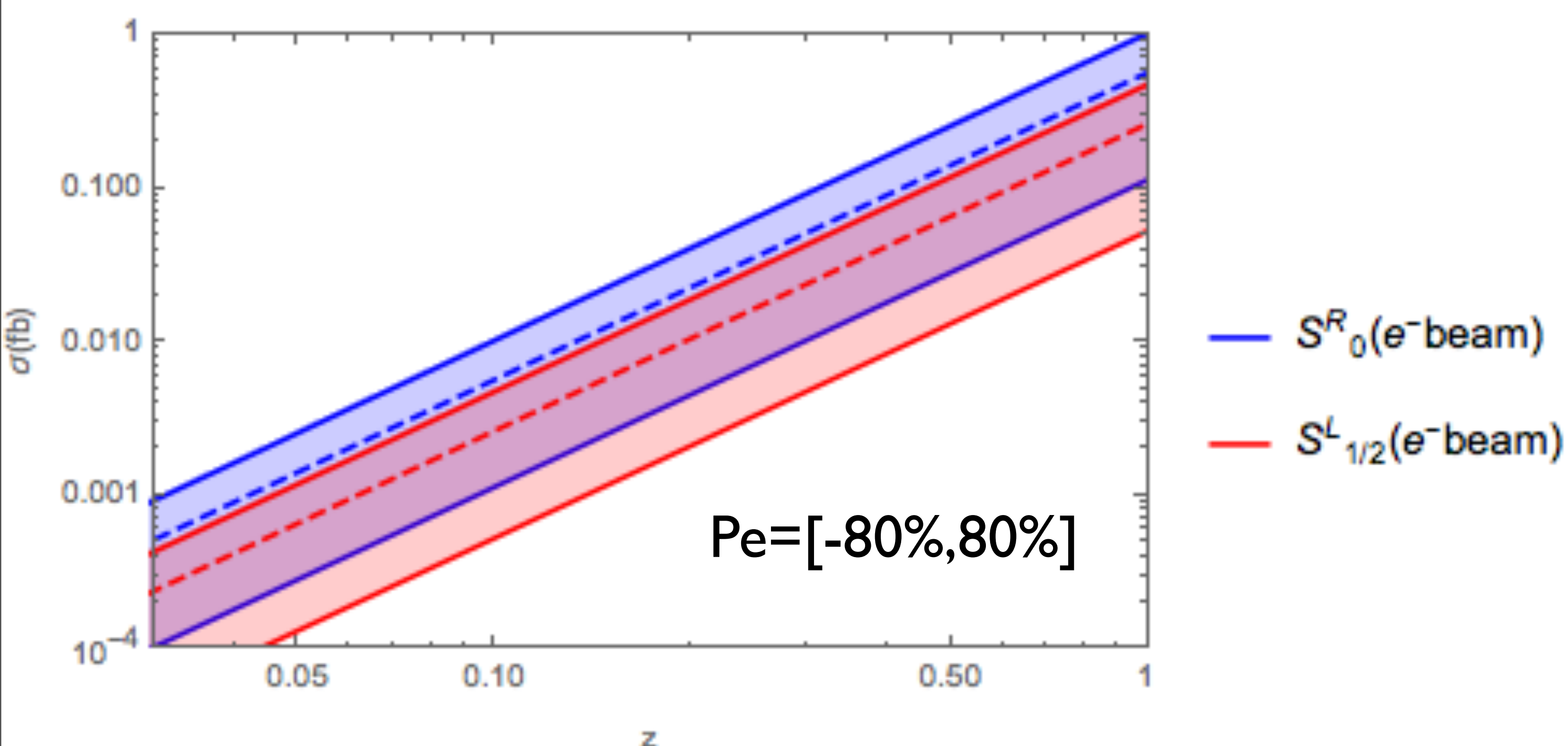
- At 1000^{-1}fb, the EIC could compete with Super-B in for first generation quark couplings but not for higher generation quark couplings.

Lepton Beam Polarization to Distinguish Between Leptoquark States

[J. Furletova, S.Mantry]



- Lepton beam polarization can be used to enhance or suppress the L vs R LQ cross section.



- For example, the cross section difference between F=2 and F=0 LQs for an unpolarized (dashed) electron beam, can be enhanced by varying the beam polarization.

Right-Handed W-Boson

Right-Handed W-Boson

				$SU(3)$	$SU(2)_L$	$U(1)_Y$
$Q^i_L =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$(u^c)^i_L =$	$(u^c)_L$	$(c^c)_L$	$(t^c)_L$	$\bar{3}$	1	$-\frac{2}{3}$
$(d^c)^i_L =$	$(d^c)_L$	$(s^c)_L$	$(b^c)_L$	$\bar{3}$	1	$\frac{1}{3}$
$L^i_L =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
$(e^c)^i_L =$	$(e^c)_L$	$(\mu^c)_L$	$(\tau^c)_L$	1	1	1

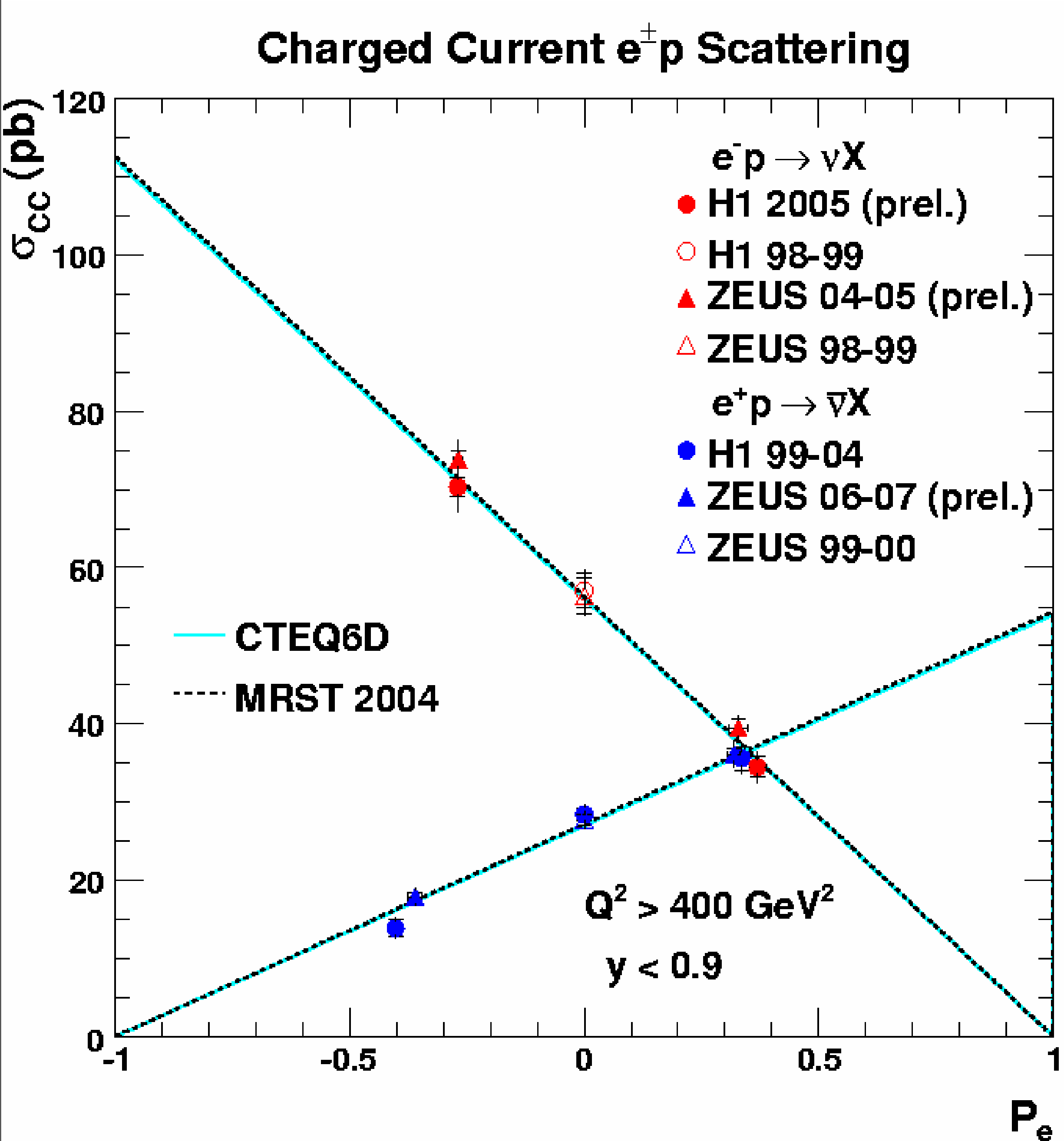
- Electroweak interactions in the Standard model violates parity maximally.
- The W-boson has interactions only with the left-handed quarks and leptons.
- Right-handed neutrinos, as evidenced by neutrino oscillations, require physics beyond the Standard Model

- Left-Right Symmetric Models restore the symmetry between and left and right-handed quarks and leptons at high energies beyond the electroweak scale:

$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \longrightarrow \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

- Left-Right symmetric models predict the existence of new degrees of freedom, including a heavy right-handed W-boson and heavy right-handed neutrinos.

Right-Handed W-Boson



- The Standard Model W-boson only couples to left-handed electrons and right-handed positrons.
- Thus, the Standard Model predicts a linear dependence of the charged current (CC) cross-section on the lepton beam polarization.
- Polarized electron and positron beams can test this Standard Model paradigm.

HERA limits on the right-handed W mass:

e^+p: > 208 GeV [A.Atkas et.al (H1)]

e^-p: > 186 GeV

(assuming equal couplings for left and right handed Ws)

Right-Handed W-Boson at EIC

- The lower center of mass energy (compared to HERA) at the EIC will lead to smaller charged current cross sections.

- However, the higher luminosity and degree of lepton beam polarization at the EIC can lead to higher precision on the charged current cross section measurements.

- Higher precision could lead to stronger mass bounds.

SM Polarization Dependence of Charged Current Cross Section

- The Standard Model W-boson only couples to left-handed electrons and right-handed positrons:

$$\sigma_{\mathrm{SM}}^{e^{\pm}p}(P_e) = (1 \pm P_e)\sigma_{\mathrm{SM}}^{e^{\pm}p}(P_e = 0)\ , \qquad P_e = \frac{N_R - N_L}{N_R + N_L}$$

- Electron and positron beams act as independent probes of the polarization dependence charged current cross section due to the difference in initial state PDFs that contribute:

$$\frac{\sigma_{\mathrm{SM}}^{e^{+}p}(P_e)}{dx\, dQ^2} = (1 + P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2\left[\bar{u}(x, Q^2) + \bar{c}(x, Q^2) + (1 - y)^2\Big(d(x, Q^2) + s(x, Q^2)\Big)\right]$$

$$\frac{\sigma_{\mathrm{SM}}^{e^{-}p}(P_e)}{dx\, dQ^2} = (1 - P_e)\frac{G_F^2}{2\pi}\left(\frac{M_W^2}{M_W^2 + Q^2}\right)^2\left[u(x, Q^2) + c(x, Q^2) + (1 - y)^2\Big(\bar{d}(x, Q^2) + \bar{s}(x, Q^2)\Big)\right]$$

BSM Polarization Dependence of Charged Current Cross Section

- SM polarization dependence:

$$\sigma_{\mathrm{SM}}^{e^\pm p}(P_e) = (1 \pm P_e)\sigma_{\mathrm{SM}}^{e^\pm p}(P_e = 0) \longrightarrow \boxed{\sigma_{\mathrm{SM}}^{e^\pm p}(P_e = \mp 1) = 0}$$

- Polarization dependence in the presence of a right-handed W boson (with SM coupling strength):

$$\sigma^{e^\pm p}(P_e) = (1 \pm P_e)\,\sigma_{\mathrm{SM}}^{e^\pm p}(P_e = 0) + (1 \mp P_e)\,\sigma_{\mathrm{SM}}^{e^\pm p}(P_e = 0, M_W \to M_R)$$

$$\downarrow$$

$$\boxed{\sigma^{e^\pm p}(P_e = \mp 1) = 2\,\sigma_{\mathrm{SM}}^{e^\pm p}(P_e = 0, M_W \to M_R) \neq 0}$$

$$\sigma^{e^\pm p}(P_e = \mp 1) = 2\,\sigma^{e^\pm p}_{\mathrm{SM}}(P_e = 0, M_W \to M_R)$$

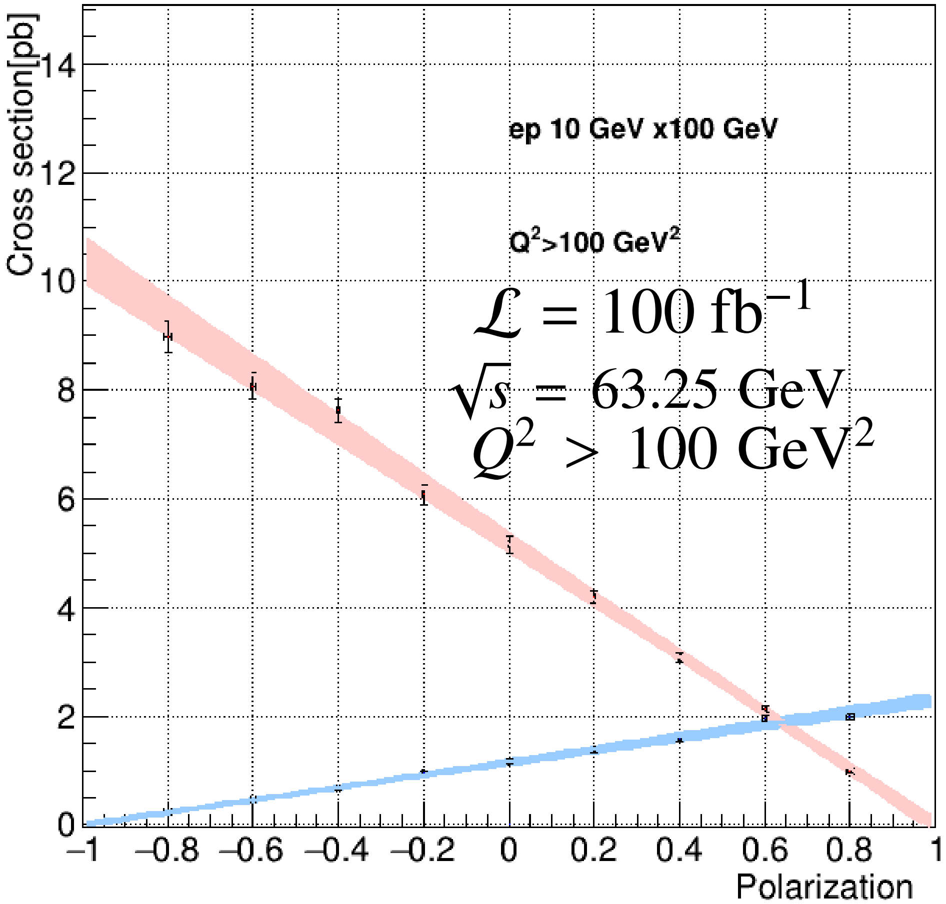
95% confidence interval of measurement leads to upper bound

$$\sigma^{e^\pm p}_{\mathrm{SM}}(P_e = 0, M_W \to M_R) < \frac{\sigma^{e^\pm p}_{\text{upper bound}}(P_e = \mp 1)}{2}$$

MR dependence leads to a mass limit

Preliminary Simulation Results

[J. Furletova, S. Mantry]

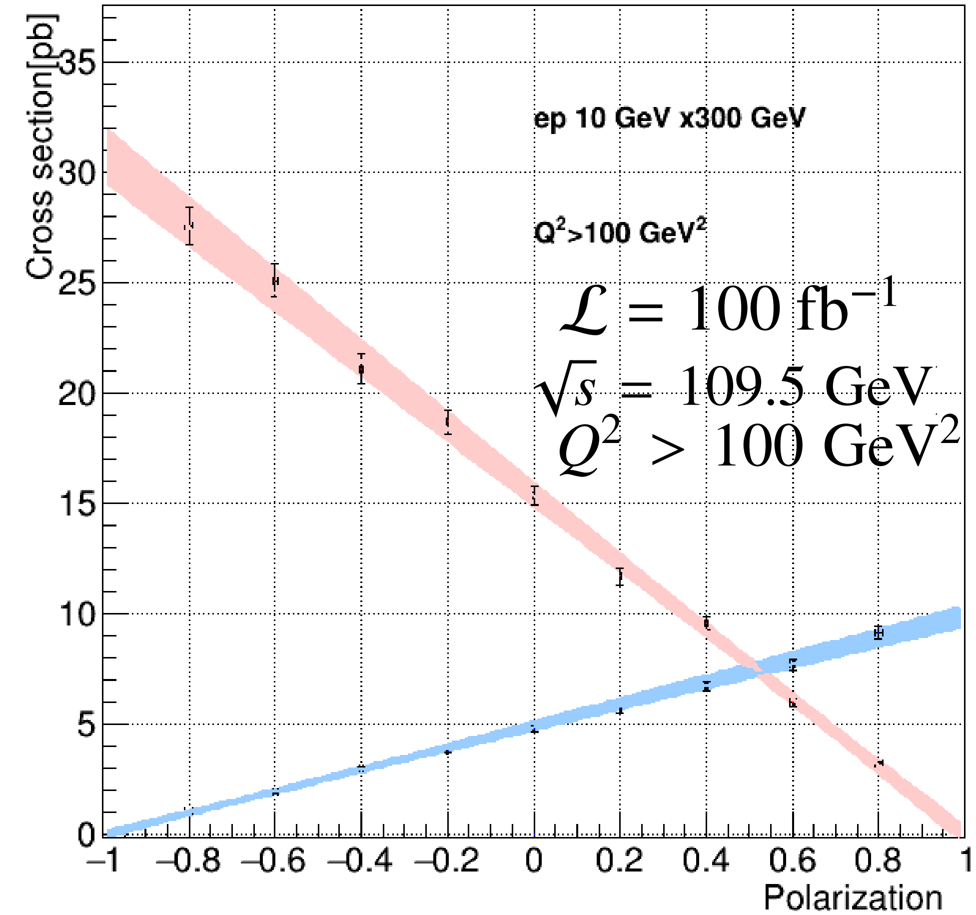


Assumed polarization uncertainty:

$$\Delta P_e / P_e \sim 1\%$$

Assumed systematic uncertainty:

$$\sim 3\%$$



- Center of mass energy:

$$\sqrt{s} = 63.25\ \mathrm{GeV}$$

- 95% CL upper bound:

$$\sigma^{e^+p}(P_e = -1) < 0.0207\mathrm{pb}$$

- WR-boson mass limit:

$$M_R \gtrsim 270\ \mathrm{GeV}$$

- Center of mass energy:

$$\sqrt{s} = 109.5\ \mathrm{GeV}$$

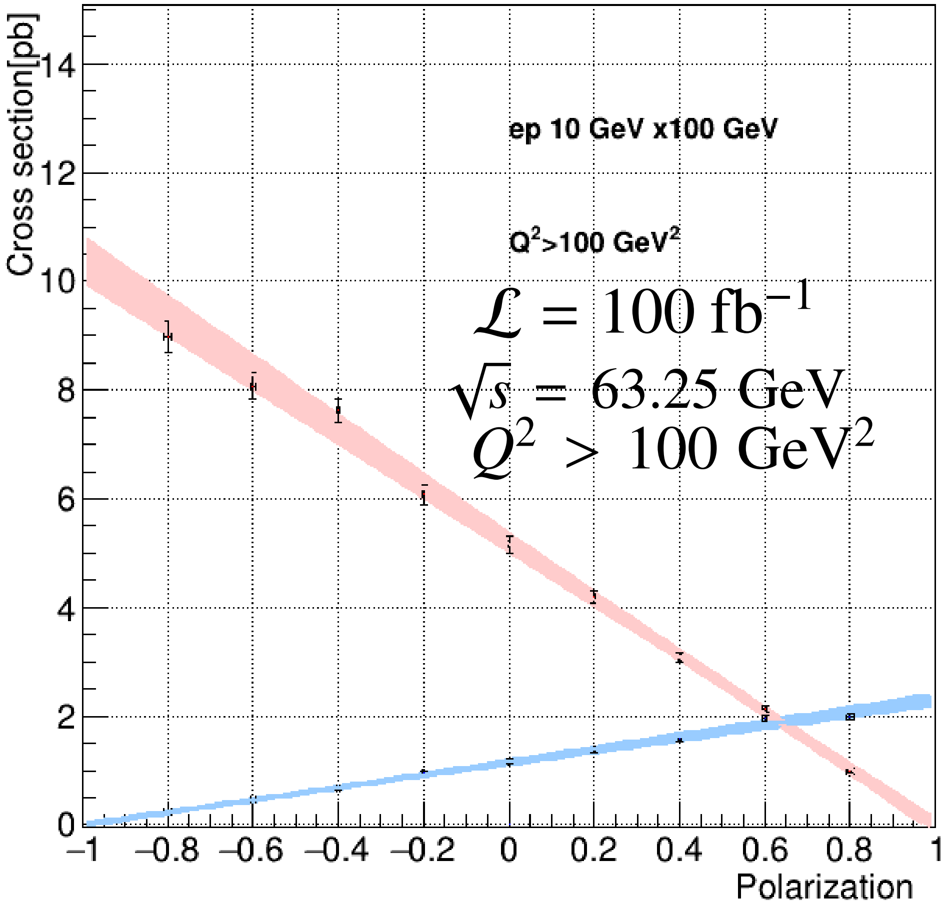
- 95% CL upper bound:

$$\sigma^{e^+p}(P_e = -1) < 0.0776\mathrm{pb}$$

- WR-boson mass limit:

$$M_R \gtrsim 285\ \mathrm{GeV}$$

Preliminary Simulation Results

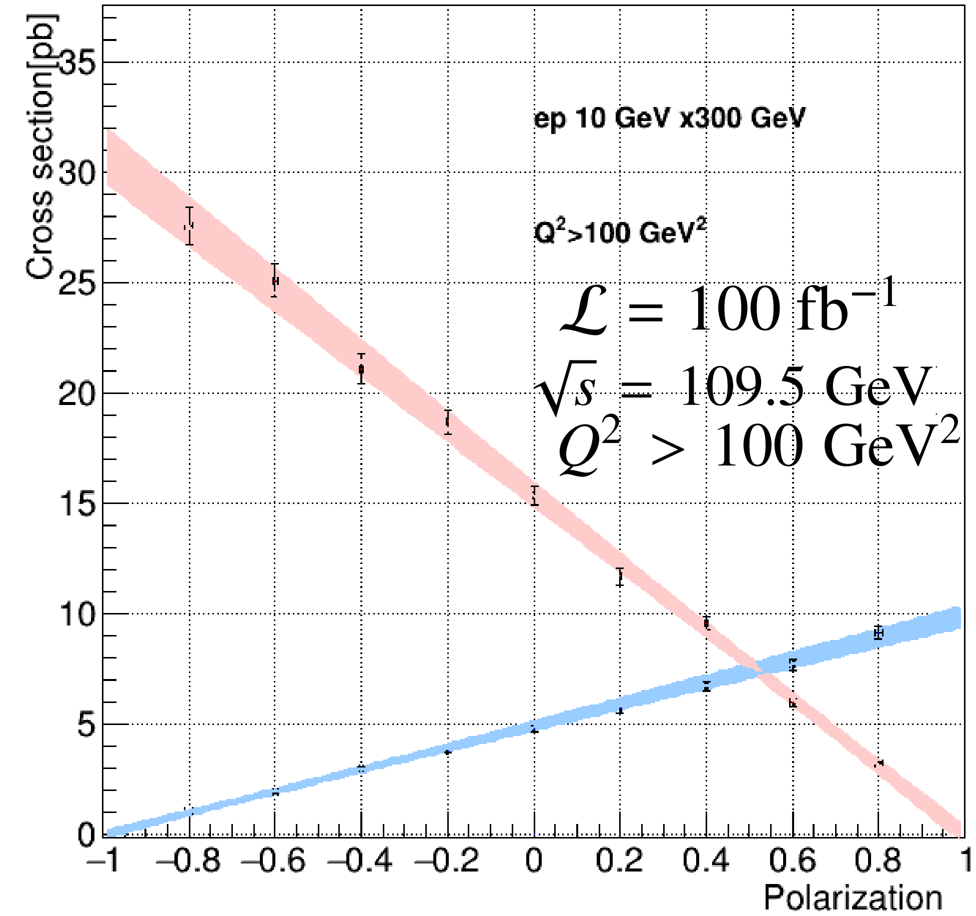


Assumed polarization uncertainty:

$$\Delta P_e / P_e \sim 1\%$$

Assumed systematic uncertainty:

$$\sim 3\%$$



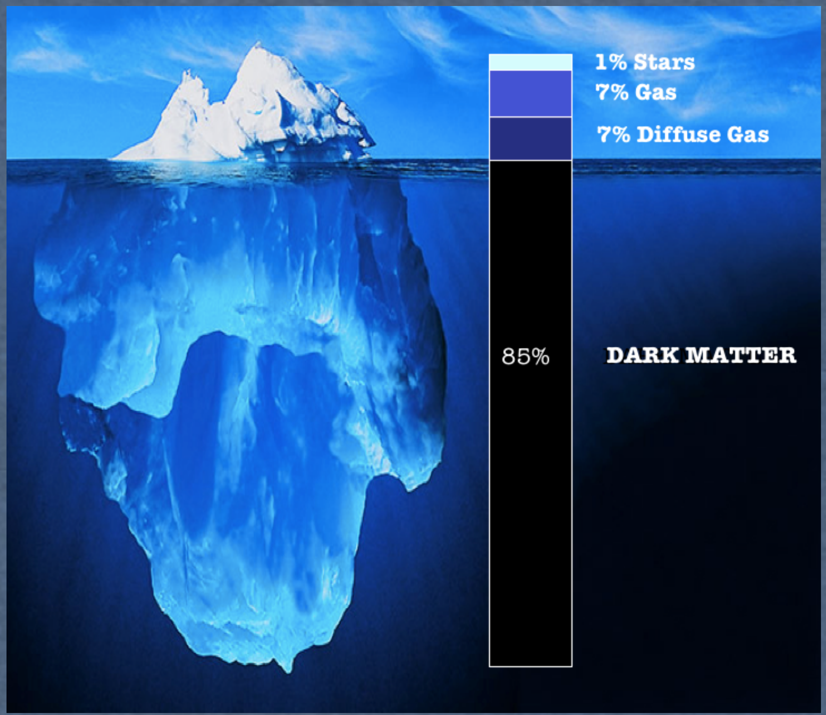
- Preliminary results indicate that the high luminosity and degree of polarization can improve the HERA limits on the right-handed W boson mass.

Following Slides by M. Battaglieri...

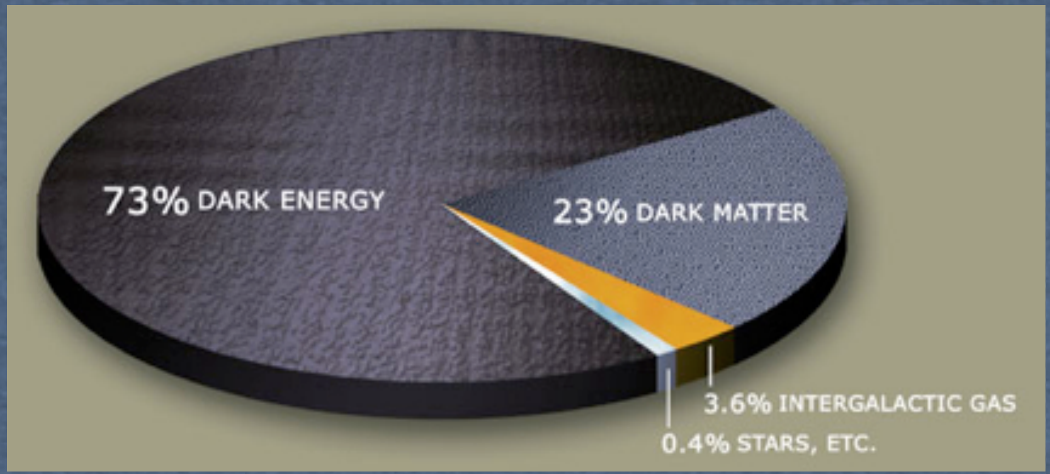
Light Dark Matter (LDM) search at EIC

Dark Matter (DM) vs Baryonic Matter (BM)

★ How much DM w.r.t. BM?



.. even worse if we consider the total balance



Only ~4% of the Universe is explained by the Standard Model of the elementary particles

★ Is DM undergoing to other interactions? is the DM made by 'particles' (such as the ones in the Standard Model)?

★ Constraint on DM mass and interactions

- should be '*dark*' (no em interaction)
- should weekly interact with SM particles
- should provide the correct relic abundance
- should be compatible with CMB power spectrum

… assuming that the gravity is not modified and DM undergoes to other interactions

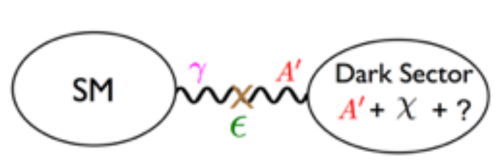
★ We can use what we know about standard model particles to build a DM theory

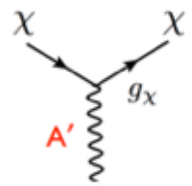
Two options:

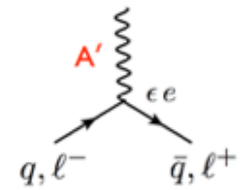
★ New matter interacting trough the same forces

★ New matter interacting trough new forces

Tuesday, December 19, 17



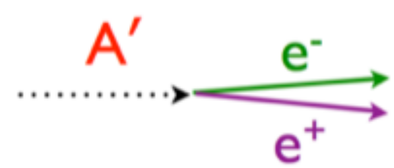




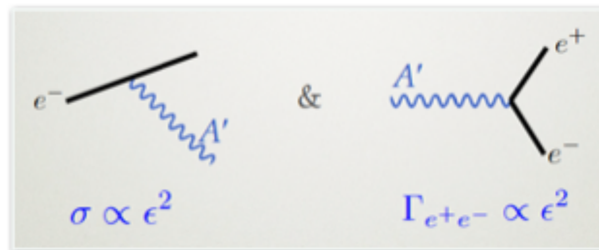
4 parameters: m_χ, $m_{A'}$, ε, α_D

m_χ, ~ $m_{A'}$: MeV - GeV

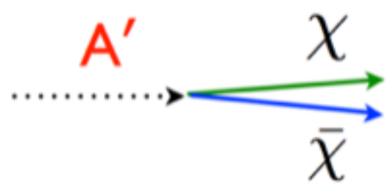
Visible



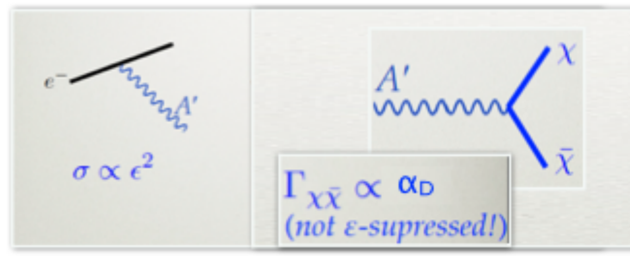
- *Minimal* decay
- Decay regulated by ε^2
- Independent of m_χ
- Requires $m_{A'} < 2m_\chi$ (on-shell)

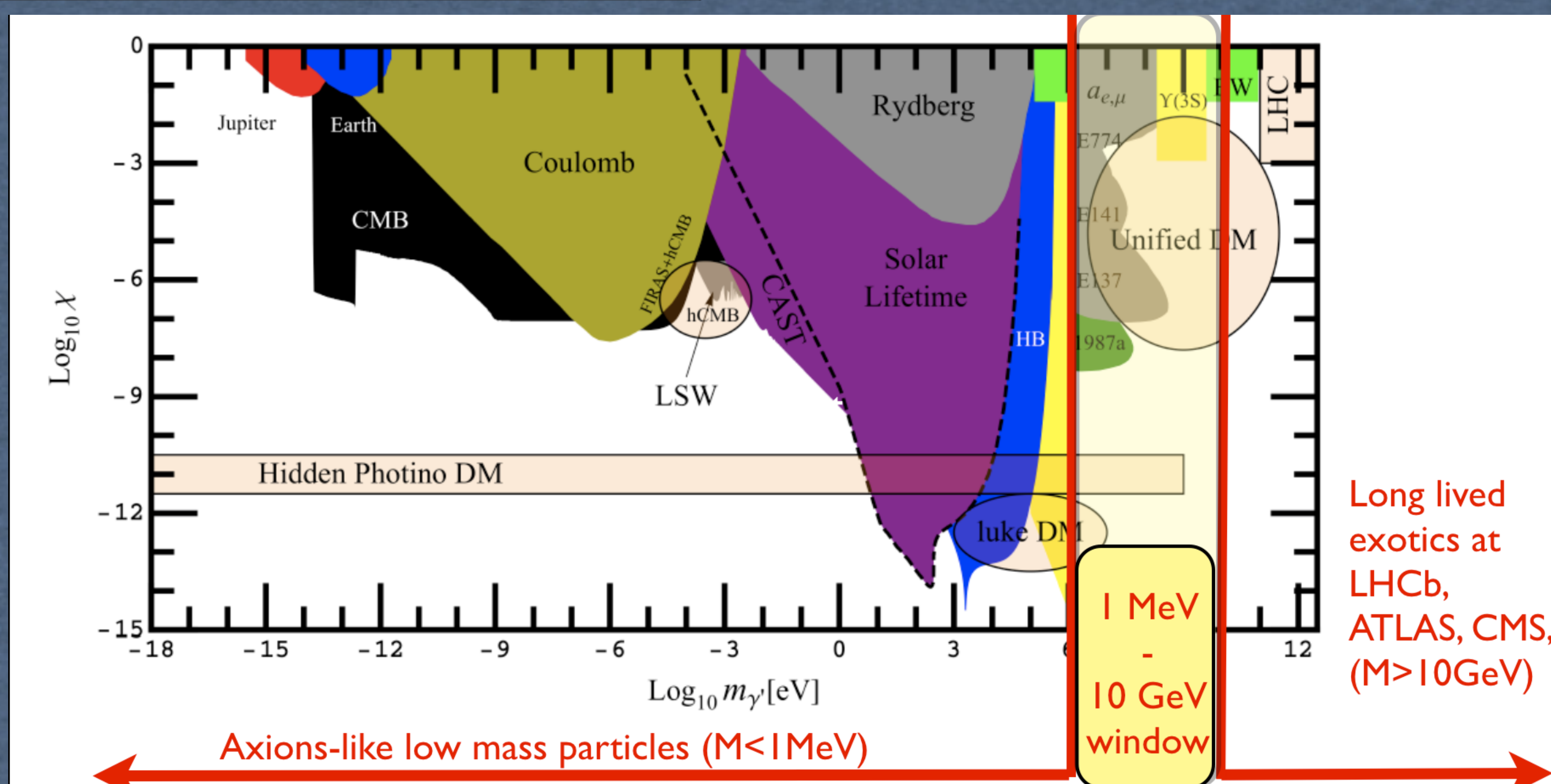


Invisible



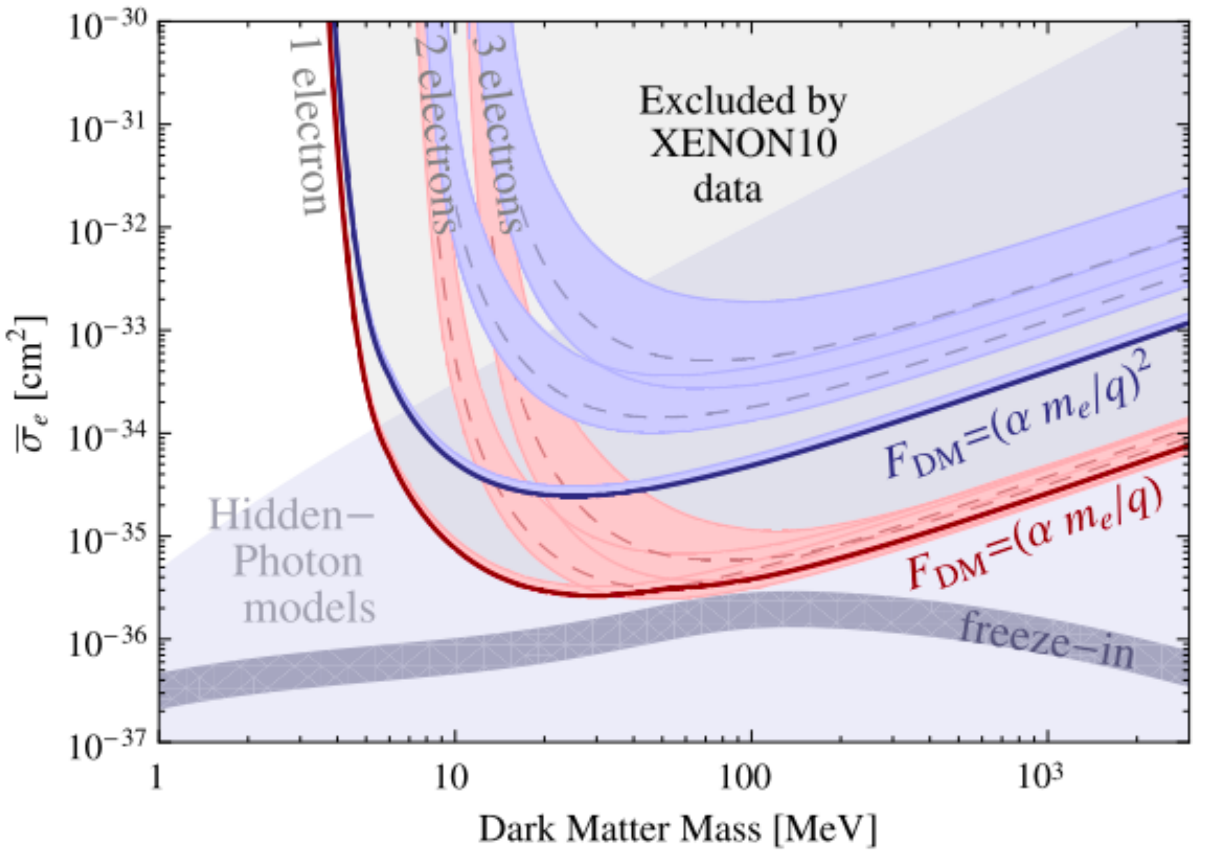
- Depends on 4 parameters
- $m_{A'} > 2m_\chi$ (on-shell)
- $\alpha_D = g^2_\chi/4\pi >> \varepsilon^2 \alpha_{EM}$





Light Dark Matter - Direct Detection limits

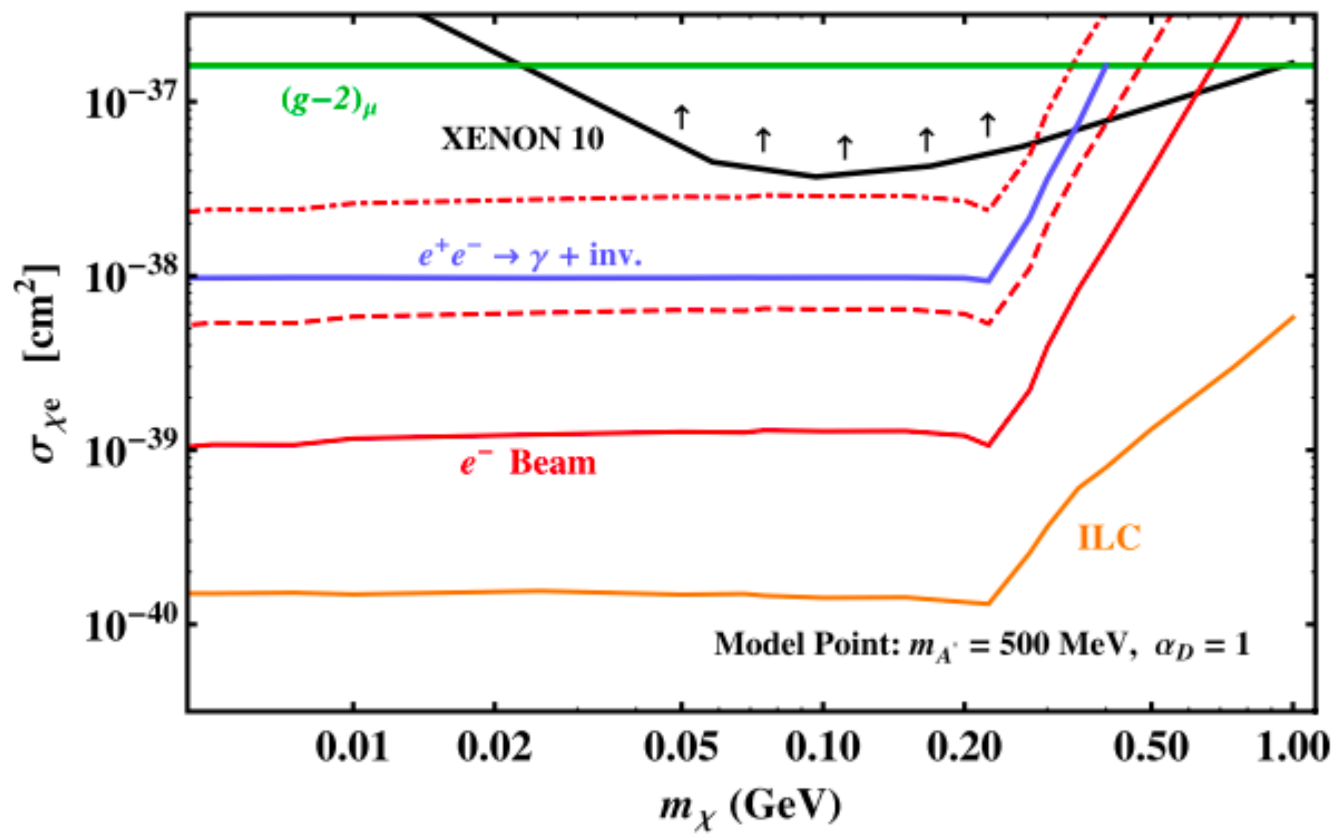
Limits from XENON10



PhysRevLett. 109.021301 R.Essig, A.Manalaysay, J.Mardon, P.Sorensen, T.Volansky,

- Best limits on LDM interaction cross section obtained by direct DM detection (XENON10)
  - χ_{cosmic}-e scattering
  - 1-electron ionization sensitivity
  - No FF for the scattering

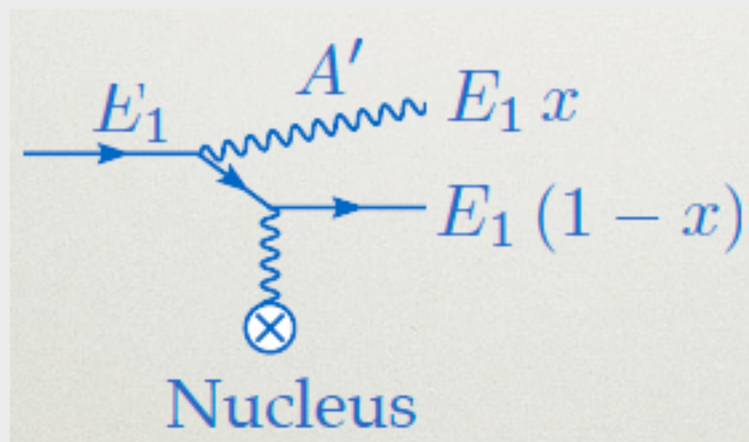
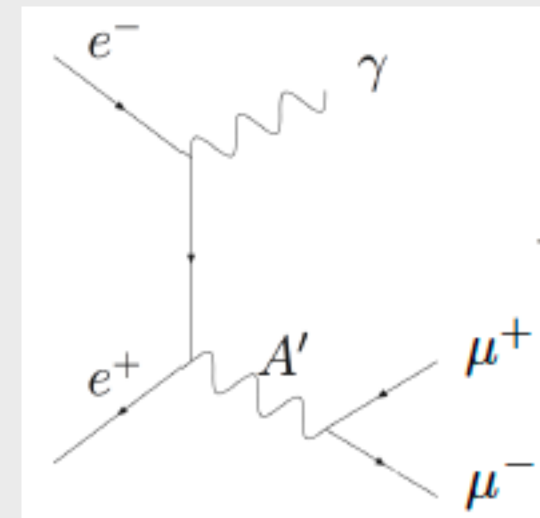
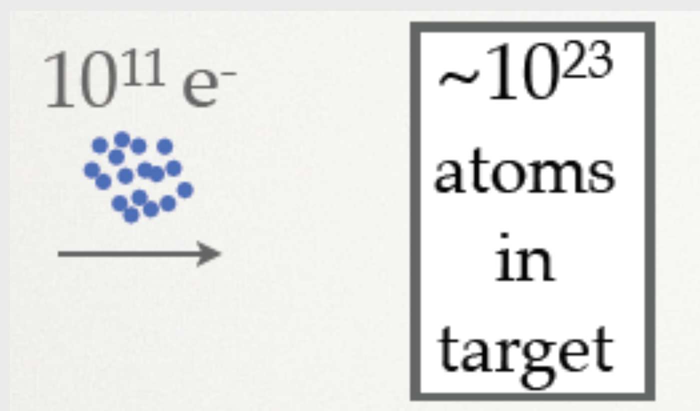
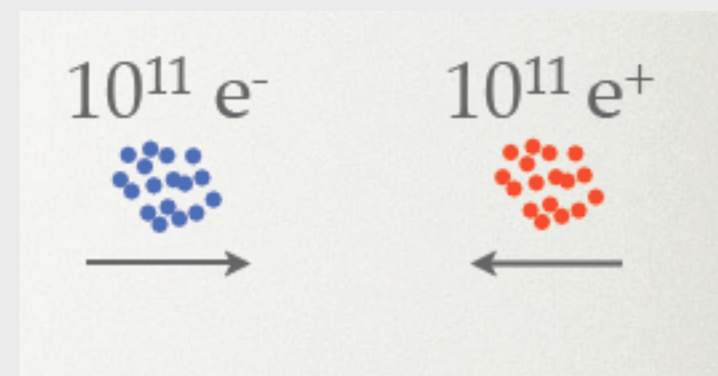
Fixed target & high intensity e⁻ beam



PhysRevD.88.114015 E.Izaguirre, G.Krnjaic, Gordan, P.Schuster, N.Toro

- Fixed target electron beam experiments can be 10^3 - 10^4 more sensitive in the 1 MeV - 1 GeV mass range

A' production: fixed target vs. collider

	Fixed Target	e+e- colliders
Process		
Luminosity		
Cross-Section	$\sigma \sim \frac{\alpha^3 Z^2 \epsilon^2}{m^2} \sim O(10\ pb)$	$\sigma \sim \frac{\alpha^2 \epsilon^2}{E^2} \sim O(10\ fb)$

✳ $1/M_{A'}$ .vs. $1/E_{beam}$
✳ Coherent scattering from Nucleus (~Z^2)

Fixed target:
- high backgrounds
- limited A' mass

e+e- colliders:
- low backgrounds
- higher A' mass

A'/LDM production at EIC

- All the advantages of a large CM energy
- Extended A' mass range exploration
- High luminosity requested to explore weekly interactive particles (A', LDM, …)
- Advantages of both fixed target + collider experiments
- Multipurpose 4pi detector to measure final states
- Possibility of including some extra detectors for uncovered regions (very forward)
- Access to meson decay with a large statistics
- EIC: detailed evolution of accessible kinematics and reach under evaluation

Conclusions

- The EIC is primarily a QCD machine. But it can also provide for a vibrant program to study physics beyond the Standard Model (BSM), complementing efforts at other colliders.

- The EIC can play an important role in searching/constraining various new physics scenarios that include:
    - Leptoquarks
    - R-parity violating Supersymmetry
    - Right-handed W-bosons
    - Excited leptons (compositeness)
    - Dark Photons
    - Charged Lepton Flavor Violation (CLFV)
    - ...

- New physics can be constrained through:
    - Precision measurements of the electroweak parameters

- Such a program physics is facilitated by:
    - high luminosity
    - wide kinematic range
    - range of nuclear targets
    - polarized beams

★ The addition of a polarized positron beam will enhance the BSM program at the EIC.