Probing Physics Beyond the Standard Model with Positrons

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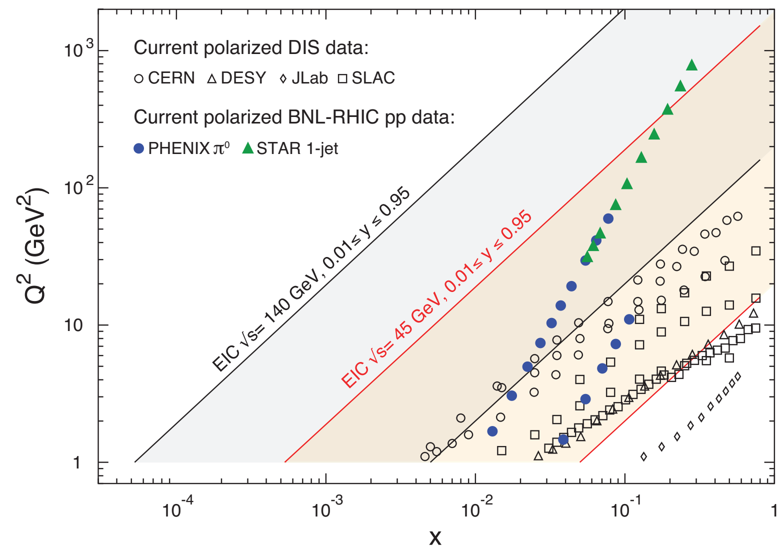
Physics Beyond the Standard Model at the EIC

- 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
  - Doubly Charged Higgs bosons
  - Excited leptons (compositeness)
  - Dark Photons
  - Charged Lepton Flavor Violation (CLFV)
  - ...

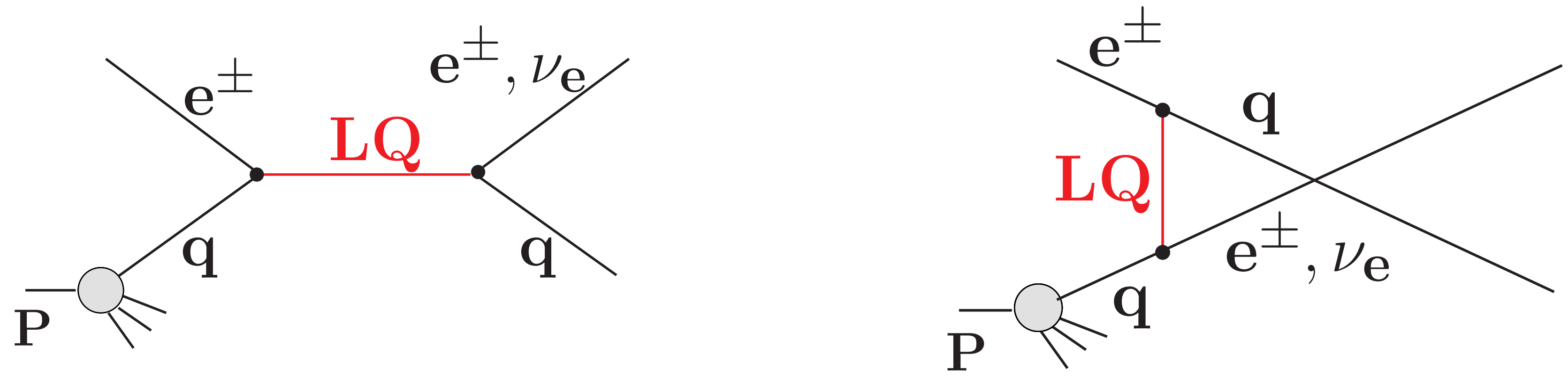
- More generally, new physics can be constrained through:
  - Precision measurements of the electroweak parameters

- Such a program physics is faciliated 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.

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:

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

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

- 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)]

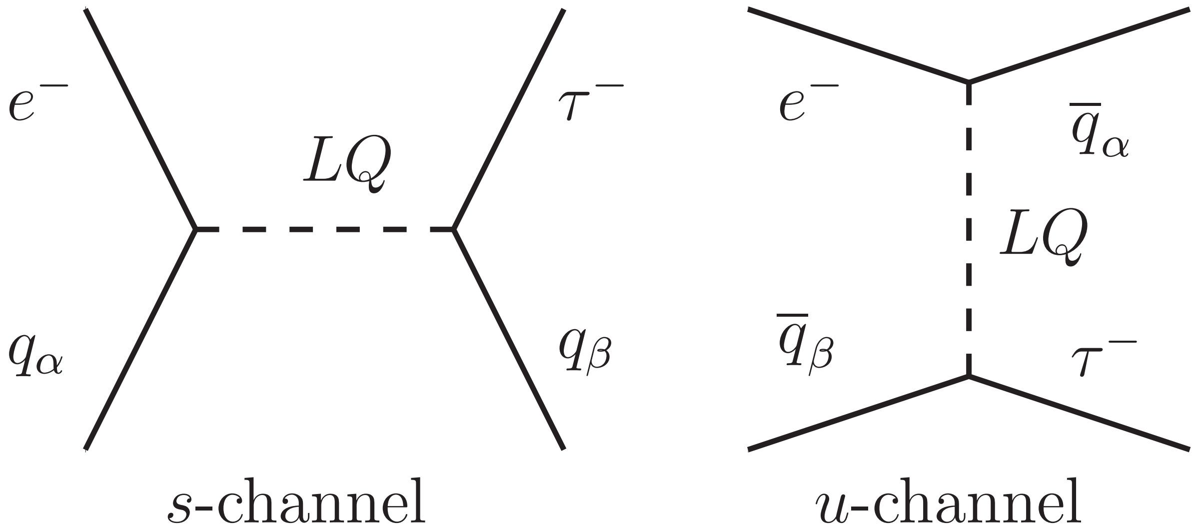
Type	J	F	Q	ep dominant process		Coupling	Branching ratio β_ℓ
S_0^L	0	2	$-1/3$	$e_L^- u_L \rightarrow$	$\ell^- u$	λ_L	$1/2$
					$\nu_\ell d$	$-\lambda_L$	$1/2$
S_0^R	0	2	$-1/3$	$e_R^- u_R \rightarrow$	$\ell^- u$	λ_R	1
$\tilde{S}_0^R$	0	2	$-4/3$	$e_R^- d_R \rightarrow$	$\ell^- d$	λ_R	1
S_1^L	0	2	$-1/3$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

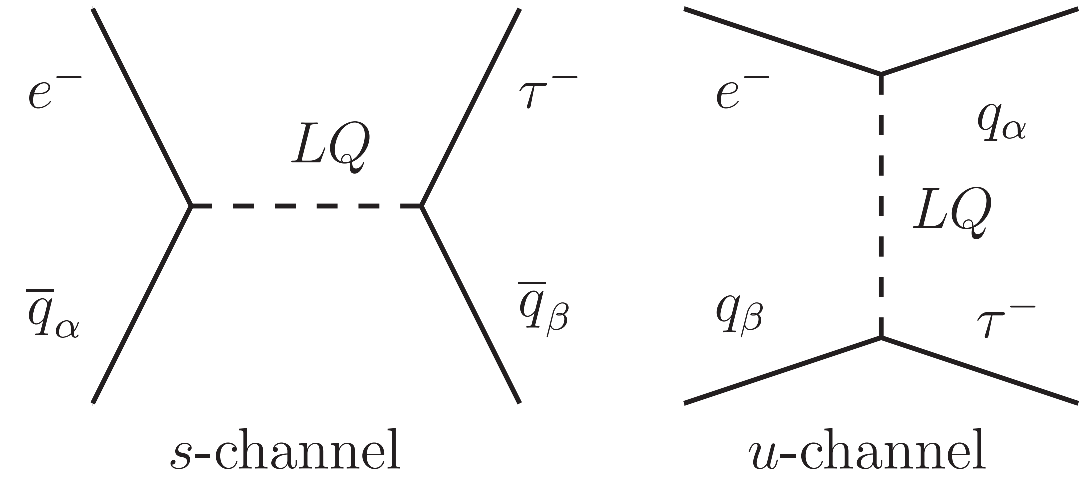
- In order to maximally exploit the phenomenology of LQs and be able to distinguish between different types of LQ states, we need:

  -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

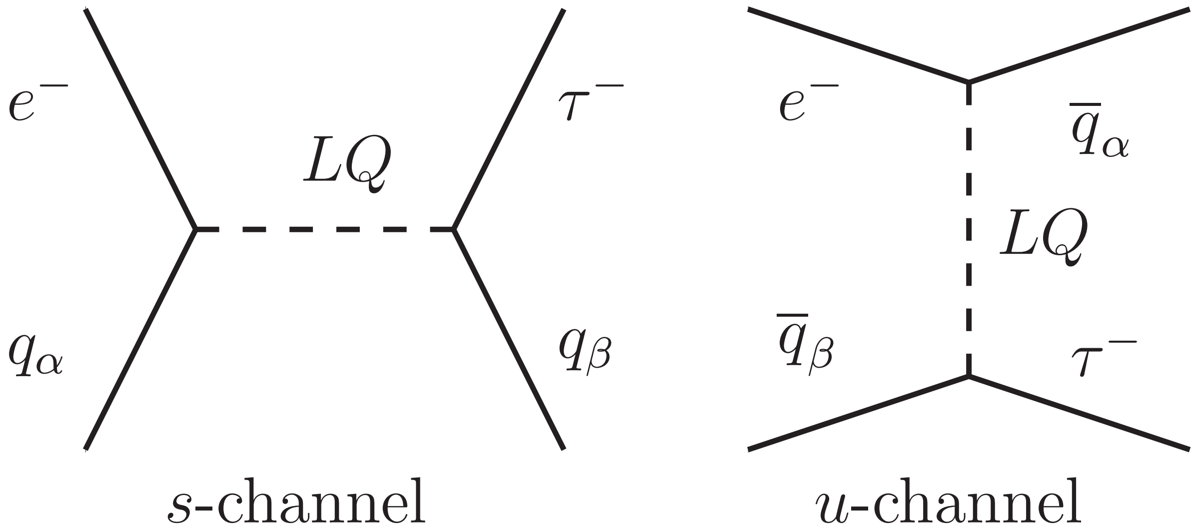
F= 0:
-antiquarks in s-channel
-quarks in the u-channel

- With positron beams, LQs couple to:

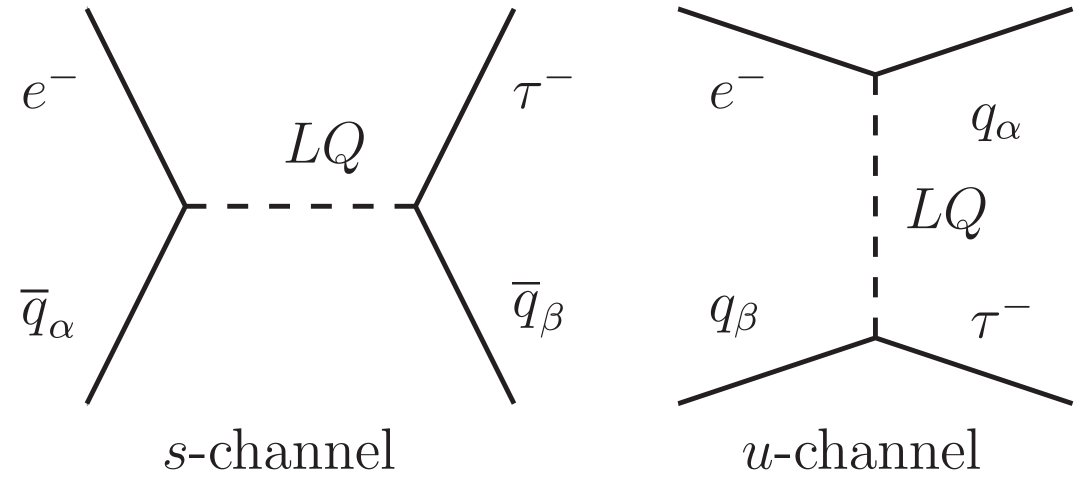
|F|= 2:
-antiquarks in s-channel
-quarks in u-channel

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

Leptoquarks: Electron vs Positron Beams



$|F| = 2$



$F = 0$

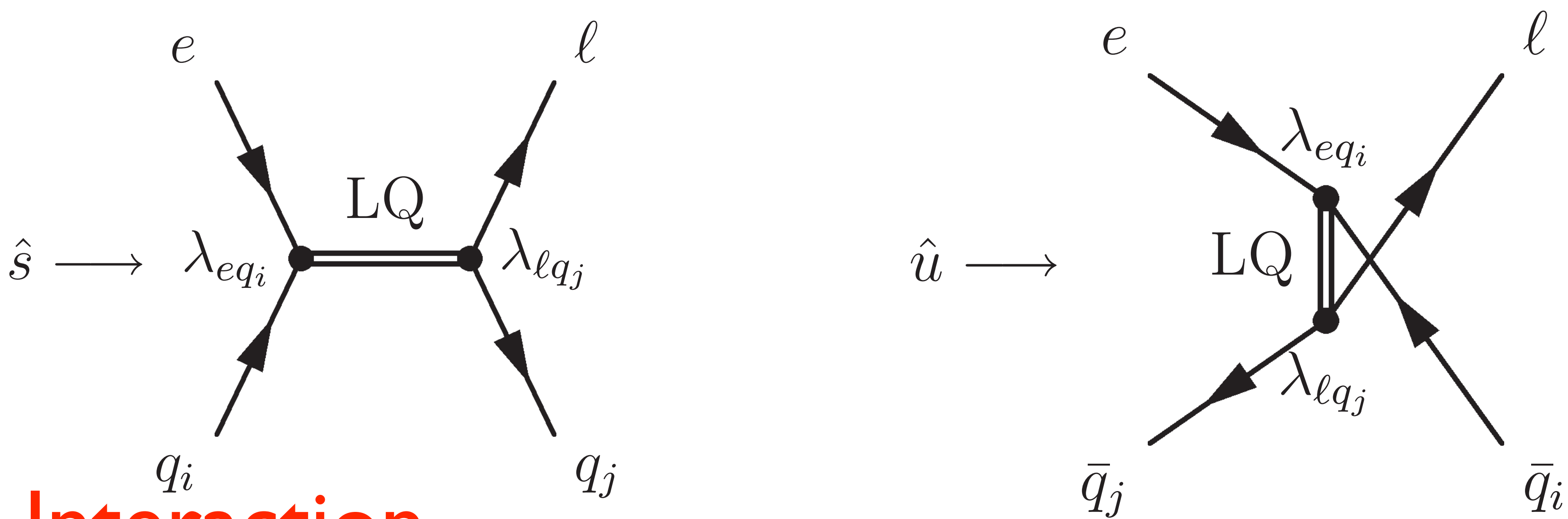
Resonant s-channel production

- For $M_{\rm LQ} \lesssim \sqrt{s}$ where resonant production is possible in the s-channel, electron and positron beams can distinguish between F=0 and |F|=2 LQs.

$$\frac{d^2\sigma_{\rm s}}{dxdy} = \frac{1}{32\pi\hat{s}} \cdot \frac{\lambda_{eq}^2 \lambda_{\ell q}^2 \hat{s}^2}{(\hat{s}^2 - m_{\rm LQ}^2)^2 + m_{\rm LQ}^2 \Gamma_{\rm LQ}^2} \cdot q_i(x, \hat{s}) \times \begin{cases} \frac{1}{2} & \text{scalar LQ} \\ 2(1-y)^2 & \text{vector LQ} \end{cases}$$

y-dependence can distinguish scalar and vector leptoquarks

Leptoquarks: Electron vs Positron Beams



Contact Interaction

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

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

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

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

→ y-dependence can distinguish scalar and vector leptoquarks

- For $M_{\rm LQ} \gg \sqrt{s}$ electron and positron beams will give similar constraints F=0 and |F|=2 since LQs will appear as contact interactions. Precision measurements of electroweak couplings can help.

Leptoquarks: Polarized Lepton and Nuclear (p,D)

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

- 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]

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

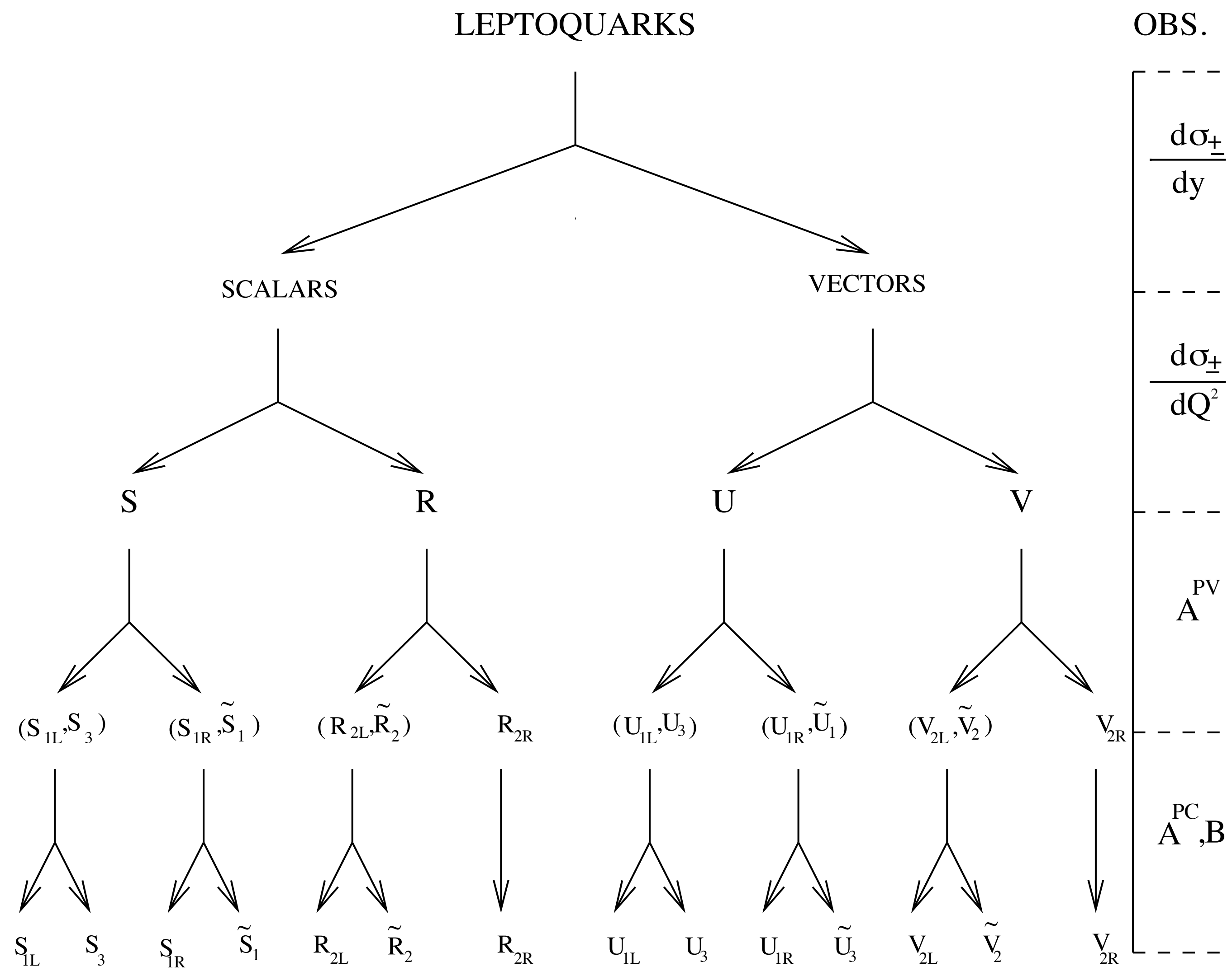
$$A_1^{PC} = \frac{\sigma_-^{--} - \sigma_-^{-+}}{\sigma_-^{--} + \sigma_-^{-+}}$$

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

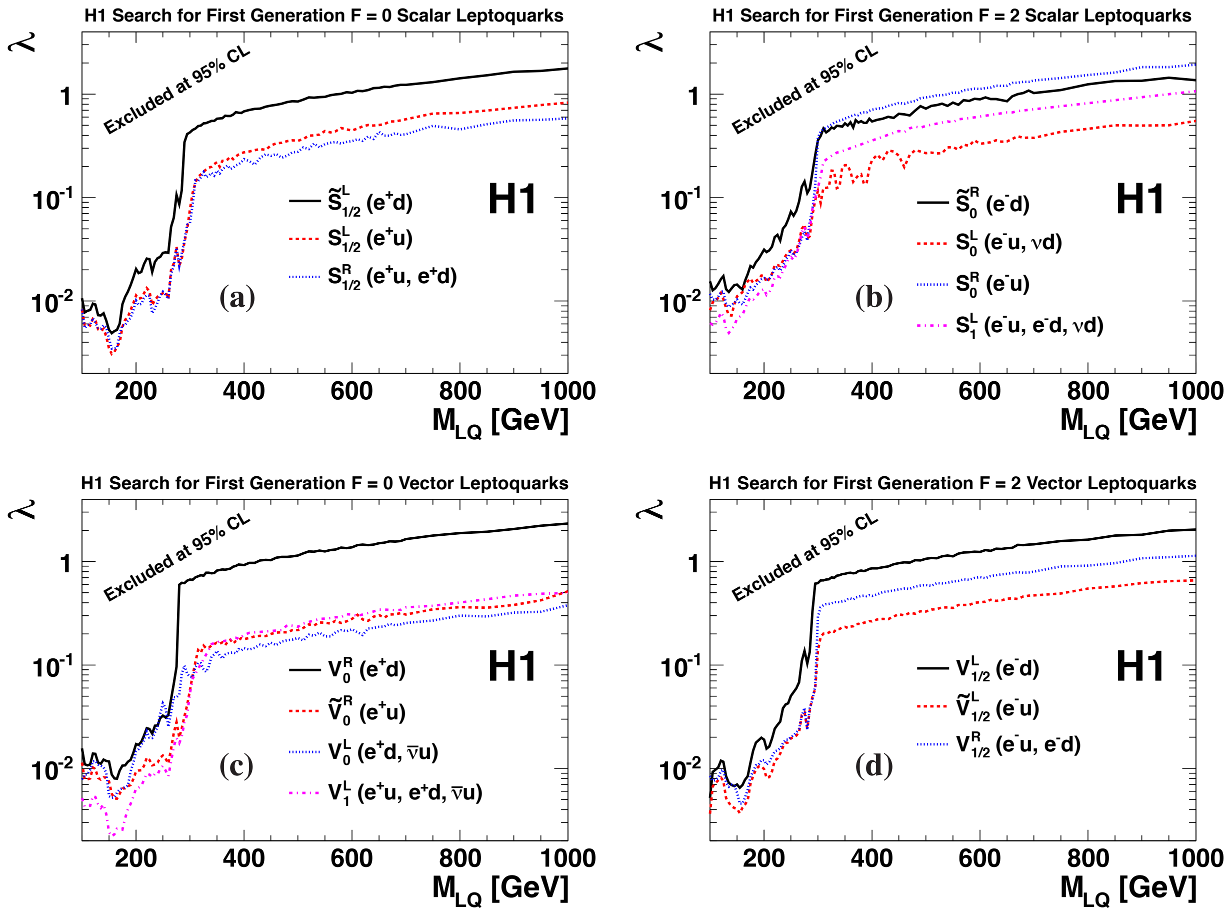
$$A_3^{PC} = \frac{\sigma_+^{++} - \sigma_+^{+-}}{\sigma_+^{++} + \sigma_+^{+-}}$$

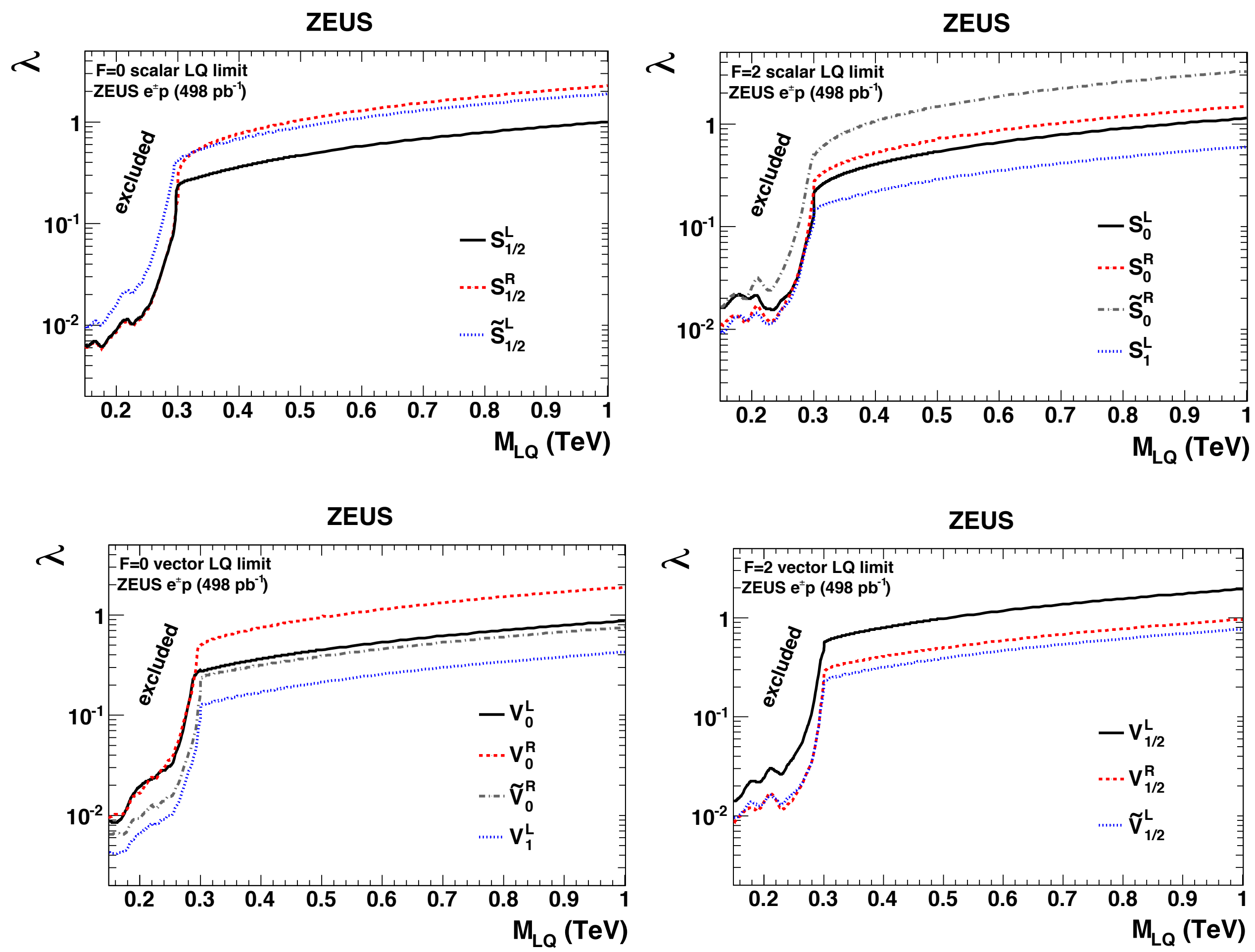
$$B_U = \frac{\sigma_-^{--} - \sigma_-^{++} + \sigma_+^{++} - \sigma_+^{--} + \sigma_-^{-+} - \sigma_-^{+-} + \sigma_+^{-+} - \sigma_+^{+-}}{\sigma_-^{--} + \sigma_-^{++} + \sigma_+^{++} + \sigma_+^{--} + \sigma_-^{-+} + \sigma_-^{+-} + \sigma_+^{-+} + \sigma_+^{+-}}$$

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



HERA Limits on LQs

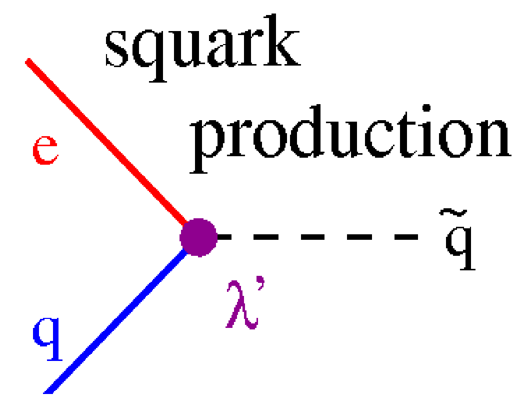




R-Parity Violating (RPV) SUSY

- 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):

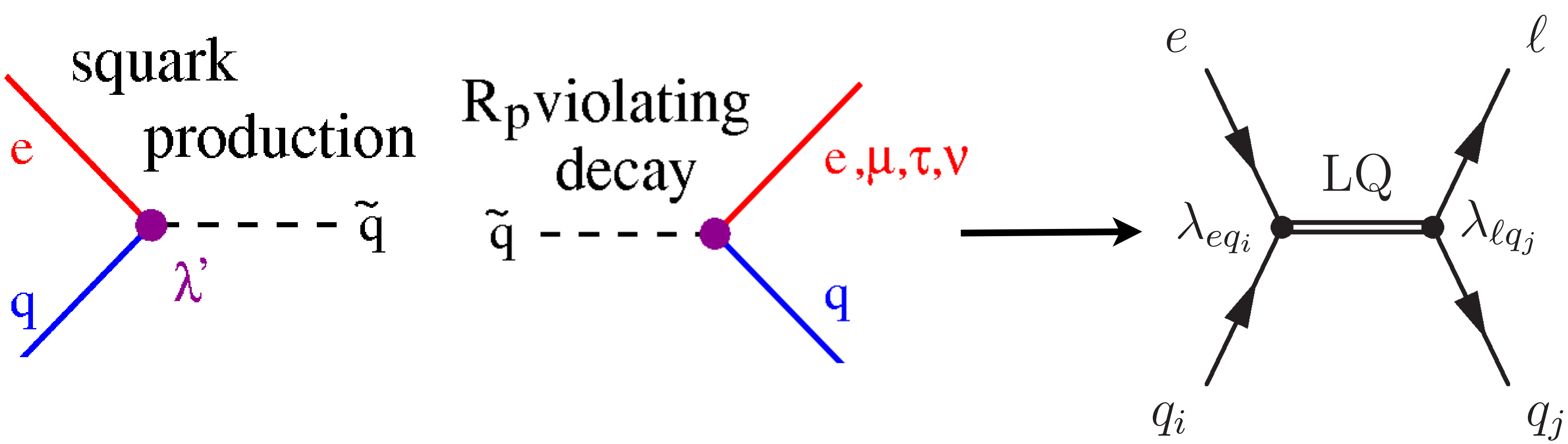
$$W_{\Delta \mathrm{L}=1} = \frac{1}{2}\lambda^{ijk} L_i L_j \overline{e}_k + \boxed{\lambda'^{ijk} L_i Q_j \overline{d}_k} + \mu'^{i} L_i H_u$$

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

Single squark production at HERA, EIC

R-Parity Violating (RPV) SUSY

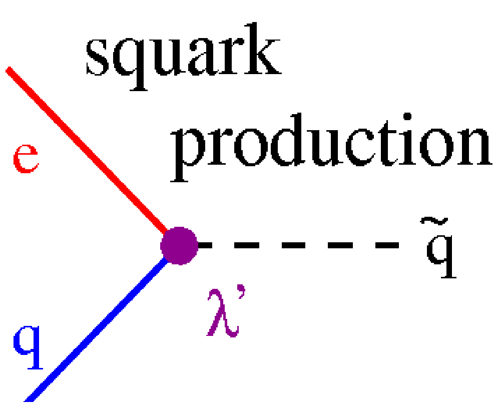
- For RPV production and RPV decay, signature is the same as for LQs:

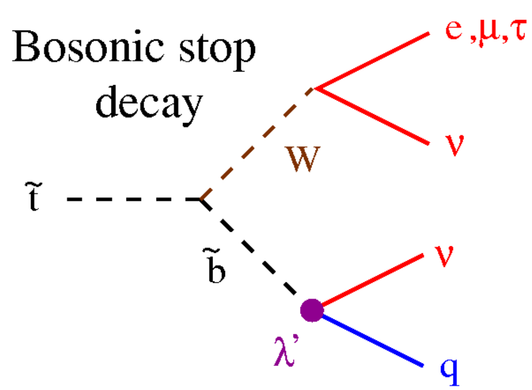


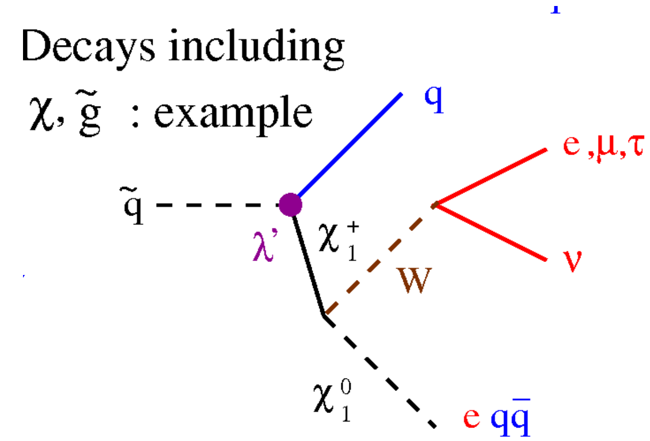
Lepton+Jet channel

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

- For other decays, the final state is more complicated:





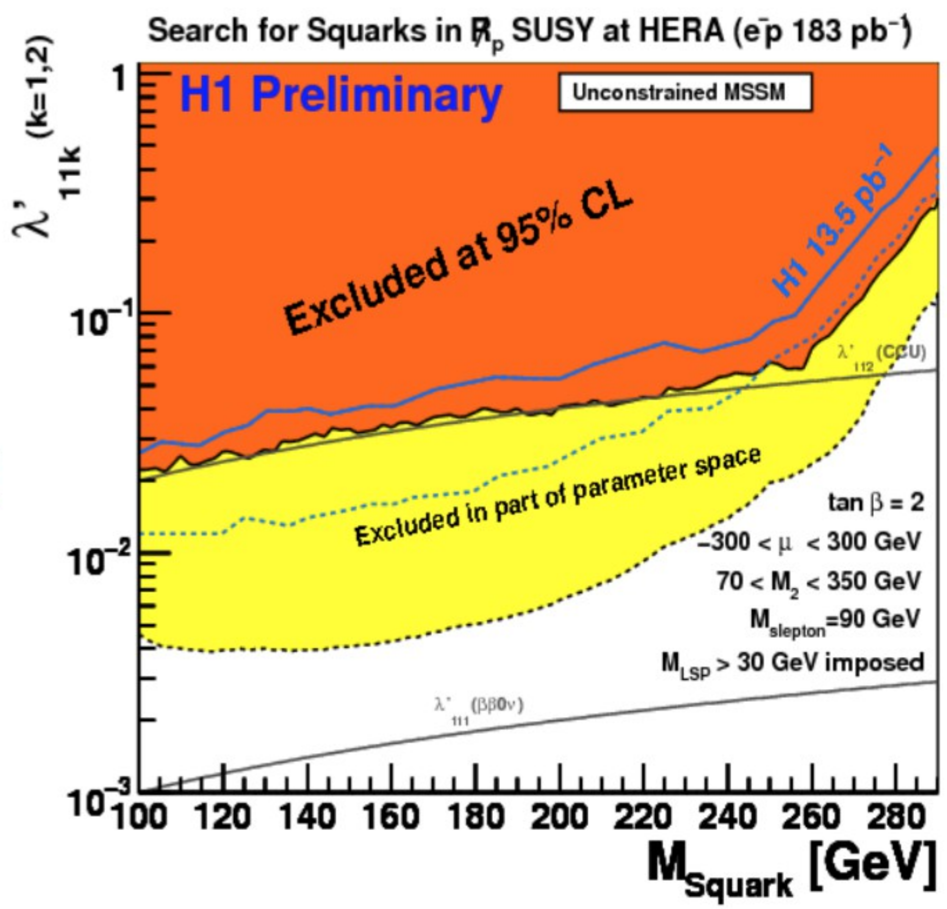


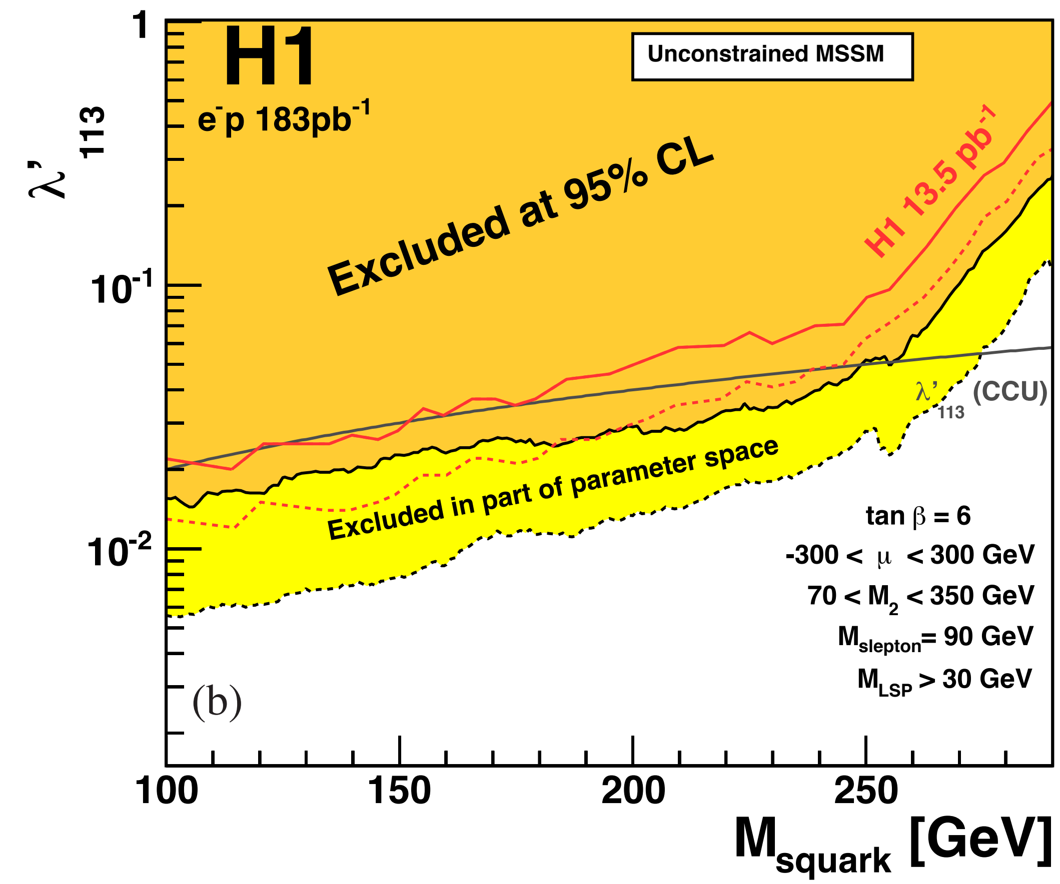
R-Parity Violating (RPV) SUSY

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

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

- Exclusion limits:





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

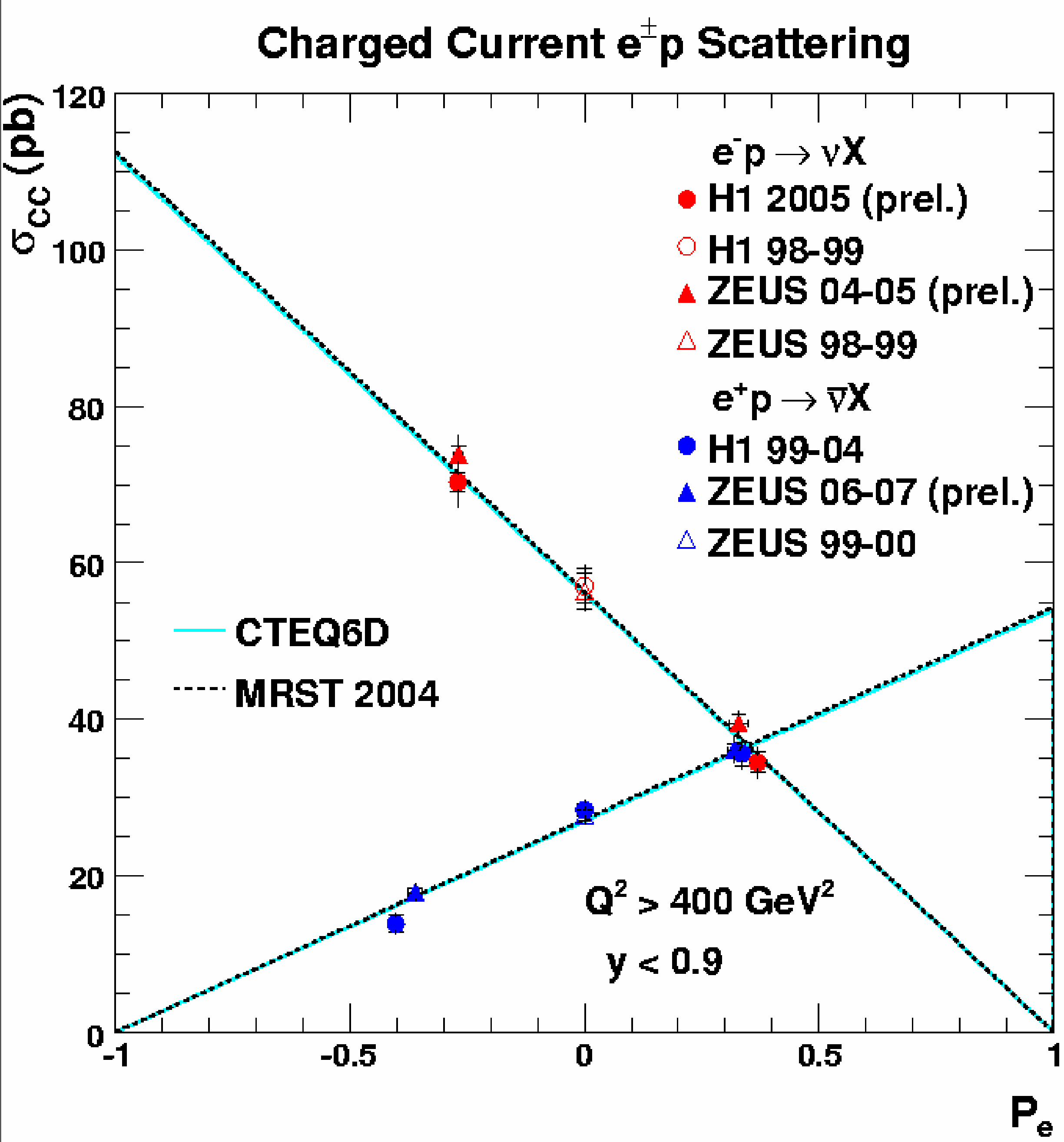
- Electroweak interactions in the Standard model violates parity maximally.
- The W-boson has interactions only with the left-handed quarks and leptons.
- Right-handed neutrinos, as evidenced by neutrino oscillations, require physics beyond the Standard Model

- 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.

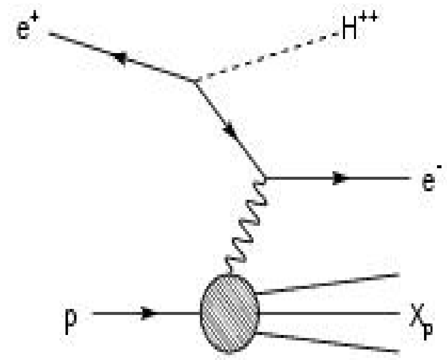
- Polarized electron and positron beams can test this Standard Model paradigm.

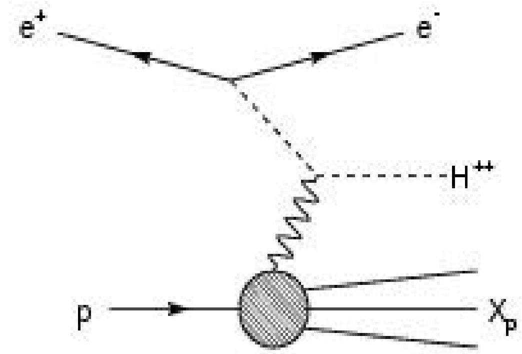
HERA limits on the right-handed W mass:

e^+p: > 208 GeV [A.Atkas et.al (H1)]
e^-p: > 186 GeV

(assuming equal couplings for left and right handed Ws)

Doubly Charged Higgs





- Associated with the right-handed W-boson might be a doubly charged Higgs.
- The spontaneous parity violation in Left-Right symmetric (LRS) models occurs through a Higgs triplet whose neutral component gets a vacuum expectation value:

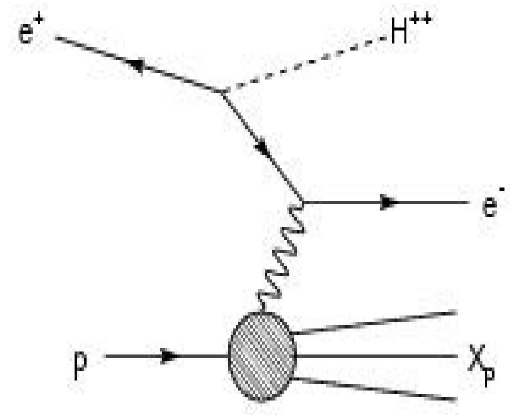
$$\mathrm{SU}(2)_L \otimes \mathrm{SU}(2)_R \otimes \mathrm{U}(1)_{B-L} \longrightarrow \mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y$$

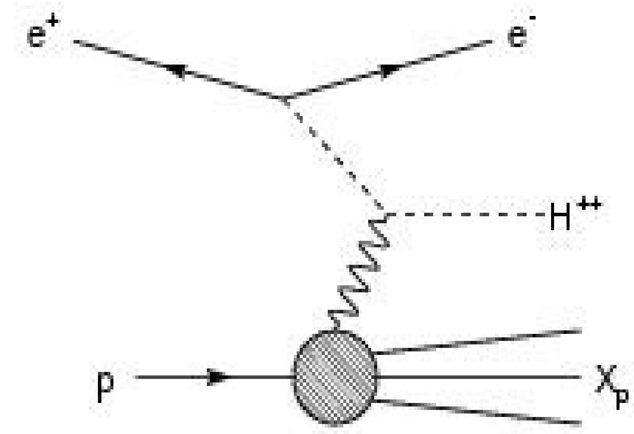
- This mechanism also generates a non-zero Majorana mass for a right-handed neutrino facilitating the Seesaw mechanism for neutrino masses.
- By the B-L symmetry, the doubly charged higgs has no couplings to quarks. It only couples to the leptons:

$$\mathscr{L} = h_{ij}^{L,R} H^{--} \bar{l}_i^c P_{L,R} l_j \ + \ h.c.$$

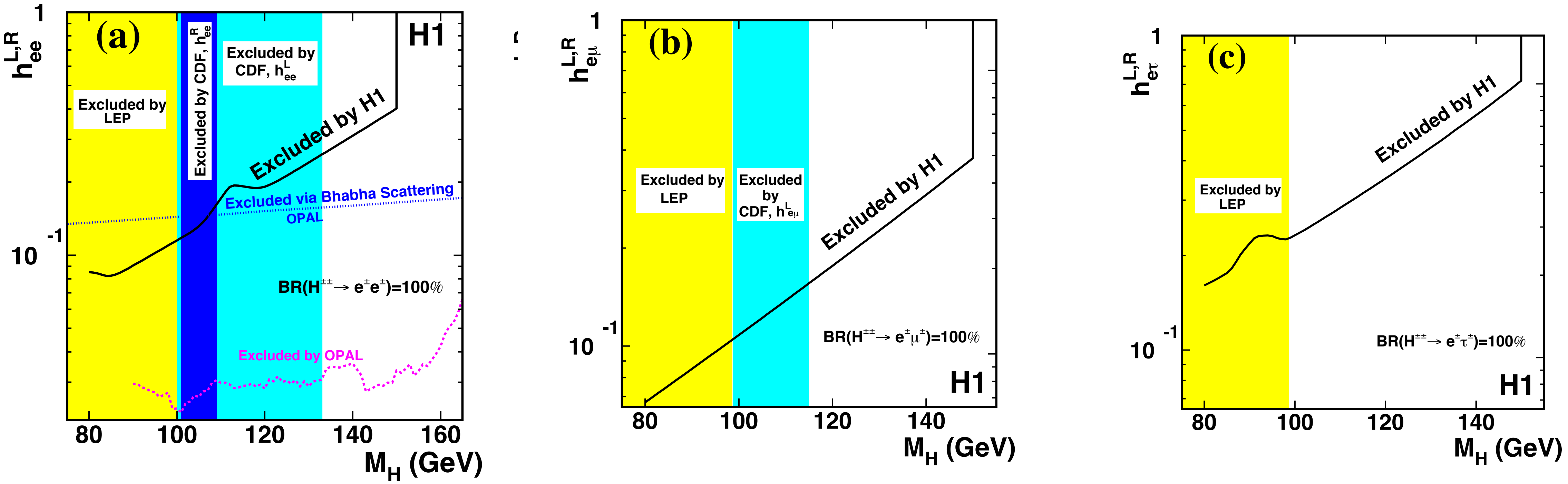
- These Yukawa couplings are unrelated to fermion mass generation for charged leptons. Thus, they are not constrained to be small. For large enough couplings, production and observation of a doubly charged Higgs production becomes feasible.
- The signal is searched for via the doubly charged Higgs decay to same-sign charged leptons.

Doubly Charged Higgs





- Exclusion limits:



Excited Leptons (Compositeness)

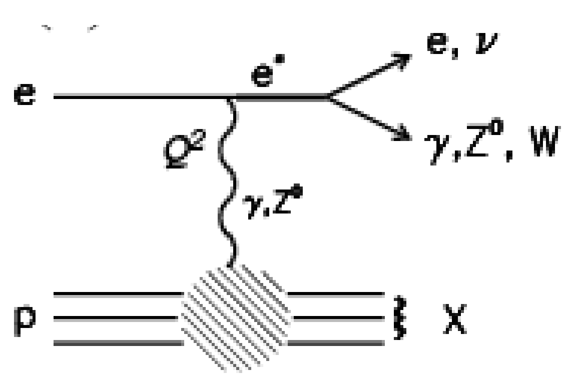
- If leptons or quarks have substructure, new types of interactions are expected at the compositeness scale. Could explain the mass hierarchy of the lepton and quark families.

- Such interactions appear as contact interactions (chirally invariant) between leptons or quarks at energies well below the compositeness scale:

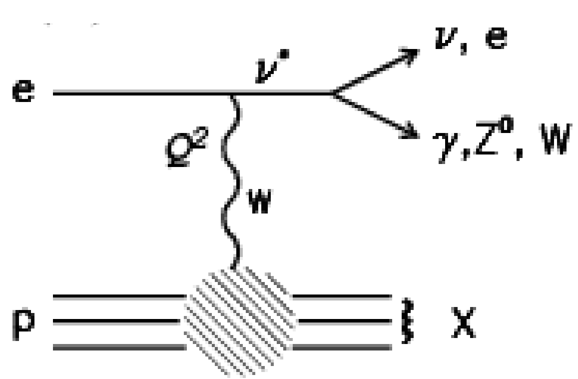
$$L = \frac{g^2}{2\Lambda^2}\left[\eta_{LL}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_L\,\gamma^\mu\,\psi_L + \eta_{RR}\,\overline{\psi}_R\,\gamma_\mu\,\psi_R\,\overline{\psi}_R\,\gamma^\mu\,\psi_R\right.$$
$$\left. +2\eta_{LR}\,\overline{\psi}_L\,\gamma_\mu\,\psi_L\,\overline{\psi}_R\,\gamma^\mu\,\psi_R\right]\;.$$

- Another interesting interaction (chirally invariant) is the magnetic transition operator:

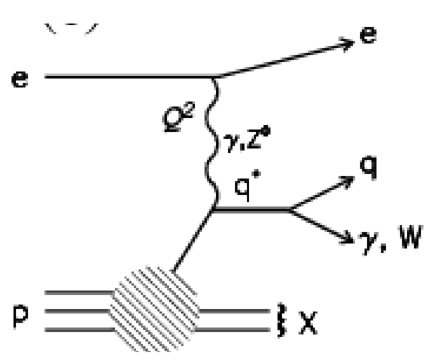
$$\mathcal{L}_{GM} = \frac{1}{2\Lambda}\bar{F}_R^*\,\sigma^{\mu\nu}\left[g f\frac{\tau^a}{2}W^a_{\mu\nu} + g' f'\frac{Y}{2}B_{\mu\nu} + g_s f_s\frac{\lambda^a}{2}G^a_{\mu\nu}\right]F_L + h.c.$$



excited electron



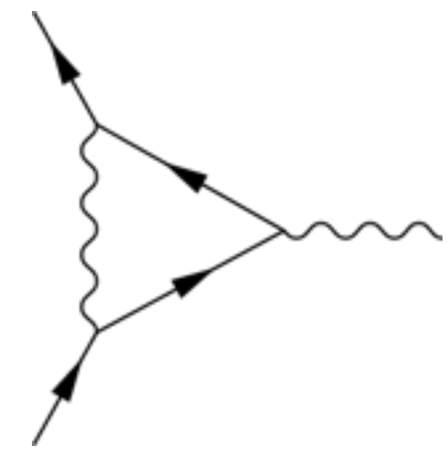
excited neutrino



excited quark

Excited Leptons (Compositeness)

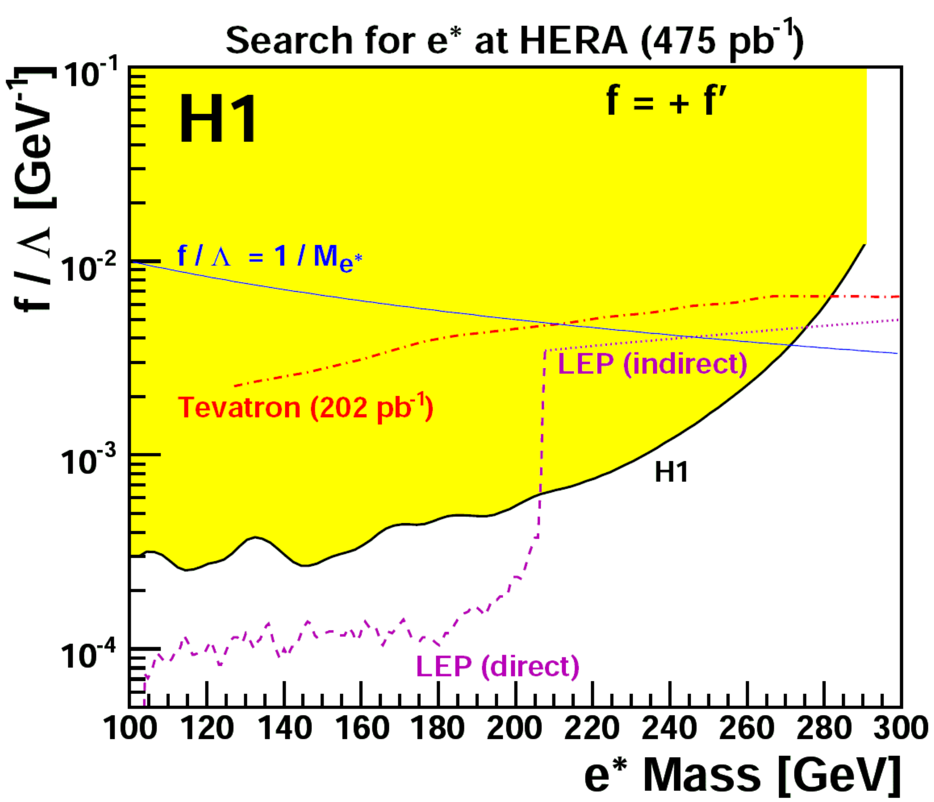
- The chirally invariant coupling of the excited lepton [left(right)-handed lepton couples only to the right(left)-handed excited electron] is motivated by success of quantum electrodymamics in predicting the g-2 value of the electron.

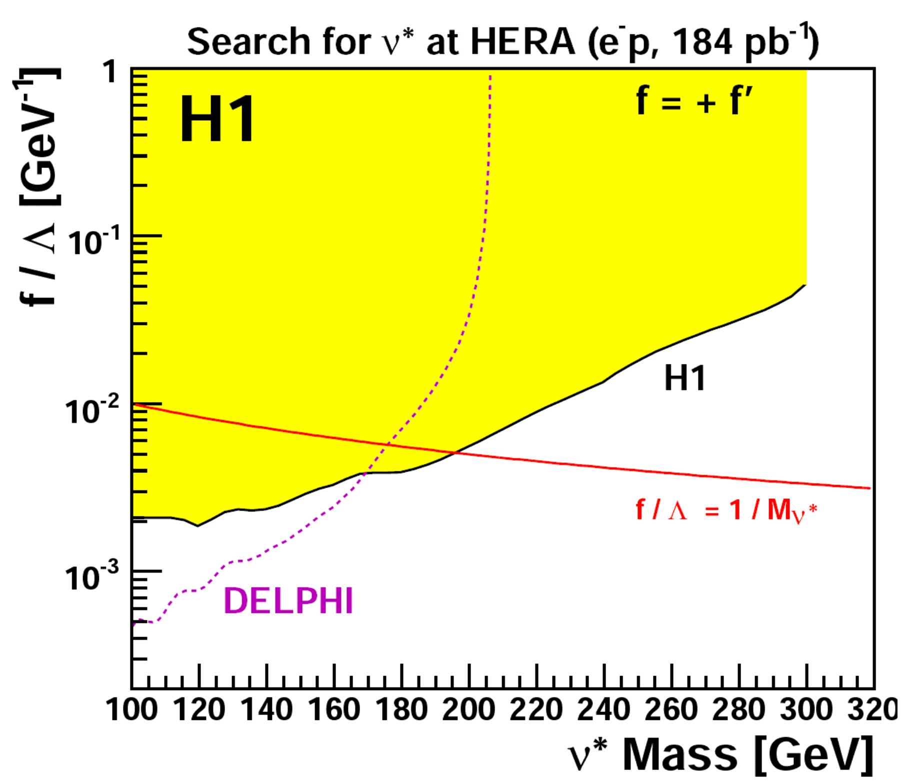


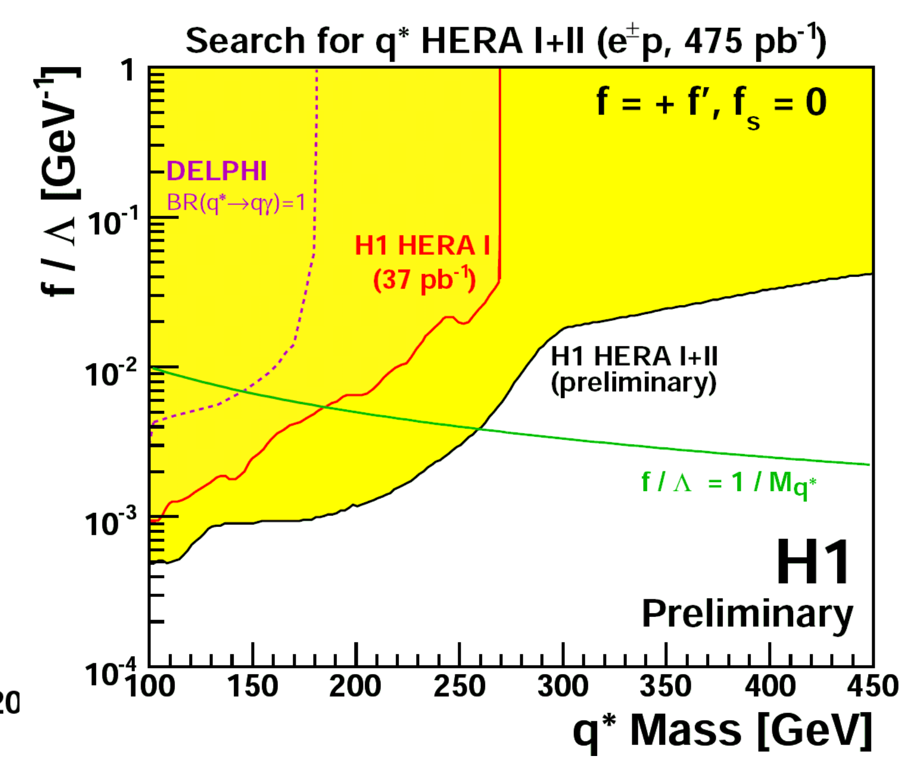
- The study of the structure of such chiral couplings (GM,and CI) is once again facilitated by polarized beams.

- For excited neutrinos, that involve W-exchange, a polarized lepton beam can be used in the same way as in the search for the right-handed W.

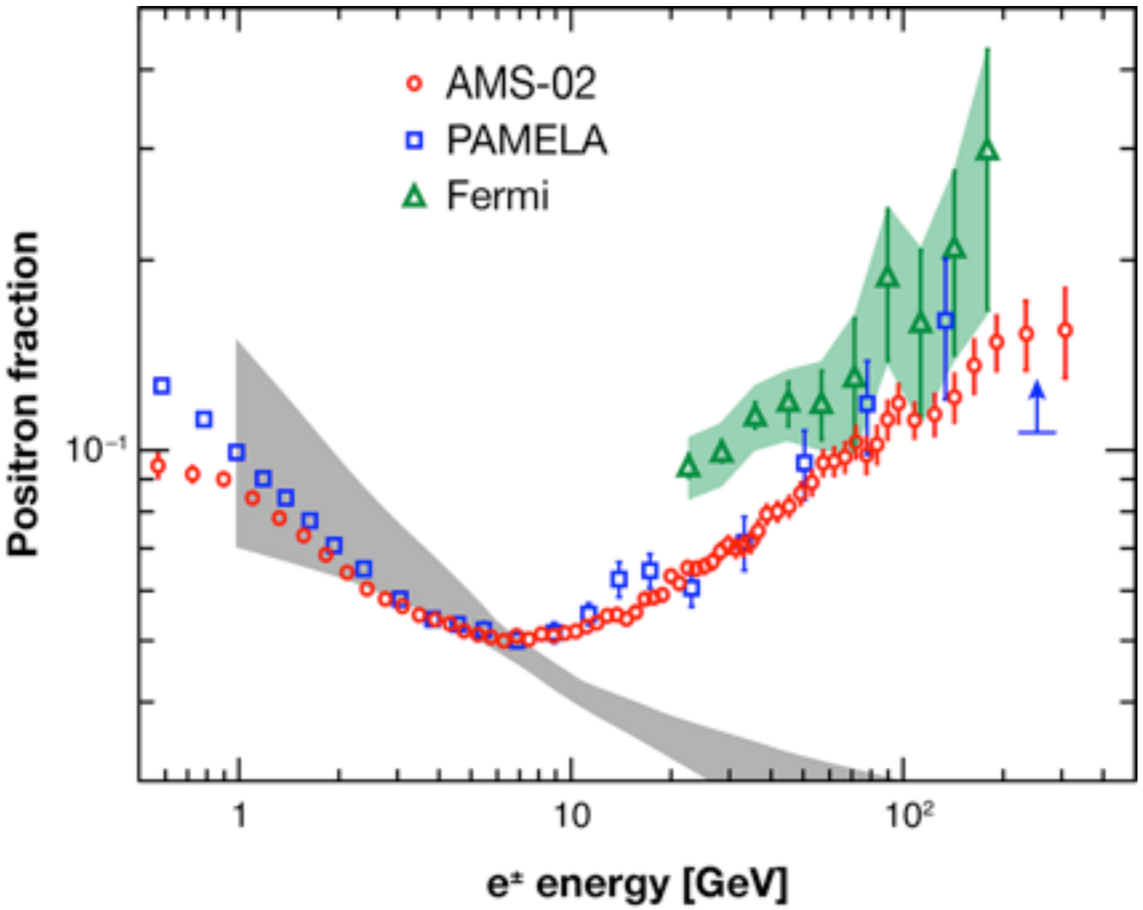
- Exclusion limits:





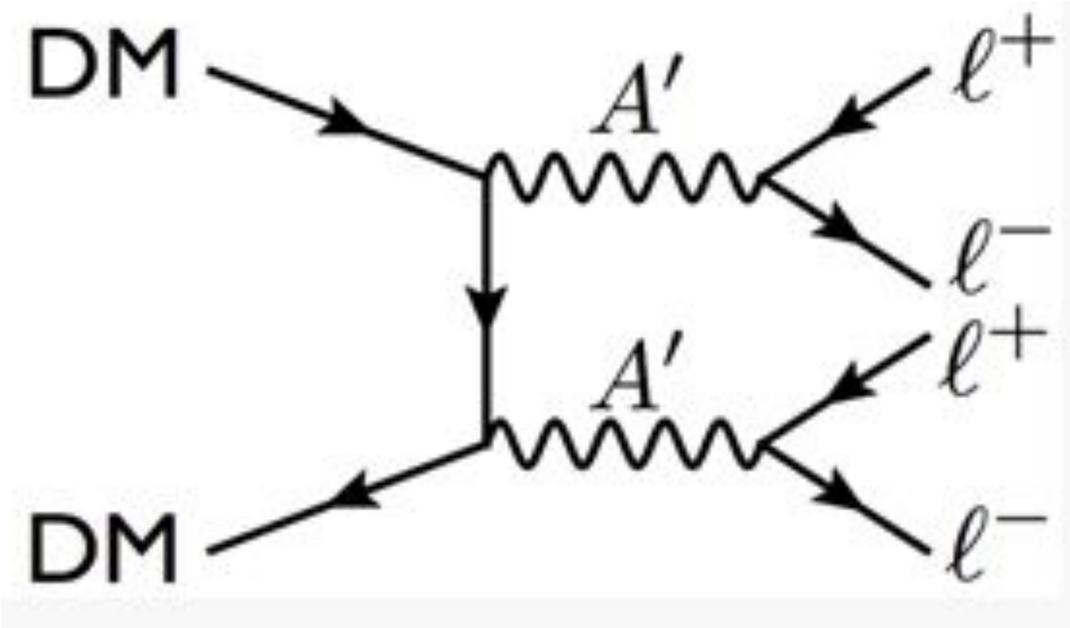


Dark Photon Search



- Observed excess of high energy cosmic ray positrons could be a tantalizing hint for dark matter annihilation through dark sector photons (dark photons, A′) that couple to leptons (for example through kinetic mixing).
- The lack of a similar excess for antiprotons suggest a dark photon mass range

$$2m_e < M_{A'} \lesssim \text{few GeV}$$



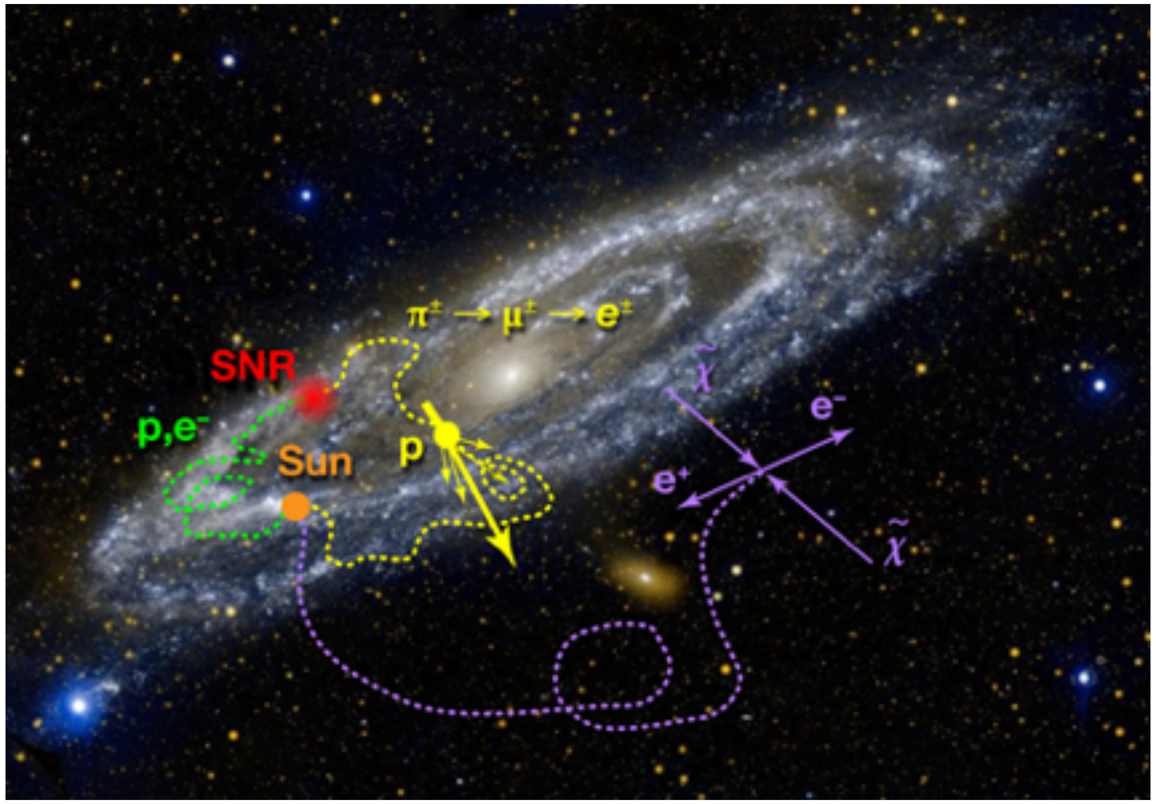
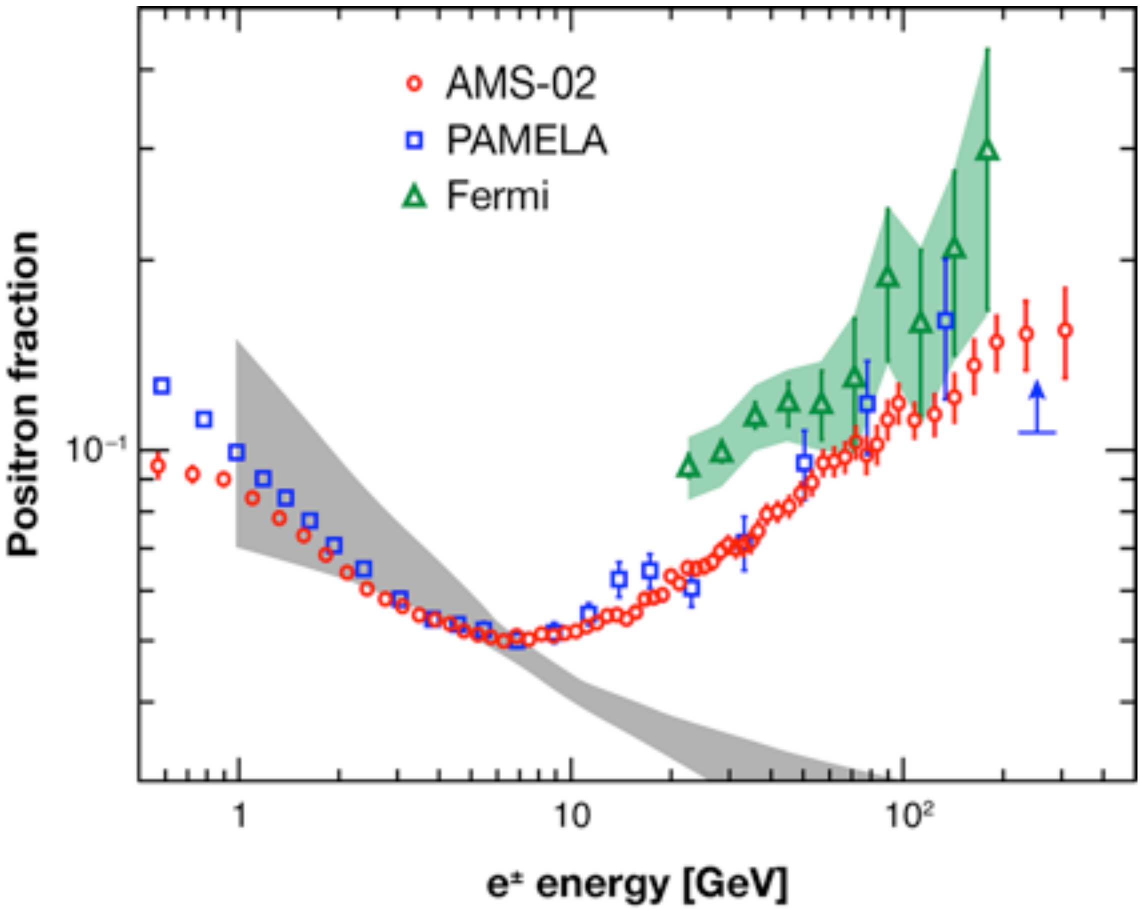


Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

Dark Photon Search



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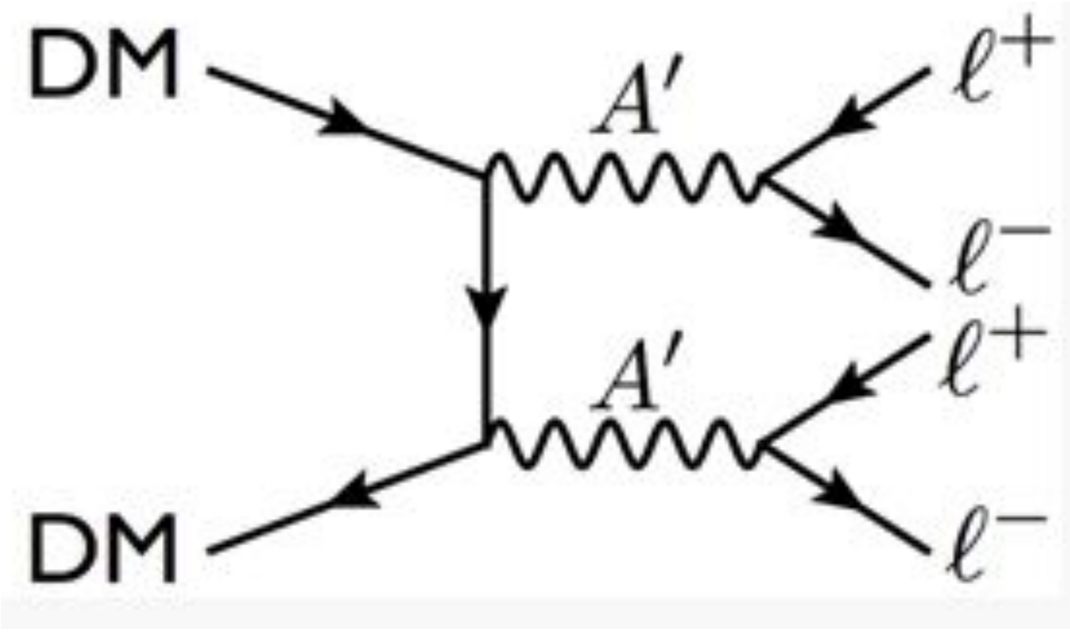
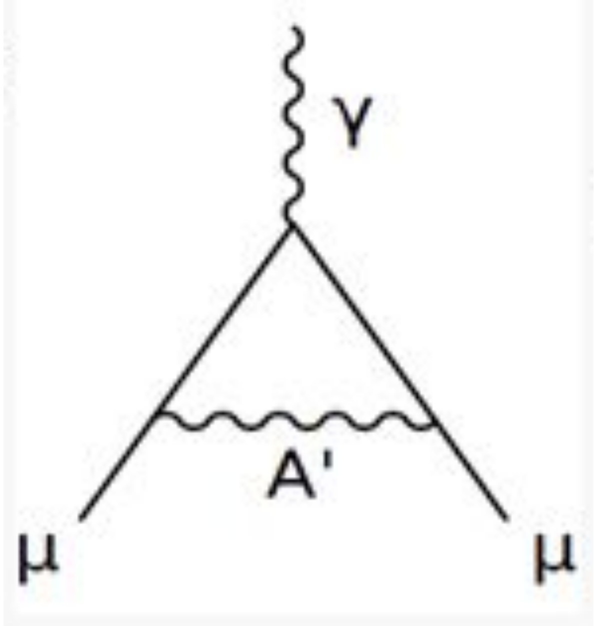
$$2m_e < M_{A'} \lesssim \text{few GeV}$$

- Such a dark photon could play a role in explaining the muon magnetic moment anomaly:

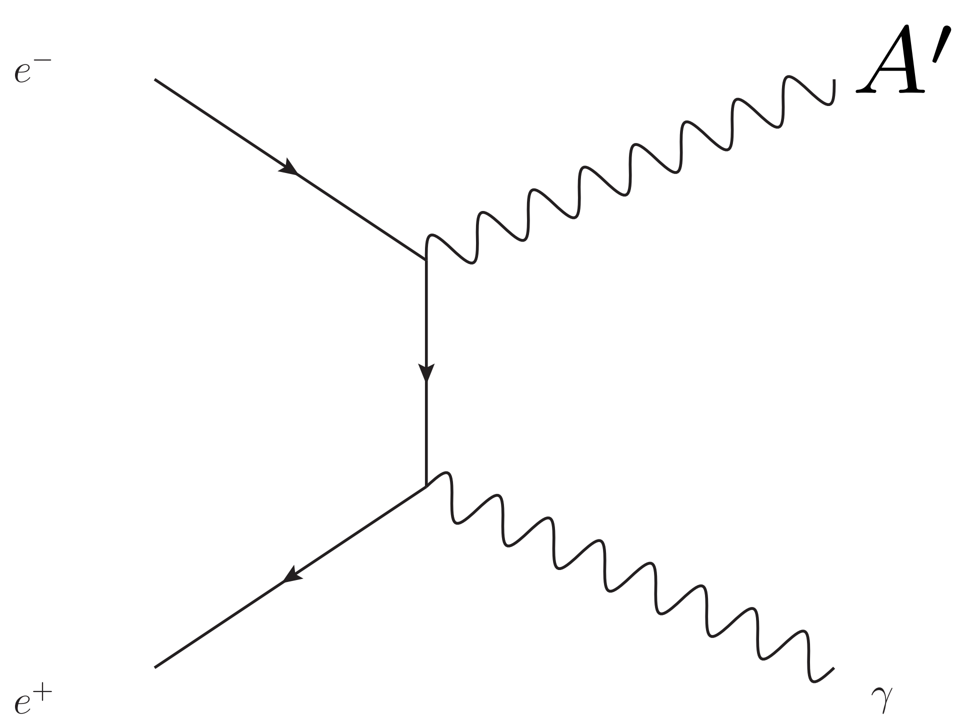




Dark Photon Search

- A positron beam incident on the target would allow a search for the dark photon:

$$e^+e^- \to \gamma A'$$



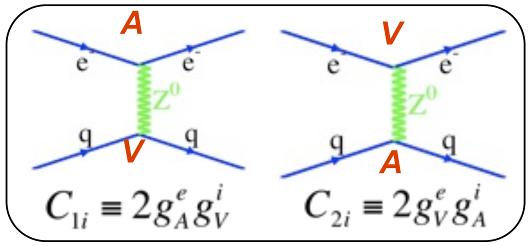
- Kinematics of process is especially simple and allows for a more general dark photon search without assumptions about its decay modes:

$$M_{A'}^2 = (P_{e^-}^{\text{target}} + P_{e^+}^{\text{beam}} - P_\gamma)^2$$

- For more details, see talk by P.Valente and L.Marsicano

Precision Measurements of the Weak Neutral Current Couplings

Contact Interactions



- New physics at low energies can be parameterized in terms of contact interactions (eg. LQs, RPV SUSY, Excited Fermions, etc.)

$$\mathcal{L}_{\text{eff}} = \sum_{\ell,q} \left\{ \eta_{LL}^{\ell q} \overline{\ell_L} \gamma_\mu \ell_L \overline{q_L} \gamma^\mu q_L + \eta_{LR}^{\ell q} \overline{\ell_L} \gamma_\mu \ell_L \overline{q_R} \gamma^\mu q_R + \eta_{RL}^{\ell q} \overline{\ell_R} \gamma_\mu \ell_R \overline{q_L} \gamma^\mu q_L + \eta_{RR}^{\ell q} \overline{\ell_R} \gamma_\mu \ell_R \overline{q_R} \gamma^\mu q_R \right\}$$

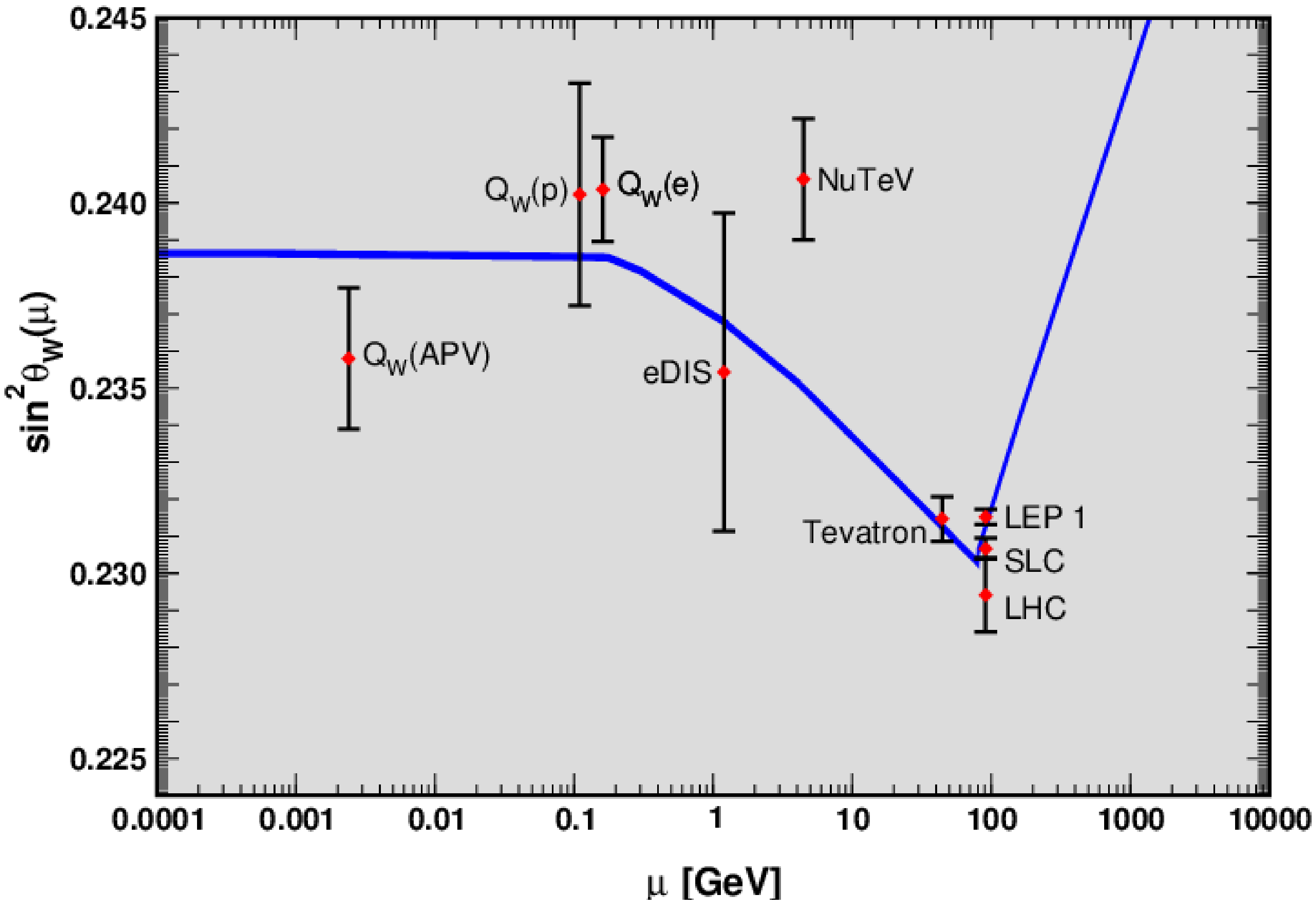
- These contact interactions can be mapped onto the usual parameterization of the electroweak couplings:

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

- Tree-level Standard Model values:

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

Precision Measurements of the Weak Mixing Angle



[PDG]

- Deviations from SM predictions can be hints for new physics

- 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

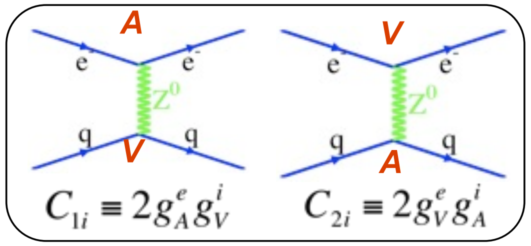
- New physics reach from various precision experiments and the combination of couplings they constrain:

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]

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

Contact Interactions



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

- Precision measurements of the electroweak couplings, can be translated into constraints in specific models.
- For example, for the different LQ states:

ZEUS (prel.) 1994-2000 $e^{\pm}p$									
	Coupling structure								95% CL [TeV]
Model	a_{LL}^{ed}	a_{LR}^{ed}	a_{RL}^{ed}	a_{RR}^{ed}	a_{LL}^{eu}	a_{LR}^{eu}	a_{RL}^{eu}	a_{RR}^{eu}	M_{LQ}/λ_{LQ}
$S_\circ^L$					$+\frac{1}{2}$				0.75
$S_\circ^R$								$+\frac{1}{2}$	0.69
$\tilde{S}_\circ^R$				$+\frac{1}{2}$					0.31
$S_{1/2}^L$						$-\frac{1}{2}$			0.91
$S_{1/2}^R$			$-\frac{1}{2}$				$-\frac{1}{2}$		0.69
$\tilde{S}_{1/2}^L$		$-\frac{1}{2}$							0.50
S_1^L	$+1$				$+\frac{1}{2}$				0.55
$V_\circ^L$	-1								0.69
$V_\circ^R$				-1					0.58
$\tilde{V}_\circ^R$								-1	1.03
$V_{1/2}^L$		$+1$							0.49
$V_{1/2}^R$			$+1$				$+1$		1.15
$\tilde{V}_{1/2}^L$						$+1$			1.26
V_1^L	-1				-2				1.42

$$\Delta C_{1q} = (\eta_{\text{LL}}^{\ell q} + \eta_{\text{LR}}^{\ell q} - \eta_{\text{RL}}^{\ell q} - \eta_{\text{RR}}^{\ell q})/(2\sqrt{2}G_F)$$
$$\Delta C_{2q} = (\eta_{LL}^{\ell q} - \eta_{LR}^{\ell q} + \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q})/(2\sqrt{2}G_F)$$
$$\Delta C_{3q} = (-\eta_{LL}^{\ell q} + \eta_{LR}^{\ell q} + \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q})/(2\sqrt{2}G_F)$$

Asymmetries as a Probe of Electroweak Couplings

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

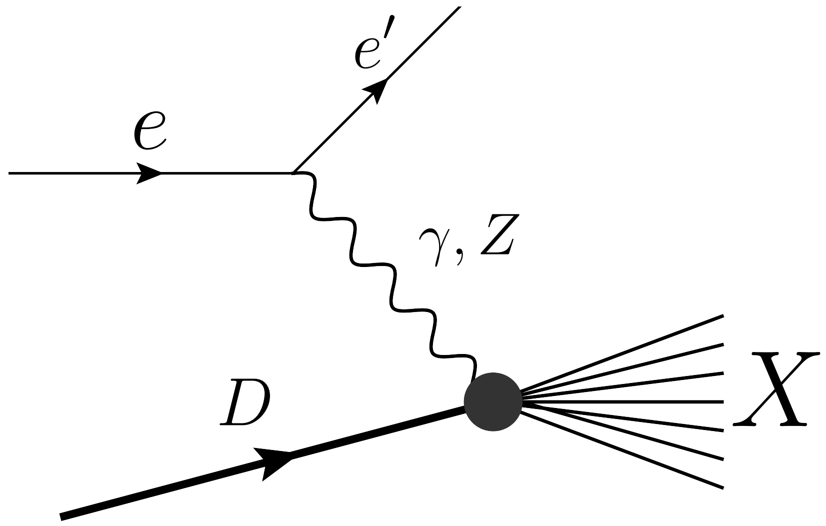
Can be further constrained by Parity-Violating eD DIS

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:

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

- The asymmetry can be brought into the form:

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

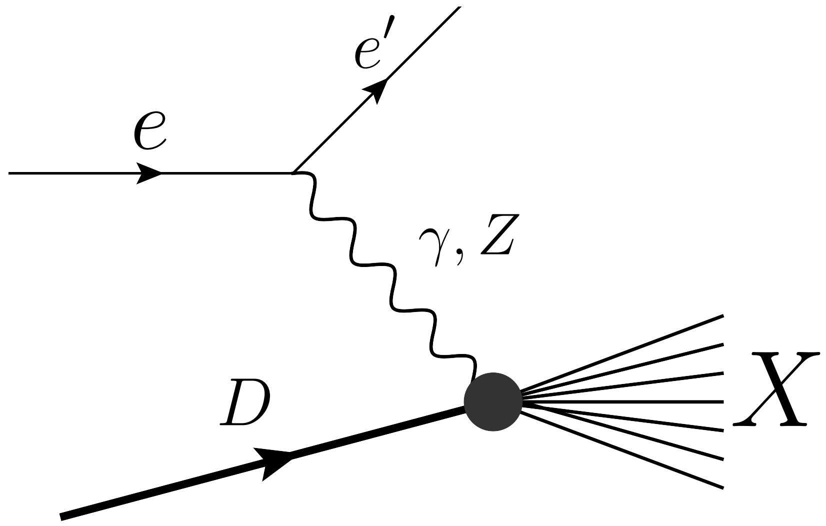
- QPM expressions:

$$a(x) \equiv \Sigma_i f_i(x) C_{1i} q_i / \Sigma_i f_i(x) q_i^2$$

$$b(x) \equiv \Sigma_i f_i(x) C_{2i} q_i / \Sigma_i f_i(x) q_i^2$$

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.

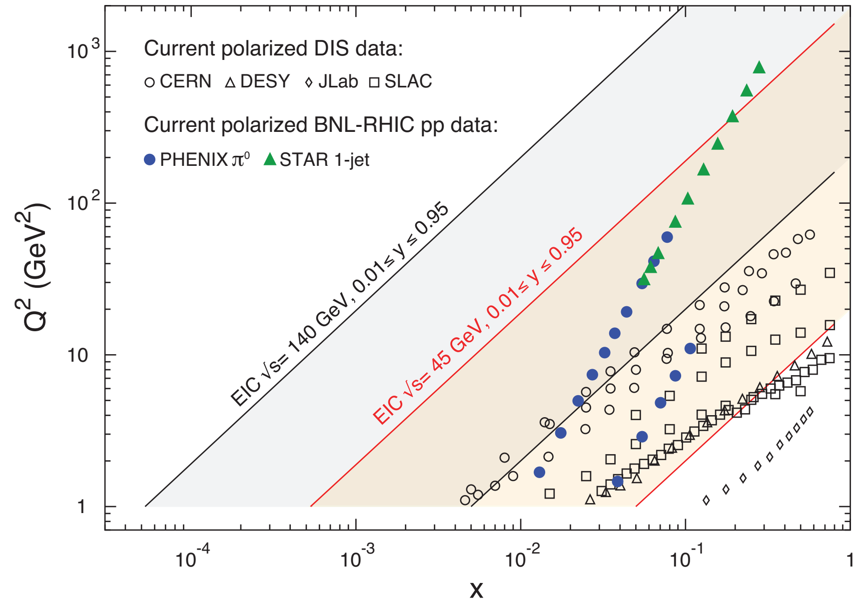
[J.Bjorken, T.Hobbs, W. Melnitchouk; S.Mantry, M.Ramsey-Musolf, G.Sacco; A.V.Belitsky, A.Mashanov, A. Schafer; C.Seng, M.Ramsey-Musolf, ...]

e-D PVDIS at EIC

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

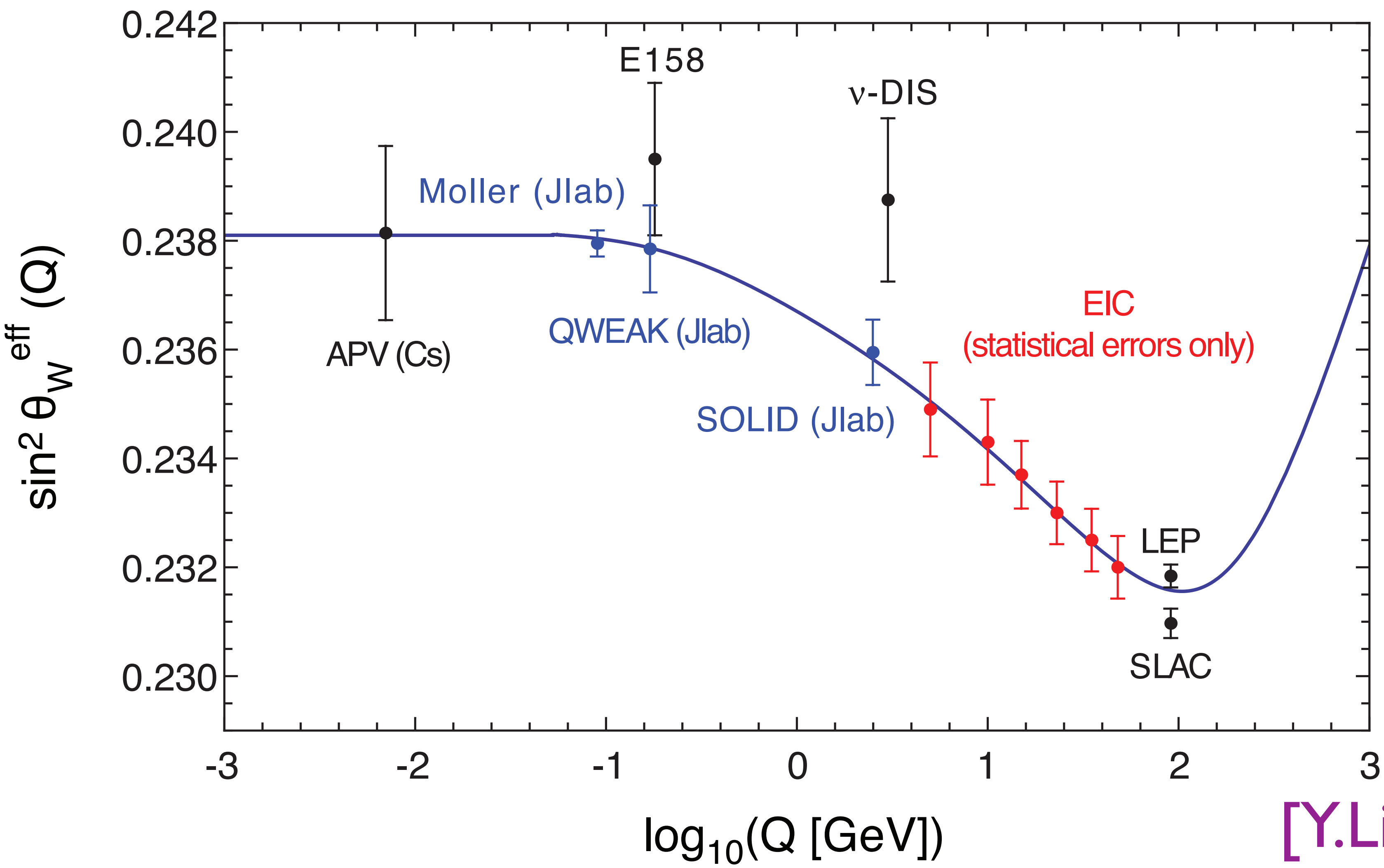
$$a(x) = \frac{6}{5}\left[(C_{1u} - \frac{1}{2}C_{1d}) + \text{corrections}\right]$$

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



- 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

Weak Mixing angle at EIC



[Y.Li, W.Marciano]

• Projected statistical uncertainties on the weak mixing angle at the EIC, for the following conditions:

$$\sqrt{s} \sim 140\ \mathrm{GeV}$$

$$\mathcal{L} \sim 200\ \mathrm{fb}^{-1}$$

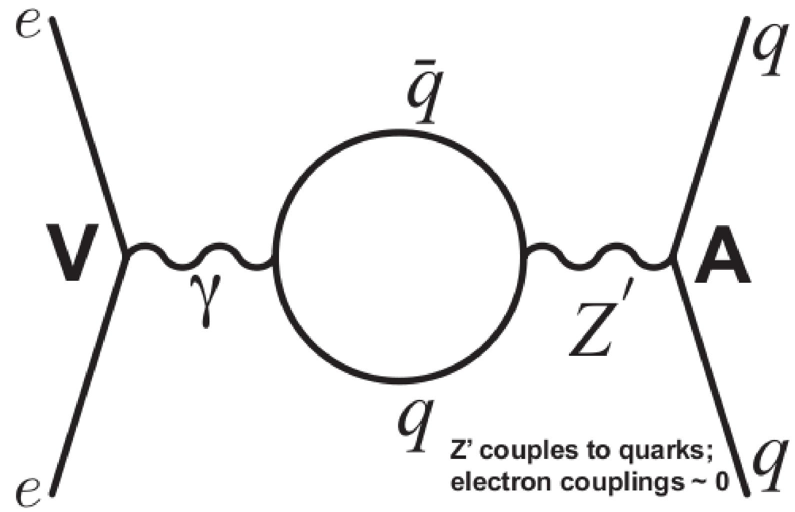
Leptophobic Z'

- 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}:

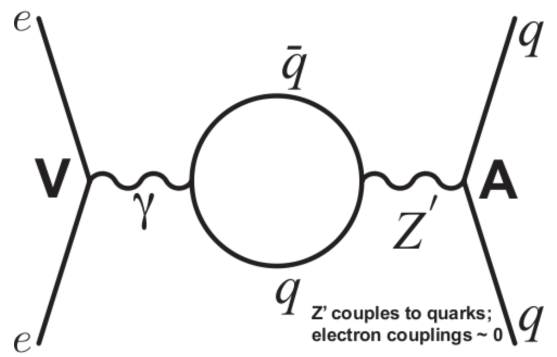


Leptophobic Z' contributes only to the C_{2q} couplings!

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

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

Leptophobic Z’



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

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

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

- Measurements over wide range of Q^2 and y at EIC:

  -allows clean separation of a(x) and b(x) terms

  -clean separation of the combinations of WNC couplings:

$2C_{1u} - C_{1d}$, $\boxed{2C_{2u} - C_{2d}}$ → Only this combination is affected by leptophobic Z’s

- JLab would be sensitive to leptophobic Z’s with mass less than 150 GeV.
- EIC can match the 12 GeV JLab measurement with ~ 75 fb^{-1} .
- EIC can improve by a factor of 2 or 3 at 100 fb^{-1} .

C-Violating Asymmetry using Polarized Electron and Positron Beams

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

- Polarized positron beams can be used to extract the C3q couplings:

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

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

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

- C3q couplings not well known. A polarized positron beam is essential for their extraction.

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:

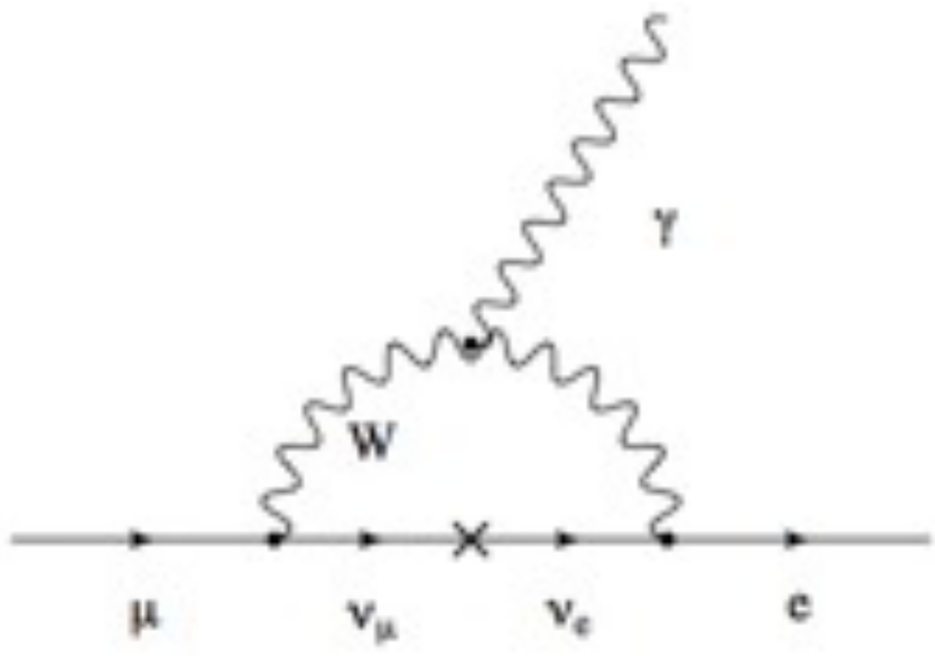
$$A_d^{e_L^- - e_R^+} = \left(\frac{3G_F Q^2}{2\sqrt{2}\pi\alpha}\right)\frac{y(2-y)}{2}\frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d})R_V}{5}, \quad R_V \equiv (u_V + d_V)/(u+d)$$

- Corrections will arise from other hadronic effects.
- More details in talk by S. Riordan

Charged 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):



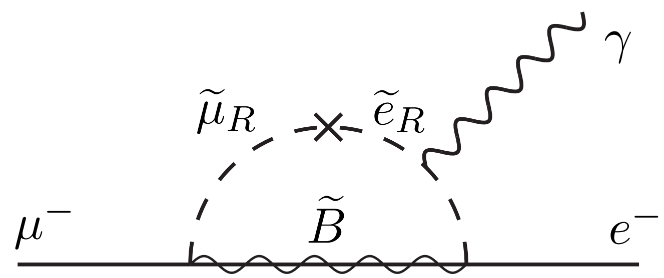
$$\mathrm{BR}(\mu \to e\gamma) < 10^{-54}$$

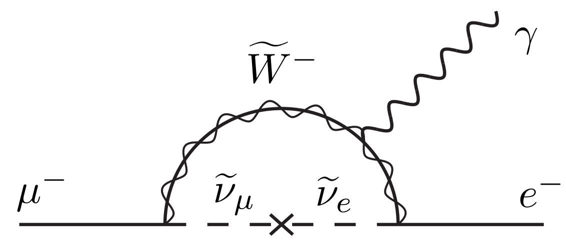
However, SM rate for CLFV is tiny due to small neutrino masses

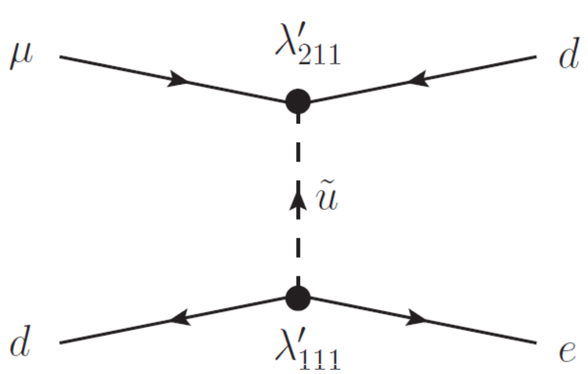
- No hope of detecting such small rates for CLFV at any present or future planned experiments!

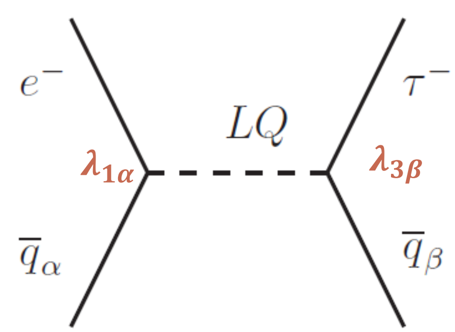
Lepton Flavor Violation in BSM

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









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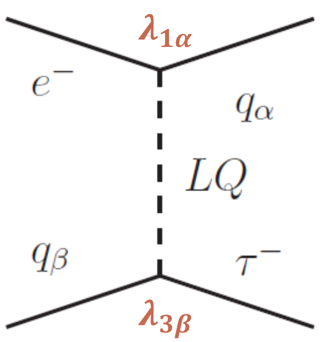


u-channel

- Enhanced rates for CLFV in BSM scenarios make them experimentally accessible.

Charged Lepton Flavor Violating Processes

- Many CLFV processes are being searched for in hopes of discovering BSM signals:

$$\mu + N \to e + N \qquad (\mu \to e \text{ conversion in nuclei})$$

$$\left.\begin{array}{l} \mu \to e\gamma \\ \tau \to e\gamma \\ \tau \to \mu\gamma \\ \mu \to 3e \\ \tau \to 3e \end{array}\right| \qquad (\text{rare CLFV decays})$$

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?

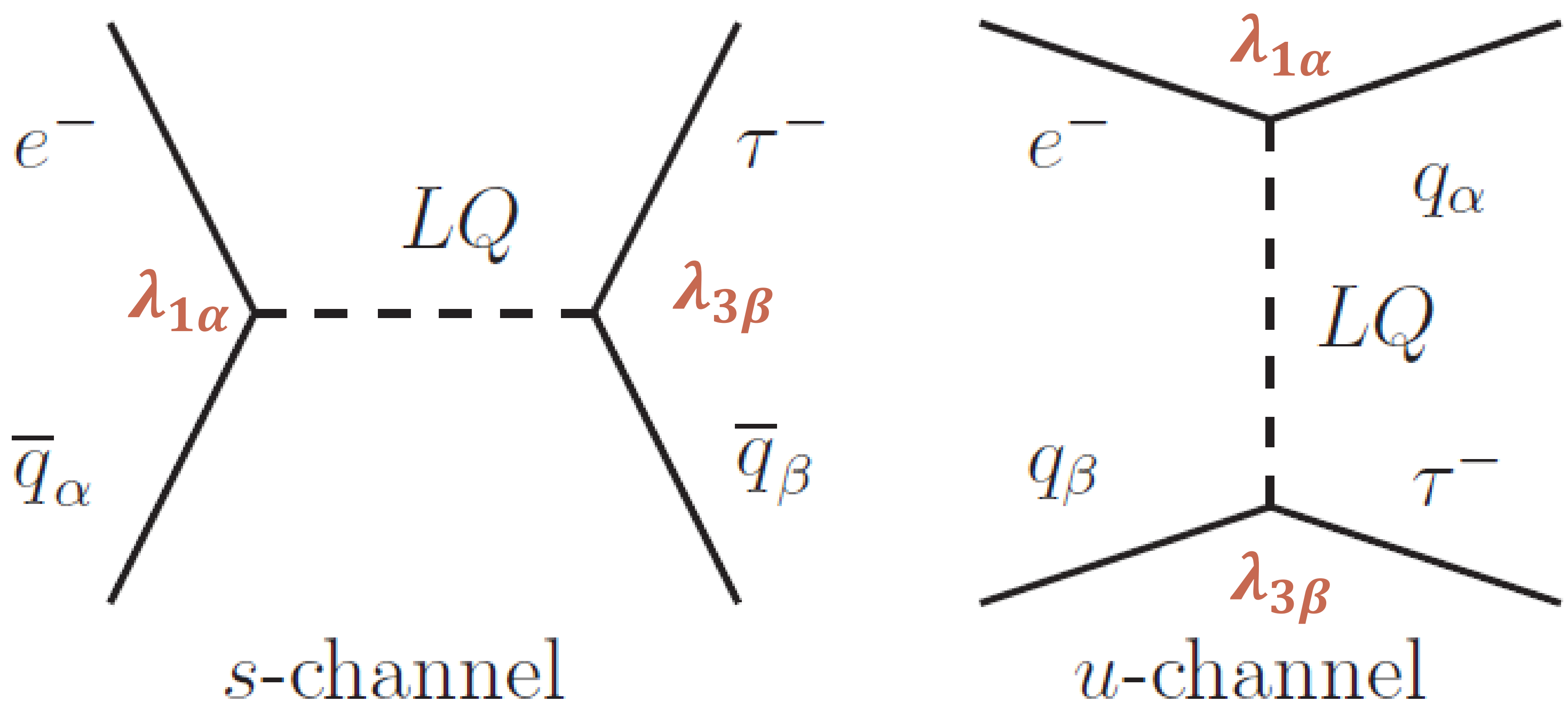
- Note that CLFV(1,2) is severely constrained. Limits on CLFV(1,3) are weaker by several orders of magnitude.
- Limits on CLFV(1,2) are expected to improve even further in future experiments.

CLFV in DIS

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

$$ep \to \tau X$$

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



CLFV limits from HERA

- The H1 and ZEUS experiments have searched for the CLFV process and set limits:

$$ep \to \tau X$$

$$\sqrt{s} \sim 320 \text{ GeV}$$

$$\mathcal{L} \sim 0.5 \text{ fb}^{-1}$$

- High luminosity EIC could surpass the best limits set by HERA :

$$ep \to \tau X$$

$$\sqrt{s} \sim 90 \text{ GeV}$$

$$\mathcal{L} \sim 10 \text{ fb}^{-1}$$

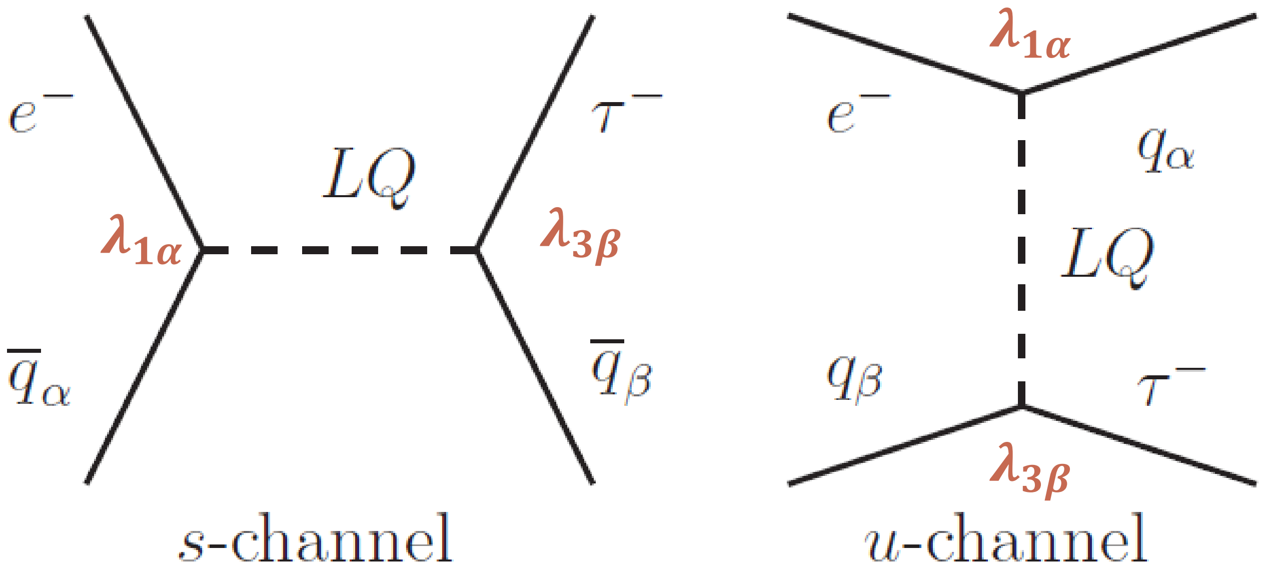
- At $\mathcal{L} \sim 100 - 200 \text{ fb}^{-1}$ the EIC could compete or surpass the current limits from $\tau \to e\gamma$

CLFV mediated by Leptoquarks

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

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

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



$F = 0$

- 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.

$$\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}$$

$\alpha\beta$	$S_{1/2}^L$ $e^-\bar{u}$ e^+u	$S_{1/2}^R$ $e^-(\bar{u}+\bar{d})$ $e^+(u+d)$	$\tilde{S}_{1/2}^L$ $e^-\bar{d}$ 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**	$\tau \to Ke$ 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**	$\tau \to Ke$ 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**

Units: TeV^{-2}

EIC Sensitivity

- How much can the EIC improve upon HERA limits?

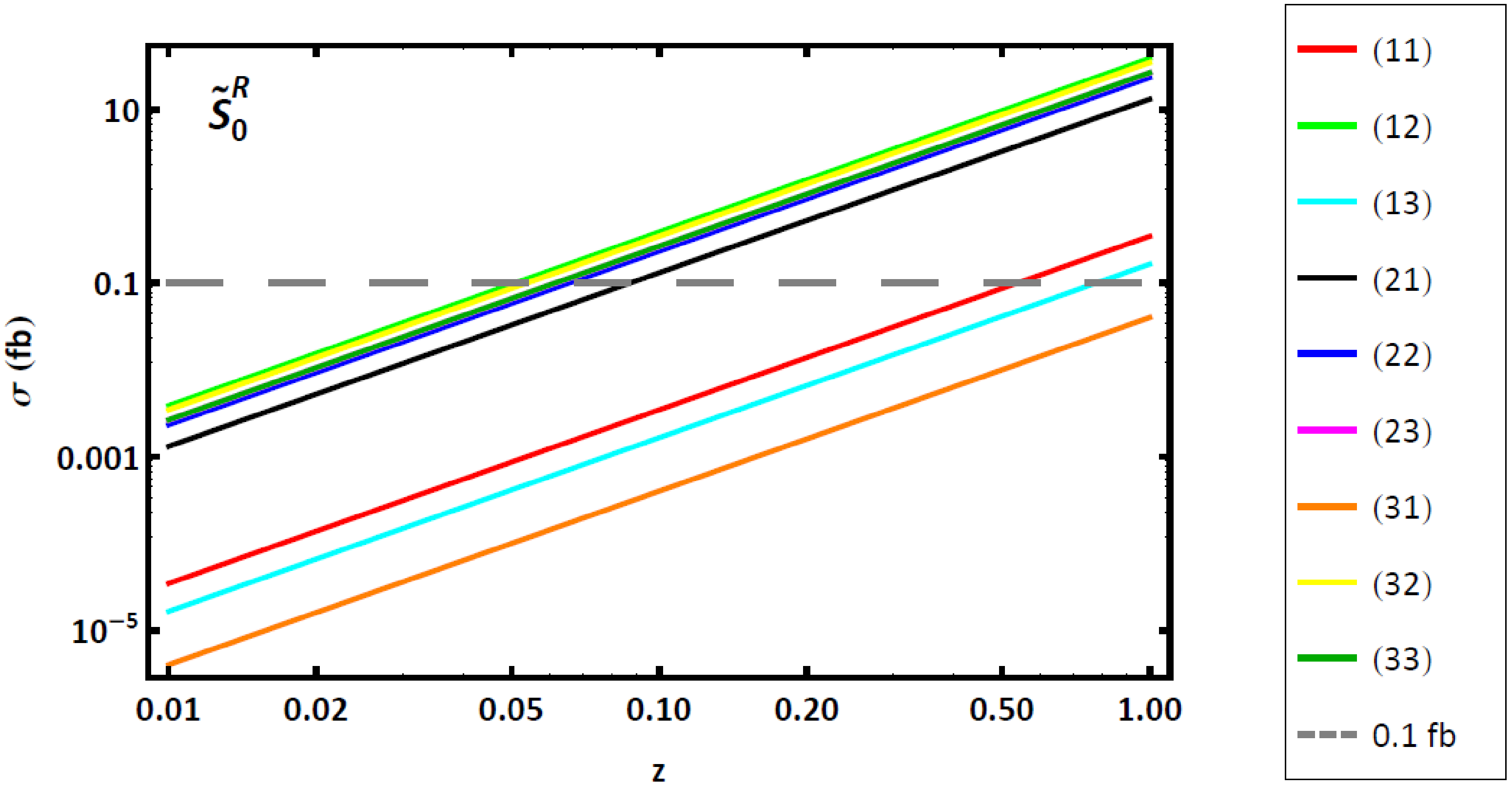
- Study was done for EIC at a center of mass energy of 90 GeV

[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.

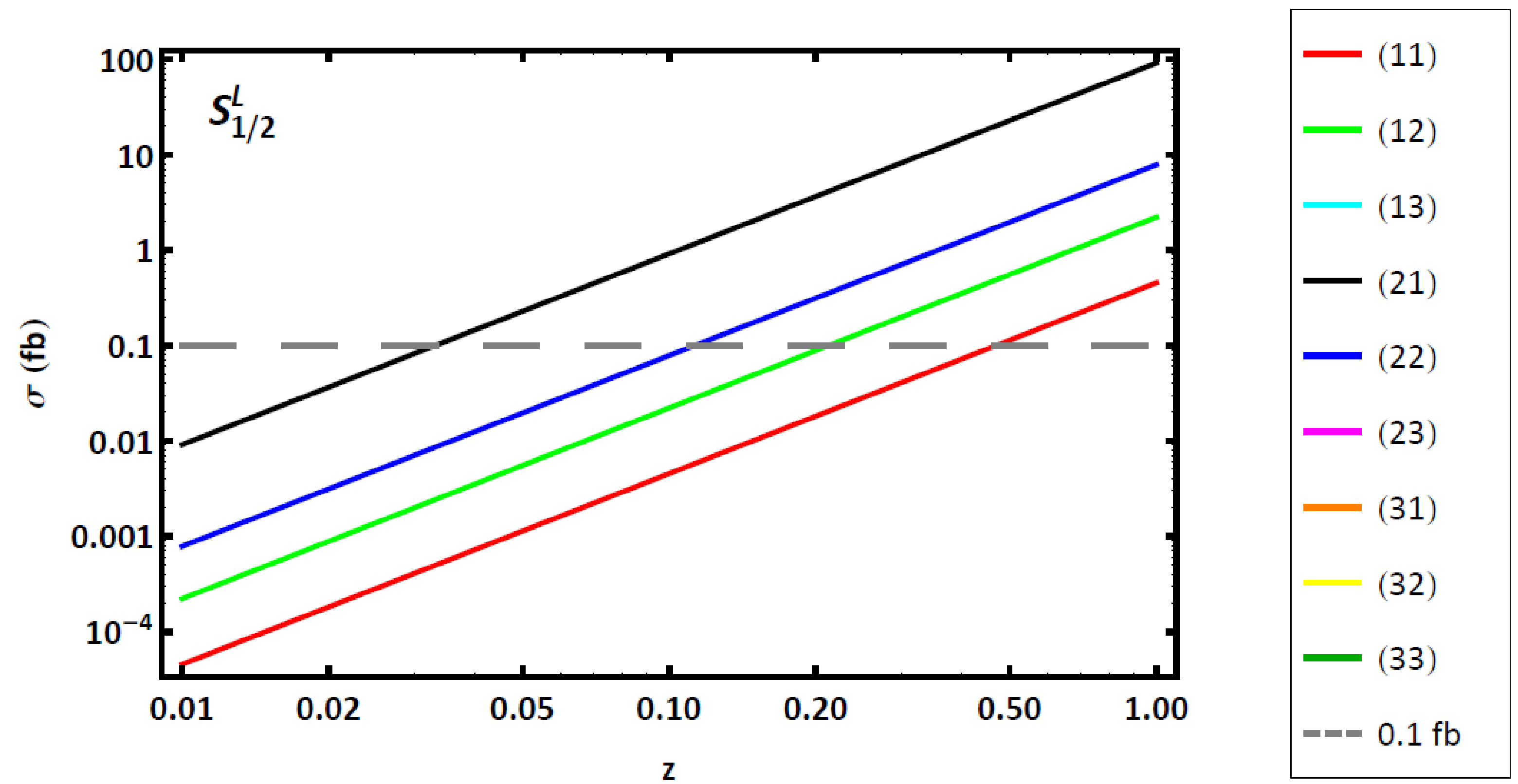
EIC Sensitivity



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

[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.

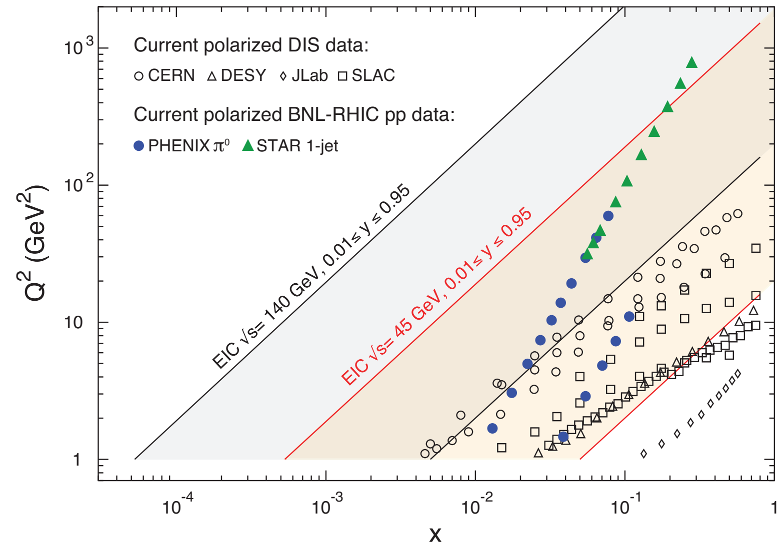
Conclusions

- 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
    - Doubly Charged Higgs bosons
    - Excited leptons (compositeness)
    - Dark Photons
    - Charged Lepton Flavor Violation (CLFV)
    - ...

- More generally, new physics can be constrained through:
    - Precision measurements of the electroweak parameters

- Such a program physics is faciliated 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.