Charged Lepton Flavor Violation at the EIC

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Workshop on Electroweak and BSM Physics at the EIC

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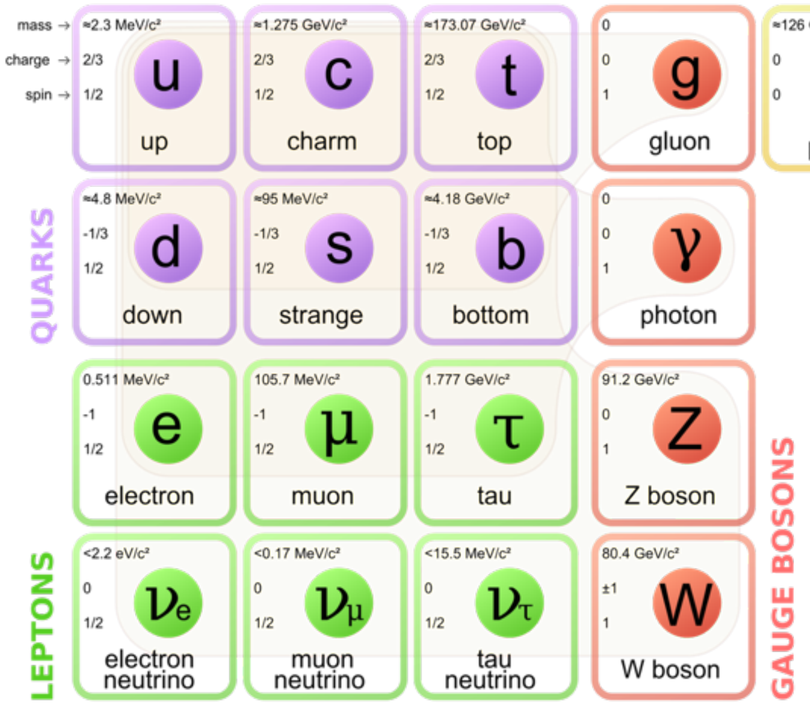
The Standard Model Flavor Structure



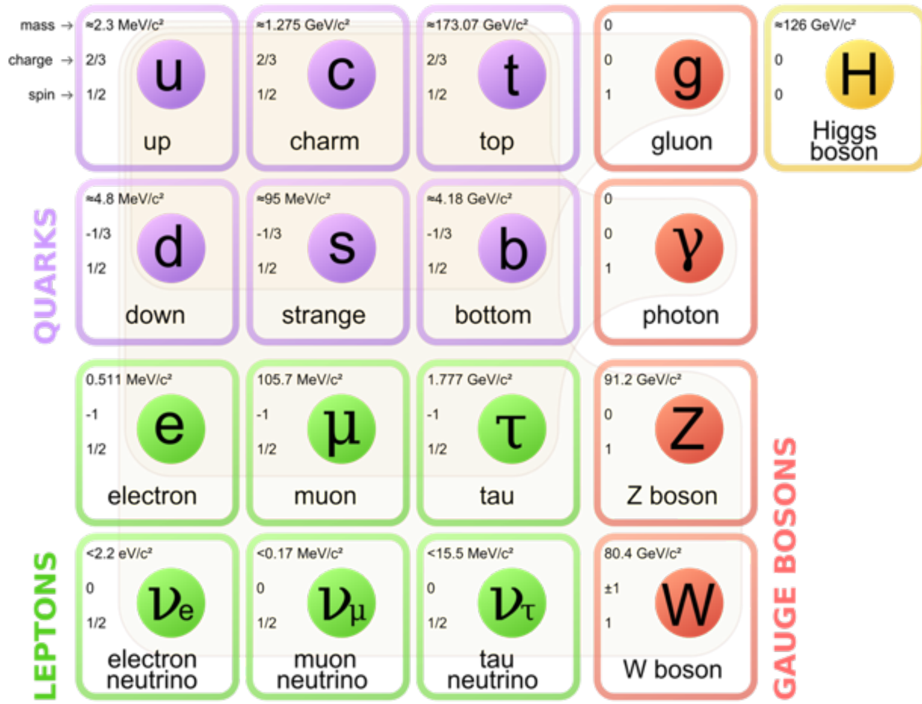
				$SU(3)$	$SU(2)_L$	$U(1)_Y$
$Q_L^i =$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} c_L \\ s_L \end{pmatrix}$	$\begin{pmatrix} t_L \\ b_L \end{pmatrix}$	3	2	$\frac{1}{6}$
$(u^c)_L^i =$	$(u^c)_L$	$(c^c)_L$	$(t^c)_L$	$\bar{3}$	1	$-\frac{2}{3}$
$(d^c)_L^i =$	$(d^c)_L$	$(s^c)_L$	$(b^c)_L$	$\bar{3}$	1	$\frac{1}{3}$
$L_L^i =$	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$	$\begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	1	2	$-\frac{1}{2}$
$(e^c)_L^i =$	$(e^c)_L$	$(\mu^c)_L$	$(\tau^c)_L$	1	1	1
			$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	$\frac{1}{2}$

$\boxed{\text{Quark sector}}$ $$SU(3)_Q \times SU(3)_U \times SU(3)_D$$

$\boxed{\text{Lepton sector}}$ $$SU(3)_L \times SU(3)_E$$

- Accidental global flavor symmetries in the quark and lepton sectors are broken by the Yukawa matrices via the Higgs Mechanism

The Standard Model Flavor Structure



				$SU(3)$	$SU(2)_L$	$U(1)_Y$
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$(d^c)^i_L =$	$(d^c)_L$	$(s^c)_L$	$(b^c)_L$	$\bar{3}$	1	$\frac{1}{3}$
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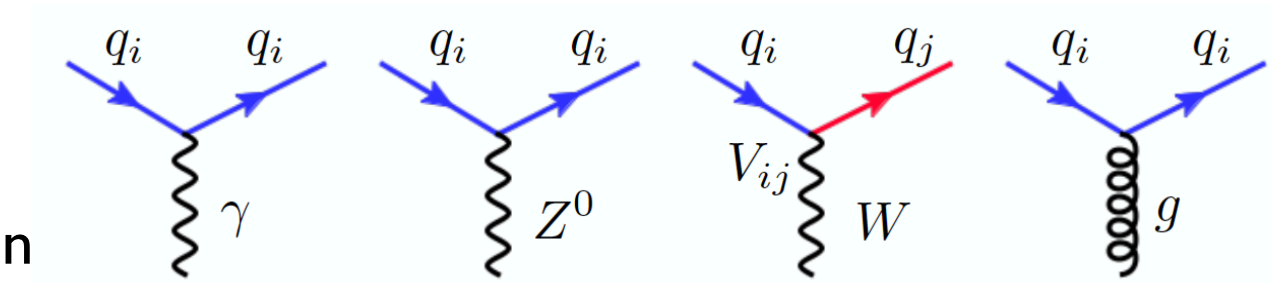
$(e^c)^i_L =$	$(e^c)_L$	$(\mu^c)_L$	$(\tau^c)_L$	1	1	1
			$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$	1	2	$\frac{1}{2}$

Flavor Structure

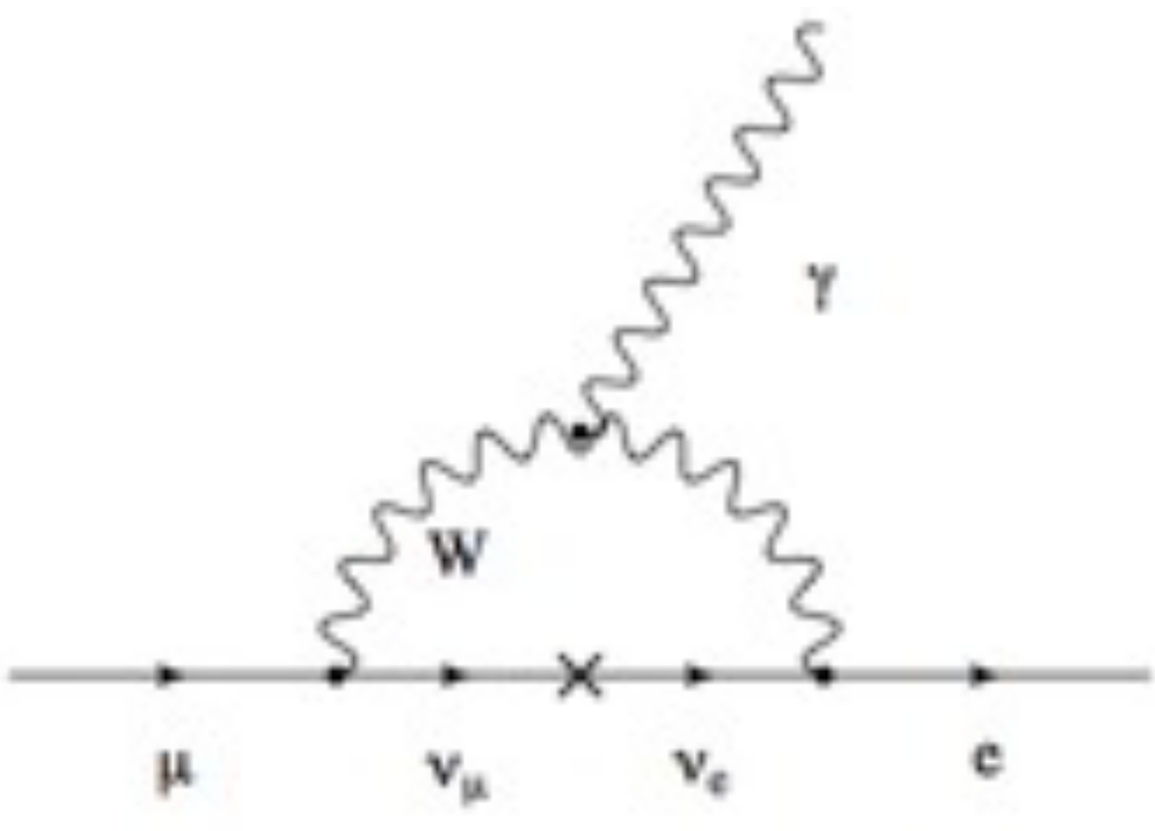


- No FCNCs at tree level (loop suppressed)
- Flavor and generation mixing via charged currents in the quark sector (CKM matrix)
- No generation mixing in the charged lepton sector.

- Discovery of neutrino oscillations already indicates physics beyond the Standard Model! (Need to extend the SM either via Dirac or Majorana neutrino mass scenario.

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):



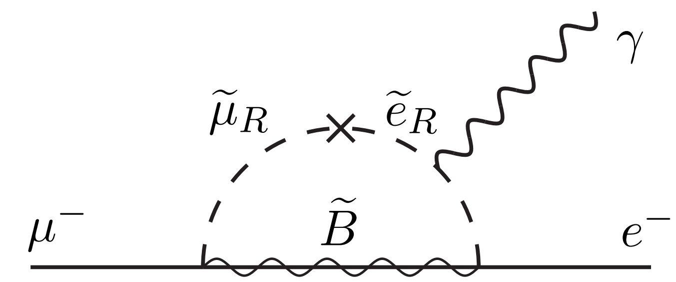
$$\mathrm{BR}(\mu \to e\gamma) < 10^{-54}$$

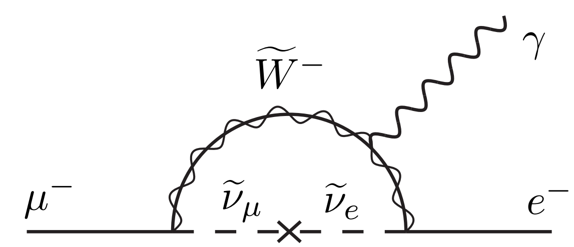
However, SM rate for CLFV is tiny due to small neutrino masses

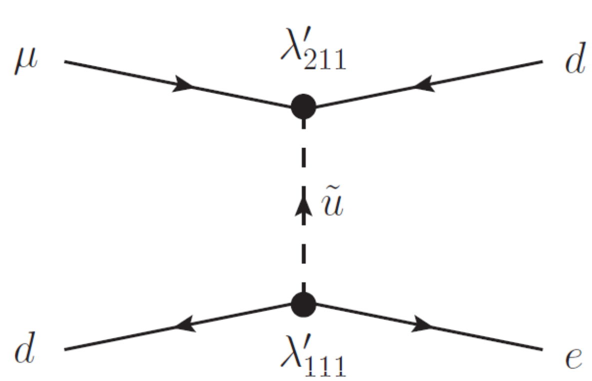
- No hope of detecting such small rates for CLFV at any present or future planned experiments!

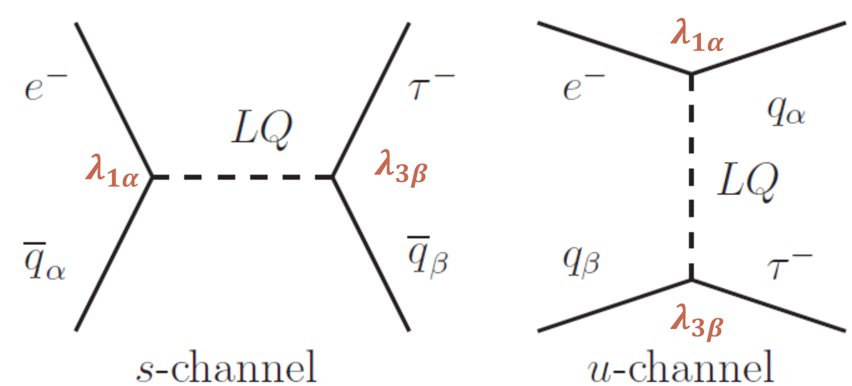
Lepton Flavor Violation in BSM

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



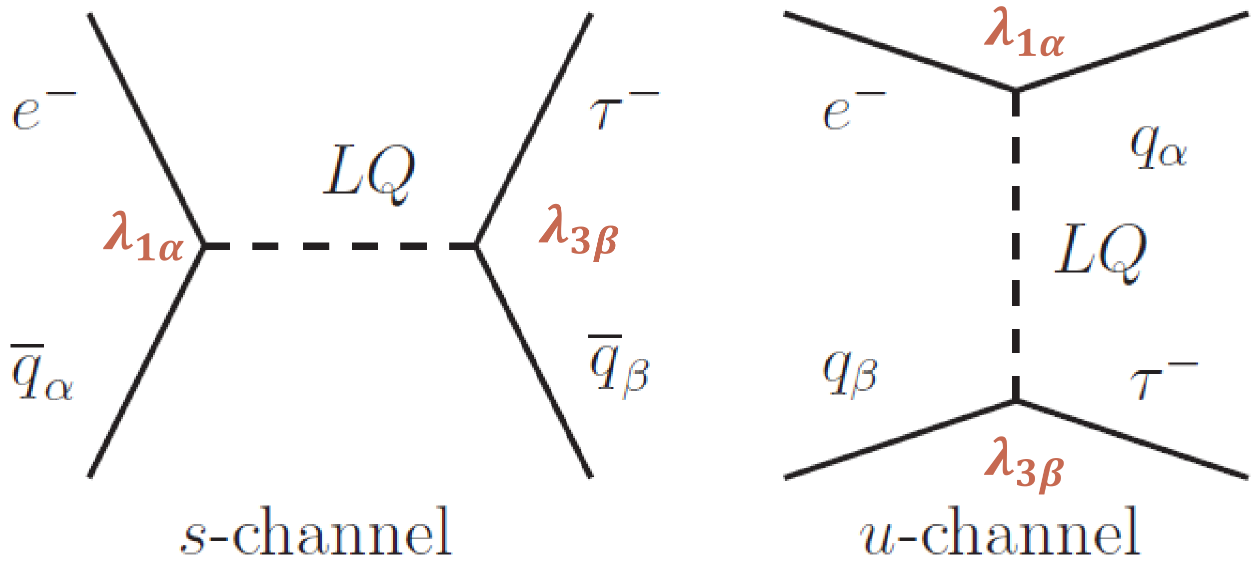






- Enhanced rates for CLFV in BSM scenarios make them experimentally accessible.

Leptoquarks



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

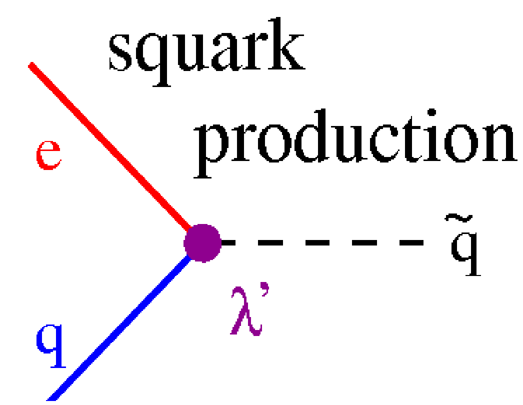
- LQs arise in many BSM models:
  - Pati-Salam Model
  - GUTs: SU(5), SO(10),....
  - Extended Technicolor

- 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]

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.

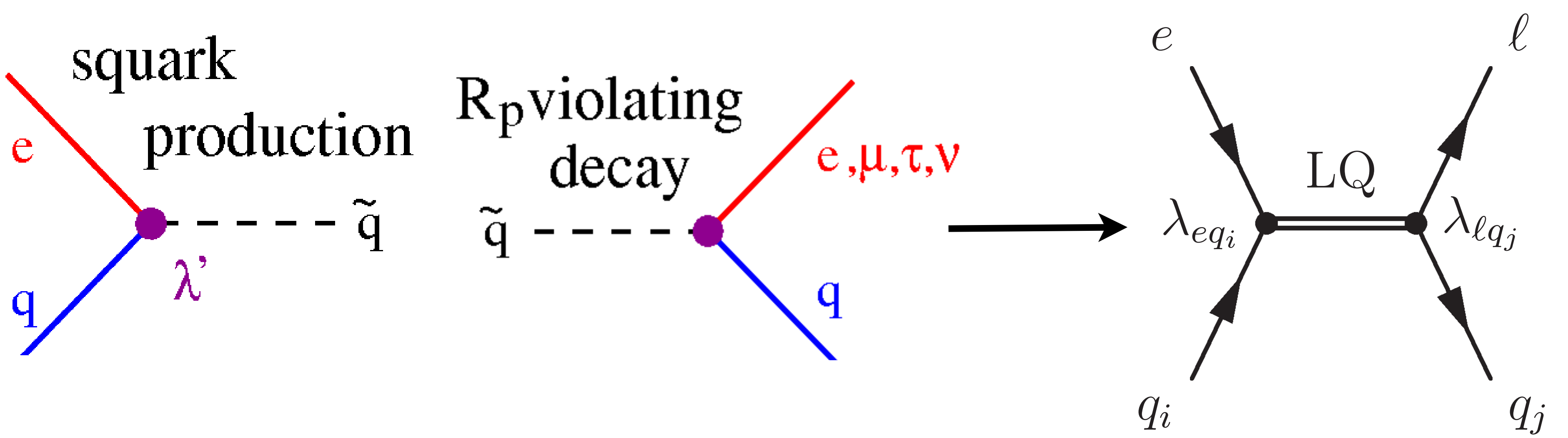
- SUSY RPV couplings (MSSM):

$$\begin{aligned} W_{\Delta \mathrm{L}=1} &= \frac{1}{2}\lambda^{ijk} L_i L_j \bar{e}_k + \boxed{\lambda'^{ijk} L_i Q_j \bar{d}_k} + \mu'^{i} L_i H_u \\ W_{\Delta \mathrm{B}=1} &= \frac{1}{2}\lambda''^{ijk} \overline{u}_i \bar{d}_j \bar{d}_k \end{aligned}$$

Single squark production at HERA, EIC

R-Parity Violating (RPV) SUSY

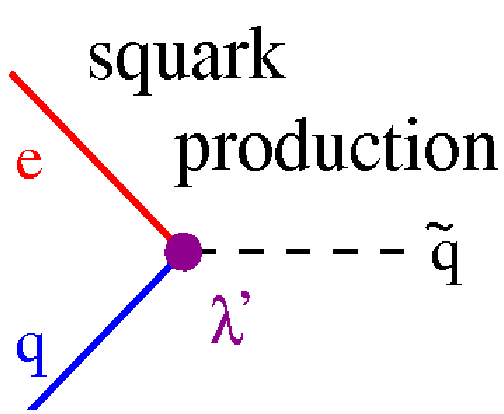
- For RPV production and RPV decay, signature is the same as for LQs:

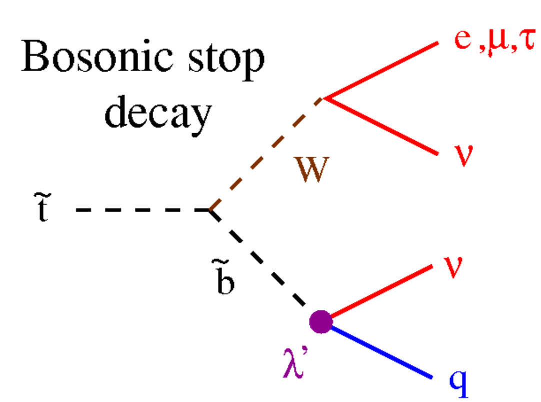


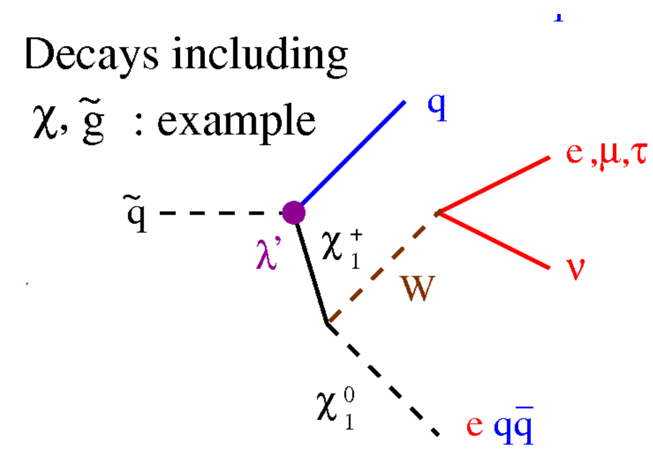
Lepton+Jet channel

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

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







Minimal Flavor Violation in Lepton Sector with Majorana Neutrino Mass

[Cirigliano, Grinstein, Isidori, Wise]

- Lepton sector with a Majorana mass generating effective operator:

$$\mathcal{L}_{\text{Sym.Br.}} = -\lambda_e^{ij}\,\bar{e}_R^i(H^\dagger L_L^j) - \frac{1}{2\Lambda_{\text{LN}}}\,g_\nu^{ij}(\bar{L}_L^{ci}\tau_2 H)(H^T\tau_2 L_L^j) + \text{h.c.}$$

After EWSB

$$\to -v\lambda_e^{ij}\,\bar{e}_R^i e_L^j - \frac{v^2}{2\Lambda_{\text{LN}}}\,g_\nu^{ij}\,\bar{\nu}_L^{ci}\nu_L^j + \text{h.c.}$$

Lepton Yukawa matrix

Neutrino mass matrix

- Global lepton flavor symmetries broken by Yukawa and Majorana neutrino mass matrices:

$$\lambda_e = \frac{m_\ell}{v} = \frac{1}{v}\,\text{diag}(m_e, m_\mu, m_\tau)\ ,$$

$$g_\nu = \frac{\Lambda_{\text{LN}}}{v^2}\,\hat{U}^* m_\nu \hat{U}^\dagger = \frac{\Lambda_{\text{LN}}}{v^2}\,\hat{U}^*\text{diag}(m_{\nu_1}, m_{\nu_2}, m_{\nu_3})\hat{U}^\dagger$$

PMNS matrix

Minimal Flavor Violation

[Cirigliano, Grinstein, Isidori, Wise]

- Higher dimension operators that parameterize BSM physics built out of the Yukawa and neutrino mass matrices using spurion analysis. Naturally allows for BSM physics to satisfy FCNC constraints.

$$
\begin{aligned}
O_{LL}^{(1)} &= \bar{L}_L \gamma^\mu \Delta L_L \; H^\dagger i D_\mu H \\
O_{LL}^{(2)} &= \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; H^\dagger \tau^a i D_\mu H \\
O_{LL}^{(3)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{Q}_L \gamma_\mu Q_L \\
O_{LL}^{(4d)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{d}_R \gamma_\mu d_R \\
O_{LL}^{(4u)} &= \bar{L}_L \gamma^\mu \Delta L_L \; \bar{u}_R \gamma_\mu u_R \\
O_{LL}^{(5)} &= \bar{L}_L \gamma^\mu \tau^a \Delta L_L \; \bar{Q}_L \gamma_\mu \tau^a Q_L
\end{aligned}
$$

$$
\begin{aligned}
O_{RL}^{(1)} &= g' H^\dagger \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, B_{\mu\nu} \\
O_{RL}^{(2)} &= g H^\dagger \bar{e}_R \sigma^{\mu\nu} \tau^a \lambda_e \Delta L_L \, W_{\mu\nu}^a \\
O_{RL}^{(3)} &= (D_\mu H)^\dagger \bar{e}_R \lambda_e \Delta D_\mu L_L \\
O_{RL}^{(4)} &= \bar{e}_R \lambda_e \Delta L_L \, \bar{Q}_L \lambda_D d_R \\
O_{RL}^{(5)} &= \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, \bar{Q}_L \sigma_{\mu\nu} \lambda_D d_R \\
O_{RL}^{(6)} &= \bar{e}_R \lambda_e \Delta L_L \, \bar{u}_R \lambda_U^\dagger i \tau^2 Q_L \\
O_{RL}^{(7)} &= \bar{e}_R \sigma^{\mu\nu} \lambda_e \Delta L_L \, \bar{u}_R \sigma_{\mu\nu} \lambda_U^\dagger i \tau^2 Q_L
\end{aligned}
$$

$$
\begin{aligned}
\Delta_{\mu e} &= \frac{\Lambda_{\rm LN}^2}{v^4} \frac{1}{\sqrt{2}} \left(s\, c\, \Delta m_{\rm sol}^2 \pm s_{13}\, e^{i\delta}\, \Delta m_{\rm atm}^2 \right) \\
\Delta_{\tau e} &= \frac{\Lambda_{\rm LN}^2}{v^4} \frac{1}{\sqrt{2}} \left(-s\, c\, \Delta m_{\rm sol}^2 \pm s_{13}\, e^{i\delta}\, \Delta m_{\rm atm}^2 \right) \\
\Delta_{\tau\mu} &= \frac{\Lambda_{\rm LN}^2}{v^4} \frac{1}{2} \left(-c^2\, \Delta m_{\rm sol}^2 \pm \Delta m_{\rm atm}^2 \right)
\end{aligned}
$$

- Higher dimension operators suppressed by LFV scale, distinct from lepton number violation scale:

$$
\mathcal{L} = \frac{1}{\Lambda_{\rm LFV}^2} \sum_{i=1}^{5} c_{LL}^{(i)} O_{LL}^{(i)} + \frac{1}{\Lambda_{\rm LFV}^2} \left(\sum_{j=1}^{2} c_{RL}^{(j)} O_{RL}^{(j)} + \text{h.c.} \right)
$$

Minimal Flavor Violation

[Cirigliano, Grinstein, Isidori, Wise]

- In MFV scenario, a large disparity between lepton number violation and lepton flavor violation scales will produce enhanced CLFV rates.

$$B_{\mu\to e\gamma} = 8.3\times 10^{-50}\left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 \qquad B_{\mu\to e} = \left(\frac{\Lambda_{\rm LN}}{\Lambda_{\rm LFV}}\right)^4 \begin{cases} 6.6\times 10^{-50} & \text{for Al} \\ 19.6\times 10^{-50} & \text{for Au} \end{cases}$$

Huge enhancement factor when:

$$\Lambda_{\rm LN} \gg \Lambda_{\rm LFV}$$

- For example:

$$\Lambda_{\rm LN} \sim 10^9 \Lambda_{\rm LFV} \quad \begin{matrix} \rightarrow B_{\mu\to e\gamma} = \mathcal{O}(10^{-13}) \\ \rightarrow B_{\mu\to e} = \mathcal{O}(10^{-13}) \end{matrix}$$

Charged Lepton Flavor Violation Limits

- Present and future limits:

LFV transitions	LFV Present Bounds (90%CL)	Future Sensitivities
$\mathrm{BR}(\mu \to e\gamma)$	4.2×10^{-13} (MEG 2016)	4×10^{-14} (MEG-II)
$\mathrm{BR}(\tau \to e\gamma)$	3.3×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
$\mathrm{BR}(\tau \to \mu\gamma)$	4.4×10^{-8} (BABAR 2010)	10^{-9} (BELLE-II)
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12} (SINDRUM 1988)	10^{-16} Mu3E (PSI)
$\mathrm{BR}(\tau \to eee)$	2.7×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$\mathrm{BR}(\tau \to \mu\mu\mu)$	2.1×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$\mathrm{BR}(\tau \to \mu\eta)$	2.3×10^{-8} (BELLE 2010)	$10^{-9,-10}$ (BELLE-II)
$\mathrm{CR}(\mu - e, \mathrm{Au})$	7.0×10^{-13} (SINDRUM II 2006)	
$\mathrm{CR}(\mu - e, \mathrm{Ti})$	4.3×10^{-12} (SINDRUM II 2004)	10^{-18} PRISM (J-PARC)
$\mathrm{CR}(\mu - e, \mathrm{Al})$		3.1×10^{-15} COMET-I (J-PARC)

[taken from a talk by Y. Furletova]

- 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.

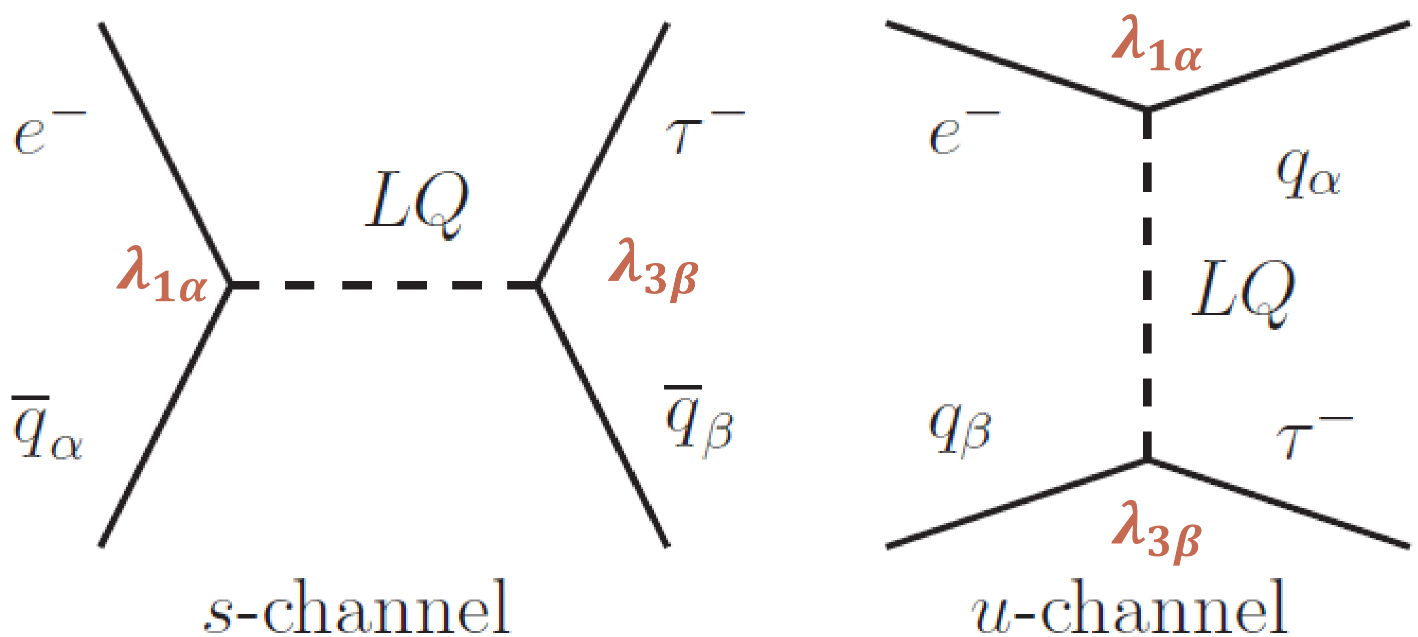
CLFV in DIS

[see also talk by Jinlong Zhang]

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

$$ep \to \tau X$$

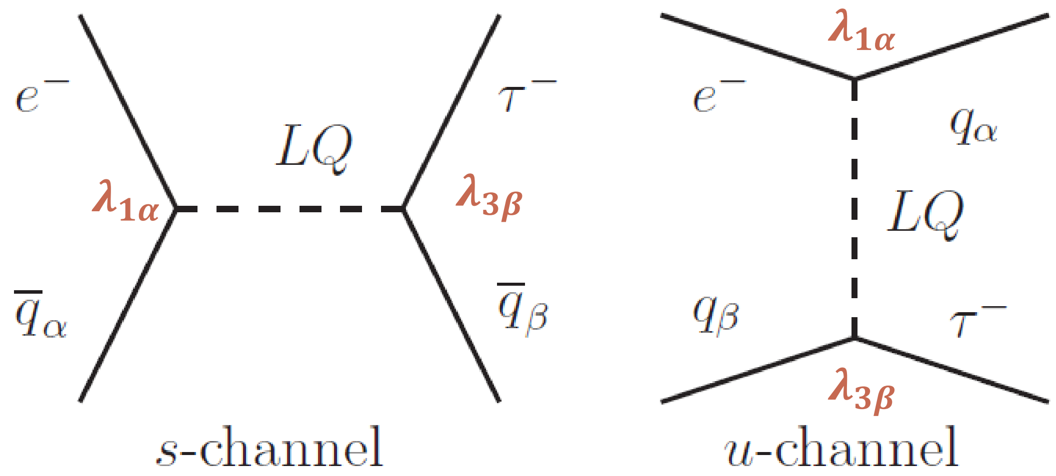
- Such a process could be mediated, for example, by leptoquarks:



- A phenomenological study of CLFV mediated by LQs at the EIC was first done in 2010.

[M.Gonderinger, M.Ramsey-Musolf]

Leptoquarks



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- LQs arise in many BSM models:
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- 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:

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

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

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

Type	J	F	Q	ep dominant process		Coupling	Branching ratio β_ℓ
S^L_0	0	2	$-1/3$	$e^-_L u_L \rightarrow$	$\ell^- u$	λ_L	$1/2$
					$\nu_\ell d$	$-\lambda_L$	$1/2$
S^R_0	0	2	$-1/3$	$e^-_R u_R \rightarrow$	$\ell^- u$	λ_R	1
$\tilde{S}^R_0$	0	2	$-4/3$	$e^-_R d_R \rightarrow$	$\ell^- d$	λ_R	1
S^L_1	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
$V^L_{1/2}$	1	2	$-4/3$	$e^-_L d_R \rightarrow$	$\ell^- d$	λ_L	1
$V^R_{1/2}$	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
$\tilde{V}^L_{1/2}$	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^L_0	1	0	$+2/3$	$e^+_R d_L \rightarrow$	$\ell^+ d$	λ_L	$1/2$
					$\bar{\nu}_\ell u$	λ_L	$1/2$
V^R_0	1	0	$+2/3$	$e^+_L d_R \rightarrow$	$\ell^+ d$	λ_R	1
$\tilde{V}^R_0$	1	0	$+5/3$	$e^+_L u_R \rightarrow$	$\ell^+ u$	λ_R	1
V^L_1	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
$S^L_{1/2}$	0	0	$+5/3$	$e^+_R u_R \rightarrow$	$\ell^+ u$	λ_L	1
$S^R_{1/2}$	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
$\tilde{S}^L_{1/2}$	0	0	$+2/3$	$e^+_R d_R \rightarrow$	$\ell^+ d$	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:

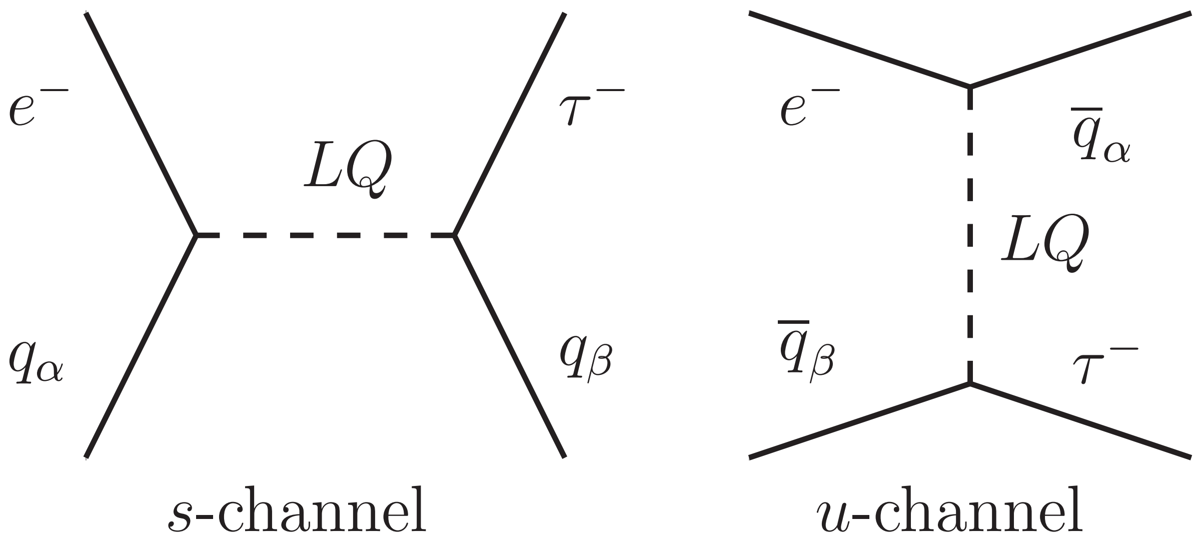
  -electron and positron beams [separate |F|=0 vs |F|=2]

  -proton and deuteron targets [separate "eu" vs "ed" LQs]

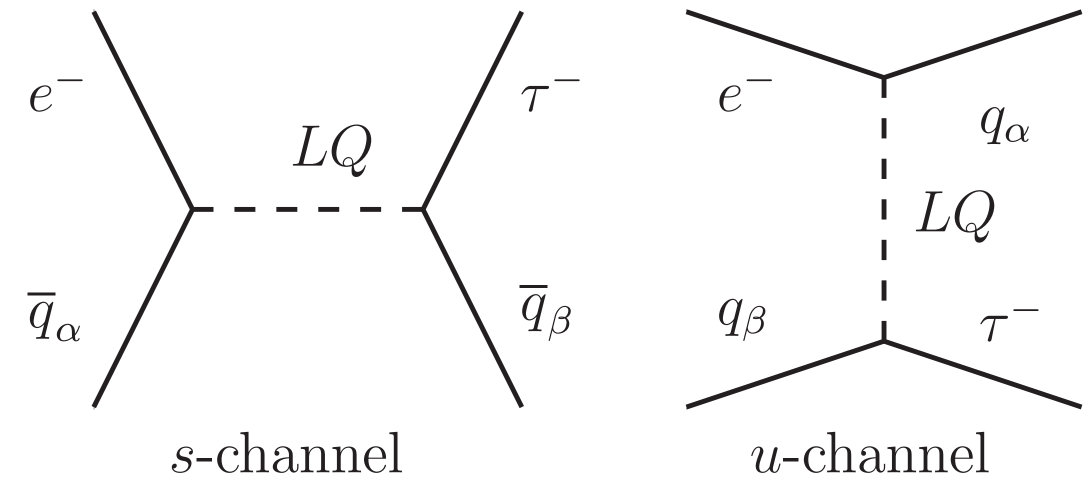
  -polarized beams [separate L vs R]

  -wide kinematic range [separate scalar vs vector LQs]

Leptoquarks: Electron vs Positron Beams



$|F| = 2$



$F = 0$

F= 3B+L

- 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

Cross Sections

- The tree level cross section using an electron beam for the F=0 and F=2 LQ channels:

$$\sigma^{e^-p}_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{LQ}}\right]^2 \left\{ \int dx \int dy\; x\bar{q}_\alpha(x, xs) f(y) + \int dx \int dy\; x q_\beta(x, -u) g(y) \right\},$$

$$\sigma^{e^-p}_{|F|=2} = \sum_{\alpha,\beta} \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{LQ}}\right]^2 \left\{ \int dx \int dy\; x q_\alpha(x, xs) f(y) + \int dx \int dy\; x\bar{q}_\beta(x, -u) g(y) \right\}$$

- The tree level cross section using a positron beam for the F=0 and F=2 LQ channels:

$$\sigma^{e^+p}_{F=0} = \sum_{\alpha,\beta} \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{LQ}}\right]^2 \left\{ \int dx \int dy\; x q_\alpha(x, xs) f(y) + \int dx \int dy\; x\bar{q}_\beta(x, -u) g(y) \right\},$$

$$\sigma^{e^+p}_{|F|=2} = \sum_{\alpha,\beta} \frac{s}{32\pi}\left[\frac{\lambda_{1\alpha}\lambda_{3\beta}}{M^2_{LQ}}\right]^2 \left\{ \int dx \int dy\; x\bar{q}_\alpha(x, xs) f(y) + \int dx \int dy\; x q_\beta(x, -u) g(y) \right\}$$

- Electron and positron beams can be used to distinguish between different LQ channels.

- Kinematic information can be used to distinguish between scalar and vector LQ channels:

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

y-dependence can distinguish scalar and vector leptoquarks

Leptoquarks: Polarized Lepton and Nuclear (p,D)

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

- 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 p,D beams have been proposed to identify the nature of LQ states.

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

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

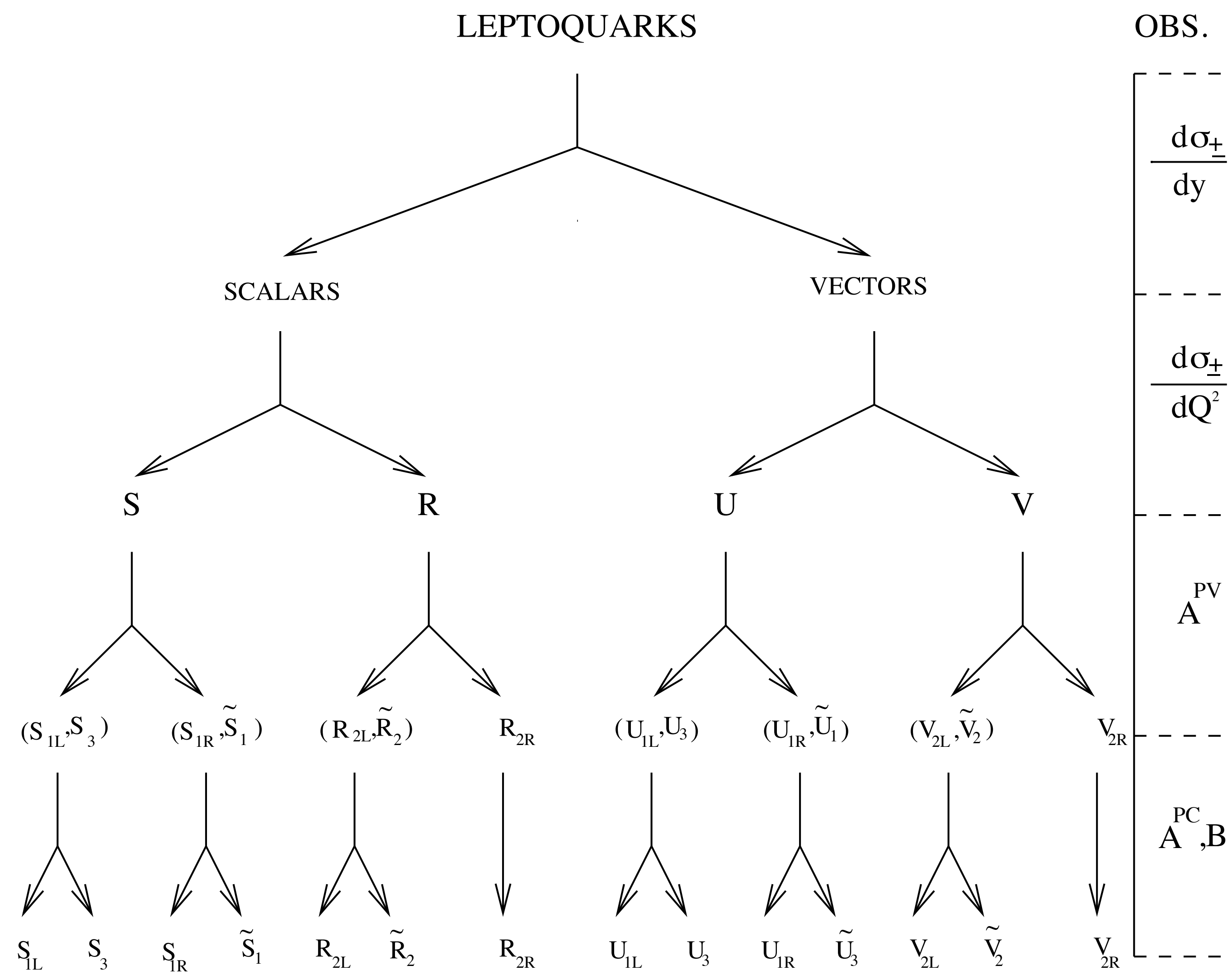
$$A_1^{PC} = \frac{\sigma_-^{--} - \sigma_-^{-+}}{\sigma_-^{--} + \sigma_-^{-+}}$$

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

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

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

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



- This analysis should be revisited in the context of the EIC.

Summary of Key Criteria to Distinguish Leptoquark States

- Electron vs. positron beams: distinguish between F=0 and F=2 LQs
- Polarization of lepton beams: distinguish between left-handed (L) and right-handed (R) LQs
- Wide kinematic range: distinguish between scalar (S) and vector (V) LQs
- Proton vs Deuteron targets: distinguish between “eu" and “ed” LQs

CLFV limits from HERA

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

$$ep \to \tau X$$

$$\sqrt{s} \sim 320 \,\mathrm{GeV}$$

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

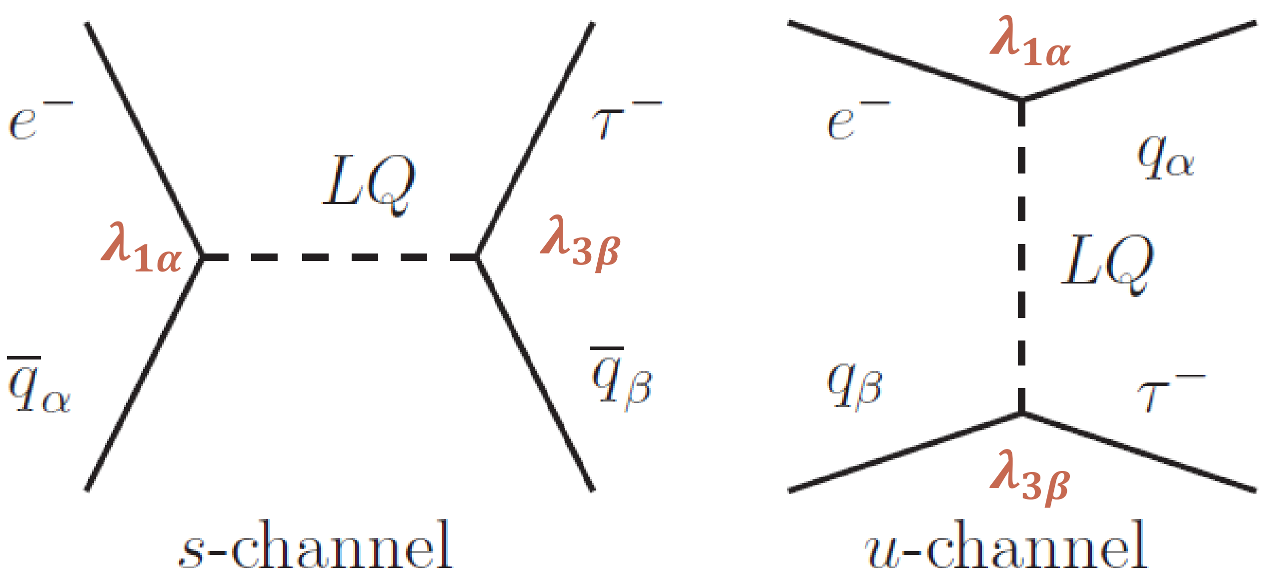
- High luminosity EIC could surpass the best limits set by HERA :

CLFV mediated by Leptoquarks

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

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

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



$F = 0$

- HERA set limits on the ratios $\boxed{\dfrac{\lambda_{1\alpha}\lambda_{3\beta}}{M_{LQ}^2}}$
  - 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.

$ep \to \tau X$ **H1** $F = 2$

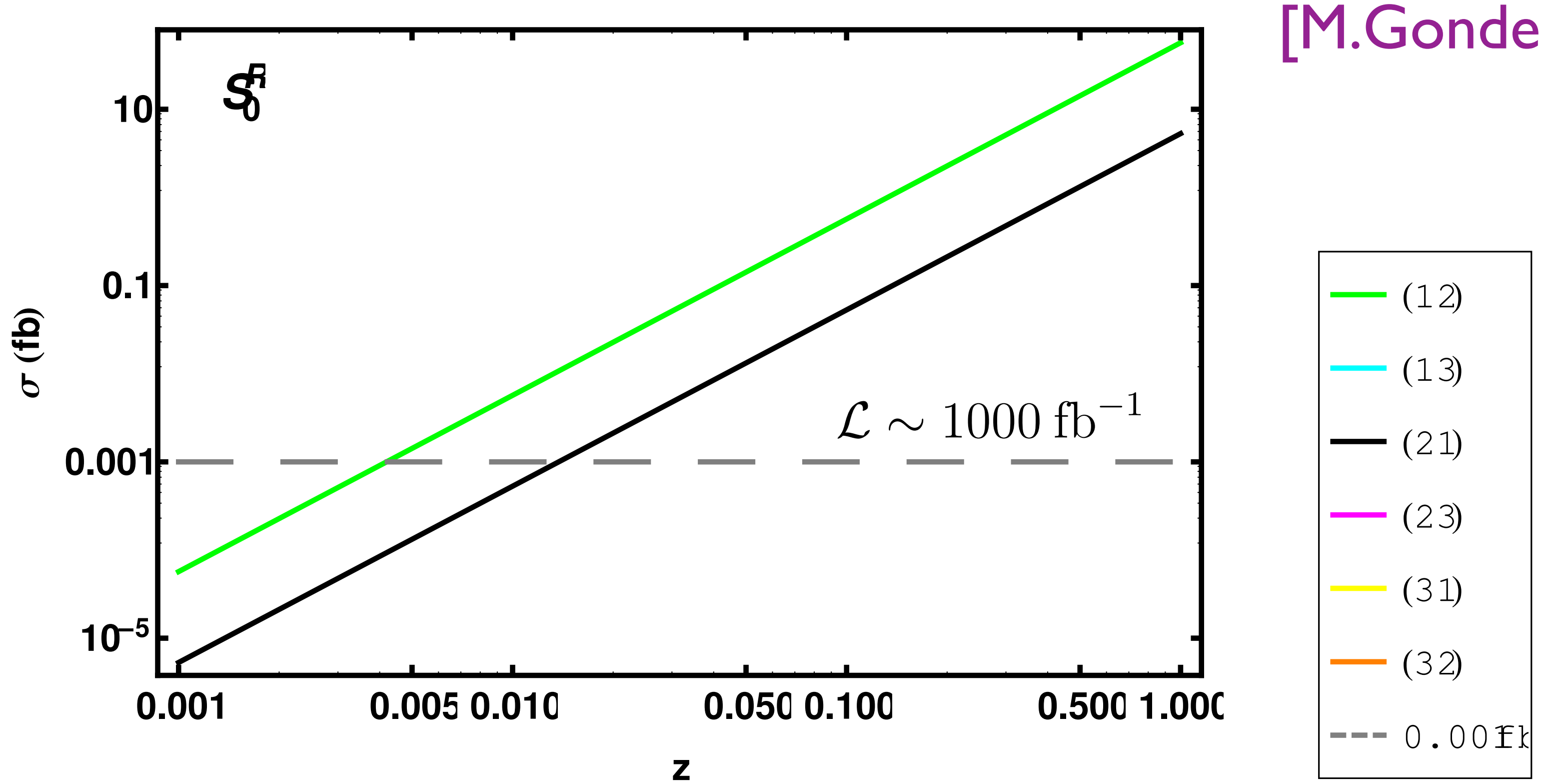
Upper exclusion limits on $\lambda_{eq_i}\lambda_{\tau q_j}/m_{\mathrm{LQ}}^2$ (TeV^{-2})
for lepton flavour violating leptoquarks at 95% CL

$q_i q_j$	S_0^L $\ell^- U$ $\ell^+ \bar{U}$	S_0^R $\ell^- U$ $\ell^+ \bar{U}$	$\tilde{S}_0^R$ $\ell^- D$ $\ell^+ \bar{D}$	S_1^L $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$V_{1/2}^L$ $\ell^- D$ $\ell^+ \bar{D}$	$V_{1/2}^R$ $\ell^- U, \ell^- D$ $\ell^+ \bar{U}, \ell^+ \bar{D}$	$\tilde{V}_{1/2}^L$ $\ell^- U$ $\ell^+ \bar{U}$
1 1	G_F 0.3 **1.6**	$\tau \to \pi e$ 0.06 **1.8**	$\tau \to \pi e$ 0.06 **2.6**	$\tau \to \pi e$ 0.01 **1.0**	$\tau \to \pi e$ 0.03 **1.1**	$\tau \to \pi e$ 0.01 **0.7**	$\tau \to \pi e$ 0.03 **0.8**
1 2	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **1.9**	**2.1**	$\tau \to Ke$ 0.04 **2.9**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.1**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.9**	$\tau \to Ke$ 0.02 **1.3**	**1.5**
1 3	*	*	$B \to \tau\bar{e}$ 0.07 **3.0**	V_{ub} 0.3 **1.3**	$B \to \tau\bar{e}$ 0.03 **2.2**	$B \to \tau\bar{e}$ 0.03 **2.4**	*
2 1	$K \to \pi\nu\bar{\nu}$ 5.8×10^{-4} **2.7**	**2.7**	$\tau \to Ke$ 0.04 **3.5**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.4**	$K \to \pi\nu\bar{\nu}$ 2.9×10^{-4} **1.2**	$\tau \to Ke$ 0.02 **0.7**	**0.9**
2 2	$\tau \to 3e$ 0.6 **6.3**	$\tau \to 3e$ 0.6 **6.8**	$\tau \to 3e$ 1.8 **5.4**	$\tau \to 3e$ 1.5 **2.3**	$\tau \to 3e$ 0.9 **2.7**	$\tau \to 3e$ 0.5 **2.2**	$\tau \to 3e$ 0.3 **3.4**
2 3	*	*	$B \to \bar{\tau}eX$ 14.0 **5.8**	$B \to \bar{\tau}eX$ 7.2 **2.7**	$B \to \bar{\tau}eX$ 7.2 **3.6**	$B \to \bar{\tau}eX$ 7.2 **4.0**	*
3 1	*	*	$B \to \tau\bar{e}$ 0.07 **4.0**	$B \to \tau\bar{e}$ 0.03 **2.0**	$B \to \tau\bar{e}$ 0.03 **1.2**	$B \to \tau\bar{e}$ 0.03 **1.3**	*
3 2	*	*	$B \to \bar{\tau}eX$ 14.0 **7.9**	$B \to \bar{\tau}eX$ 7.2 **3.7**	$B \to \bar{\tau}eX$ 7.2 **2.9**	$B \to \bar{\tau}eX$ 7.2 **3.1**	*
3 3	*	*	$\tau \to 3e$ 1.8 **10.1**	$\tau \to 3e$ 1.5 **4.6**	$\tau \to 3e$ 0.9 **4.7**	$\tau \to 3e$ 0.5 **4.9**	*

EIC Sensitivity

[Deshpande, Faroughy, Gonderinger, Kumar, Taneja]

[M.Gonderinger, M.Ramsey-Musolf]



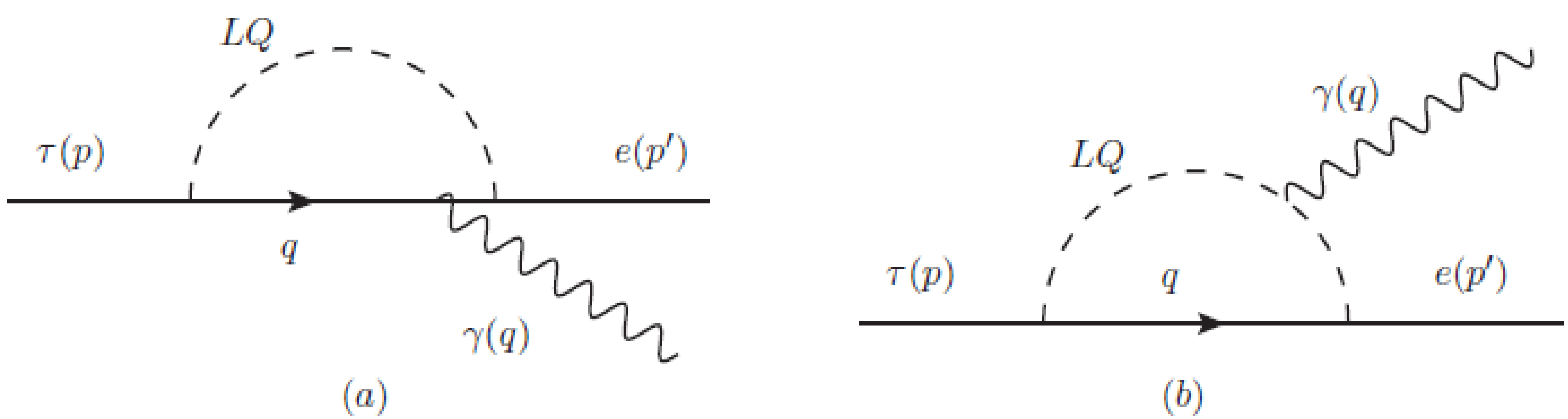
$$z = \frac{(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)}{[(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)]_{\text{HERAlimit}}}$$

- $z=1$ corresponds to evaluating the cross section at the HERA limit.
- EIC will be sensitive to cross sections with $z<1$, thereby improving upon HERA limits.
- With 1000 fb^{-1} of integrated luminosity, the EIC could improve on HERA limits by a factor of between 10 and 200, depending on the specific LQ state.

Leptoquark Mediated CLFV(1,3) Decays

- Leptoquarks can also mediate the rare decay:

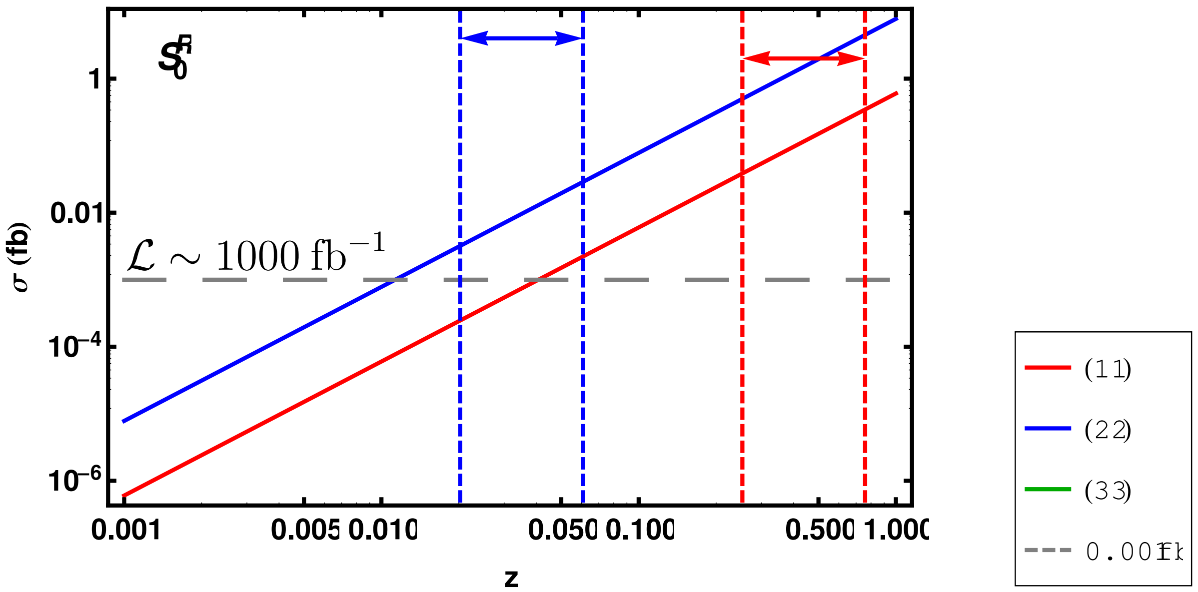
$$\tau \to e\gamma$$

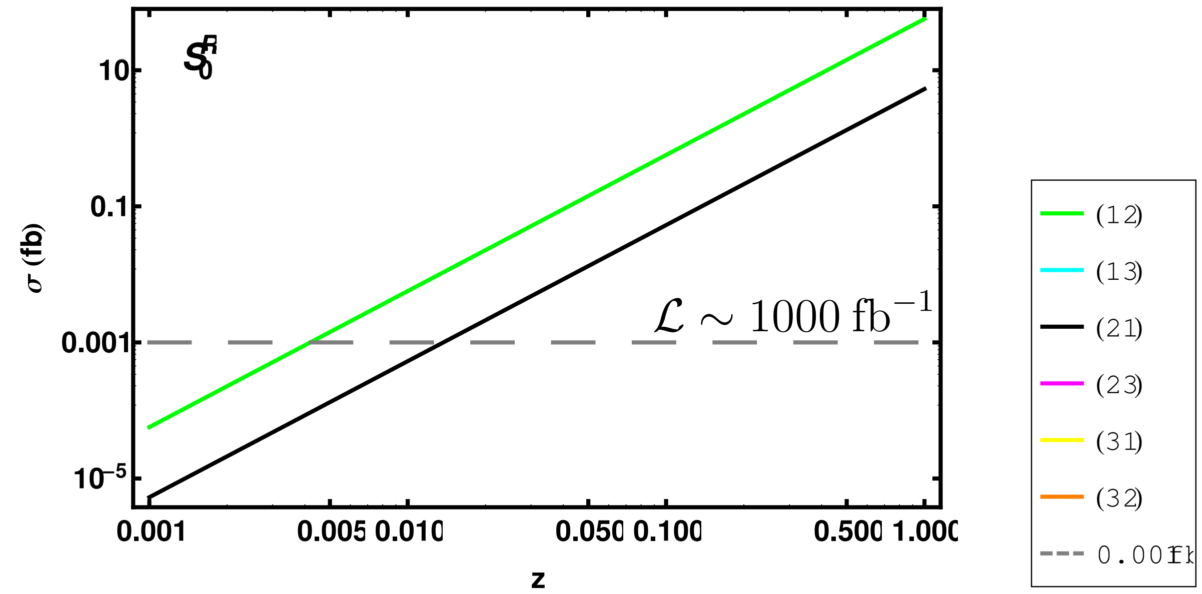


- These diagrams are also proportional to the combination:

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

("quark flavor-diagonal case")



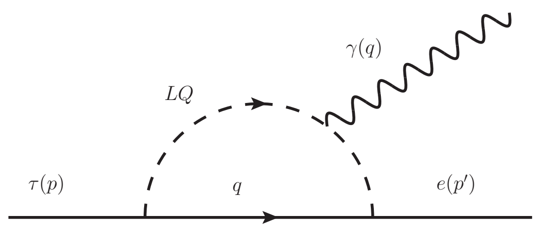


- Vertical dashed lines and horizontal arrows indicate the range of limits ("totalitarian" vs "democratic") from CLFV tau decay limits projected at Super-B.

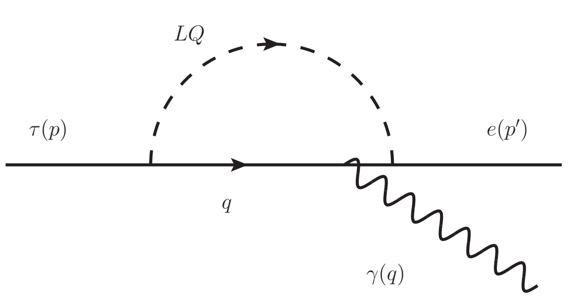
$$\tau \to e\gamma$$

Totalitarian: single quark flavor dominates loop

Democratic: all flavors contribute equally



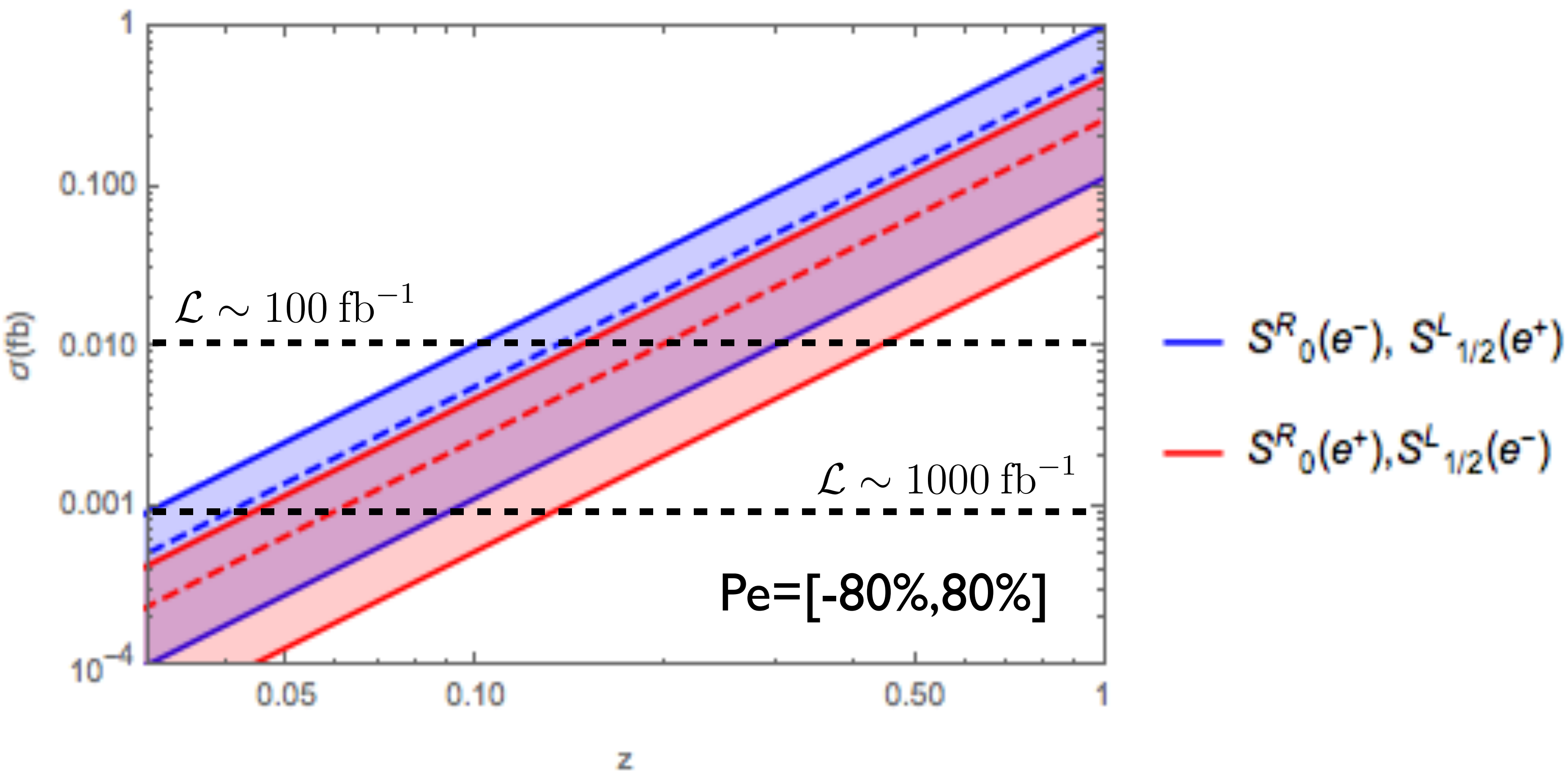
- More stringent limit comes from "democratic" scenario.



- Note that CLFV tau decay limits do not apply to the "quark off-diagonal" case.

Lepton Beam Polarization

[SM, Furletova: in proceedings for JPOS 17]



- EIC sensitivity to CLFV(1,3) to specific LQ channels can be improved using polarized lepton beams.

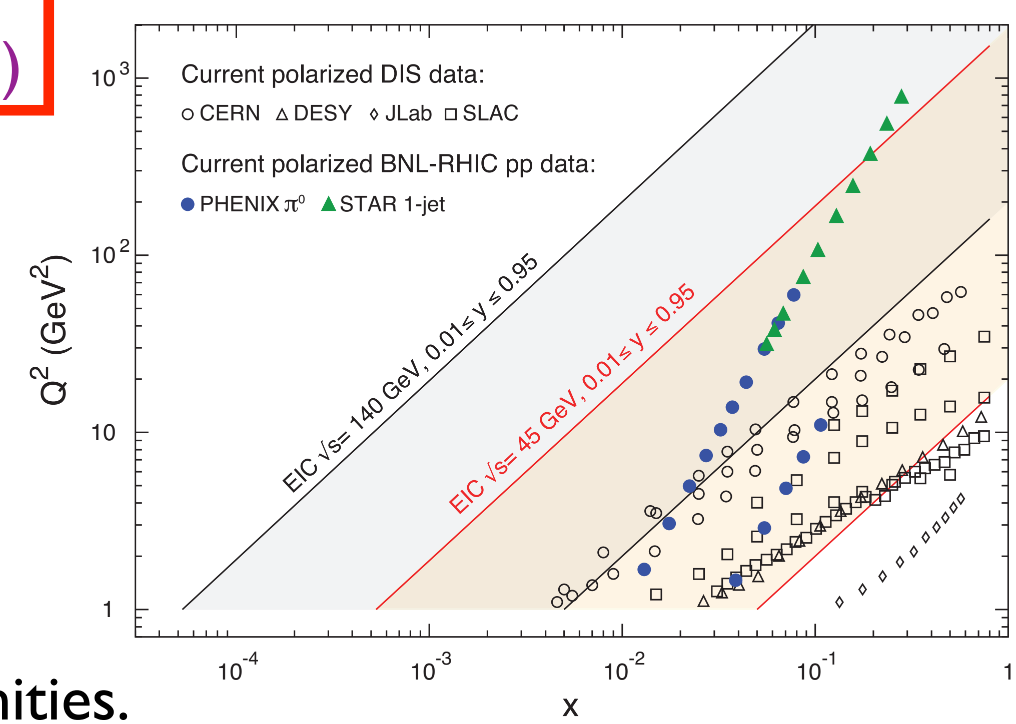
- In addition, polarized electron and positron beams can be used in conjunction to constrain specific LQ channels.

Conclusions

- The EIC can play an important role in searching/constraining various new physics scenarios that include:
  - Leptoquarks
  - R-parity violating Supersymmetry
  - Excited leptons (compositeness)
  - Leptophobic Z's
  - Charged Lepton Flavor Violation (CLFV)
  - ...

- New physics can be constrained through:
  - Precision measurements of the electroweak parameters
  - Direct searches for charged lepton flavor violation CLFV(1,3)

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



- Addition of a positron beam can provide additional opportunities.

- See talk by Jinlong Zhang for simulation studies of CLFV at the EIC.