Charged Lepton Flavor Violation at the EIC

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Workshop on Electroweak and BSM Physics at the EIC

May 6th-7th, 2020
The Standard Model Flavor Structure

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.3 ± 0.3</td>
<td>2/3</td>
<td>1/2</td>
<td>up</td>
</tr>
<tr>
<td>177.6 ± 0.7</td>
<td>2/3</td>
<td>1/2</td>
<td>charm</td>
</tr>
<tr>
<td>177.6 ± 0.7</td>
<td>2/3</td>
<td>1/2</td>
<td>top</td>
</tr>
<tr>
<td>4.1 ± 0.2</td>
<td>2/3</td>
<td>1/2</td>
<td>down</td>
</tr>
<tr>
<td>4.1 ± 0.2</td>
<td>-2/3</td>
<td>1/2</td>
<td>strange</td>
</tr>
<tr>
<td>4.1 ± 0.2</td>
<td>-2/3</td>
<td>1/2</td>
<td>bottom</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>electron</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>muon</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>tau</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>electron neutrino</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>muon neutrino</td>
</tr>
<tr>
<td>0.511 ± 0.000</td>
<td>-1</td>
<td>1/2</td>
<td>tau neutrino</td>
</tr>
<tr>
<td>80.4 ± 0.0</td>
<td>-1</td>
<td>1/2</td>
<td>W boson</td>
</tr>
</tbody>
</table>

\[
Q_L^i = \begin{pmatrix} u_L^i \\ d_L^i \\ s_L^i \\ c_L^i \\ t_L^i \\ b_L^i \end{pmatrix}, \quad (S) \quad (S) \quad (S) \\
(u^c)_L^i = \begin{pmatrix} (u^c)_L^i \\ (e^c)_L^i \\ (\nu^c)_L^i \\ (\bar{\nu}^c)_L^i \end{pmatrix}, \quad (S) \quad (S) \quad (S) \\
(d^c)_L^i = \begin{pmatrix} (d^c)_L^i \\ (s^c)_L^i \\ (\nu^c)_L^i \\ (\bar{\nu}^c)_L^i \end{pmatrix}, \quad (S) \quad (S) \quad (S) \\
L_L^i = \begin{pmatrix} (\nu_e)_L^i \\ (\nu_\mu)_L^i \\ (\nu_\tau)_L^i \end{pmatrix}, \quad (S) \quad (S) \quad (S) \\
(e^c)_L^i = \begin{pmatrix} (e^c)_L^i \\ (\mu^c)_L^i \\ (\tau^c)_L^i \end{pmatrix}, \quad (S) \quad (S) \quad (S)
\]

\[
\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}
\]

\[
SU(3)_Q \times SU(3)_U \times SU(3)_D \\
SU(3)_L \times SU(3)_E
\]

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

\[ \text{BR}(\mu \rightarrow e\gamma) < 10^{-54} \]

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)$_L \times$ 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):

\[
\begin{align*}
W_{\Delta L=1} &= \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}_k \\
W_{\Delta B=1} &= \frac{1}{2} \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu^i L_i H_u
\end{align*}
\]

Single squark production at HERA, EIC
R-Parity Violating (RPV) SUSY

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

  squark production \[ e \rightarrow \tilde{q} \lambda' \]  
  \[ R_{p} \text{ violating decay} \]  
  \[ \tilde{q} \rightarrow e, \mu, \tau, \nu \]  

  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:

  Bosonic stop decay
  \[ \tilde{t} \rightarrow W \tilde{b} \]  
  Decays including \( \chi, \tilde{g} \): example

  \[ \tilde{q} \rightarrow e, \mu, \tau \]
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

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

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.

\[
O_{LL}^{(1)} = \bar{L}_L \gamma^\mu \Delta L_L H^\dagger i D_\mu H \\
O_{LL}^{(2)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L H^\dagger \tau^a i D_\mu H \\
O_{LL}^{(3)} = \bar{L}_L \gamma^\mu \Delta L_L \bar{Q}_L \gamma_\mu Q_L \\
O_{LL}^{(4d)} = \bar{L}_L \gamma^\mu \Delta L_L \bar{d}_R \gamma_\mu d_R \\
O_{LL}^{(4u)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L \bar{u}_R \gamma_\mu u_R \\
O_{LL}^{(5)} = \bar{L}_L \gamma^\mu \tau^a \Delta L_L \bar{Q}_L \gamma_\mu \tau^a Q_L \\
O_{RL}^{(1)} = g' H^\dagger \bar{e}_R \sigma^{\mu\nu} \lambda_\mu \Delta L_L B_{\mu\nu} \\
O_{RL}^{(2)} = g H^\dagger \bar{e}_R \sigma^{\mu\nu} \tau^a \lambda_\mu \Delta L_L W^a_{\mu\nu} \\
O_{RL}^{(3)} = (D_\mu H)^\dagger \bar{e}_R \lambda_\mu \Delta D_\mu L_L \\
O_{RL}^{(4)} = \bar{e}_R \lambda_\mu \Delta L_L \bar{Q}_L \lambda D d_R \\
O_{RL}^{(5)} = \bar{e}_R \sigma^{\mu\nu} \lambda_\mu \Delta L_L \bar{Q}_L \sigma_{\mu\nu} \lambda D d_R \\
O_{RL}^{(6)} = \bar{e}_R \lambda_\mu \Delta L_L \bar{u}_R \lambda U^\dagger \tau^2 Q_L \\
O_{RL}^{(7)} = \bar{e}_R \sigma^{\mu\nu} \lambda_\mu \Delta L_L \bar{u}_R \sigma_{\mu\nu} \lambda U^\dagger \tau^2 Q_L \\
\Delta_{we} = \frac{\Lambda_{LN}^2}{v^4} \frac{1}{\sqrt{2}} (s_c \Delta m_{sol}^2 + s_{13} e^{i\delta} \Delta m_{atm}^2) \\
\Delta_{\tau e} = \frac{\Lambda_{LN}^2}{v^4} \frac{1}{\sqrt{2}} (-s_c \Delta m_{sol}^2 + s_{13} e^{i\delta} \Delta m_{atm}^2) \\
\Delta_{\tau \mu} = \frac{\Lambda_{LN}^2}{v^4} \frac{1}{2} (-c^2 \Delta m_{sol}^2 + \Delta m_{atm}^2) \\
\]

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

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

\[ B_{\mu \rightarrow e\gamma} = 8.3 \times 10^{-50} \left( \frac{\Lambda_{LN}}{\Lambda_{LFV}} \right)^4 \]

\[ B_{\mu \rightarrow e} = \left( \frac{\Lambda_{LN}}{\Lambda_{LFV}} \right)^4 \begin{cases} 6.6 \times 10^{-50} & \text{for Al} \\ 19.6 \times 10^{-50} & \text{for Au} \end{cases} \]

Huge enhancement factor when:

\[ \Lambda_{LN} \gg \Lambda_{LFV} \]

- For example:

\[ \Lambda_{LN} \sim 10^9 \Lambda_{LFV} \]

\[ B_{\mu \rightarrow e\gamma} = \mathcal{O}(10^{-13}) \]

\[ B_{\mu \rightarrow e} = \mathcal{O}(10^{-13}) \]
Charged Lepton Flavor Violation Limits

• Present and future limits:

<table>
<thead>
<tr>
<th>LFV transitions</th>
<th>LFV Present Bounds (90%CL)</th>
<th>Future Sensitivities</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR(μ → eγ)</td>
<td>4.2 × 10^{-13} (MEG 2016)</td>
<td>4 × 10^{-14} (MEG-II)</td>
</tr>
<tr>
<td>BR(τ → eγ)</td>
<td>3.3 × 10^{-8} (BABAR 2010)</td>
<td>10^{-9} (BELLE-II)</td>
</tr>
<tr>
<td>BR(τ → μγ)</td>
<td>4.4 × 10^{-8} (BABAR 2010)</td>
<td>10^{-9} (BELLE-II)</td>
</tr>
<tr>
<td>BR(μ → eee)</td>
<td>1.0 × 10^{-12} (SINDRUM 1988)</td>
<td>10^{-16} Mu3E (PSI)</td>
</tr>
<tr>
<td>BR(τ → eee)</td>
<td>2.7 × 10^{-8} (BELLE 2010)</td>
<td>10^{-9},-10 (BELLE-II)</td>
</tr>
<tr>
<td>BR(τ → μμμ)</td>
<td>2.1 × 10^{-8} (BELLE 2010)</td>
<td>10^{-9},-10 (BELLE-II)</td>
</tr>
<tr>
<td>BR(τ → μη)</td>
<td>2.3 × 10^{-8} (BELLE 2010)</td>
<td>10^{-9},-10 (BELLE-II)</td>
</tr>
<tr>
<td>CR(μ → e, Au)</td>
<td>7.0 × 10^{-13} (SINDRUM II 2006)</td>
<td>10^{-18} PRISM (J-PARC)</td>
</tr>
<tr>
<td>CR(μ → e, Ti)</td>
<td>4.3 × 10^{-12} (SINDRUM II 2004)</td>
<td>3.1 × 10^{-15} COMET-I (J-PARC)</td>
</tr>
<tr>
<td>CR(μ → e, Al)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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.

[taken from a talk by Y. Furletova]
CLFV in DIS

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

\[ ep \rightarrow \tau X \]

- 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

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 $[\text{scalar (S) or vector (V)}]$ $[S=0, 1]$
- Chirality of coupling to leptons $[L \text{ or } R]$ $[L \text{ or } R]$ $[L \text{ or } R]$
- Gauge group quantum numbers $[SU(2)_L \times U(1)_Y]$ $[SU(2)_L \times U(1)_Y]$

Leptoquarks $e^- \rightarrow \tau^- \bar{q}_\alpha \lambda_{1\alpha} \lambda_{3\beta}$
Leptoquarks

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

\[
L_{F=0} = h_{1/2} U_R \ell LS_{1/2} + h_{1/2} \bar{q}_L e_R S_{1/2} + \tilde{h}_{1/2} d_R \ell \tilde{S}_{1/2} + h_{0} \bar{q}_L \gamma_{\mu} \ell LV_{0}^{L\mu} \\
+ h_{0} d_R \gamma_{\mu} e_R V_{0}^{R\mu} + \tilde{h}_{0} \bar{d}_R \gamma_{\mu} e_R \tilde{V}_{0}^{R\mu} + h_{1} \bar{q}_L \gamma_{\mu} \ell_L \tilde{V}_1^{L\mu} + \text{h.c.}
\]

\[
L_{|F|=2} = g_{0} \bar{q}_L \epsilon_{\ell L} S_{0}^{L} + g_{0} \bar{d}_R \epsilon_{R} e_R S_{0}^{R} + \tilde{g}_{0} \bar{d}_R \epsilon_{L} \tilde{S}_{0}^{L} + g_{1} \bar{q}_L \epsilon_{L} \ell_L \tilde{S}_{1}^{L} + g_{1} \bar{L} \epsilon_{\nu L} \gamma_{\mu} \ell_L V_{1/2}^{L\mu} \\
+ g_{1/2} \bar{q}_L \gamma_{\mu} e_R \tilde{V}_{1/2}^{R\mu} + \tilde{g}_{1/2} \bar{d}_R \gamma_{\mu} \ell_L \tilde{V}_1^{L\mu} + \text{h.c.}
\]

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

[Leptoquarks at EIC](#) by [David South](#)

#### High Higginoity (~10^0 - 10^3 GeV)

<table>
<thead>
<tr>
<th>Type</th>
<th>J</th>
<th>F</th>
<th>Q</th>
<th>$e\bar{p}$ Dominant Process</th>
<th>Coupling</th>
<th>Branching Ratio $\beta_{\ell}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_0^L$</td>
<td>0</td>
<td>2</td>
<td>$-1/3$</td>
<td>$\ell^- u_L \rightarrow \nu d$</td>
<td>$\lambda_L$</td>
<td>1/2</td>
</tr>
<tr>
<td>$S_0^R$</td>
<td>0</td>
<td>2</td>
<td>$-1/3$</td>
<td>$\ell^- u_R \rightarrow \nu d$</td>
<td>$\lambda_R$</td>
<td>1</td>
</tr>
<tr>
<td>$\tilde{S}_0^R$</td>
<td>0</td>
<td>2</td>
<td>$-4/3$</td>
<td>$\ell^- d_R \rightarrow \nu d$</td>
<td>$\lambda_R$</td>
<td>1</td>
</tr>
<tr>
<td>$S_1^L$</td>
<td>0</td>
<td>2</td>
<td>$-1/3$</td>
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</tr>
</thead>
<tbody>
<tr>
<td>$V_0^L$</td>
<td>1</td>
<td>0</td>
<td>$+2/3$</td>
<td>$e^+ d_L \rightarrow \ell^+ u$</td>
<td>$\lambda_L$</td>
<td>1/2</td>
</tr>
<tr>
<td>$V_0^R$</td>
<td>1</td>
<td>0</td>
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<td>$e^+ d_R \rightarrow \ell^+ u$</td>
<td>$\lambda_R$</td>
<td>1</td>
</tr>
<tr>
<td>$\tilde{V}_0^R$</td>
<td>1</td>
<td>0</td>
<td>$+5/3$</td>
<td>$e^+_R u_R \rightarrow \ell^+ u$</td>
<td>$\lambda_R$</td>
<td>1</td>
</tr>
<tr>
<td>$V_1^L$</td>
<td>1</td>
<td>0</td>
<td>$+2/3$</td>
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<tr>
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<td>$e^+_R d_R \rightarrow \ell^+ u$</td>
<td>$\lambda_L$</td>
<td>1/2</td>
</tr>
</tbody>
</table>

- 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]

---

[Buchmuller, Ruckl, Wyler (BRW)]
Leptoquarks: Electron vs Positron Beams

- 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:

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

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

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

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

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

- 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:

\[
f(y) = \begin{cases} 
1/2 & \text{(scalar)} \\
2 (1 - y)^2 & \text{(vector)} 
\end{cases}, \quad g(y) = \begin{cases} 
(1 - y)^2/2 & \text{(scalar)} \\
2 & \text{(vector)} 
\end{cases}
\]
Leptoquarks: Polarized Lepton and Nuclear (p,D)

- 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.

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]

\[ A_{LL}^{PV}(e^+) = \frac{\sigma_{++} - \sigma_{++}}{\sigma_{++} + \sigma_{++}} \]

\[ A_1^{PC} = \frac{\sigma_{--} - \sigma_{--}}{\sigma_{--} + \sigma_{--}} \]

\[ A_2^{PC} = \frac{\sigma_{++} - \sigma_{--}}{\sigma_{++} + \sigma_{--}} \]

\[ A_3^{PC} = \frac{\sigma_{++} - \sigma_{++}}{\sigma_{++} + \sigma_{++}} \]

\[ B_U = \frac{\sigma_{--} - \sigma_{++} + \sigma_{--} + \sigma_{--} - \sigma_{--} + \sigma_{++} - \sigma_{++} + \sigma_{--} - \sigma_{--}}{\sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++}} \]

\[ B_V = \frac{\sigma_{--} - \sigma_{++} + \sigma_{--} - \sigma_{--} + \sigma_{++} - \sigma_{++} + \sigma_{--} - \sigma_{--}}{\sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++} + \sigma_{++}} \]

- 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:

\[ e p \rightarrow \tau X \]

\[ \sqrt{s} \sim 320 \text{ GeV} \]
\[ \mathcal{L} \sim 0.5 \text{ fb}^{-1} \]

• High luminosity EIC could surpass the best limits set by HERA:
CLFV mediated by Leptoquarks

- Cross-section for $e p \rightarrow \tau X$ takes the form:

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

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

- 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.

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<th>$q_i q_j$</th>
<th>$S^L_{0}$</th>
<th>$S^R_{0}$</th>
<th>$S^R_{1}$</th>
<th>$S^L_{1}$</th>
<th>$V^L_{1/2}$</th>
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<th>$\tilde{V}^L_{1/2}$</th>
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$\epsilon p \rightarrow \tau X$ for lepton flavour violating leptoquarks at 95% CL.

Upper exclusion limits on $\lambda_{eq} \lambda_{\tau q_j} / m^2_{LQ}$ (TeV$^{-2}$)
EIC Sensitivity

[Deshpande, Faroughy, Gonderinger, Kumar, Taneja]

[M. Gonderinger, M. Ramsey-Musolf]

\[ z = \frac{(\lambda_1 \alpha \lambda_3 \beta)}{(M_{LQ}^2)} \left[ \frac{(\lambda_1 \alpha \lambda_3 \beta)}{(M_{LQ}^2)} \right]_{\text{HERA limit}} \]

- \( z = 1 \) 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:

\[ \tau \rightarrow e\gamma \]

- 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.

**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.
• 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.