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 facilitated by:

  • high luminosity
  • wide kinematic range
  • range of nuclear targets
  • polarized beams

★ The addition of a polarized positron beam will enhance the BSM program at the EIC.
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 $F=3B+L$  $\left[ |F|=0, 2 \right]$
  - Spin  $\left[ \text{scalar (S) or vector (V)} \right]$
  - Chirality of coupling to leptons  $\left[ \text{L or R} \right]$
  - Gauge group quantum numbers  $\left[ \text{SU(2)}_L \times \text{U(1)}_Y \right]$
Leptoquarks

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

\[
\mathcal{L}_{F=0} = h_{1/2}^L \bar{u}_R \ell L S^L_{1/2} + h_{1/2}^R \bar{q}_L e_R S^R_{1/2} + \tilde{h}_{1/2}^L \bar{d}_R \ell L \tilde{S}^L_{1/2} + h_0^L \bar{q}_L \gamma_\mu \ell L V^L_0 \mu \\
+ h_0^R \bar{d}_R \gamma_\mu e_R V^R_0 \mu + \tilde{h}_0^R \bar{u}_R \gamma_\mu e_R \tilde{V}^R_0 \mu + h_1^L \bar{q}_L \gamma_\mu \ell L \tilde{V}^L_1 \mu + \text{h.c.}
\]

\[
\mathcal{L}_{|F|=2} = g_0^L \bar{q}_L \epsilon L S^L_0 + g_0^R \bar{e}_R e_R S^R_0 + \tilde{g}_0^L \bar{d}_R e_R \tilde{S}^R_0 + g_1^L \bar{q}_L \epsilon L \tilde{S}^L_1 + g_1^L \bar{d}_R \gamma_\mu \ell L V^L_{1/2} \\
+ g_1^L \bar{u}_R \gamma_\mu e_R V^R_{1/2} + \tilde{g}_1^L \bar{c}_R \gamma_\mu \ell L \tilde{V}^L_{1/2} + \text{h.c.}
\]

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

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<thead>
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Leptoquarks

[Buchmuller, Ruckl, Wyler (BRW)]

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- 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
  - proton and deuteron targets
  - polarized beams
  - wide kinematic range

[separate $|F|=0$ vs $|F|=2$]
[separate “eu” vs “ed” LQs]
[separate L vs R]
[separate scalar vs vector LQs]
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

\[ |F| = 2 \]
\[ F = 0 \]
\[ s\text{-channel} \]
\[ u\text{-channel} \]
Leptoquarks: Electron vs Positron Beams

Resonant s-channel production

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

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

- $y$-dependence can distinguish scalar and vector leptoquarks.
Leptoquarks: Electron vs Positron Beams

Contact Interaction

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

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

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

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

Y-dependence can distinguish scalar and vector leptoquarks

- For $M_{LQ} \gg \sqrt{s}$ 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)

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

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

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

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

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

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

\[ B_V = \frac{\sigma_{-+} - \sigma_{++} + \sigma_{-+} + \sigma_{++} - \sigma_{-+} + \sigma_{++} - \sigma_{-+} + \sigma_{++}}{\sigma_{-+} + \sigma_{-+} + \sigma_{-+} + \sigma_{-+} + \sigma_{-+} + \sigma_{-+} + \sigma_{-+} + \sigma_{++}} \]
HERA Limits on LQs

H1 Search for First Generation F = 0 Scalar Leptoquarks

(a)

H1 Search for First Generation F = 0 Vector Leptoquarks

(c)

H1 Search for First Generation F = 2 Scalar Leptoquarks

(b)

H1 Search for First Generation F = 2 Vector Leptoquarks

(d)

ZEUS

Fubo scalar LQ limit
ZEUS e+p (498 pb^-1)

ZEUS e+p (498 pb^-1)

ZEUS

Fubo vector LQ limit
ZEUS e+p (498 pb^-1)

ZEUS e+p (498 pb^-1)
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):

\[
W_{\Delta L=1} = \frac{1}{2} \lambda^{ijk} L_i L_j \bar{e}_k + \lambda'^{ijk} L_i Q_j \bar{d}_k + \mu'^i L_i H_u \\
W_{\Delta B=1} = \frac{1}{2} \lambda''^{ijk} \bar{u}_i \bar{d}_j \bar{d}_k
\]

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

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

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

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

```
Squark production

e → q' → \tilde{q}

R_{\text{p}} \text{violating decay}

\tilde{q} \rightarrow e, \mu, \tau, \nu

LQ

\lambda_{eq_i} \rightarrow \lambda_{eq_j} \rightarrow e, \mu, \tau

Lepton+Jet channel
```

Decays including \( \chi, \tilde{g} \) : example

```
\tilde{q} \rightarrow \chi^+_1 \rightarrow q \rightarrow e, \mu, \tau

\tilde{g} \rightarrow \chi^0_1 \rightarrow e q q

Bosonic stop decay

\tilde{\tau} \rightarrow \tilde{b} \rightarrow v
```

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

-1 for SUSY particles)

Rp = +1 for SM particles,

Rp = (-1)
R-Parity Violating (RPV) SUSY

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

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

- Exclusion limits:

![Graph showing exclusion limits for \( \lambda' \) and \( \lambda'' \) with parameter space regions excluded at 95% CL.]
Table 2.1: A comparative summary of the properties of the Standard and Left-Right Symmetric breaking)

2.2.4 Summary

Neutrinos

- 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:

\[ \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes U(1)_{B-L} \rightarrow \text{SU}(2)_L \otimes U(1)_Y \]

- 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:

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

(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:

\[ \text{SU}(2)_L \otimes \text{SU}(2)_R \otimes \text{U}(1)_{B-L} \rightarrow \text{SU}(2)_L \otimes \text{U}(1)_Y \]

- 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:

\[ \mathcal{L} = h^{L,R}_{ij} H^{--} \bar{l}_i^c P_{L,R} l_j + h.c. \]

- 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:

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

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

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

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

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

- 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:

\[ e^+ e^- \rightarrow \gamma A' \]

- 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 (e.g. LQs, RPV SUSY, Excited Fermions, etc.)

\[ \mathcal{L}_{\text{eff}} = \sum_{\ell,q} \left\{ \eta^{\ell q}_{LL} \bar{\ell} \gamma_{\mu} \ell \bar{q} L \gamma^\mu q_L + \eta^{\ell q}_{LR} \bar{\ell} \gamma_{\mu} \ell \bar{q} R \gamma^\mu q_R + \eta^{\ell q}_{RL} \bar{\ell} \gamma_{\mu} \ell \bar{q} L \gamma^\mu q_L + \eta^{\ell q}_{RR} \bar{\ell} \gamma_{\mu} \ell \bar{q} R \gamma^\mu q_R \right\} \]

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

\[ \mathcal{L}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{\ell,q} \left[ C_1 q \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_{\mu} q + C_2 q \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_{\mu} q + C_3 q \bar{\ell} \gamma^\mu \gamma_5 \ell \bar{q} \gamma_{\mu} \gamma_5 q \right] \]

- Tree-level Standard Model values:

\[
\begin{align*}
C_{1u} &= -\frac{1}{2} + \frac{4}{3} \sin^2(\theta_W), & C_{2u} &= -\frac{1}{2} + 2 \sin^2(\theta_W), & C_{3u} &= \frac{1}{2}, \\
C_{1d} &= \frac{1}{2} - \frac{2}{3} \sin^2(\theta_W), & C_{2d} &= \frac{1}{2} - 2 \sin^2(\theta_W), & C_{3d} &= -\frac{1}{2}
\end{align*}
\]
Precision Measurements of the Weak Mixing Angle

- 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:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Lambda$</th>
<th>Coupling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cesium APV</td>
<td>9.9 TeV</td>
<td>$C_{1u} + C_{1d}$</td>
</tr>
<tr>
<td>E-158</td>
<td>8.5 TeV</td>
<td>$C_{ee}$</td>
</tr>
<tr>
<td>Qweak</td>
<td>11 TeV</td>
<td>$2C_{1u} + C_{1d}$</td>
</tr>
<tr>
<td>SoLID</td>
<td>8.9 TeV</td>
<td>$2C_{2u} - C_{2d}$</td>
</tr>
<tr>
<td>MOLLER</td>
<td>19 TeV</td>
<td>$C_{ee}$</td>
</tr>
<tr>
<td>P2</td>
<td>16 TeV</td>
<td>$2C_{1u} + C_{1d}$</td>
</tr>
</tbody>
</table>

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

Contact Interactions

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

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

<table>
<thead>
<tr>
<th>Model</th>
<th>( a^d_{LL} )</th>
<th>( a^u_{LL} )</th>
<th>( a^d_{LR} )</th>
<th>( a^u_{LR} )</th>
<th>( a^d_{RR} )</th>
<th>( a^u_{RR} )</th>
<th>Coupling structure</th>
<th>95% CL [TeV] ( M_{\text{LQ}}/\lambda_{\text{LQ}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( S_3 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.75</td>
<td>0.57</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_2 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.69</td>
<td>0.50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_2 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.31</td>
<td>0.22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( S_2 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.09</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_1 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.60</td>
<td>0.49</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_1 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>0.93</td>
<td>0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_1 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>1.03</td>
<td>1.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( V_1 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>1.15</td>
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</tr>
<tr>
<td>( V_1 )</td>
<td>-1</td>
<td>+1</td>
<td>-1</td>
<td>+1</td>
<td>1.26</td>
<td>1.26</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ \Delta C_{1q} = (\eta_{LL} + \eta_{LR} - \eta_{RL} - \eta_{RR})/(2\sqrt{2}G_F) \]
\[ \Delta C_{2q} = (\eta_{LL} - \eta_{LR} + \eta_{RL} - \eta_{RR})/(2\sqrt{2}G_F) \]
\[ \Delta C_{3q} = (-\eta_{LL} + \eta_{LR} + \eta_{RL} - \eta_{RR})/(2\sqrt{2}G_F) \]
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:

\[ A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \sim \frac{|A_Z|}{|A_\gamma|} \sim \frac{G_F Q^2}{4\pi \alpha} \sim 10^{-4} Q^2 \]

- 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:

\[ A_{PV} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{|A_Z|}{|A_\gamma|} \approx \frac{G_F Q^2}{4\pi\alpha} \approx 10^{-4} Q^2 \]

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

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

All hadronic effects cancel!

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

Clean probe of WNC
Corrections to Cahn-Gilman

- Hadronic effects appear as corrections to the Cahn-Gilman formula

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

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

- 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

Figure 4.2: EIC physics at a future EIC

Current polarized DIS data:
- CERN
- DESY
- JLab
- SLAC

Current polarized BNL-RHIC pp data:
- PHENIX
- STAR 1-jet

For typical fixed target experiments, a clean separation of the combinations of WNC couplings:

\[ \frac{2C_{1u}}{C_{1d}} = 0.232, \quad \frac{2C_{2u}}{C_{2d}} = 0.242 \]
- Projected statistical uncertainties on the weak mixing angle at the EIC, for the following conditions:

\[ \sqrt{s} \sim 140 \text{ GeV} \]

\[ \mathcal{L} \sim 200 \text{ fb}^{-1} \]
**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 $A_{PV}$:

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

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

- 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:
    \[ 2C_{1u} - C_{1d}, \quad 2C'_{2u} - C_{2d} \]
    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 $\sim 75 \text{ fb}^{-1}$.
- EIC can improve by a factor of 2 or 3 at $100 \text{ fb}^{-1}$.

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

[References]

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

Electroweak physics at a future EIC
C-Violating Asymmetry using Polarized Electron and Positron Beams


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

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

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

[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


- C-violating asymmetry:

\[ A_{L^+ - L^-} = \frac{d\sigma (l_L^{-} + N \rightarrow l_L^{-} + X) - d\sigma (l_R^{+} + N \rightarrow l_R^{+} + X)}{d\sigma (l^{-} + N \rightarrow l^{-} + X) + d\sigma (l^{+} + N \rightarrow l^{+} + X)} \]

- Proton target:

\[ A_{p L^- - L^+} = \left( \frac{3G_F Q^2}{2\sqrt{2\pi\alpha}} \right) \frac{y(2-y)}{2} \frac{2C_{2u}\nu - C_{2d}\nu + 2C_{3u}\nu - C_{3d}\nu}{4u+d} \]

- Isoscalar deuteron target:

\[ A_{d L^- - L^+} = \left( \frac{3G_F Q^2}{2\sqrt{2\pi\alpha}} \right) \frac{y(2-y)}{2} \frac{(2C_{2u} - C_{2d} + 2C_{3u} - C_{3d}) R_V}{5}, \quad R_V \equiv (u\nu + d\nu)/(u+d) \]

- 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):

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

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.
Charged Lepton Flavor Violating Processes

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

\[ \mu + N \rightarrow e + N \quad (\mu \rightarrow e \text{ conversion in nuclei}) \]

\[ \mu \rightarrow e\gamma \]
\[ \tau \rightarrow e\gamma \]
\[ \tau \rightarrow \mu\gamma \quad \text{(rare CLFV decays)} \]
\[ \mu \rightarrow 3e \]
\[ \tau \rightarrow 3e \]
Charged Lepton Flavor Violation Limits

- Present and future limits:

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

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

\[ e\rho \rightarrow \tau X \]

• 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:

\[ ep \rightarrow \tau X \quad \sqrt{s} \sim 320 \text{ GeV} \]
\[ \mathcal{L} \sim 0.5 \text{ fb}^{-1} \]

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

\[ ep \rightarrow \tau X \quad \sqrt{s} \sim 90 \text{ GeV} \]
\[ \mathcal{L} \sim 10 \text{ fb}^{-1} \]

• At \( \mathcal{L} \sim 100 - 200 \text{ fb}^{-1} \) the EIC could compete or surpass the current limits from \( \tau \rightarrow e\gamma \)
CLFV mediated by Leptoquarks

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

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

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

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

[S. Chekanov et.al (ZEUS), A. Atkas et.al (H1)]
• Comparison of HERA limits with limits from other rare CLFV processes:
  [S. Davidson, D.C. Bailey, B.A. Campbell]

• HERA limits that are stronger are highlighted in yellow.

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

<table>
<thead>
<tr>
<th>$\alpha/\beta$</th>
<th>$S^L_{1/2}$</th>
<th>$S^R_{1/2}$</th>
<th>$\tilde{S}^L_{1/2}$</th>
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<tbody>
<tr>
<td></td>
<td>$e^-u$</td>
<td>$e^-((u+d))$</td>
<td>$e^+(u+d)$</td>
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<tr>
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<td>$\tau \to \pi e$</td>
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<td>12</td>
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<td>$K \to \pi \nu \bar{\nu}$</td>
<td>6.3</td>
<td>5.8 $\times 10^{-4}$</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>7.8</td>
</tr>
</tbody>
</table>

Units: $\text{TeV}^{-2}$
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

\[ \tilde{S}_0^R \]

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

- 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.

[M.Gonderinger, M.Ramsey-Musolf]
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 facilitated by:

- high luminosity
- wide kinematic range
- range of nuclear targets
- polarized beams

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