Charged Lepton Flavor Violation and other BSM Searches at the EIC

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POETIC XI
February 24-28, 2025

Searching for BSM Physics at the EIC

(A non-exhaustive list)

Rare or Forbidden Standard Model Processes

- Charged Lepton Flavor Violation
- 'Dark' Vector Bosons
- Axion-like particles
  - $a \to \gamma\gamma$
  - $a \to \tau^- e^+$
- Heavy Neutral Leptons
- Probes of Higher Dimension SMEFT Operators
  - (see previous talk by R. Boughezal)

Precision EW Measurements of SM Parameters/Processes

- Parity Violating Asymmetries
  - Weak Mixing Angle
    - Proton
    - Deuteron
  - Parity Violating Asymmetries
  - Polarized and Unpolarized PDFs
    - PDF uncertainties limit many BSM sensitive channels
    - Many talks this conference

Flavor Violation Background

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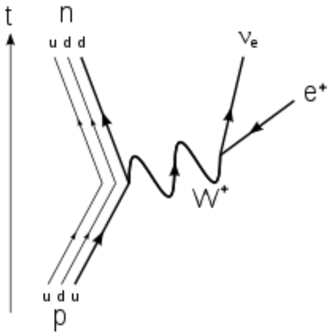
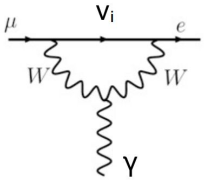
- Known Flavor violation
  - Quark Flavor violation
    - Beta decay first characterized in the early 1900s
    - Leads to the development of EW theory
  - Neutrino Flavor Oscillation
    - First hinted at through the solar neutrino problem
    - Observed BSM physics!
- Charged Lepton Flavor Violation
  - Unobserved so far
  - SM + Neutrino Masses allow for CLFV but suppressed
    - $BR(e\rightarrow\mu\gamma) \propto \Sigma(\Delta m_{ij}/M_W)^4$

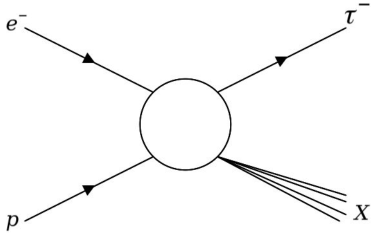




Charged Lepton Flavor Violation (CLFV)

- Due to the suppressed SM rate ($<10^{-54}$) of CLFV, observation ⇒ BSM signal
- Non-observations provides constraints on many BSM models that allow CLFV
- The $e \to \tau$ process has not been as constrained by experiment as much as the $e \to \mu$ process
  - $\Gamma(\tau \to e\gamma) < 3.3*10^{-8}$
  - $\Gamma(\mu \to e\gamma) < 4.2*10^{-13}$

    Particle Data Group, Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) and 2023
  - EIC could improve on $\Gamma(\tau \to e\gamma)$ limits set by HERA and BABAR



EIC Event Selection Sketch

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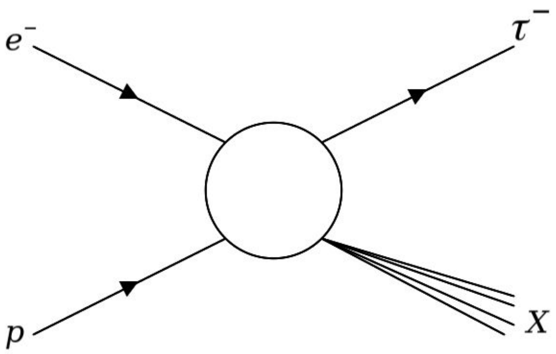
- Primary vertex is reconstructed (PrVtx)
- $\Sigma_h(E\text{-}p_z) > 18$ GeV (Epzh)
- 1 GeV < $p_{T,missing}$ < 9 GeV (misspt)

  Photoproduction events　　DIS events with large missing P_T
- High P_T jet back-to-back of the τ (away1GeV)
- τ-decay signature



➢

3-prong decays	15.2(0.06)%
$\pi^-\pi^+\pi^-\nu$	9.31(0.05)%
$\pi^-\pi^+\pi^-\pi^0\nu$	4.62(0.05)%
Others	

1-prong decays	85.24(0.06)%
$e^-\nu\nu$	17.82(0.04)%
$\mu^-\nu\nu$	17.39(0.04)%
$\pi^-\nu$	10.82(0.05)%
$\pi^-\pi^0\nu$	25.49(0.09)%
$\pi^-\pi^0\pi^0\nu$	9.26(0.10)%
Others	

➢ Lifetime = 290.3(.5)x10^{-15}s

➢ M_τ = 1776.86(0.12) MeV

EIC Event Selection Sketch

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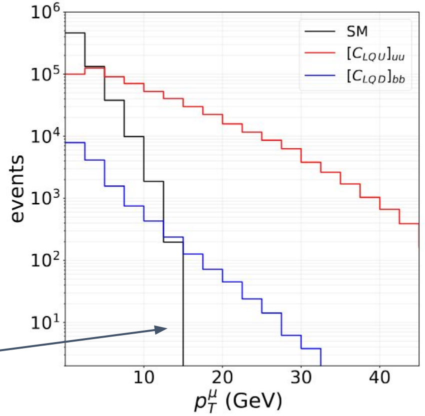
$\tau \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ Selection

- ❖ 3 charged pions in a cone $\sqrt{(\Delta\phi 2+\Delta\eta 2)} < 1$ (3-pion)
- ❖ 3 separate cuts using pairs of the 3-pions to constrain the secondary vertex (30μm, dRsum, decayL)

$\tau \rightarrow \mu^- \nu_\mu \nu_\tau$ Selection

- ❖ 1 charged track identifiable as a muon
- ❖ Displaced muon vertex
- ❖ Cuts to reject mis-ID'd pions
- ❖ P_T > 15 GeV



https://doi.org/10.1007/JHEP03(2021)256

EIC Event Selection Sketch

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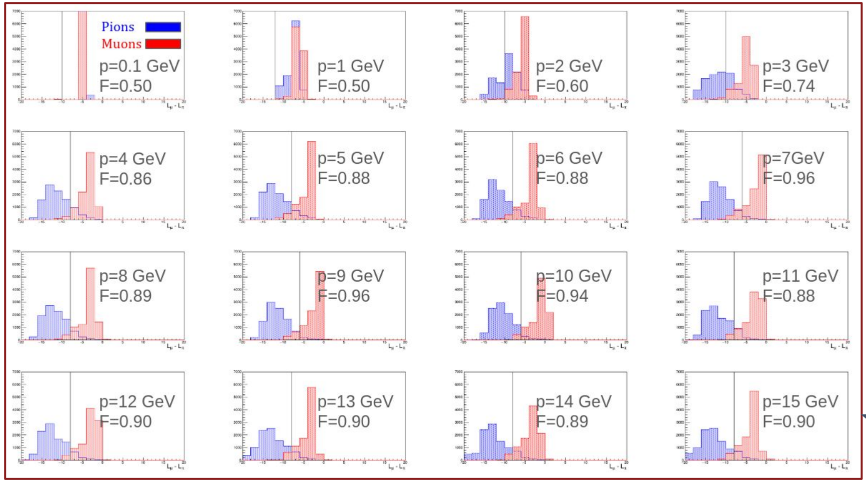
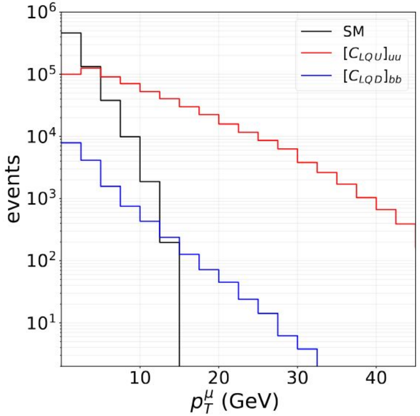


Ln(Likelihood) differences between muons and pions in single particle simulations in the EPIC detector using the barrel calorimeters

$\tau \rightarrow \mu^- \nu_\mu \nu_\tau$ Selection

- 1 charged track identifiable as a muon
- Displaced muon vertex
- Cuts to reject mis-ID'd pions
- P_T > 15 GeV



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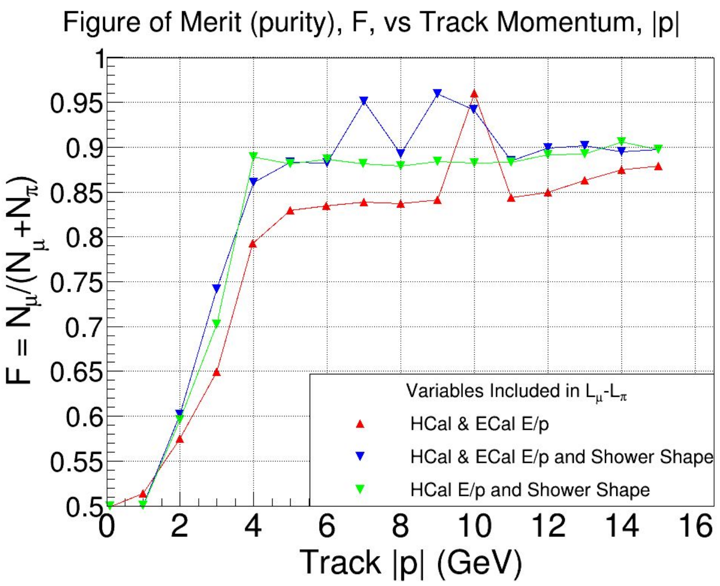

Purity of muons ($N_\mu/(N_\mu+N_\pi)$) based on example ln(likelihood) cuts.

$\tau\rightarrow\mu^-\nu_\mu\nu_\tau$ Selection

- ❖ 1 charged track identifiable as a muon
- ❖ Displaced muon vertex
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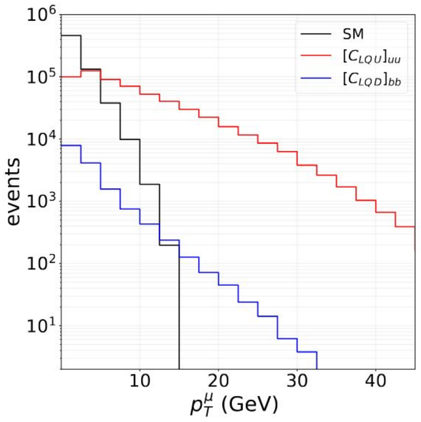
- ❖ $P_T > 15$ GeV



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ECCE 3-prong study: Event Selection

18x275 GeV

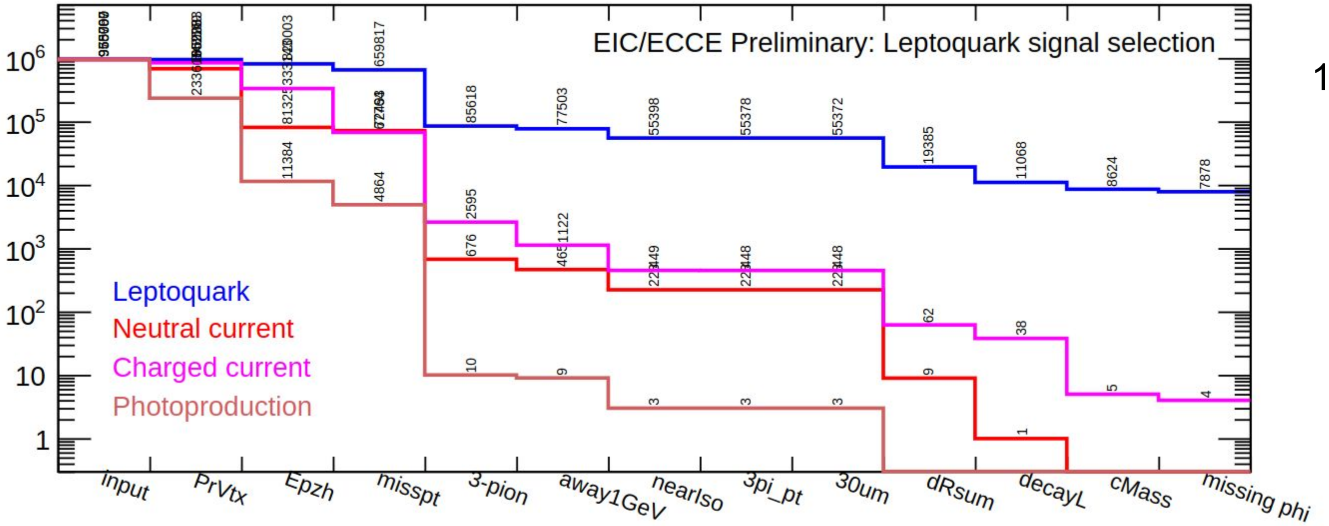
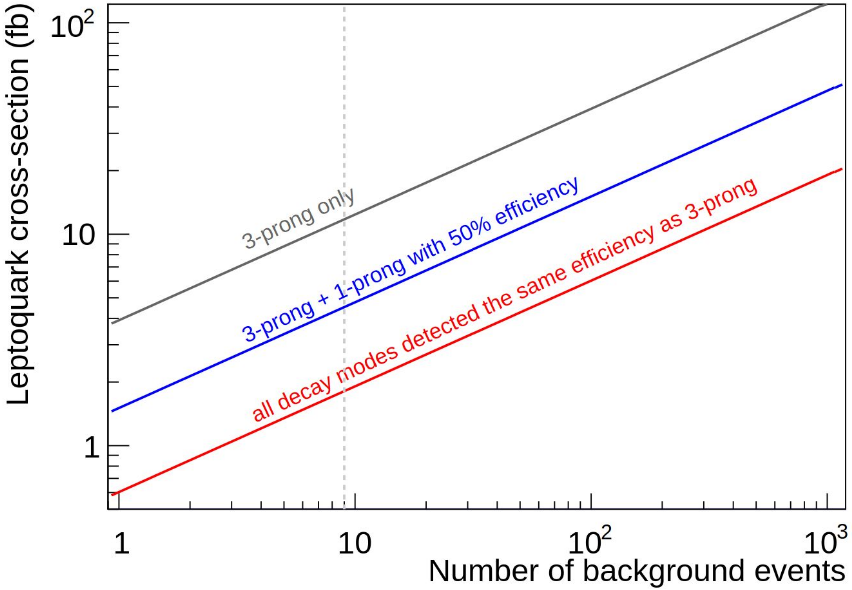


Figure 4: MC statistics of leptoquark (blue), DIS CC (red), DIS NC (magenta), and photoproduction (orange) events, as ten selection criteria are progressively applied on 1 M input events for each channel. Please see text for details.

3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
https://doi.org/10.1016/j.nima.2023.168276

ECCE 3-prong Sensitivity



sensitivity for leptoquark cross section vs # remaining background

Calculated assuming 100 fb^{-1} integrated luminosity.

3) Zhang et al. Search for e ⟶ τ Charged Lepton Flavor Violation at the EIC with the ECCE Detector (2022)
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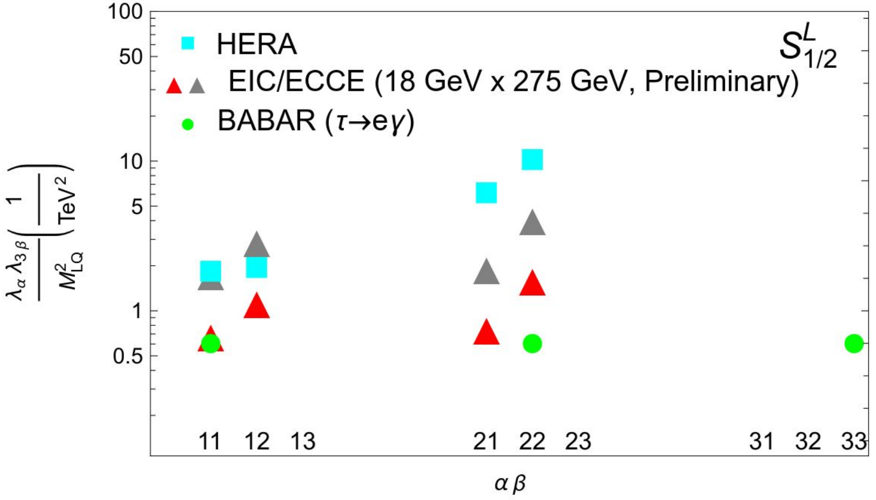
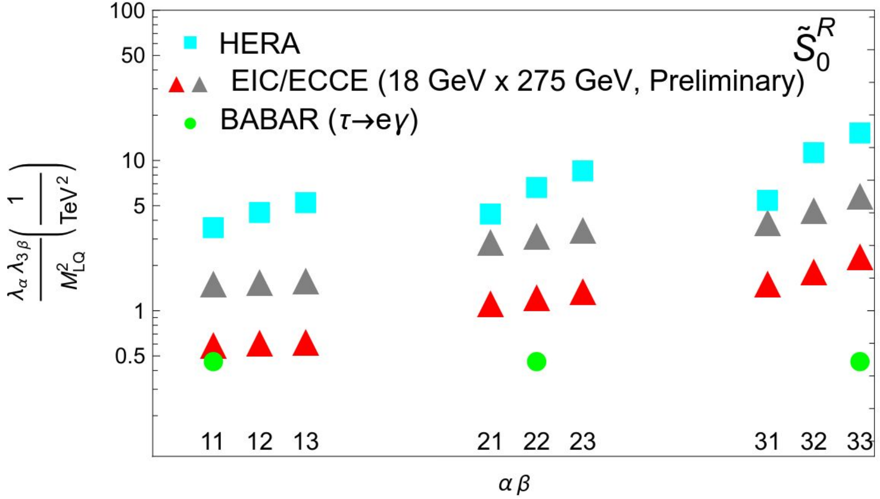
Scalar Leptoquark Sensitivity





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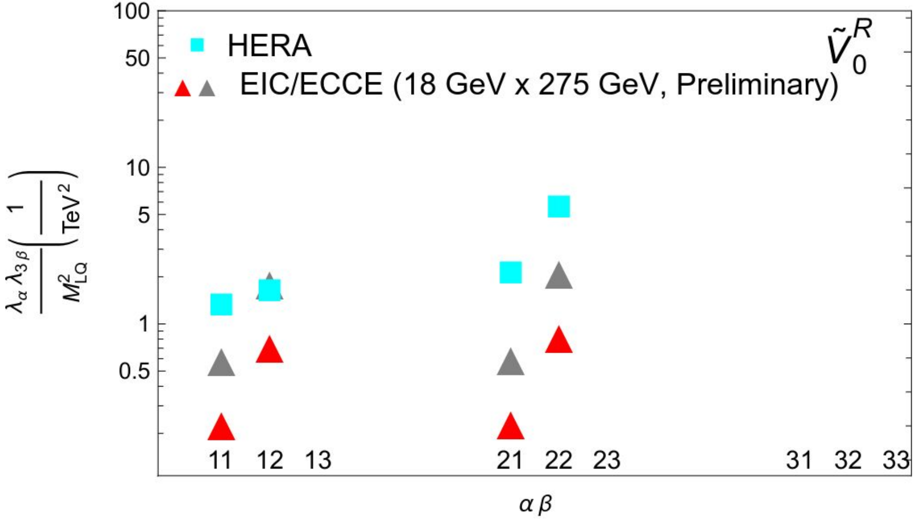
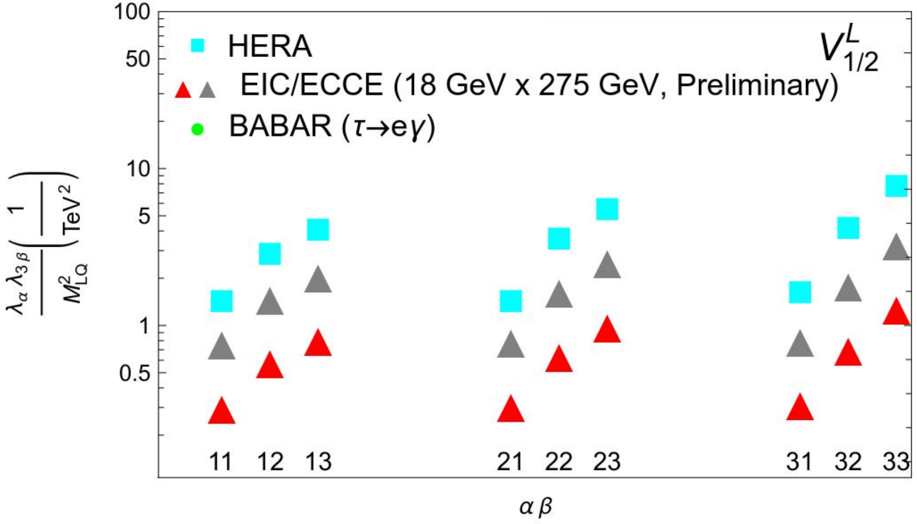
Vector Leptoquark Sensitivity





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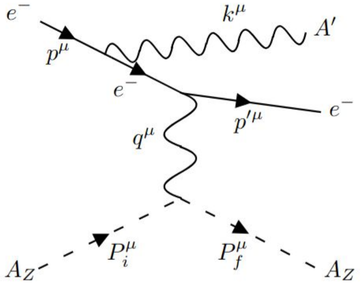
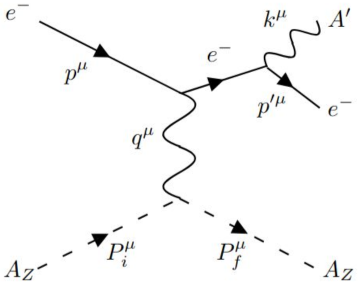
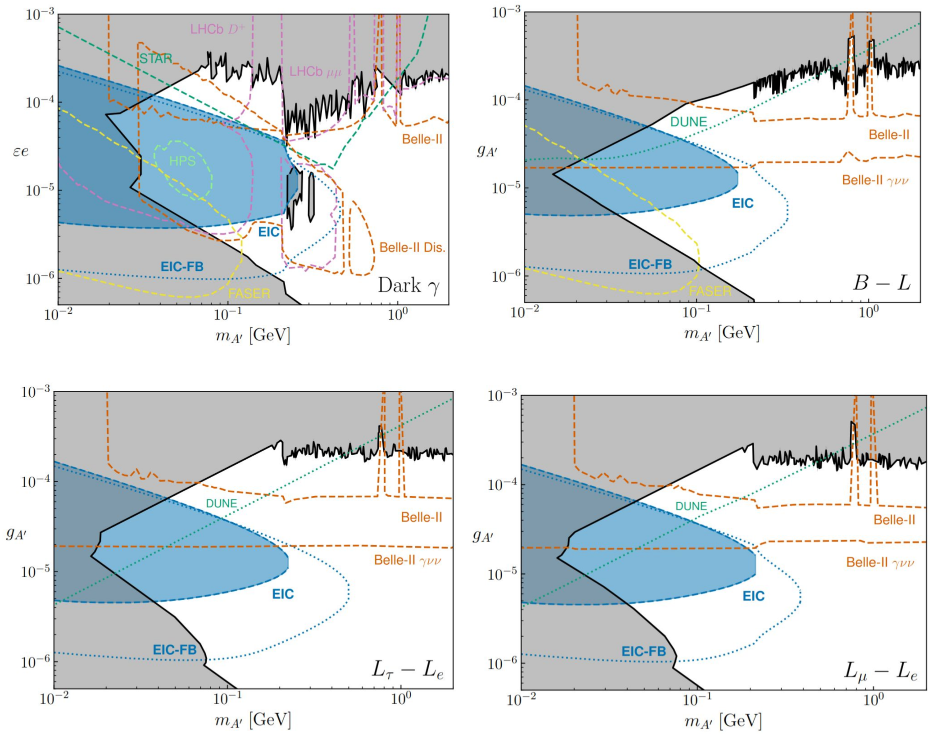
Hidden Vectors

H.Davoudiasl, R.Marcarelli, E. Neil Phys.Rev.D 108 (2023) 7, 075017





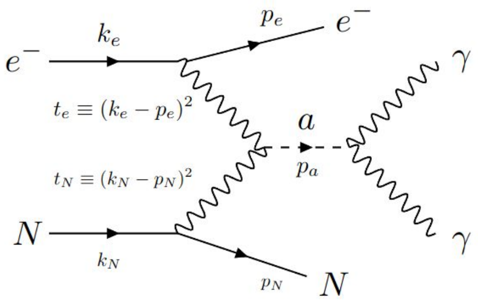


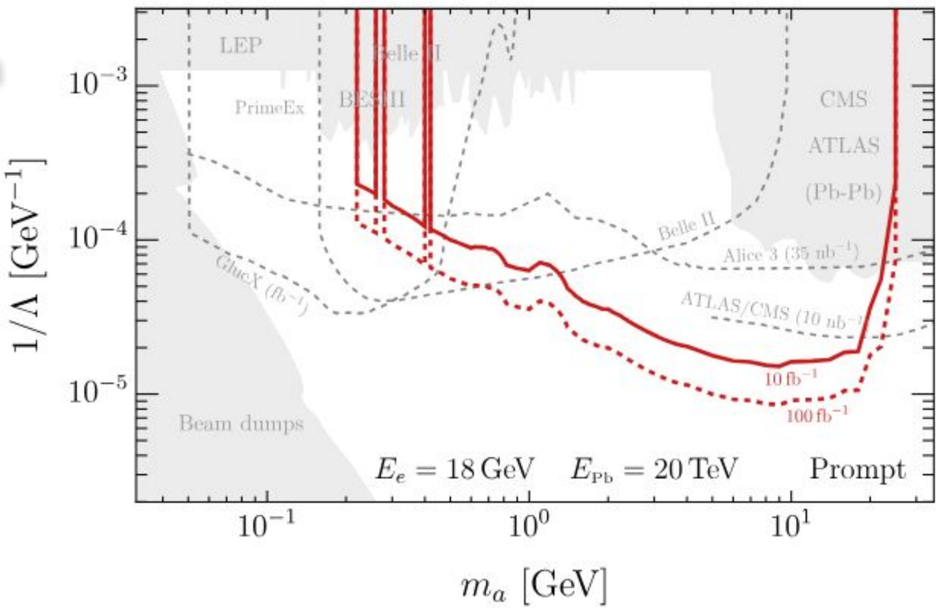
- Dark γ, B-L gauge boson, Leptophilic gauge bosons (L_τ-L_e, L_μ-L_e)
- A' decay may have a displaced vertex, allowing clean identification
- Projects improvement on interaction strength constraints for each A' studied

Axion-Like Particles (ALPs)

R. Balkin, et al. J. High Energ. Phys. 2024, 123 (2024). https://doi.org/10.1007/JHEP02(2024)123

- QCD axions are motivated as a solution to the strong-CP problem
  - ALPs more generally arise in many theories and frameworks and are less constrained compared to the QCD axion
- Dark Matter candidate
- Prompt decay of ALPs EIC search studied by Balkin, et al.
  - Couples to photons
    - Coherent production
    - Decay to two photons

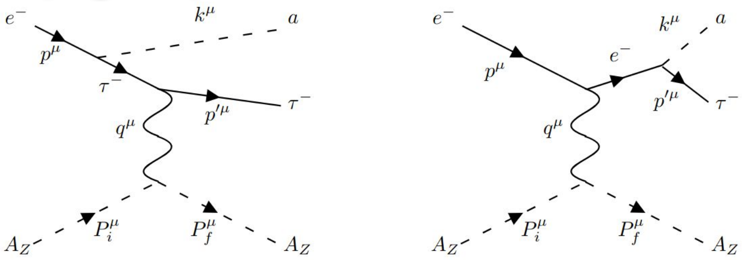




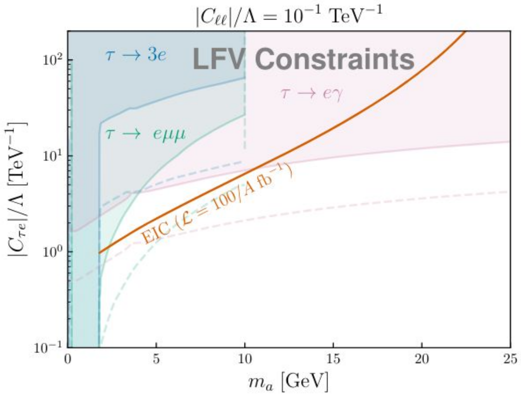
Lepton Flavor Violating (LFV) ALPs

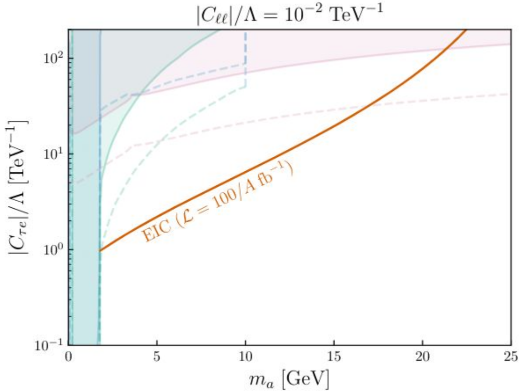
H.Davoudiasl, R.Marcarelli, E. Neil J. High Energ. Phys. 2023, 71 (2023). https://doi.org/10.1007/JHEP02(2023)071

- EIC could be sensitive to GeV scale LFV ALPs
  - Enhanced by larger ion charges (e.g. Au)



    - $a \to \tau^- e^+$
    - $a \to \tau^- \tau^+$

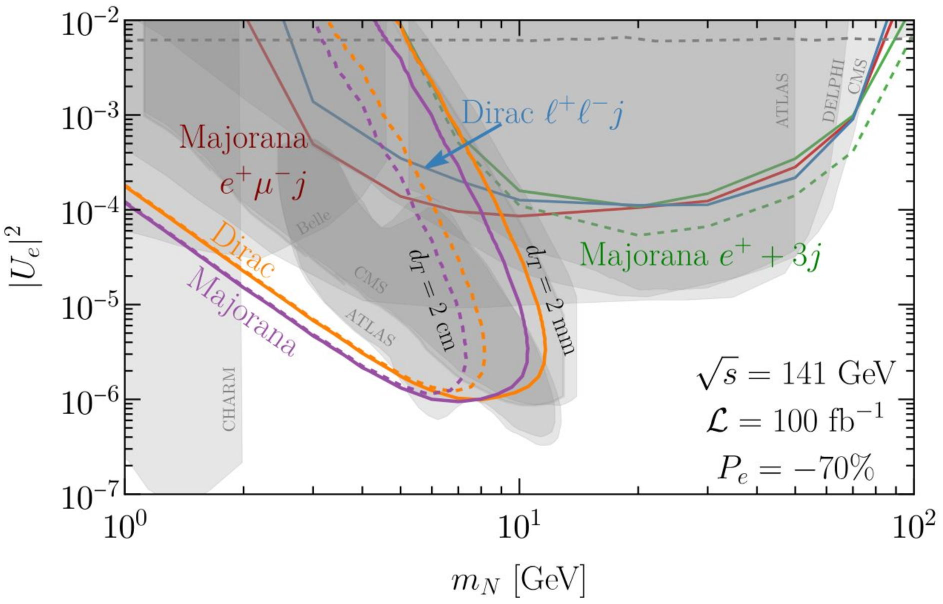




Heavy Neutral Leptons (HNLs)

B. Batell, T. Ghosh, T. Han, K. Xie J. High Energ. Phys. 2023, 20 (2023). https://doi.org/10.1007/JHEP03(2023)020

- HNLs are proposed particles with a connection to neutrino mass generation
- Signatures of Majorana and Dirac HNLs in prompt searches at the EIC were studied:
  - Majorana: e^+3j
  - Majorana: $e^+\mu j+\not{E}_T$
  - Dirac: $\ell^+\ell^- j+\not{E}_T$
- Bounds based on existing data can be improved upon at the EIC (especially in the case of a displaced decay vertex)



Weak Mixing Angle

R. Boughezal et al. https://doi.org/10.1103/PhysRevD.106.016006

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- Makes use of the polarized beams at the EIC
- Map Q^2 behavior in region between the Z-pole and the lower Q^2 measurments

$$A_{PV}^{(e)} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{d\sigma_e}{d\sigma_0}$$

$$A_{RL}^{e^-} = \frac{|\lambda|\eta_{\gamma Z}\left[g_A^e 2yF_1^{\gamma Z} + g_A^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_V^e(2-y)F_3^{\gamma Z}\right]}{2yF_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e 2yF_1^{\gamma Z} + g_V^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_A^e(2-y)F_3^{\gamma Z}\right]}$$

Where

$g_A^{e(q)}$ and $g_V^{e(q)}$: axial and vector neutral weak couplings of the electron (quark)

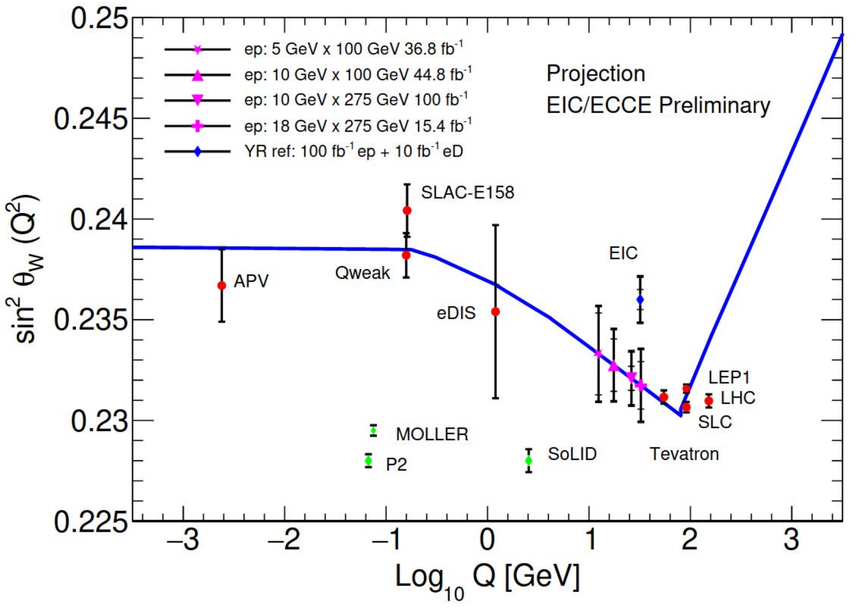
$$[F_2^{\gamma}, F_2^{\gamma Z}, F_2^{Z}] = x\sum_q [e_q^2, 2e_q\, g_V^q, (g_V^q)^2 + (g_A^q)^2](q + \bar{q})$$

$$[F_3^{\gamma}, F_3^{\gamma Z}, F_3^{Z}] = x\sum_q [0, 2e_q g_A^q, 2g_V^q g_A^q](q - \bar{q})$$

$$g_A^e = -\frac{1}{2} \qquad g_A^q = \pm\frac{1}{2}$$

$$g_V^e = -\frac{1}{2} + 2\sin^2\theta_W \qquad g_V^q = \pm\frac{1}{2} - 2e_q\sin^2\theta_W$$

M. Nycz et al, INT EW&BSM Workshop Talk



Summary

- The EIC will provide ample opportunities to look for physics beyond the standard model
  - Promt searches for new interactions/particles
  - Precision measurements of SM parameters
  - Better understanding of nuclear interactions
- Current studies indicate the EIC will be able to improve constraints on BSM models at a minimum
- Current work in the ePIC EW&BSM working group is to develop analysis tools and quantify expected efficiencies+backgrounds in the planned detector configuration
- Open Question: What other BSM physics searches can be improved upon with a second detector or upgrades to the first detector?

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