Heavy Neutral Leptons at the Electron-Ion Collider

Brian Batell
University of Pittsburgh
with T. Ghosh, T. Han, K. Xie, to appear

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Introduction and Motivation

- The EIC is a new U.S. DOE funded accelerator facility to be located at Brookhaven National Laboratory.

- The EIC will collide polarized electrons with polarized protons and ions over a wide range of energies and with high luminosities (10 - 1000 times HERA).

- The primary goals of the EIC are to elucidate nuclear structure, including:
  - 3D tomographic imaging of partonic substructure
  - Precise determination of quark and gluon contributions to proton spin
  - Exploration of novel phases of nuclear matter at high densities

- Given the substantial investment and promising capabilities of this facility, it is clearly of interest to consider what additional physics opportunities may be exist.

- Here we consider the capability of the EIC to probe physics beyond the Standard Model, taking the case of new Heavy Neutral Leptons as a case study.

The Electron-Ion Collider (EIC)

- We will focus on electron - proton collisions:

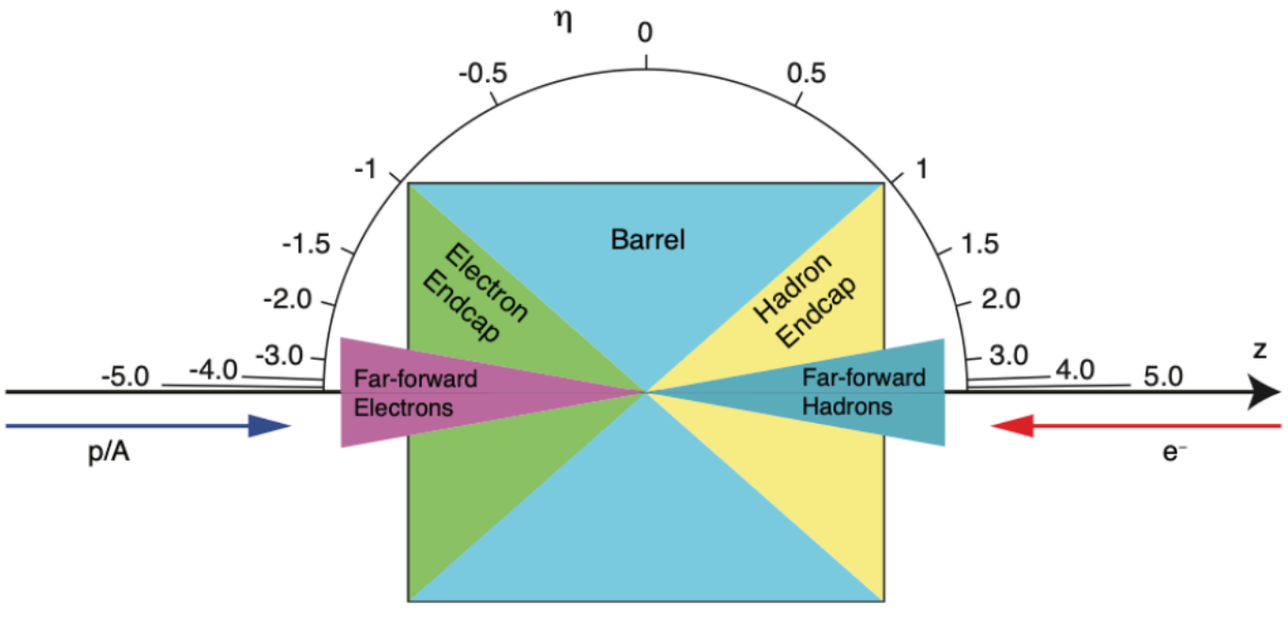
$$e(20\,\mathrm{GeV}) + p(250\,\mathrm{GeV}),\ \sqrt{s} = 140\,\mathrm{GeV}$$

- Assume integrated luminosity of $\mathcal{L} = 200\,\mathrm{fb}^{-1}$

- Primary physics goals require a multi-purpose Hermitic detector with excellent tracking resolution and particle ID capabilities over a broad momentum range

- Detector still under design; see EIC Detector Requirements R&D Handbook:

http://www.eicug.org/web/sites/default/files/EIC_HANDBOOK_v1.2.pdf



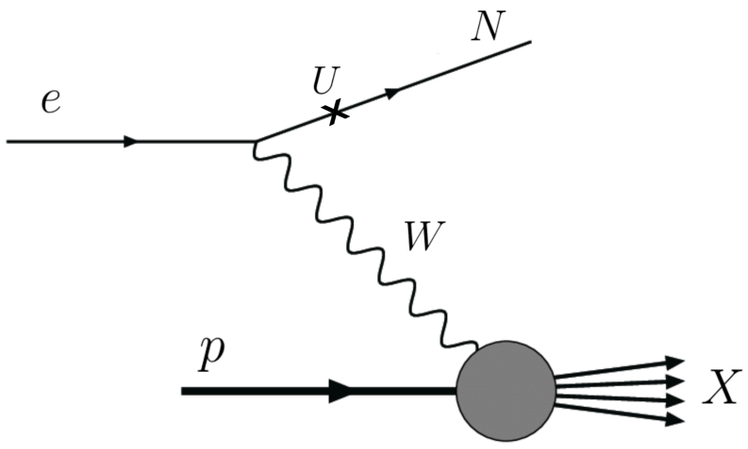
η	Resolution
Tracking (σ_p/p)	
$2.5 < \lvert\eta\rvert \leq 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \lvert\eta\rvert \leq 2.5$	$0.05\% \times p \oplus 1\%$
$\lvert\eta\rvert \leq 1.0$	$0.05\% \times p \oplus 0.5\%$
Electromagnetic calorimeter (σ_E/E)	
$-4.5 \leq \eta < -2.0$	$2\%/\sqrt{E}$
$-2.0 \leq \eta < -1.0$	$7\%/\sqrt{E}$
$-1.0 \leq \eta \leq 4.5$	$12\%/\sqrt{E}$
Hadronic calorimeter (σ_E/E)	
$1.0 < \lvert\eta\rvert \leq 3.5$	$50\%/\sqrt{E}$
$\lvert\eta\rvert \leq 1.0$	$100\%/\sqrt{E}$

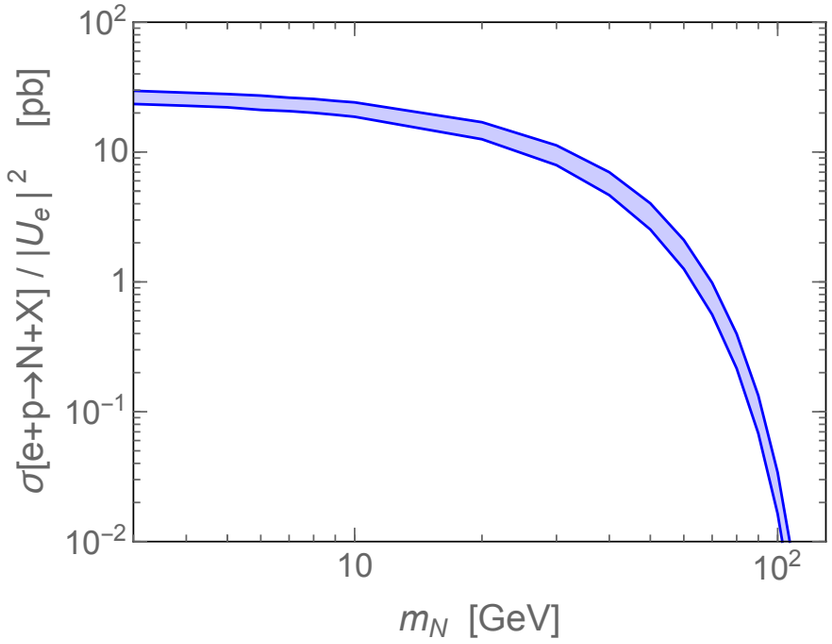
Heavy Neutral Leptons at the EIC

- HNLs motivated by potential connections to neutrino mass generation
- Lagrangian, Interactions

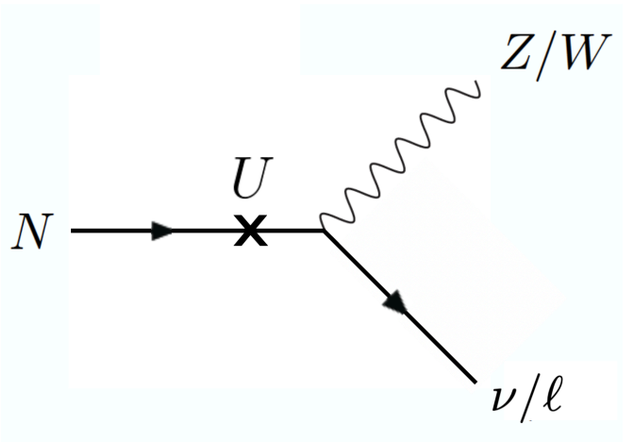
$$-\mathcal{L} \supset y_\nu^{iI}\, L_i\, H N_I + \text{H.c.} \quad \Rightarrow \quad \mathcal{L} \supset \frac{g}{\sqrt{2}} U_{iI} W_\mu^-\, \ell_i^\dagger\, \overline{\sigma}^\mu N_I + \frac{g}{2\, c_W} U_{iI}\, Z_\mu\, \nu_i^\dagger\, \overline{\sigma}^\mu N_I + \text{H.c.}$$

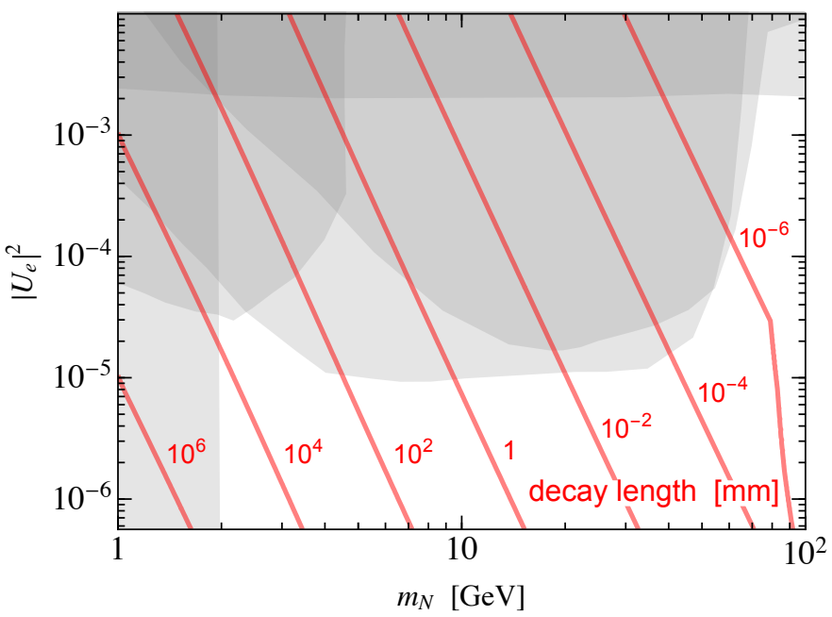
- HNL production





- HNL decays, lifetime



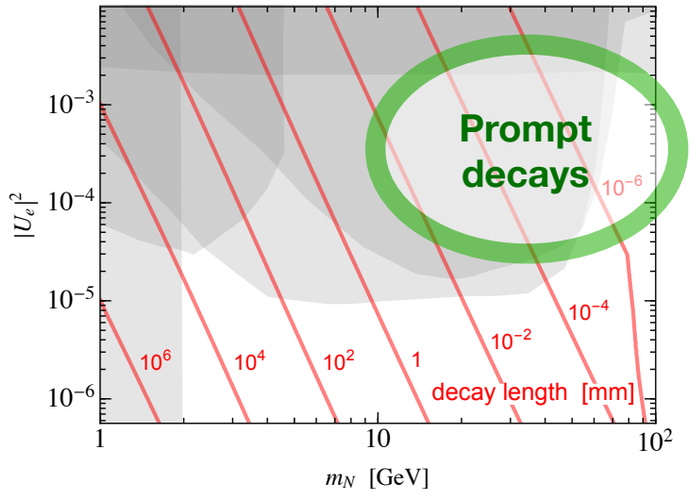


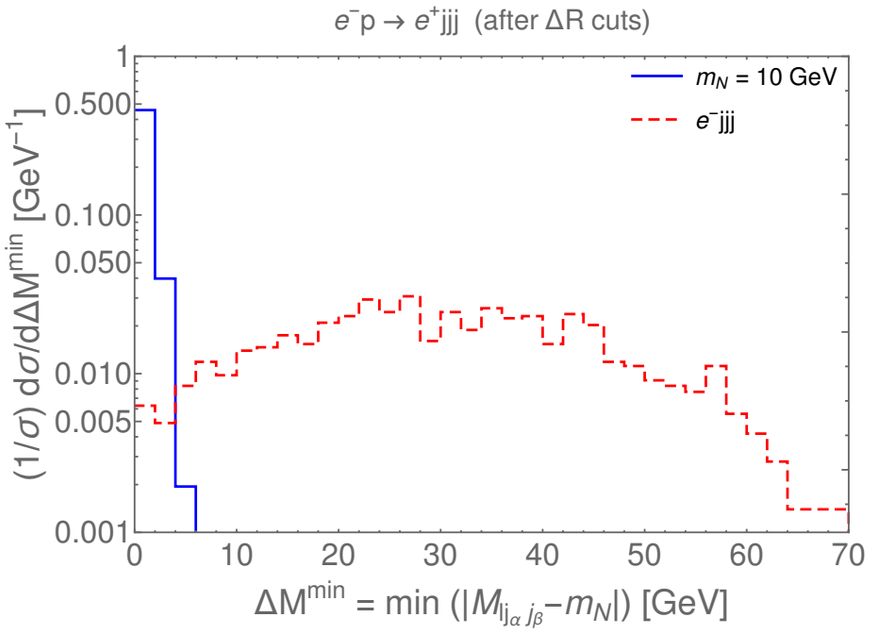
Prompt HNL Searches

- HNLs decay promptly for larger masses/mixing angle strengths
- Focus here on lepton number violating signature e^+jjj:

$$e^- p \to N j \to (e^+ jj) j$$

- Hadronic mode allows for full final state reconstruction
- Main SM background: neutral current processes with e^- misidentified as e^+
- e^+jj invariant mass, lepton pseudo-rapidity, jet transverse momentum provide efficient discrimination
- Order 1 - 10 background events after all cuts, depending on mis-identification rate

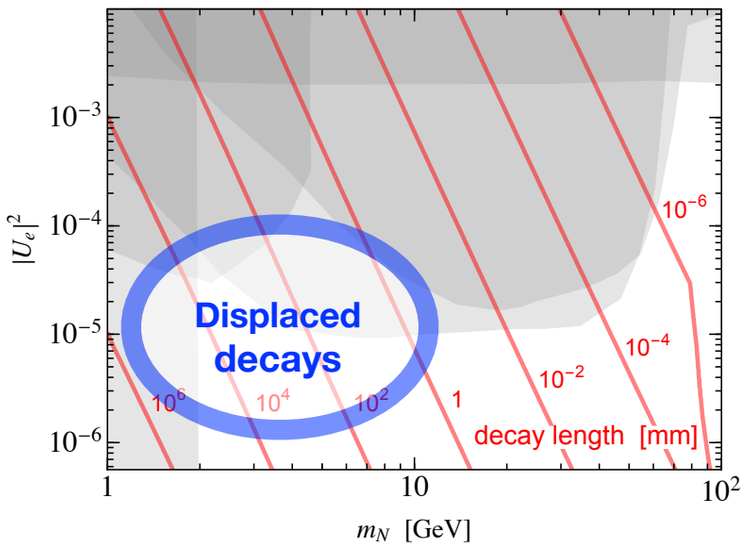


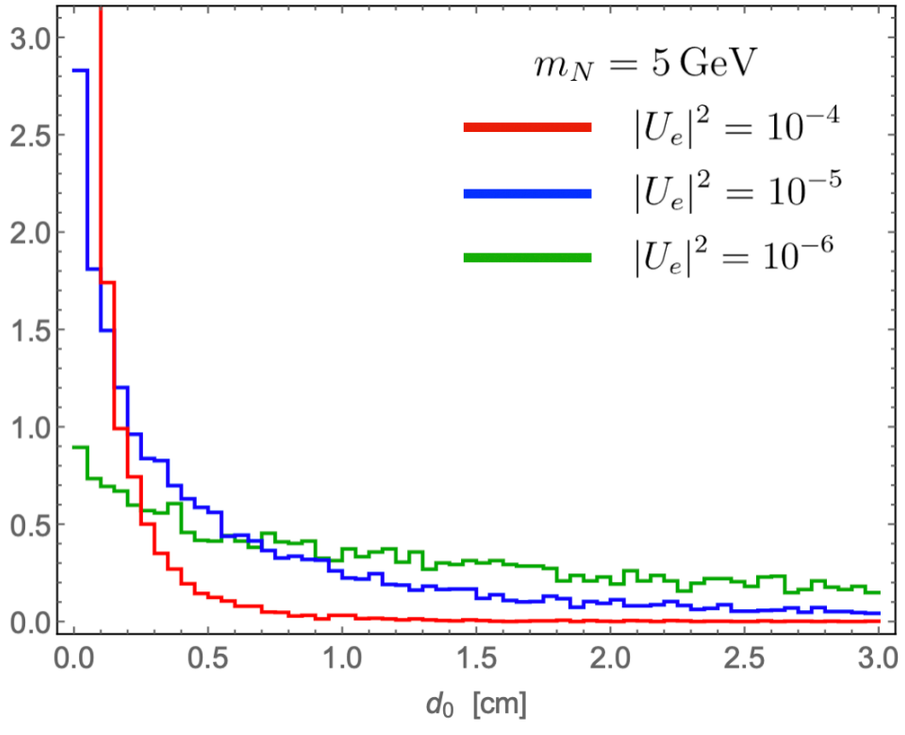


Cut selection	Signal		e^-jjj
	$m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	[pb]
Production	5.53	0.95	449
Exactly 1ℓ: $p_{T_\ell} > 2$ GeV, $0 < \eta_\ell < 3.5$	2.43	0.74	36.7
Exactly $3j$: $p_{T_{j_1}} > 20$ GeV, $p_{T_{j_{2,3}}} > 5$ GeV, $\lvert\eta_{j_{1,2,3}}\rvert < 3.5$	0.84	0.43	1.30
Isolation: $\Delta R(\ell, j_{1,2,3}) > 0.4$	0.52	0.41	1.30
$\min\left(\lvert M(\ell j_\alpha j_\beta) - m_N\rvert\right) < 5$ GeV $(\alpha, \beta = 1,2,3)$	0.52 × 0.52	× 0.33 × 0.33	4.31×10^{-2} 0.59
Require one e^+ [$f^{\rm MID} = 0.1\%$]	0.52 × 0.52	× 0.33 × 0.33	4.31×10^{-5} 5.93×10^{-4}
Require one e^+ [$f^{\rm MID} = 0.01\%$]	0.52 × 0.52	× 0.33 × 0.33	4.31×10^{-6} 5.93×10^{-5}

Displaced HNL Searches

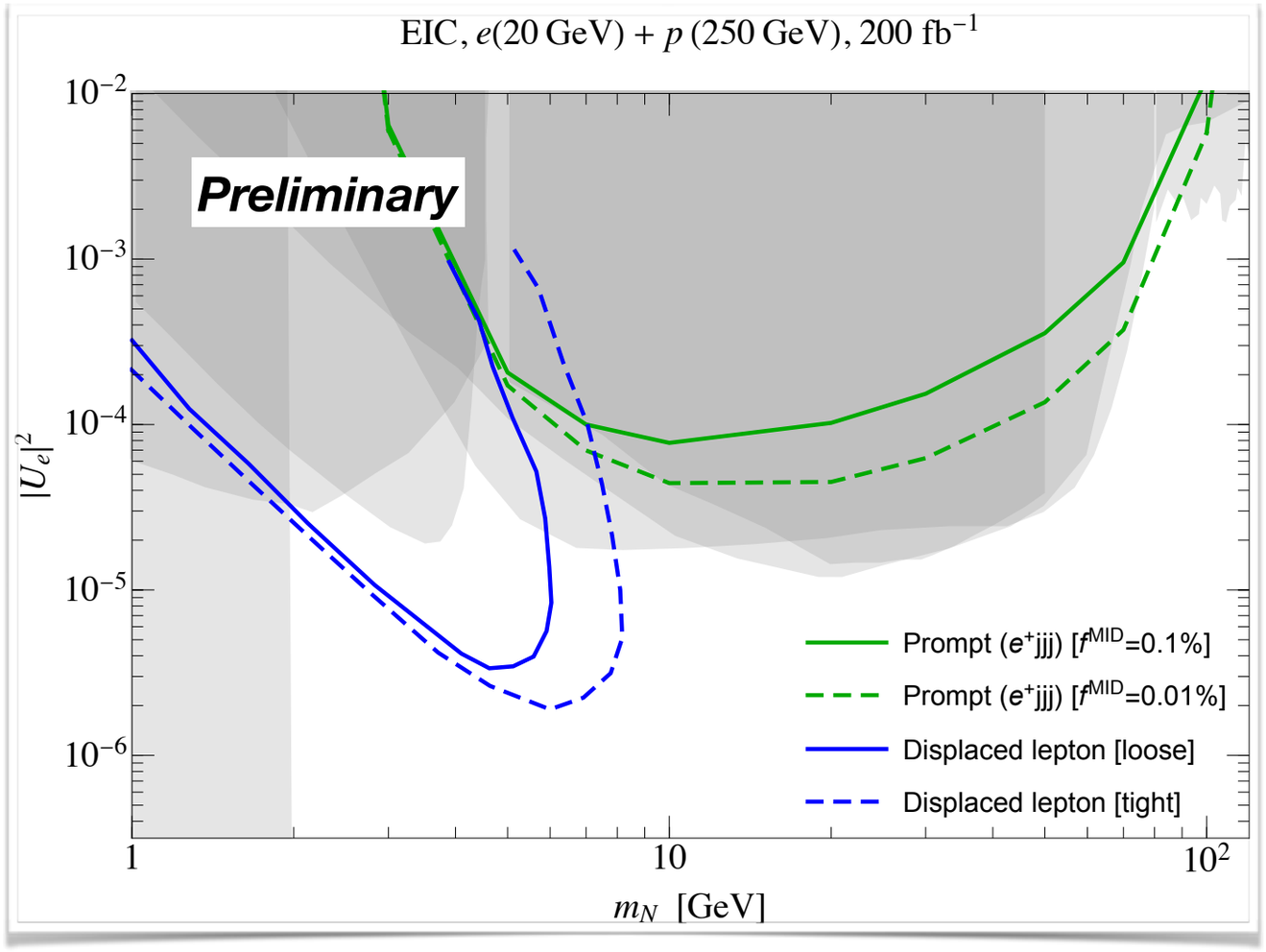
- HNLs are long lived for smaller masses/mixing angle strengths
- Focus here on signature of displaced lepton with large transverse impact parameter
- Event selection — loose (tight) cuts:
  - HNL decay within cylinder of length 2m, radius 40cm
  - At least one lepton with:
    - p_T > 1 GeV (5 GeV)
    - Transverse impact parameter > 2mm (2cm)
  - Jet at primary vertex must have p_T > 5 GeV (10 GeV)
- Main SM background expected to arise heavy flavor decays - currently under investigation
- We will show EIC sensitivity to 5 signal events
- Additional handles can come from displaced vertices





EIC Sensitivity

- EIC can explore new parameter space beyond current bounds
- Can improve by up to one order of magnitude in squared mixing angle at low masses ~ 5 GeV
- Potential to extend beyond existing limits at high masses
- Other experiments can probe HNLs in these mass ranges - see e.g., Physics Beyond Colliders report, arXiv:1901.09966



Outlook

- The EIC will open up a new QCD frontier. It is also interesting to ask if BSM physics can be explored at the EIC .

- We have found the EIC has the potential to search for HNLs, particularly in the few GeV mass range

- Studies of this kind can inform EIC detector design (e.g., tracking system for displaced particle searches).

- It would be worth exploring other BSM physics cases:
  - new light particles in 1-100 GeV range
  - SMEFT interactions [Boughezal, Petriello, Wiegand, 2004.00748]
  - lepton flavor violation [Gonderinger, Ramsey-Musolf, 1006.5063]
  - precision EW physics [Kumar et al., 1302.6263]

- It is very early days for the EIC. There is much room for exploration!