Heavy Neutral Leptons at the Electron-Ion Collider

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with B. Batell, T. Ghosh, T. Han, to appear

Introduction and Motivation

- The Electron-Ion Collider (EIC) is approved by the U.S. DOE with an estimated cost of $1.6 to $2.6 billion, to be located at Brookhaven National Laboratory (BNL).
- The EIC features [1212.1701]
  - Highly polarized (70%) electron and nucleon beams
  - Ions: proton, deuteron to uranium or lead
  - C.o.M energies: 20–100 GeV, upgradable to 140 GeV
  - high luminosity: 10^{33-34} cm^{-2}s^{-1} (10-1000 times HERA)
- The EIC goals: (designed as a QCD machine)
  - The proton spin
  - The motion of quarks and gluons in the proton
  - the tomographic images of the proton
  - QCD matter at the extreme gluon density
  - Quark hadronization
- Other physics opportunities: EW and BSM.
  We take the Heavy Neutral Leptons as a case study.

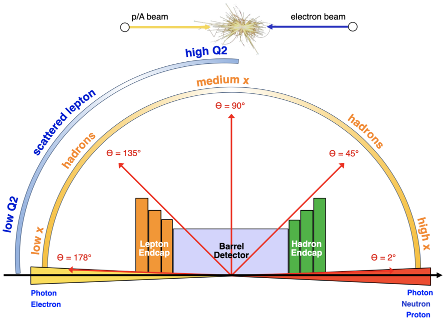
The Electron-Ion Collider (EIC)

- We want to maximize the machine reachability

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

- We assume the integrated luminosity to be $\mathscr{L} = 200\ \mathrm{fb}^{-1}$.
- 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)	
$2.5 < \lvert\eta\rvert \le 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \lvert\eta\rvert \le 2.5$	$0.05\% \times p \oplus 1\%$
$\lvert\eta\rvert \le 1.0$	$0.05\% \times p \oplus 0.5\%$
Electromagnetic calorimeter (σ_E/E)	
$-4.5 \le \eta < -2.0$	$2\%/\sqrt{E}$
$-2.0 \le \eta < -1.0$	$7\%/\sqrt{E}$
$-1.0 \le \eta \le 4.5$	$12\%/\sqrt{E}$
Hadronic calorimeter (σ_E/E)	
$1.0 < \lvert\eta\rvert \le 3.5$	$50\%/\sqrt{E}$
$\lvert\eta\rvert \le 1.0$	$100\%/\sqrt{E}$

The Heavy Neutral Leptons (HNLs) at the EIC

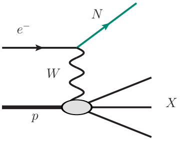
- The HNLs are motivated by the potential connection to the neutrino mass generation, through the Type-I Seesaw Mechanism [Minkowski PLB '77, Gell-Mann et. al. '79, etc.]
- The Lagrangian

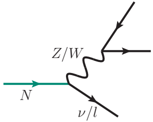
$$\mathscr{L} \supset y_\nu^{iI} L_i H N_I + \text{ h.c.}$$

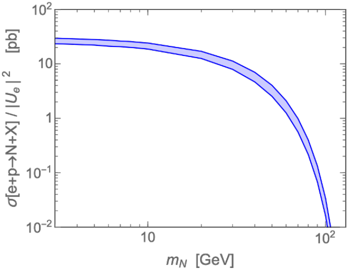
The interactions can be written as

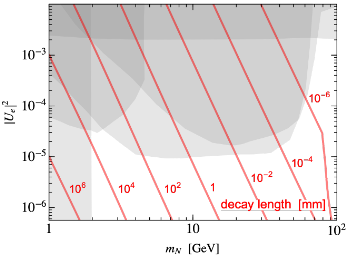
$$\mathscr{L} \supset \frac{g}{\sqrt{2}} U_{iI} W_\mu^- l_i^\dagger \bar{\sigma}^\mu N_I + \frac{g}{2c_W} U_{iI} Z_\mu \bar{\nu}_i^\dagger \bar{\sigma}^\mu N_I + \text{ h.c.}$$

- The HNL production and decays (lifetime)



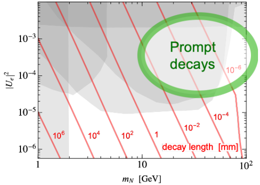


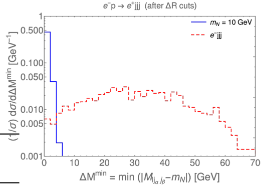




The Prompt HNL Searches

- The HNLs decay promptly for larger masses and mixing angle
- The strongest signal comes the lepton number violating e^+jjj: $e^-p \to (N \to e^+jj)j$.
- The hadronic mode gives largest rate, and allows for full final state reconstruction.
- the main SM background comes from charge mis-identification: e^- fakes as e^+.
- the e^+jj invariant mass window cut very efficiently

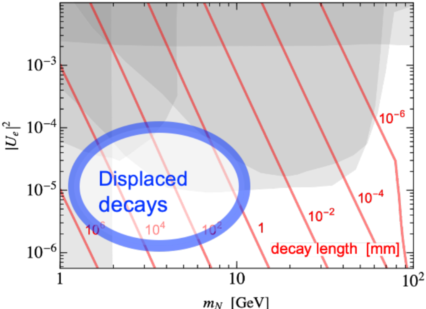


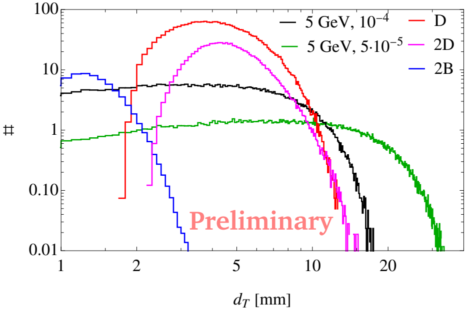


Cut selection	Signal $m_N = 10$ GeV [pb]	Signal $m_N = 50$ GeV [pb]	e^-jjj [pb]
Production	5.53	0.95	449
Exactly 1ℓ: $p_{T_\ell} > 2$ GeV, $0 < \eta_\ell < 3.5$	2.43	0.74	36.7
Exactly $3j$: $p_{T_{j_1}} > 20$ GeV, $p_{T_{j_{2,3}}} > 5$ GeV, $\lvert\eta_{j_{1,2,3}}\rvert < 3.5$	0.84	0.43	1.30
Isolation: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

The Displaced HNL Searches

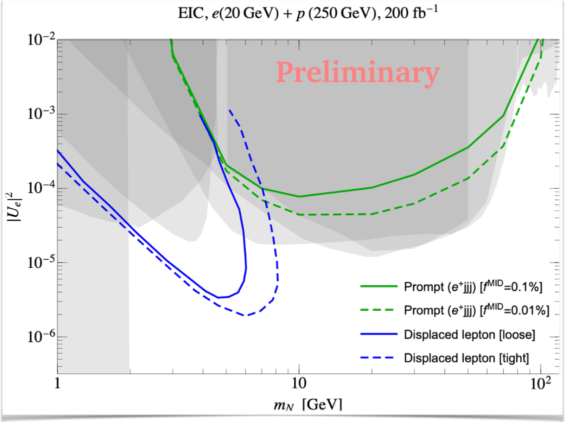
- At a small mass/mixing angle, the HNLs are long lived
- The signature of displaced lepton with large transverse impact parameter.
- Event selection: loose (tight) cuts
  - HNL decays with cylinder of length 2 m and radius 40 cm
  - At least one lepton with $p_T > 1(5)$ GeV
  - Transverse impact parameter $d_T > 2$ (20) mm
  - Jet at primary vertex must have $p_T > 5(10)$ GeV.
- The SM background arises from the heavy-flavor decay.
  - At large impact parameter $d_T = 20$ mm, no SM background.
  - At small impact parameter $d_T = 2$ mm, we can perform the isolation cut $\Delta R > 0.4$ to exclude largely the SM background.





The EIC sensitivity

- We show the EIC sensitivity to 5 displaced events
- the EIC can explore new parameter beyond the current bounds
- At low mass around 5 GeV, we can improve the current bound by up to one order of magnitude in $|U_e|^2$
- Potential to extend beyond the existing limits at high masses
- Other experimental limits can also probe HNLs in these masses ranges. see Physics Beyond Colliders report [1901.09966]

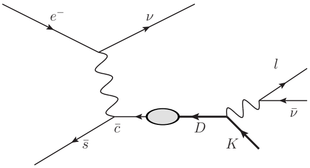


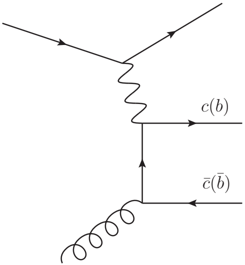
Conclusions and Outlooks

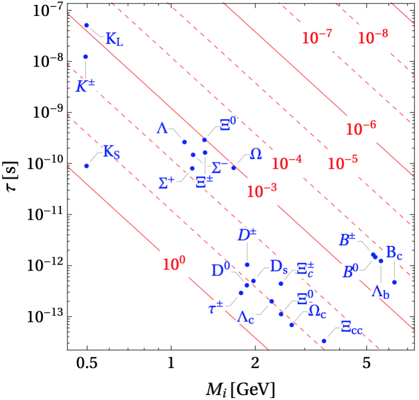
- The EIC will open up a new QCD frontier. It is also interesting to ask the opportunity to search the BSM physics.
- We find the EIC has the potential to search HNLs, especially in the few GeV mass range, through the displaced vertex.
- Such studies can inform the EIC detector design, (e.g. tracking system for displaced particle searches)
- Other BSM physics exploration:
  - new light particle in 1–100 GeV mass range
  - SMEFT interactions [Boughezal, Petriello, Wiegand, 2004.00748]
  - lepton flavor voilation [Gonderinger, Ramsey-Musolf, 1006.5063]
  - precision EW physics [Kumar et al. 1302.6263]
- It is very early days for the EIC. There is much more room for exploration.

The SM background for the displaced search

SM background, $D(B) \to lX$, can be suppressed with isolation cut.







cuts	c	$c\bar{c}$	$b\bar{b}$
no cut	0.427		
$p_{T,l} > 2$ GeV, $\lvert\eta_l\rvert < 3.5$, $\Delta R_{ll} > 0.3$	0.135	13.0	0.151
$p_{T,j} > 5$ GeV, $\lvert\eta_j\rvert < 3.5$, $\Delta R_{jj} > 0.4$	0.0529	0.0855	5.02e-3
$\Delta R_{jl} > 0.4$	–	–	1.73e-3