Heavy Neutral Leptons at the Electron Ion Collider

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Snowmass whitepaper 2203.06705, and work to appear soon

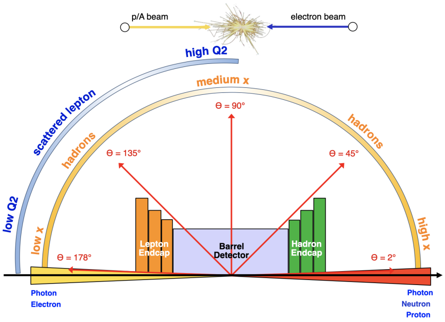
Introduction and Motivation

- 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.
- The EIC features [1212.1701 and Yellow Report, 2103.05419].
  - 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 [Snowmass whitepaper, 2203.13199].
  We take the Heavy Neutral Leptons as a case study.

The Electron-Ion Collider (EIC)

- We want to maximize the machine reachability
$$e(10/18 \text{ GeV}) + p(100/275 \text{ GeV}).$$
- We assume the integrated luminosity to be $\mathscr{L} = 100 \text{ fb}^{-1}$.
- 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)	
$2.5 < \|\eta\| \leq 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \|\eta\| \leq 2.5$	$0.05\% \times p \oplus 1\%$
$\|\eta\| \leq 1.0$	$0.05\% \times p \oplus 0.5\%$
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)	
$1.0 < \|\eta\| \leq 3.5$	$50\%/\sqrt{E}$
$\|\eta\| \leq 1.0$	$100\%/\sqrt{E}$

The Heavy Neutral Leptons (HNLs) at the EIC

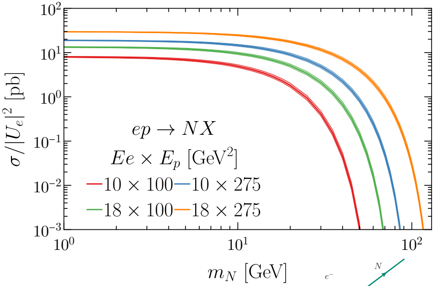
- The HNLs are motivated by the potential connection to the neutrino mass generation, through the Type-I Seesaw Mechanism [Minkowski PLB '77, Gell-Mann et. al. '79, etc.]
- The Lagrangian

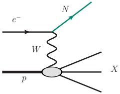
$$\mathscr{L} \supset y_\nu^{iI} L_i H N_I + \text{h.c.}$$

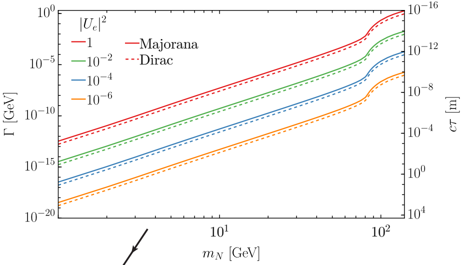
The interactions can be written as

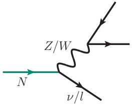
$$\mathscr{L} \supset \frac{g}{\sqrt{2}} U_{iI}\, W_\mu^- \,\ell_i^\dagger \overline{\sigma}^\mu N_I + \frac{g}{2\, c_W} U_{iI}\, Z_\mu\, \nu_i^\dagger \overline{\sigma}^\mu N_I + \text{h.c.}$$

- The HNL production and decays (lifetime)



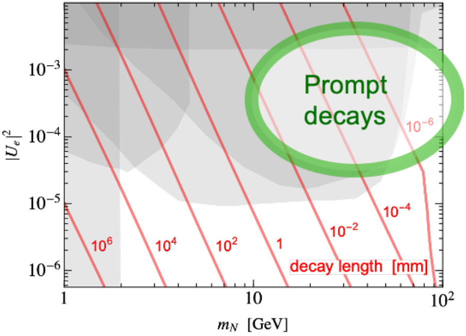


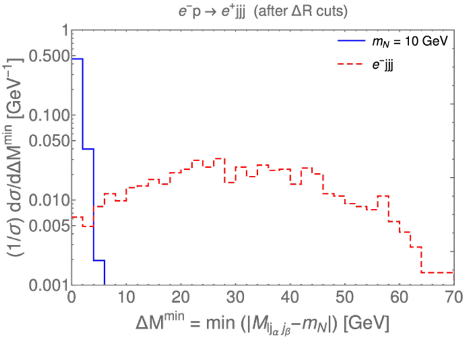




The Prompt HNL Searches

- The HNLs decay promptly for larger masses and mixing angle
- Three channels are considered
  - Majorana: $e^+ 3j$
  - Majorana: $e^+ \mu^- j + \not{E}_T$
  - Dirac: $\ell^+ \ell^- j + \not{E}_T$





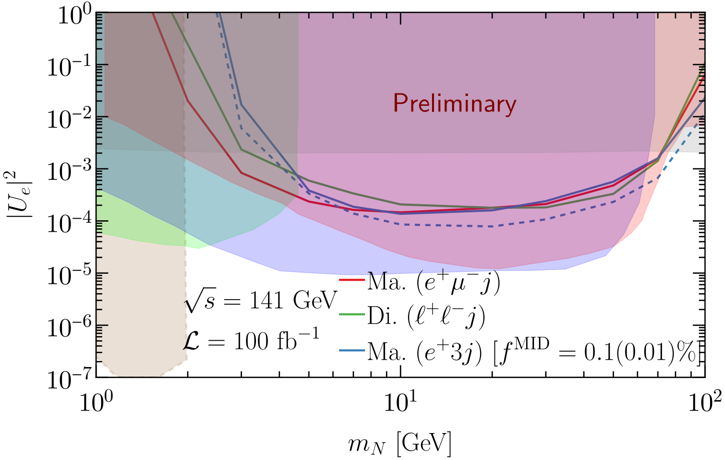
Majorana signature: e^+3j

- The strongest signal comes the lepton number violating e^+3j: $e^-p \to (N \to e^+jj)j$.
- 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 $\left(\lvert M(\ell j_\alpha j_\beta) - m_N\rvert\right) < 5$ 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}

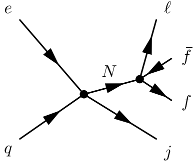
Other channels [2203.06705]

- Majorana signature: $\mu^- e^+ j + \not{E}_T$, BK: $\gamma p \to (\tau^- \to \mu^- j \nu)(\tau^+ \to e^+ j \nu) j$
- Dirac search: $\ell^+ \ell^- j + \not{E}_T$

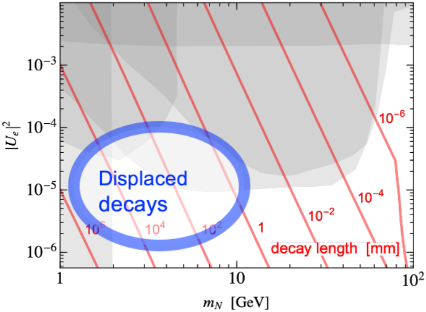


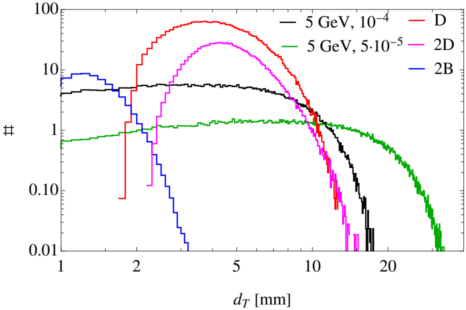
With the designed energy and integrated luminosity, EIC can probe HNL prompt decay in the mass range 1–100 GeV and the mixing able of the order 10^{-3}.

Long-Lived signature



- At a small mass/mixing angle, the HNLs are long lived
- The signature of displaced lepton with large transverse impact parameter.
- The SM background arises from the heavy-flavor decay $ep \to \nu(c \to D)$ and $eg \to e(c/b \to D/B)(\bar{c}/\bar{b} \to \bar{D}/\bar{B})$.
  - At large impact parameter $d_T = 20$ mm, no SM background.
  - At small impact parameter $d_T = 2$ mm, we can perform cuts, such as $\Delta R_{j\ell} > 0.4$, to largely suppress the SM backgrounds [see backup slides].



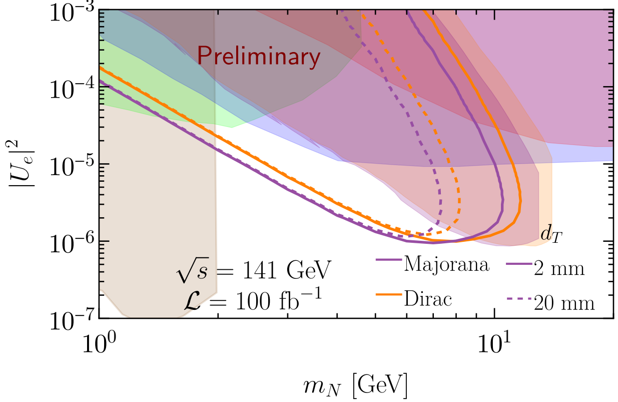


Displaced vertex searches

- Event selection

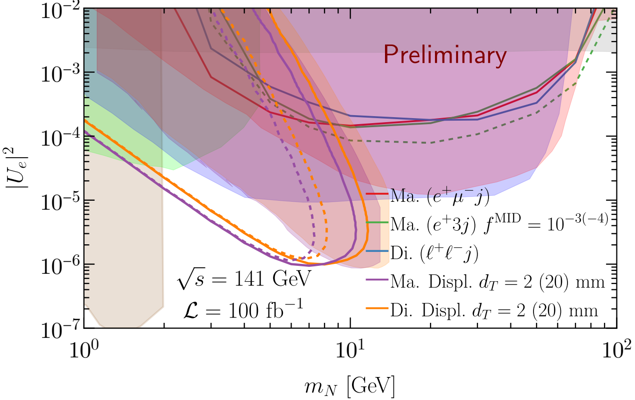
$$p_T^j > 5 \text{ GeV}, \; p_T^\ell > 1 \text{ GeV}, \; |\eta_{j,\ell}| < 3.5.$$

- Transverse impact factor $d_T = 2(20)$ mm
- Cylinder detector configuration $r = 0.4$ m, $d = 4$ m.
- We show the EIC sensitivity to 5 displaced events



The EIC sensitivity [2203.06705]

- the EIC can explore new parameter beyond the current bounds
- At low mass around 5 GeV, we can improve the current bound down to a lower mass
- Other experimental limits [1901.09966,2203.08039].



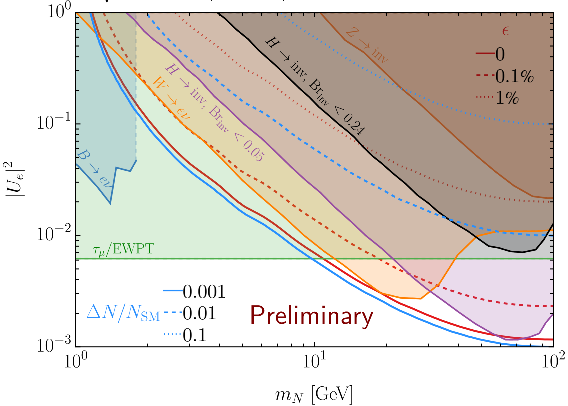
Invisible decay: $N \to$ DMs

- Signal: $ep \to j + \not{E}_T$
- The mono-jet event

$$\sigma(p+e\to j+\not{E}_T) = \sigma(p+e\to j+\nu_e) + \sigma(p+e\to j+N)$$
$$= \sigma_{\rm SM}(p+e\to j+\nu_e)\left[(1-|U_e|^2)+|U_e|^2\Phi(m_N)\right],$$

- Sensitivity

$$\mathscr{S} = \frac{\Delta N}{\sqrt{N_{\rm SM}+(\varepsilon N_{\rm SM})^2}} = 2,\ \Delta N = |N - N_{\rm SM}|.$$



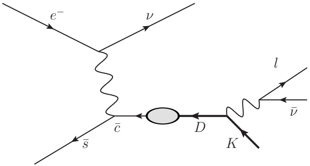
[Existing bounds: 1709.07001]

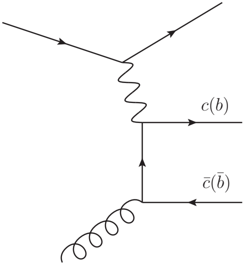
Conclusions and Outlooks

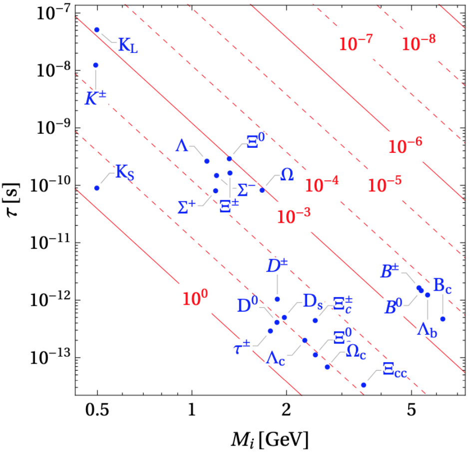
- The EIC will open up a new QCD frontier. It is also interesting to ask the opportunity to search the BSM physics.
- We find the EIC has the potential to search HNLs, especially in the few GeV mass range, through the displaced vertex.
- EIC is able to probe HNL prompt decay in the mass range 1–100 GeV and mixing angle of the order 10^{-3}.
- Such studies can inform the EIC detector design, (e.g. tracking system for displaced particle searches)
- Other BSM physics exploration [Snowmass whitepaper, 2203.13199]
    - 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 backgrounds for the displaced searches

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







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