Heavy neutral leptons and beyond at the electron-ion collider

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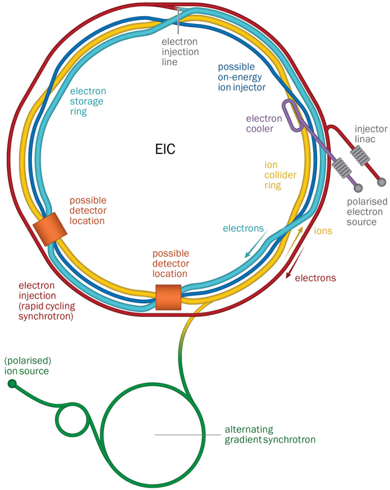
In collaboration with B. Batell, T. Han (U. Pitt) and T. Ghosh (HRI, India)
JHEP 03 (2023) 020, 2210.09287
EIC Snowmass Whitepapers: 2203.06705, 2203.13199

The Electron-Ion Collider



[1212.1701, 2103.05419]

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 Lepton as a case study [2210.09287].

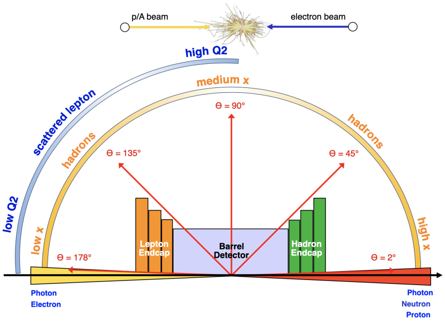
Collider configuration

- We want to maximize the machine reachability

$$e(10/18 \text{ GeV}) + p(100/275 \text{ GeV}).$$

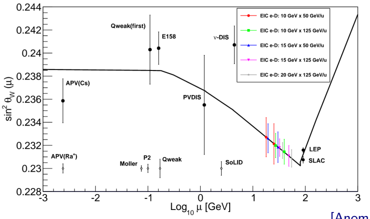
- We assume the integrated luminosity to be $\mathscr{L} = 100 \text{ fb}^{-1}$.
- Primary physics goals require a multi-purpose Hermitic detector with excellent tracking resolution and particle ID capabilities over a broad momentum range.
- Detector still under design; see EIC Detector Requirements R&D Handbook

[EIC CDR 2021]

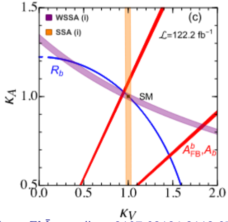


η	Resolution
Tracking (σ_p/p)	
$2.5 < \lvert\eta\rvert \leq 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \lvert\eta\rvert \leq 2.5$	$0.05\% \times p \oplus 1\%$
$\lvert\eta\rvert \leq 1.0$	$0.05\% \times p \oplus 0.5\%$
Electromagnetic calorimeter (σ_E/E)	
$-4.5 \leq \eta < -2.0$	$2\%/\sqrt{E}$
$-2.0 \leq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

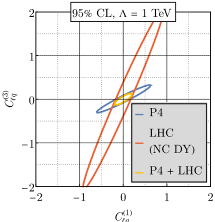
Precision and new physics studies at the EIC [2203.13199]



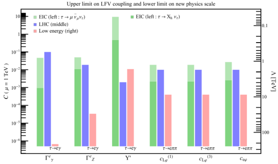
[Weak mixing angle: 1612.06927]



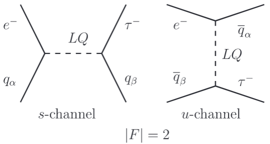
[Anomalous $Zb\bar{b}$ coupling: 2107.02134,2112.07747]



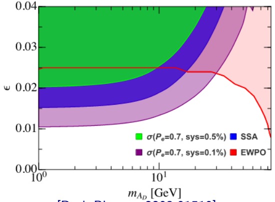
[SMEFT: 2107.02134,2204.07557]



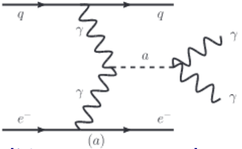
[CLFV: 2102.06176]



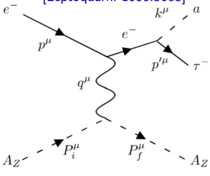
[Leptoquark: 1006.5063]



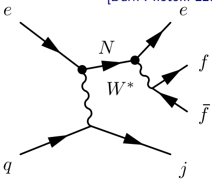
[Dark Photon: 2203.01510]



[Axion: 2112.02477,2310.08827]



[LFV ALP: 2112.04513]



[HNL: 2210.09287]

The Heavy Neutral Leptons (HNLs) at the EIC

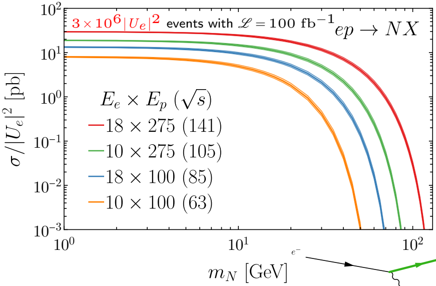
- The HNLs are motivated by the potential connection to the neutrino mass generation, through the Type-I Seesaw Mechanism [Minkowski PLB '77, Gell-Mann et. al. '79, etc.]
- The Lagrangian

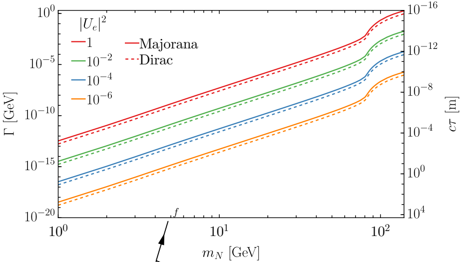
$$\mathscr{L} \supset y_\nu^{iI} L_i H N_I + \text{h.c.}$$

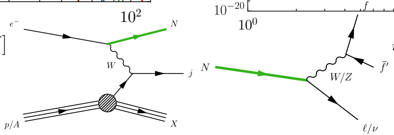
The interactions can be written as

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

- The HNL production and decays (lifetime)

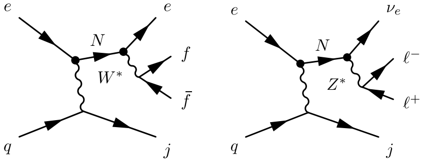


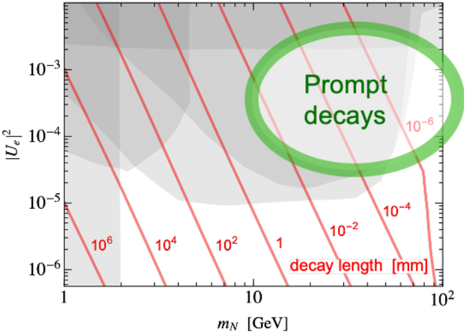


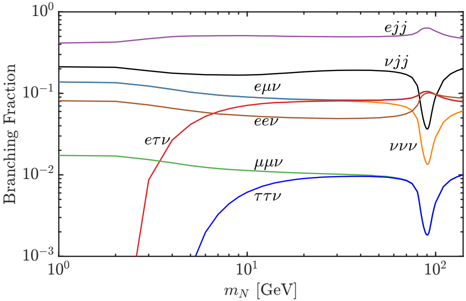


The Prompt HNL Searches

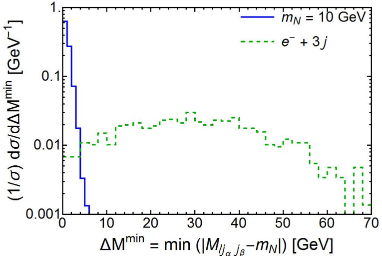
- The HNLs decay promptly for larger masses and mixing angle
- Three channels are considered
  - Majorana: $e^+ 3j$
  - Majorana: $e^+ \mu^- j + \not{E}_T$
  - Dirac: $\ell^+ \ell^- j + \not{E}_T$

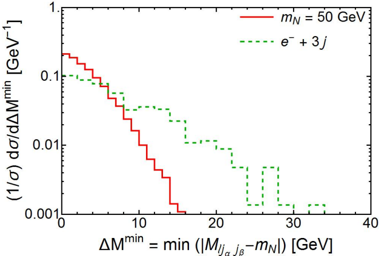






Majorana signature: e^+3j (lepton number violating)

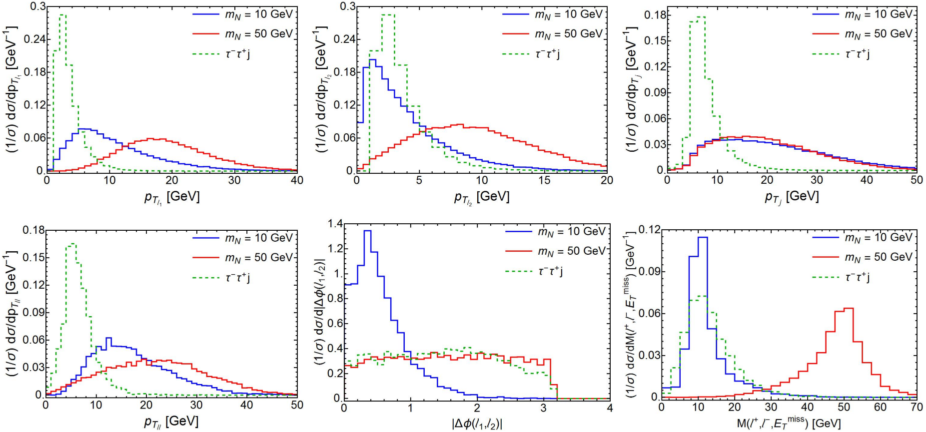




- The hadronic mode gives largest rate, and allows for full final state reconstruction.
- the main SM background comes from charge mis-identification: e^- fakes as e^+.
- the e^+jj invariant mass window cut very efficiently [2210.09287]

Cut selection	Signal $[e^-p \to (N \to e^+jj)j]$ [pb] $m_N = 10$ GeV	Signal $[e^-p \to (N \to e^+jj)j]$ [pb] $m_N = 50$ GeV	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, $\lvert\eta_{j_{1,2,3}}\rvert < 3.5$	0.81	0.43	1.35
Isolation: $\Delta R(\ell/j_\alpha, j_\beta) > 0.4$ $(\alpha, \beta = 1,2,3)$	0.22	0.39	1.35
$\Delta M^{\rm min} = \min\left(\lvert M(\ell j_\alpha j_\beta) - m_N\rvert\right) < 5$ GeV	0.22 $\times$	$\times$ 0.30	0.03 0.64
Require one e^+ $[f^{\rm MID} = 0.1\%]$	0.22 $\times$	$\times$ 0.30	3.23×10^{-5} 6.40×10^{-4}
Require one e^+ $[f^{\rm MID} = 0.01\%]$	0.22 $\times$	$\times$ 0.30	3.23×10^{-6} 6.40×10^{-5}
Polarization $P_e = -70\%$	$\times 1.7$	$\times 1.7$	$\times 1$

Majorana signature: $e^+\mu^- j + E_T^{\mathrm{miss}}$



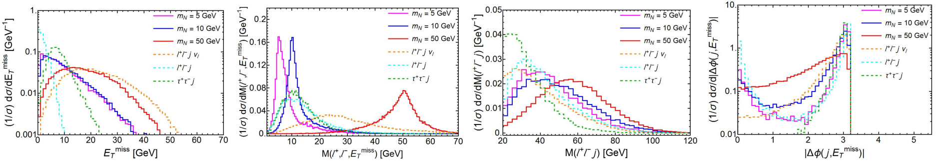
- Main background comes from $(\tau^+ \to e^+ 2\nu)(\tau^- \to \mu^- 2\nu)j$
- Isolation and invariant mass cuts reduce backgrounds.

Majorana signature: $e^+\mu^- j + E_T^{\text{miss}}$

Cut selection	Signal $[e^- p \to (N \to \ell^-\ell^+\nu)j]$		$\tau^-\tau^+ j \to$
	$m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	$\ell^-\ell^+ j + 4\nu$ [pb]
Production	3.16	0.55	0.05
Exactly 2ℓ: $p_{T_{\ell_{1,2}}} > 2$ GeV, $\lvert\eta_{\ell_{1,2}}\rvert < 3.5$	2.10	0.53	0.01
Exactly $1j$: $p_{T_j} > 10$ GeV, $\lvert\eta_j\rvert < 3.5$	1.82	0.44	3.19×10^{-3}
Isolation: $\Delta R(\ell_1, \ell_2) > 0.3$, $\Delta R(\ell_{1,2}, j) > 0.4$	1.61	0.43	3.13×10^{-3}
Require one μ^- and one e^+	0.51	0.13	7.83×10^{-4}
$p_{T_{\ell\ell}} > 12$ GeV	0.37	0.10	3.90×10^{-5}
$\lvert\Delta\phi(\ell_1, \ell_2)\rvert < 1$ $[m_N < 20$ GeV$]$	0.35	$\times$	1.72×10^{-5}
$\lvert M(\ell^+, \ell^-, E_T^{\text{miss}}) - m_N\rvert < 10$ GeV $[m_N \geq 20$ GeV$]$	$\times$	0.08	2.07×10^{-7}
Polarization $P_e = -70\%$	$\times 1.7$	$\times 1.7$	$\times 1$

- Main background comes from $(\tau^+ \to e^+ 2\nu)(\tau^- \to \mu^- 2\nu)j$
- Isolation and invariant mass cuts reduce backgrounds.

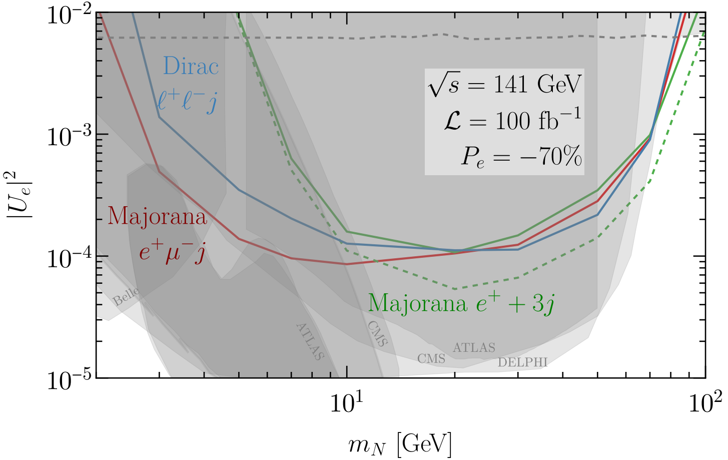
Dirac signature: $\ell^+\ell^- j + E_T^{\rm miss}$



- Main background comes from $(\tau^+ \to \ell^+ 2\nu)(\tau^- \to \ell^- 2\nu) j$ and $\ell^+\ell^-\nu_\ell j$.
- Isolation and invariant mass cuts reduce backgrounds.

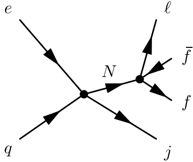
Cut selection	Signal $[e^- p \to (N \to \ell^+\ell^-\nu) j]$ 5 GeV	10 GeV	50 GeV	$\ell^+\ell^-\nu_\ell j$	$\ell^+\ell^- j$	$\tau^-\tau^+ j \to \ell^-\ell^+ j + 4\nu$
Production	3.98	3.38	0.55	2.20×10^{-3}	5.06	0.05
Exactly 2ℓ: $p_{T_{\ell_{1,2}}} > 2$ GeV, $\lvert\eta_{\ell_{1,2}}\rvert < 3.5$	2.05	1.95	0.53	9.68×10^{-4}	2.65	0.01
Exactly $1j$: $p_{T_j} > 10$ GeV, $\lvert\eta_j\rvert < 3.5$	1.86	1.71	0.44	7.48×10^{-4}	0.35	3.20×10^{-3}
Isolation: $\Delta R(\ell_1,\ell_2) > 0.3$, $\Delta R(\ell_{1,2}, j) > 0.4$	1.25	1.58	0.43	5.45×10^{-4}	0.33	3.14×10^{-3}
$E_T^{\rm miss} > 5$ GeV	0.80	1.07	0.40	5.32×10^{-4}	0.02	2.46×10^{-3}
$p_{T_{\ell\ell}} > 12$ GeV	0.43	0.64	0.29	1.50×10^{-4}	5.47×10^{-3}	8.90×10^{-5}
$\lvert M(\ell^+,\ell^-,E_T^{\rm miss}) - m_N\rvert < 5$ GeV	0.27	$\times$	$\times$	2.39×10^{-6}	5.97×10^{-4}	1.56×10^{-5}
	$\times$	0.42	$\times$	7.12×10^{-6}	1.37×10^{-3}	3.15×10^{-5}
	$\times$	$\times$	0.17	2.34×10^{-5}	1.42×10^{-4}	4.15×10^{-7}
$M(\ell^+\ell^- j) > 45$ GeV [$m_N < 10$ GeV]	0.18	$\times$	$\times$	1.34×10^{-6}	1.82×10^{-4}	6.43×10^{-6}
$0.2 < \lvert\Delta\phi(j, E_T^{\rm miss})\rvert < 3$ [$m_N \geq 10$ GeV]	$\times$	0.24	$\times$	5.00×10^{-6}	–	9.75×10^{-6}
	$\times$	$\times$	0.16	2.06×10^{-5}	–	2.07×10^{-7}
Polarization $P_e = -70\%$	$\times1.7$	$\times1.7$	$\times1.7$	$\times1.6$	$\times1$	$\times1$

Prompt search sensitivity

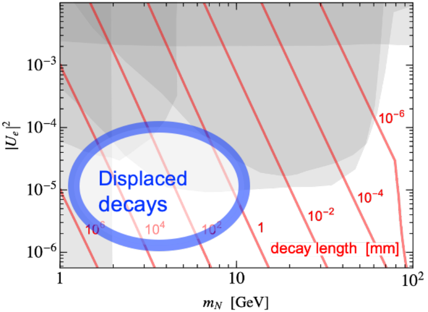


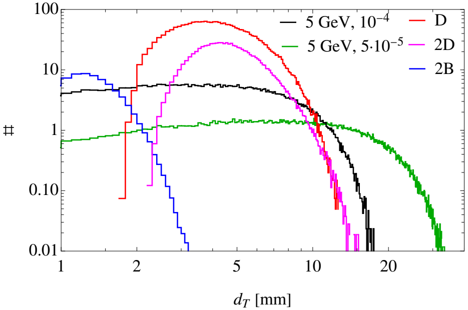
- With the designed energy and integrated luminosity, EIC can probe HNL prompt decay in the mass range 1–100 GeV and the mixing able of the order $10^{-4} - 10^{-3}$.
- We can win a slightly better sensitivity than the existing CMS $3\ell + E_T^{\text{miss}}$ limit [1802.02965] around $70 < m_N < 90$ GeV with an optimistic MID rate of 0.01%.

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].



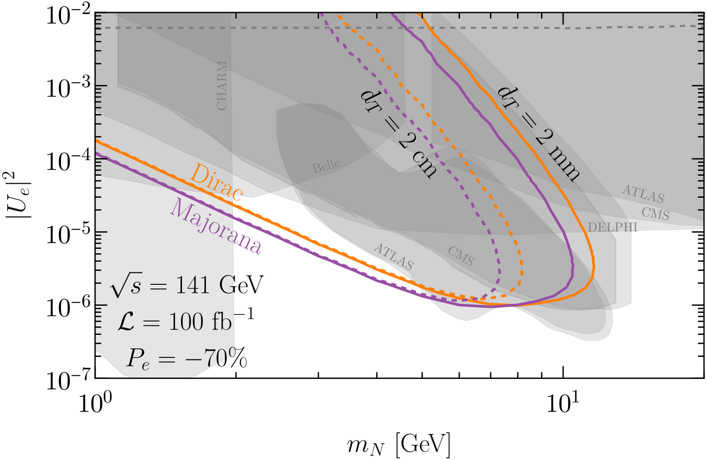


Displaced vertex searches

- Event selection

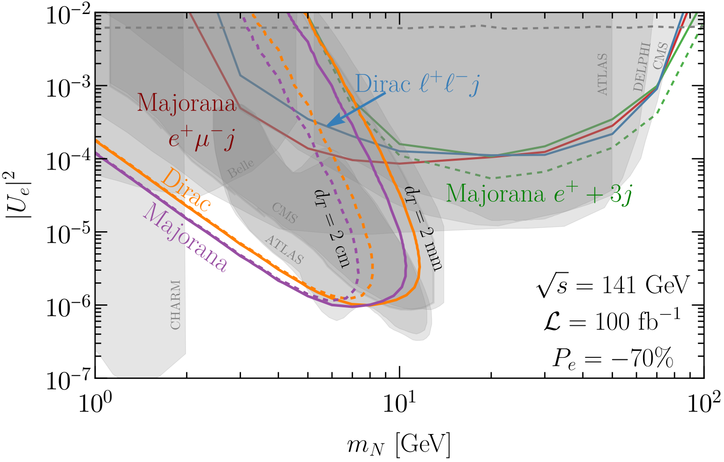
$$p_T^j > 5 \text{ GeV},\ p_T^\ell > 2 \text{ GeV},\ |\eta_{j,\ell}| < 3.5.$$

- Transverse impact factor $d_T = 2(20)$ mm
- Cylinder detector configuration $r = 0.4$ m, $l = 1.2$ m.
- We show the EIC sensitivity to 5 displaced events



The EIC sensitivity

- 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].



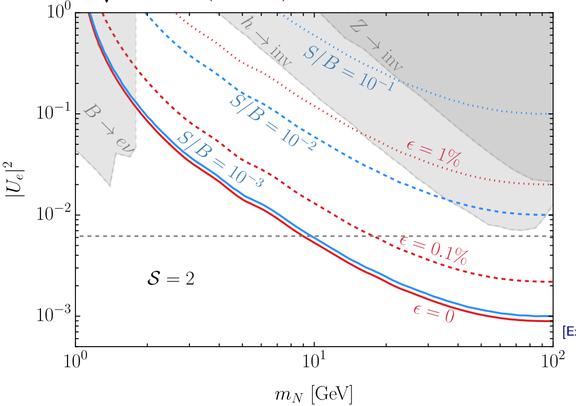
Invisible decay: $N \to$ DMs

- 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

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

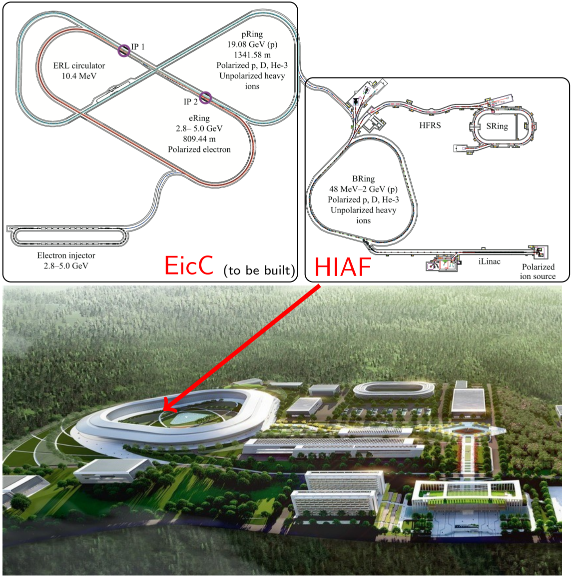


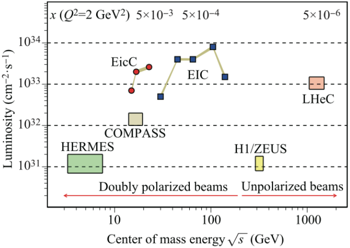
[Existing bounds: 1709.07001]

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 $10^{-4} - 10^{-3}$.
- Such studies can inform the EIC detector design, (e.g. tracking system for displaced particle searches)
- The mono-jet events can probe the invisible decay of the HNL.
- Other BSM physics exploration [Snowmass whitepaper, 2203.13199]
  - new light particle in mass range 1–100 GeV: Axion [2112.02477,2310.08827], leptoquark [1006.5063], dark photon [2203.01510]
  - precision EW physics [Kumar et al. 1612.06927]
  - SMEFT interactions [Boughezal, Petriello, Wiegand, 2004.00748]
  - lepton flavor violation [2102.06176]
- It is very early days for the EIC. There is much more room for exploration.

A Chinese version: EicC $e(5\ \mathbf{GeV})p(20\ \mathbf{GeV})$



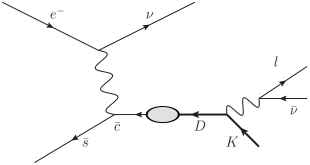


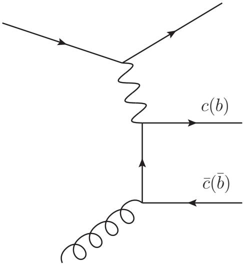
[2102.09222]

High Intensity heavy-ion Accelerator Facility
(Under Construction in Huizhou) [Jinlong Zhang, DIS2022]

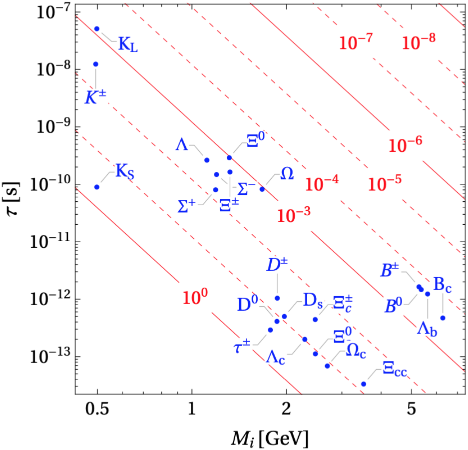
The SM backgrounds for the displaced searches

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





[1903.06100]



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