Heavy Neutral Leptons @ EIC

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Uncovering New Laws of Nature @ EIC

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Neutrinos

the most elusive/least known particles in the SM

- How many species: 3 $\boldsymbol{\nu}_L$ ’s + N_R?
- Absolute mass scale: $m_\nu \sim y_\nu\, v < 1$ eV?

  or a new physics scale: $M_{majorana} >> v$?
- Mass-ordering?

- Flavor oscillations & CP violation?
- Non-standard interactions?
- Mixing with sterile ν’s?
- Portal to dark sector?

→ 6+ Nobel Prizes related to ν’s, more than other discoveries, and more excitement to come!

→ New Laws of Nature!

See BSM talks: M. Nycz; V. Cirigliano; K. Fuyuto; N. Neil; H. Liu; S. Mantry; S. Trifinopoulos …

SM as a low-energy effective field theory:

The leading SM gauge invariant operator is at dim-5:*

$$\frac{1}{\Lambda}(y_\nu L H)(y_\nu L H) + h.c. \quad \Rightarrow \quad \frac{y_\nu^2 v^2}{\Lambda}\,\overline{\nu_L}\;\nu_R^c.$$

*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

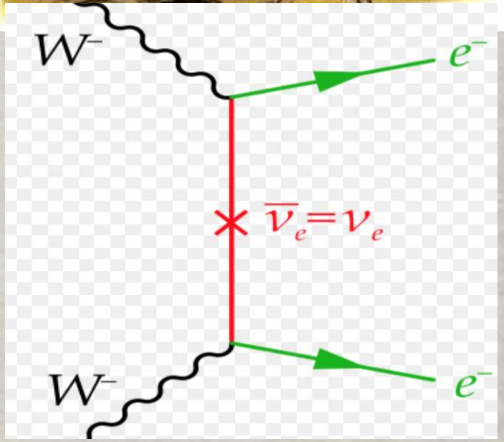
Implications:

- Theoretical: Λ → new scale / particles, implies an underlying (UV) theory!

The See-saw spirit: †

If $m_\nu \sim 1$ eV, then $\Lambda \sim y_\nu^2\,(10^{14}$ GeV).

$$\Lambda \Rightarrow \begin{cases} 10^{14}\ \text{GeV for } y_\nu \sim 1; \\ 100\ \text{GeV for } y_\nu \sim 10^{-6}. \end{cases}$$



- Observational:

ΔL=2 → Majorana mass (Majorana neutrinos)

→ Opens the door to BSM ν physics at low & high energies!

†Yanagita (1979); Gell-Mann, Ramond, Slansky (1979), S.L. Glashow (1980); Mohapatra, Senjanovic (1980) …

UV-complete theoretical Models:

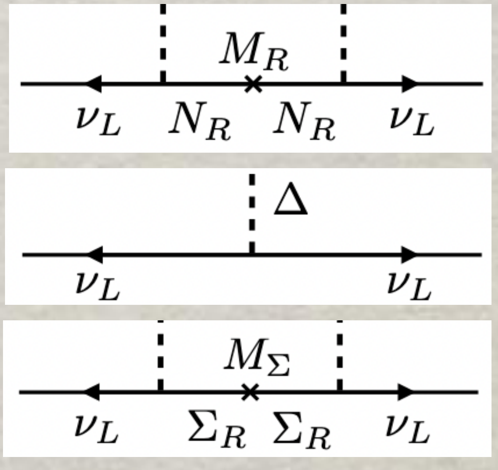
The Weinberg operator non-renormalizable
→ Need Ultra-Violet completion at/above Λ .

Group representations based on SM $SU_L(2)$ doublets:

$$2 \otimes 2 = 1(\text{singlet}) + 3(\text{triplet})$$

→ There are three BSM extensions @ Tree-level:

- Type I: Fermion singlets $\otimes(L\,H)_S$
- Type II: Scalar triplet $\otimes(L\,L)_T$
- Type III: Fermion triplets $\otimes(L\,H)_T$



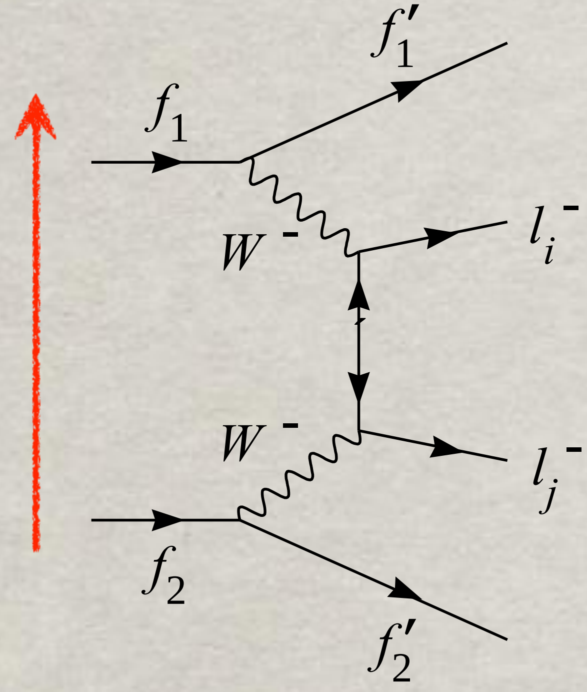
(There are loop-generated radiative models…)

E. Ma: PRL 81, 1771 (1998).
For recent reviews: Z.Z. Xing: arXiv:1406.7739;
Y. Cai, TH, T. Li & R. Ruiz: arXiv:1711.02180.

Observational Aspects:

the most-wanted process: ΔL=2

The fundamental diagram:



$$U_{iN}\ \frac{\not p + m_N}{p^2 - m_N^2 + i\epsilon}\ U_{jN}\ .$$

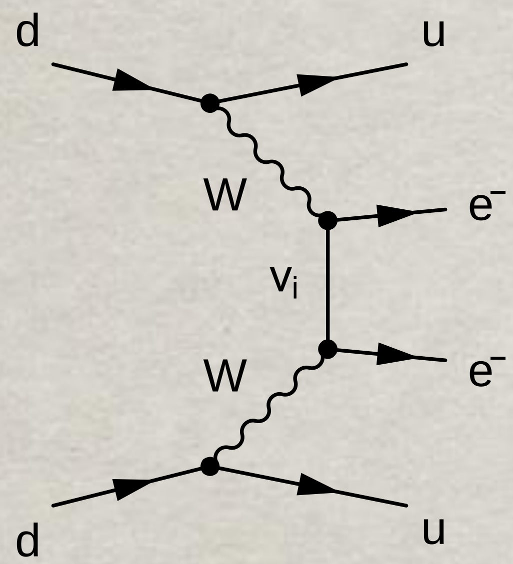
The crossing diagrams lead to rich processes involving N/T^0, W^+_R, H^{++}

The transition rates are proportional to

$$|M|^2 \propto \begin{cases} \langle m \rangle^2_{\ell_1\ell_2} = \left| \sum_{i=1}^{3} U_{\ell_1 i} U_{\ell_2 i} m_i \right|^2 & \text{for light } \nu; \\ \frac{\left| \sum_i^n V_{\ell_1 i} V_{\ell_2 i} \right|^2}{m_N^2} & \text{for heavy } N; \\ \frac{\Gamma(N \to i)\ \Gamma(N \to f)}{m_N \Gamma_N} & \text{for resonant } N \text{ production.} \end{cases}$$

1. Neutrino-less double-beta decay

arXiv:1902.04097, M. Dolinski, A. Poon, W. Rodejohann

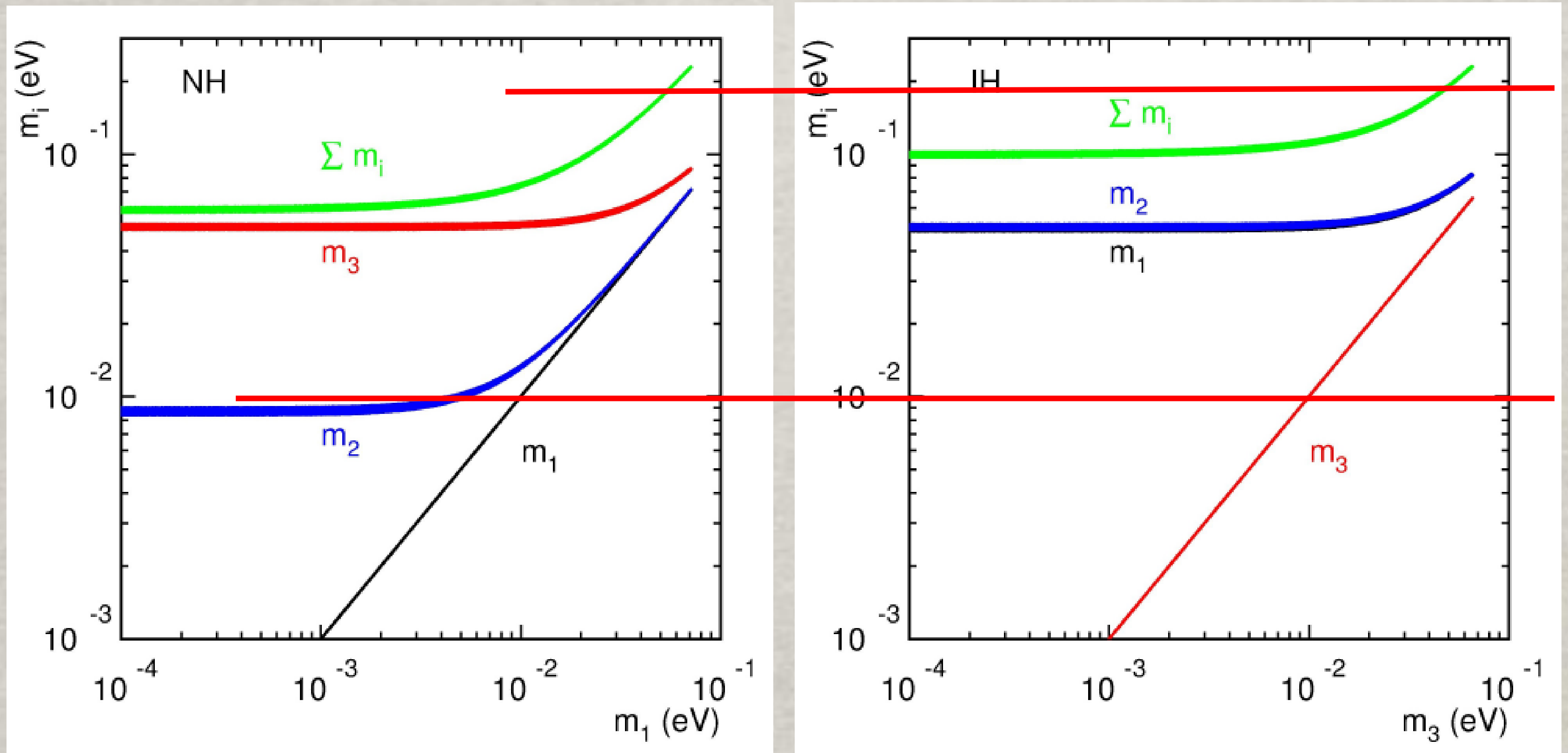


Current bound on light neutrino:
$\langle m_{ee} \rangle \sim 0.2$ eV

Future: $\langle m_{ee} \rangle \sim 0.01$ eV

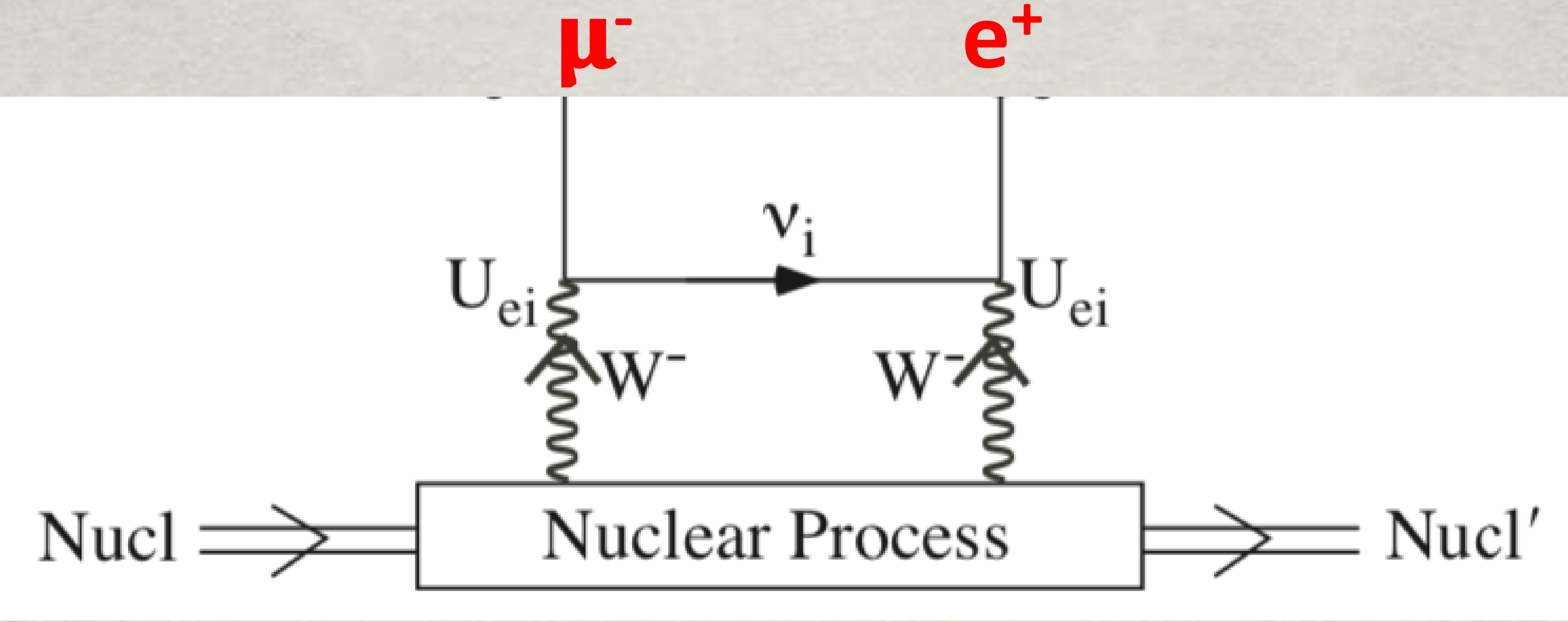
Future expts:

- SNO+
- SuperNEMO
- nEXO
- CUPID
- LEGEND100



(a) (b)

2. μ^- - e^+ conversion



PDG expt bound:

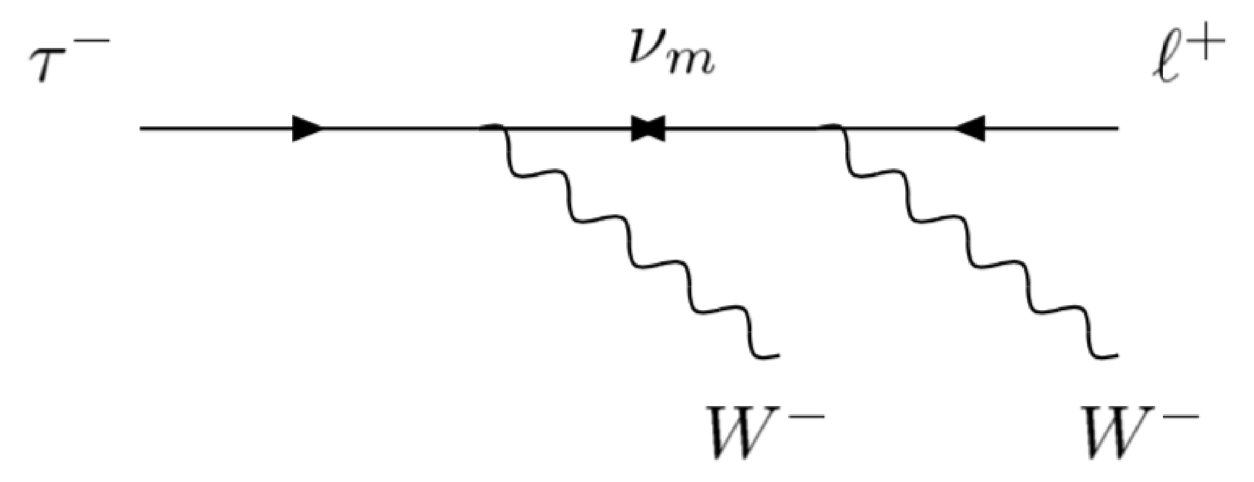
$$B = \frac{\Gamma(Ti + \mu^- \to e^+ + Ca_{gs})}{\Gamma(Ti + \mu^- \to \nu_\mu + Sc)} < 1.7 \times 10^{-12} \sim \left(\frac{\langle m \rangle_{e\mu}}{m_e}\right)^2$$

→ $\langle m \rangle_{e\mu} \leq 17\ (82)\ \mathrm{MeV}$, for nuclear singlet (triplet)

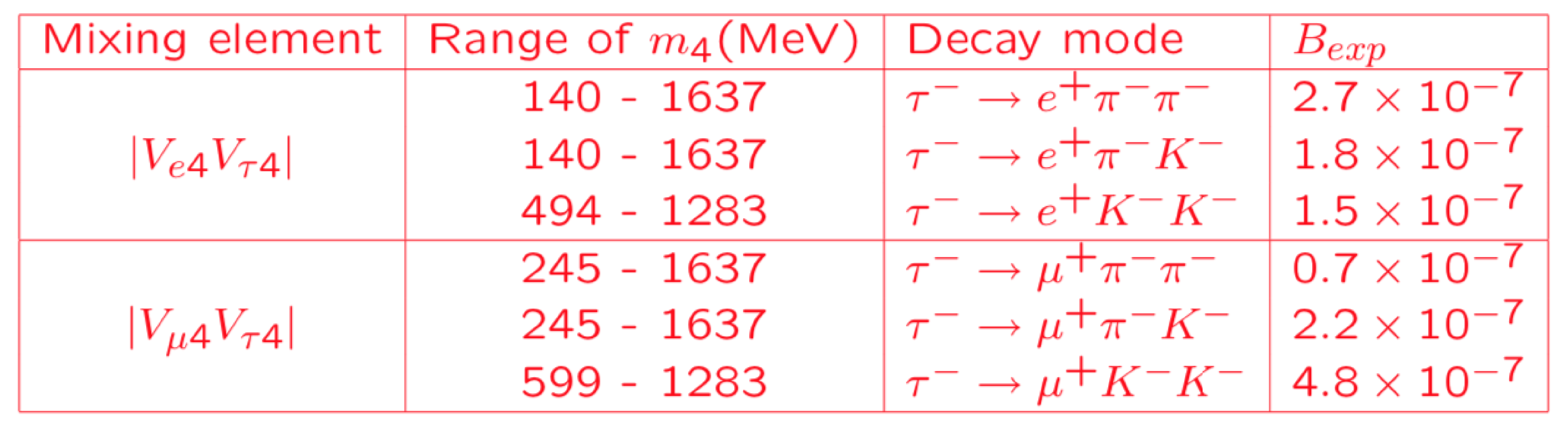
Near future experiments:

Mu2e (FNAL), COMET (J-PARC)

3. $\tau^{\pm}$ lepton decays



On resonance at m_N, only V_{4l}^2 suppressed!



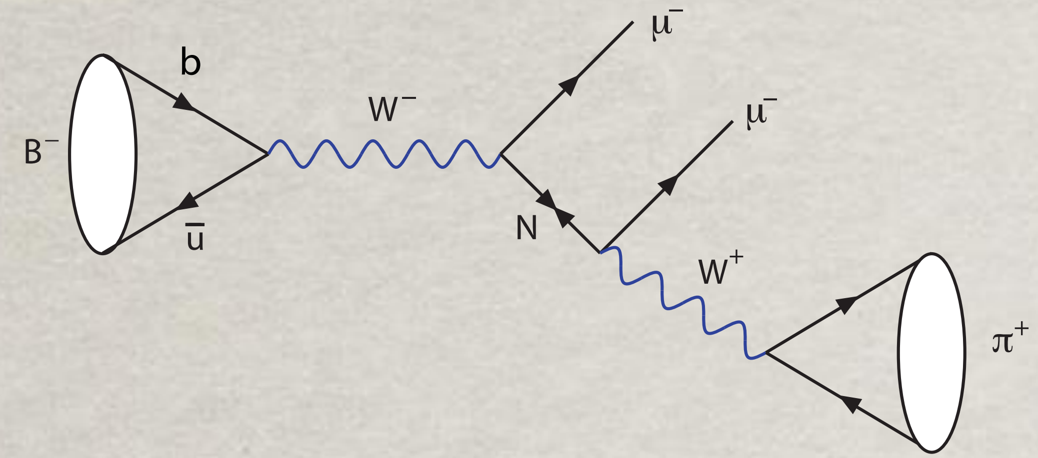
Mixing element	Range of m_4(MeV)	Decay mode	B_{exp}
$\|V_{e4}V_{\tau 4}\|$	140 - 1637	$\tau^- \to e^+\pi^-\pi^-$	2.7×10^{-7}
	140 - 1637	$\tau^- \to e^+\pi^-K^-$	1.8×10^{-7}
	494 - 1283	$\tau^- \to e^+K^-K^-$	1.5×10^{-7}
$\|V_{\mu 4}V_{\tau 4}\|$	245 - 1637	$\tau^- \to \mu^+\pi^-\pi^-$	0.7×10^{-7}
	245 - 1637	$\tau^- \to \mu^+\pi^-K^-$	2.2×10^{-7}
	599 - 1283	$\tau^- \to \mu^+K^-K^-$	4.8×10^{-7}

For non-resonance, weaker bound:

$\langle m \rangle_{e\tau}$ and $\langle m \rangle_{\mu\tau}$ < O(1 TeV)

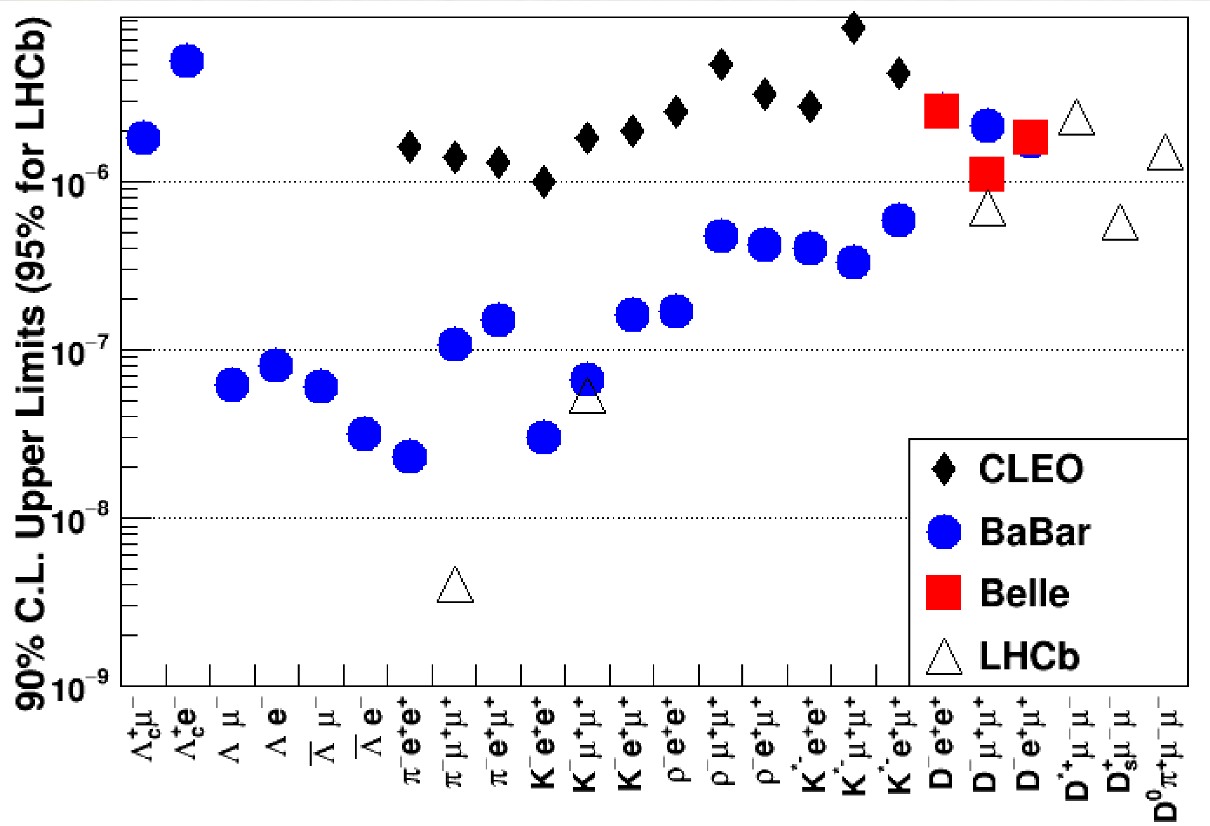
Atre, TH, Pascoli, Zhang, arXiv:0901.3589

4. τ, K, D, B decays via N: $M^+ \rightarrow l^+ l^+ M^-$

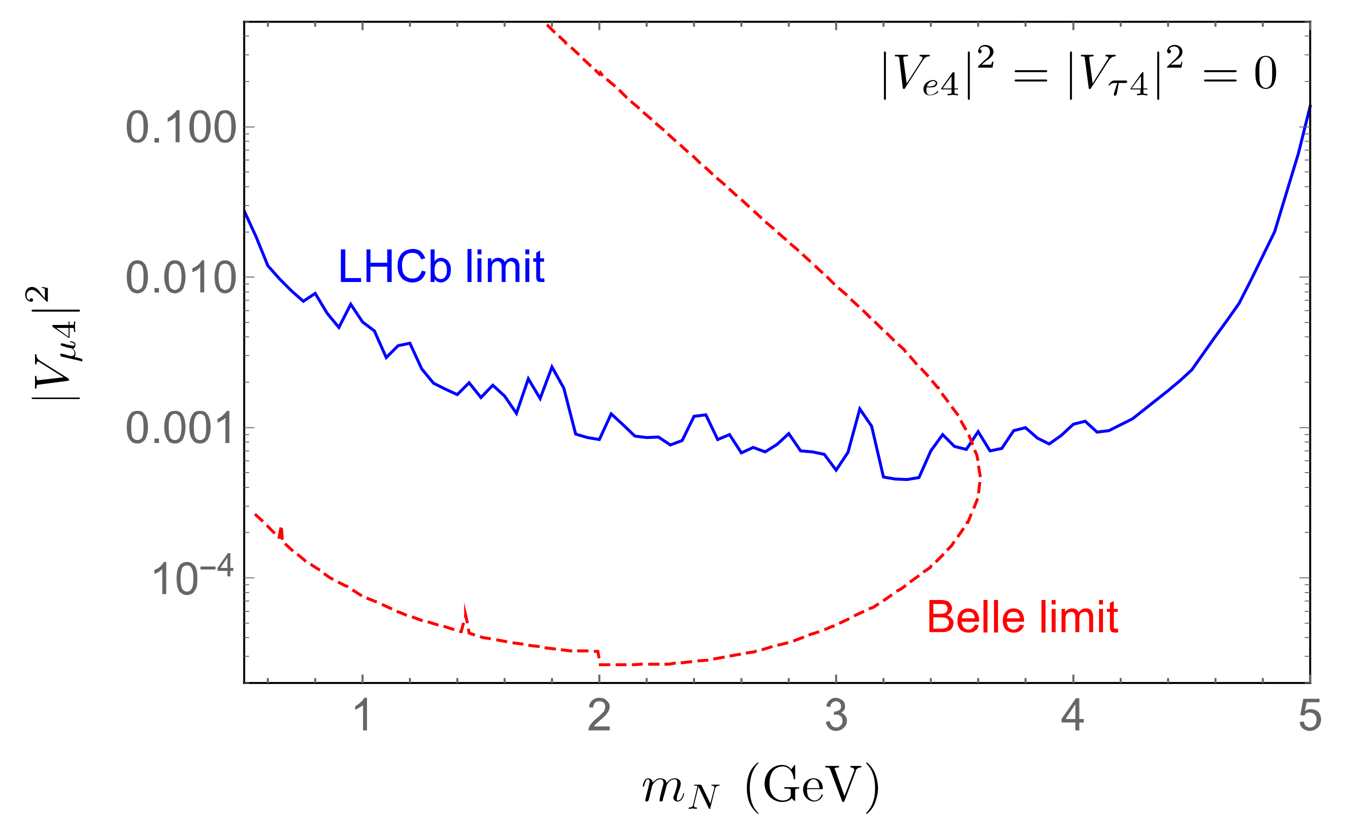


CERN NA62, arXiv:1905.07770

$$\begin{aligned}\mathcal{B}(K^+ \rightarrow \pi^- e^+ e^+) &< 2.2 \times 10^{-10},\\ \mathcal{B}(K^+ \rightarrow \pi^- \mu^+ \mu^+) &< 4.2 \times 10^{-11}.\end{aligned}$$



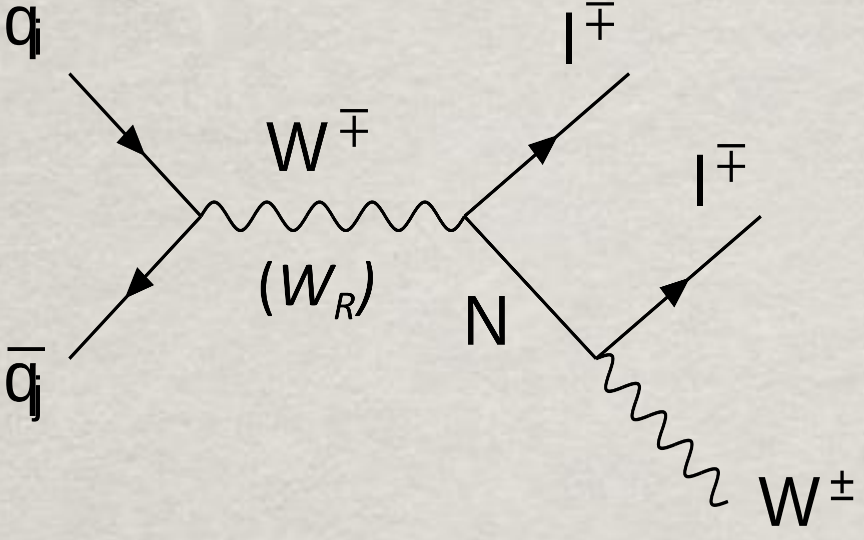
BaBar collaboration: arXiv:1503.08267v1.

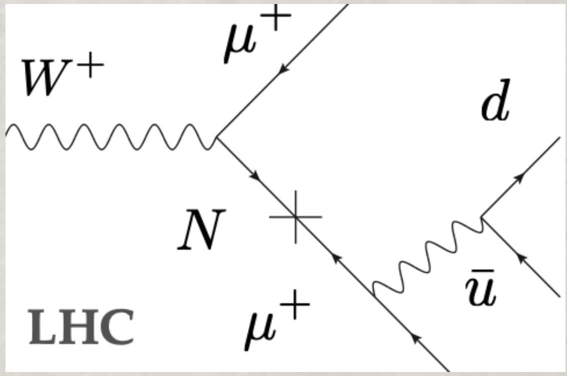


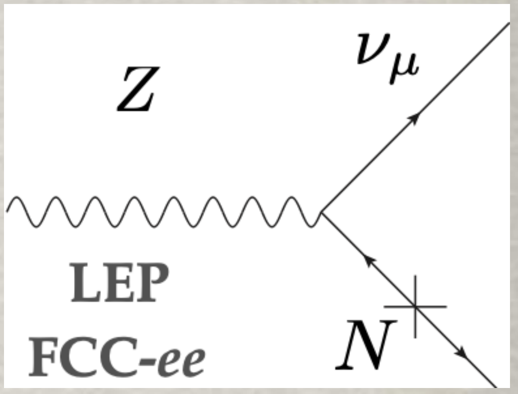
LHCb collaboration: arXiv:1401.5361v2.
Atre, TH, Pascoli, Zhang, arXiv:0901.3589,
B. Shuve & M. Peskin, arXiv:1607.04258

5. HNL (N) at Colliders

At hadron colliders: [§] $pp(\bar{p}) \to \ell^\pm \ell^\pm j\, j\, X$



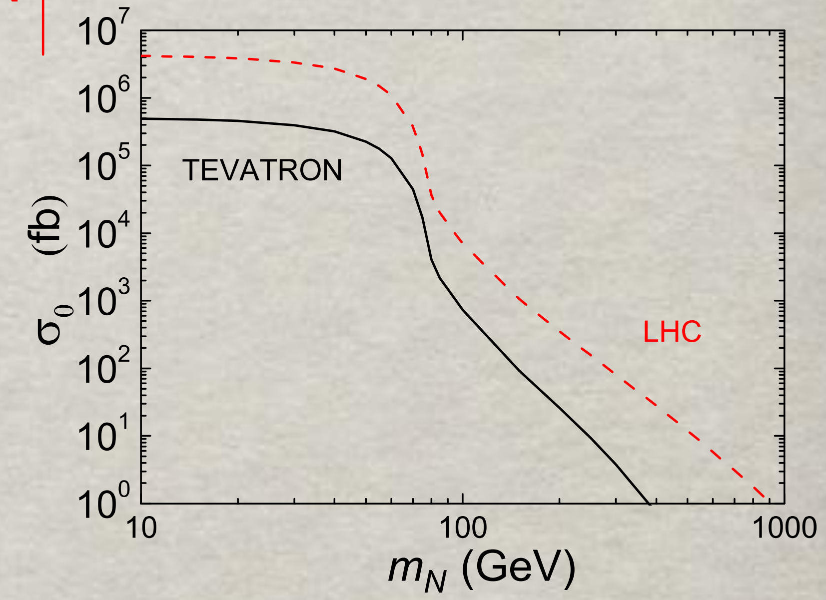




$$\sigma(pp \to \mu^\pm \mu^\pm W^\mp) \approx \sigma(pp \to \mu^\pm N) Br(N \to \mu^\pm W^\mp) \equiv \frac{V_{\mu N}^2}{\sum_l \left|V_{\ell N}\right|^2} V_{\mu N}^2 \ \sigma_0.$$

A very clean channel:

- like-sign di-muons plus two jets;
- no missing energies;
- $m(jj) = M_W, \ m(jj\mu) = m_N.$



→ being actively searched for at the LHC

[§] Keung, Senjanovic (1983); Dicus et al. (1991); A. Datta, M. Guchait, A. Pilaftsis (1993); ATLAS TDR (1999); F. Almeida et al. (2000); F. del Aguila et al. (2007).

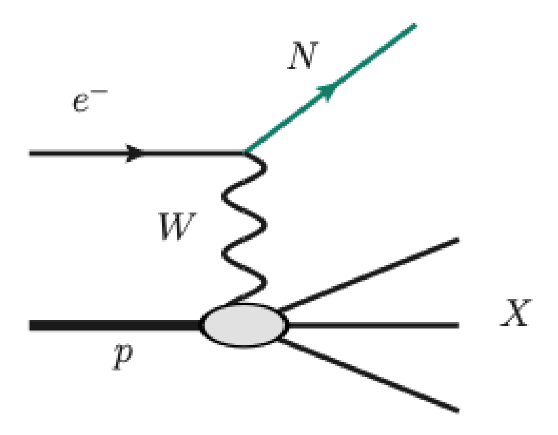
[†] T. Han and B. Zhang, hep-ph/0604064, PRL (2006).

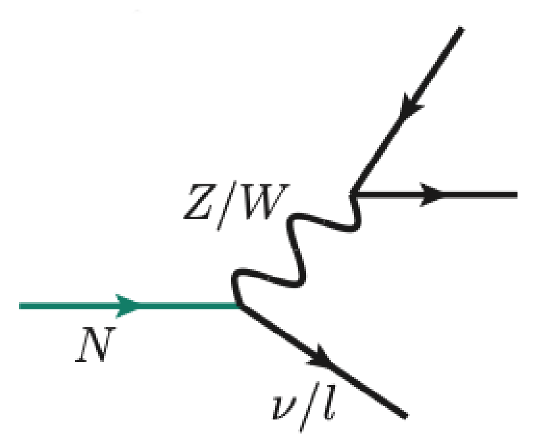
Heavy Neutral Leptons @ EIC

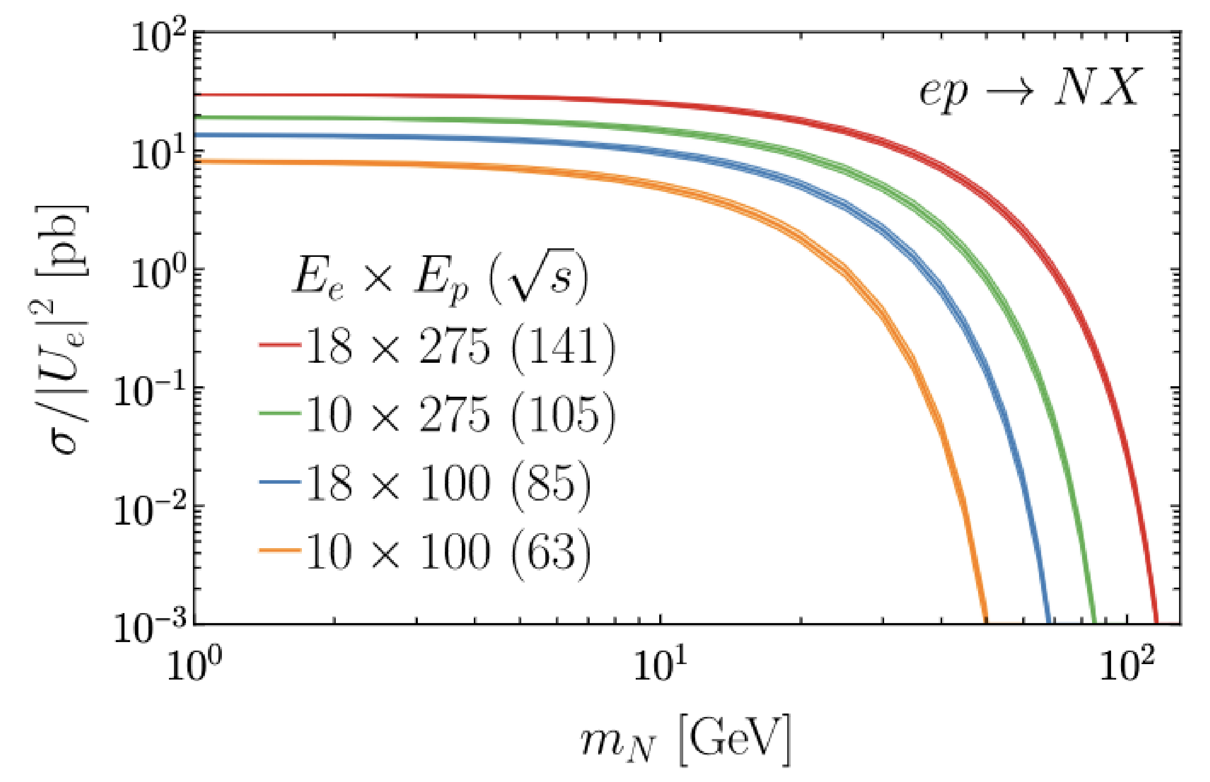
Both in NC and CC:

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} U_{iI}\, W^-_\mu\, \ell_i^\dagger\, \overline{\sigma}^\mu N_I + \frac{g}{2\, c_W} U_{iI}\, Z_\mu\, \nu_i^\dagger\, \overline{\sigma}^\mu N_I + \mathrm{H.c.}$$

- Production $e^- p \rightarrow N X$: Decay $N \rightarrow l^\pm W^\mp$, $\boldsymbol{\nu} Z$



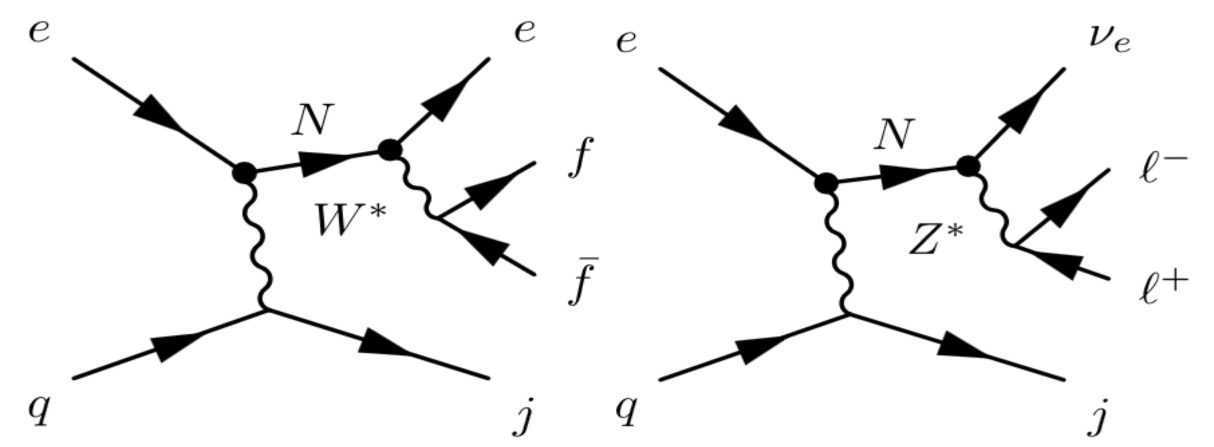


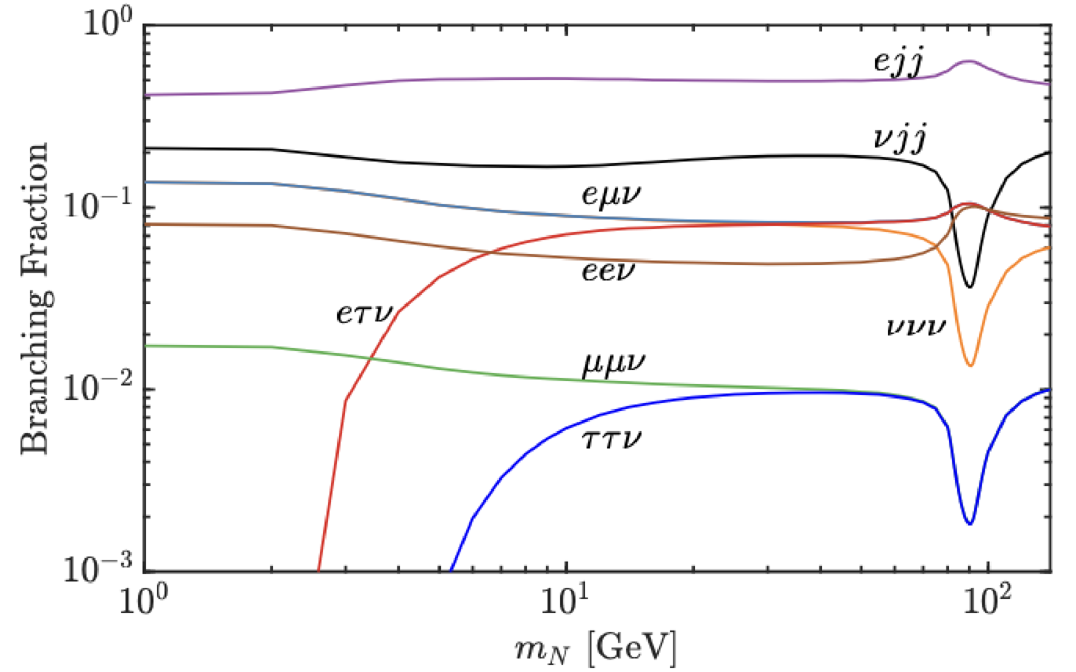


B. Batell, T. Ghosh, T. Han, K. Xie, arXiv:2210.09287

$\boldsymbol{\sigma}$ ~ O(a few fb) @ $U^2 \sim 10^{-4}$

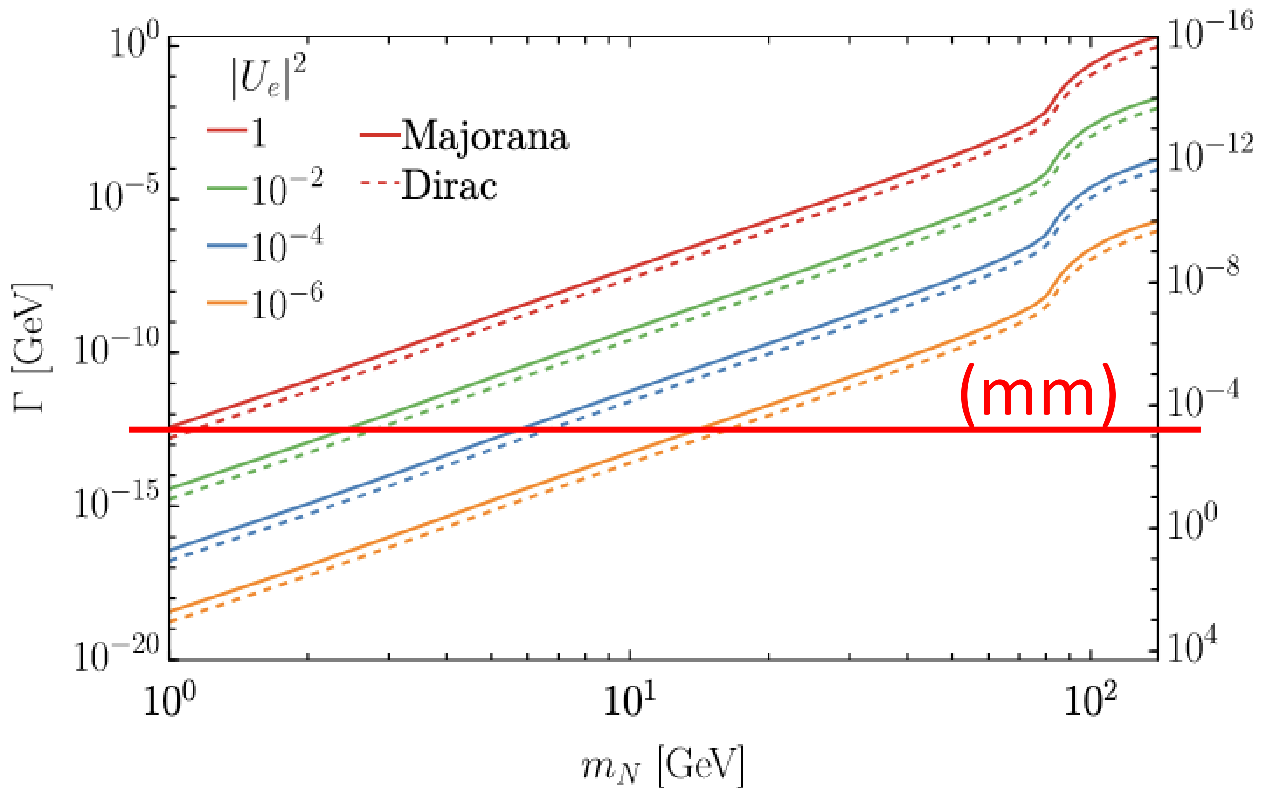
• Decay length: N → $l^{\pm}$ $W^{\mp}$, **ν** Z

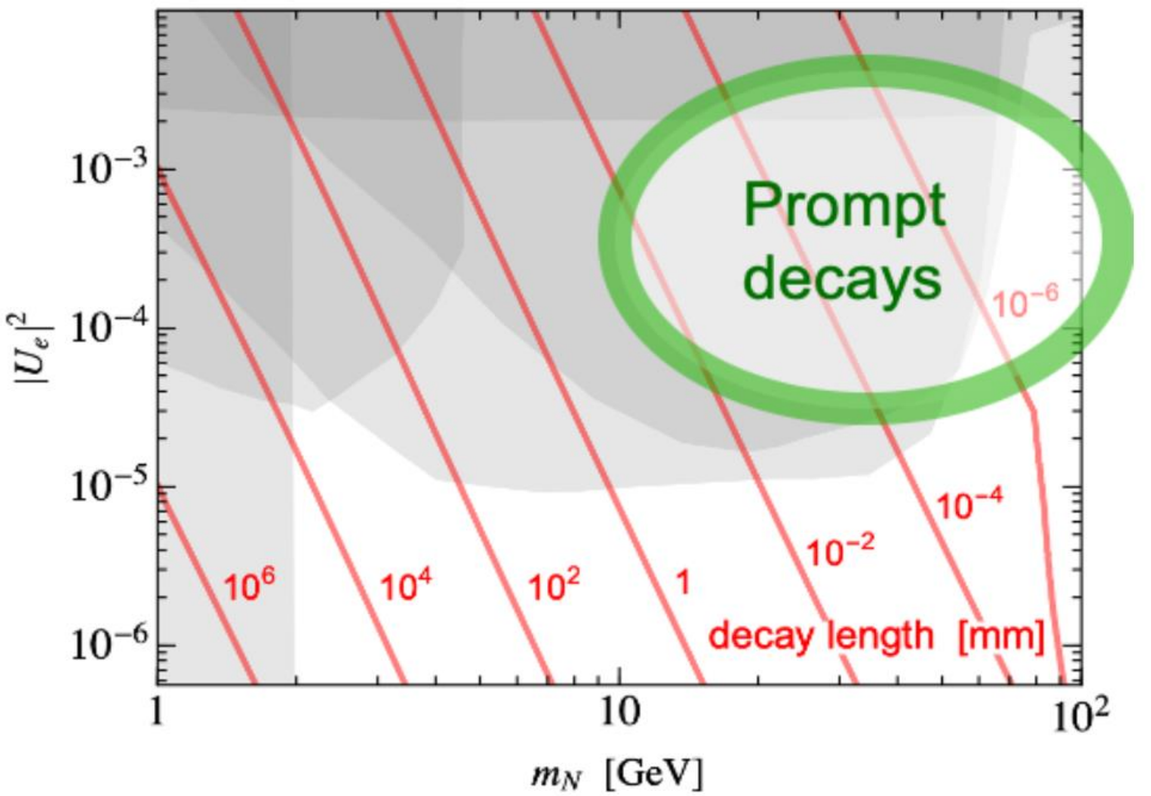




$$\Gamma_N \sim \frac{G_F^2 m_N^5}{192\pi^3}|U_e|^2 \sum_{i=\ell,q} N_c^i \Theta(m_N - m_X^i) C_V^i$$

$$\tau_N = \frac{1}{\Gamma_N} \sim\ 10^{-9}\ \mathrm{s} \times \left(\frac{1\ \mathrm{GeV}}{m_N}\right)^5 \left(\frac{10^{-3}}{|U_e|^2}\right)$$





B. Batell, T. Ghosh, T. Han, K. Xie, arXiv:2210.09287

• N prompt decay signal:

Three channels are considered

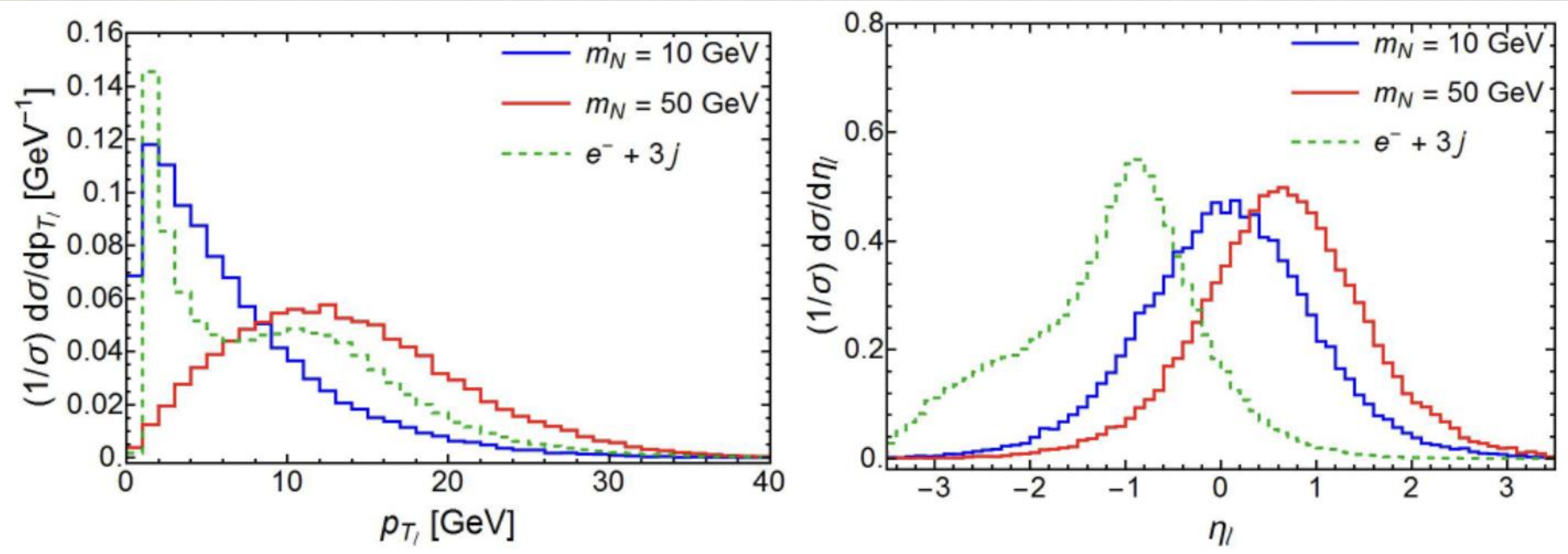
- Majorana: e^+3j
- Majorana: $e^+\mu^-j+\not{E}_T$
- Dirac: $\ell^+\ell^-j+\not{E}_T$

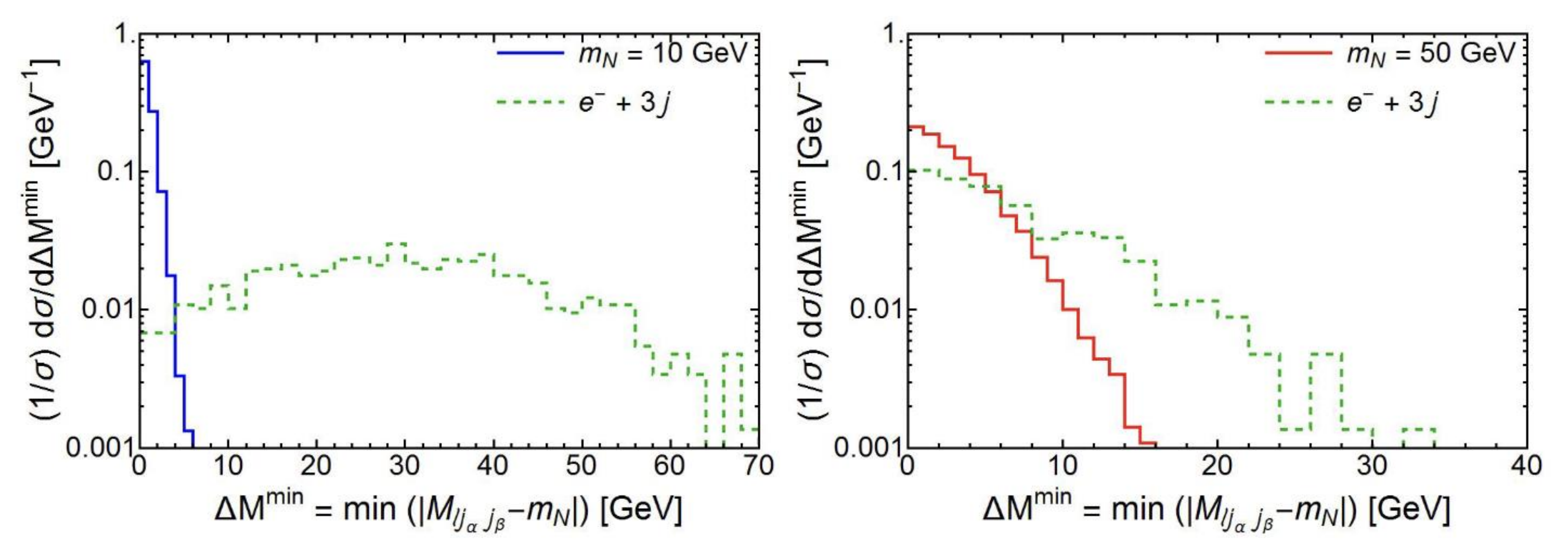
(1). e^- p → N(e^+ jj’) + j (Majorana ΔL=2)

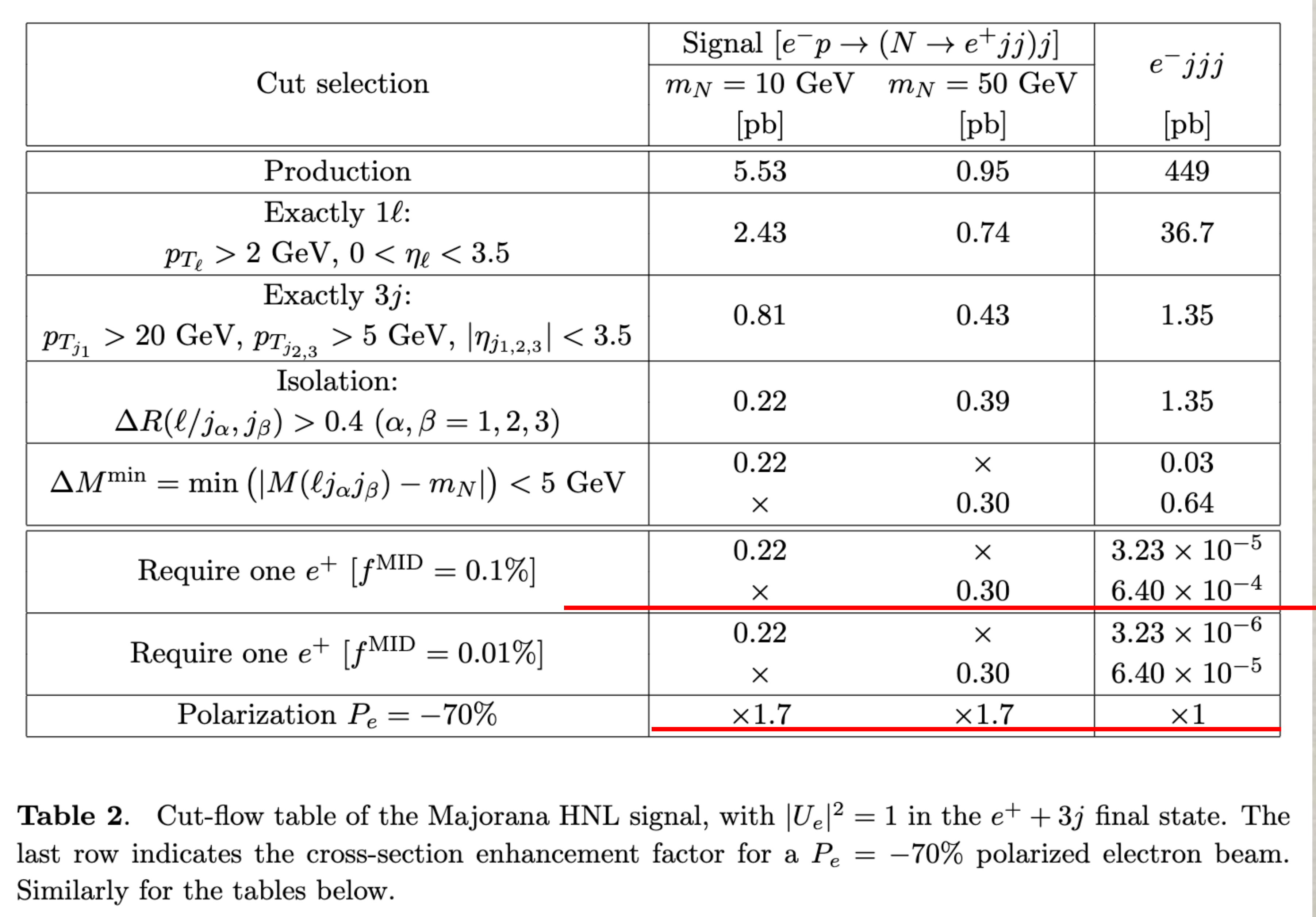
Though NO SM background for e^+, unless e^- fakes e^+ .

Acceptance cuts:

$p_{T_\ell} > 2$ GeV and $0 < \eta_\ell < 3.5$. $|\eta_j| < 3.5$ with $p_{T_{j_1}} > 20$ GeV, and $p_{T_{j_{2,3}}} > 5$ GeV.





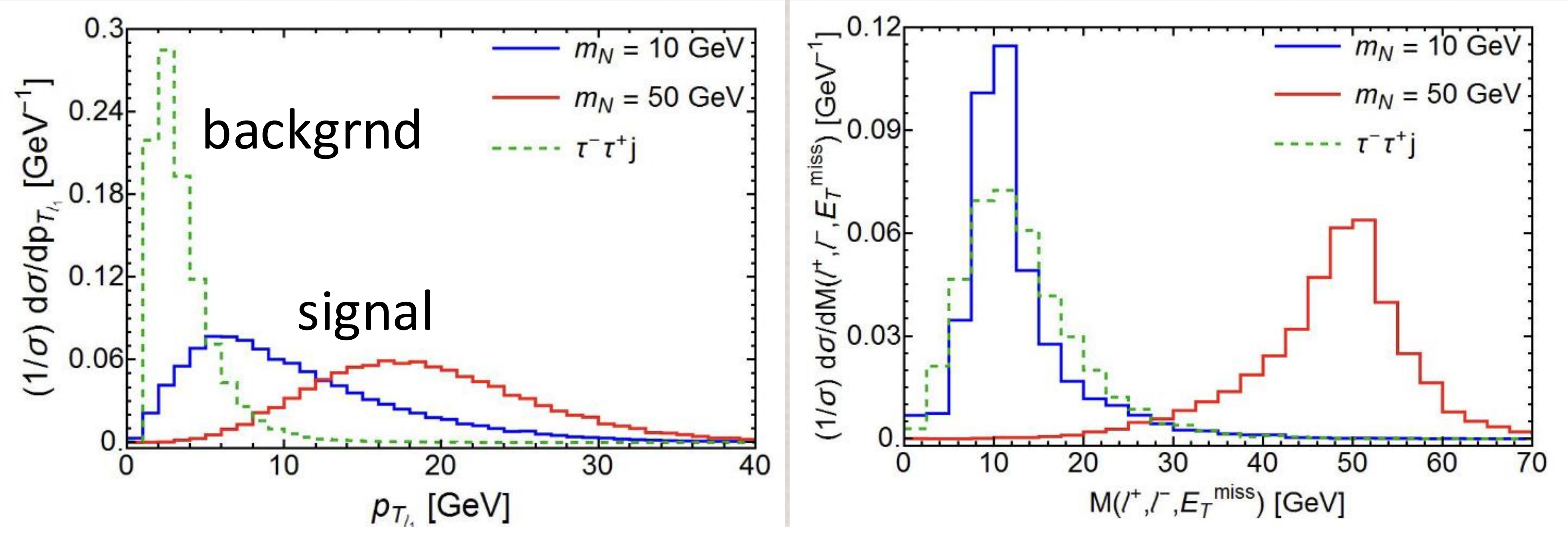


Cut selection	Signal $[e^-p \to (N \to e^+jj)j]$		e^-jjj
	$m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	[pb]
Production	5.53	0.95	449
Exactly 1ℓ: $p_{T_\ell} > 2$ GeV, $0 < \eta_\ell < 3.5$	2.43	0.74	36.7
Exactly $3j$: $p_{T_{j_1}} > 20$ GeV, $p_{T_{j_{2,3}}} > 5$ GeV, $\lvert\eta_{j_{1,2,3}}\rvert < 3.5$	0.81	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
$\Delta M^{\min} = \min\left(\lvert M(\ell j_\alpha j_\beta) - m_N\rvert\right) < 5$ GeV	0.22 ×	× 0.30	0.03 0.64
Require one e^+ $[f^{\text{MID}} = 0.1\%]$	0.22 ×	× 0.30	3.23×10^{-5} 6.40×10^{-4}
Require one e^+ $[f^{\text{MID}} = 0.01\%]$	0.22 ×	× 0.30	3.23×10^{-6} 6.40×10^{-5}
Polarization $P_e = -70\%$	×1.7	×1.7	×1

Table 2. Cut-flow table of the Majorana HNL signal, with $|U_e|^2 = 1$ in the $e^+ + 3j$ final state. The last row indicates the cross-section enhancement factor for a $P_e = -70\%$ polarized electron beam. Similarly for the tables below.

miss ID

(2). $e^- p \rightarrow N(e^+ \mu^- \nu) + j$ (Majorana $\Delta L=2$)

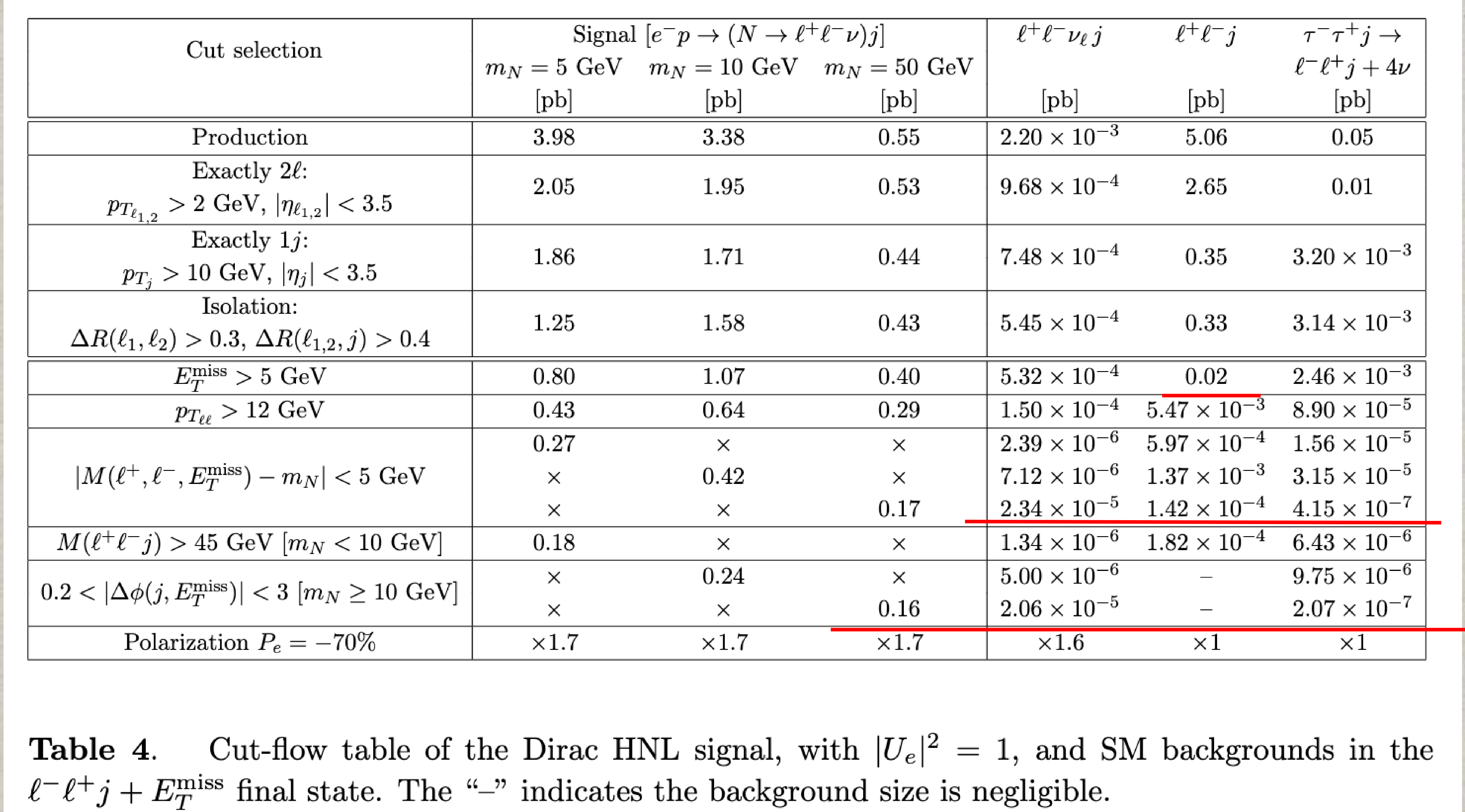


Cut selection	Signal $[e^-p \to (N \to \ell^-\ell^+\nu)j]$ $m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	$\tau^-\tau^+j \to \ell^-\ell^+j + 4\nu$ [pb]
Production	3.16	0.55	0.05
Exactly 2ℓ: $p_{T_{\ell_{1,2}}} > 2$ GeV, $\lvert\eta_{\ell_{1,2}}\rvert < 3.5$	2.10	0.53	0.01
Exactly $1j$: $p_{T_j} > 10$ GeV, $\lvert\eta_j\rvert < 3.5$	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	×	1.72×10^{-5}
$\lvert M(\ell^+, \ell^-, E_T^{\text{miss}}) - m_N\rvert < 10$ GeV [$m_N \geq 20$ GeV]	×	0.08	2.07×10^{-7}
Polarization $P_e = -70\%$	×1.7	×1.7	×1

Table 3. Cut-flow table of the Majorana HNL signal, with $|U_e|^2 = 1$ in the $\mu^- e^+ j + E_T^{\text{miss}}$ final state.

(3). $e^- p \to N(e^- \mu^+ \nu) + j$ (Dirac-like $\Delta L=0$)

More SM backgrounds to e^-

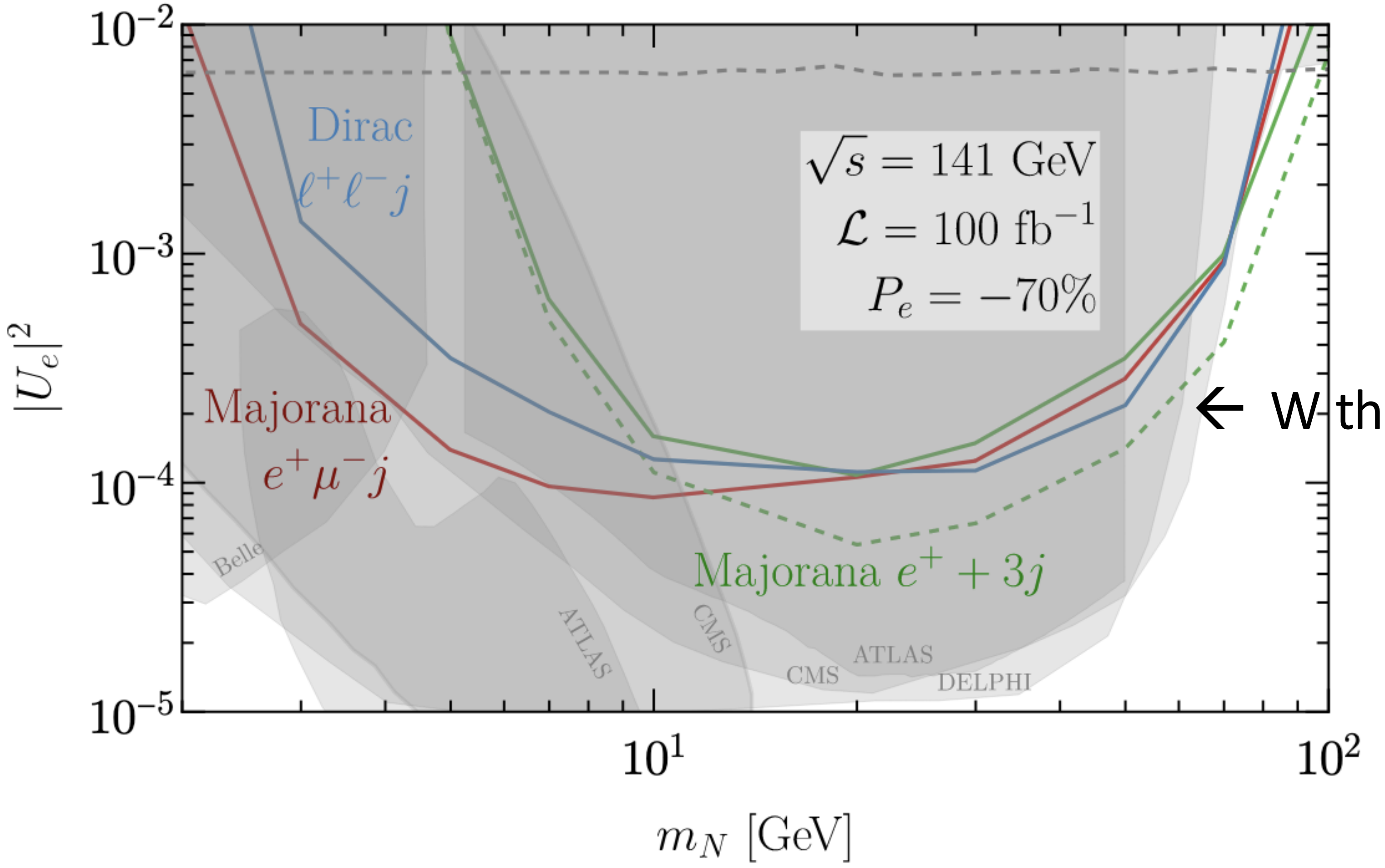


Cut selection	Signal $[e^-p \to (N \to \ell^+\ell^-\nu)j]$			$\ell^+\ell^-\nu_\ell j$	$\ell^+\ell^- j$	$\tau^-\tau^+ j \to \ell^-\ell^+ j + 4\nu$
	$m_N = 5$ GeV [pb]	$m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	[pb]	[pb]	[pb]
Production	3.98	3.38	0.55	2.20×10^{-3}	5.06	0.05
Exactly 2ℓ: $p_{T_{\ell_{1,2}}} > 2$ 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	×	×	2.39×10^{-6}	5.97×10^{-4}	1.56×10^{-5}
	×	0.42	×	7.12×10^{-6}	1.37×10^{-3}	3.15×10^{-5}
	×	×	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	×	×	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$]$	×	0.24	×	5.00×10^{-6}	–	9.75×10^{-6}
	×	×	0.16	2.06×10^{-5}	–	2.07×10^{-7}
Polarization $P_e = -70\%$	×1.7	×1.7	×1.7	×1.6	×1	×1

Table 4. Cut-flow table of the Dirac HNL signal, with $|U_e|^2 = 1$, and SM backgrounds in the $\ell^-\ell^+ j + E_T^{\rm miss}$ final state. The "–" indicates the background size is negligible.

Summary for the prompt decay search

EIC: N → $l^{\pm}$ $W^{\mp}$,   LHC: DY $W^{\mp}$ → N $l^{\pm}$

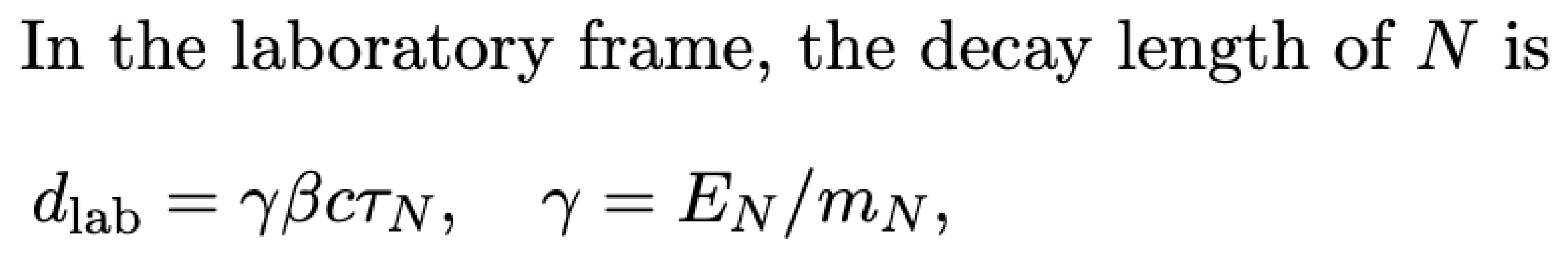


← W threshold

Figure 9. The expected 95% C.L. exclusion limits from prompt searches at the EIC with $\sqrt{s} = 141$ GeV and 100 fb^{-1} of integrated luminosity for HNLs (colored lines), compared with the existing bounds from direct searches [66–71] (gray shaded regions) and indirect precision electroweak constraints [72] (horizontal dashed line). The solid (dashed) green line indicates the sensitivity of the prompt Majorana HNL decay $N \to e^+ + 3j$, with a misidentification rate assumed as 0.1% (0.01%).

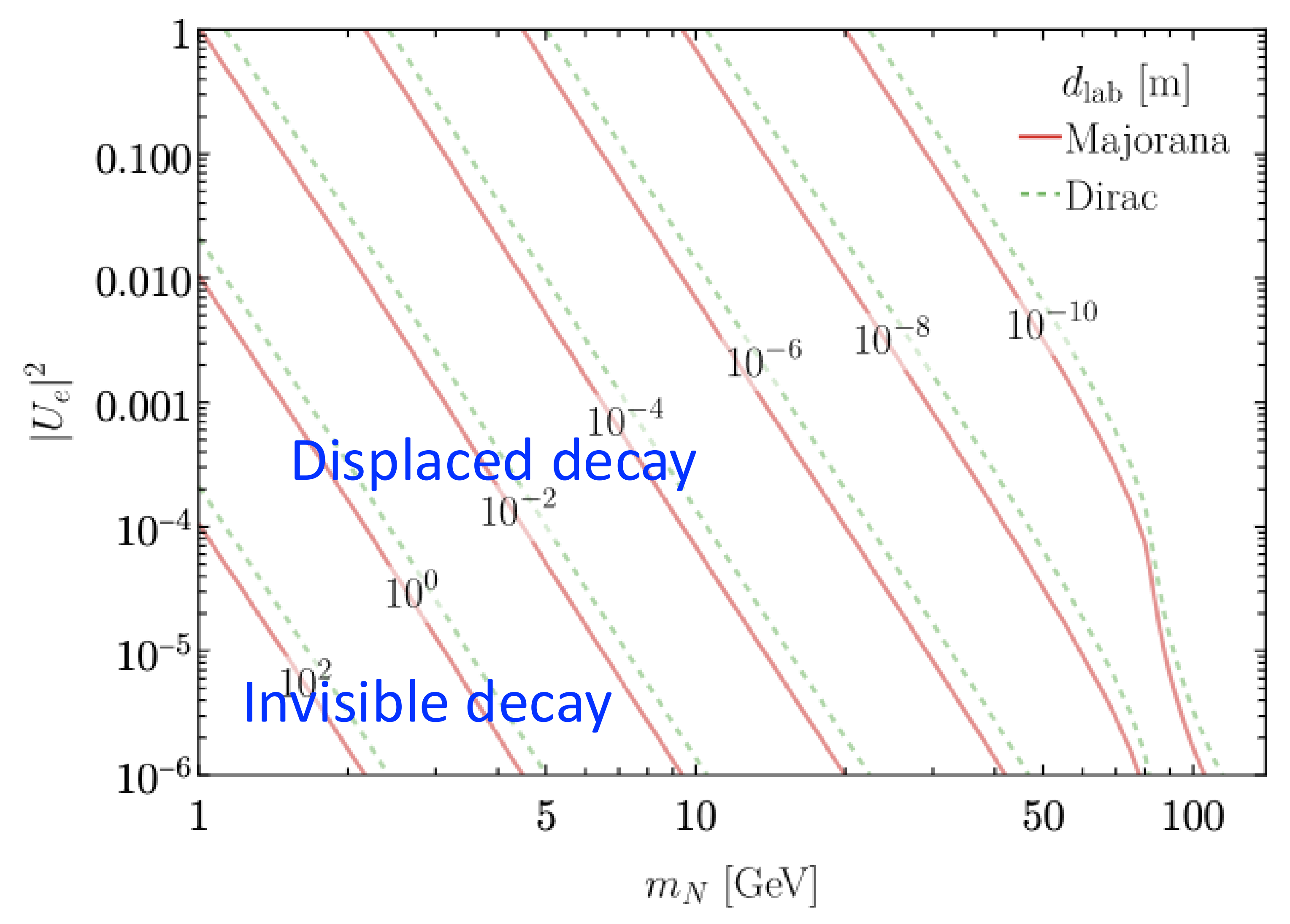
Other bounds from "Physics Beyond Colliders" report, arXiv:1901.09966

- **Long-lived particle N (LLP)**


In the laboratory frame, the decay length of N is

$$d_{\text{lab}} = \gamma\beta c\tau_N, \quad \gamma = E_N/m_N,$$

Assuming the detector coverage: r = 0.4 m, l = 1.2 m
and displaced impact parameter: d_T = 2 (20) mm



Summary for LLP decays:

N → $e^{\pm}\,\mu^{\mp}\,\nu$, $e^{\pm}\,jj'$

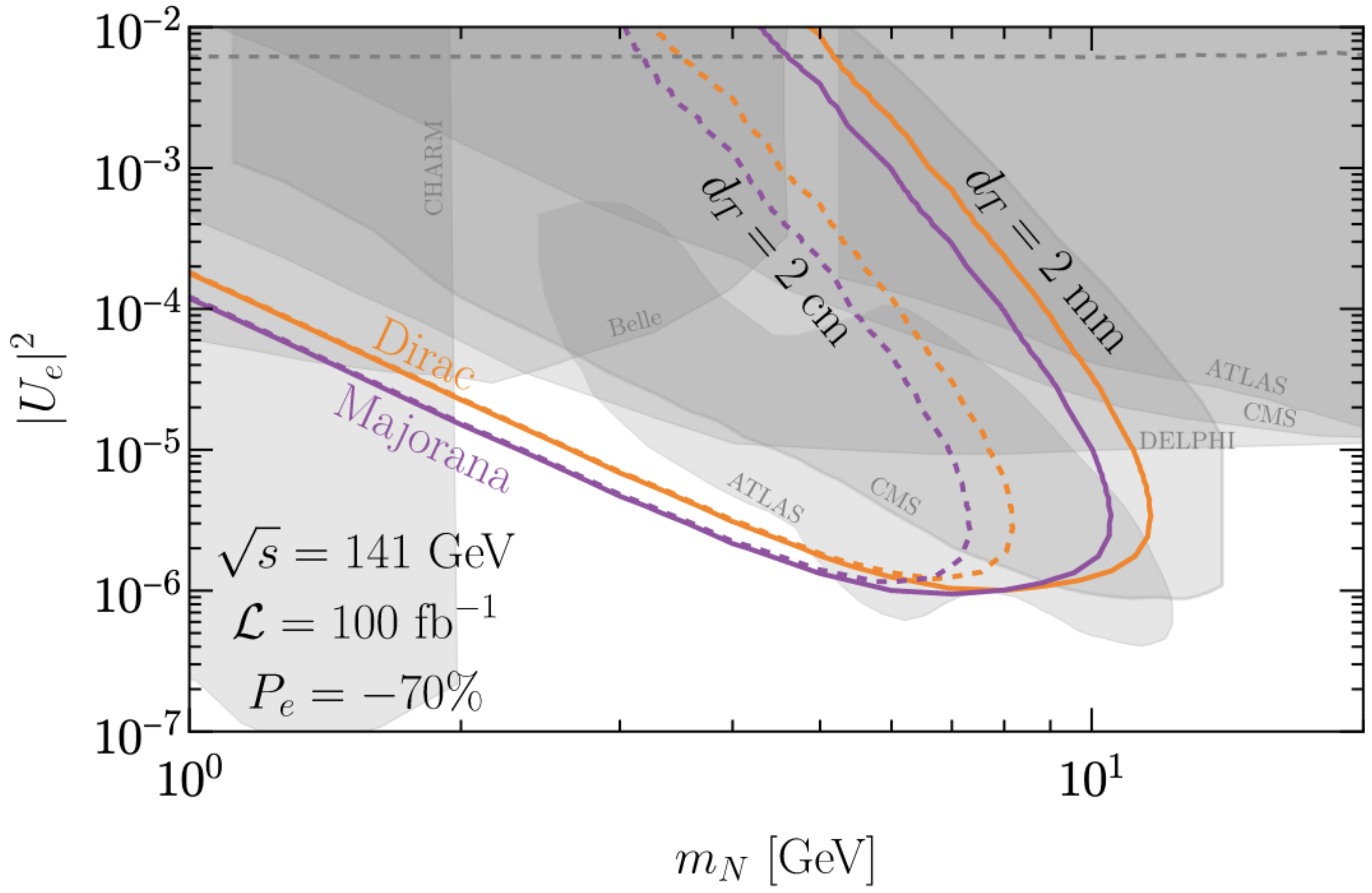


Figure 11. The expected contours of $N = 5$ displaced vertex events detected in the EIC detector. The Majorana (Dirac) type events are shown as purple (orange) lines. The solid (dashes) lines indicate the impact parameter choice as $d_T = 2$ (20) mm. These results are compared with the existing bounds from direct searches [65–71] (gray shaded regions) and indirect precision electroweak constraints [72] (horizontal dashed line). In particular, we include existing displaced vertex searches in the 13 TeV CMS [69] and ATLAS [71] experiments (dark shaded islands).

Summary plot for both prompt & LLPs

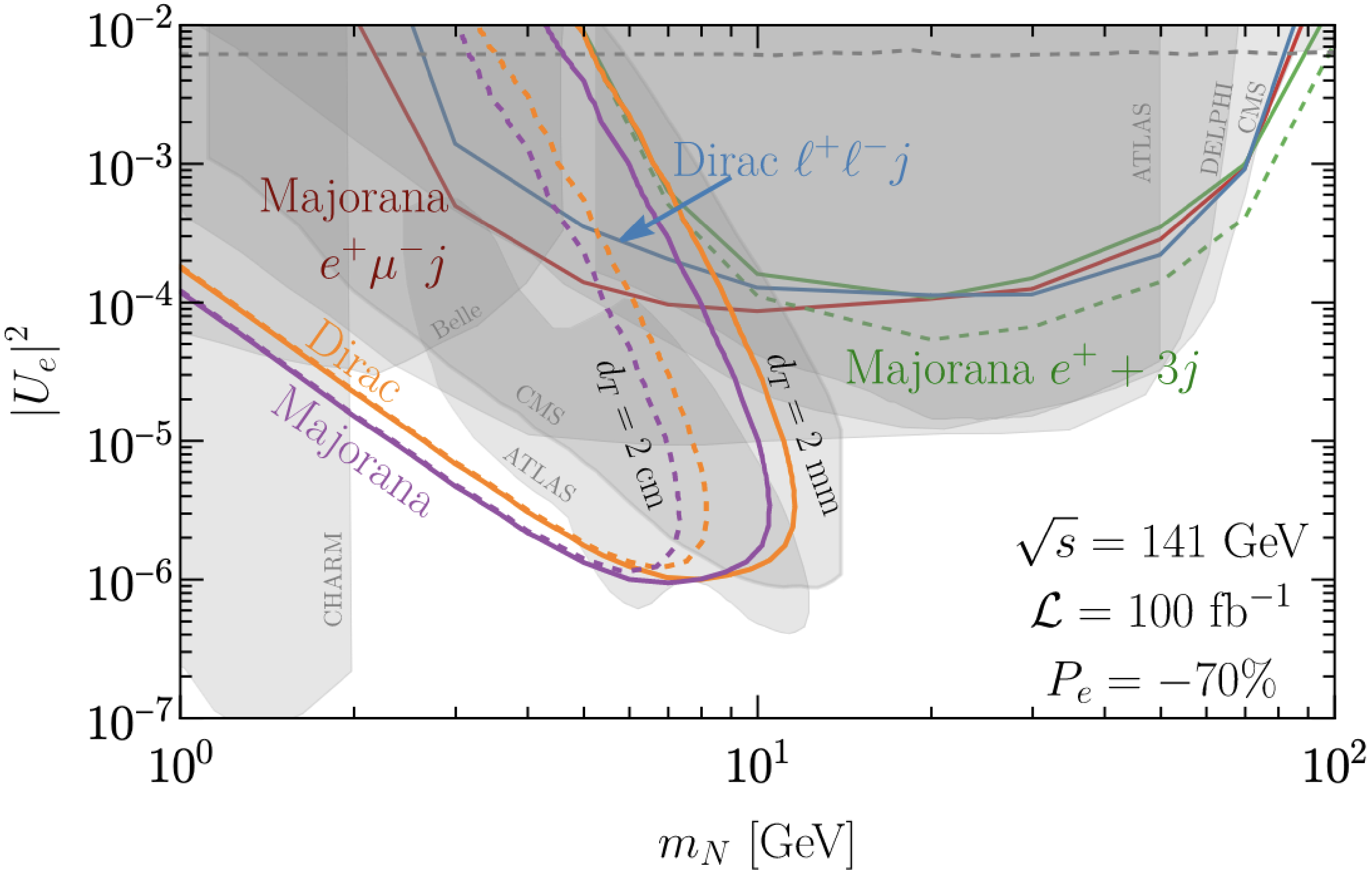


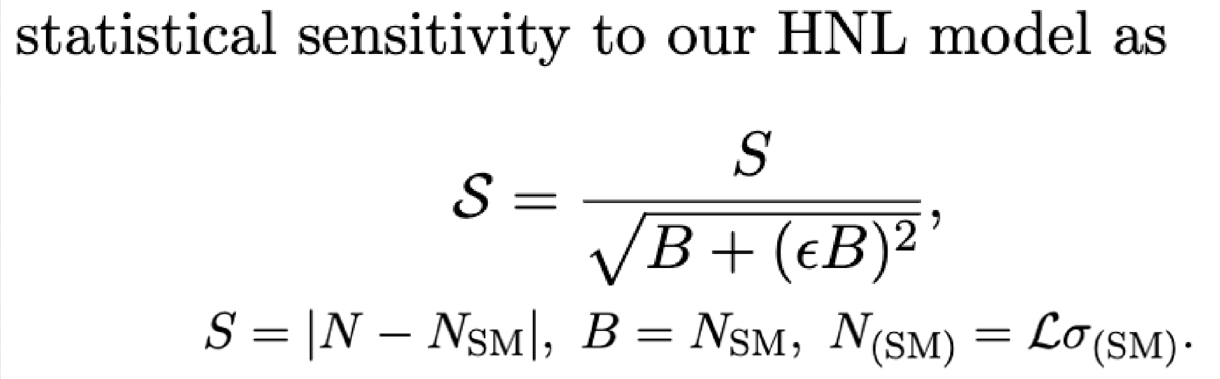
Figure 15. The combined EIC sensitivity to HNL, compared with the existing bounds [65–72]. For details we refer the reader to Figs. 9 and 11.

B. Batell, T. Ghosh, T. Han, K. Xie, arXiv:2210.09287

N very long-lived, invisible passing through the detection:

e^- p → missing N + j: Mono-jet events

No shape difference, rely on event counting …



statistical sensitivity to our HNL model as

$$\mathcal{S} = \frac{S}{\sqrt{B + (\epsilon B)^2}},$$

$$S = |N - N_{\rm SM}|, \ B = N_{\rm SM}, \ N_{\rm (SM)} = \mathcal{L}\sigma_{\rm (SM)}.$$

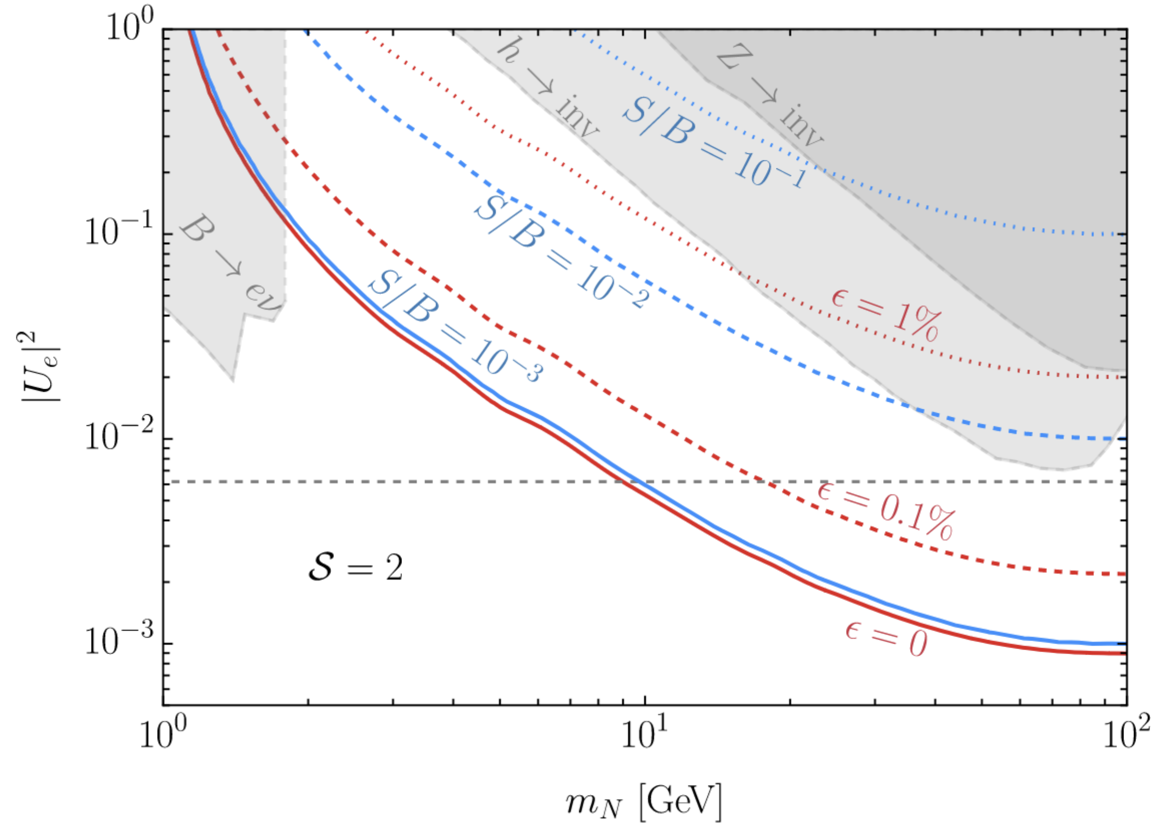
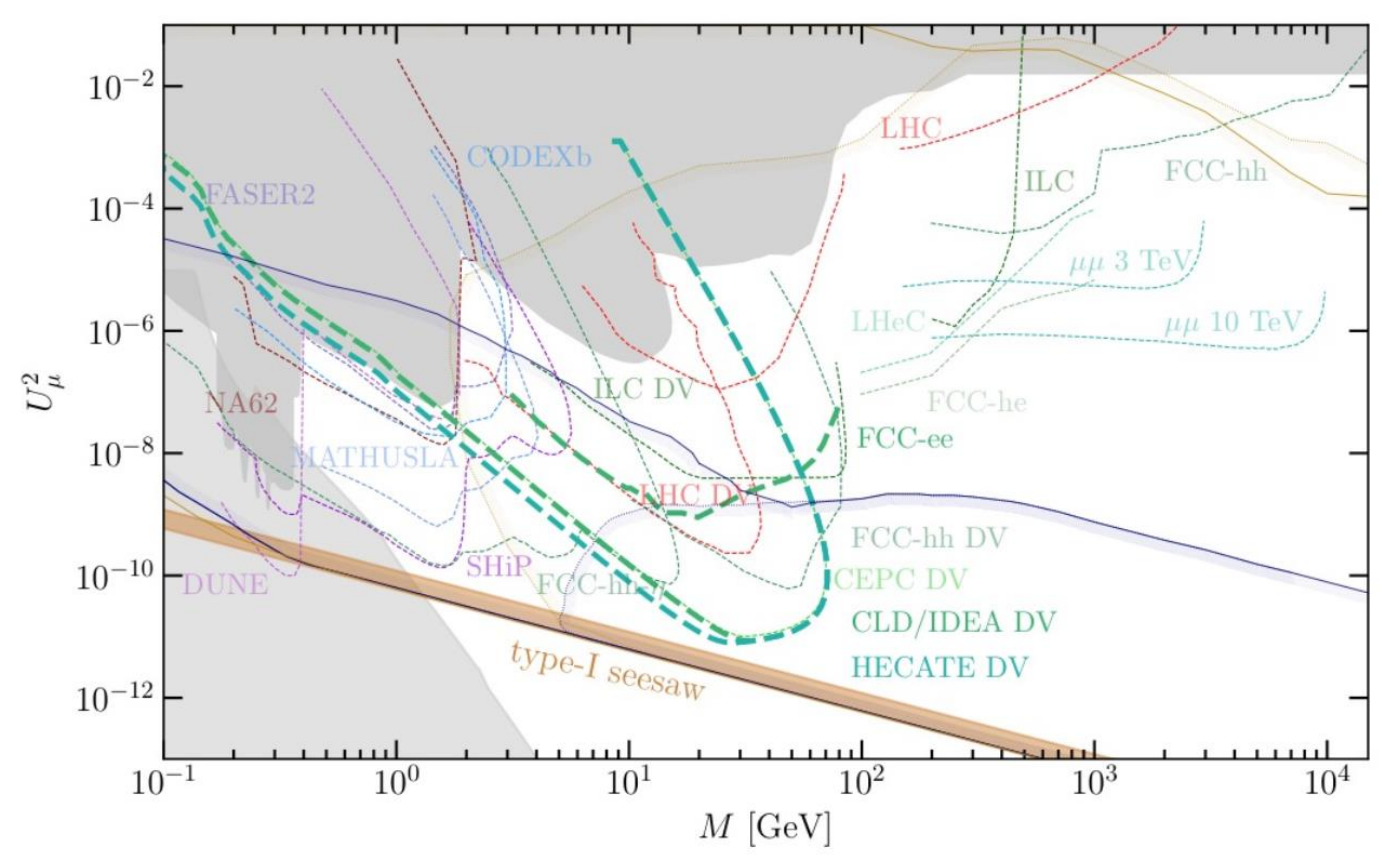


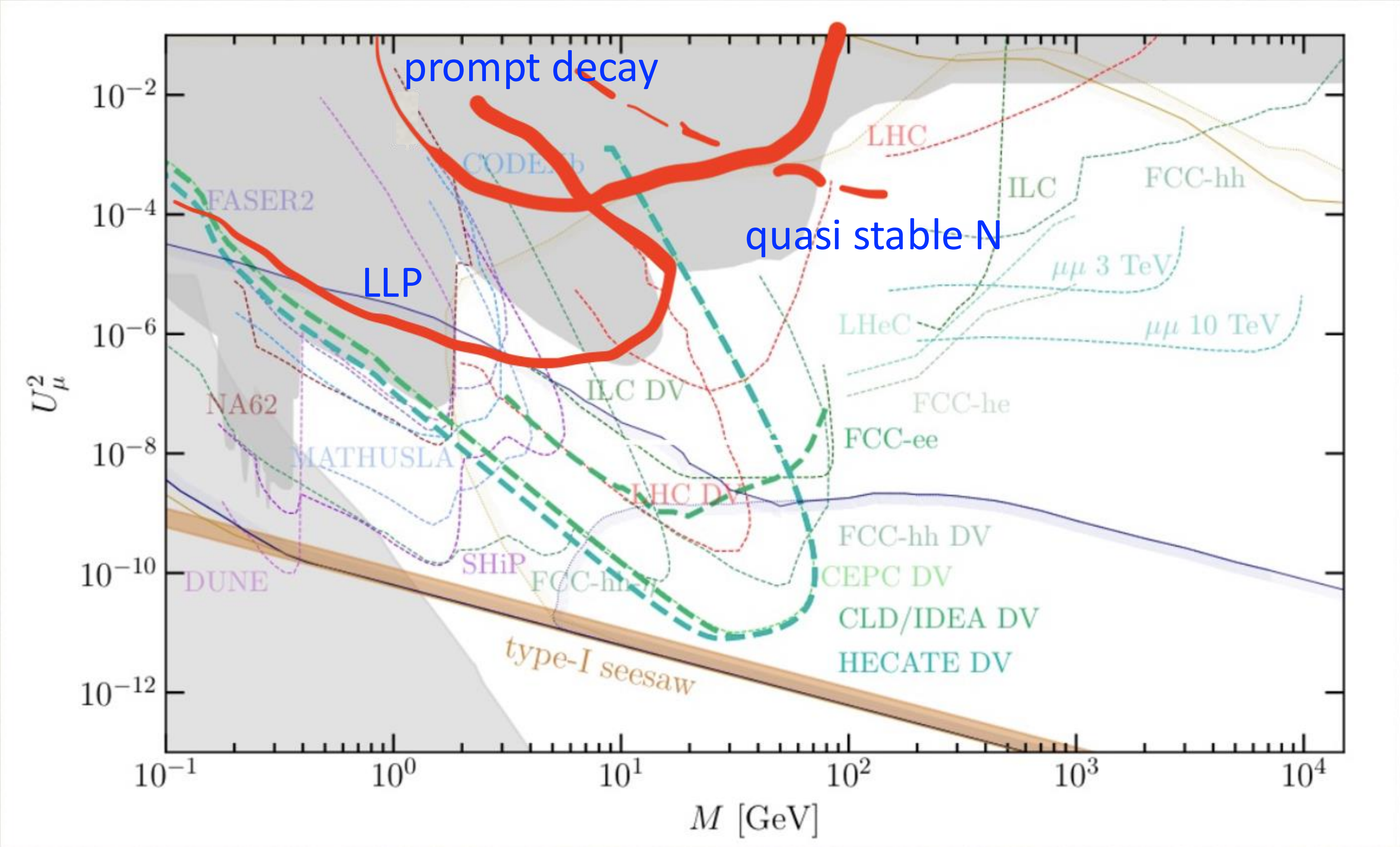
Figure 14. The sensitivity probe (red lines) of the EIC based on the mono-jet search, quantified with $\mathcal{S} = 2$ in Eq. (4.12), with the relative systematic uncertainty as $\epsilon = 0, \ 0.1\%$, and 1%. The existing bounds come from invisible decays of Z and Higgs bosons [1, 81], peak searches in $B \to e\nu$ decays [82] (gray shaded) and indirect constraints from precision electroweak observables (dashed line) [72]. Also shown are contours of signal-to-background ratios $S/B = 10^{-3}, \ 10^{-2}$, and 10^{-1} (light blue lines).

Significant efforts in searching for N

(https://arxiv.org/pdf/2203.08039)



EIC can be complementary to the low-energy oscillation and high-energy colliders



Summary

- EIC will open up a new QCD frontier
- EIC also has potential to seek for BSM new physics, complementary to LHC & other experiments

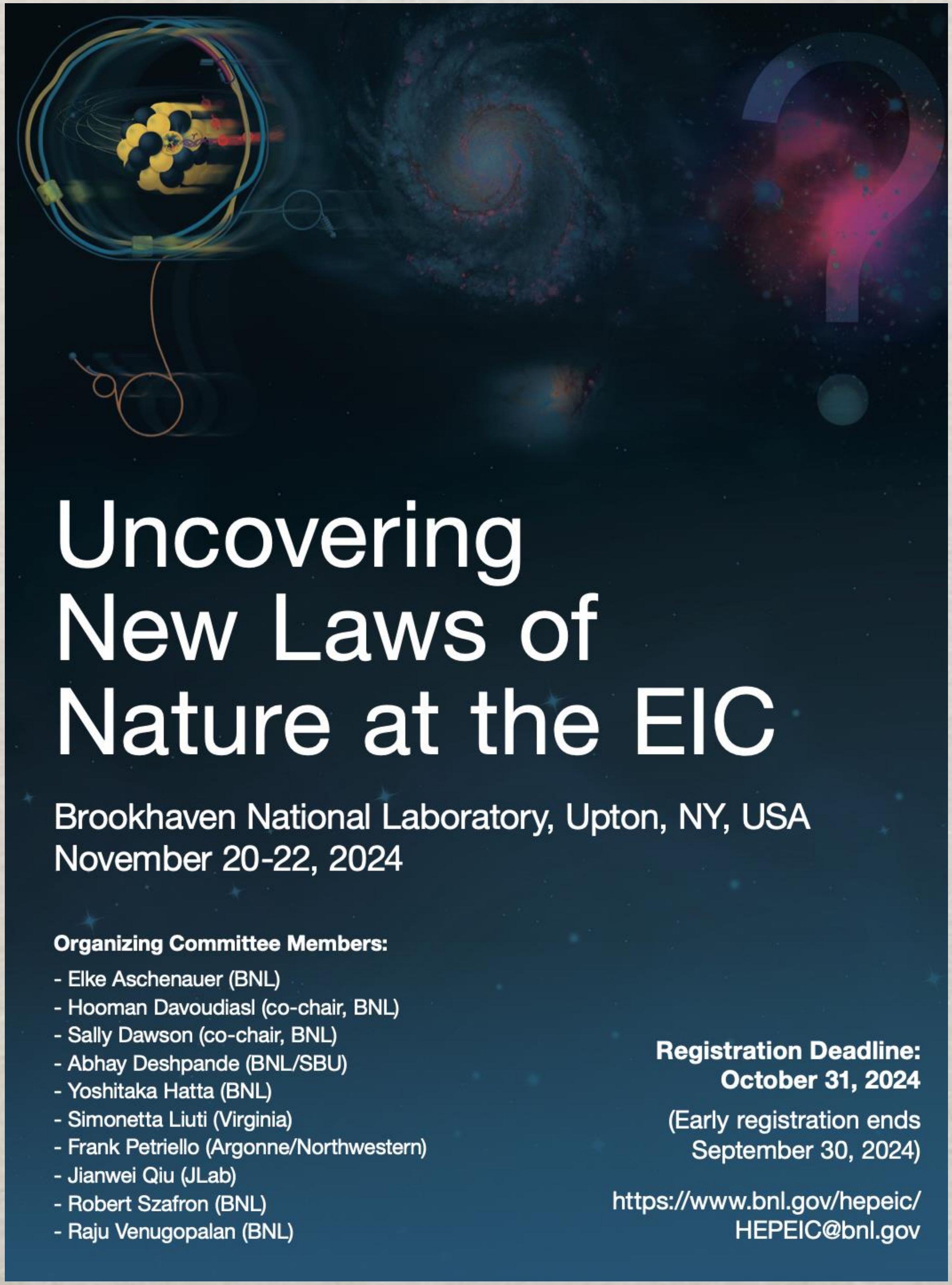
Snowmass White paper: arXiv:2203.13199

- We studied HNL signals at EIC: all flavors $e^{\pm}$, $\mu^{\pm}$, $\tau^{\pm}$ in particular for the Majorana nature.

Prompt decay signal: $M_N \sim 1 - 100$ GeV, $U^2_{eN} \sim 10^{-3}$
Displaced vertex signal: $M_N \sim O(\text{few GeV})$, $U^2_{eN} \sim 10^{-5}$
Invisible decay mono-jet signal: 2σ sensitivity

Exciting journey ahead!

Thank you: Sally, Hooman, Nicole …
for a great workshop & the hospitality!



Uncovering New Laws of Nature at the EIC

Brookhaven National Laboratory, Upton, NY, USA
November 20-22, 2024

Organizing Committee Members:

- Elke Aschenauer (BNL)
- Hooman Davoudiasl (co-chair, BNL)
- Sally Dawson (co-chair, BNL)
- Abhay Deshpande (BNL/SBU)
- Yoshitaka Hatta (BNL)
- Simonetta Liuti (Virginia)
- Frank Petriello (Argonne/Northwestern)
- Jianwei Qiu (JLab)
- Robert Szafron (BNL)
- Raju Venugopalan (BNL)

Registration Deadline:
October 31, 2024

(Early registration ends
September 30, 2024)

https://www.bnl.gov/hepeic/
HEPEIC@bnl.gov

Type I Seesaw: Singlet N_R's – Sterile neutrinos

$L_{aL} = \begin{pmatrix}\nu_a \\ l_a\end{pmatrix}_L$, a = 1, 2, 3; N_{bR}, b = 1, 2, 3, ...n ≥ 2.

Dirac plus Majorana mass terms: $\left(\overline{\nu_L}\ \ \overline{N^c_L}\right)\begin{pmatrix} 0_{3\times 3} & \boxed{D^{\nu}_{3\times n}} \\ D^{\nu T}_{n\times 3} & \boxed{M_{n\times n}} \end{pmatrix}\begin{pmatrix}\nu^c_R \\ N_R\end{pmatrix}$

Majorana neutrinos:

$$\nu_{aL} = \sum_{m=1}^{3} U_{am}\nu_{mL} + \sum_{m'=4}^{3+n} V_{am'}N^c_{m'L},$$

$$N^c_{aL} = \sum_{m=1}^{3} X_{am}\nu_{mL} + \sum_{m'=4}^{3+n} Y_{am'}N^c_{m'L},$$

<u>The charged currents:</u>

$$-L_{CC} = \frac{g}{\sqrt{2}}W^+_\mu \sum_{\ell=e}^{\tau}\sum_{m=1}^{3} U^*_{\ell m}\,\overline{\nu_m}\gamma^\mu P_L \ell + \text{h.c.}$$

$$+ \frac{g}{\sqrt{2}}W^+_\mu \sum_{\ell=e}^{\tau}\sum_{m'=4}^{3+n} V^*_{\ell m'}\,\overline{N^c_{m'}}\gamma^\mu P_L \ell + \text{h.c.}$$

Type I Seesaw features:

😀 Existence of N_R (possibly low mass*)

$$U^2_{\ell m} \sim V^2_{PMNS} \approx \mathcal{O}(1);\ \ V^2_{\ell m} \approx m_\nu / m_N.$$

$U_{\ell m},\ \Delta m_\nu$ are from oscillation experiments

m_N a free parameter: could be accessible!

🙁 But difficult to see N_R:

The mixing is typically small, mass wide open:

$$V^2_{\ell m} \approx (m_\nu/eV)/(m_N/GeV) \times 10^{-9}$$
$$< 6 \times 10^{-3} (low\ energy\ bound)$$

- Fine-tune or hybrid could make it sizeable.
- "Inverse seesaw"

Casas and Ibarra (2001);
A. Y. Smirnov and R. Zukanovich Funchal (2006);
A. de Gouvea, J. Jenkins and N. Vasudevan (2007);
W. Chao, Z. G. Si, Z. Z. Xing and S. Zhou (2008).

A Variation: Inverse seesaw [#]

Inverse Seesaw: (ν_L, N_R^c, S_L)

$$M_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M^T \\ 0 & M & \boxed{\mu_S} \end{pmatrix} \qquad m_\nu \simeq \left(\frac{M_D}{M}\right) \boxed{\mu_S} \left(\frac{M_D}{M}\right)^T$$

$$M_H \simeq \begin{pmatrix} 0 & M^T \\ M & \mu_S \end{pmatrix}.$$

Small Majorana mass μ_s renders the Dirac mass M_D
Yukawa couplings & N mixings sizable!

$$V_{\ell m}^2 \approx (M_D/M_N)^2 \approx m_\nu/\mu_s$$

* **ν** Majorana-like; N Dirac-like.

[#] R. Mohapatra, J. Valle (1986)

Type II Seesaw: No need for N_R, with Φ-triplet*

With a scalar triplet Φ $(Y = 2)$: $\varphi^{\pm\pm}, \varphi^{\pm}, \varphi^{0}$ (many representative models).
Add a gauge invariant/renormalizable term:

$$Y_{ij} L_i^T C (i\sigma_2) \Phi L_j + \text{h.c.}$$

That leads to the Majorana mass:

$$M_{ij} \nu_i^T C \nu_j + \text{h.c.}$$

where

$$M_{ij} = Y_{ij} \langle \Phi \rangle = Y_{ij} v' \lesssim 1 \text{ eV},$$

Very same gauge invariant/renormalizable term:

$$\mu H^T (i\sigma_2) \Phi^\dagger H + \text{h.c.}$$

predicts

$$v' = \mu \frac{v^2}{M_\varphi^2},$$

leading to the Type II Seesaw. †

[*] Magg, Wetterich (1980); Lazarides, Shafi (1981); Mohapatra, Senjanovic (1981). ...

[†] In Little Higgs model: T.Han, H.Logan, B.Mukhopadhyaya, R.Srikanth (2005).

Radiative Seesaw Models*

- New fields + (Z_2) symmetry → no tree-level mass terms
- Close the loops: Quantum corrections could generate m_ν.

Suppressions (up to 3-loops) make both m_ν and M low:

$$m_\nu \sim (\frac{1}{16\pi^2})^\ell (\frac{v}{M})^k \ \mu$$

With (Majorana) mass scale **μ**

Generic features:

- New scalars: φ^0, $H^\pm$, $H^{\pm\pm}$, …

→ BSM Higgs physics, possible flavor relations

- Additional Z_2 symmetry → Dark Matter $\boldsymbol{\eta}$

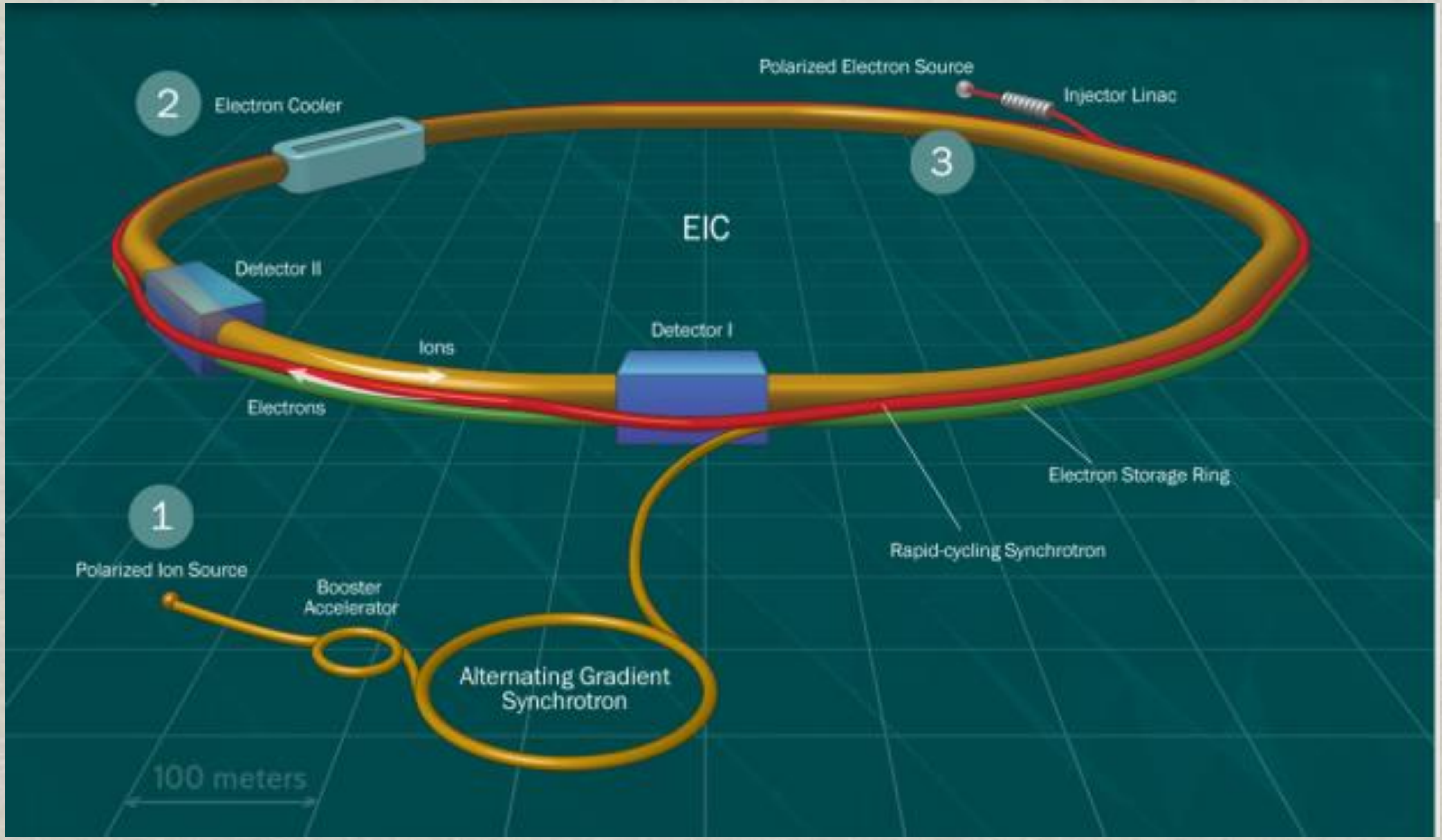
$h^0 \rightarrow \eta\eta$ invisible!

* Zee (1980, 1986); Babu (1988); Ma (2006), Aoki et al. (2009).

Introduction to EIC

The Electron-Ion Collider (EIC) at BNL

- CM energies: 20 – 100 (140) GeV
- Luminosity: $10^{33\text{-}34}$ /cm^2/s (10-100 fb^{-1}/yr, 10 -1000 times of HERA)
- Polarized electron ~ 70%; light A ~ 70%
- Range of nuclear targets: proton/deuteron/gold/uranium



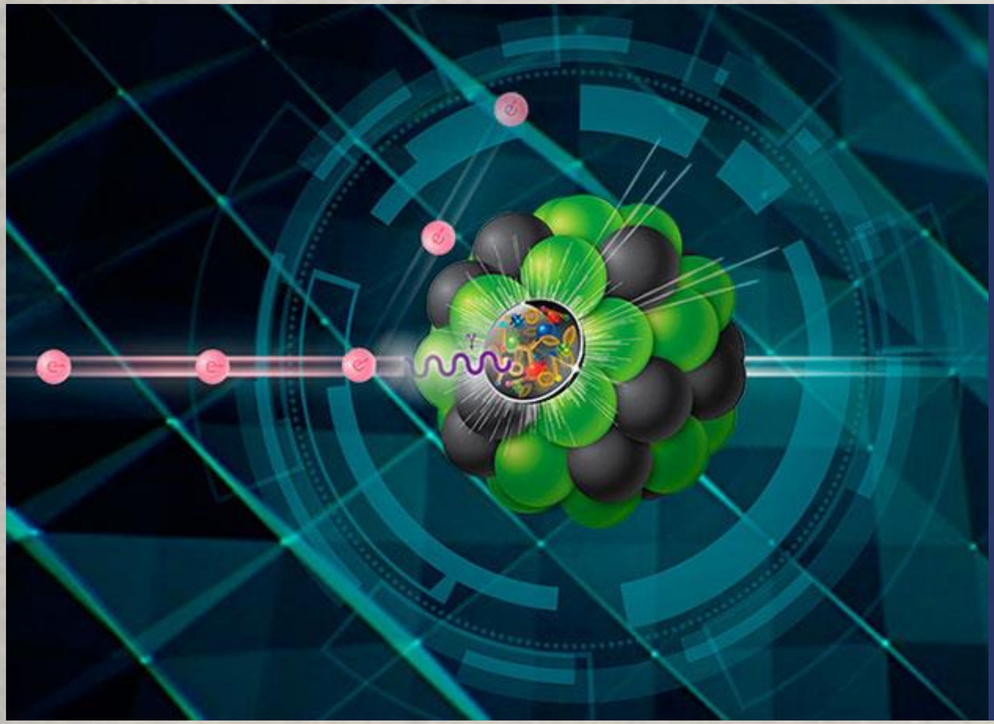
See, Silvia Dalla Torre talk; arXiv:1212.1701, 2103.05419

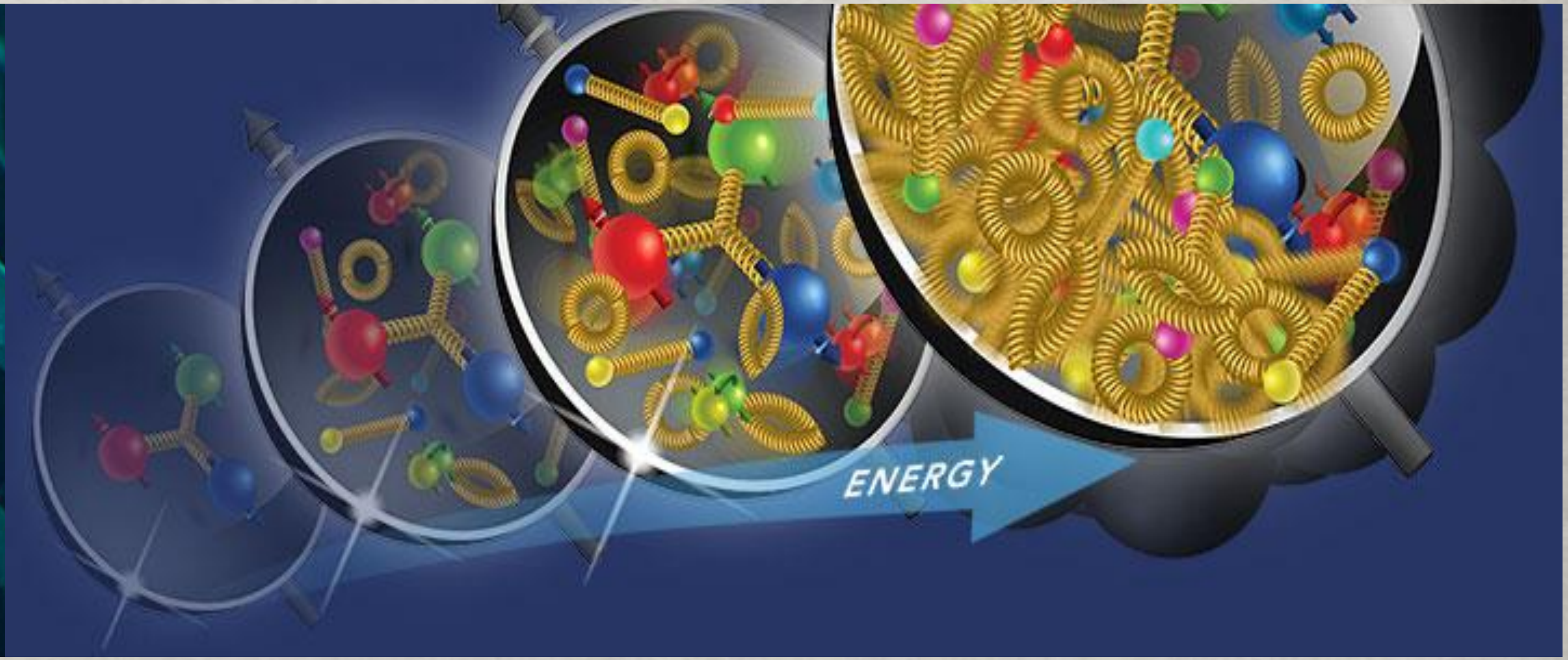
The primary physics goal of EIC

- 3D tomographic imaging of parton structure
- Precise determination of quark/gluon momentum distributions & contributions to proton spin
- Exploration of novel phases of nuclear matter at high densities

Other physics opportunities

- Precision EW physics: coupling constants
- Fundamental symmetries: parity, flavor, etc.



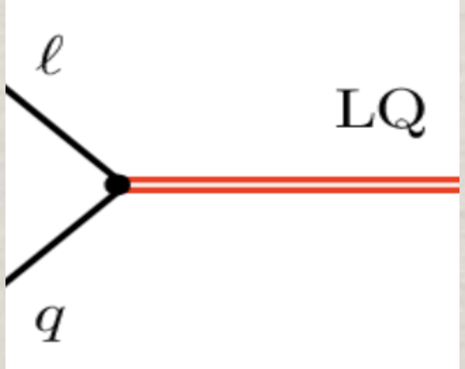


arXiv:1212.1701, 2103.05419, 2305.14572; Snowmass White paper: 2203.13199

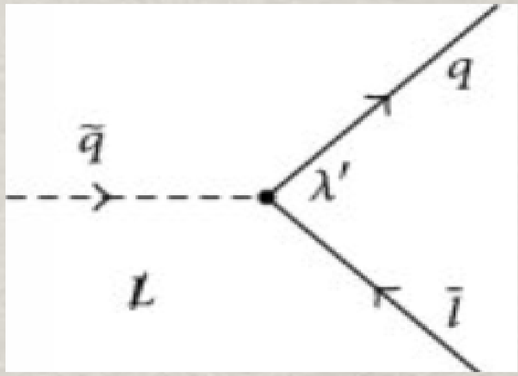
BSM physics @ EIC

Although lower energies than HERA & LHC, there are many BSM scenarios accessible

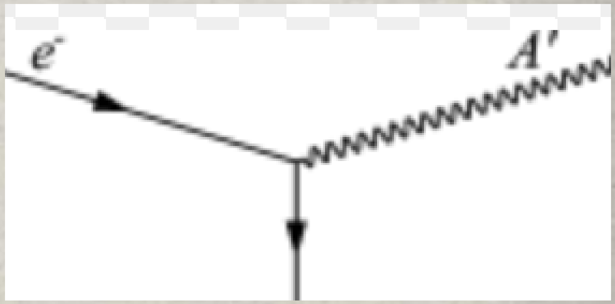
- Lepto-quarks:



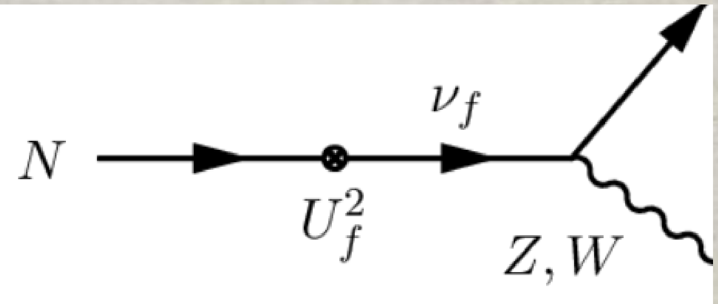
- Squarks from R-parity violation:



- Light neutral gauge boson: “Dark force”



- Light neutral fermion: “sterile neutrino”
- … …

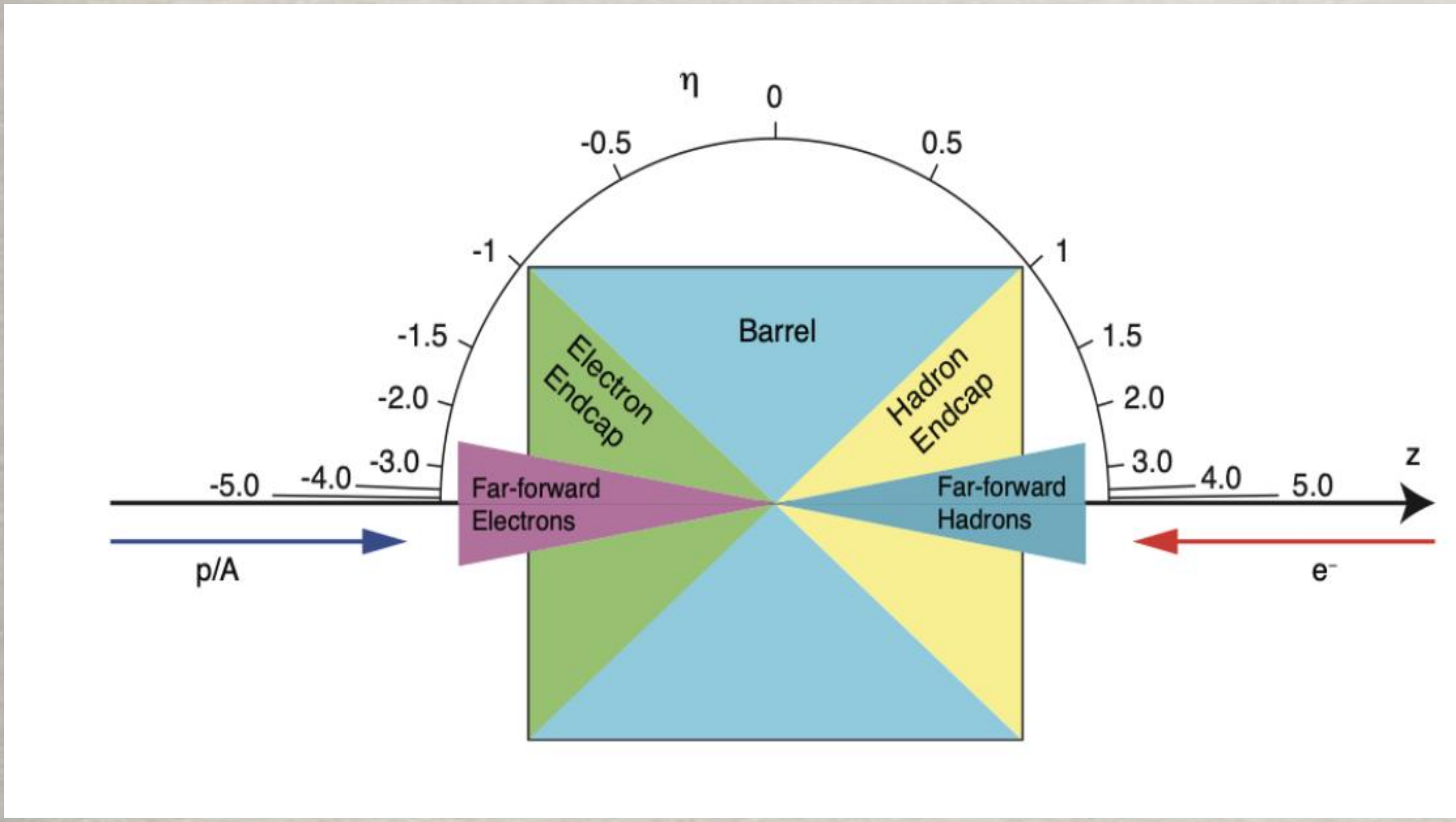


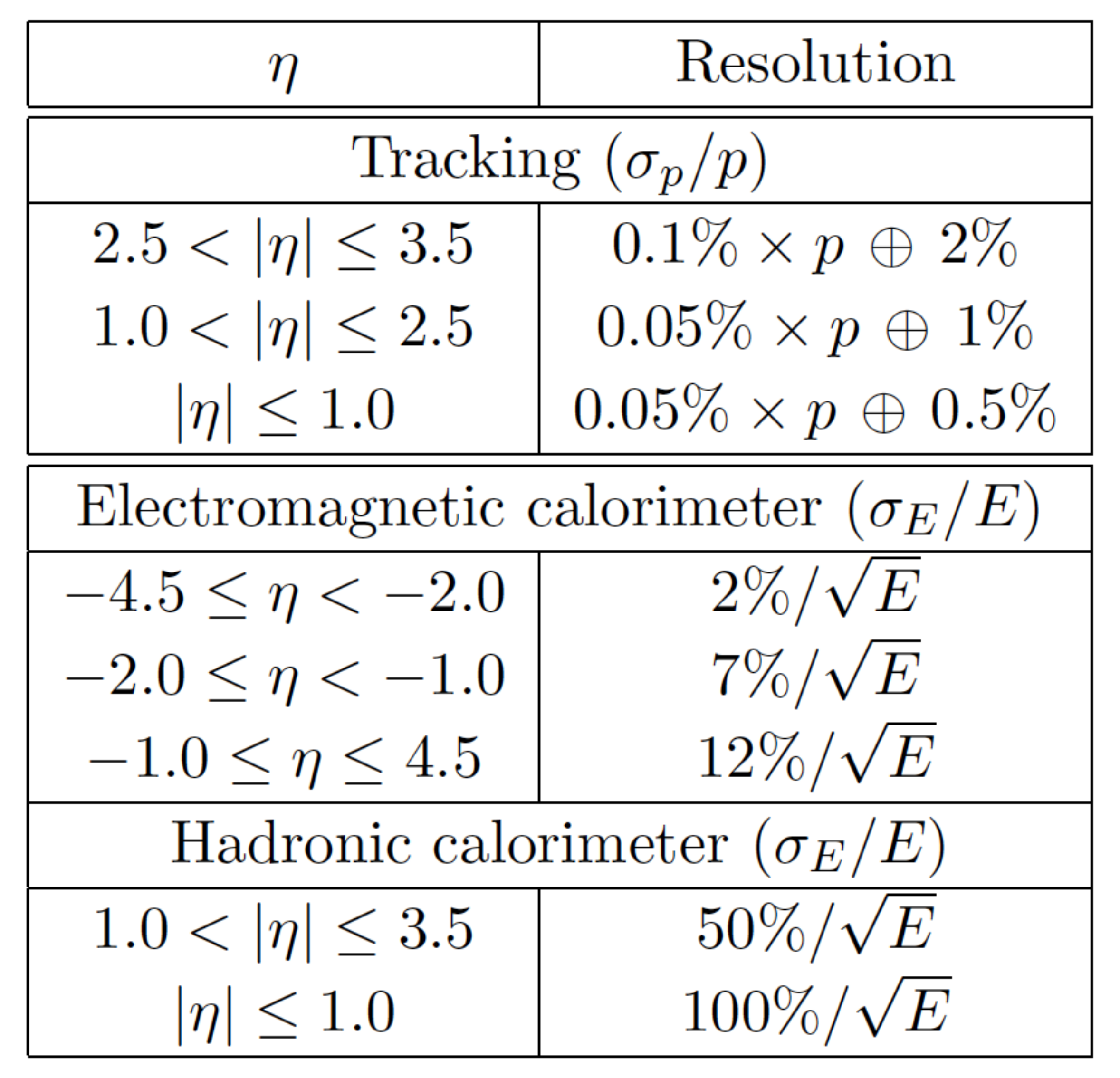
Instead, I will take a “signature driven” approach …

arXiv:1212.1701, 2203.13199

Detector capacity

- Multi-purpose detector(s)
- Good hermitic coverage of electron/hadron endcaps
- Good tracking/calorimeters resolutions





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)	
$1.0 < \lvert\eta\rvert \leq 3.5$	$50\%/\sqrt{E}$
$\lvert\eta\rvert \leq 1.0$	$100\%/\sqrt{E}$

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