Beyond the SM Physics @ EIC

Tao Han
University of Pittsburgh

798 WE-Heraeus Seminar
On Forward Physics and QCD at the LHC and EIC
Bad Honnef, Oct. 26, 2023

The Standard Model:

Triumph in science!

With the Higgs discovery, completion of the SM:

- A relativistic & quantum-mechanical
- Perturbative & unitary
- Renormalizable & ultra-violet (UV) complete

→ **potentially valid up to an exponentially high scale, perhaps to the Planck scale!**

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All known physics

$$W = \int_{k<\Lambda} [\mathcal{D}g \ldots] \; \exp\left\{ \frac{i}{\hbar} \int d^4x \sqrt{-g} \left[\frac{1}{16\pi G} R - \frac{1}{4} F^2 + \bar{\psi} i \not{D} \psi - \lambda \phi \bar{\psi} \psi + |D\phi|^2 - V(\phi) \right] \right\}$$

amplitude | current understanding | quantum mechanics | spacetime | gravity | strong & electroweak | matter | Higgs

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Dark energy or Λ?
Dark Matter?
Cosmic inflation?

All known physics

B-asymmetry?
CP violation?
M_ν ? Scale hierarchy …

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amplitude · current understanding · quantum mechanics · spacetime · gravity · strong & electroweak · matter · Higgs

Prelude : Collider needs

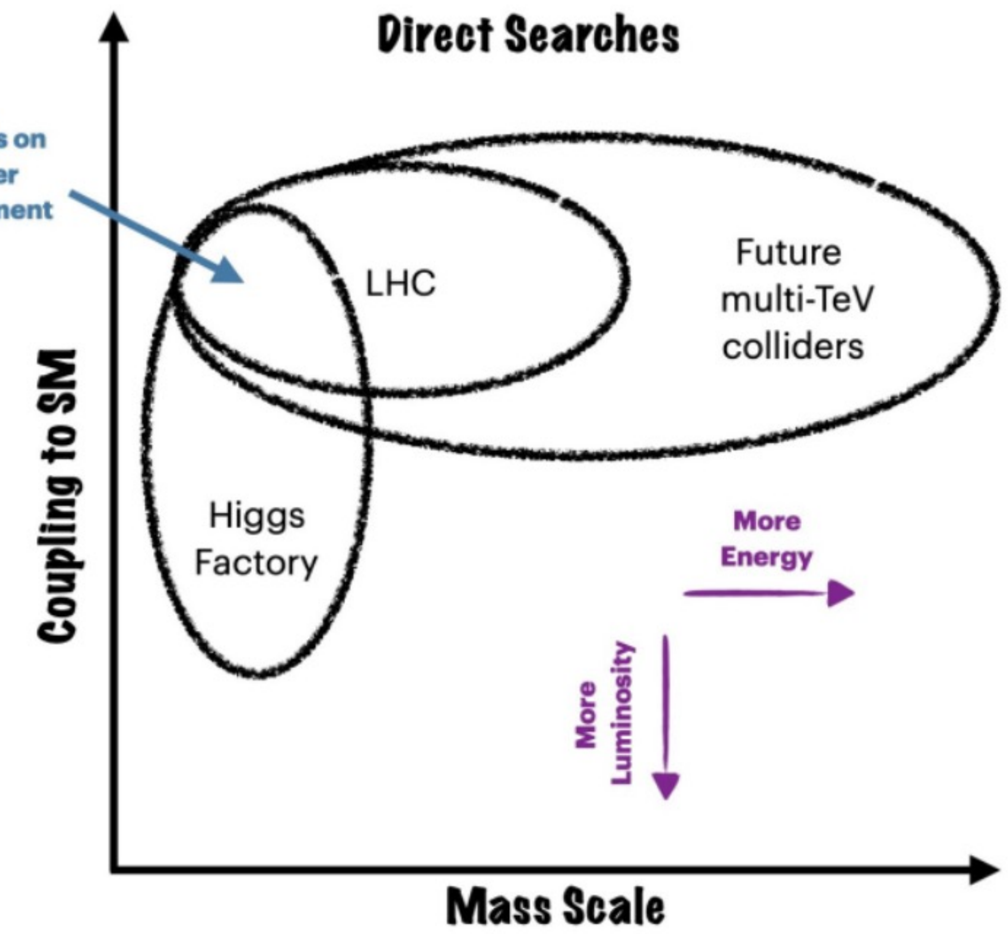

Figure 1-2. *The direct coverage of various colliders in the schematic space of coupling to the SM versus mass scale of BSM physics. "Higgs factory" and "multi-TeV colliders" correspond to a generic option among the ones listed in Table 1-1 and Table 1-2 respectively.*

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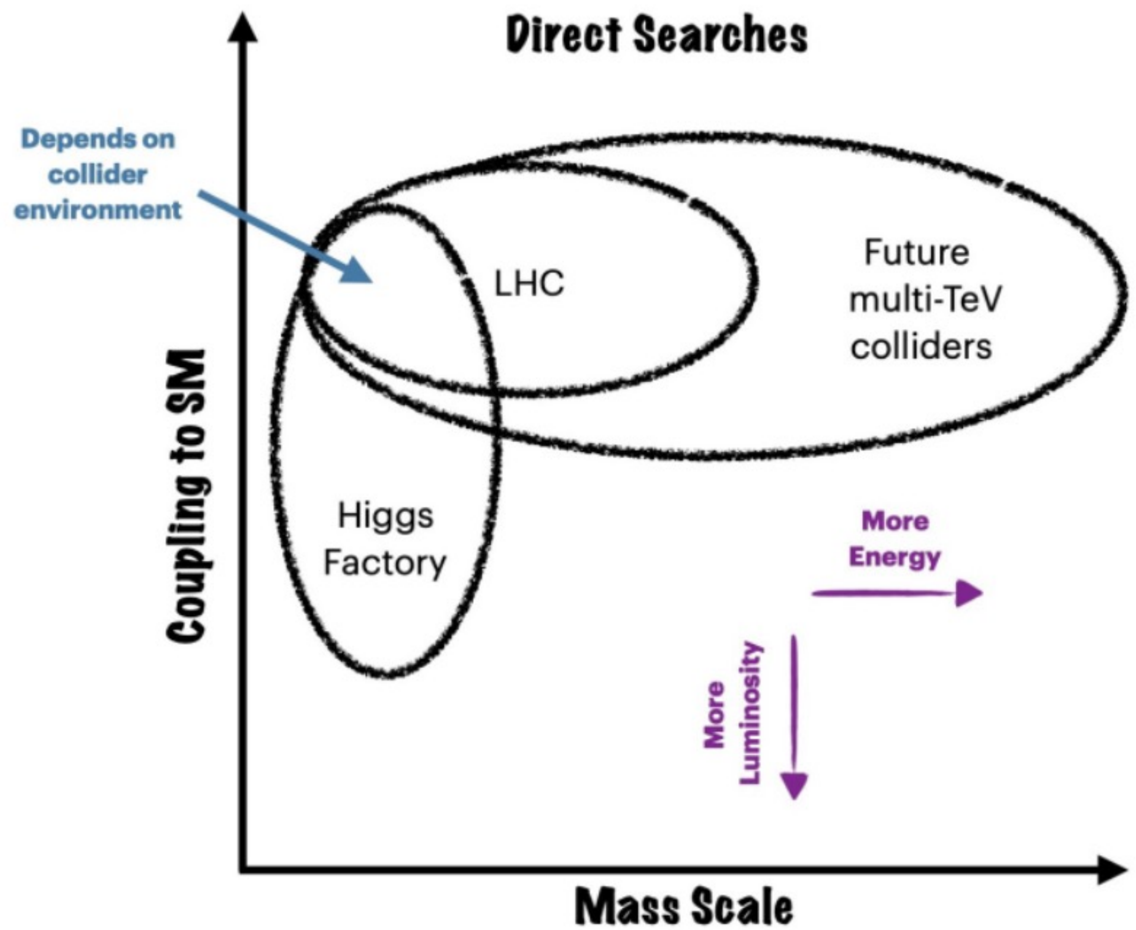

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Snowmass 2021 Energy Frontier Vision

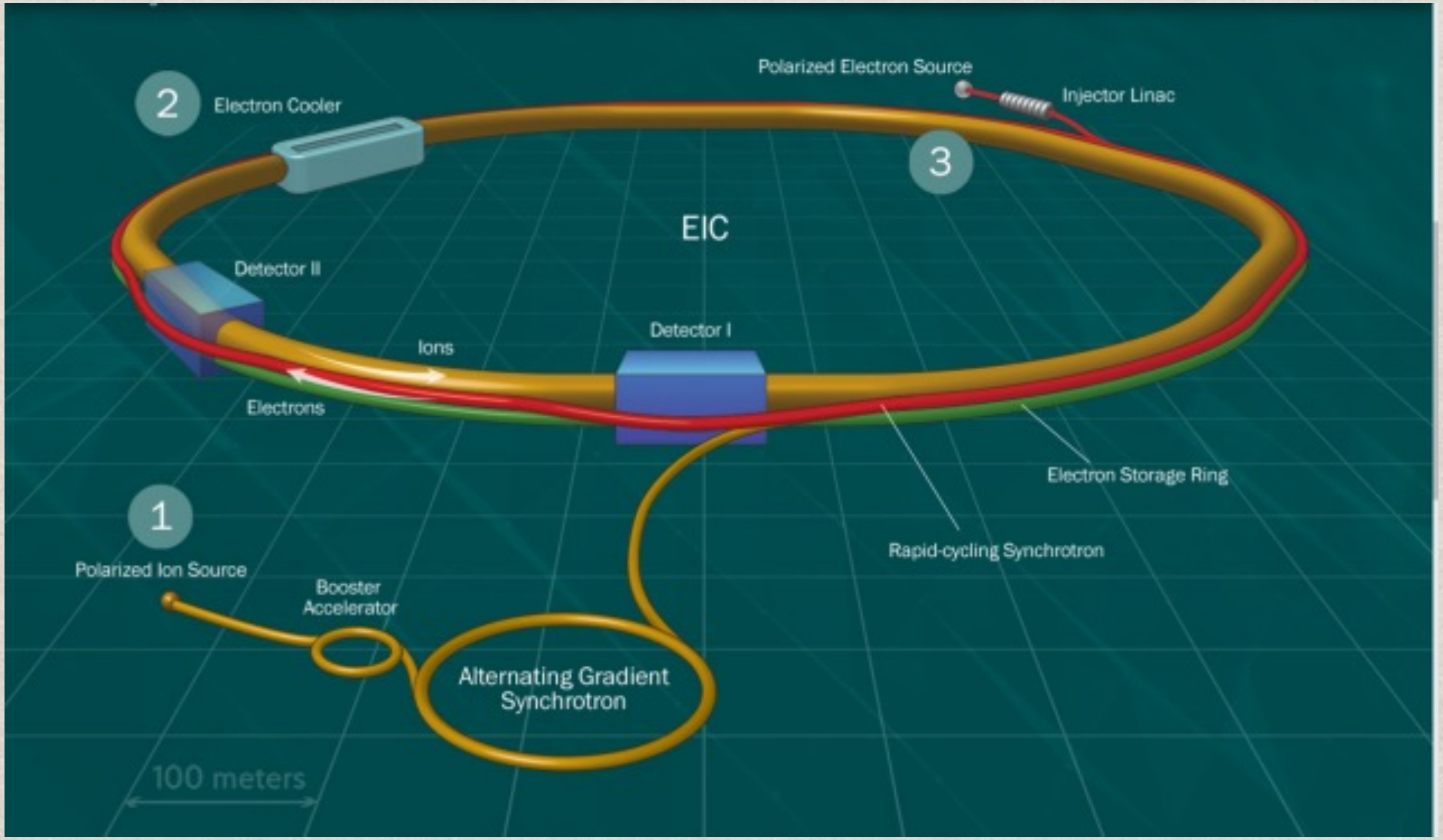
https://snowmass21.org/

- **Complete the HL-LHC program,**
- **Start now a targeted program for detector R&D for Higgs Factories**
- **Support construction of a Higgs factory**
- **Ensure the long-term viability of the field by developing a multi-TeV energy frontier facility such as a *muon collider* or a *hadron collider*.**

Introduction to EIC

The Electron-Ion Collider (EIC) at BNL

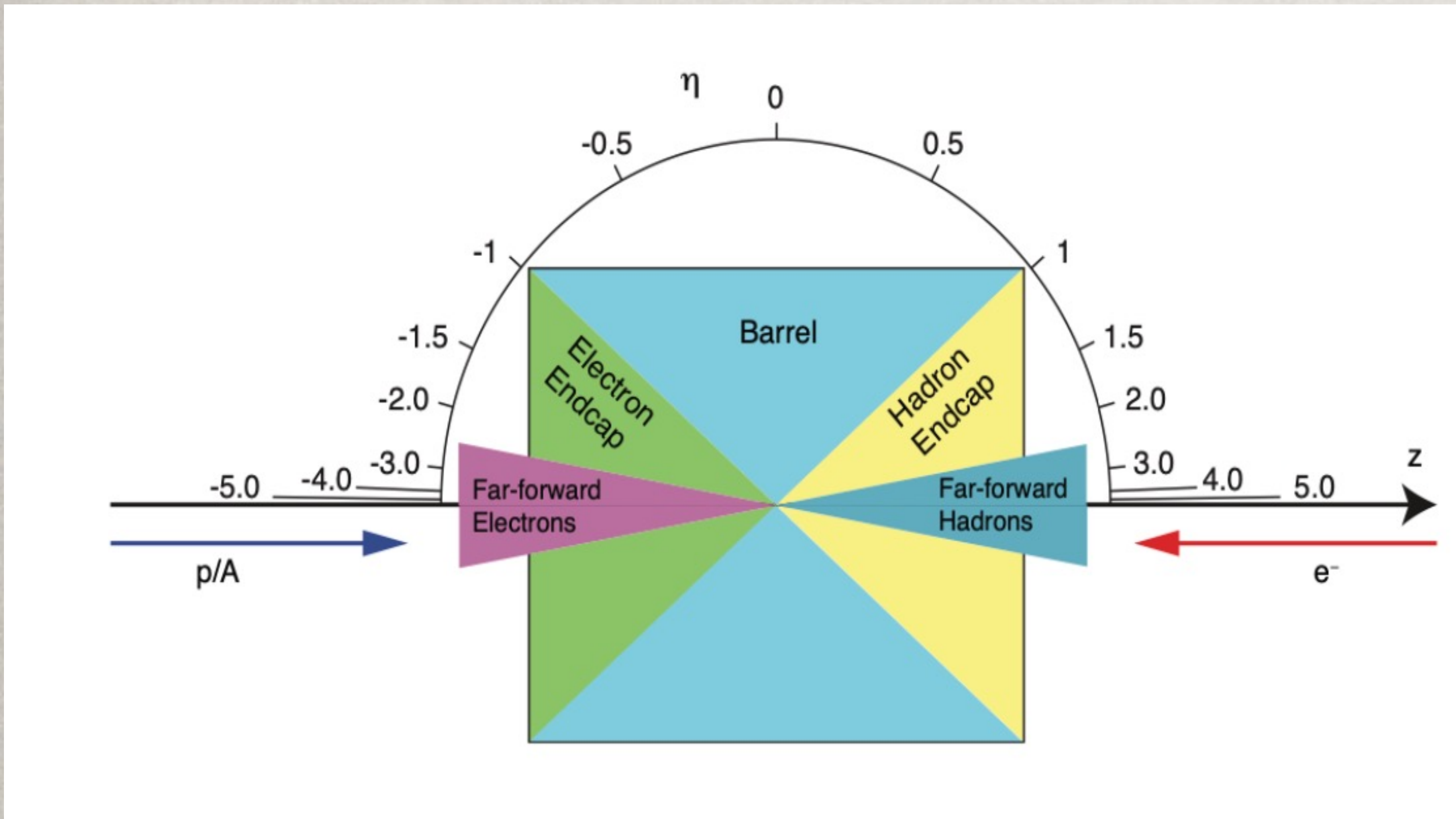
- CM energies: 20 – 100 (140) GeV
- Luminosity: $10^{33\text{-}34}$ /cm^2/s (10-100 fb^{-1}/yr, 10 -1000 times of HERA)
- Polarized electron ~ 70%; light A ~ 70%
- Range of nuclear targets: proton/deuteron/gold/uranium



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

Detector capacity

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



η	Resolution
Tracking (σ_p/p)	
$2.5 < \|\eta\| \leq 3.5$	$0.1\% \times p \oplus 2\%$
$1.0 < \|\eta\| \leq 2.5$	$0.05\% \times p \oplus 1\%$
$\|\eta\| \leq 1.0$	$0.05\% \times p \oplus 0.5\%$
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)	
$1.0 < \|\eta\| \leq 3.5$	$50\%/\sqrt{E}$
$\|\eta\| \leq 1.0$	$100\%/\sqrt{E}$

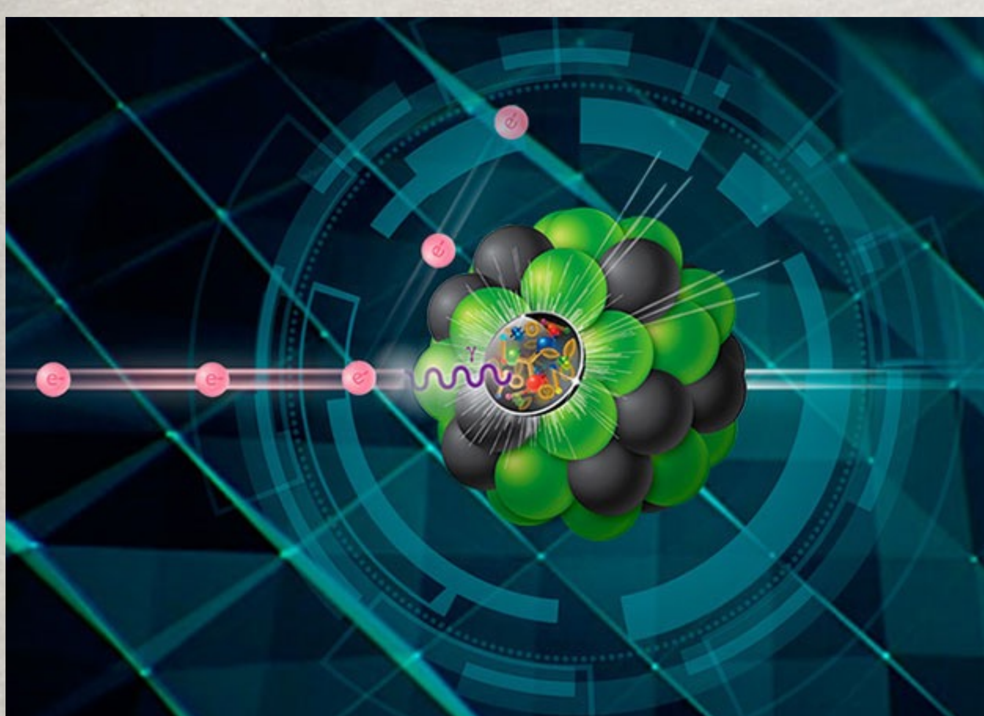
http://www.eicug.org/web/sites/default/files/EIC_HANDBOOK_v1.2.pdf

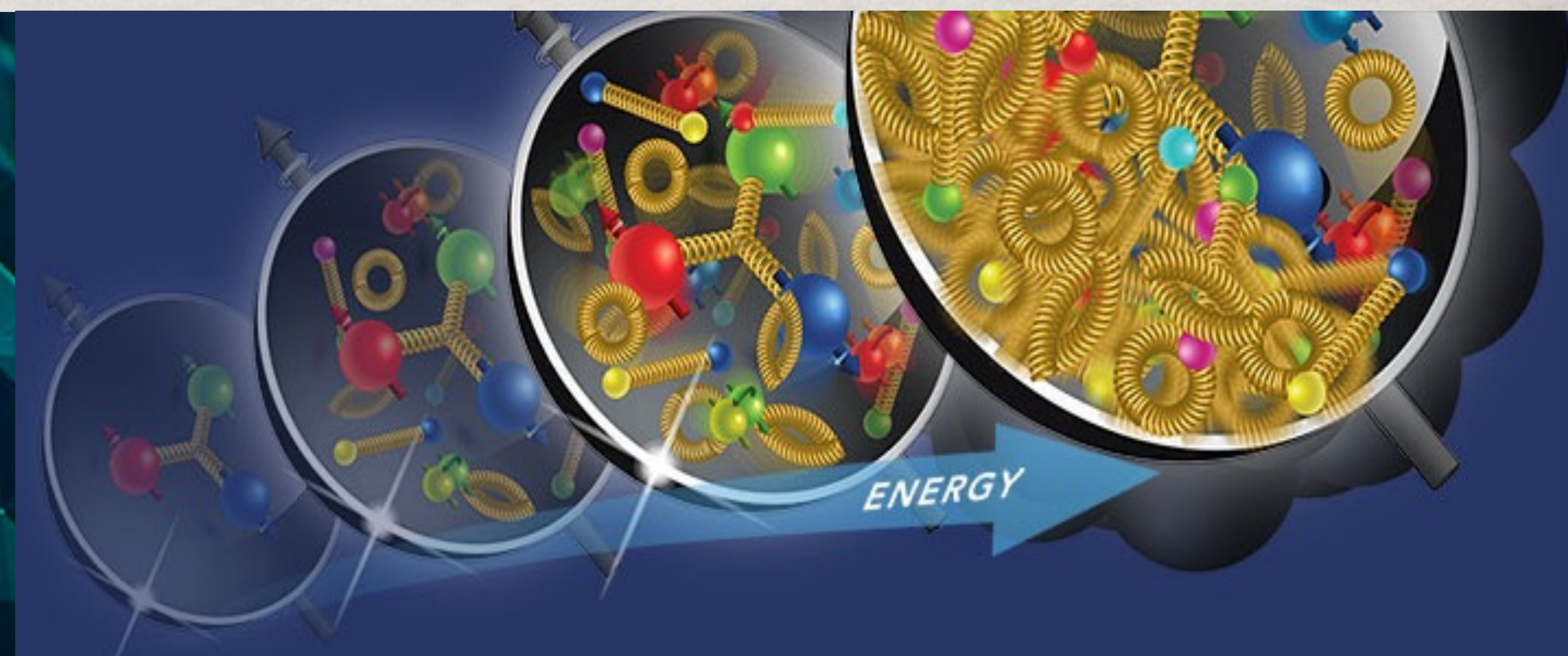
The primary physics goal of EIC

- 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.



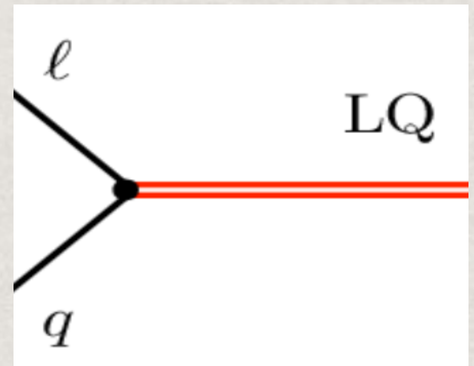


arXiv:1212.1701, 2103.05419, 2305.14572; Snowmass White paper: 2203.13199

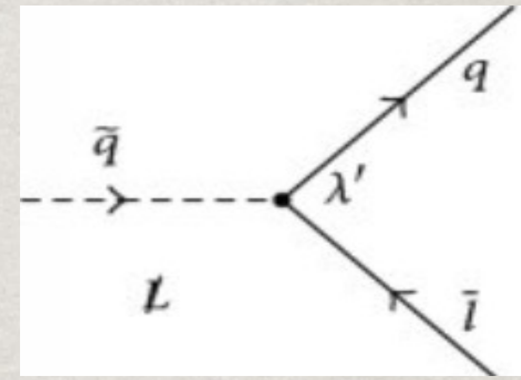
BSM physics @ EIC

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

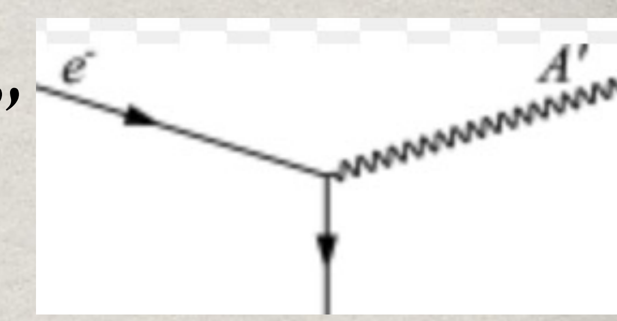
- Lepto-quarks:



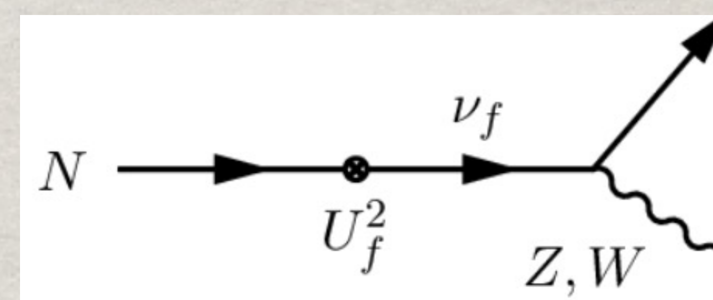
- Squarks from R-parity violation:



- Light neutral gauge boson: "Dark force"



- Light neutral fermion: "sterile neutrino"



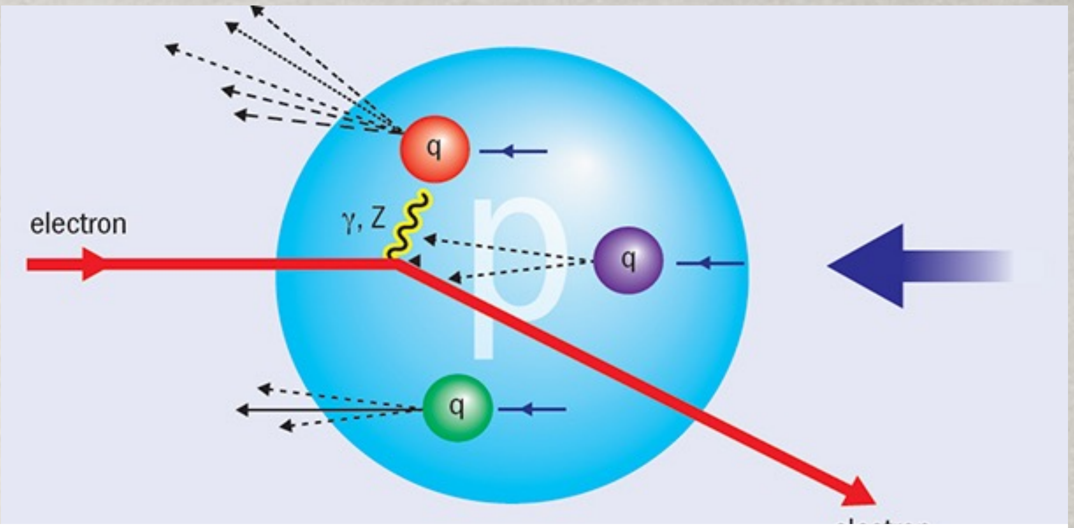
- … …

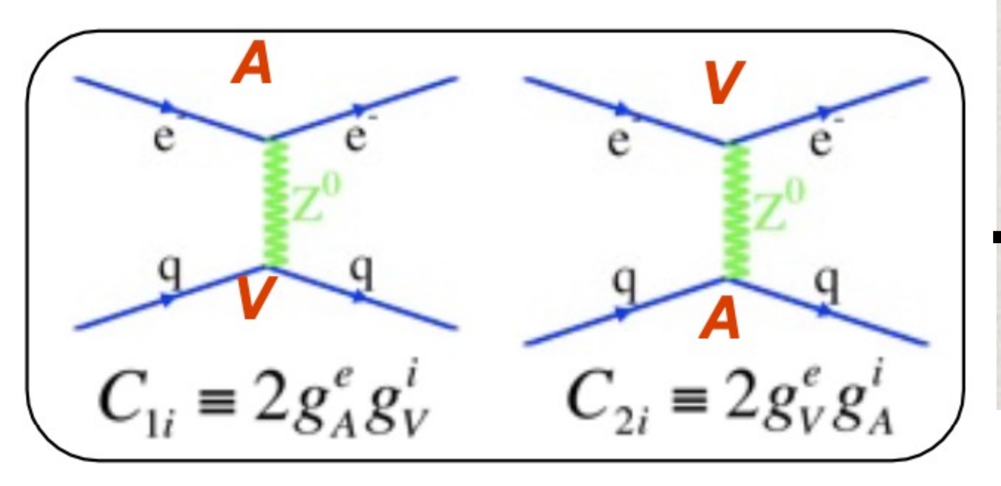
Instead, I will take a "signature driven" approach …

arXiv:1212.1701, 2203.13199

(1). Precision measurements of neutral currents

e p → e' X





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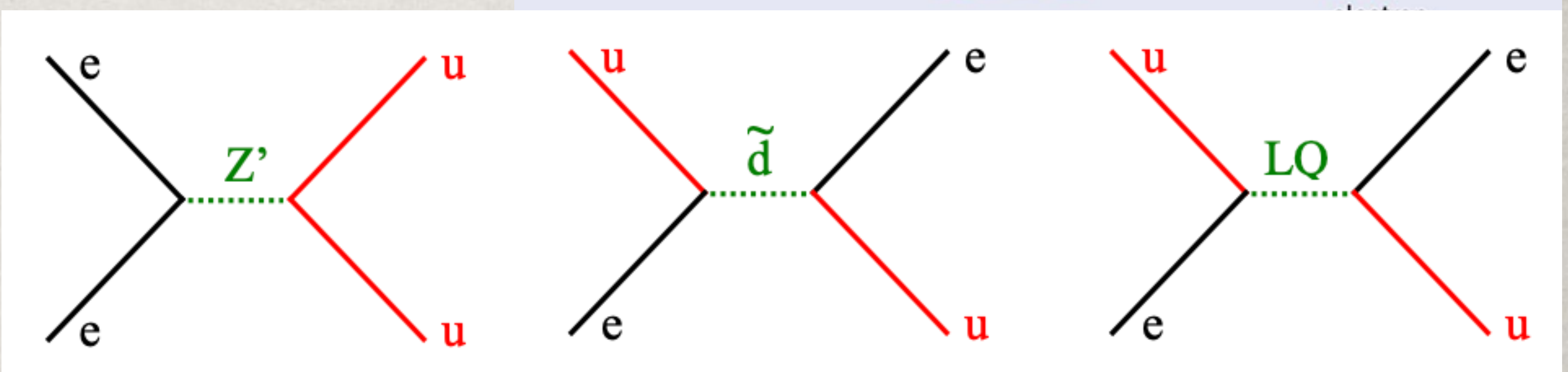


$$C_{iq} = C_{iq}(\mathrm{SM}) + \Delta C_{iq}$$

SM NC: $$\mathcal{L} = \frac{G_F}{\sqrt{2}}\left[\bar{e}\gamma^\mu\gamma_5 e\left(C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right) + \bar{e}\gamma^\mu e\left(C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\right)\right]$$

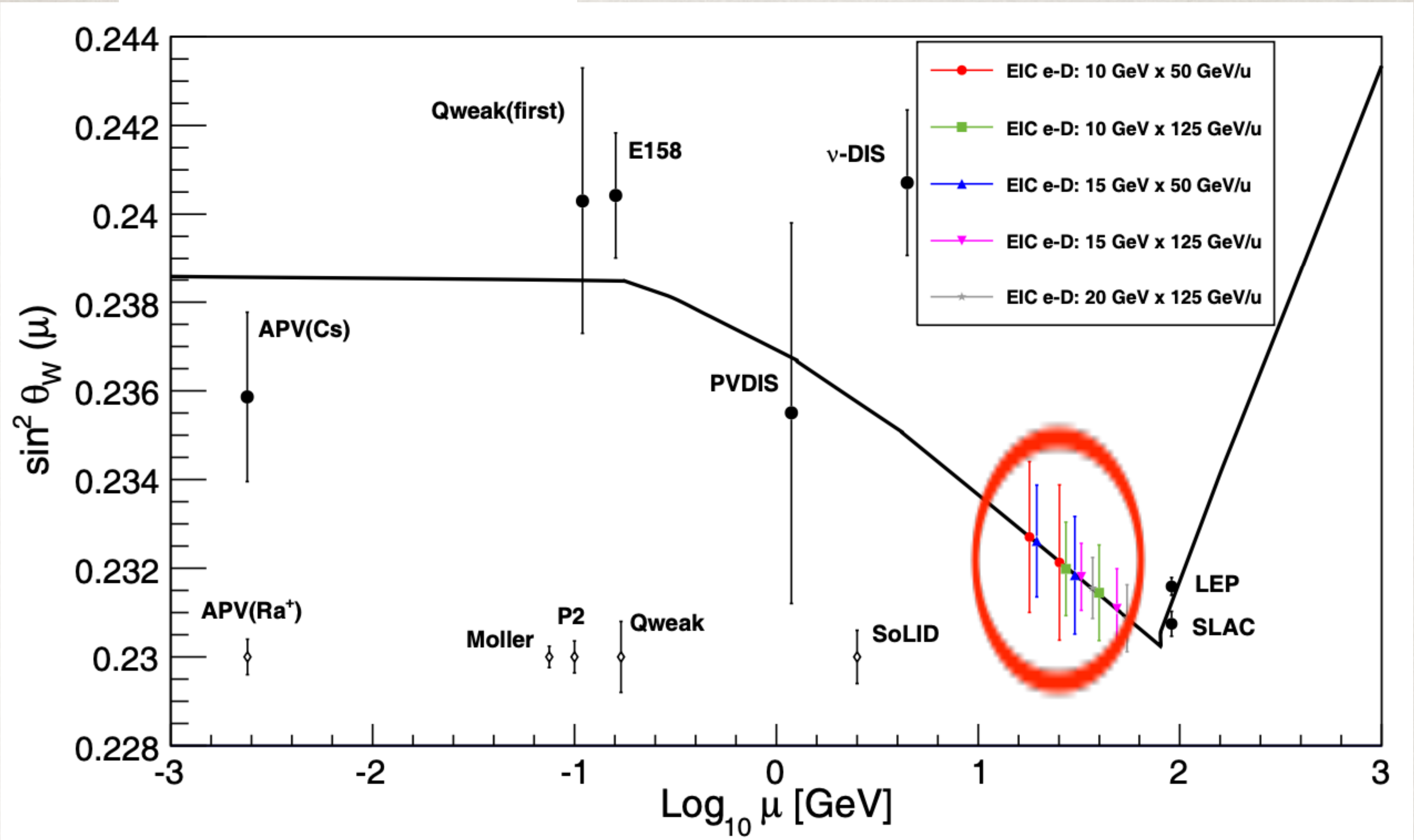
BSM Effective Field Theory (EFT) at dim-6:

$$\delta\mathcal{L} = \frac{g^2}{\Lambda^2}\sum_{\ell,q}\left\{\eta_{LL}^{\ell q}\,\bar{\ell}_L\gamma_\mu\ell_L\bar{q}_L\gamma_\mu q_L + \eta_{LR}^{\ell q}\,\bar{\ell}_L\gamma_\mu\ell_L\bar{q}_R\gamma_\mu q_R + \eta_{RL}^{\ell q}\,\bar{\ell}_R\gamma_\mu\ell_R\bar{q}_L\gamma_\mu q_L + \eta_{RR}^{\ell q}\,\bar{\ell}_R\gamma_\mu\ell_R\bar{q}_R\gamma_\mu q_R\right\}$$

$$\Delta C_{1q} = \frac{g^2}{\Lambda^2}\frac{\eta_{LL}^{\ell q} + \eta_{LR}^{\ell q} - \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q}}{2\sqrt{2}G_F},\quad \Delta C_{2q} = \frac{g^2}{\Lambda^2}\frac{\eta_{LL}^{\ell q} - \eta_{LR}^{\ell q} + \eta_{RL}^{\ell q} - \eta_{RR}^{\ell q}}{2\sqrt{2}G_F}$$

- **Weak mixing angle & parity violation**
  EIC sensitivity in unique energy region

$$A_{PV}^{\mathrm{electron}} = \frac{\sigma^R - \sigma^L}{\sigma^R + \sigma^L} \quad A_{PV}^{\mathrm{hadron}} = \frac{\sigma^{(+)} - \sigma^{(-)}}{\sigma^{(+)} + \sigma^{(-)}} \rightarrow \sin^2\boldsymbol{\theta}_w$$



Y.X.Zhao, A.Deshpande et al., arXiv:1612.06927

- **Light Z' contribution to parity violation**

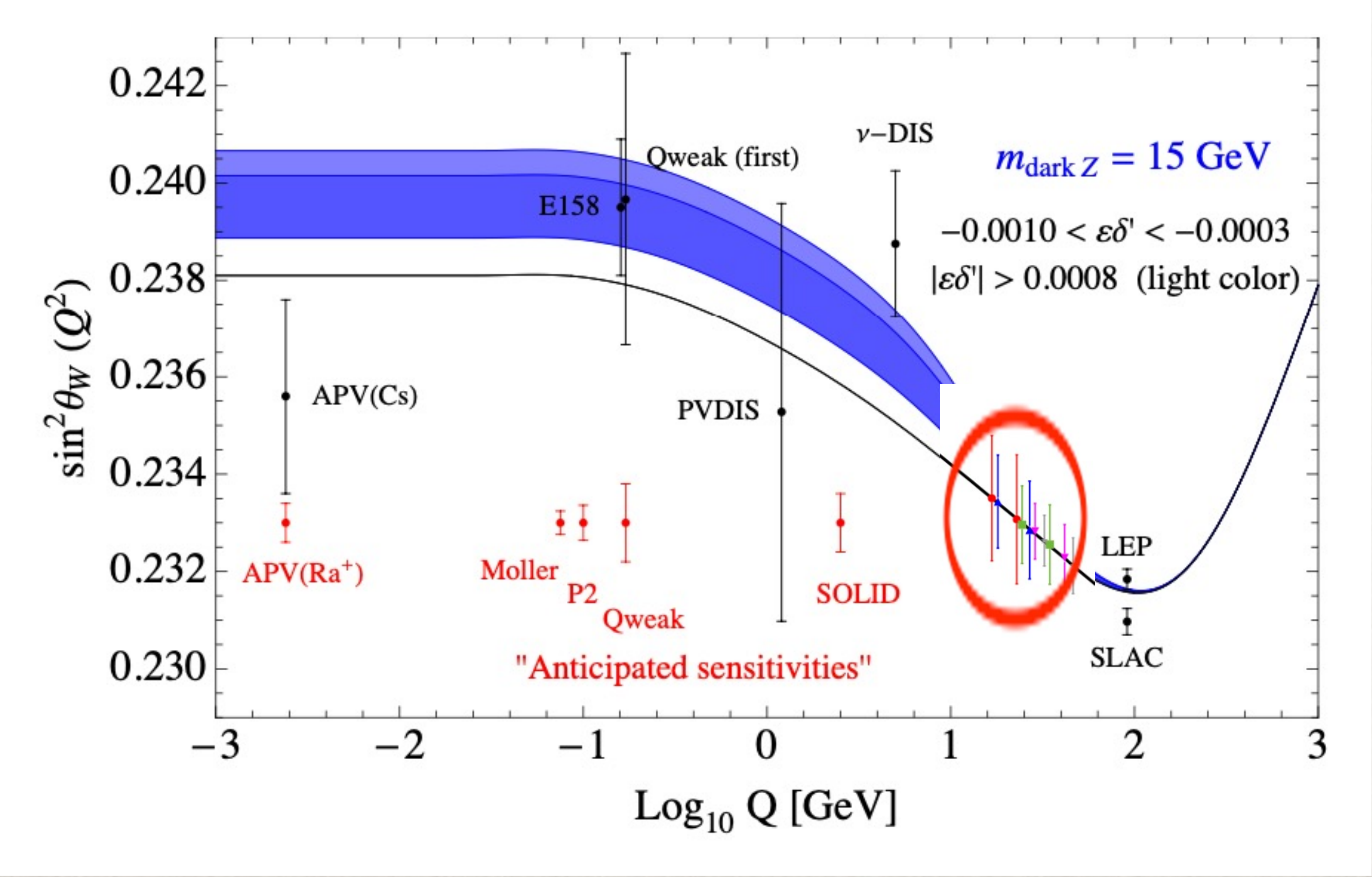
H. Davoudiasl, H. Lee, W. Marciano, arXiv:1203.2947v3

$$B_\mu \to B_\mu + \frac{\varepsilon}{\cos\theta_W} Z_{d\mu}$$

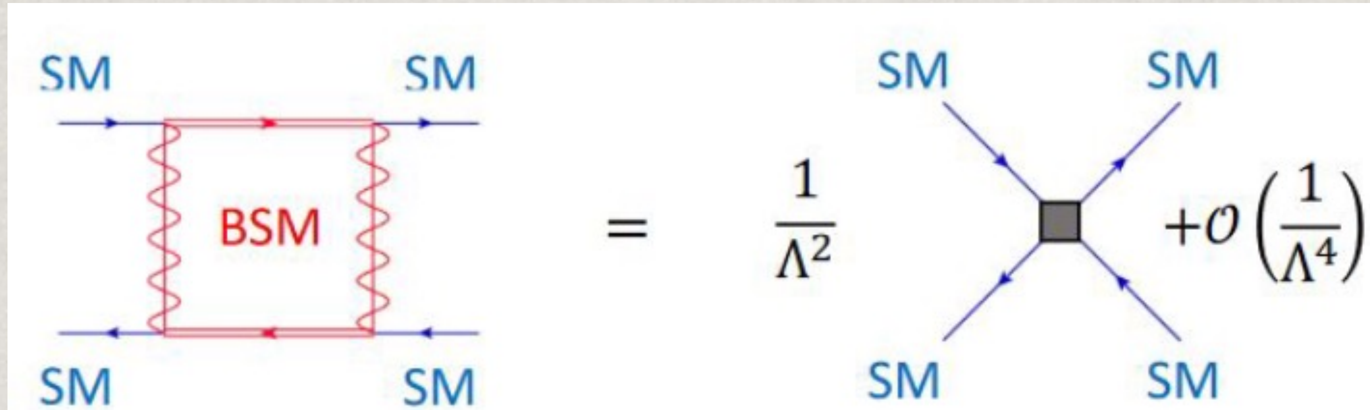
$$\mathcal{L}_{\rm int} = -e\varepsilon J^\mu_{em} Z_{d\mu}$$
$$J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$$

$$G_F \to \rho_d G_F$$
$$\sin^2\theta_W \to \kappa_d \sin^2\theta_W$$

$$\Delta \sin^2\theta_W(Q^2) \simeq -0.42\,\varepsilon\delta\,\frac{m_Z}{m_{Z'}}\frac{1}{1+Q^2/m_{Z'}^2}$$



- **Complementary SMEFT**



$$\mathcal{L}_{\mathrm{SMEFT}} = \frac{1}{\Lambda^2}\sum_r \tilde{C}_r \Big\{ \sum_f \bar{e}\gamma^\mu (c^e_{V_r} - c^e_{A_r}\gamma_5) e\, \bar{q}_f \gamma^\mu (c^f_{V_r} - c^f_{A_r}\gamma_5) q_f \Big\} + \cdots$$

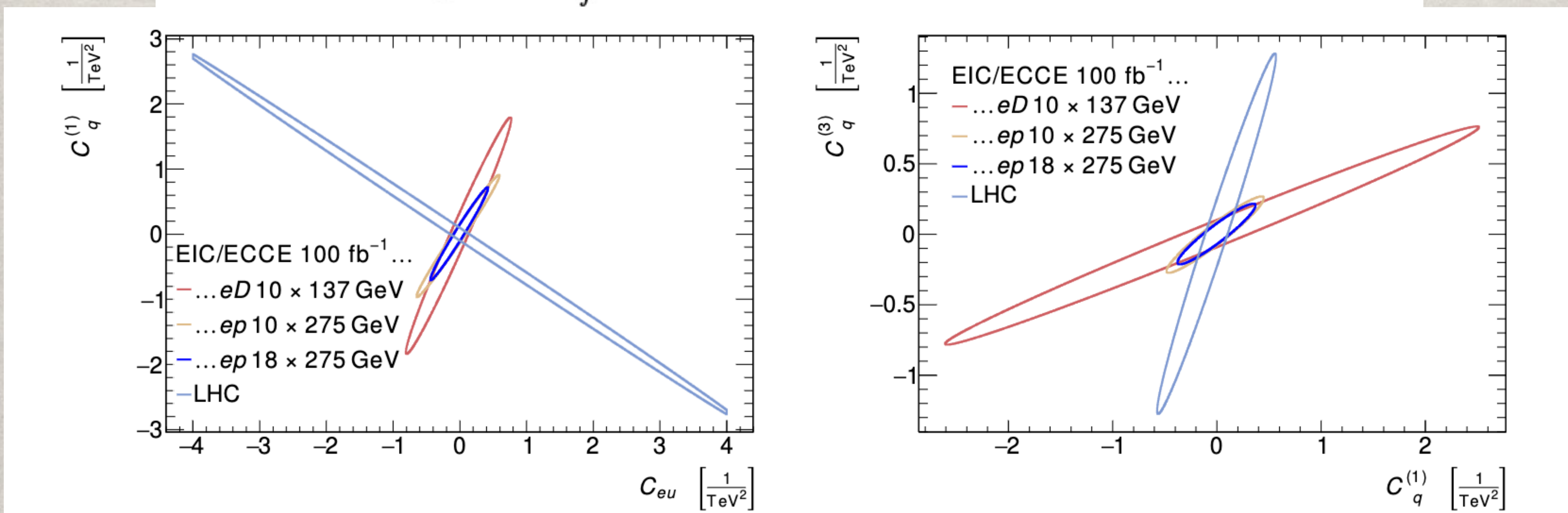


FIG. 4. From [6]: Examples of 'flat directions' when using only LHC data to constrain Wilson coefficients. The Wilson coefficients plotted correspond to the operators defined in Table I. The inclusion of high precision $A_{PV}^{(e)}$ data from EIC (projected here using the ECCE detector) would provide strong, complementary constraints on the parameter space.

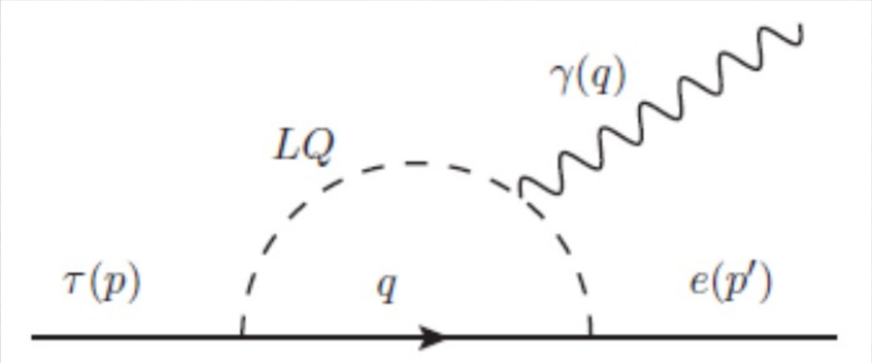
R. Boughezal et al., arXiv:2204.07557; Snowmass White Paper: arXiv:2203.13199

(2). Lepton flavor violation

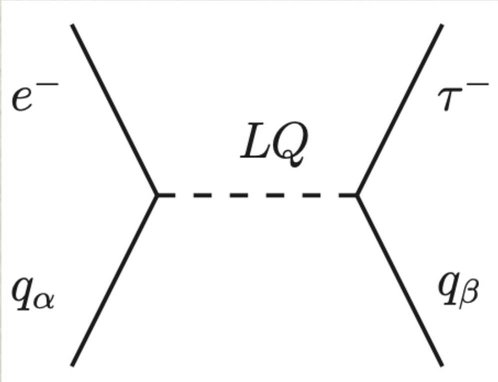
$e\,p \rightarrow \mu X,\ \tau X$

BSM flavor physics is of high importance!

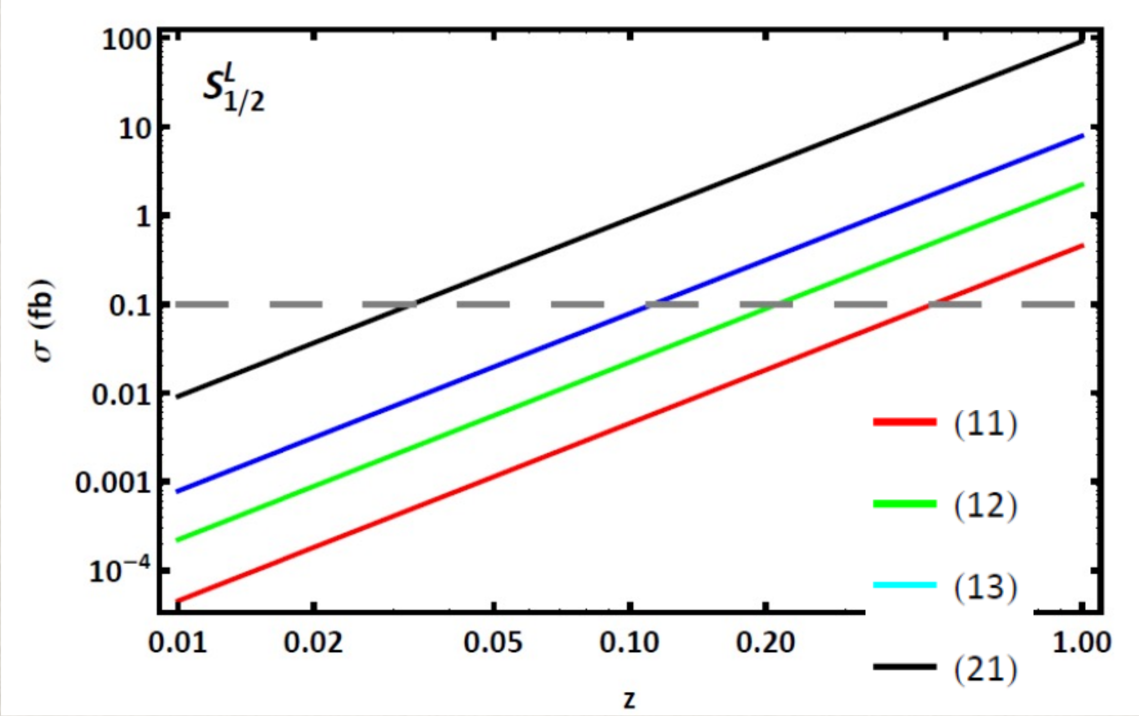
- SUSY – RPv
- GUTs SU(5), SO(10)
- Lepto-quarks in E6 etc.
- Left-right symmetric models
- Randall-Sundrum, extra-dim



M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063



$$z = \frac{(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)}{[(\lambda_{1\alpha}\lambda_{3\beta})/(M_{LQ}^2)]_{\text{HERAlimit}}}$$



Heavy flavor still viable,
beyond HERA reach, thanks to high lumi EIC.

(3). Exotic lepton pair signal

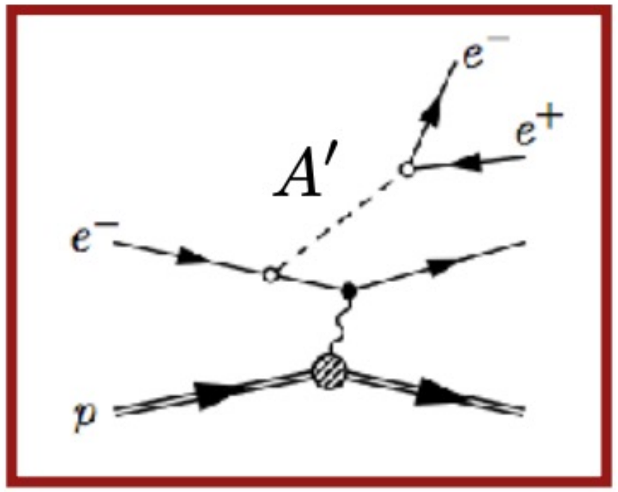
Production of dark photon/dark force

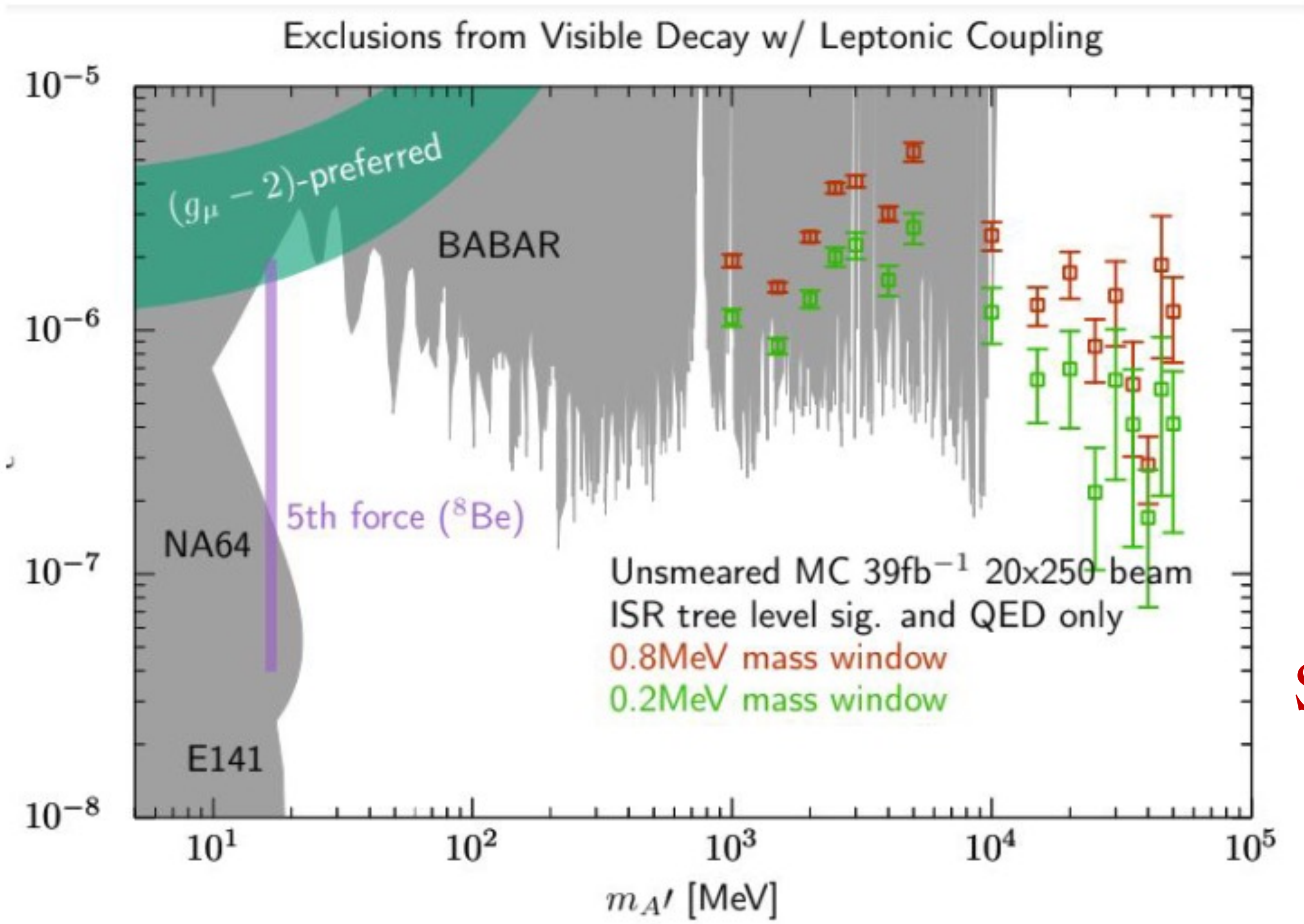
$e\,p \rightarrow e\,X + e^+e^-,\ \mu^+\mu^-$

$$L \supset \frac{\epsilon}{2} F_{\mu\nu} F'^{\mu\nu}$$

Current bounds & sensitivity:

A' Signal





Ross Corliss

$$\alpha_D = S \frac{\alpha_{D0}}{\sqrt{L}} \frac{\sqrt{\sigma_{QED}}}{\sigma_{A0}}$$

Snowmass White Paper: arXiv:2203.13199

(4). Lepton-number violation

SM gauge invariant operator is at dim-5:*

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

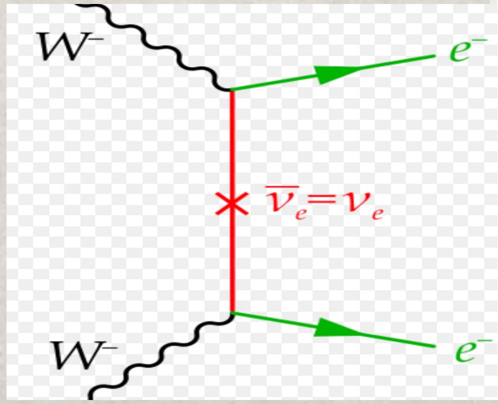
*S. Weinberg, Phys. Rev. Lett. 1566 (1979)

"Heavy Neutral Lepton" (HNL) as a prototype:
Type-I Seesaw for neutrino mass

$$-\mathcal{L} \supset y_\nu^{iI}\, \hat{L}_i\, H \hat{N}_I + \text{H.c.}\,, + (1/2) M_M N^T N$$

Minkowski '77; Yanagita '79; Gell-Mann '79 …

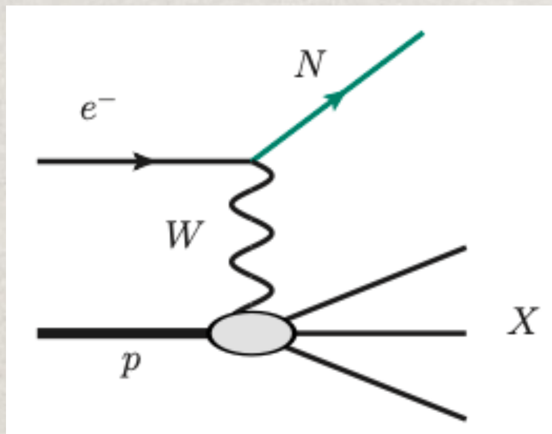
- "Seesaw" spirit: light **ν** < -- > heavy N
- Lepton-number violation by 2 units
  → most wanted: 0**ν**2**β** decay:

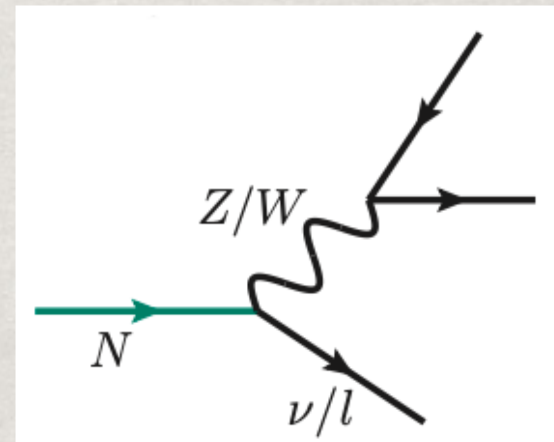


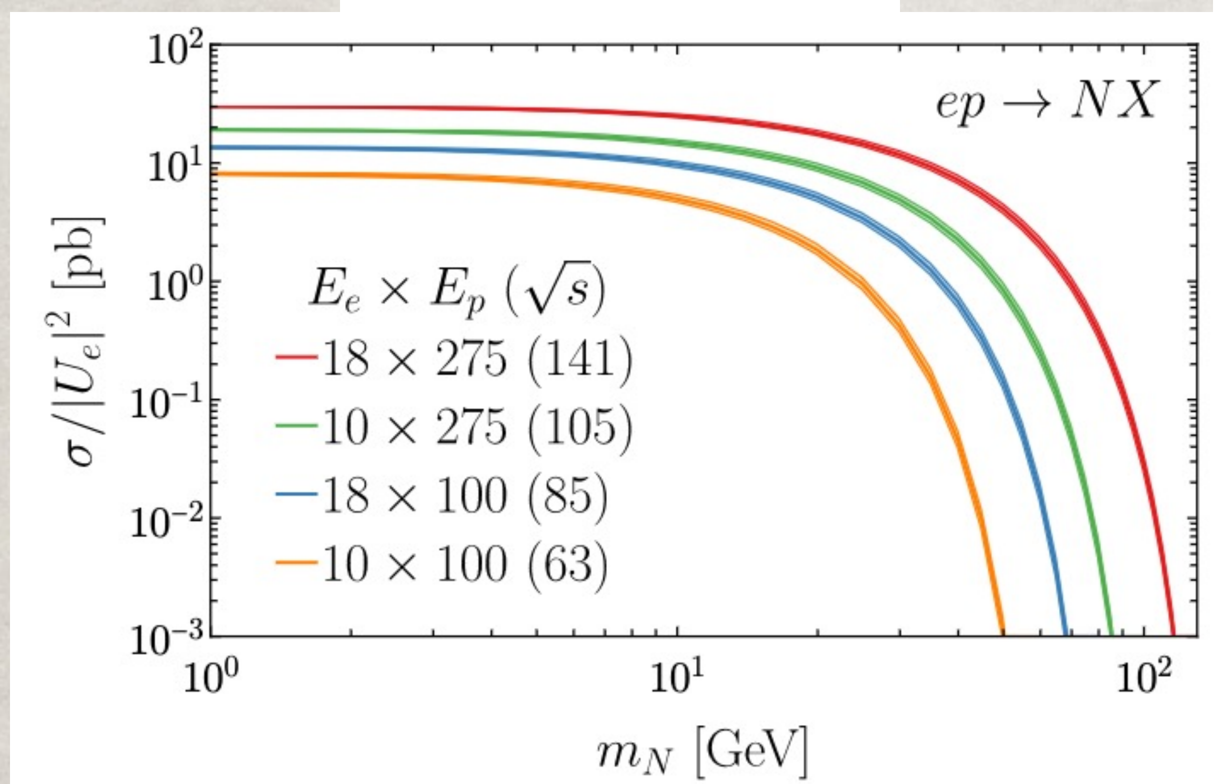
- N - **ν** mixing effects in NC and CC:

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

Production $e^- p \rightarrow N X$: Decay $N \rightarrow l^\pm W^\mp$, **ν** Z



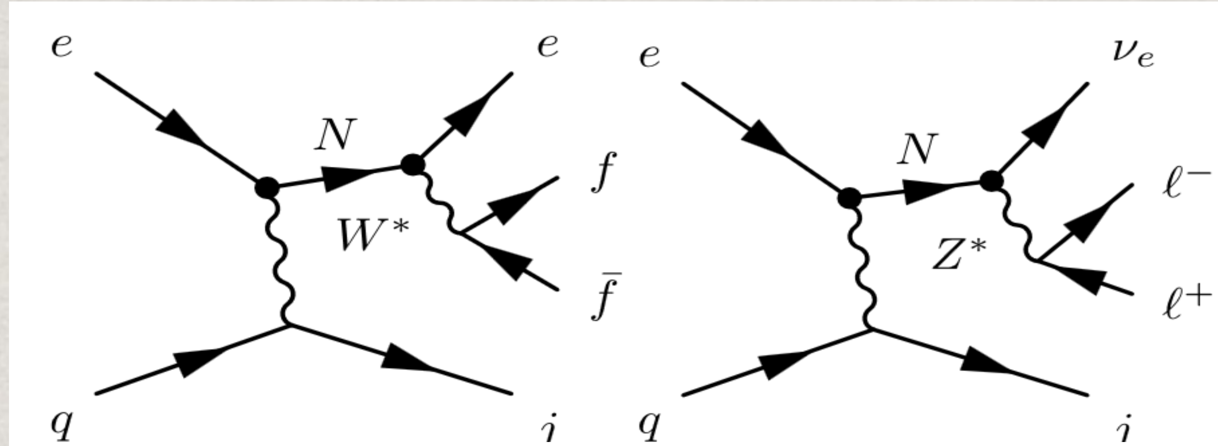




B. Batell, T. Ghosh, T. Han, K. Xie, arXiv:2210.09287

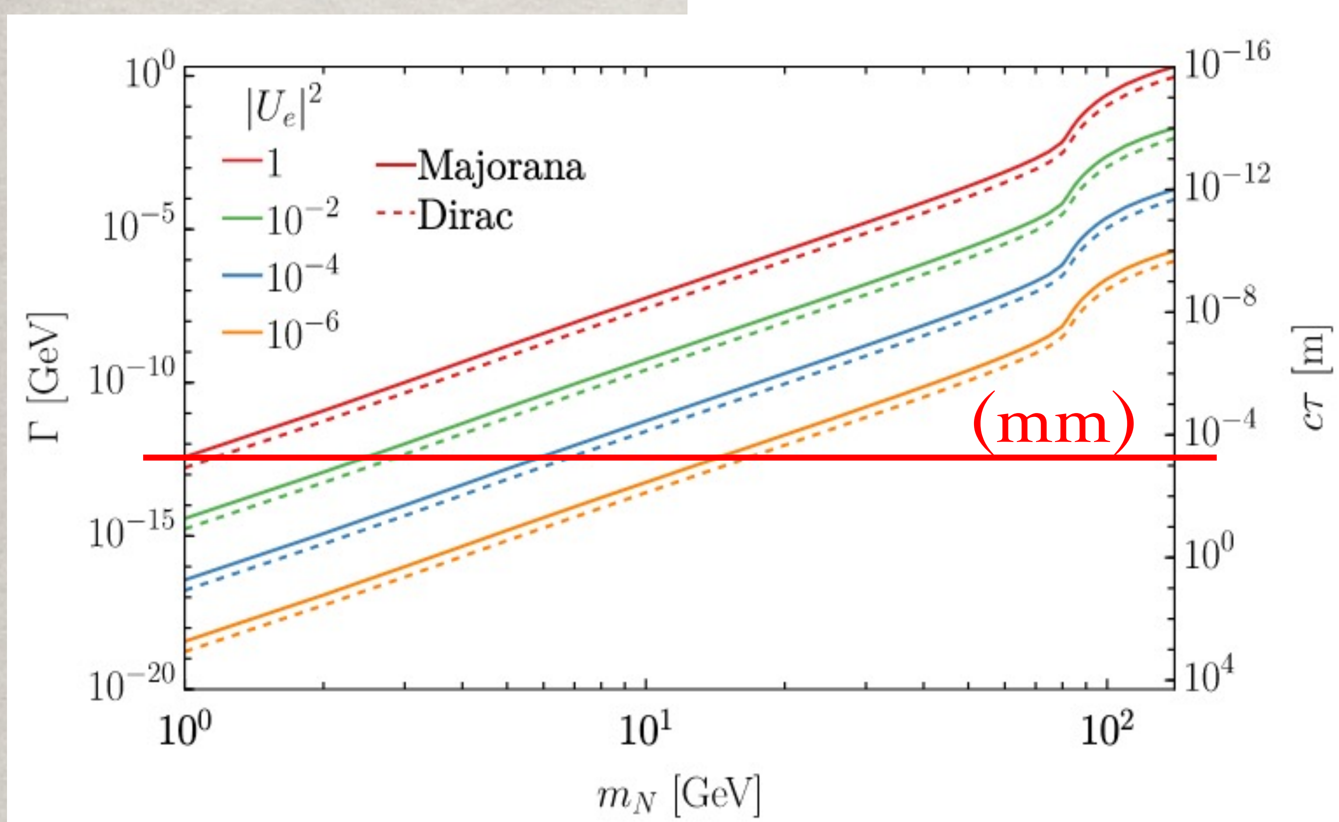
σ ~ O(a few fb) @ $U^2 \sim 10^{-4}$

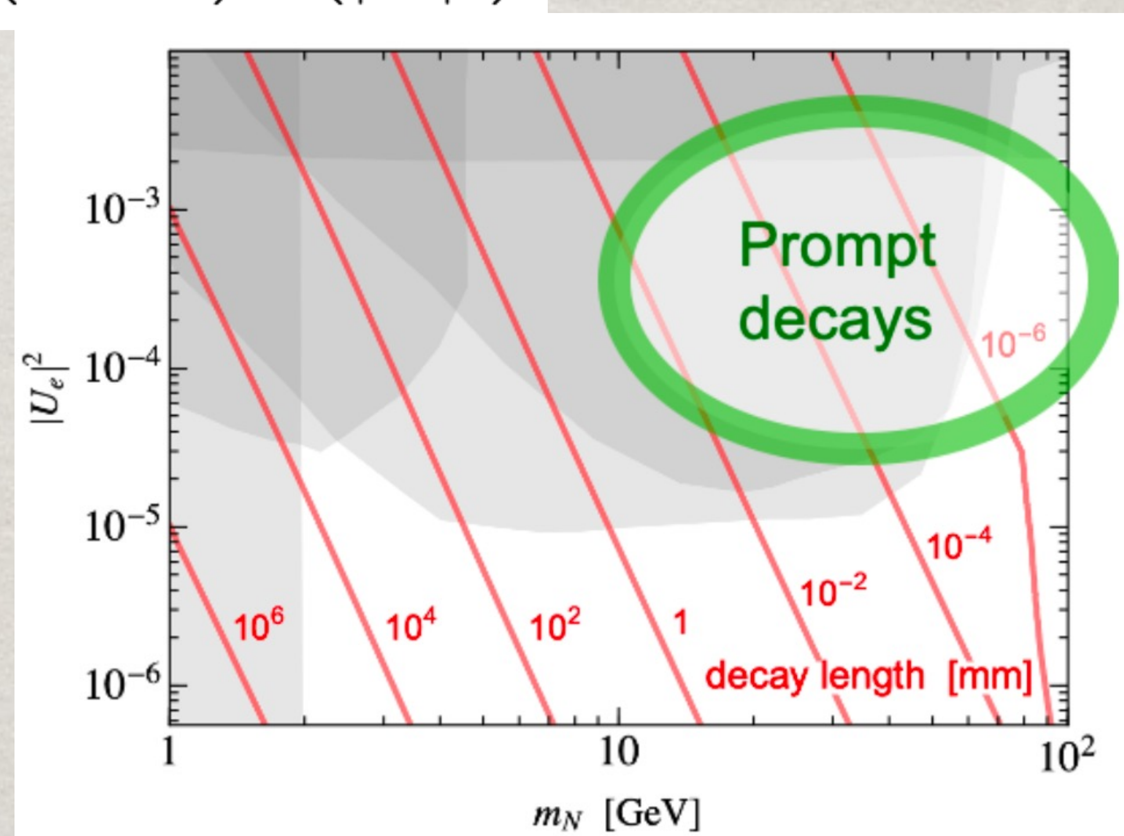
$N \rightarrow l^{\pm} W^{\mp}$, $\boldsymbol{\nu}$ Z: Majorana or Dirac



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

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





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

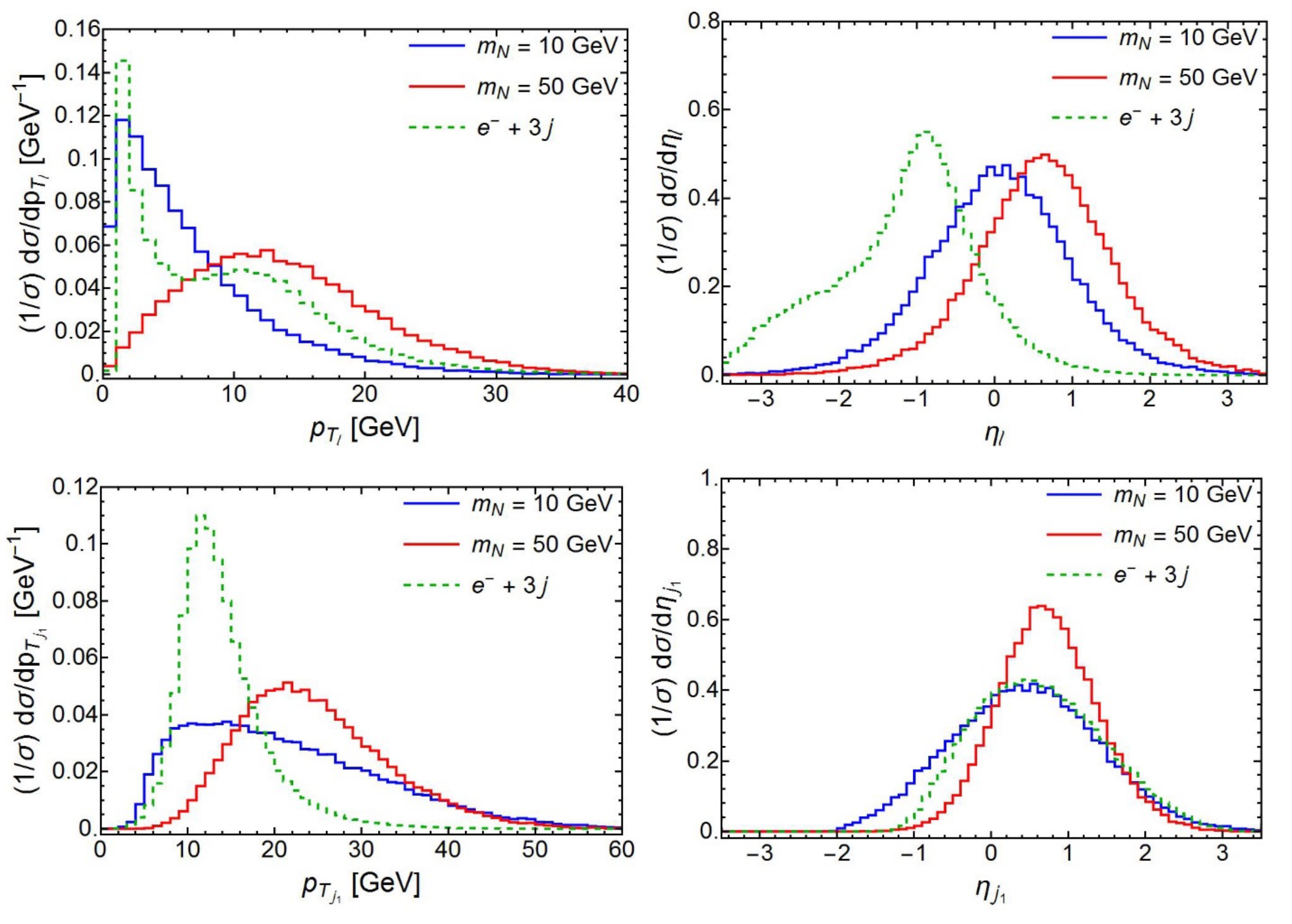
- # N prompt decay signal:

Three channels are considered

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

Though NO SM background for e^+, e^- may fake e^+ as backgrnd!

$e^- p \rightarrow N(e^+ jj') + j$ (Majorana $\Delta L=2$)

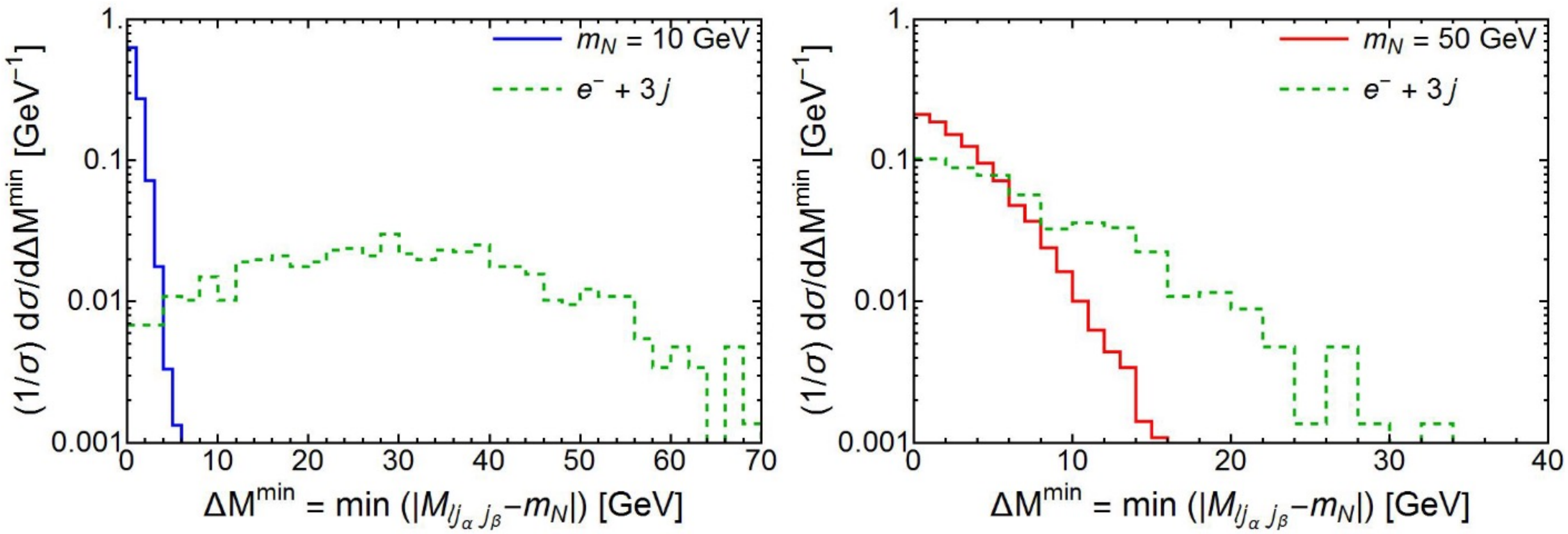


Acceptance cuts:

$p_{T_\ell} > 2$ GeV and $0 < \eta_\ell < 3.5$.

$|\eta_j| < 3.5$ with $p_{T_{j_1}} > 20$ GeV,

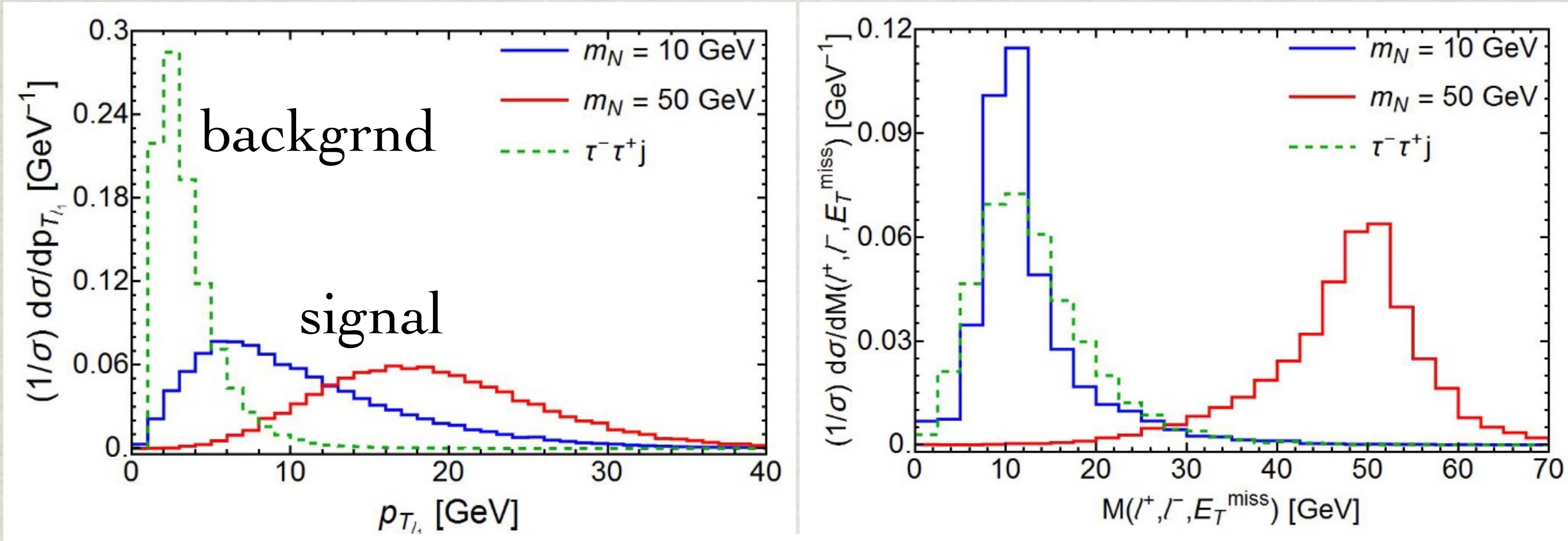
and $p_{T_{j_{2,3}}} > 5$ GeV.



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 $\times$	$\times$ 0.30	0.03 0.64
Require one e^+ $[f^{\text{MID}} = 0.1\%]$	0.22 $\times$	$\times$ 0.30	3.23×10^{-5} 6.40×10^{-4}
Require one e^+ $[f^{\text{MID}} = 0.01\%]$	0.22 $\times$	$\times$ 0.30	3.23×10^{-6} 6.40×10^{-5}
Polarization $P_e = -70\%$	$\times 1.7$	$\times 1.7$	$\times 1$

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.

$e^- p \rightarrow N(e^+ \mu^- \nu) + j$ (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	$\times$	1.72×10^{-5}
$\lvert M(\ell^+, \ell^-, E_T^{\rm miss}) - m_N\rvert < 10$ GeV $[m_N \geq 20$ GeV$]$	$\times$	0.08	2.07×10^{-7}
Polarization $P_e = -70\%$	$\times 1.7$	$\times 1.7$	$\times 1$

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

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

More SM backgrounds to e^-

Cut selection	Signal $[e^-p \to (N \to \ell^+\ell^-\nu)j]$ $m_N = 5$ GeV [pb]	$m_N = 10$ GeV [pb]	$m_N = 50$ GeV [pb]	$\ell^+\ell^-\nu_\ell j$ [pb]	$\ell^+\ell^- j$ [pb]	$\tau^-\tau^+ j \to \ell^-\ell^+ j + 4\nu$ [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 $\lvert U_e\rvert^2 = 1$, 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: $N \rightarrow l^{\pm} W^{\mp}$,   LHC: DY $W^{\mp} \rightarrow N l^{\pm}$

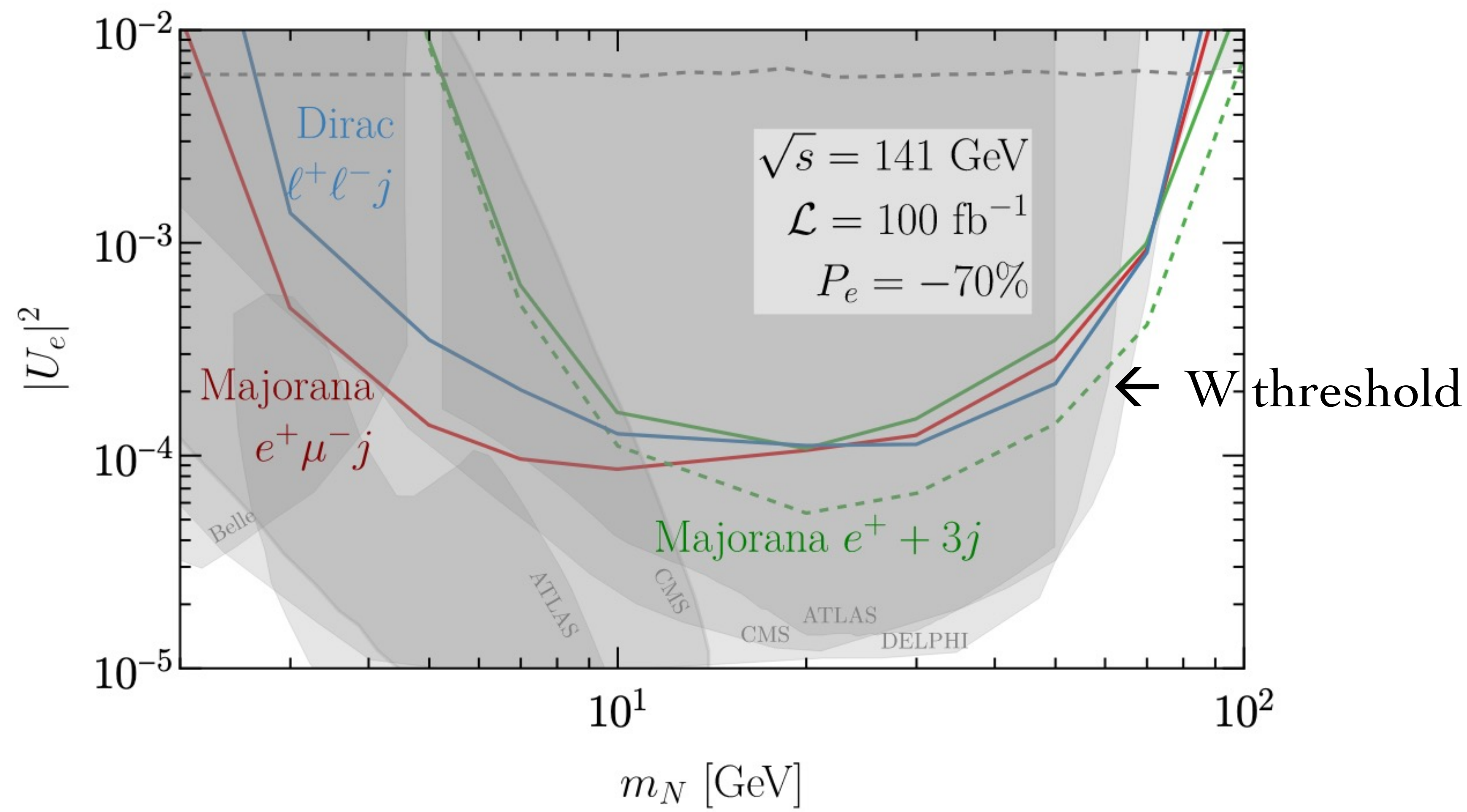


Figure 9. The expected 95% C.L. exclusion limits from prompt searches at the EIC with $\sqrt{s} = 141$ GeV and 100 fb^{-1} of integrated luminosity for HNLs (colored lines), compared with the existing bounds from direct searches [66–71] (gray shaded regions) and indirect precision electroweak constraints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

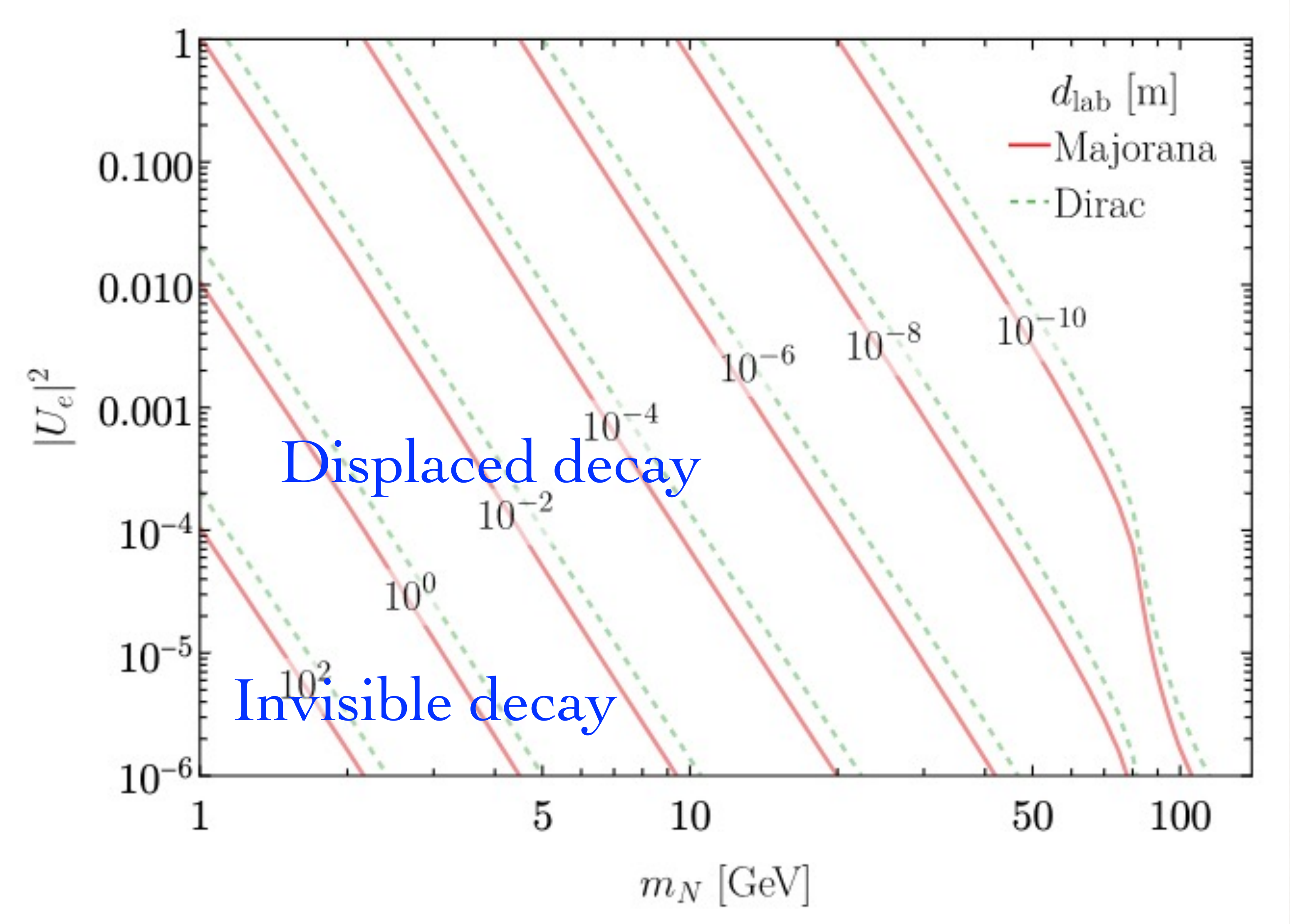
Bounds from "Physics Beyond Colliders" report, arXiv:1901.09966

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

In the laboratory frame, the decay length of N is

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

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'

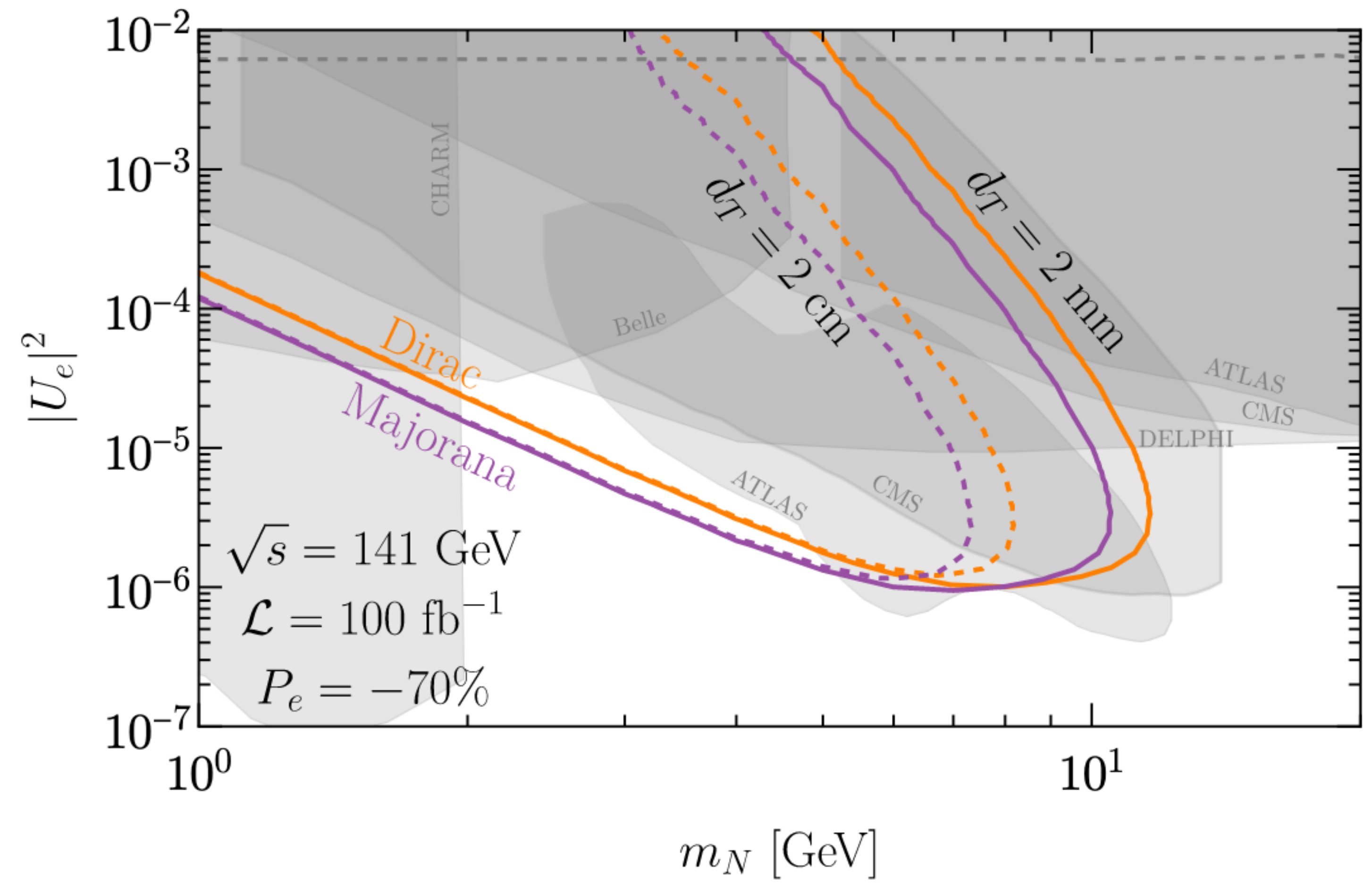


Figure 11. The expected contours of $N = 5$ displaced vertex events detected in the EIC detector. The Majorana (Dirac) type events are shown as purple (orange) lines. The solid (dashes) lines indicate the impact parameter choice as $d_T = 2$ (20) mm. These results are compared with the existing bounds 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

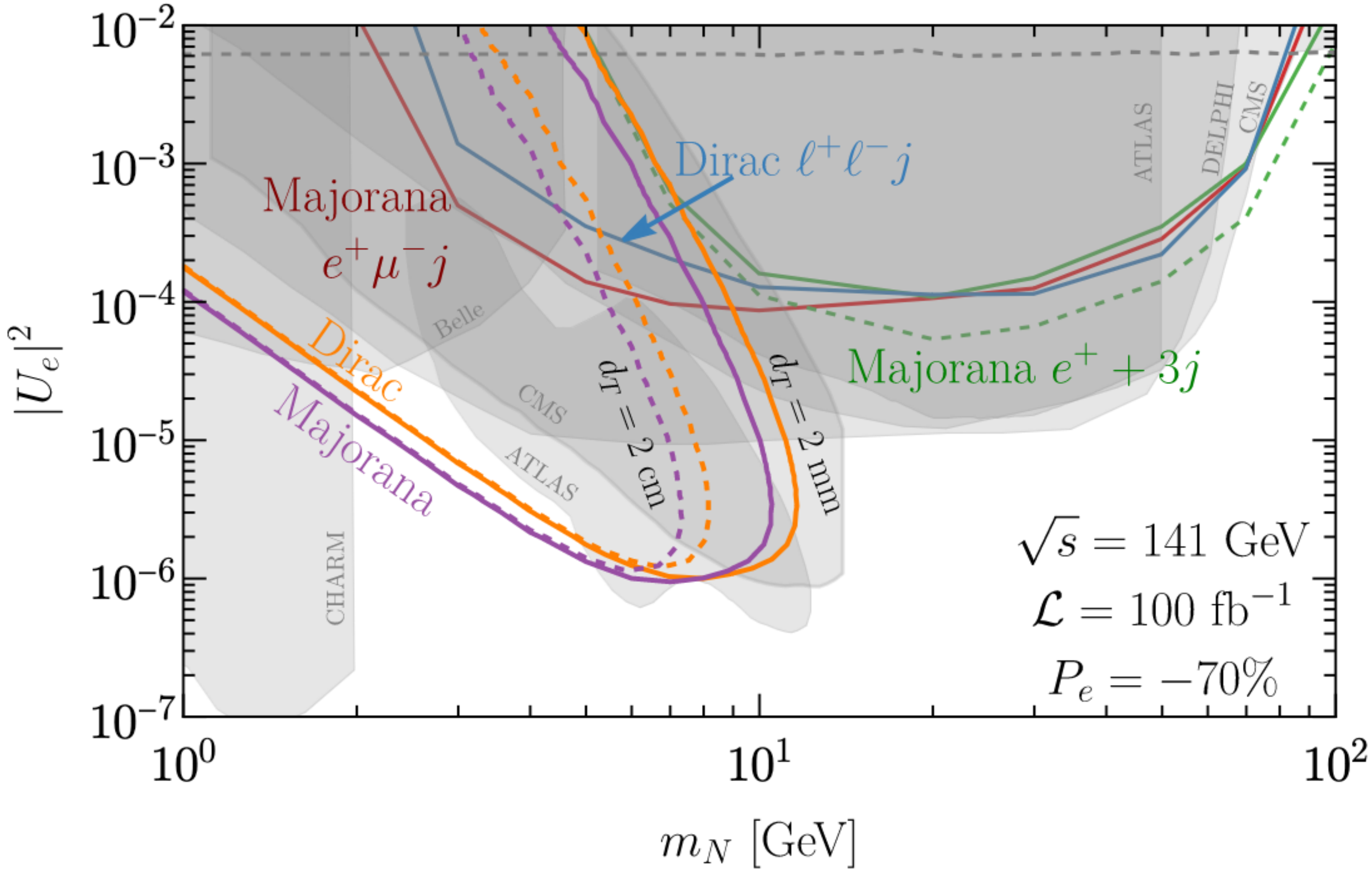


Figure 15. The combined EIC sensitivity to HNL, compared with the existing bounds [65–72]. For details we refer the reader to Figs. 9 and 11.

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

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

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

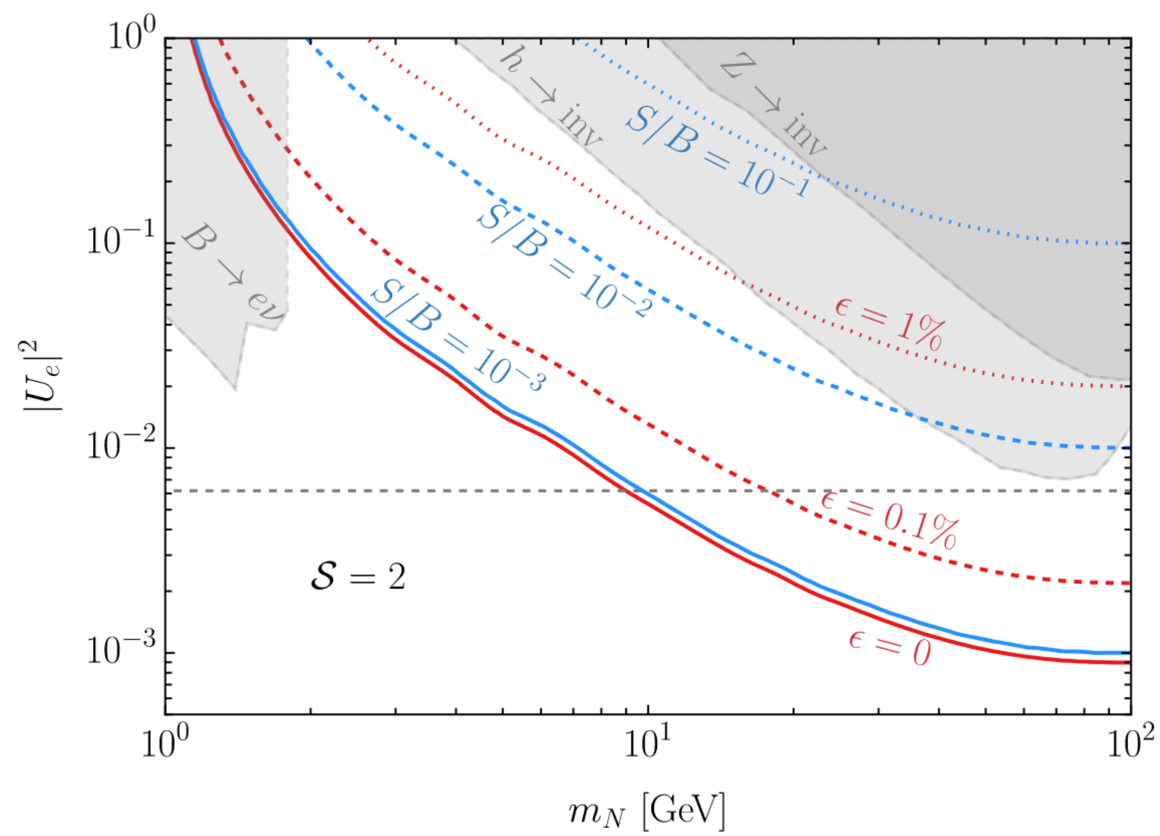


Figure 14. The sensitivity probe (red lines) of the EIC based on the mono-jet search, quantified with $\mathcal{S} = 2$ in Eq. (4.12), with the relative systematic uncertainty as $\epsilon = 0$, 0.1%, and 1%. The existing bounds come from invisible decays of Z and Higgs bosons [1, 81], peak searches 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).

Summary

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

Snowmass White paper: arXiv:2203.13199

new light particles in 1-100 GeV range

SMEFT interactions [Boughezal, Petriello, Wiegand, 2004.00748]

lepton flavor violation [Gonderinger, Ramsey-Musolf, 1006.5063]

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- We studied HNL signals:

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Prompt decay signal: $M_N \sim 1 - 100$ GeV, $U^2_{eN} \sim 10^{-3}$

Displaced vertex signal: $M_N \sim O$(few GeV), $U^2_{eN} \sim 10^{-5}$

Invisible decay mono-jet signal: 2σ sensitivity

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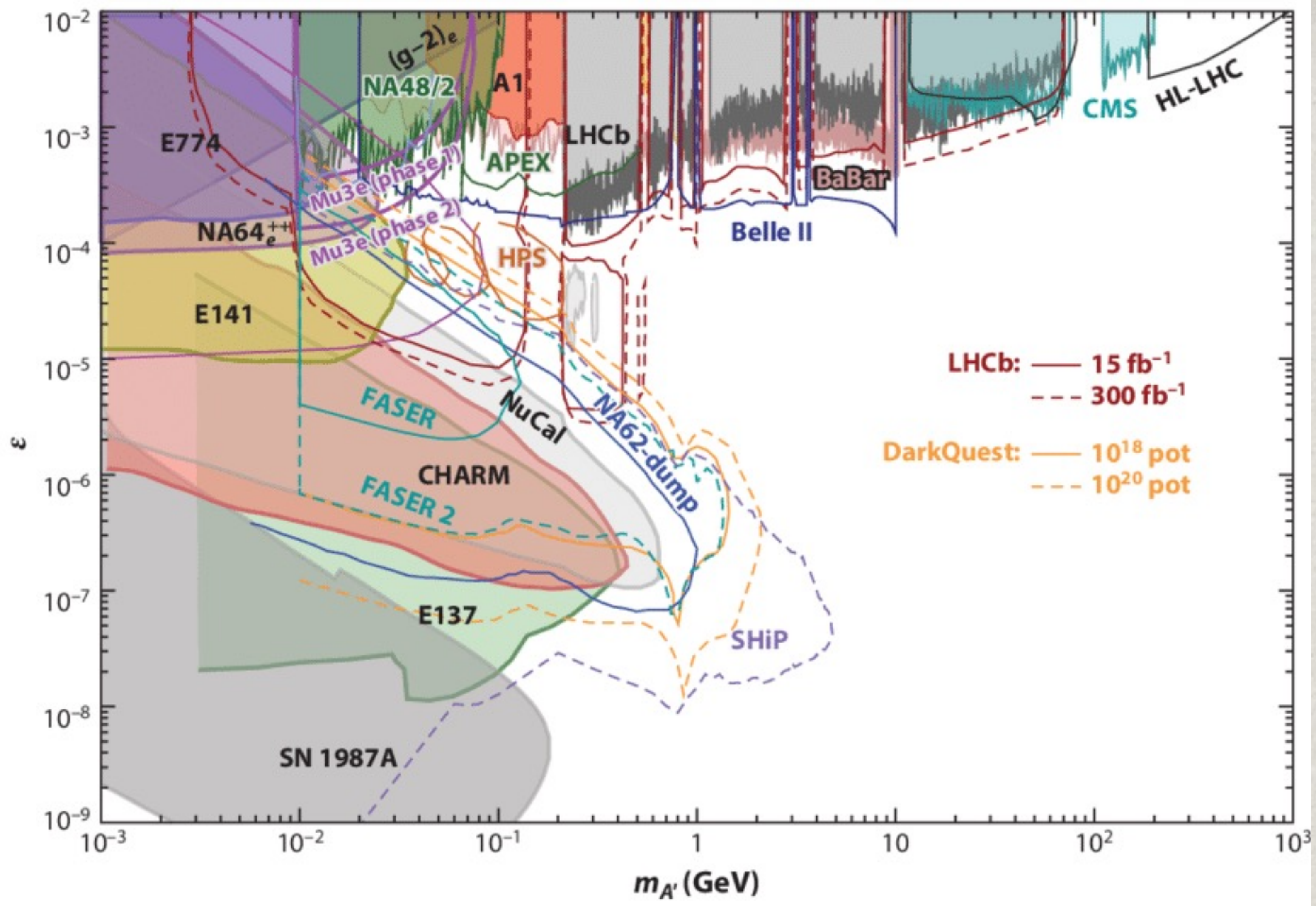
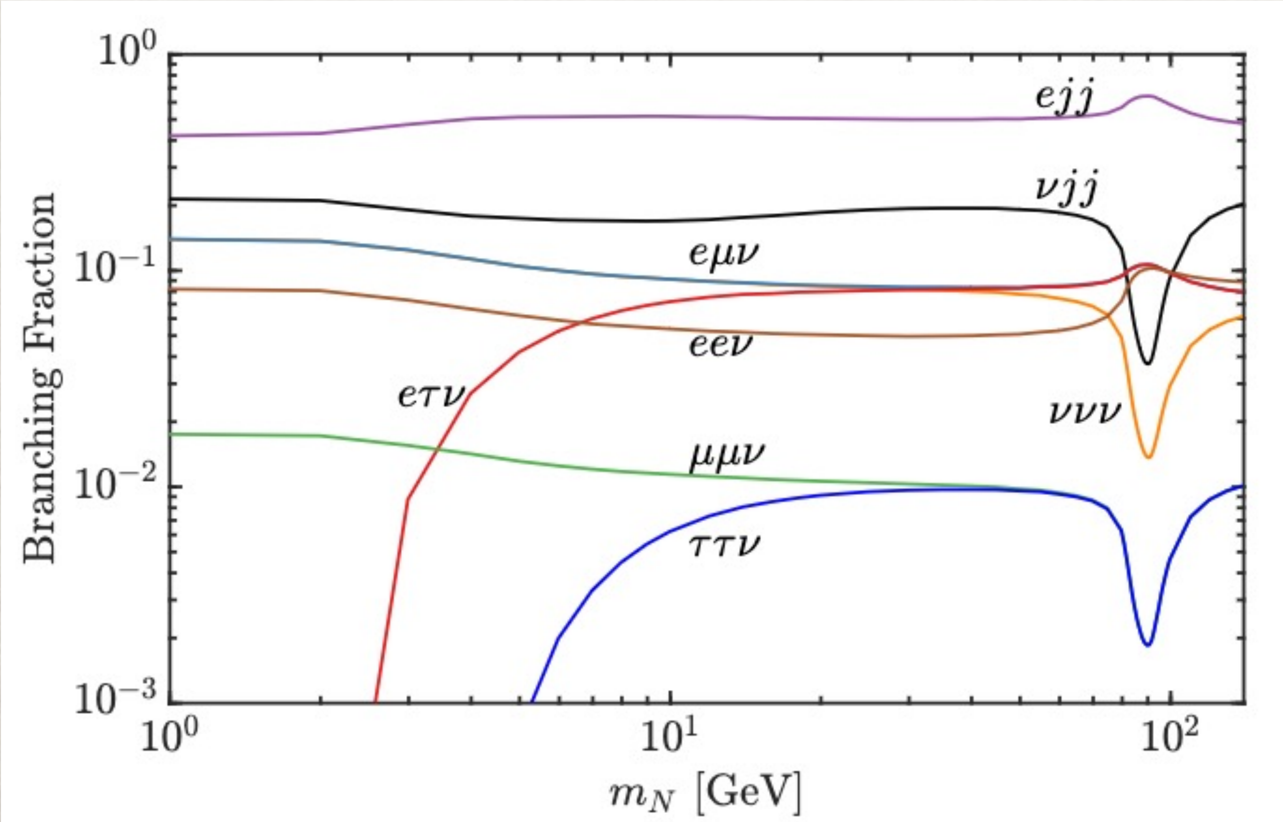
Exciting journey ahead!



E774
NA48/2
A1
LHCb
APEX
Mu3e (phase 1)
Mu3e (phase 2)
BaBar
Belle II
HPS
CMS
HL-LHC
E141
FASER
NuCal
NA62-dump
CHARM
FASER 2
E137
SHiP
SN 1987A
LHCb: 15 fb⁻¹
300 fb⁻¹
DarkQuest: 10^18 pot
10^20 pot
ε
m_A' (GeV)



ejj
νjj
eμν
eeν
eτν
ννν
μμν
ττν
Branching Fraction
m_N [GeV]