INSTITUTE for NUCLEAR THEORY

A Tale of Two Neutrinos: Sterile neutrinos @ EIC

New opportunities for BSM searches at the EIC @ CFNS

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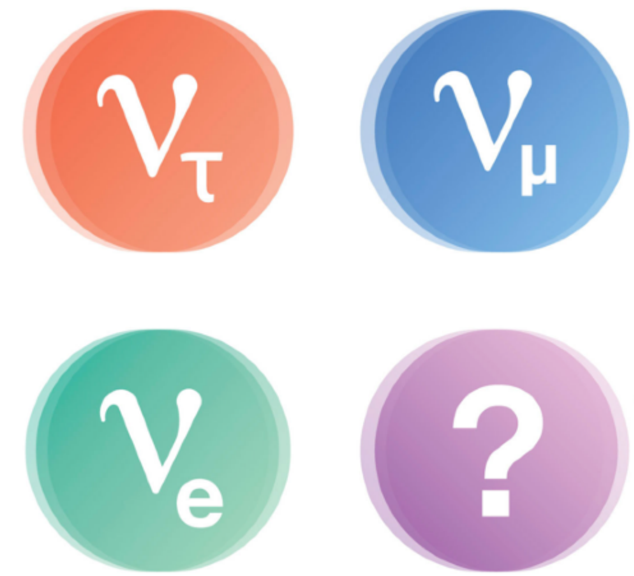
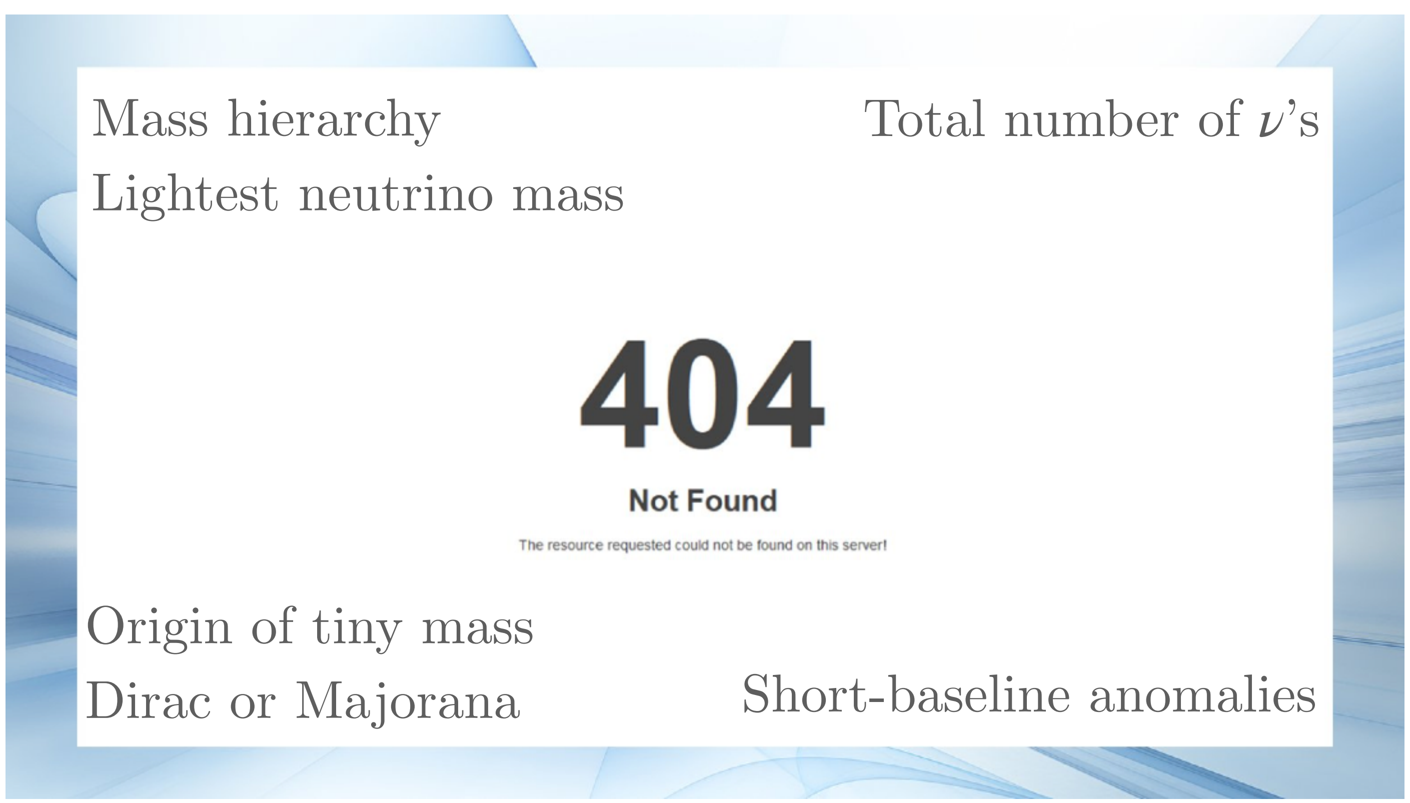
Active neutrinos

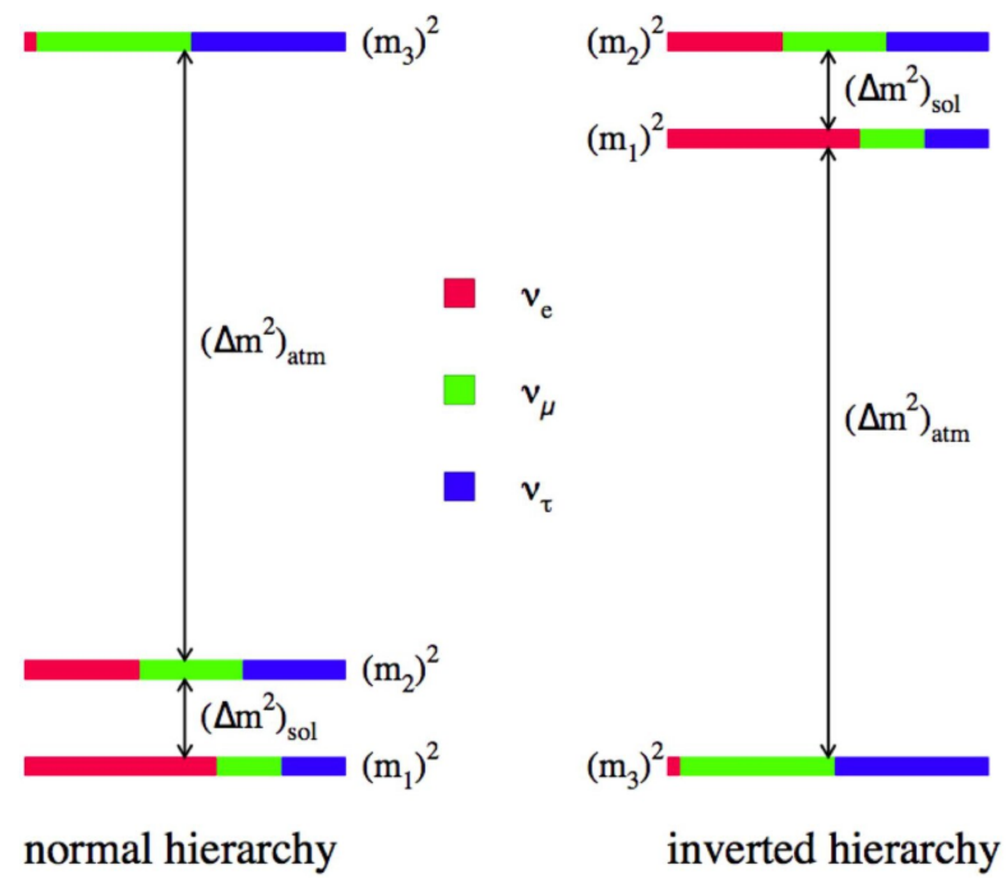


- Precision measurements at LEP (Z boson decay): only three neutrinos couple to the weak force

- Oscillation experiments: active neutrinos are massive and they mix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

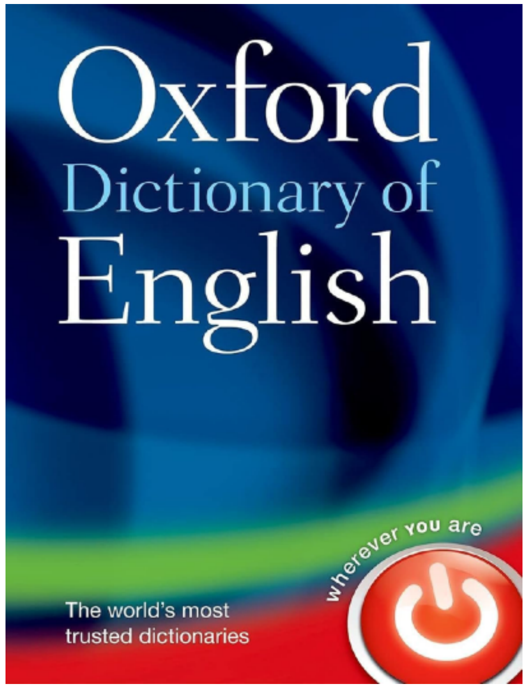




Sterile neutrinos

- Sterile neutrinos are fermions, uncharged under the SM $\mathrm{SU(3)_c \times SU(2)_L \times U(1)_Y}$ interactions → *hence the name 'sterile.'*

Definition time!



- They could be charged under new interactions and they could have other quantum numbers, including lepton number.

- Sterile neutrinos interact with SM degrees of freedom mostly through the neutrino portal (LHN) → *hence the name 'neutrino.'*

$U_{\alpha i}$ ← $i = 4, \ldots$

↑

$\alpha = e, \mu, \tau$

- They have many names, including gauge-singlet fermions, right-handed neutrinos, heavy neutral leptons, and heavy neutrinos.

Outline

- What are sterile neutrinos?
  - ➡ *New particles closely related to neutrinos*
- Are they a reasonable assumption?
  - ➡ YES!
- Should they exist in nature?
  - ➡ Yes? Maybe?
- Does the EIC provide a discovery opportunity?
  - ➡ Yes**

Disclaimer: talk based on a few examples; not a comprehensive list review.

Sterile neutrinos and the neutrino mass puzzle

- $M_\nu \neq 0$ requires introducing new degrees of freedom

$$\mathscr{L}_{\nu\mathrm{SM}} = \mathscr{L}_{\mathrm{SM}} + \mathscr{L}_{\nu-\mathrm{mass}} + \dots$$

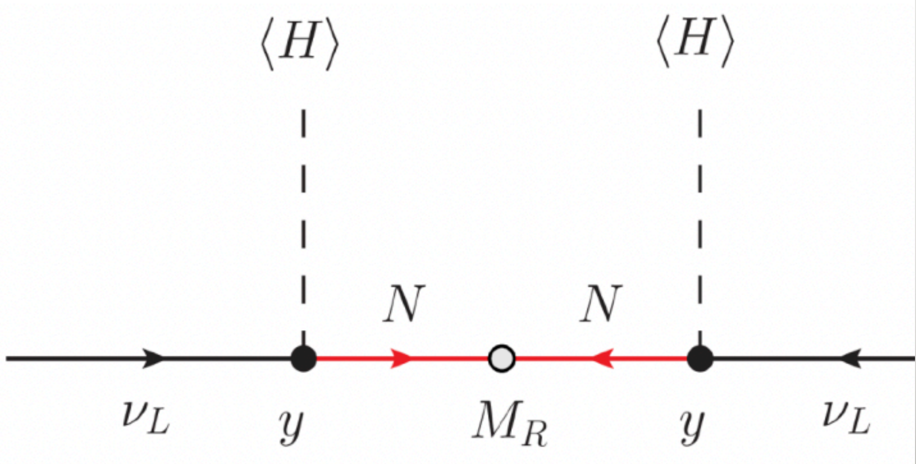
- **Key questions:**
  - ➡ *Is Lepton Number a good symmetry of the new dynamics?*
  - ➡ *What are the sources and mediators of Lepton Flavor Violation?*

- **Theory checklist:**
  - ➡ Smallness of neutrino mass
  - ➡ Self-consistency and predictive power

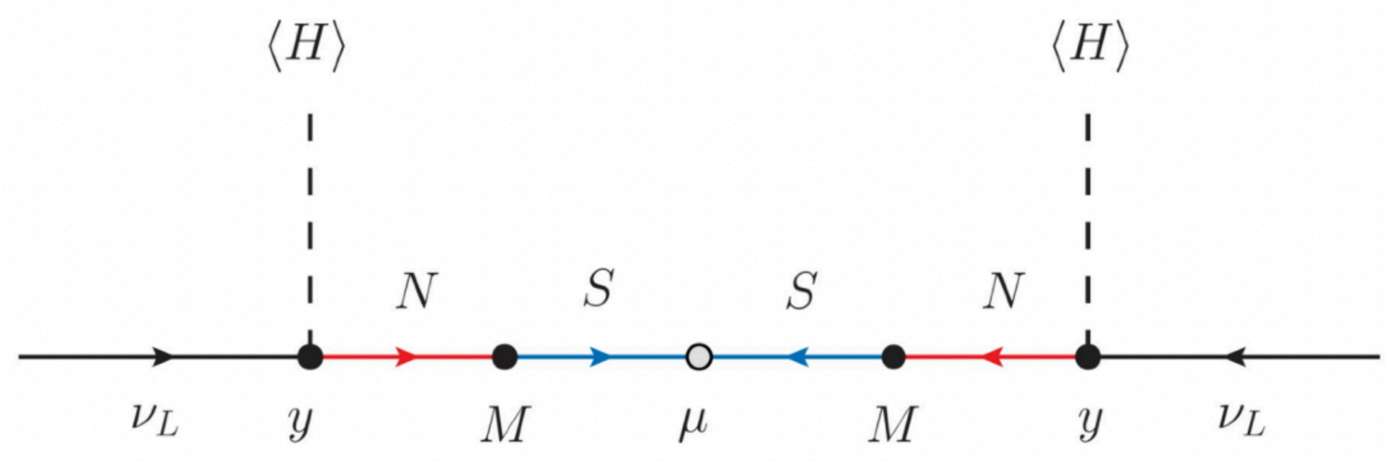
The world of ~~Coca-Cola~~ M_ν

The world of neutrino mass models

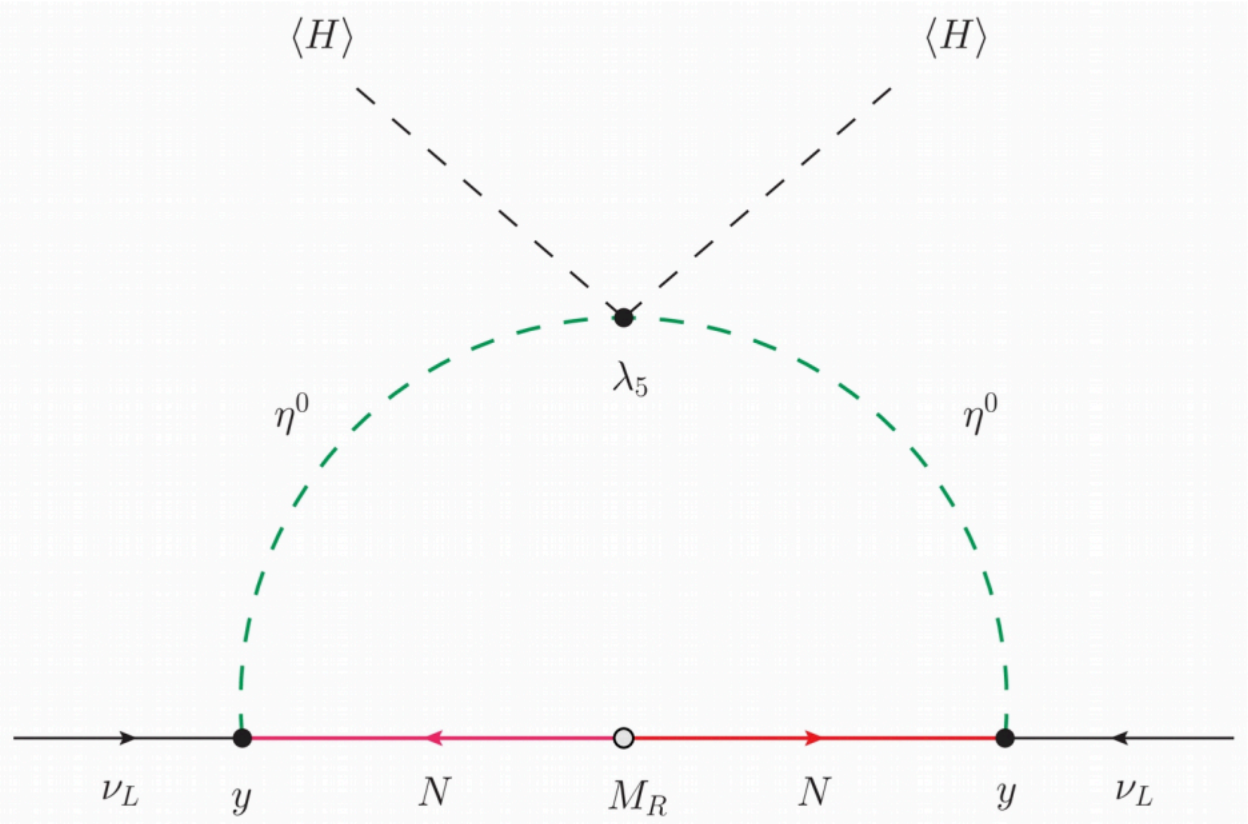
Type-I seesaw [Minkowski,... , 1977]



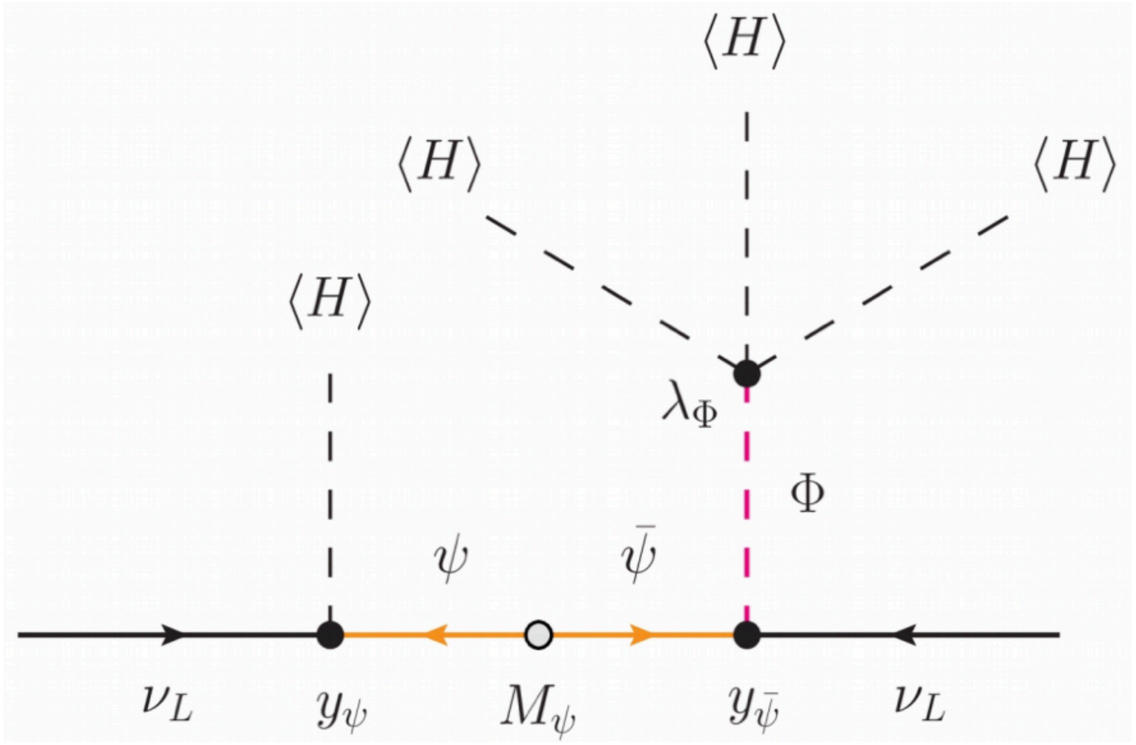
Inverse seesaw [Mohapatra, Valle, 1986]



Scotogenic [Ma, 2006]



BNT [Babu, Nandi, Tavartkiladze, 2009]



The νSM: the simple 3+3 case

- Arguably, the simplest, renormalizable Lagrangian that allows for neutrino mass is:

$$\mathscr{L}_{\nu\mathrm{SM}} \ni \frac{1}{2} M_R^{ij}\, \bar{\nu}^c_{Ri} \nu_{Rj} + Y_D^{\alpha i}\, \bar{L}_\alpha \widetilde{H} \nu_{Ri} + \mathrm{h.c.}$$

- Here, ν_{Ri} ($i = 1,2,3$ for concreteness) are SM gauge singlet fermions. After symmetry breaking, $\mathscr{L}_{\nu\mathrm{SM}}$ describes 6 Majorana fermions:

$$\mathscr{L}_{\mathrm{mass}} = -\frac{1}{2} \bar{N}^c M_\nu N + \mathrm{h.c.} \qquad N = \begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix} \qquad M_\nu = \begin{pmatrix} 0 & \frac{v}{\sqrt{2}} Y_D^* \\ \frac{v}{\sqrt{2}} Y_D^\dagger & M_R^\dagger \end{pmatrix}$$

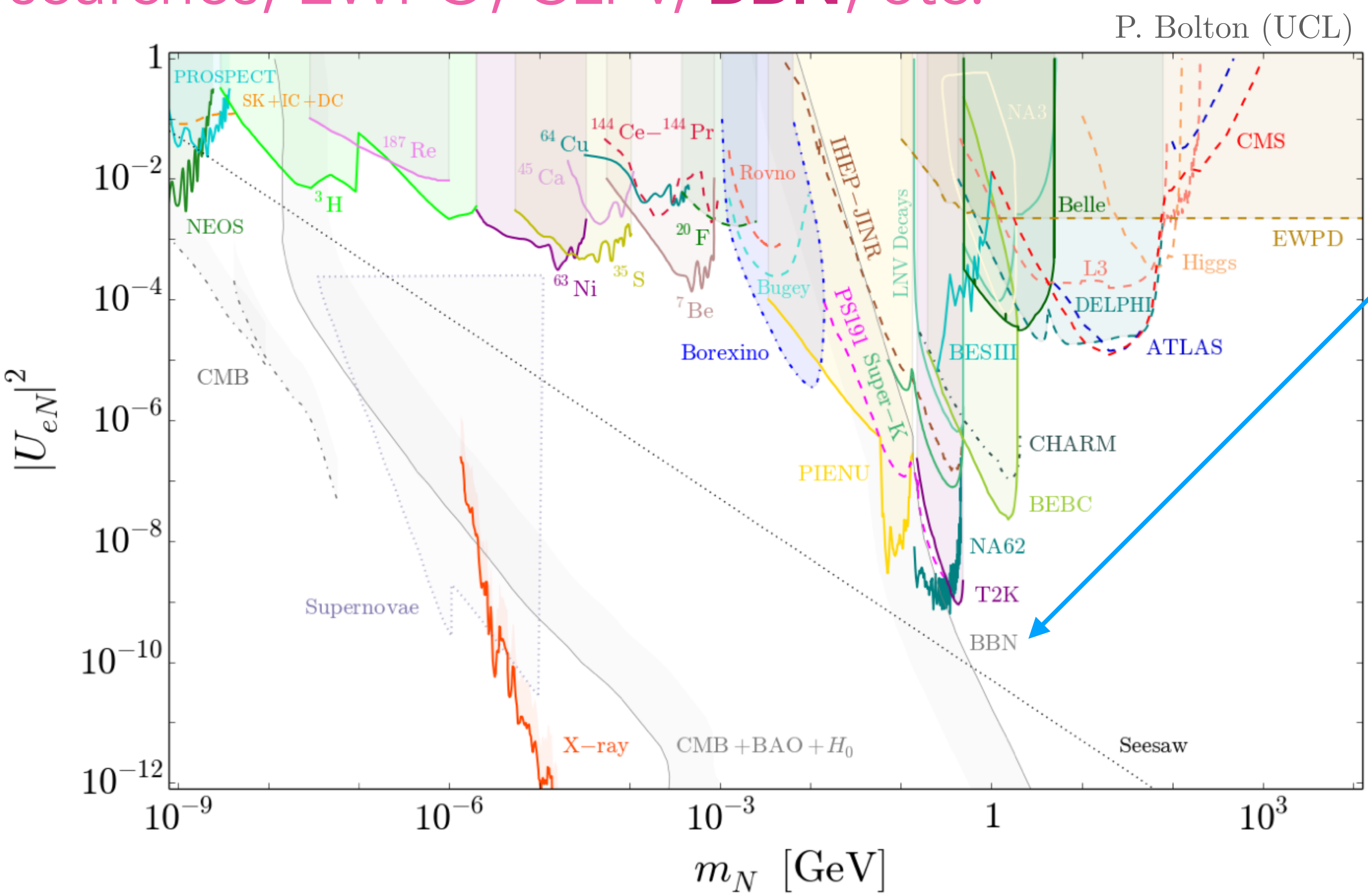
- After diagonalization, the mass (N_m) and flavor (N) eigenstates are related by a 6×6 unitary matrix $\mathscr{U}$

$$N = \mathscr{U} N_m \qquad \mathscr{U} = \begin{pmatrix} U_{aa} & U_{as} \\ U_{sa} & U_{ss} \end{pmatrix}_{\alpha i}$$

The νSM: the simple 3+3 case

- In virtue of the seesaw mechanism, the mixing angle scales as $\mathcal{U}^2_{\alpha i} \sim m_{\text{active}}/M_{\text{sterile}}$

- Different experimental constraints depending on the mass range: direct searches, EWPO, CLFV, **BBN**, etc.



Non-standard cosmological scenarios could overcome the BBN constraints; for example:

- Entropy production [**G. M. Fuller et al. (2011)**]

- Axion-like particles [**F. F. Deppisch et al. (2024)**]

The νSM: the simple 3+3 case

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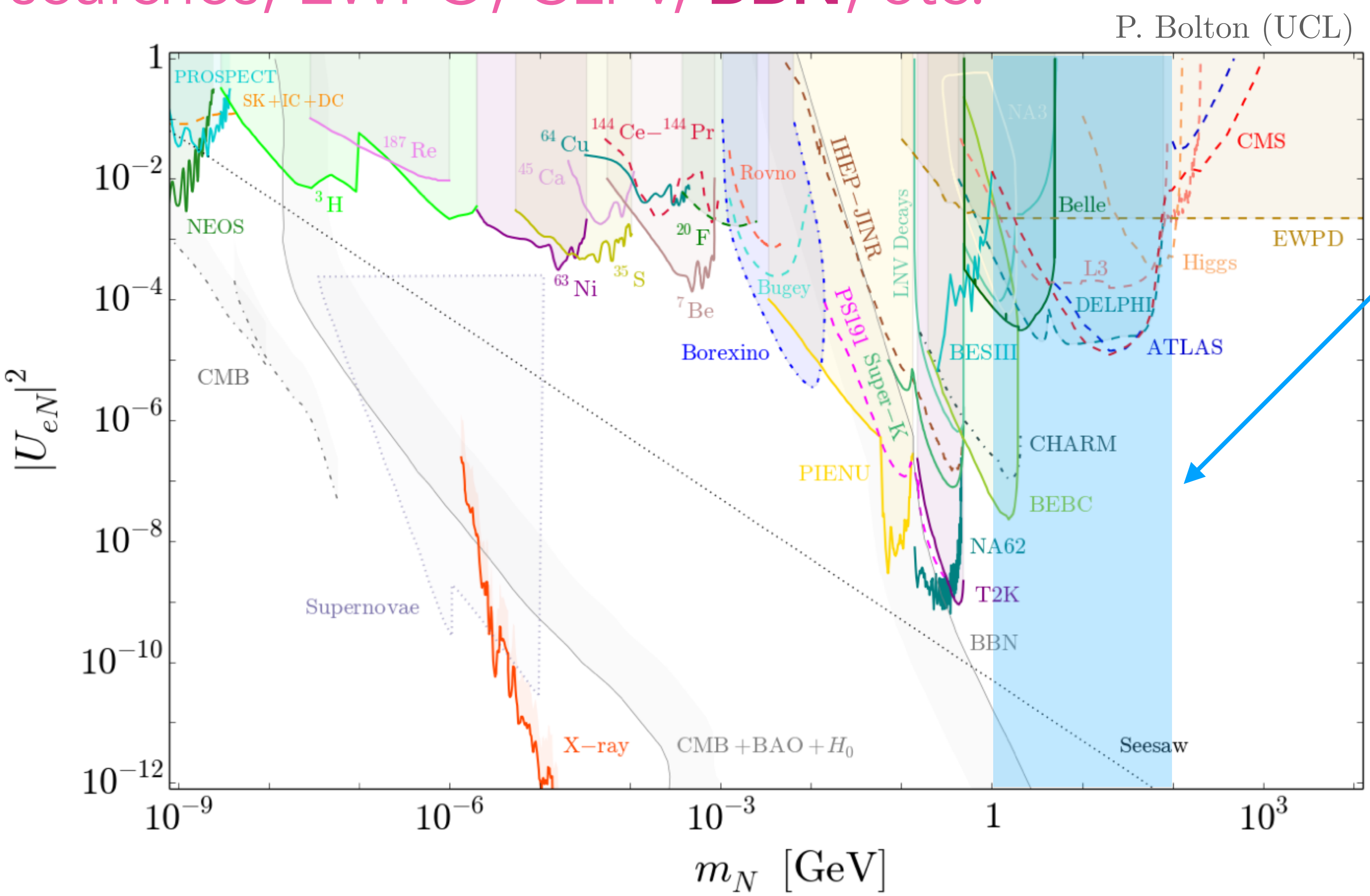
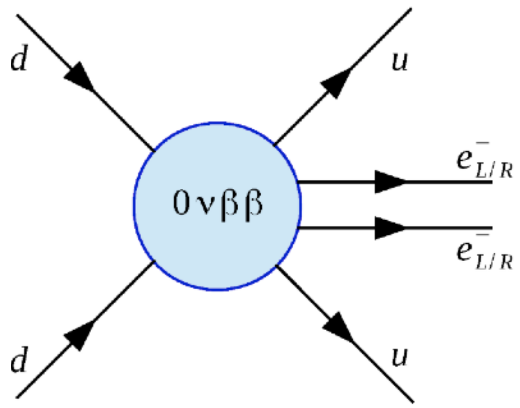


Mass range $\mathcal{O}(1 - 100\,\text{GeV})$ relevant for searches at the EIC

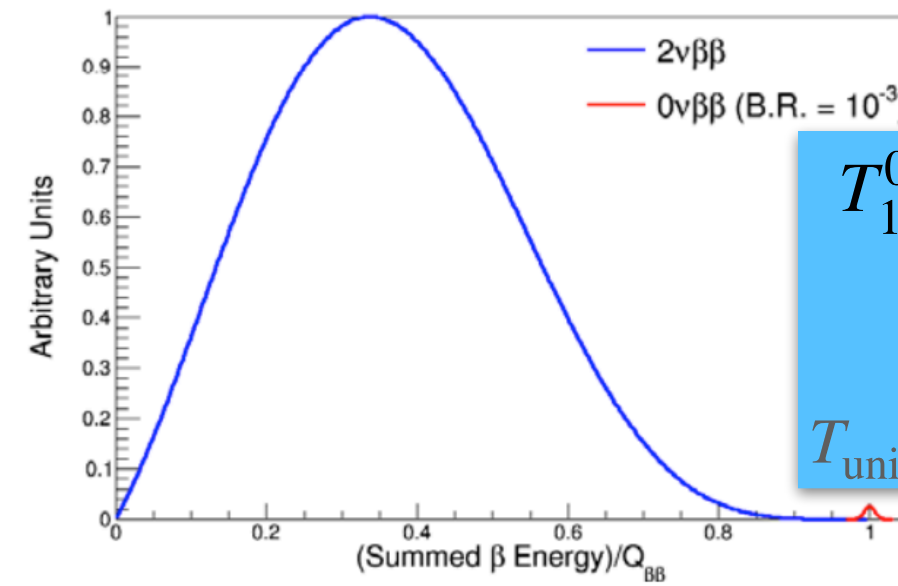
- Prompt & Displaced signatures [**B. Batell et al. (2022)**]

Detour: $0\nu\beta\beta$ and lepton number violation

$$(N, Z) \to (N-2, Z+2) + 2e^-$$



$$\Delta L = 2$$



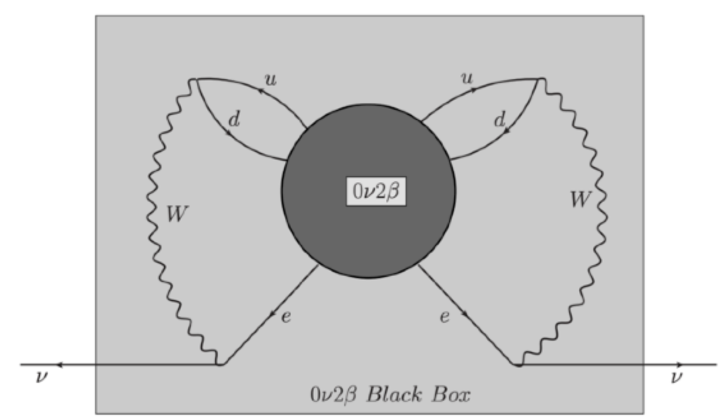
$$T^{0\nu}_{1/2} \gtrsim 10^{26}\,\text{yr}$$

$$T^{2\nu}_{1/2} \simeq 10^{21}\,\text{yr}$$

$$T_{\text{universe}} \gtrsim 10^{10}\,\text{yr}$$

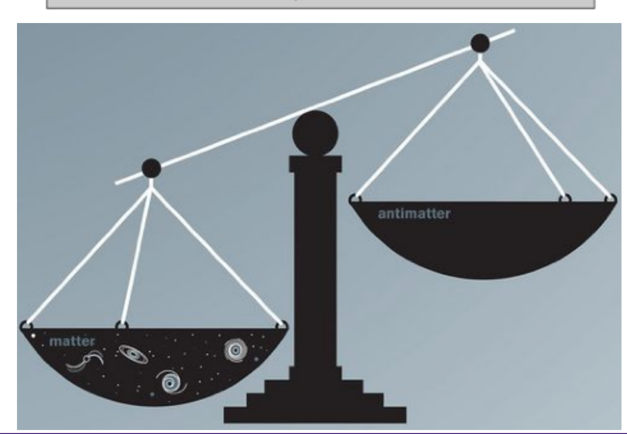
- SM conserves $(B-L) \to 0\nu\beta\beta$ observation would signal new physics

✓ Demonstrate that neutrinos are Majorana fermions



Schechter-Valle 1982

✓ Establish a key ingredient to generate the baryon asymmetry via leptogenesis



Fukugita-Yanagida 1987

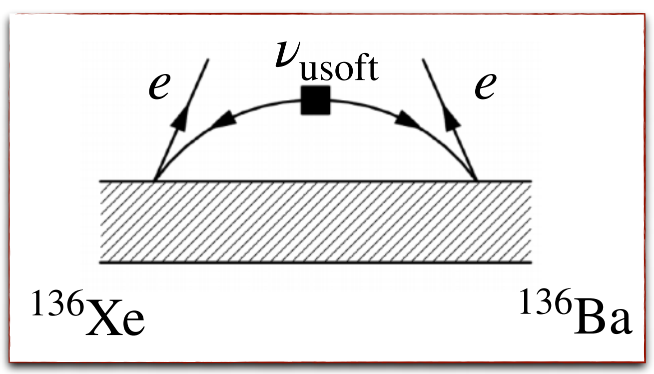
Detour: $0\nu\beta\beta$ beyond light neutrinos

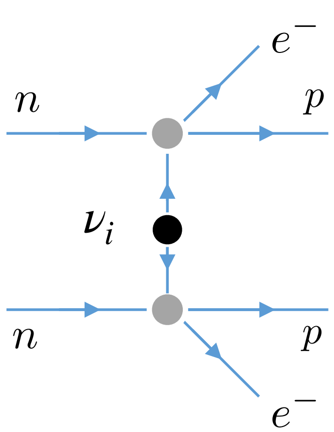
Ramsey-Musolf et al. '03; Cirigliano et al. '17; Detmold et al. '22; Nicholson et al. '18; Dekens et al. '24

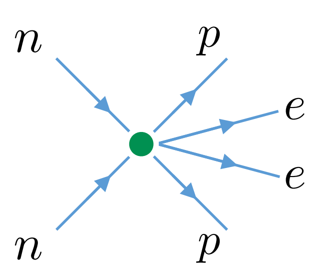
- The contribution of an active or sterile neutrino of mass m_i to the inverse half-life can be written as:

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 G_{01} \left| \sum_{i=1}^{6} \frac{\mathcal{U}_{ei}^2 m_i}{m_e} A_\nu(m_i) \right|^2$$

- Here A_ν is the amplitude, which receives contributions from (sterile) neutrinos with different momentum scalings, depending on their masses.

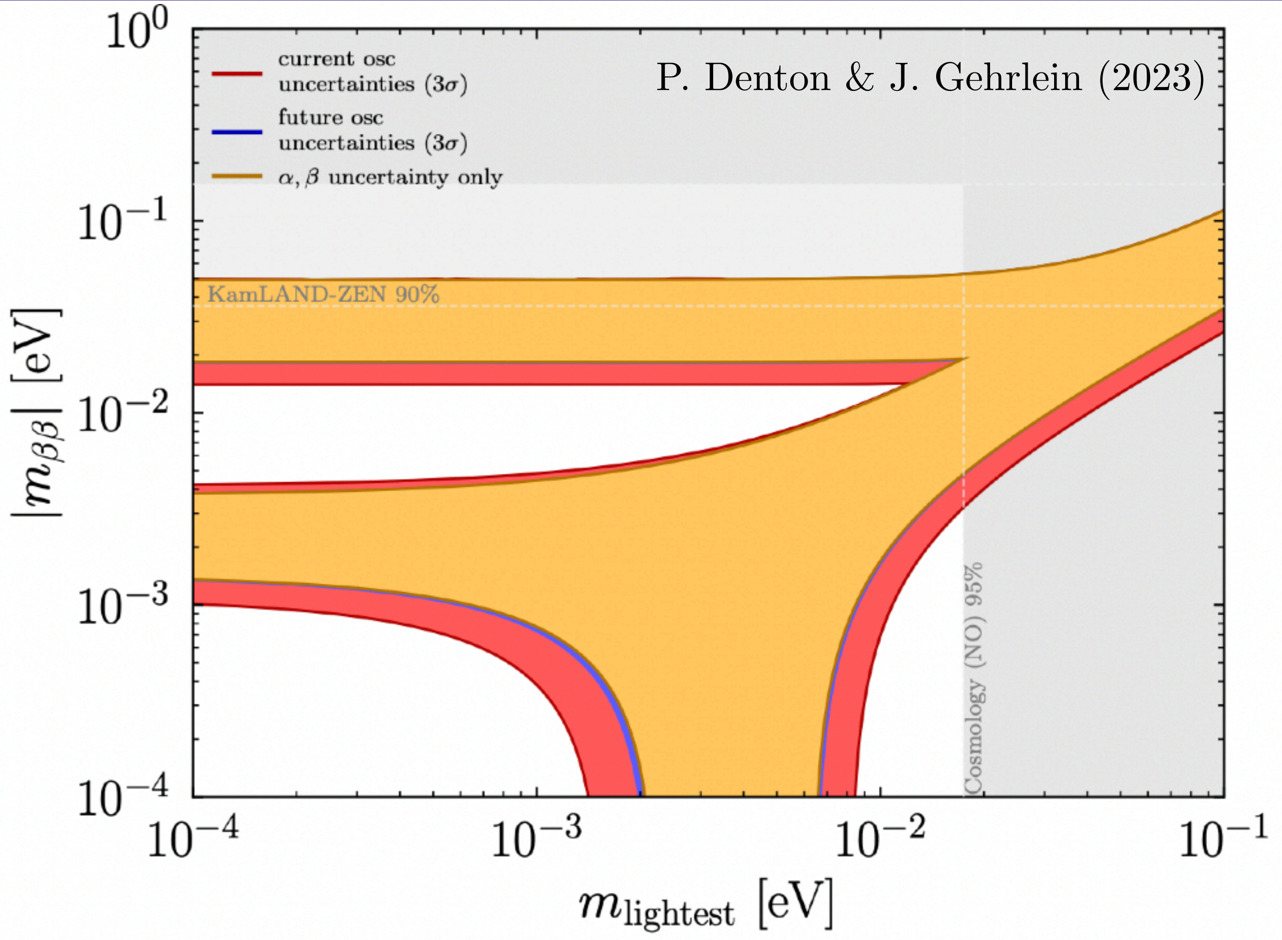






$A_\nu(m_i)$

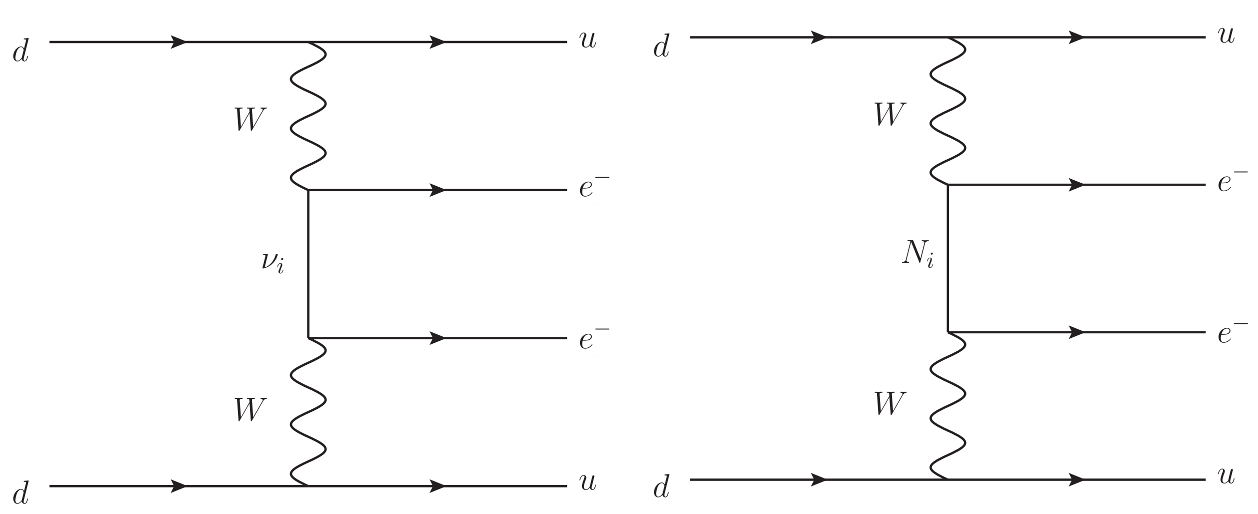
Detour: $0\nu\beta\beta$ beyond light neutrinos

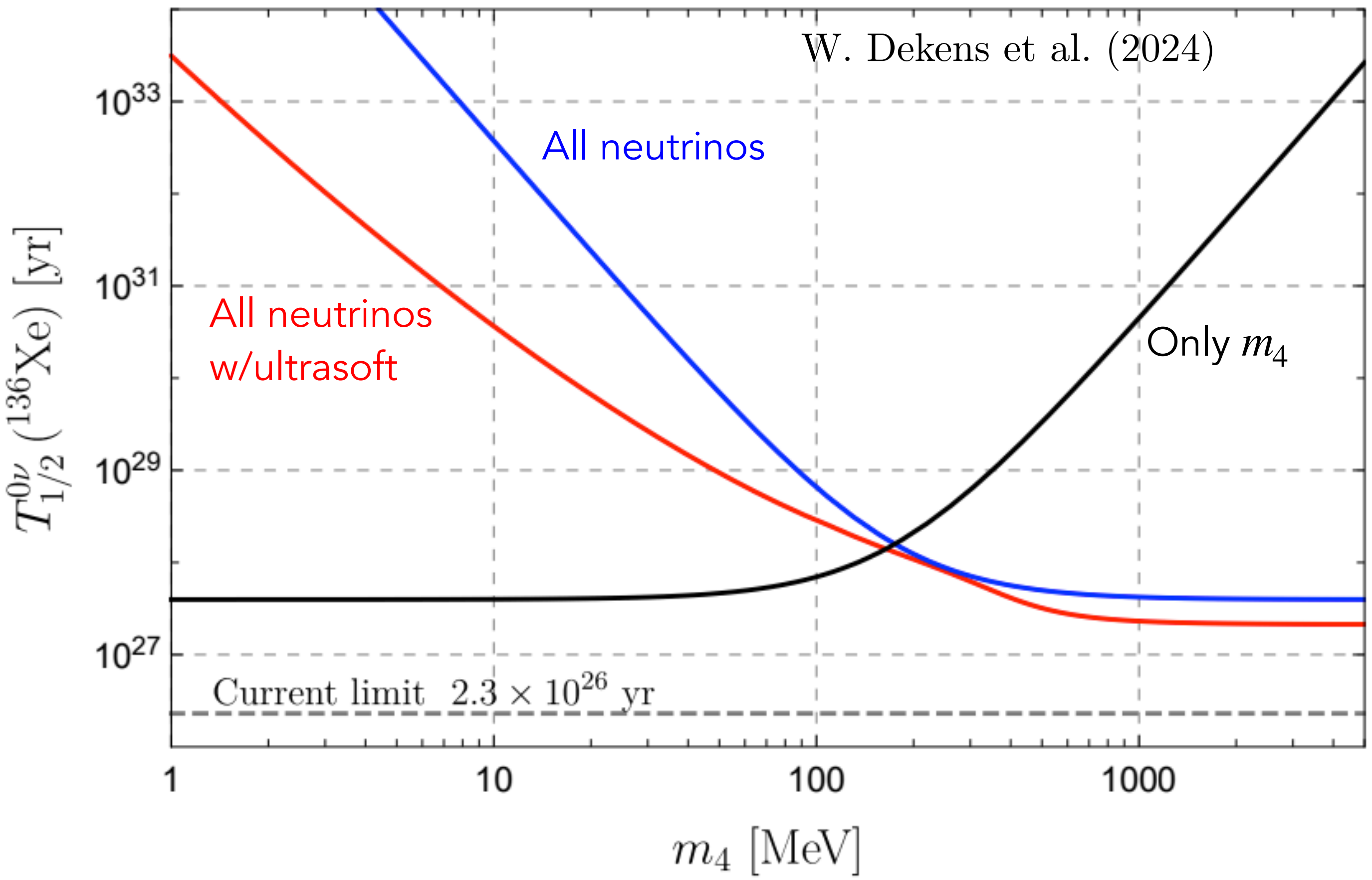


$$m_{\beta\beta} = \sum_{i=1}^{3} \mathcal{U}_{ei}^2 m_i$$

$M_{\text{heavy}} \gg v_{\text{ew}}$

$$|m_{\beta\beta}^{\text{eff}}| = \frac{m_e}{g_A^2 |V_{ud}|^2 \mathcal{M}_\nu^{(3)} G_{01}^{1/2}} \left(T_{1/2}^{0\nu}\right)^{-1/2}$$





The νSM: the simple 3+3 case

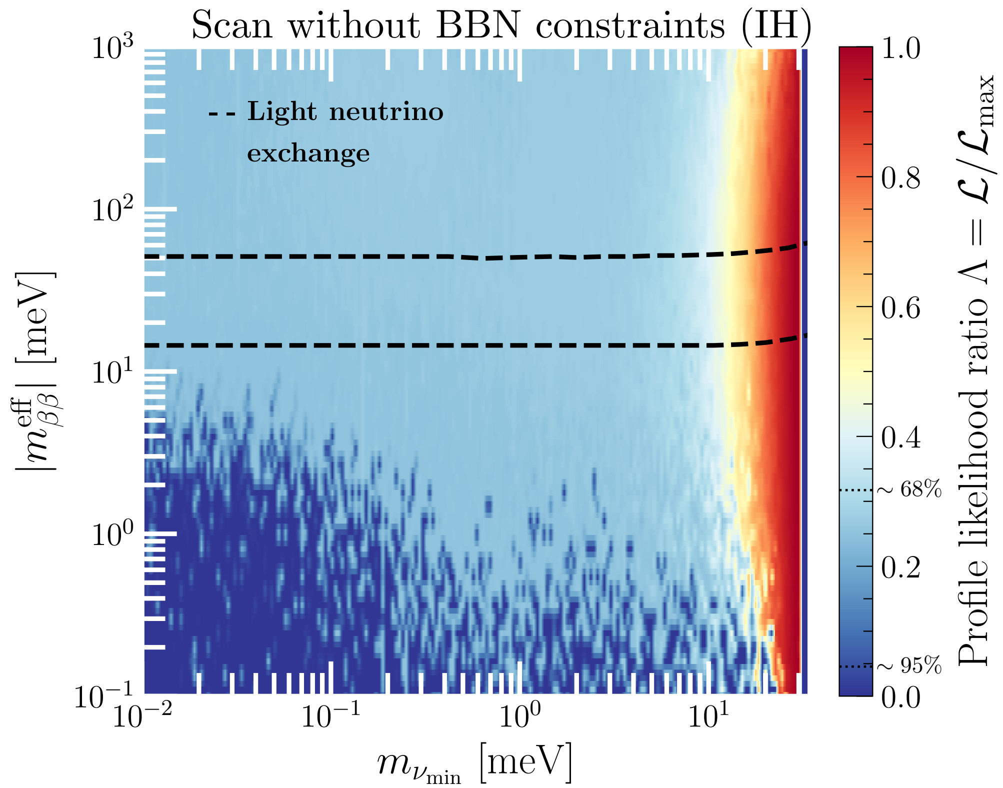
Cirigliano, Dekens, SUQ (2024)

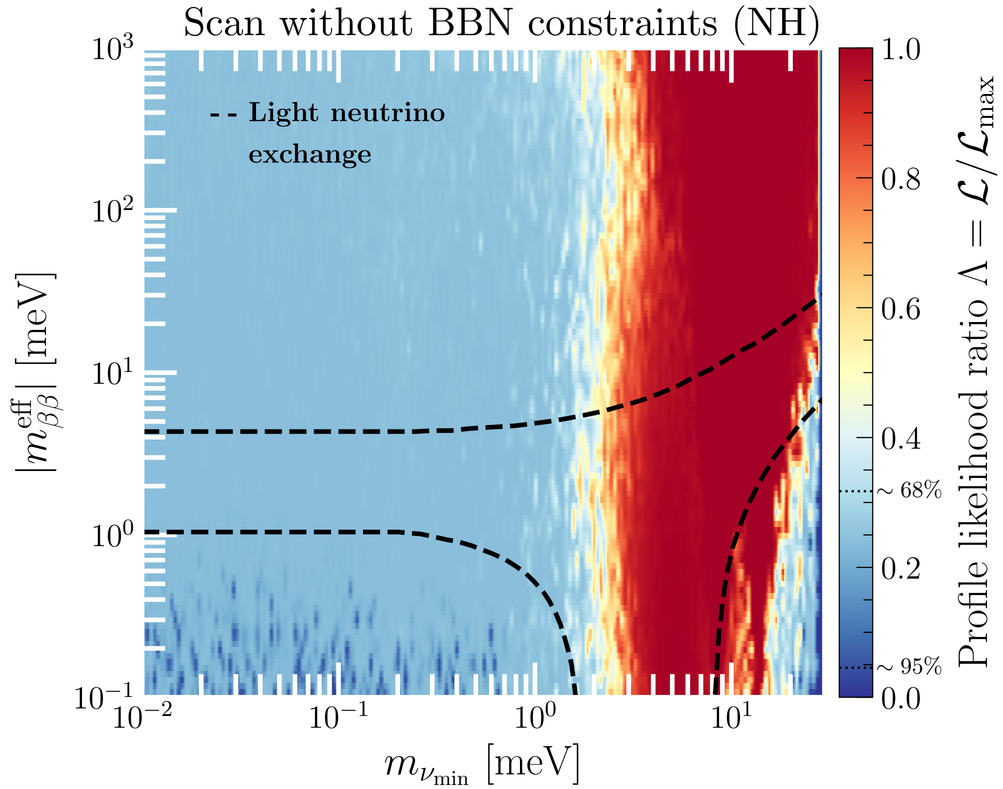
- Implications of current experimental constraints on $0\nu\beta\beta$ beyond the light-neutrino exchange scenario:
  - *Active neutrino oscillation data*
  - *EW precision observables & CKM unitarity*
  - *CLFV & Lepton universality*
  - *Direct searches (colliders, nuclear β decay, beam dumps, etc.)*
  - ***BBN***

- Broad range of sterile neutrino masses (from $1\,\mathrm{keV}$ to $10\,\mathrm{TeV}$) and $m_{\nu_{\min}} \neq 0$

- $T^{0\nu}_{1/2}$ computed using ChEFT and results presented using profile likelihoods

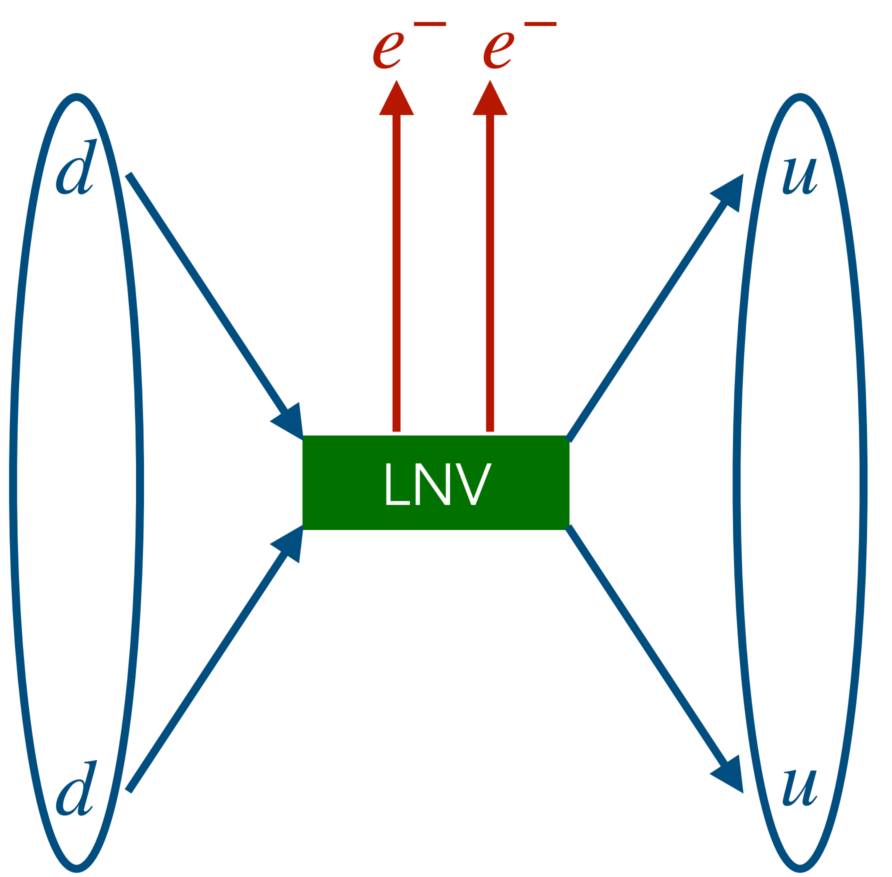
$$\mathscr{L}(\mathbf{x}) \equiv \max_{\mathbf{x}'} \mathscr{L}(\mathbf{x}, \mathbf{x}')\ , \quad \mathscr{L}(\mathbf{x}, \mathbf{x}') \equiv \mathbb{P}(\mathrm{Data}\,|\,\mathbf{x}, \mathbf{x}')$$





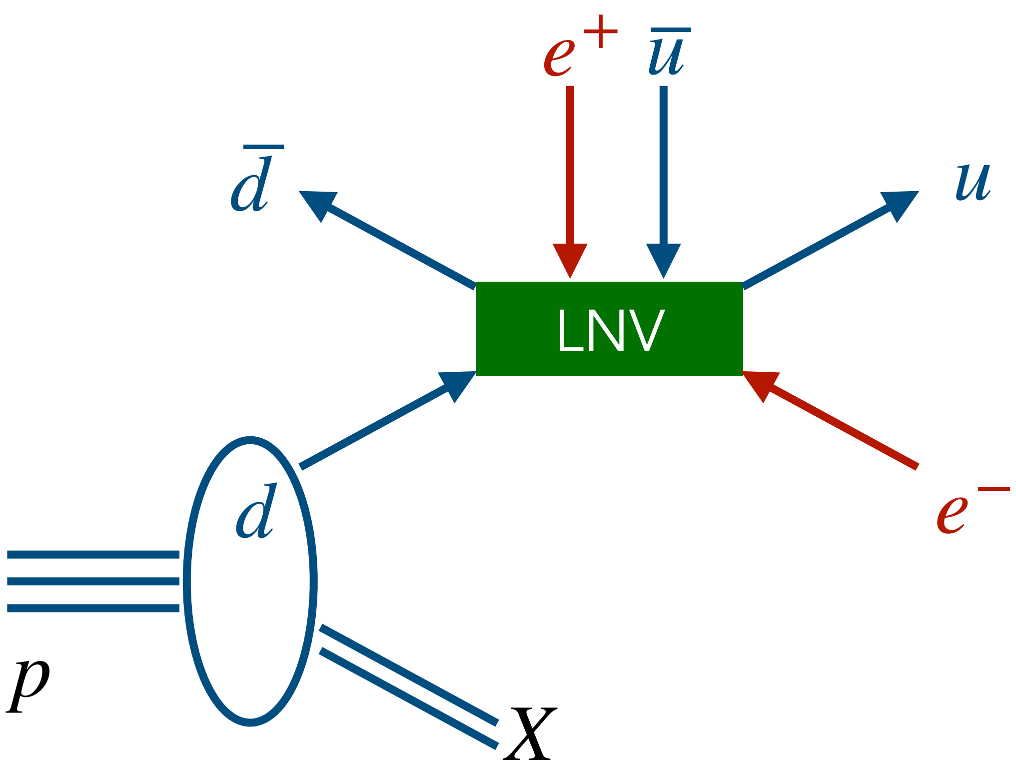
It's all coming back ♪♫

$0\nu\beta\beta$ decay



$A(Z, N)$ $A(Z+2, N-2)$

ep collisions



$e^- p \to e^+ jjj$

(Based on M. Ramsey-Musolf's sketch)

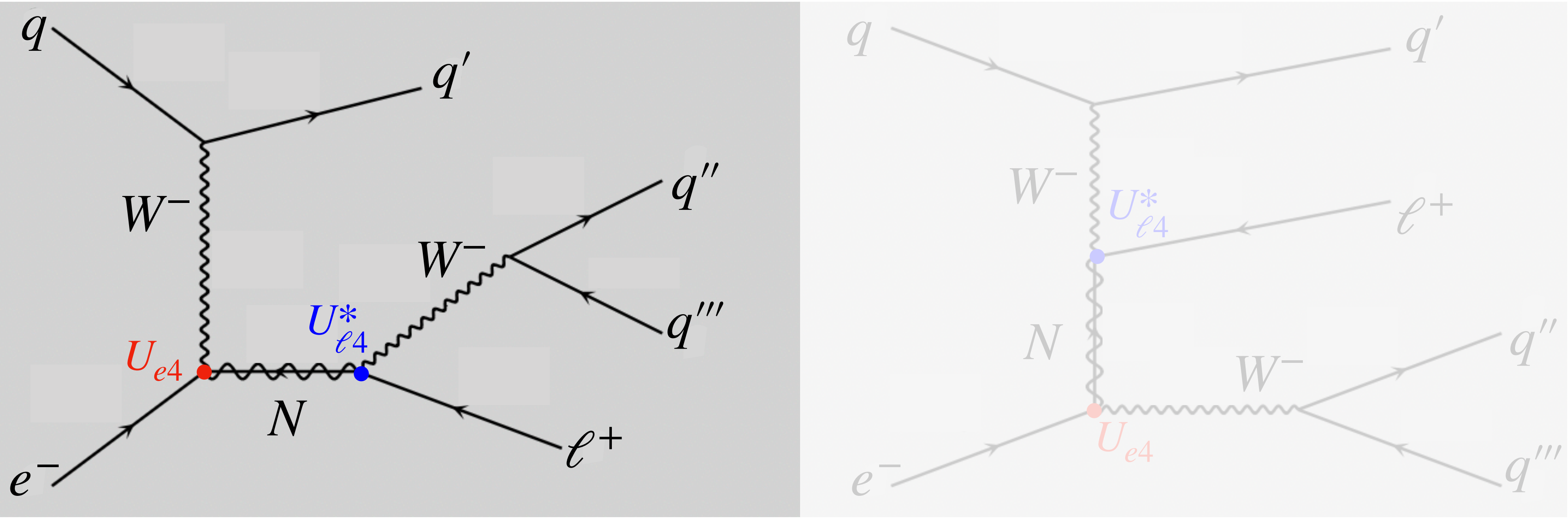
Sterile neutrinos at the EIC

In collaboration with V. Cirigliano, W. Dekens, K. Fuyuto, E. Mereghetti

- Focusing on the LNV process: $e^- p \to \ell^+ jjj$
  - Only one sterile neutrino $\to \{m_N, U_{\ell N}\}$
  - Mass range $3 - 100\,\mathrm{GeV}$
  - Simulation pipeline:

    `MadGraph + Pythia8 + Delphes` M. Arratia, S. Sekula (2021)
  - Zero-background analysis T. Junk (1999), P. N. Bhattiprolu, S. P. Martin, J. D. Wells (2020)

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



Dominant contribution: $\sigma \simeq \dfrac{|U_{eN} U^*_{\ell N}|^2}{\sum_{\ell'} |U_{\ell' N}|^2}\,\sigma_0(m_N)$

Sterile neutrinos at the EIC

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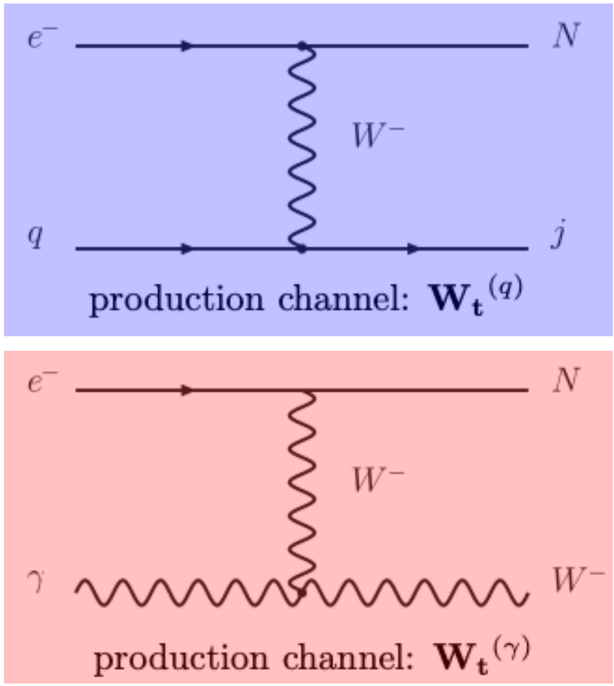
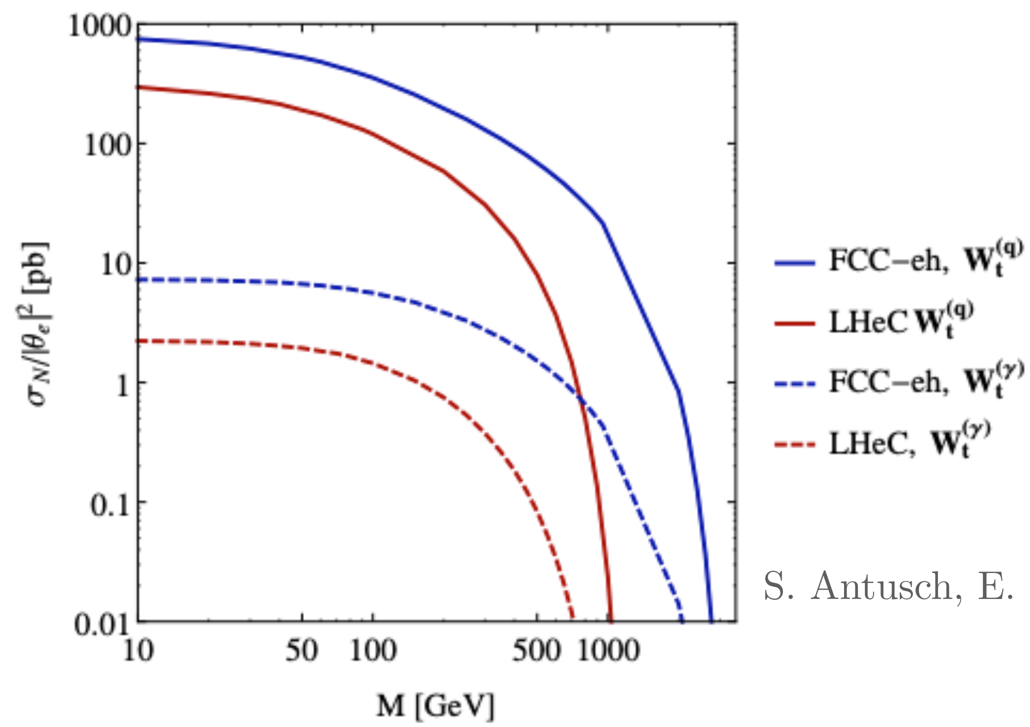
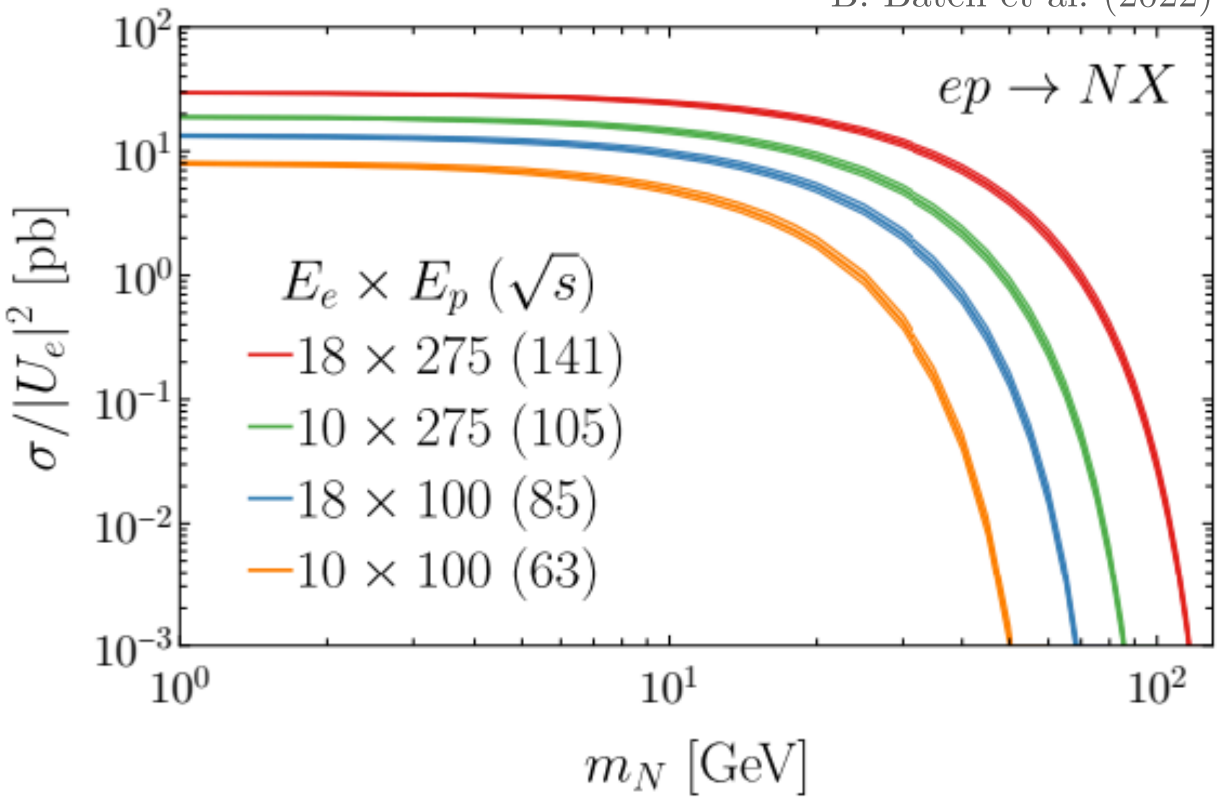




S. Antusch, E. Cazzato, O. Fischer (2016)

B. Batell et al. (2022)



EIC settings:

- ✓ $\sqrt{s} = 141\ \mathrm{GeV}$
- ✓ $\mathscr{L} = 100\ \mathrm{fb}^{-1}$
- ✓ $P_e = -70\ \%$
- ✓ General-purpose detector (Yellow Report)

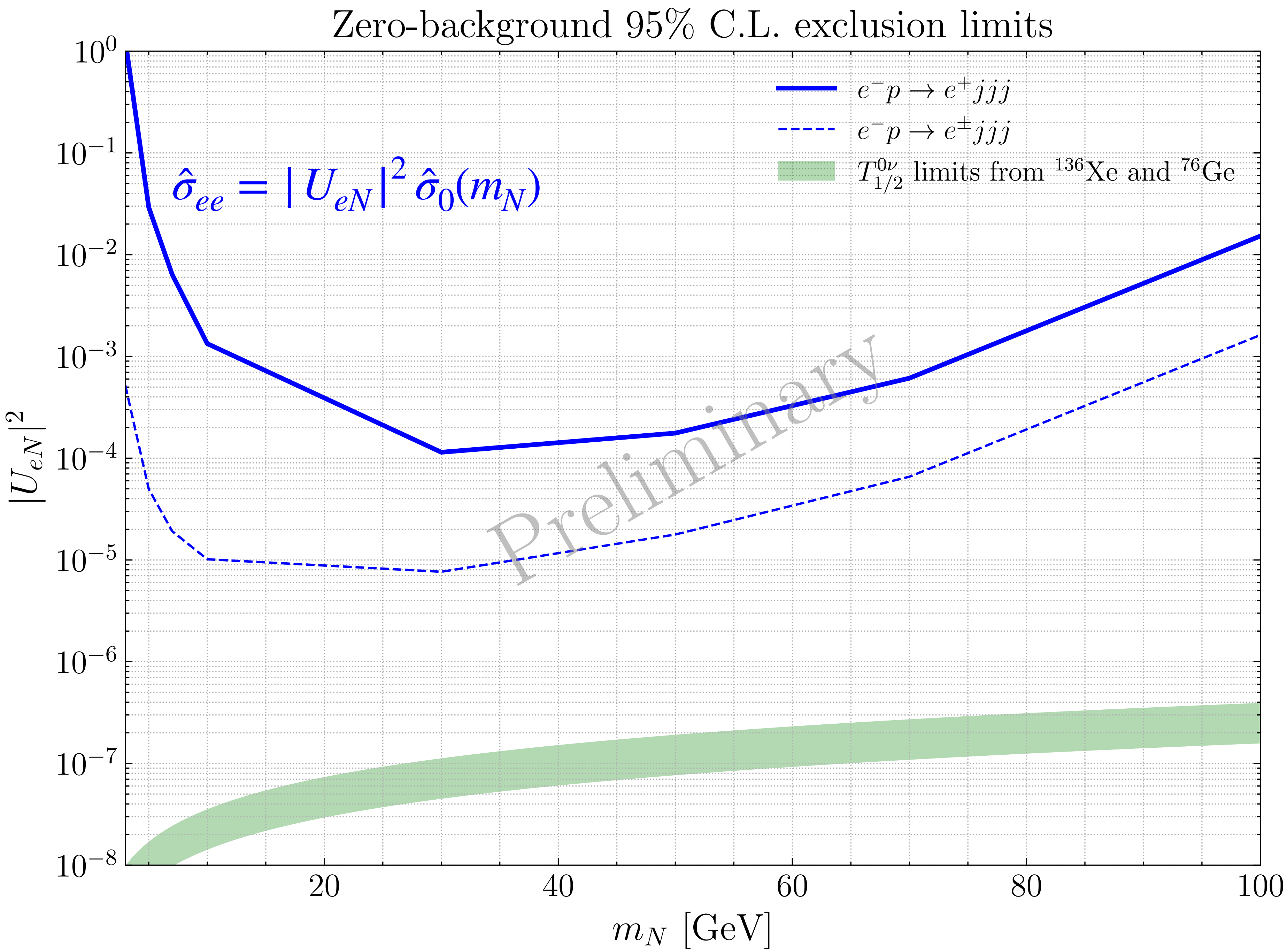
M. Arratia, S. Sekula (2021)

$$\sigma(P) = \frac{1}{2}[(1-P)\sigma_- + (1+P)\sigma_+].$$

Inputs are welcomed!

Sterile neutrinos at the EIC — ee sector

- Let's study the process $e^- p \to e^+ jjj$, the direct competitor of $0\nu\beta\beta$ $(U_{\mu N} = U_{\tau N} \equiv 0)$



Sterile neutrinos at the EIC — $e\ell$ sector

- Some low-energy constraints:

$\mathrm{CR}(\mu^- \to e^+, N)$
P. Domin, A. Faessler, S. Kovalenko, F. Simkovic (2004)

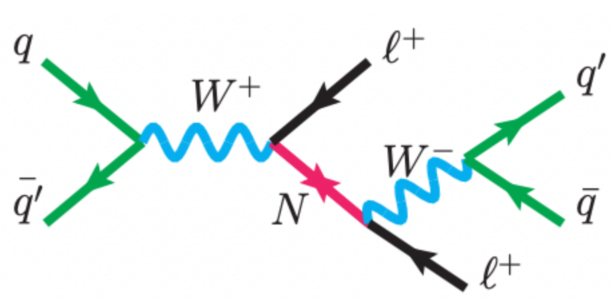
$$|U_{eN}||U_{\mu N}| \lesssim 4.25 \left(\frac{m_N}{\mathrm{GeV}}\right)\left(\frac{m_\mu}{Q_{\mathrm{had}}}\right)^3 \simeq 3.1\times 10^3 \left(\frac{m_N}{\mathrm{GeV}}\right)$$

$\tau^- \to e^+\pi^-\pi^-$
Y. Liao, X.-D. Ma, H.-L. Wang (2021)

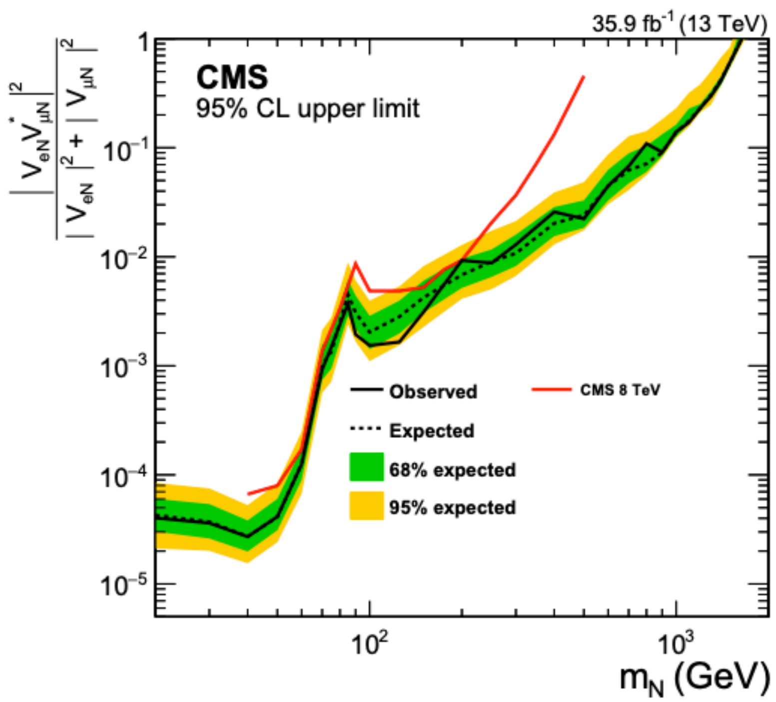
$$|U_{eN}||U_{\tau N}| \lesssim 6.2\times 10^3 \left(\frac{m_N}{\mathrm{GeV}}\right)$$

- The current EIC design doesn't consider specific μ/τ ID *strategies*:
  - Using ee events, assuming similar reconstruction properties
  - $e\mu$ $(U_{\tau N} \equiv 0)$ as a case study

$$\hat{\sigma} = \frac{|U_{eN}U^*_{\mu N}|^2}{|U_{eN}|^2 + |U_{\mu N}|^2}\,\hat{\sigma}_0(m_N)$$

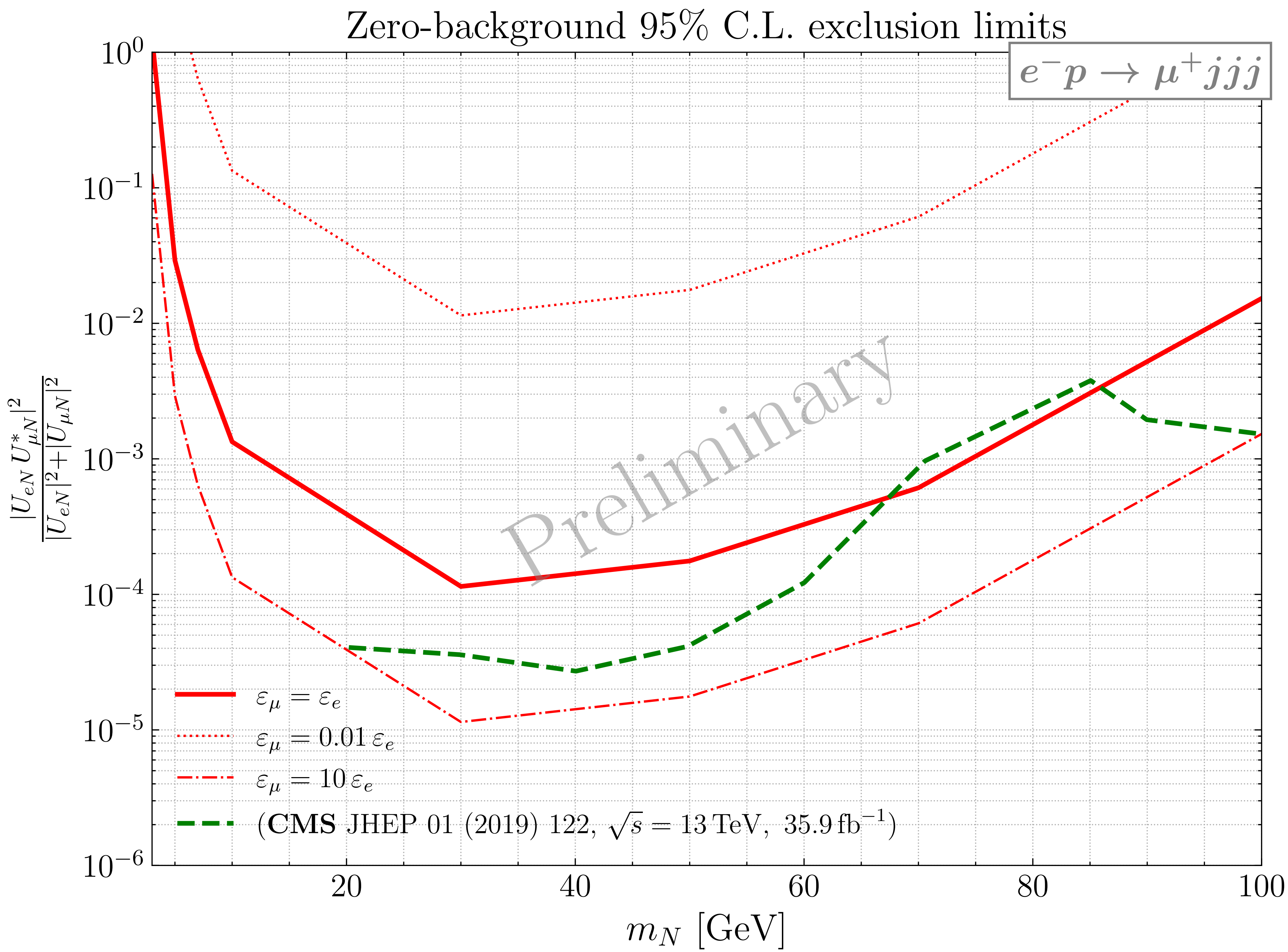


CMS-EXO-17-028 (2019)



Sterile neutrinos at the EIC — $e\mu$ sector

$(U_{\tau N} \equiv 0)$



Some conclusions

- What are sterile neutrinos?
  - ➡ *Sterile neutrinos are a simple, helpful, and harmless extension of the Standard Model.*

- Are they a reasonable assumption?
  - ➡ *It is not hard to believe they are hiding somewhere inside an unbounded parameter space.*
  - ➡ *They may play a central role in explaining why active neutrinos have tiny, nonzero masses. However, even in this scenario, the allowed parameter space remains unresolved.*

- Should they exist in nature?
  - ➡ *Strong experimental evidence, but no discovery yet*

- Does the EIC provide a discovery opportunity?
  - ➡ *Tremendous potential, and we need the community's support*

Thanks for your attention!

Lilo

Spin