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Probing the νSMEFT at FCC-ee

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work in collaboration with Patrick Bolton, Suchita Kulkarni, Chayan Majumdar, Wenna Pei, arXiv:2502.06972

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Dirac versus Majorana

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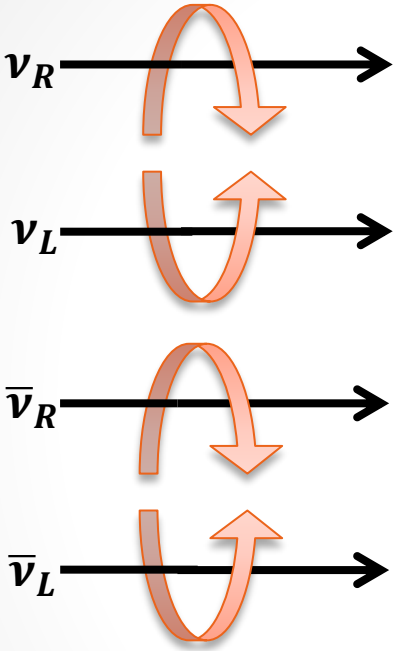
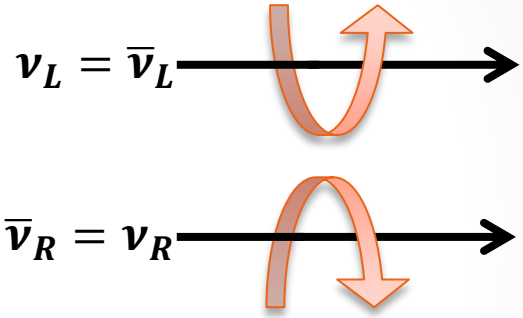
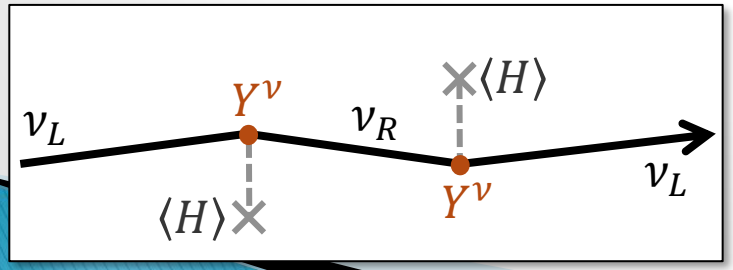
- Two possibilities to define fermion mass

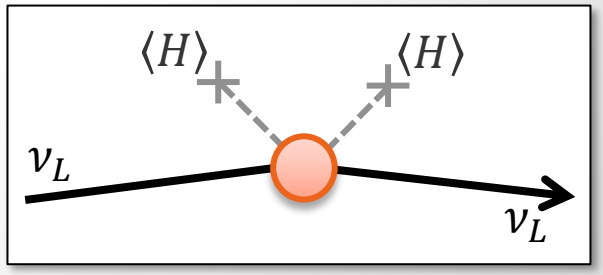




Dirac mass analogous to other fermions but with $m_\nu / \Lambda_{EW} \approx 10^{-12}$ couplings to Higgs



Majorana mass, using only a left-handed neutrino → Lepton Number Violation



Dirac versus Majorana

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- Origin of neutrino masses beyond the Standard Model
- Crucial role of total lepton number L symmetry
  - Arises accidentally as global $U(1)_L$ in SM from particle content and gauge symmetry
  - L broken non-perturbatively but $B-L$ conserved
  - Global symmetries expected to be broken gravitational effects?

$$m_\nu \approx \frac{v^2}{M_{\text{Planck}}} \approx 10^{-5}\ \text{eV}$$

  - Too small to explain oscillations but too large as subdominant splitting
  - Connection to matter-antimatter asymmetry

Heavy Sterile Neutrinos

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- SM + Sterile Neutrinos

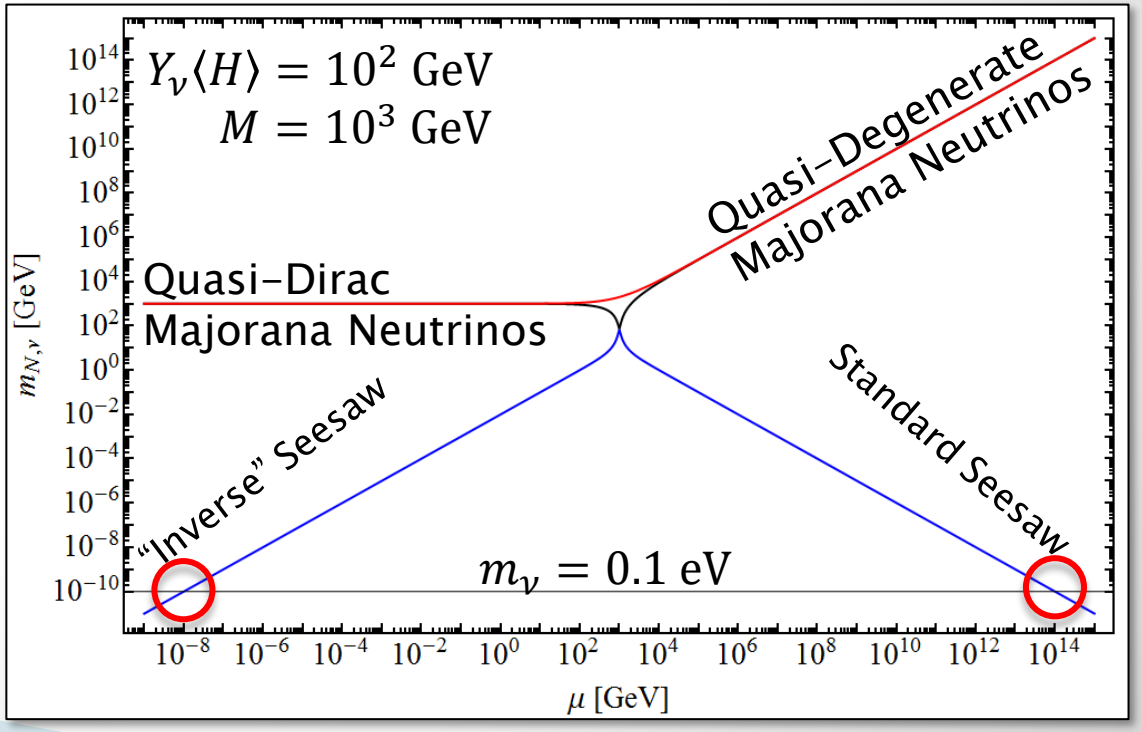
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_{iR}\partial\!\!\!/ N_{iR} - (Y_\nu)_{\alpha i}\bar{L}_\alpha \tilde{H} N_{iR} - \frac{1}{2}(\mathcal{M}_S)_{ij}\bar{N}^c_{iR}N_{jR} + \text{h.c.}\,.$$

  - Seesaw Mechanism with TeV scale heavy neutrinos
    - Standard Seesaw with small Yukawa couplings

$$V^{\nu N} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$$

  - "Bent" Seesaw mechanisms
    - Decouple $\Lambda_{\rm LNV}$ from heavy neutrino mass

$$\begin{matrix} & \nu & N_1 & N_2 \end{matrix}$$
$$\mathcal{M} = \begin{pmatrix} 0 & Y_\nu\langle H\rangle & 0 \\ Y_\nu\langle H\rangle & \mu & M \\ 0 & M & \mu \end{pmatrix}$$



HNL Searches – Current

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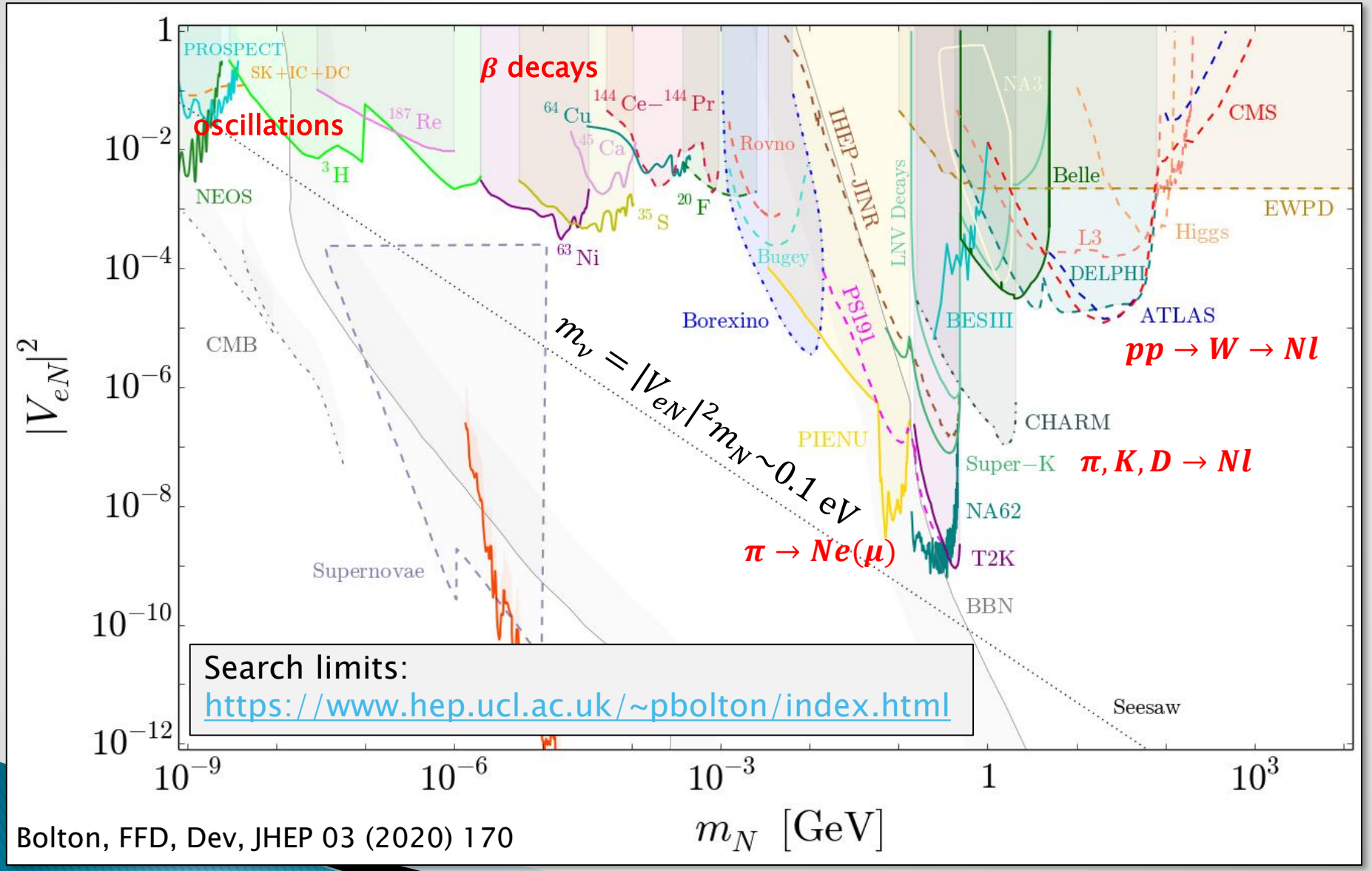
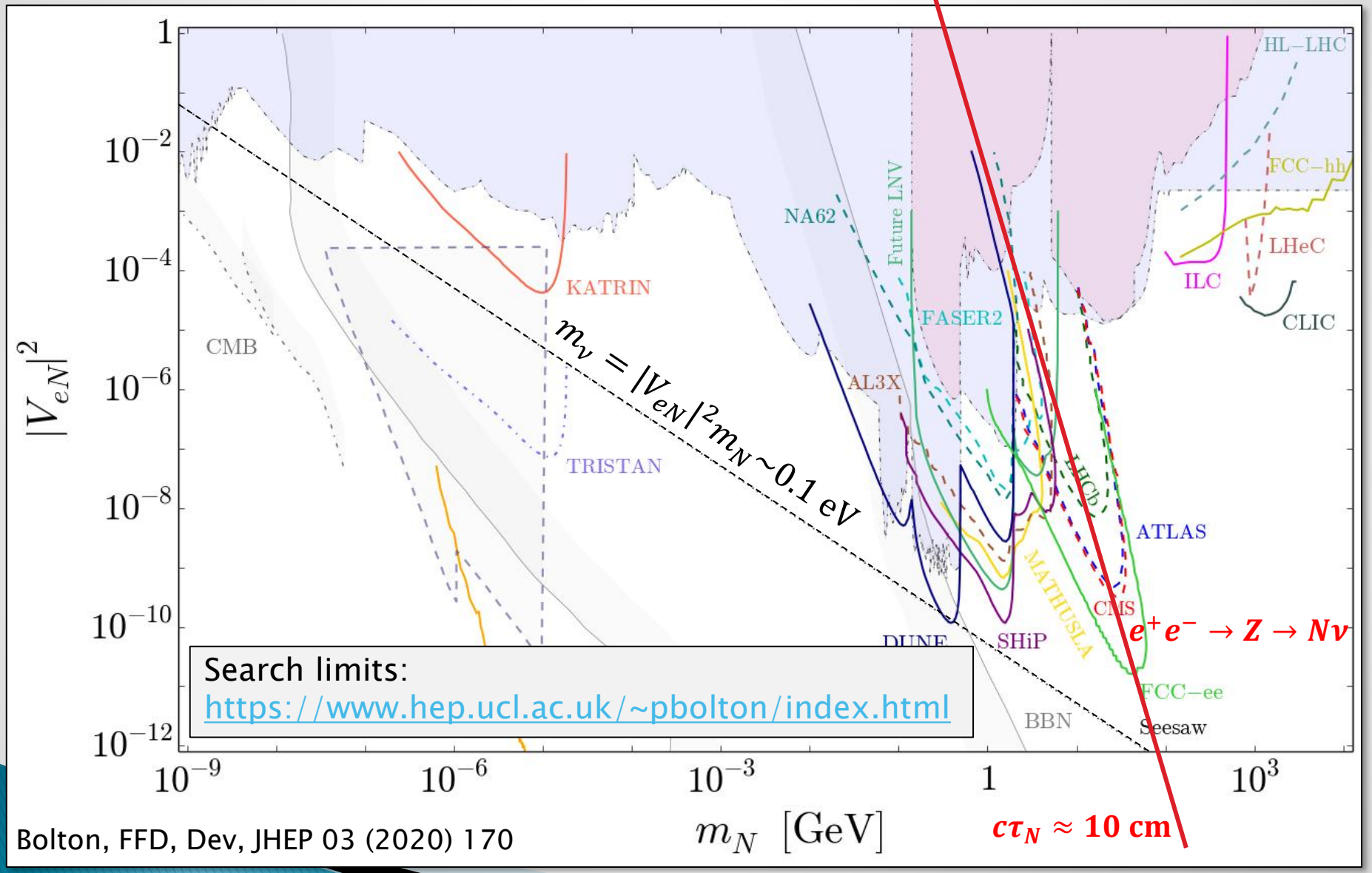


Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL Searches – Proposed



Bolton, FFD, Dev, JHEP 03 (2020) 170

HNL Searches at FCC-ee

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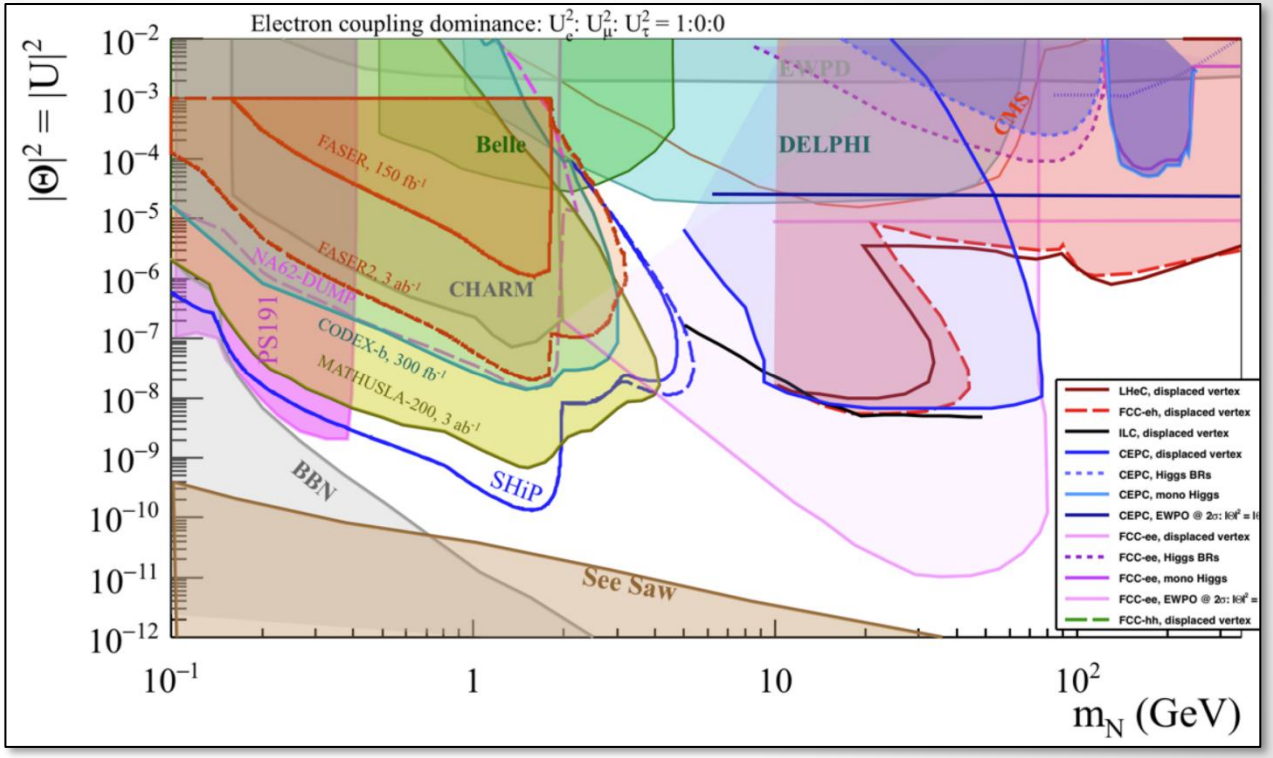
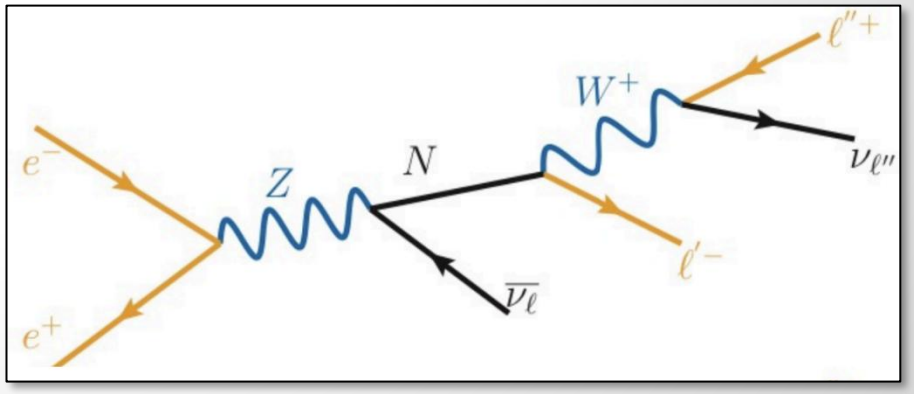
- Production and decay via active-sterile mixing
- HNLs are long-lived
- Displaced vertex search
- Difficult to reach seesaw expectation



European Strategy for Particle Physics Preparatory Group, Update 2020



νSMEFT

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- Consider HNL EFT operators
- Describing New Physics portals for production

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \bar{N} i \not{\partial} N - \left[\bar{L} Y_\nu N \tilde{H} + \frac{1}{2} \bar{N}^c M N + \text{h.c.} \right] + \sum_i C_i^{(d)} Q_i^{(d)}$$

d=5

$\psi^2 H^2$	
Q_5	$\epsilon_{ij}\epsilon_{mn}(\bar{L}^{ic}L^m)H^jH^n$
Q_N	$(\bar{N}_R^c N_R)(H^\dagger H)$

d=6

$\psi^2 H^3$	
Q_{lNH}	$(\bar{L}N_R)\tilde{H}(H^\dagger H)$
$\psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(\bar{L}\gamma_\mu L)(H^\dagger i\overleftrightarrow{D}^\mu H)$
$Q_{Hl}^{(3)}$	$(\bar{L}\gamma_\mu \tau^I L)(H^\dagger i\overleftrightarrow{D}^{I\mu} H)$
Q_{HN}	$(\bar{N}_R\gamma_\mu N_R)(H^\dagger i\overleftrightarrow{D}^\mu H)$
Q_{HNe}	$(\bar{N}_R\gamma_\mu e_R)(\tilde{H}^\dagger i\overleftrightarrow{D}^\mu H)$

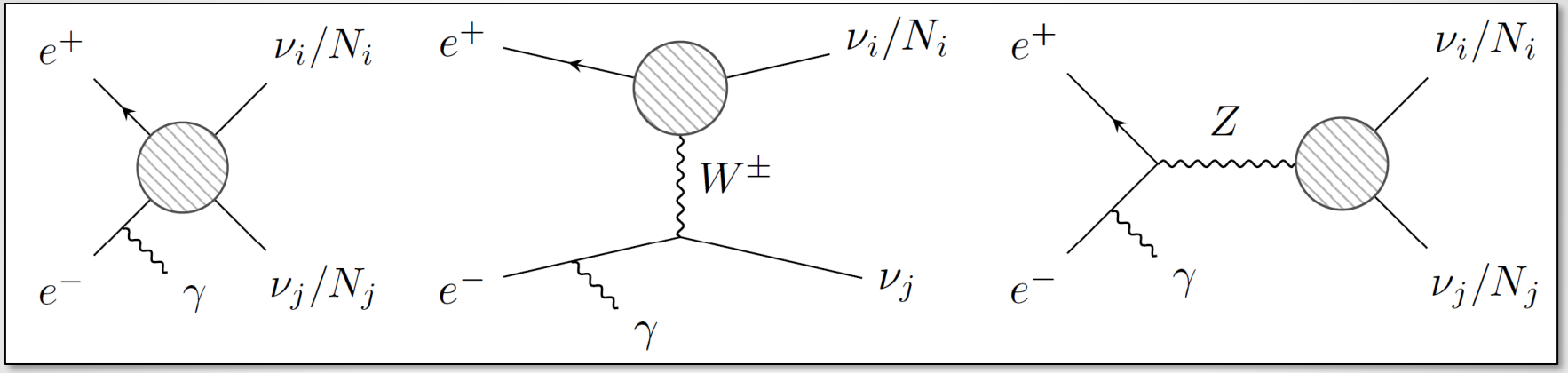
ψ^4	
Q_{ll}	$(\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$
Q_{le}	$(\bar{L}\gamma_\mu L)(\bar{e}_R\gamma^\mu e_R)$
Q_{lNle}	$\epsilon_{ij}(\bar{L}^i N_R)(\bar{L}^j e_R)$
Q_{lN}	$(\bar{L}\gamma_\mu L)(\bar{N}_R\gamma^\mu N_R)$
Q_{eN}	$(\bar{e}_R\gamma_\mu e_R)(\bar{N}_R\gamma^\mu N_R)$

d=7

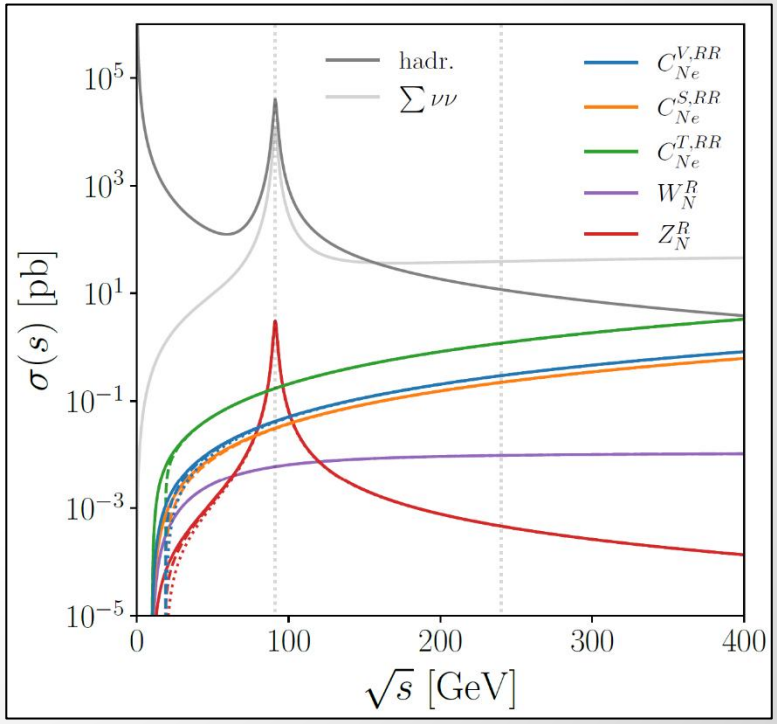
$\psi^2 H^4$	
Q_{lH}	$\epsilon_{ij}\epsilon_{mn}(\bar{L}^{ic}L^m)H^jH^n(H^\dagger H)$
Q_{NH}	$(\bar{N}_R^c N_R)(H^\dagger H)^2$
$\psi^2 H^3 D$	
Q_{Nl1}	$\epsilon_{ij}(\bar{N}_R^c\gamma_\mu L^i)(iD^\mu H^j)(H^\dagger H)$
Q_{Nl2}	$\epsilon_{ij}(\bar{N}_R^c\gamma_\mu L^i)H^j(H^\dagger i\overleftrightarrow{D}^\mu H)$
Q_{leHD}	$\epsilon_{ij}\epsilon_{mn}(\bar{L}^{ic}\gamma_\mu e_R)H^jH^mD^\mu H^n$

$\psi^4 H$	
Q_{lleH}	$\epsilon_{ij}\epsilon_{mn}(\bar{e}_R L^i)(\bar{L}^{jc}L^m)H^n$
Q_{lNlH}	$\epsilon_{ij}(\bar{L}\gamma_\mu L)(\bar{N}_R^c\gamma^\mu L^i)H^j$
Q_{eNlH}	$\epsilon_{ij}(\bar{e}_R\gamma_\mu e_R)(\bar{N}_R^c\gamma^\mu L^i)H^j$
Q_{lNeH}	$(\bar{L}N_R)(\bar{N}_R^c e_R)H$
Q_{elNH}	$H^\dagger(\bar{e}_R L)(\bar{N}_R^c N_R)$

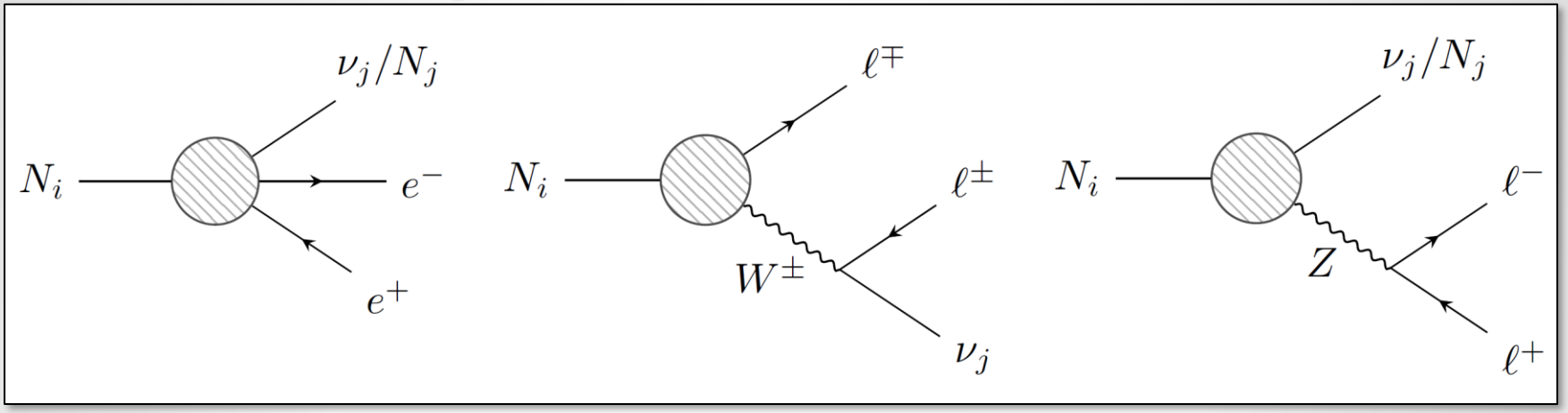
HNL Production



- CS calculated at LO
- EFT operators implemented in Feynrules
- Simulated in MadGraph_aMC@NLO
- $\sqrt{s} = 91.2$ GeV @ 100 ab^{-1}
- $\sqrt{s} = 240$ GeV @ 5 ab^{-1}

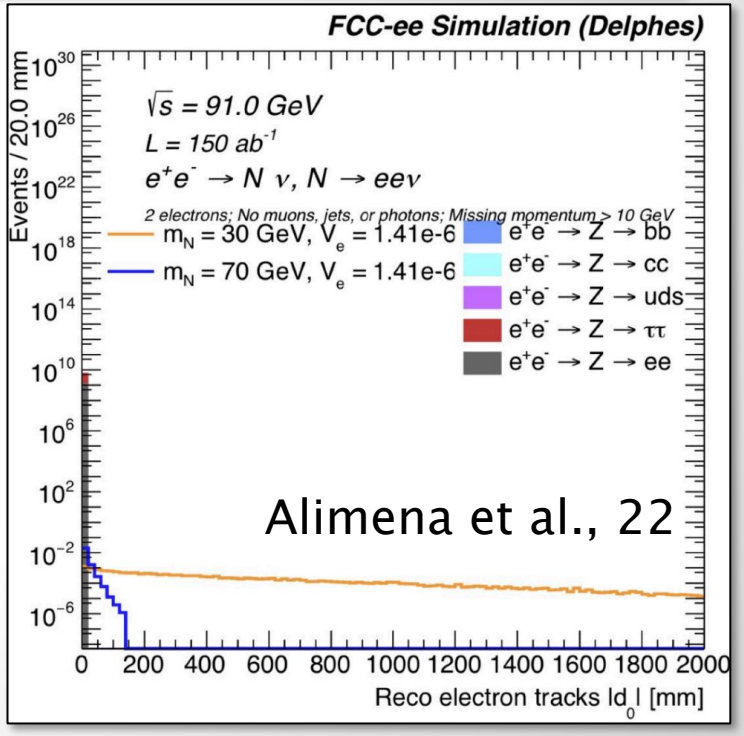


HNL Decay

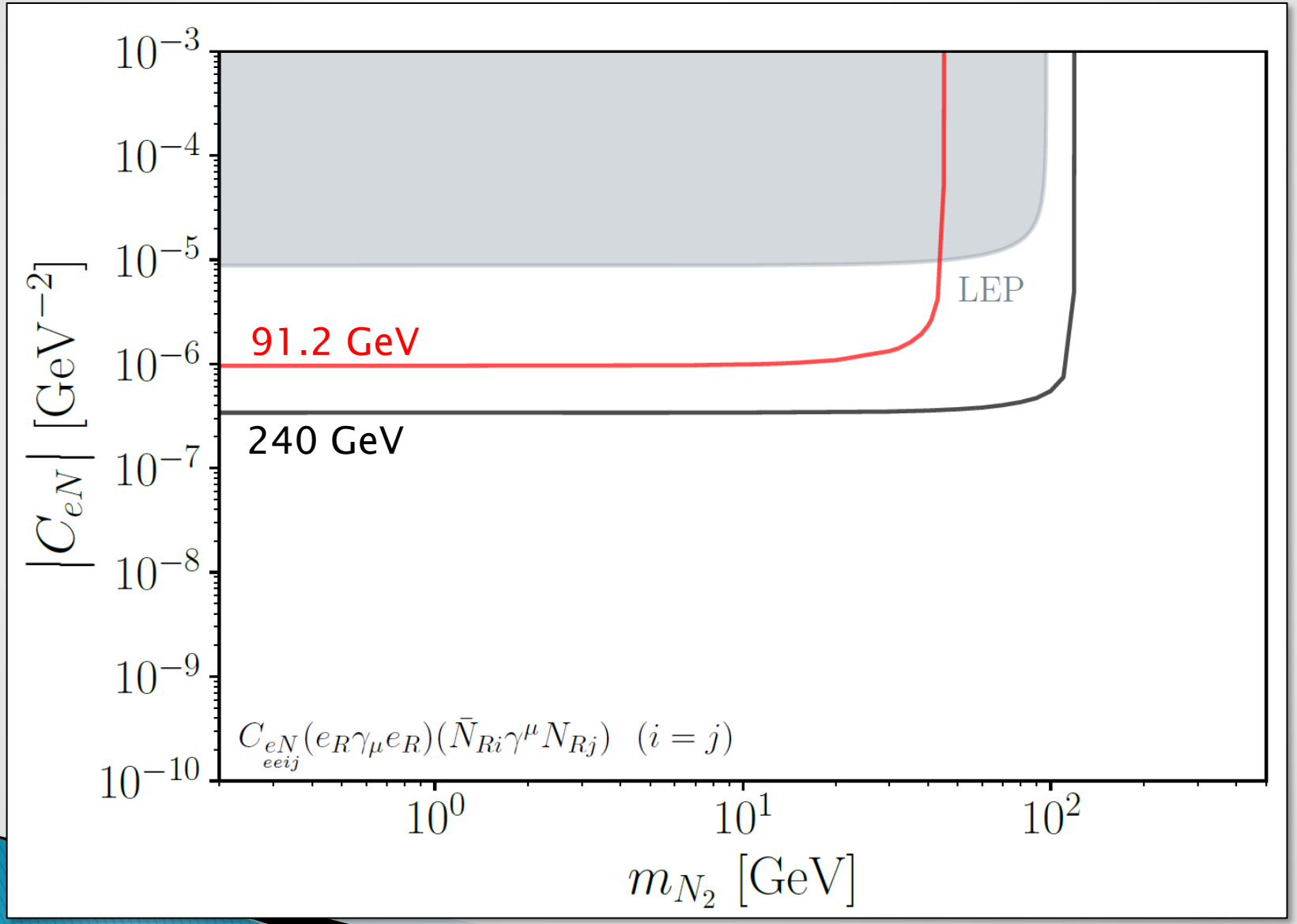


- Decay via same EFT operators (if allowed)
- Spherical detector with radius

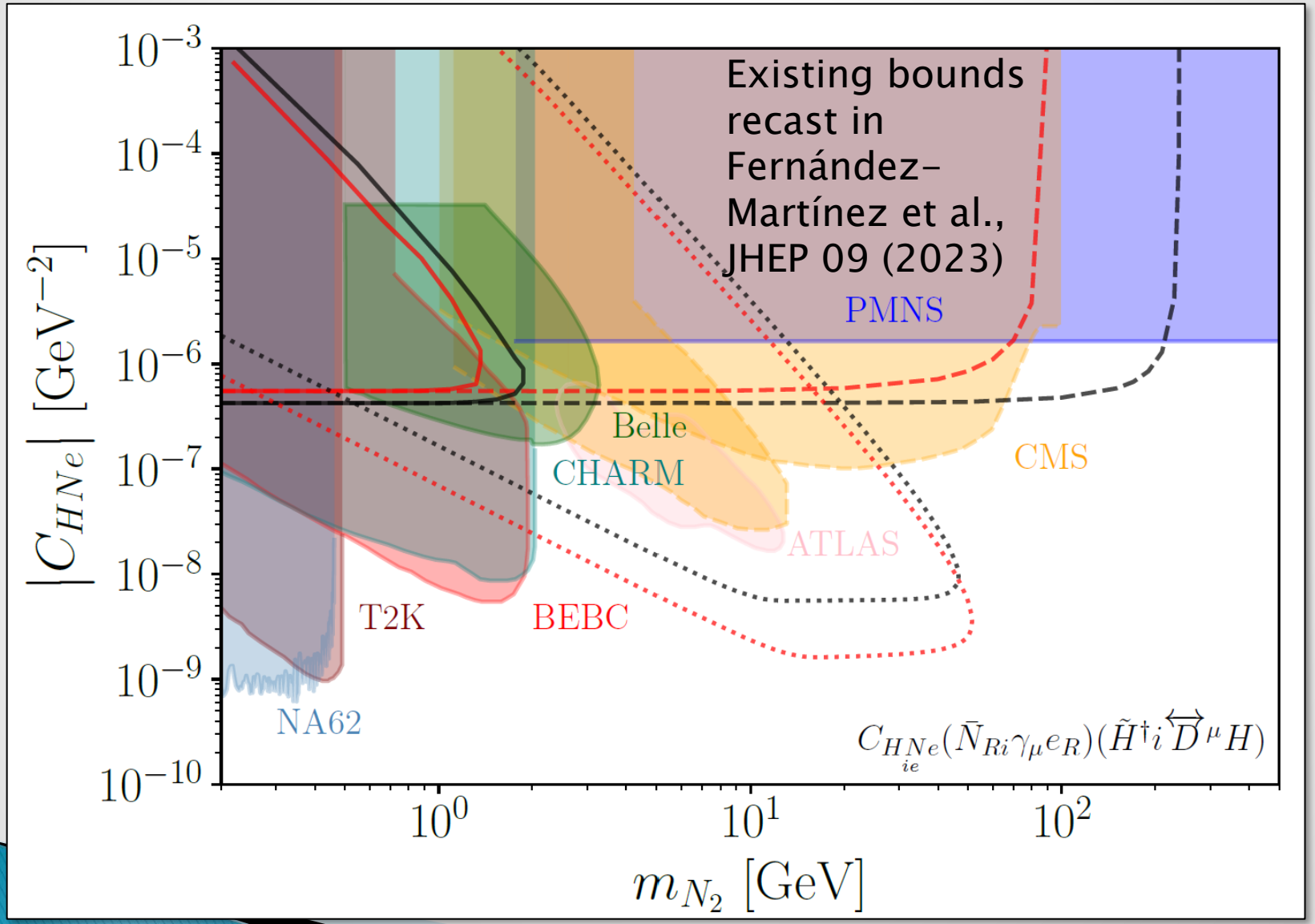
$$0.1\,\mathrm{mm} < R < 5\,\mathrm{m}$$



FCC-ee Sensitivity



FCC-ee Sensitivity



FCC-ee Sensitivity

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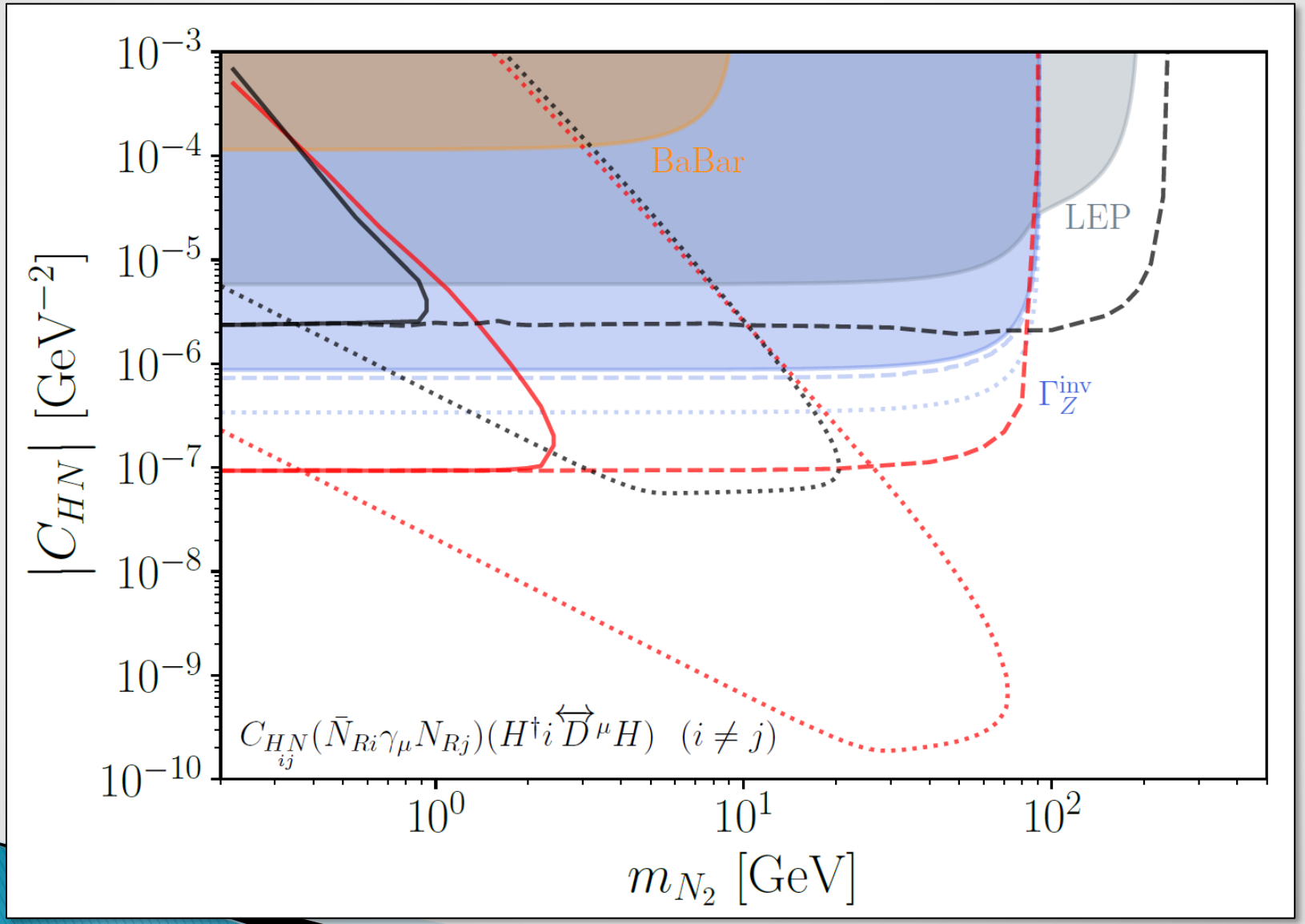

Conclusion

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- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Determination of absolute mass scale
- **Searching for HNLs**
  - Testing the mechanism of neutrino mass generation
  - Baryon asymmetry of the Universe via Leptogenesis
  - Light neutrino masses → small active-sterile mixing
    - HNLs are LLPs
    - Suppressed production via SM NCs and CCs
  - Consider efficient HNL portals beyond mixing → νSMEFT
- **HNL SMEFT at FCC-ee**
  - Analysis of monophoton and displaced vertex searches for dim-6 and dim-7 operators
  - Strong sensitivity to νSMEFT scales up to $\Lambda \approx 60\ \mathrm{TeV}$