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Neutrino Nature and Heavy Neutral Leptons

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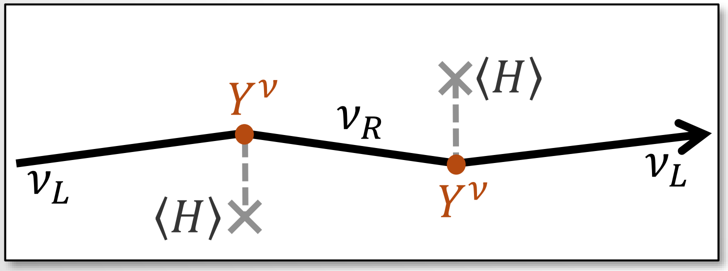
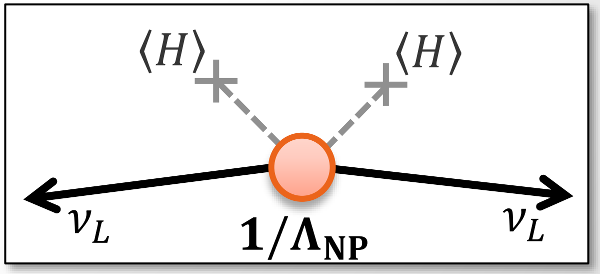
Dirac vs Majorana

- Origin of neutrino masses beyond the Standard Model
- Two possibilities to define neutrino 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





Heavy Sterile Neutrinos

- SM + Sterile Neutrinos

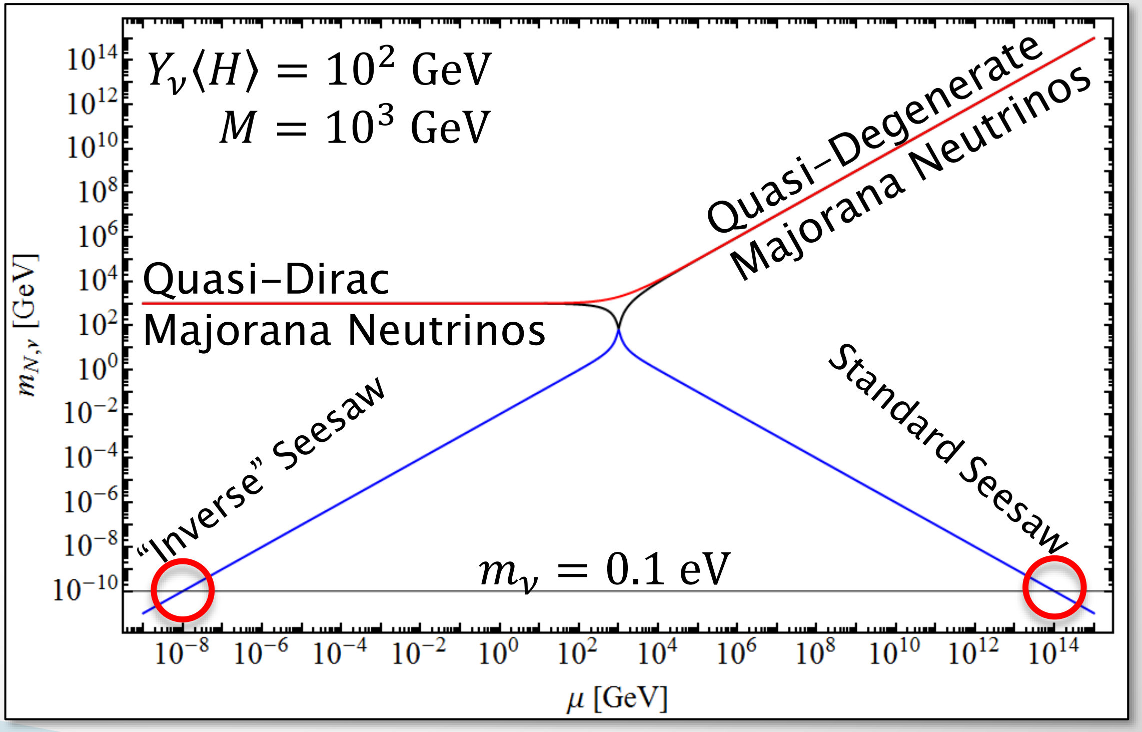
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_{iR}\partial\!\!\!/ N_{iR} - (Y_\nu)_{\alpha i}\bar{L}_\alpha\tilde{H}N_{iR} - \frac{1}{2}(\mathcal{M}_S)_{ij}\bar{N}^c_{iR}N_{jR} + \text{h.c.}\,.$$

  - 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 Λ_{LNV} from heavy neutrino mass

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



$1\nu + 2N$: Pheno Parametrization

- Parametrization

$$\mathrm{diag}(m_\nu, M_N, M_N + \Delta M_N) = V \cdot \begin{array}{c} \begin{array}{ccc} \nu & N_1 & N_2 \end{array} \\ \begin{pmatrix} 0 & m_D & 0 \\ m_D & \mu_R & M \\ 0 & M & \mu_S \end{pmatrix} \end{array} \cdot V^T$$

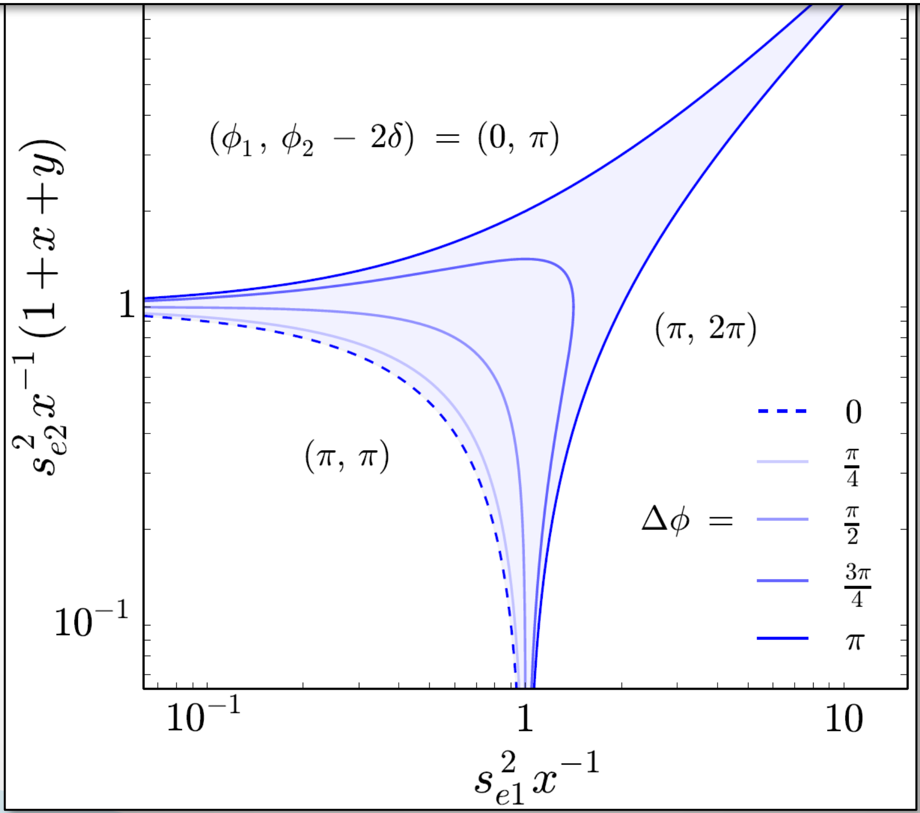
$$V = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{12} & \sin\theta_{12} \\ 0 & -\sin\theta_{12} & \cos\theta_{12} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e2} & 0 & \sin\theta_{e2} e^{i\delta} \\ 0 & 1 & 0 \\ -\sin\theta_{e2} e^{i\delta} & 0 & \cos\theta_{e2} \end{pmatrix} \cdot \begin{pmatrix} \cos\theta_{e1} & \sin\theta_{e1} & 0 \\ -\sin\theta_{e1} & \cos\theta_{e1} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot D$$

- Contribution of heavy and light neutrinos to $0\nu\beta\beta$
  - See, e.g., Lopez-Pavon, Pascoli, Wong, Phys. Rev. D 87, 093007; Hernández, Jones-Pérez, Suarez-Navarro, Eur. Phys. J. C (2019) 79: 220
- Masses and observable active-sterile mixing as input
  - Large mass-splitting $\Delta m_N = m_{N_2} - m_{N_1}$ lead to large loop-contribution to light neutrino mass

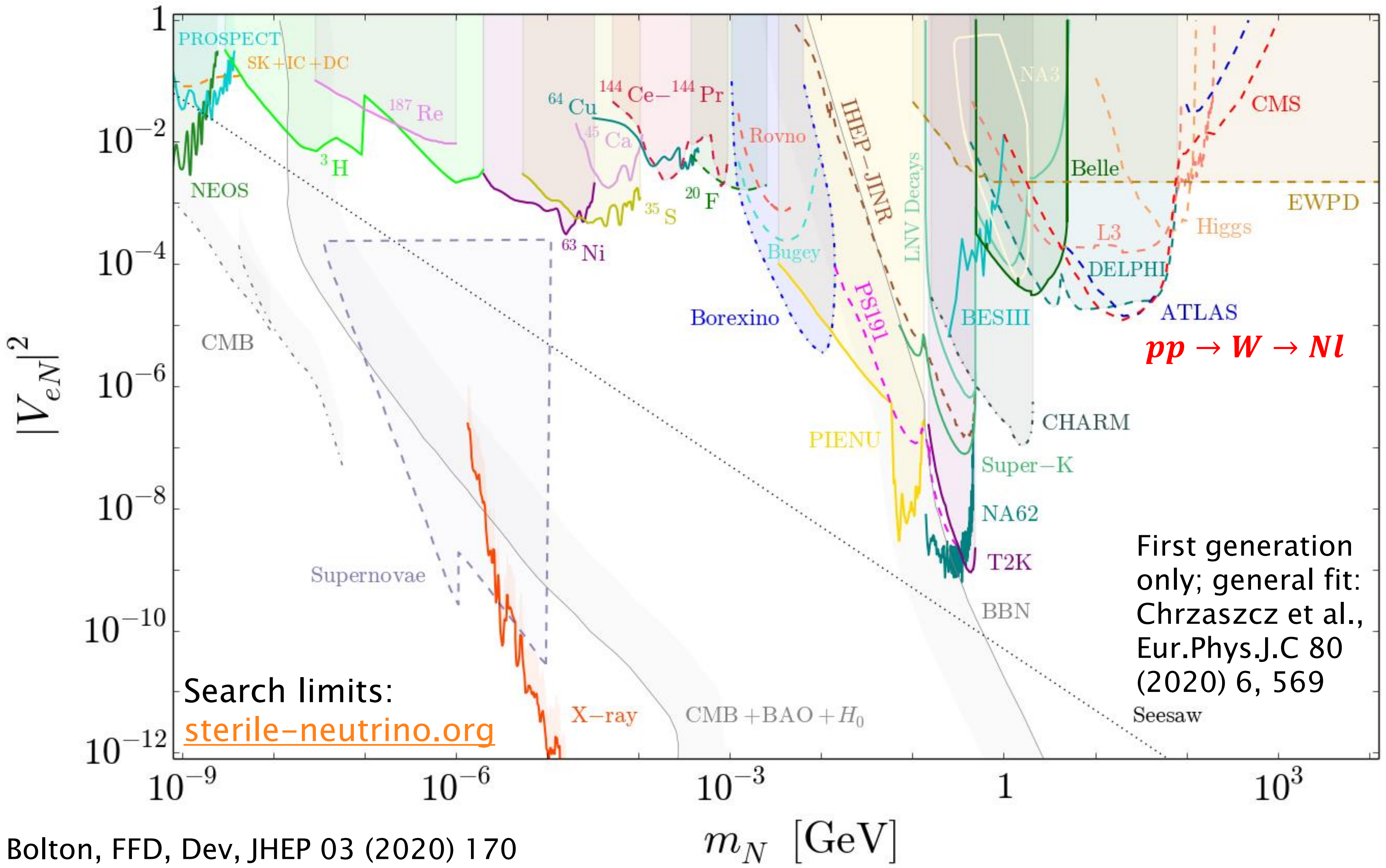
$1\nu + 2N$: Pheno Parametrization

- Relation between active-sterile mixing angles (tree level)

$$(\mathcal{M}_\nu)_{\alpha\beta} = 0 \quad \Rightarrow \quad 0 = \sum_{i=1}^{\mathcal{N}_A} m_i U_{\alpha i} U_{\beta i} + \sum_{k=1}^{\mathcal{N}_S} m_{N_\kappa} U_{\alpha N_\kappa} U_{\beta N_\kappa}$$



HNL Searches – Current



$pp \to W \to Nl$

First generation only; general fit: Chrzaszcz et al., Eur.Phys.J.C 80 (2020) 6, 569

Search limits: sterile-neutrino.org

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

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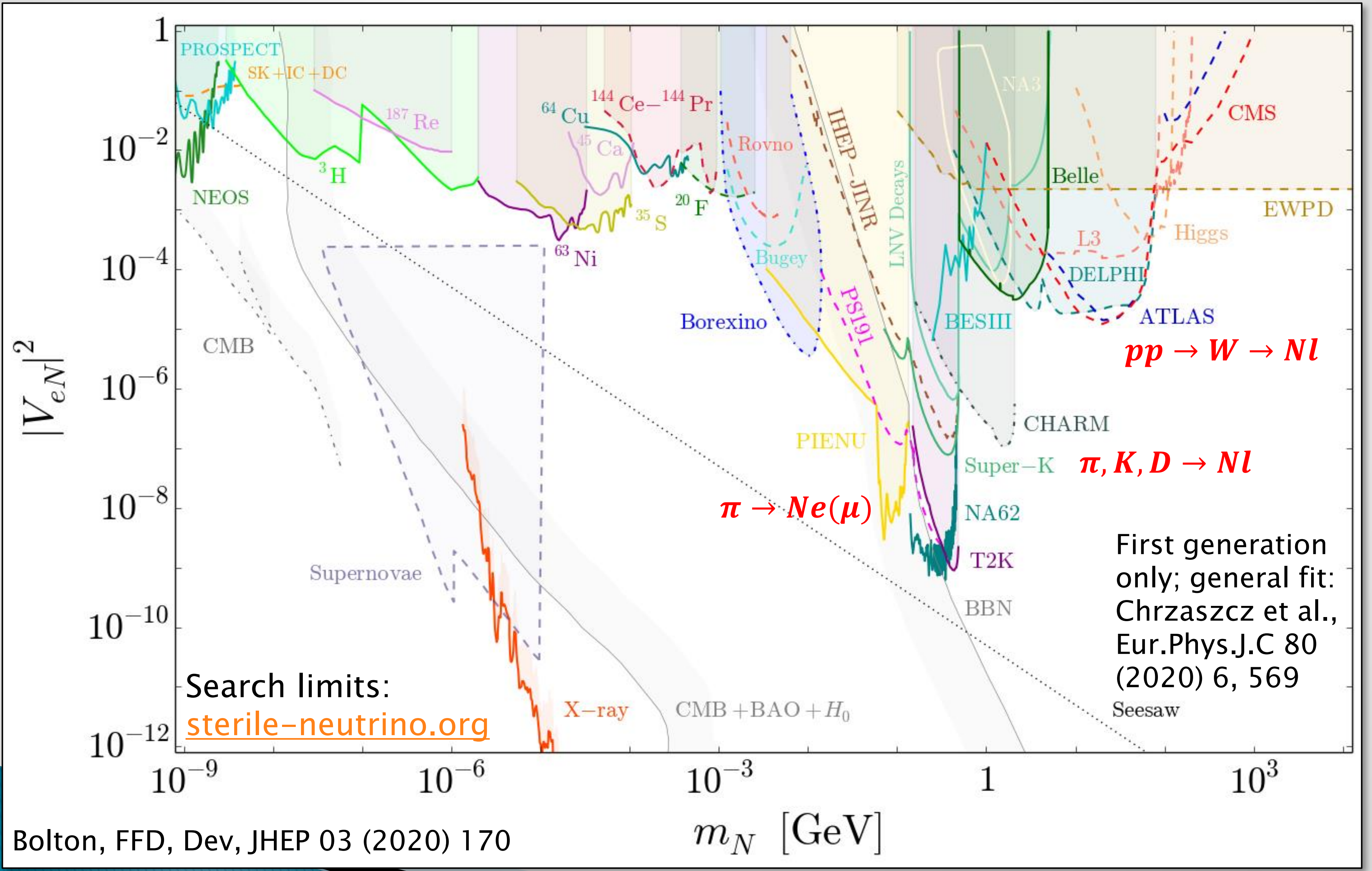

$pp \to W \to Nl$

$\pi, K, D \to Nl$

$\pi \to Ne(\mu)$

First generation only; general fit: Chrzaszcz et al., Eur.Phys.J.C 80 (2020) 6, 569

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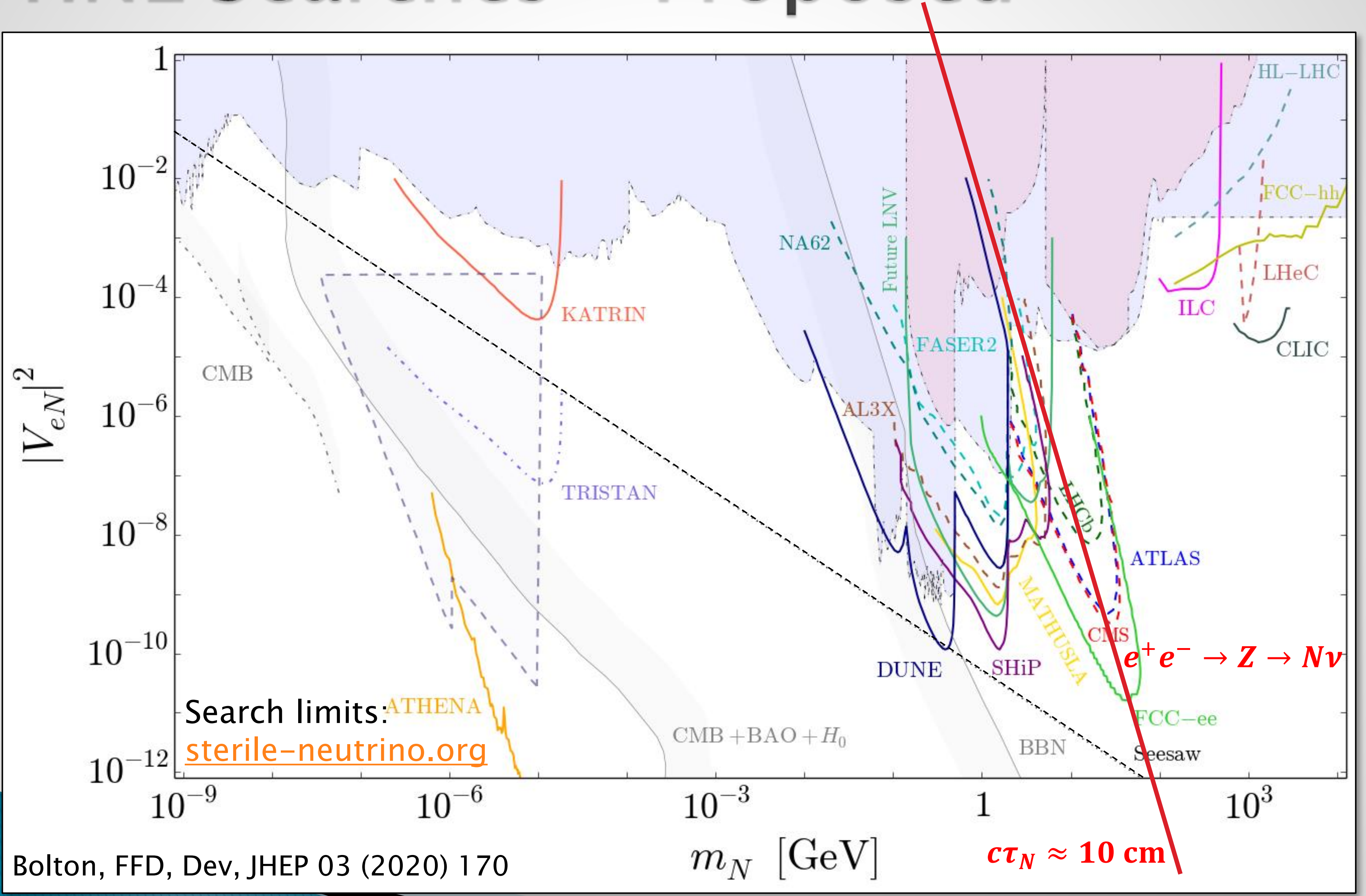
HNL Searches – Proposed



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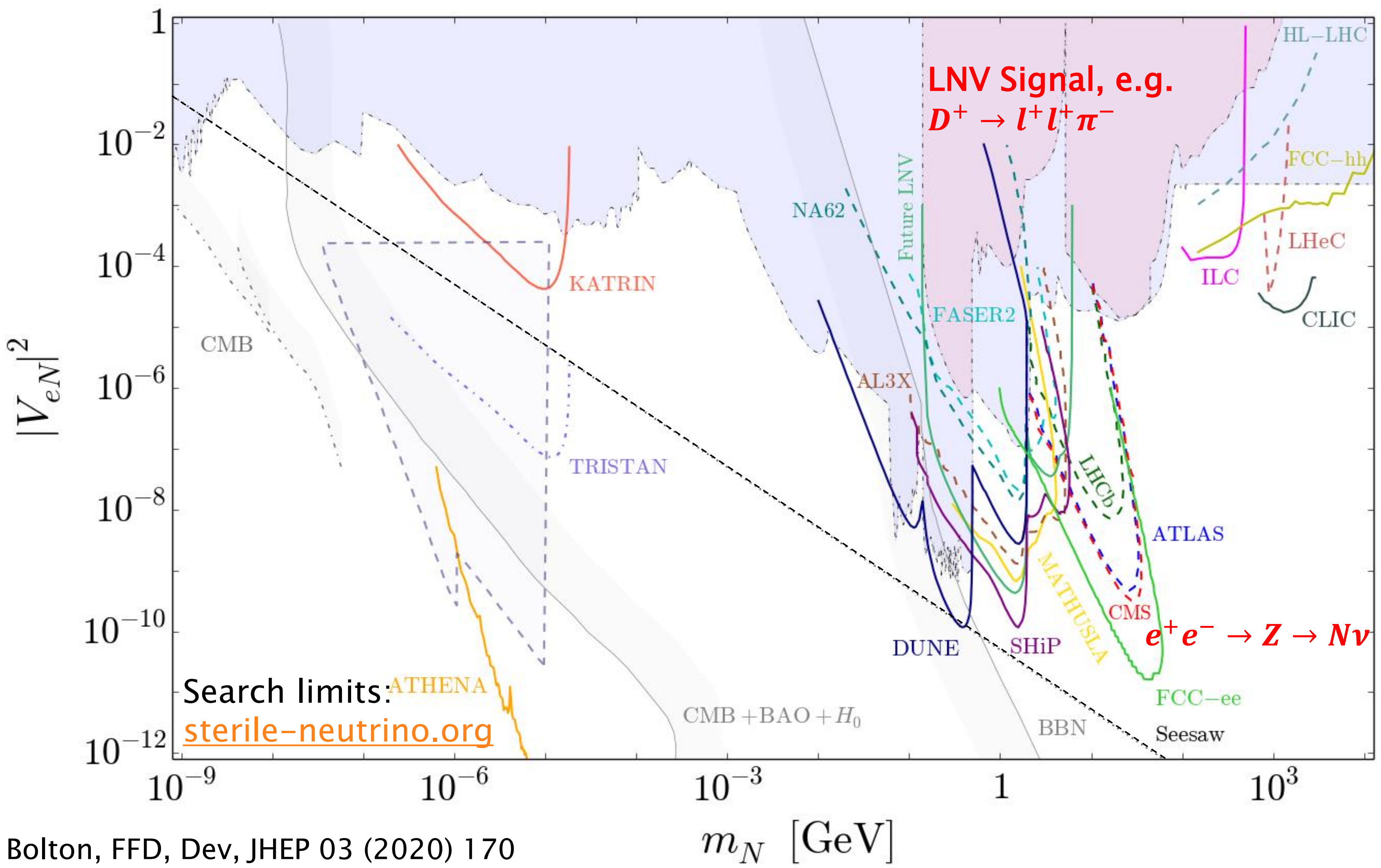
$e^+e^- \to Z \to N\nu$

$c\tau_N \approx 10$ cm

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

HNL Searches – Proposed



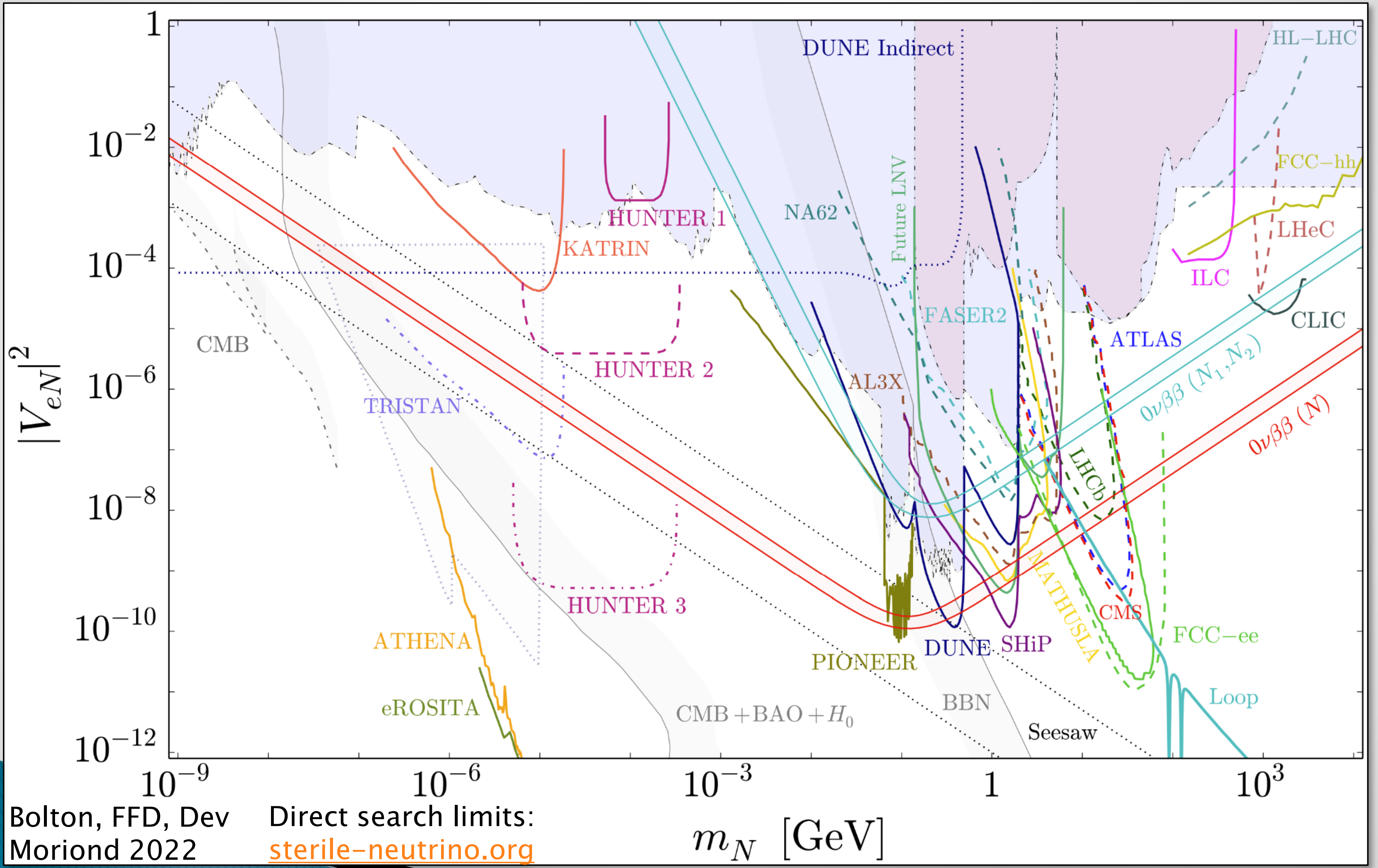
LNV Signal, e.g.
$D^+ \to l^+ l^+ \pi^-$

$e^+ e^- \to Z \to N\nu$

Search limits: sterile-neutrino.org

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

HNL in $0\nu\beta\beta$



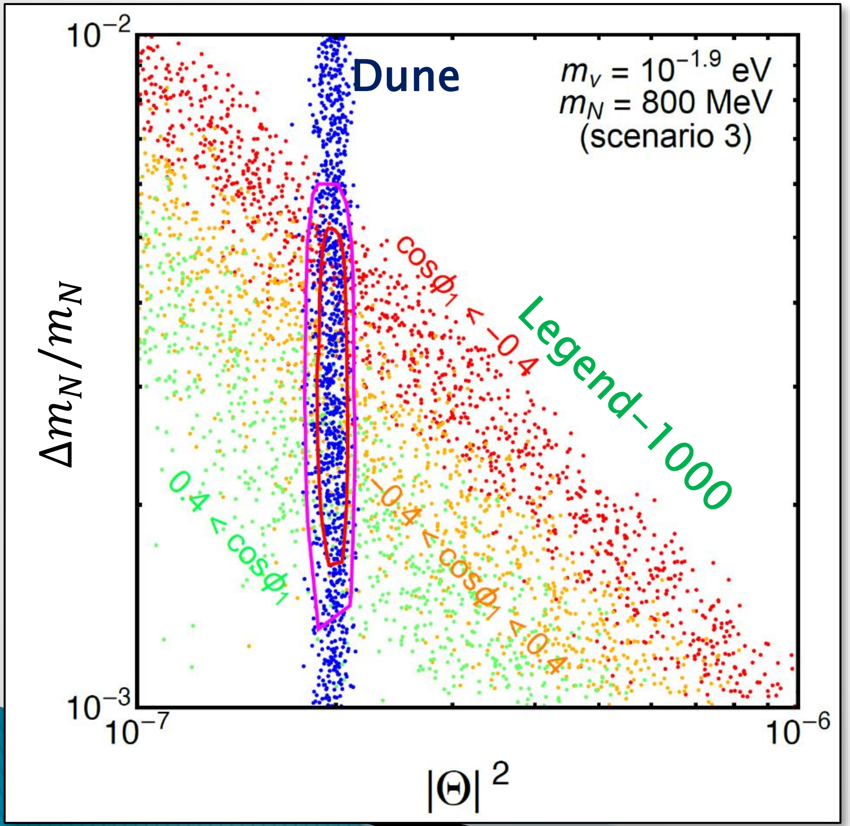
Bolton, FFD, Dev
Moriond 2022

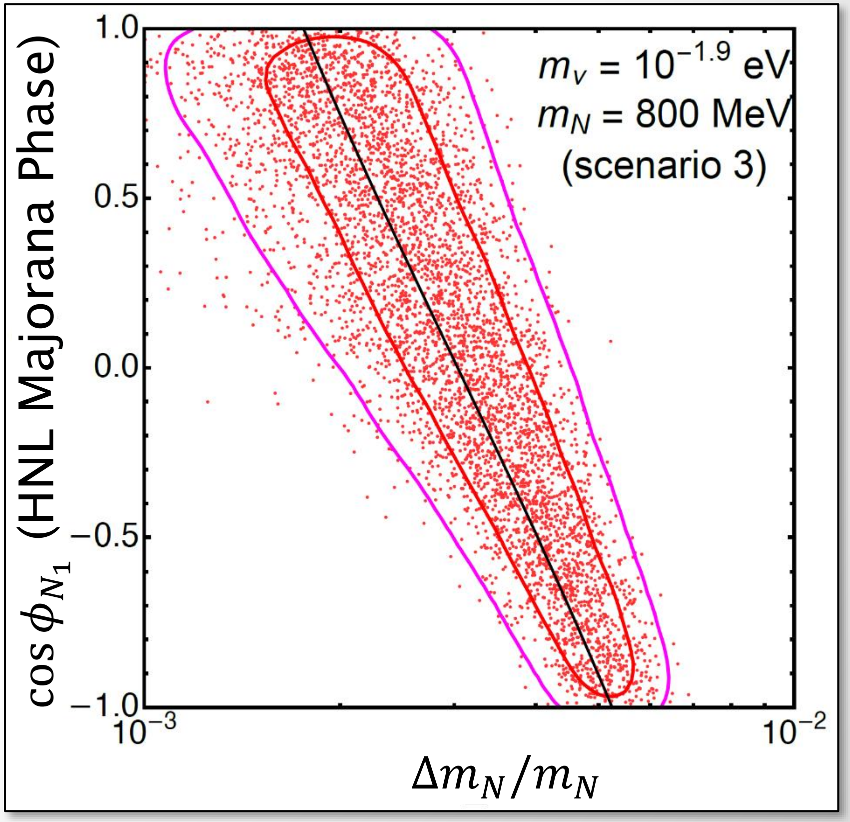
Direct search limits:
sterile-neutrino.org

Complementarity

Patrick Bolton, FFD, Mudit Rai, Zhong Zhang, arXiv:2212.14690

- Between direct searches and $0\nu\beta\beta$
  - Simulation of DUNE-like setup
  - Measurement of events at “DUNE” and $0\nu\beta\beta$ decay at LEGEND-1000 near expected sensitivity





Baryon Asymmetry Washout

FFD, Harz, Hirsch, Phys.Rev.Lett. 112 (2014) 221601

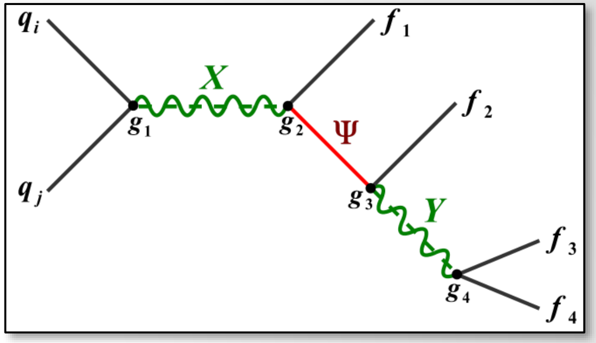
- Compare collider cross section with lepton number asymmetry washout

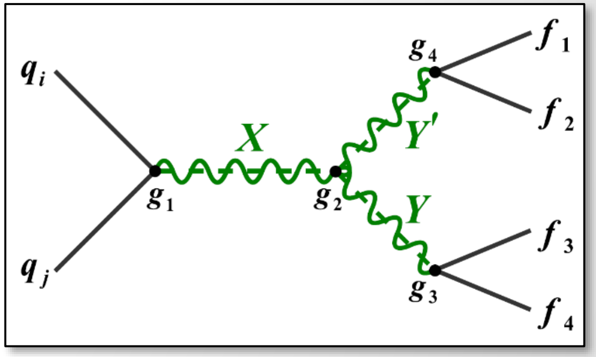
$$\boxed{\frac{\Gamma_W}{H} > 3 \times 10^{-3} \frac{M_P M_X^3}{T^4} \frac{K_1(M_X/T)}{f_{q_1 q_2}(M_X/\sqrt{s})} \times (s\, \sigma_{\mathrm{LHC}})}$$

  - Lower limit on total washout rate
    - Neglecting other washout processes

$$\boxed{\log_{10} \frac{\Gamma_W}{H} > 7 + 0.6 \left(\frac{M_X}{\mathrm{TeV}} - 1 \right) + \log_{10} \frac{\sigma_{\mathrm{LHC}}}{\mathrm{fb}}}$$

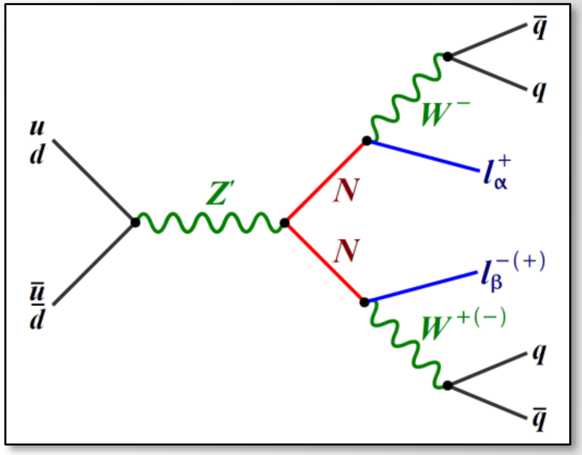
  - Observation of LNV @ Collider corresponds to highly effective washout $\Gamma_W/H \gg 1$
  - Disfavours baryogenesis models above M_X

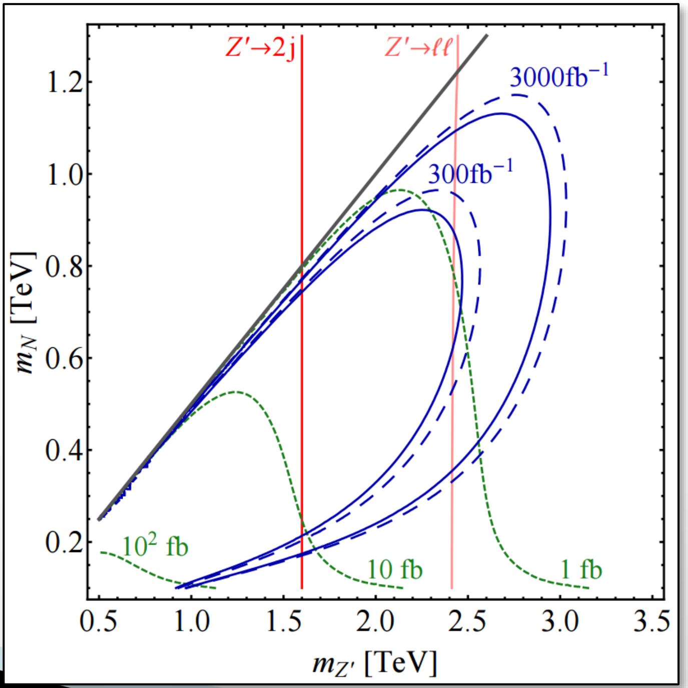


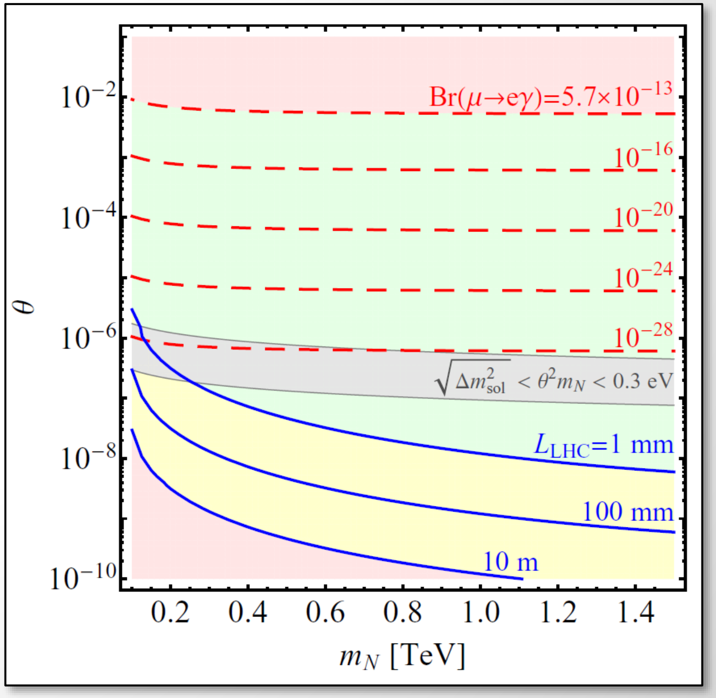


Extended Gauge Sectors

- Additional $U(1)_{B-L}$ gauge symmetry
  - Production via Z' portal
  - Ability to measure small couplings via displaced vertices
  - N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$







FFD, Desai, Valle
PRD 89 (2014) 051302

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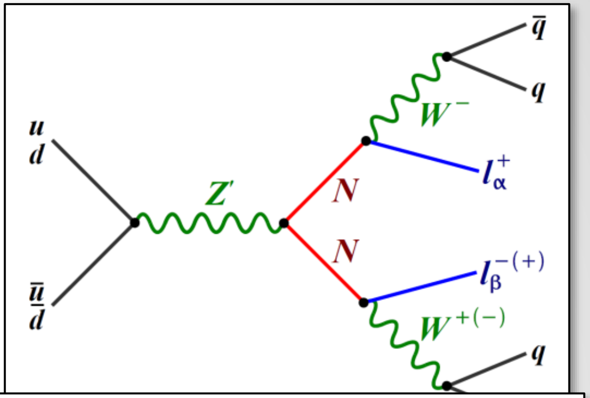
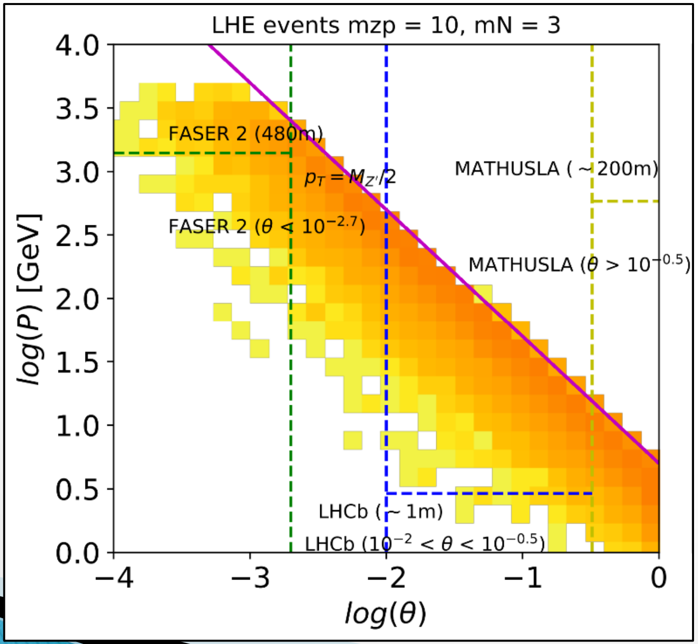
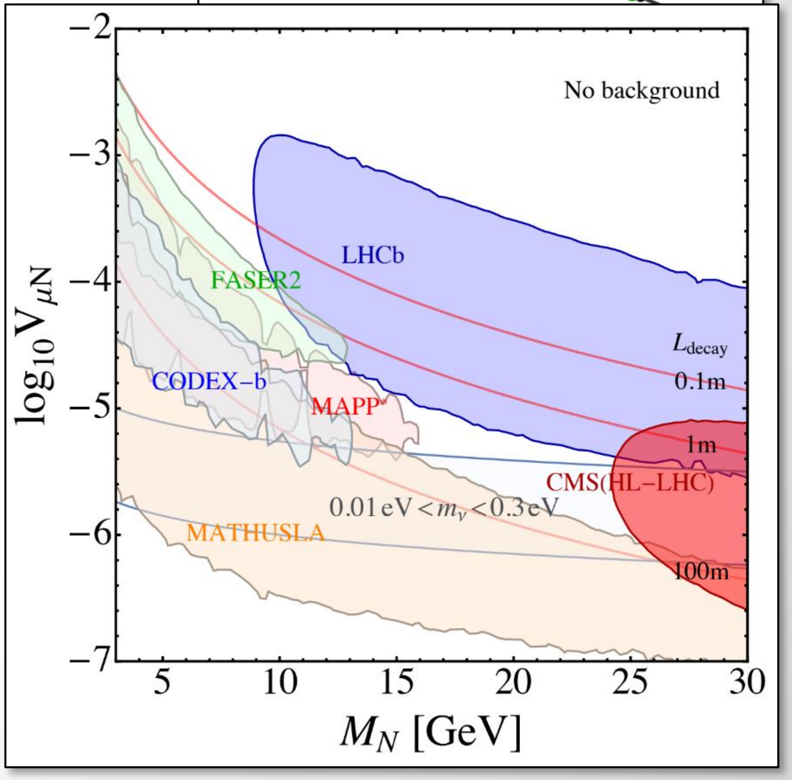
  - **Sensitivity at LHC LLP detectors**



FFD, Kulkarni, Wei
Phys.Rev.D 100
(2019) 3, 035005





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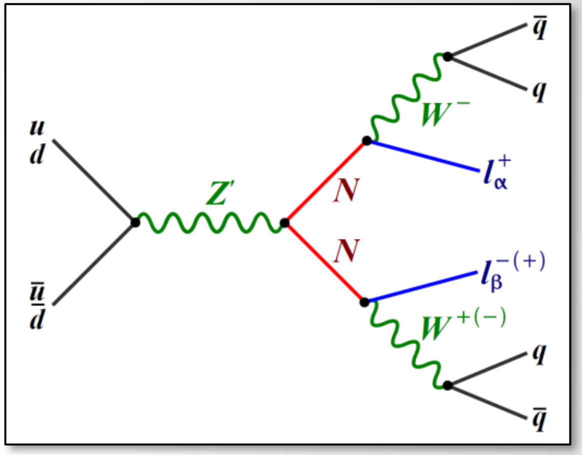
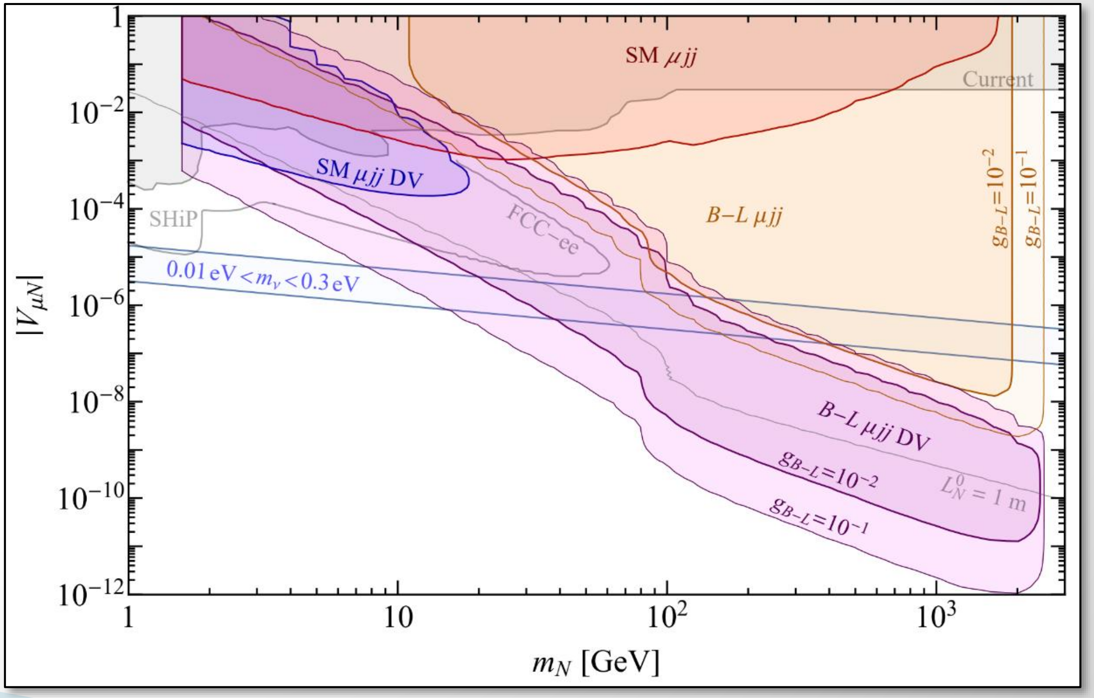
  - **Sensitivity at FCC-hh**





Wei, Kulkarni, FFD
Phys.Rev.D 105 (2022) 9, 095043

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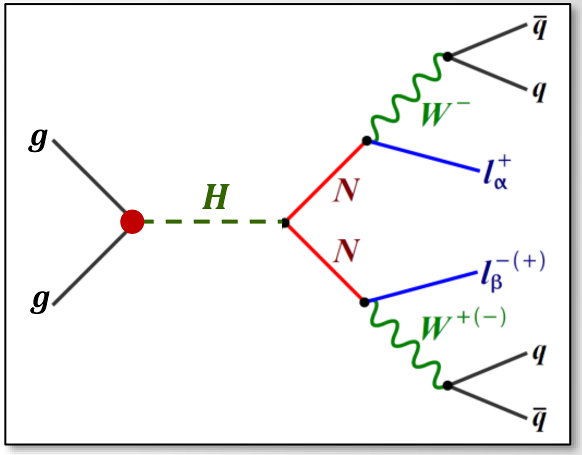
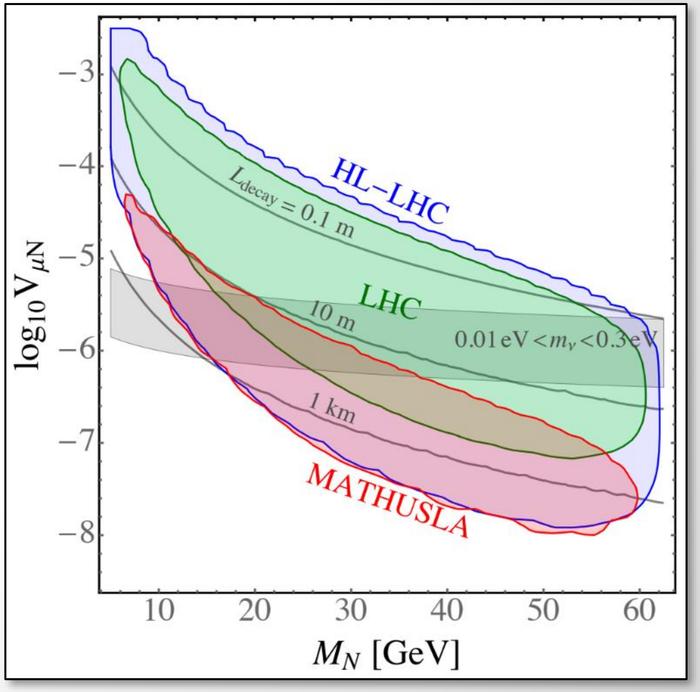
  - **HNL LLP Searches probe natural regime of neutrino mass generation**





FFD, Liu, Mitra JHEP 1808 (2018) 181

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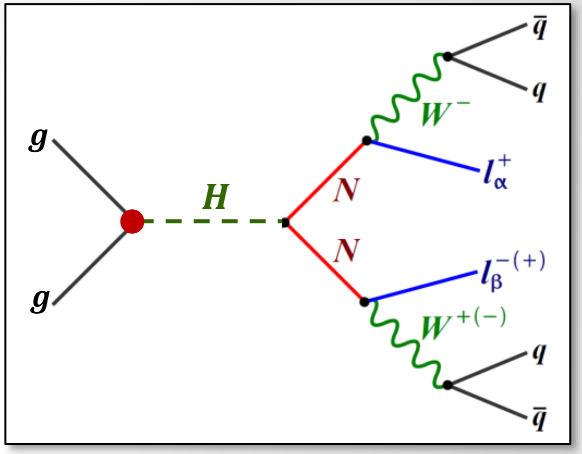

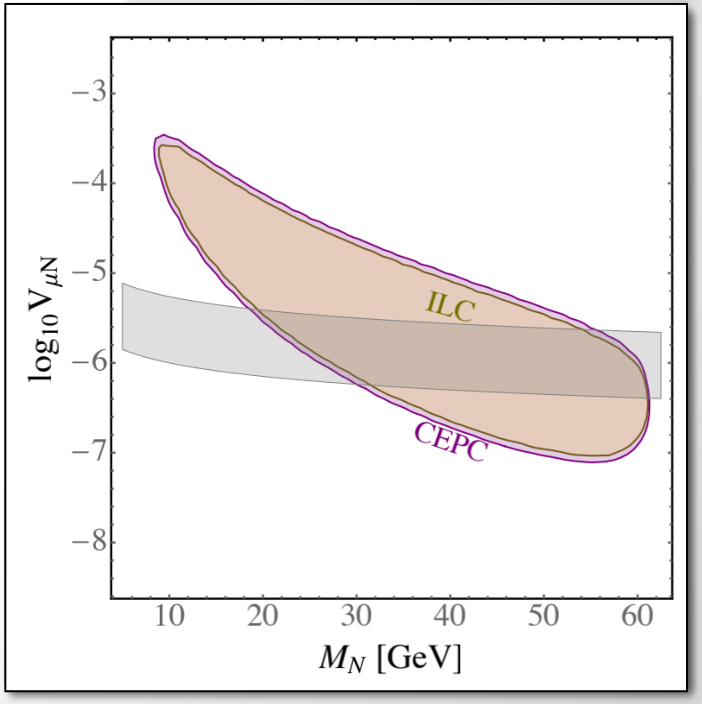

FFD, Liu, Mitra JHEP 1808 (2018) 181

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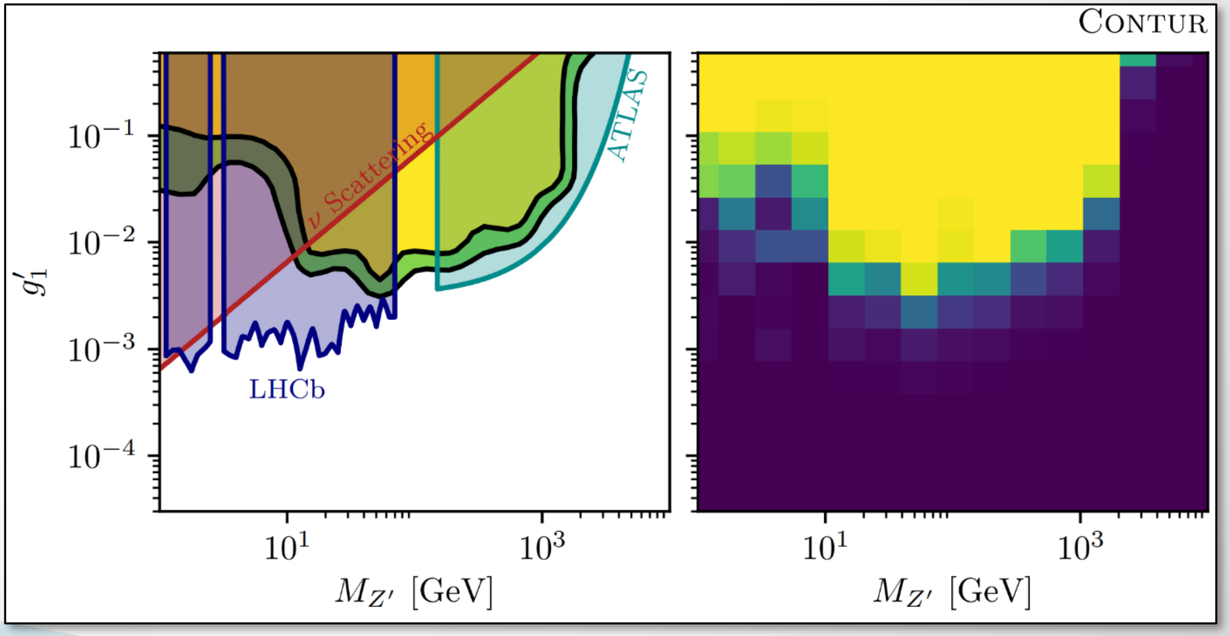
  - **Probing gauge and Higgs sector directly**
  - **Integration of SM measurements using CONTUR**



Amrith, Butterworth, FFD, Liu, Varma JHEP 05 (2019) 154

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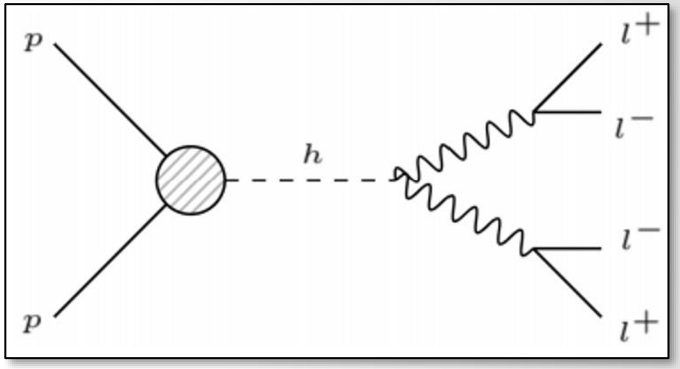
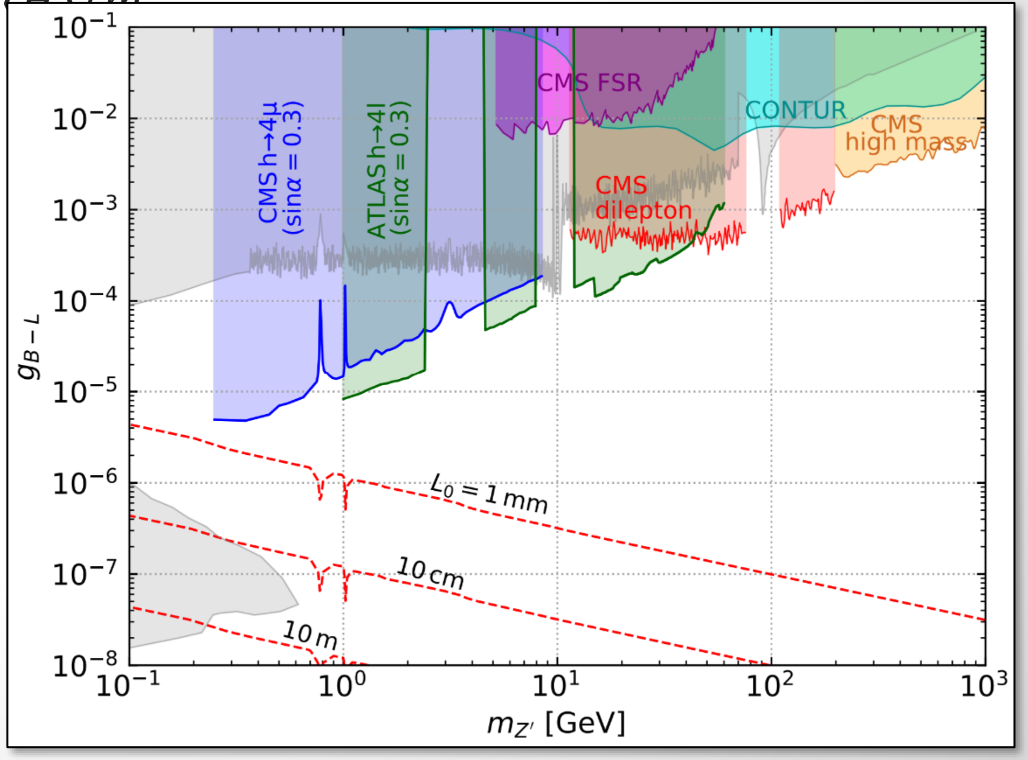
  - **Higgs production of Z'**





FFD, Kulkarni, Wei, Phys.Rev.D 100 (2019) 11, 115023

Conclusion

- **Neutrinos much lighter than other fermions**
  - Dirac or Majorana? Lepton Number Violation?
  - Determination of absolute mass scale
- **Probing LNV and HNLs**
  - Testing the mechanism of neutrino mass generation
  - Baryon asymmetry of the Universe via Leptogenesis
  - Observing LNV at collider can rule out high-scale baryogenesis
  - Light neutrino masses generically require small Yukawa couplings → Small active-sterile mixing → HNLs are LLPs
- **Beyond sterile: exotic gauge interactions**
  - SM + $U(1)_{B-L}$
  - Efficient BSM portals to produce HNLs:
    - Gauge Z', SM (via mixing) and singlet Higgs
  - Potential to probe natural regime of neutrino mass generation