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Probing HNLs with Non-standard Interactions

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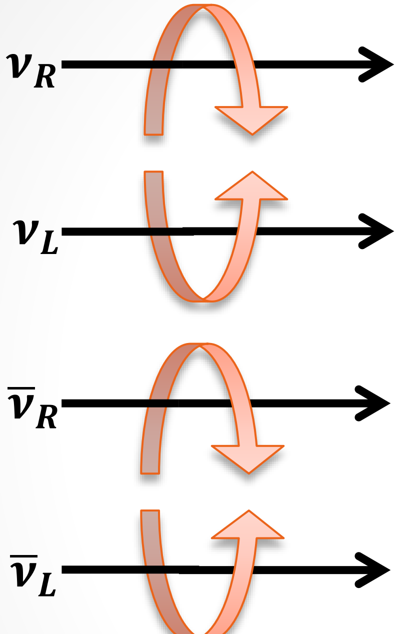
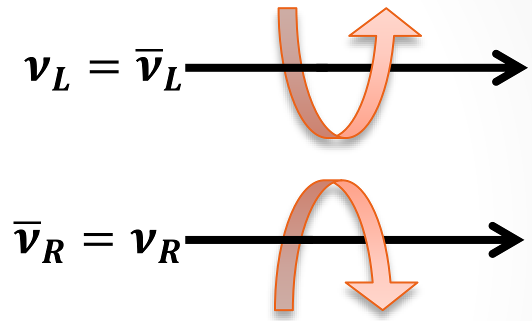
work in collaboration with R. Beltran, P. Bolton, C. Hati, M. Hirsch, JHEP 07 (2024) 153; W. Liu, S. Kulkarni, 2407.20676

Workshop on SM and Beyond | Corfu2024 | 26/8-3/9/2024

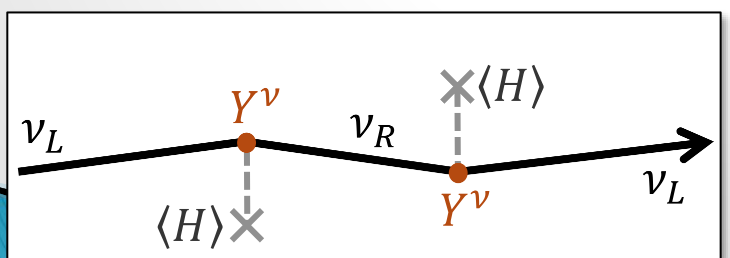
Dirac vs Majorana

- Two possibilities to define fermion mass

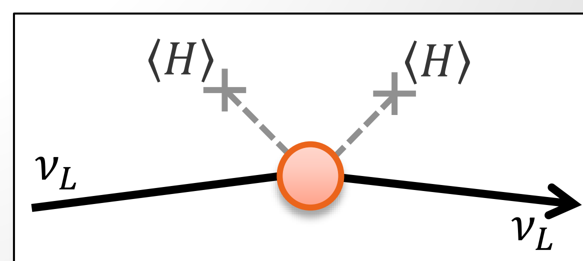




Dirac mass analogous to other fermions but with $m_\nu/\Lambda_{EW} \approx 10^{-12}$ couplings to Higgs



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



Dirac versus Majorana

- 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

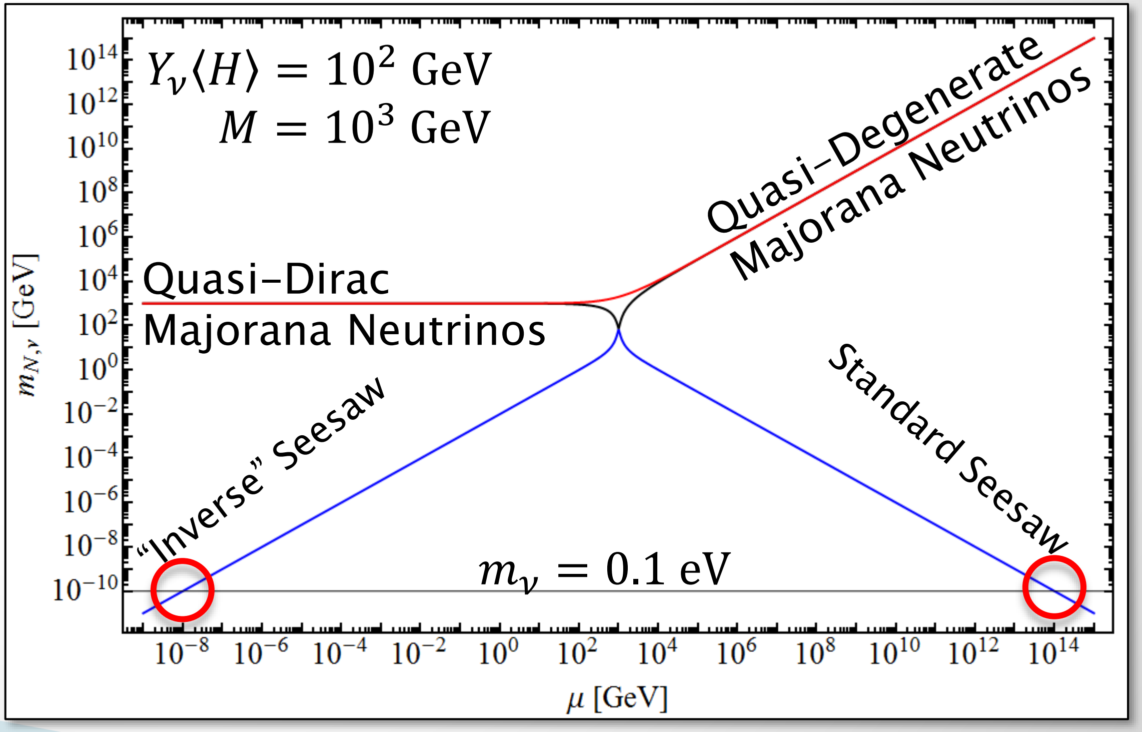
$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\bar{N}_{iR}\partial\!\!\!/ N_{iR} - (Y_\nu)_{\alpha i}\bar{L}_\alpha \tilde{H} N_{iR} - \frac{1}{2}(\mathcal{M}_S)_{ij}\bar{N}^c_{iR}N_{jR} + \text{h.c.}\,.$$

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

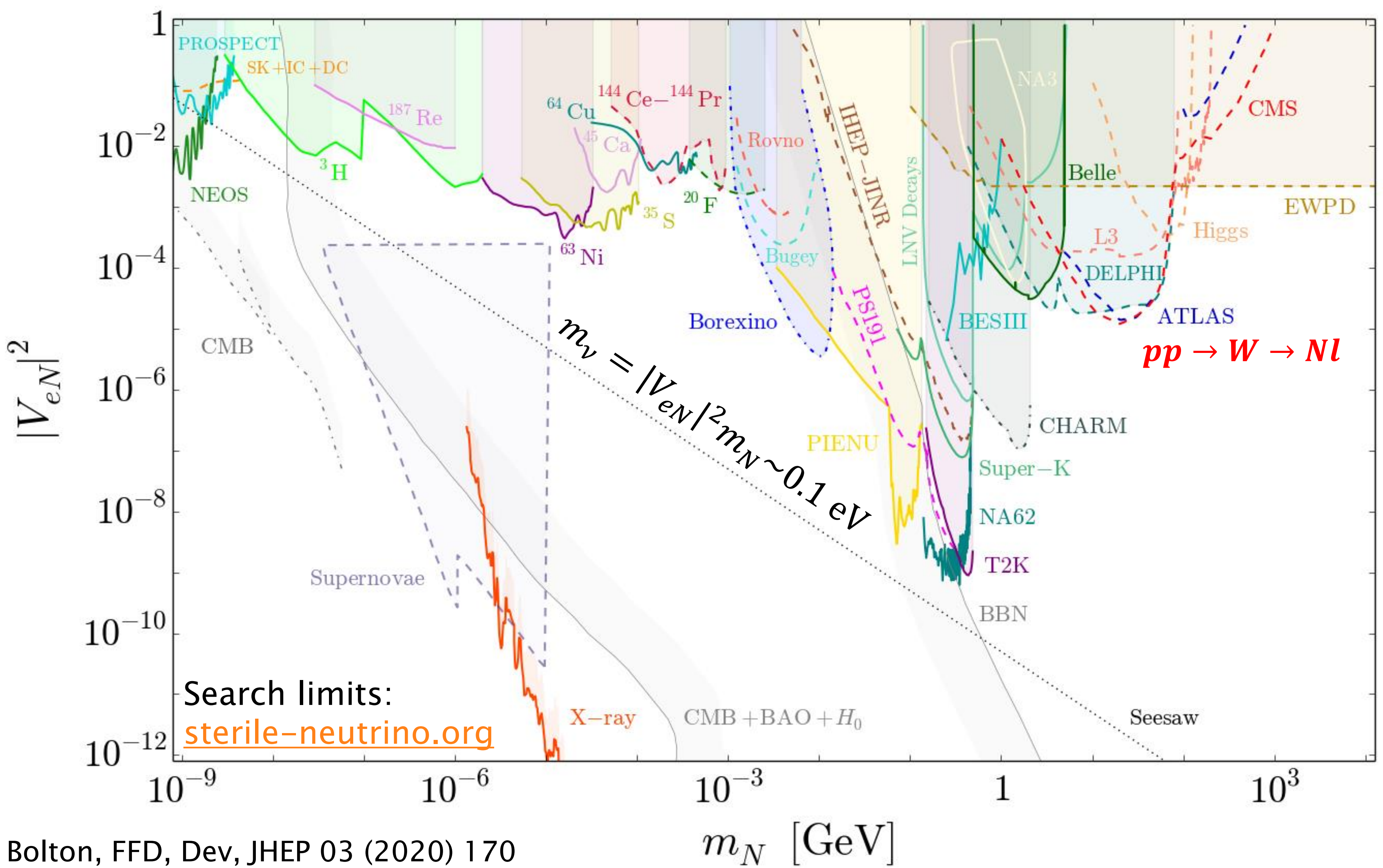
$$V^{\nu N} \approx Y_\nu \approx 10^{-6}\sqrt{M_N/\text{TeV}}$$

  - "Bent" Seesaw mechanisms
    - Decouple Λ_{LNV} from heavy neutrino mass

$$\begin{array}{cccc} & \nu & N_1 & N_2 \\ \mathcal{M} = & \left(\begin{array}{c} 0 \\ Y_\nu\langle H\rangle \\ 0 \end{array}\right. & \begin{array}{c} Y_\nu\langle H\rangle \\ \mu \\ M \end{array} & \left.\begin{array}{c} 0 \\ M \\ \mu \end{array}\right) \end{array}$$



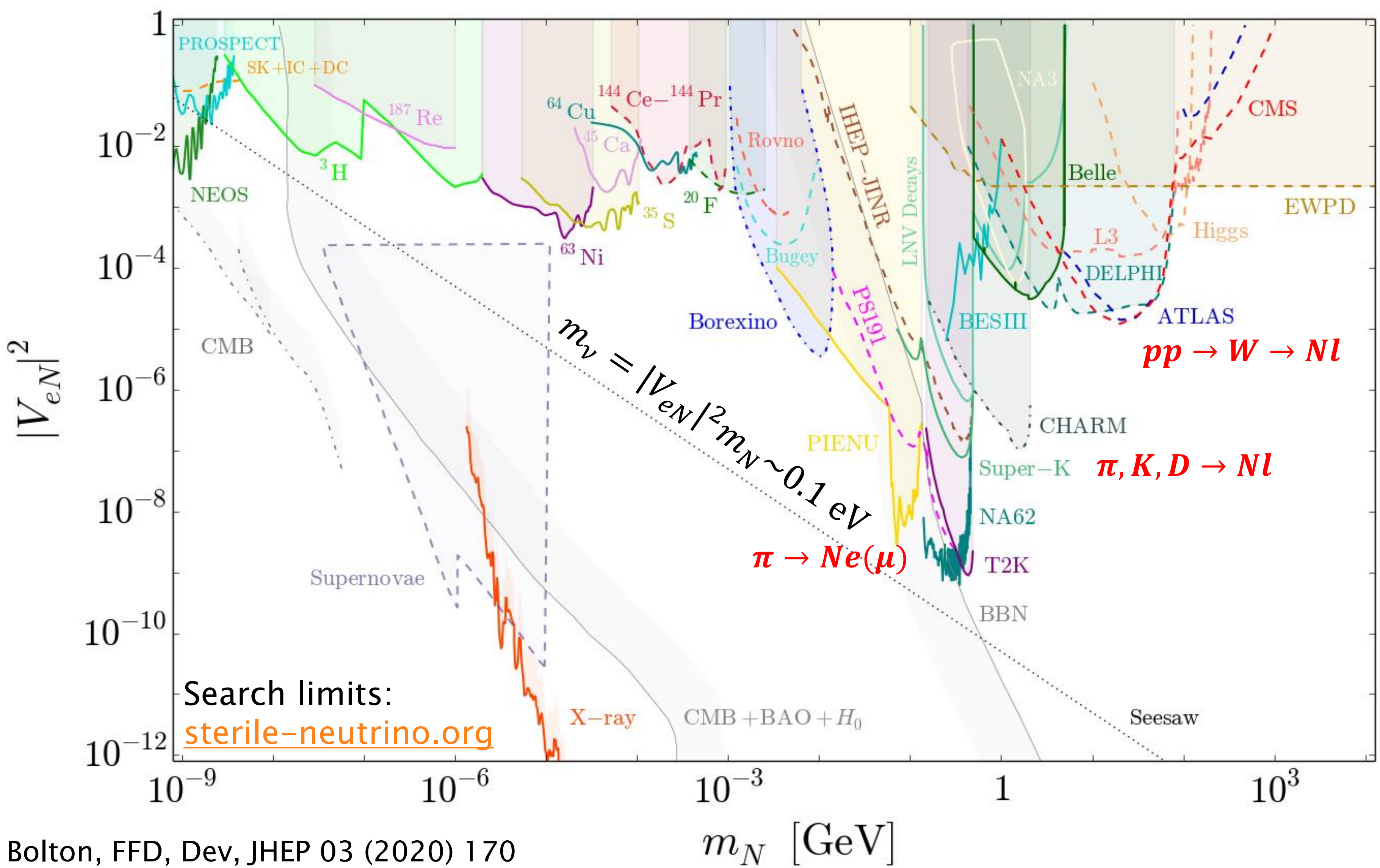
HNL Searches – Current



Search limits: sterile-neutrino.org

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

HNL Searches – Current



Search limits:
sterile-neutrino.org

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

HNL Searches – Proposed

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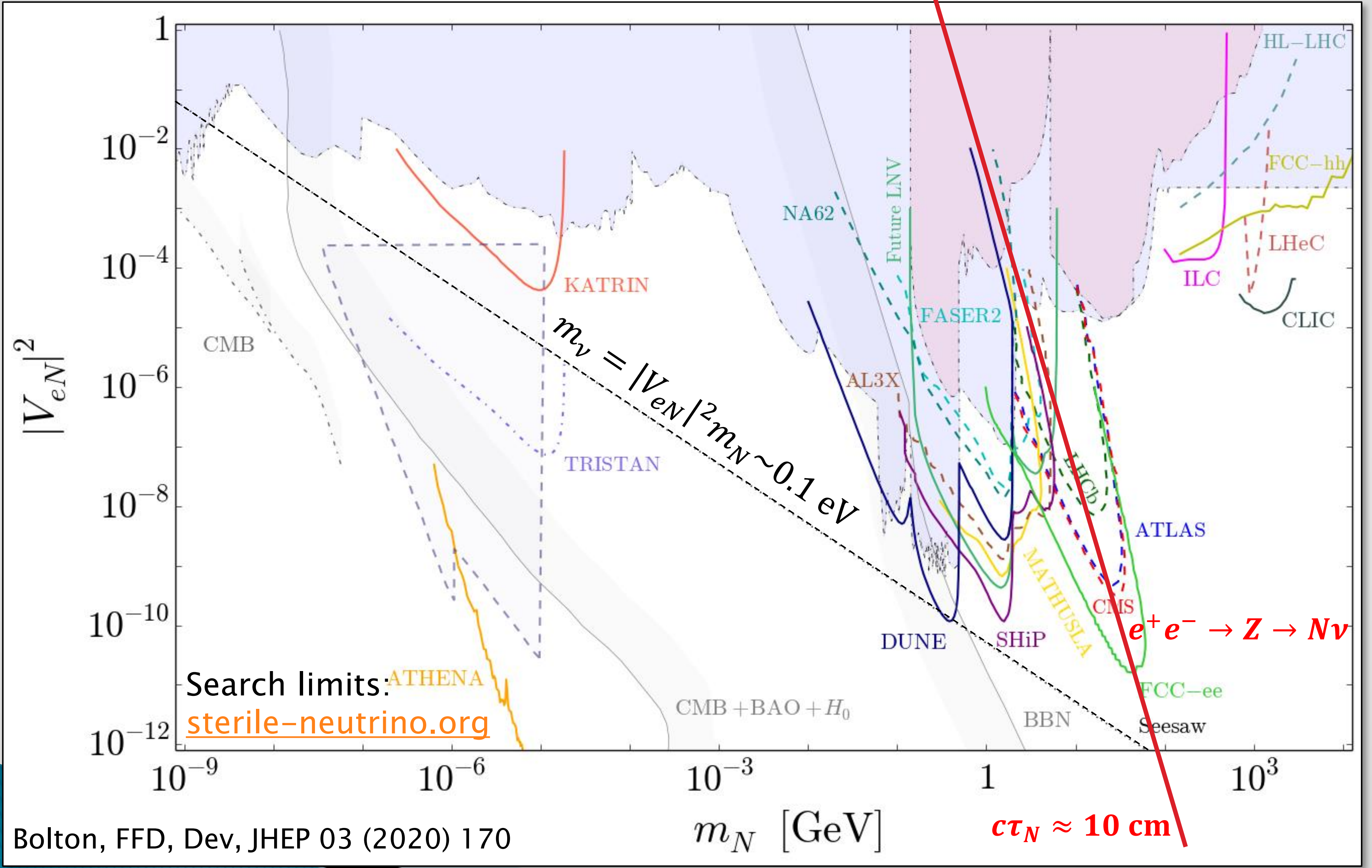

HNL Portals

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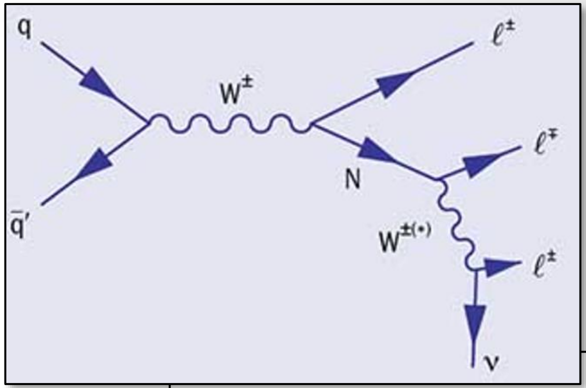
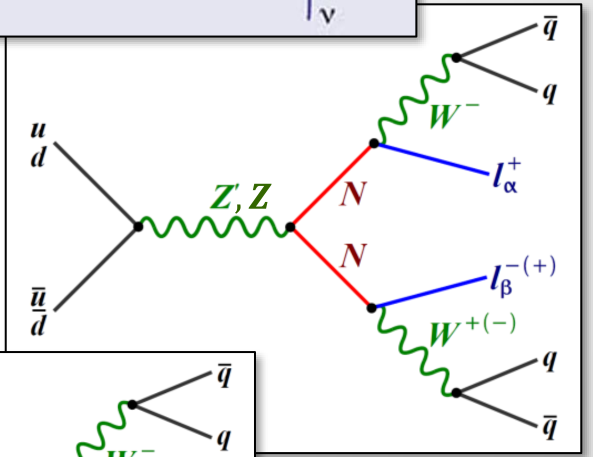
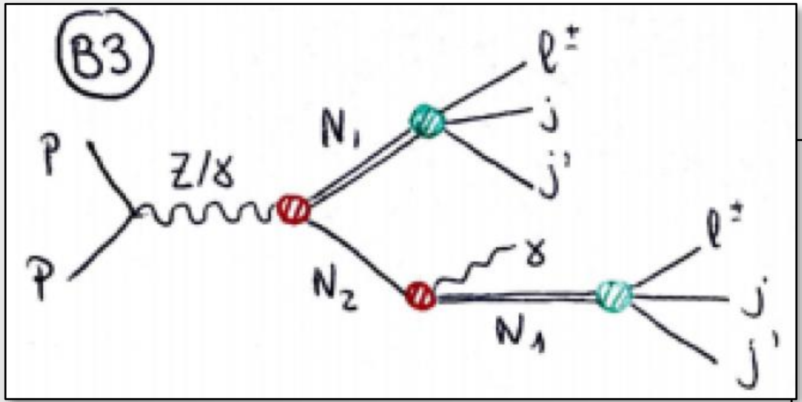
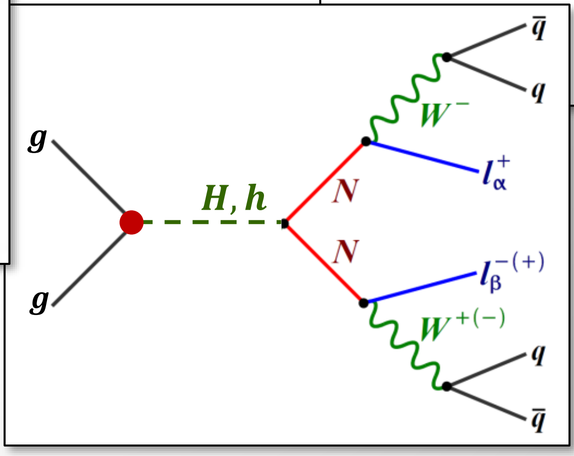
- Active–sterile neutrino mixing
- Gauge portal
- Higgs portal
- HNL dipole portal









Extended Gauge Sectors

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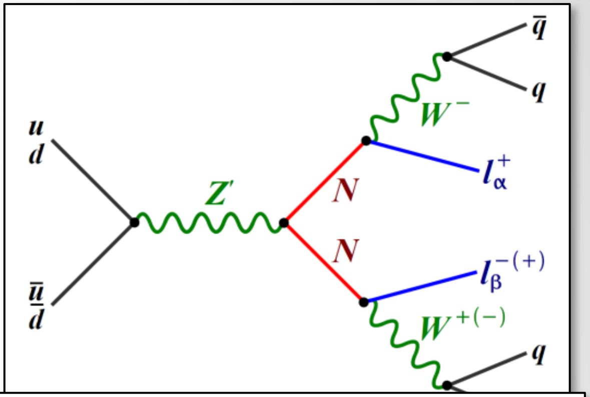
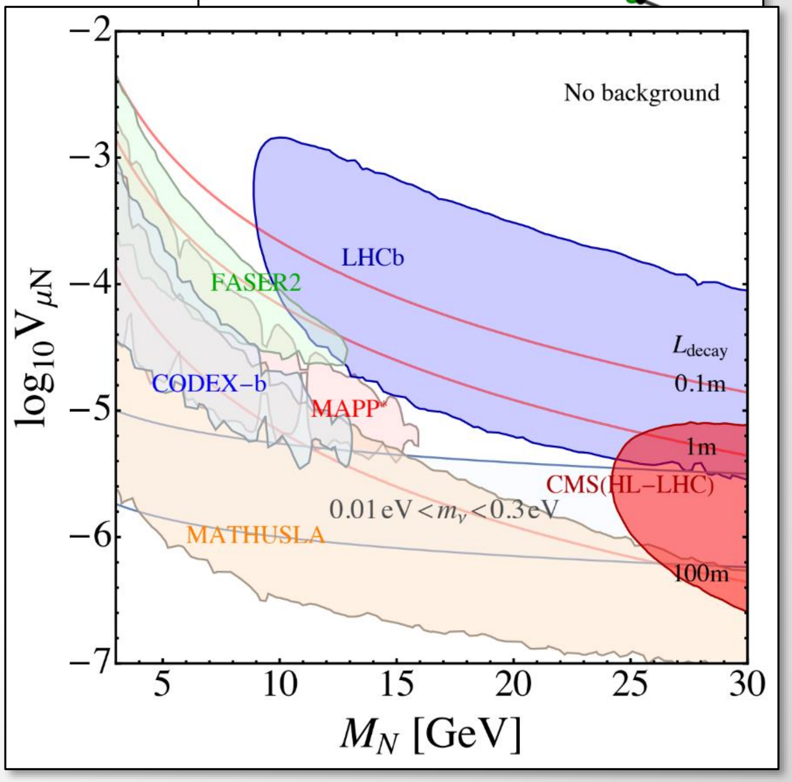
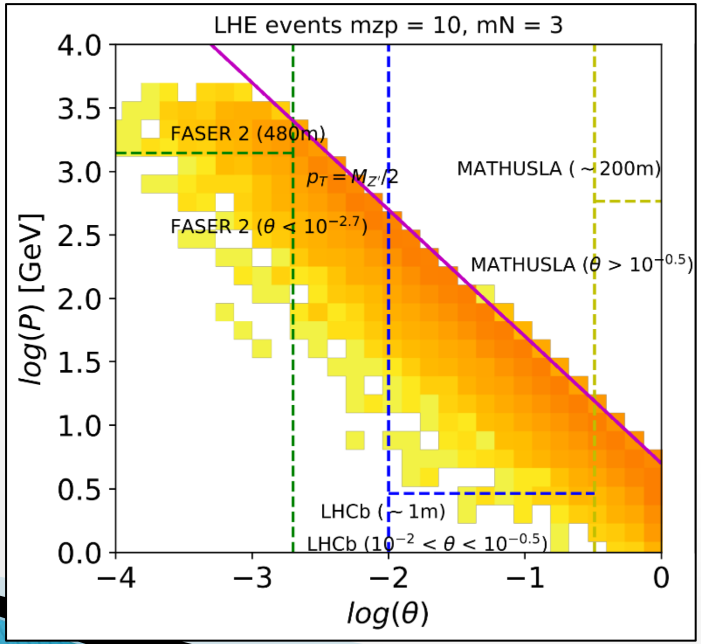
- Additional $U(1)_{B-L}$ gauge symmetry
  - Production via Z' portal
  - Ability to measure small couplings via displaced vertices
  - N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$
  - **Sensitivity at LHC LLP detectors**







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

Extended Gauge Sectors

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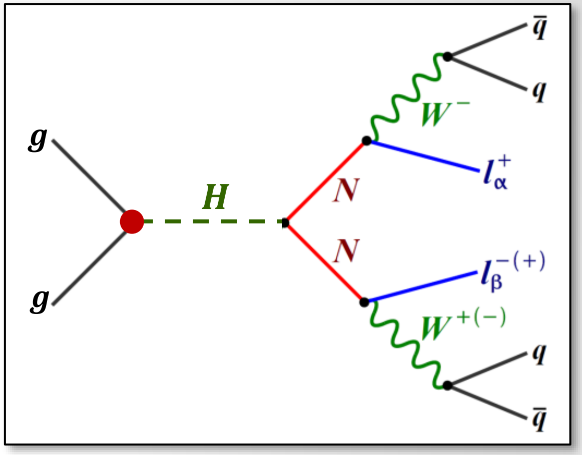
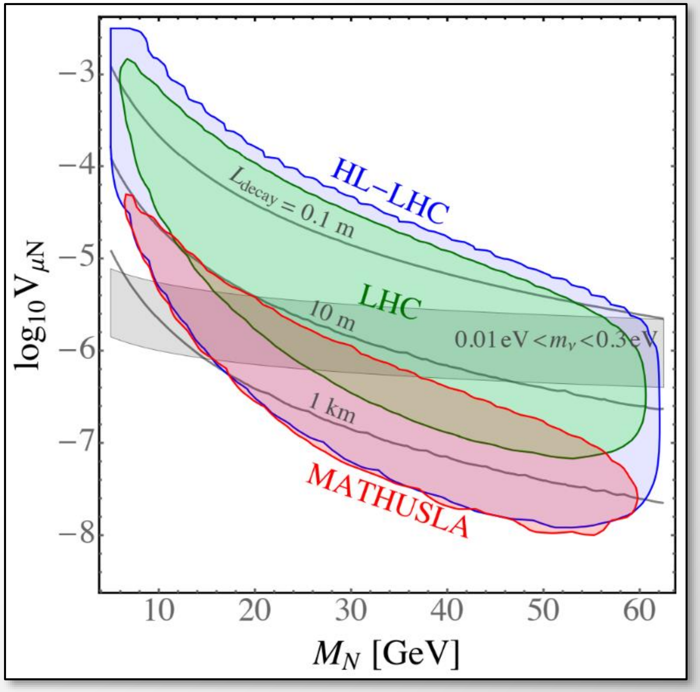
  - Production via Z' portal
  - Ability to measure small couplings via displaced vertices
  - N can only decay through heavy-light suppressed coupling $\theta = Y_\nu \langle H \rangle / m_N$
  - **SM Higgs mixing with $U(1)_{B-L}$ breaking Higgs → Scalar Portal --> LNV Higgs decays (Maiezza, Nemevšek, Nesti, PRL 115 (2015) 081802)**





FFD, Liu, Mitra JHEP 1808 (2018) 181

LLPs in CMS Muon Endcap

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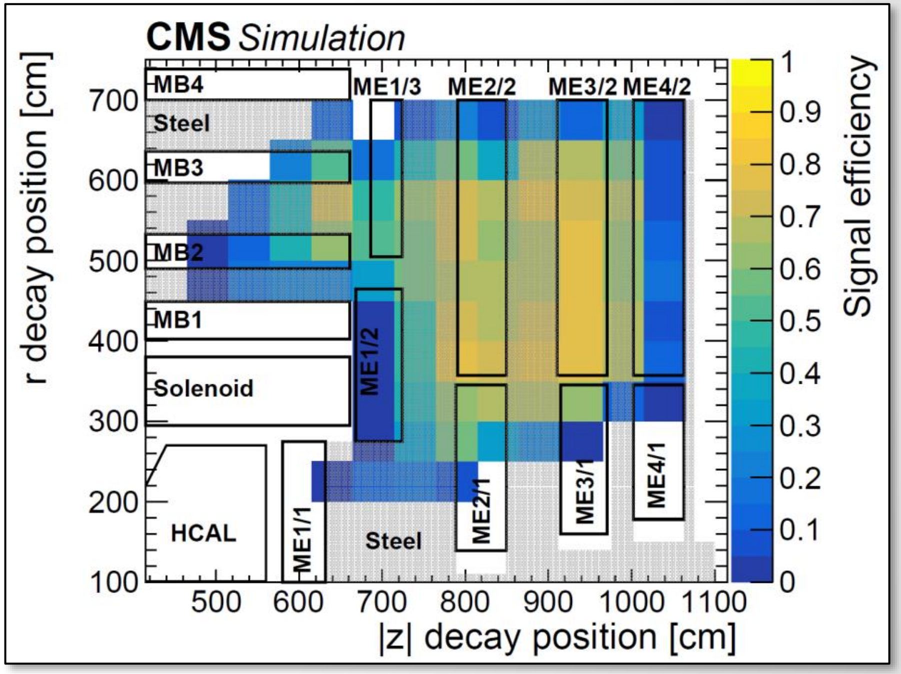
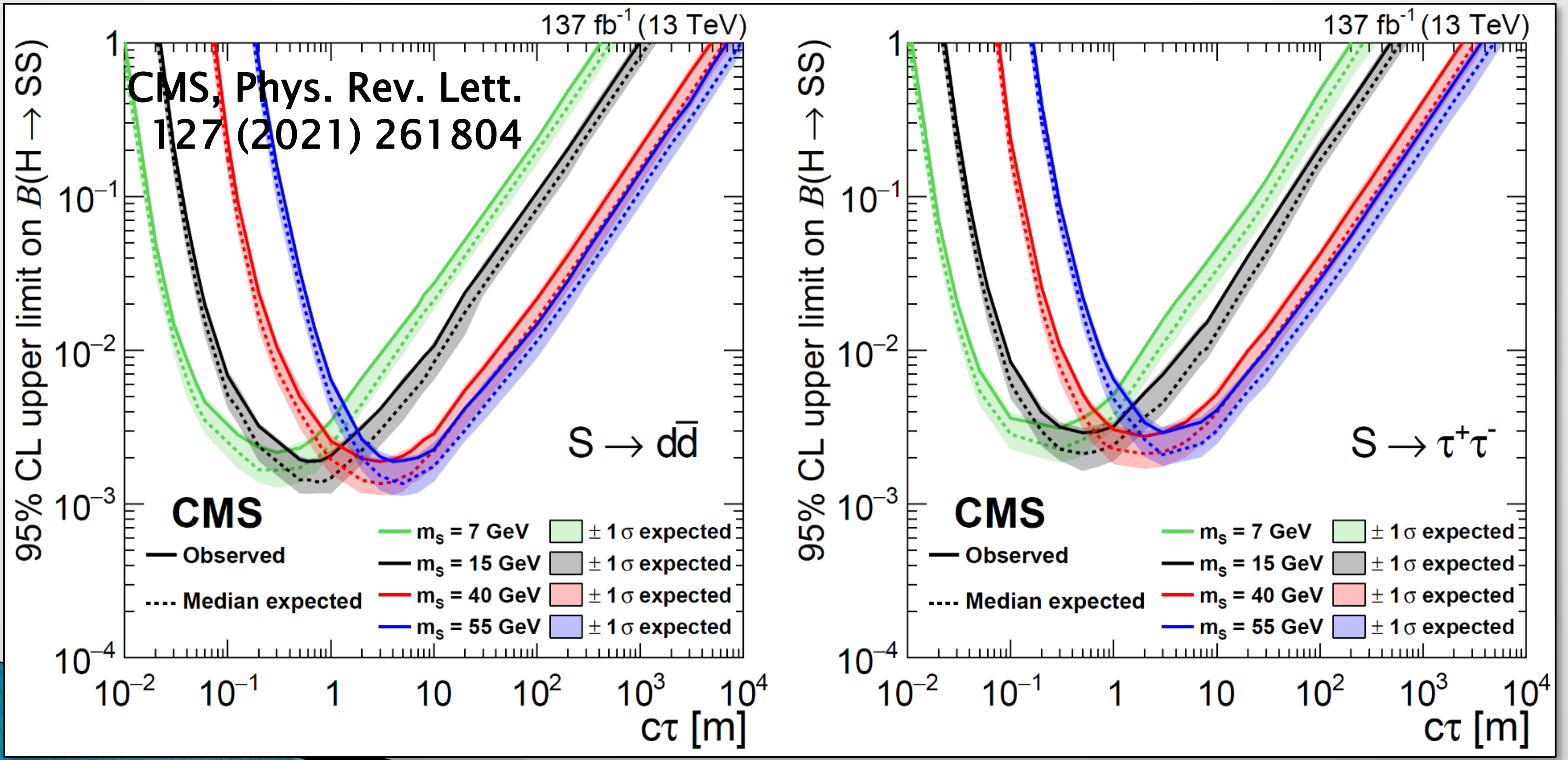
- Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ (CMS, PRL 127 (2021) 261804)
  - LLPs producing hadronic and electromagnetic showers in the CMS endcap muon detectors (CSCs = cathode strip chamber)
  - Sensitivity to single or multiple LLPs decaying to hadrons, τ, e, γ
  - Original search for $h \to SS$ ($S \to b\bar{b}$, $d\bar{d}$, $\tau^+\tau^-$)



CMS, Phys. Rev. Lett. 127 (2021) 261804

LLPs in CMS Muon Endcap

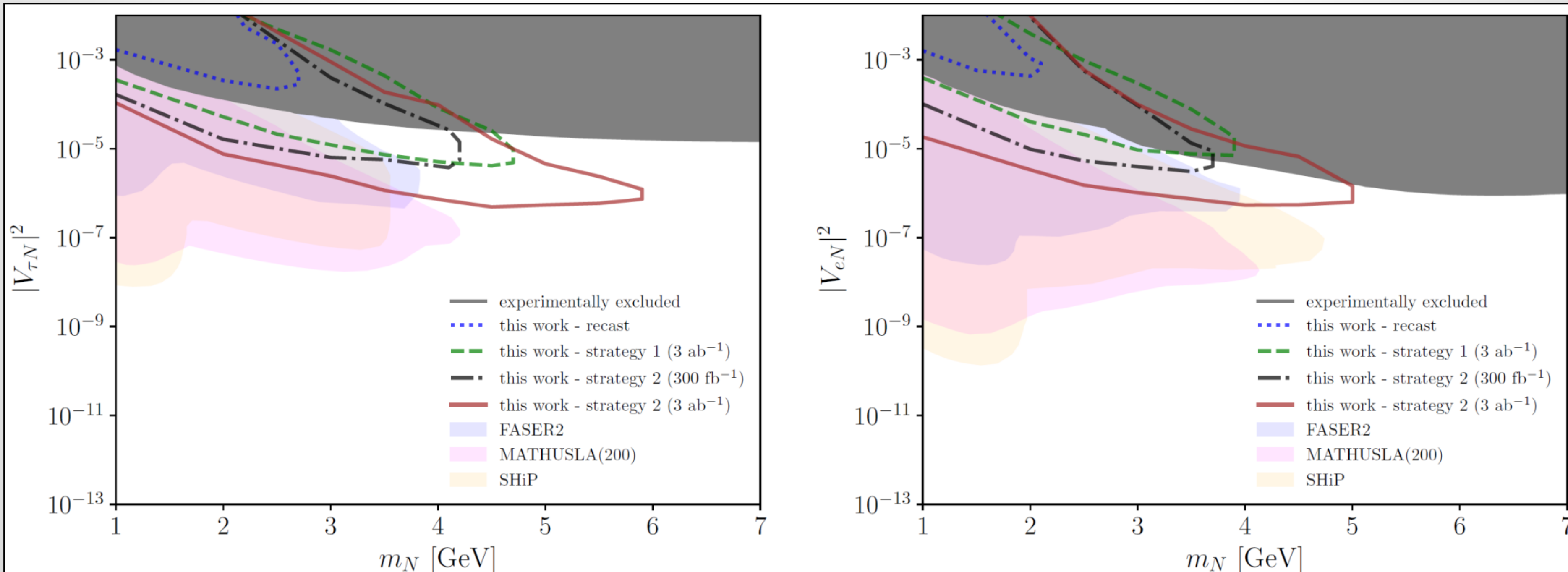
- Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13\ \mathrm{TeV}$ (CMS, PRL 127 (2021) 261804)
  - Stringent limits for $m_{LLP} = 10 - 50\ \mathrm{GeV}$ with $c\tau > O(1\ \mathrm{m})$



HNLs in CMS Muon Endcap

- Interpretation in Neutrino Minimal SM

$$L_N^0 \approx 3\ \mathrm{m} \times \left(\frac{10^{-12}}{|V_{\ell N}|^2}\right)\left(\frac{40\ \mathrm{GeV}}{m_N}\right)^5$$



Cottin, Helo, Hirsch, Pena, Wang, JHEP 02 (2023) 011

HNLs in CMS Muon Endcap

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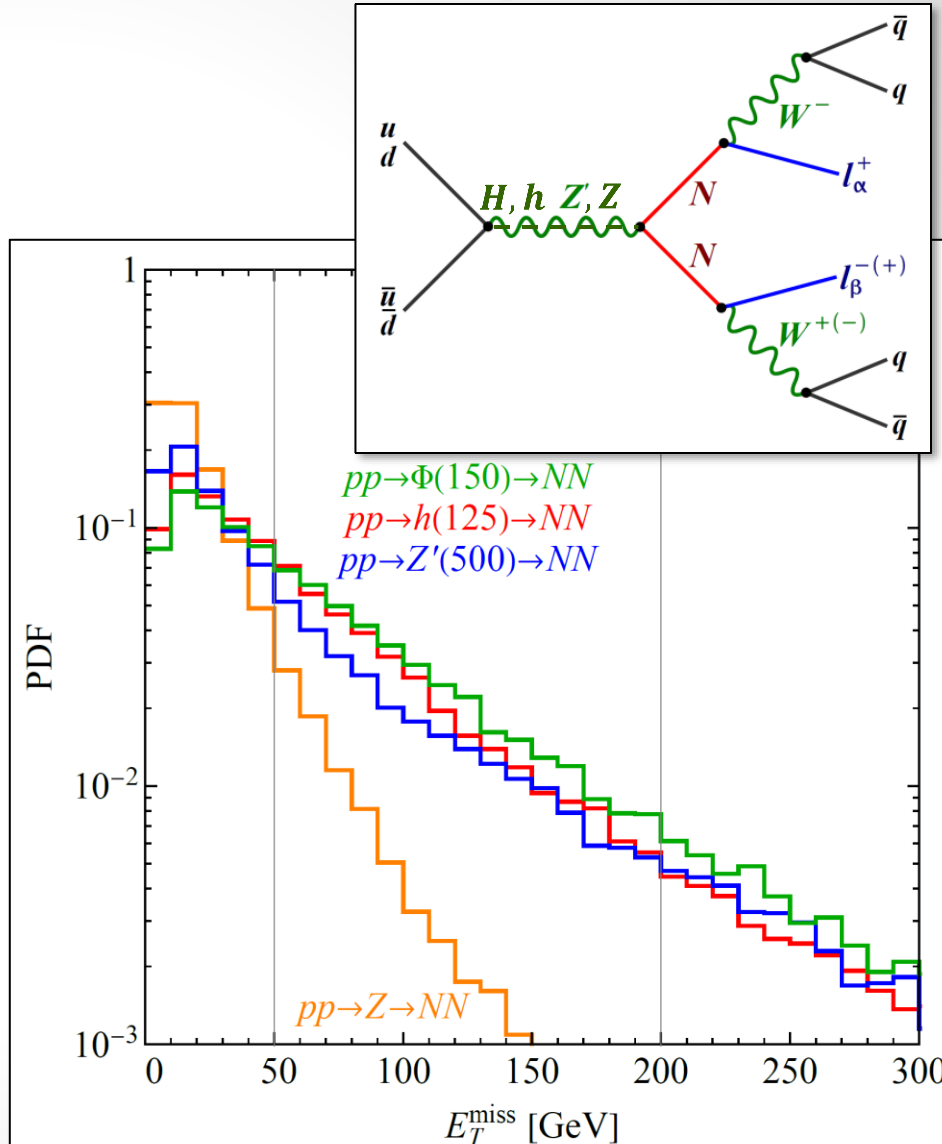
- Interpretation via gauge and Higgs portal production
  - Specifically, $U(1)_{B-L}$ model
  - $pp \to Z, Z', \boldsymbol{h}, \boldsymbol{\Phi} \to NN$
  - Selection criteria:
    - $E_T^{miss} > 200\ \mathrm{GeV}$ in tracker or calorimeter
    - At least one CSC cluster aligned with $\mathbf{p}_T^{miss}$
  - CMS Delphes card and modules
  - Effective gluon-gluon Higgs coupling at LO
  - Enhanced E_T^{miss} for gluon-gluon fusion
  - Background determined in data: $b = 2.0 \pm 1.0$, Observed: $N = 3$



W. Liu, S. Kulkarni, FFD
arXiv:2407.20676

HNLs in CMS Muon Endcap

- Interpretation via Higgs portal production
  - Specifically, $U(1)_{B-L}$ model
  - $pp \to \boldsymbol{h} \to NN$
  - Branching ratio

$$\mathrm{Br}(h \to NN) \approx \frac{\tan^2\alpha}{16\pi}\frac{m_N^2}{\langle\Phi\rangle^2}\frac{m_h}{\Gamma_h^{\mathrm{SM}}}\left(1 - \frac{4m_N^2}{m_h^2}\right)^{3/2}$$

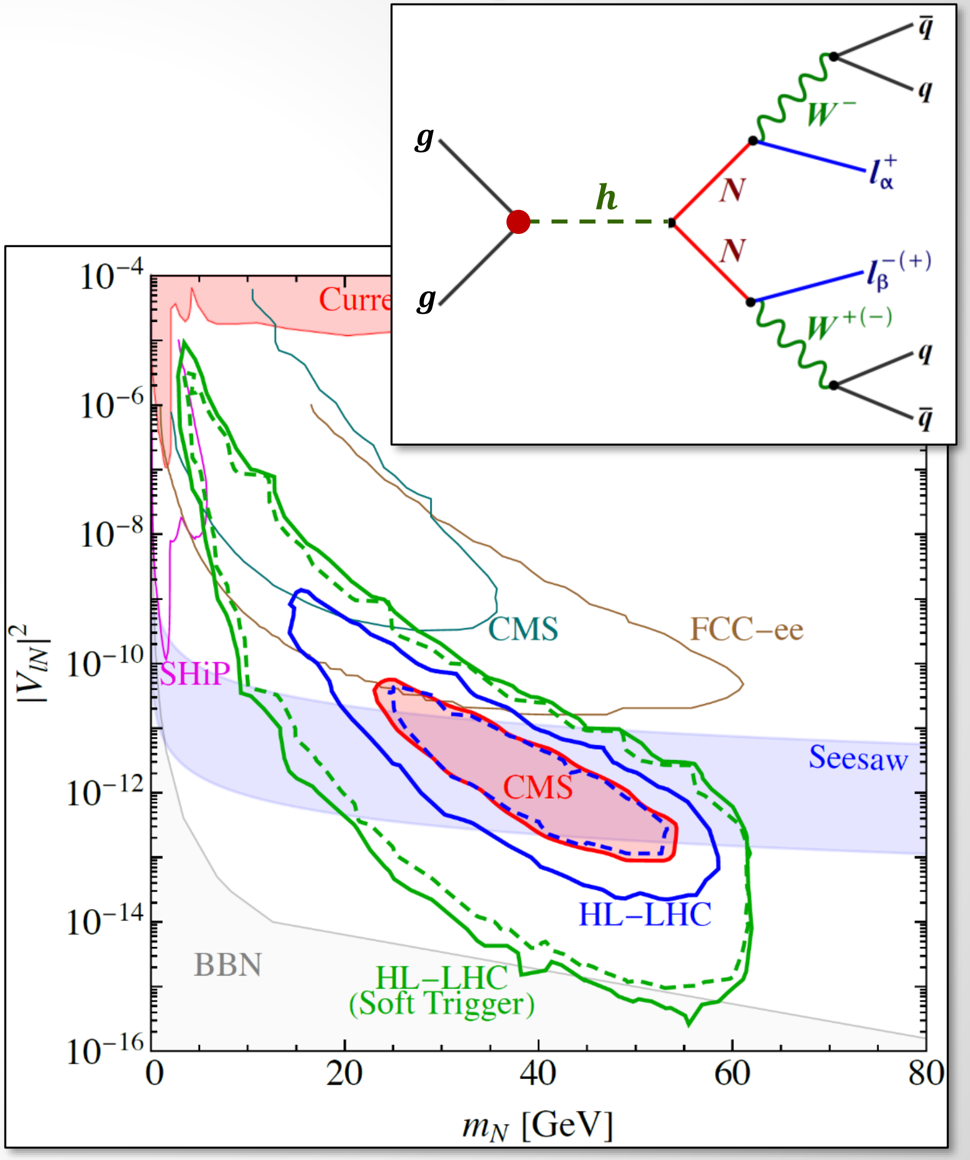
max for $m_N = \frac{m_h}{\sqrt{10}} \sim 40$ GeV

  - HNL proper decay length

$$L_N^0 \approx 3\ \mathrm{m} \times \left(\frac{10^{-12}}{|V_{\ell N}|^2}\right)\left(\frac{40\ \mathrm{GeV}}{m_N}\right)^5$$

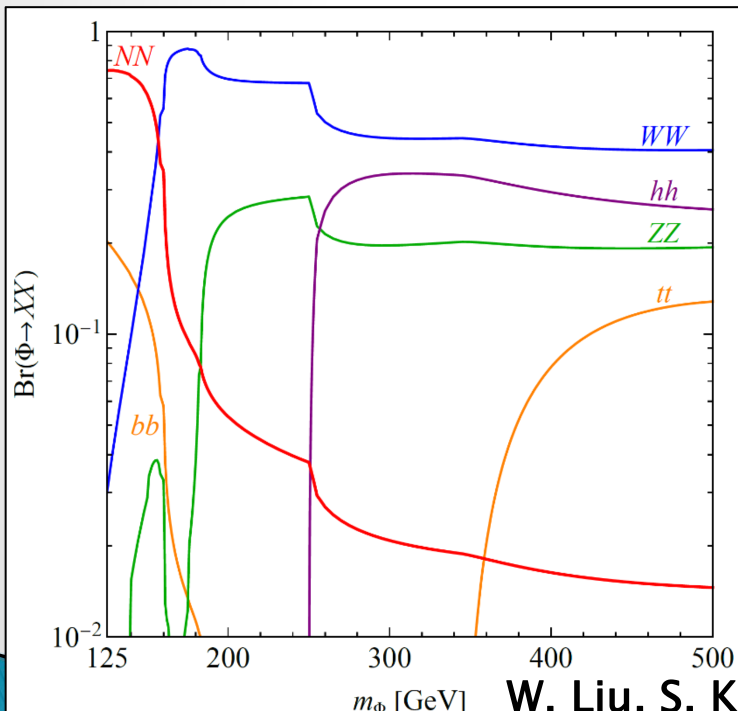
  - Sensitivity at Seesaw "floor" for $\sin\alpha > 0.17$, $\langle\Phi\rangle < 3.75$ TeV

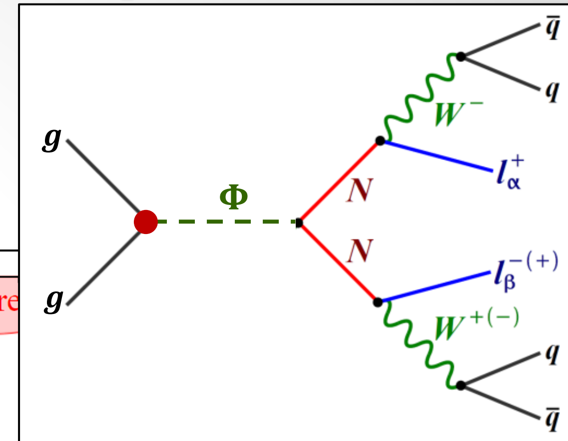
W. Liu, S. Kulkarni, FFD
arXiv:2407.20676

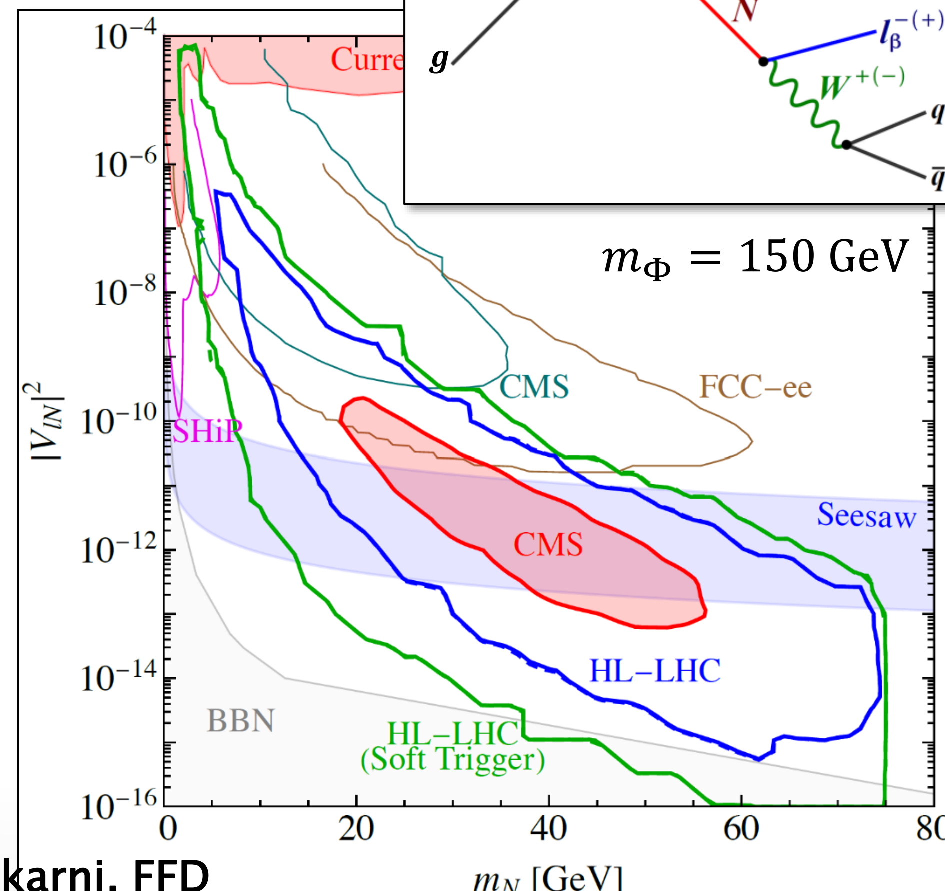


HNLs in CMS Muon Endcap

- Interpretation via Higgs portal production
  - Specifically, $U(1)_{B-L}$ model
  - $pp \to \Phi \to NN$
  - Branching ratio







W. Liu, S. Kulkarni, FFD
arXiv:2407.20676

HNLs in CMS Muon Endcap

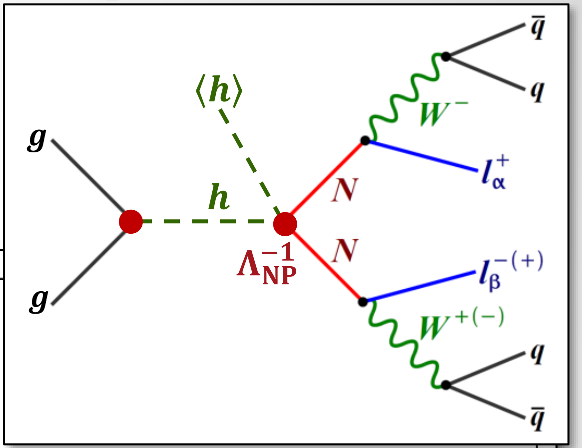
- Interpretation via effective operator
  - 5-dim HNL+SM EFT

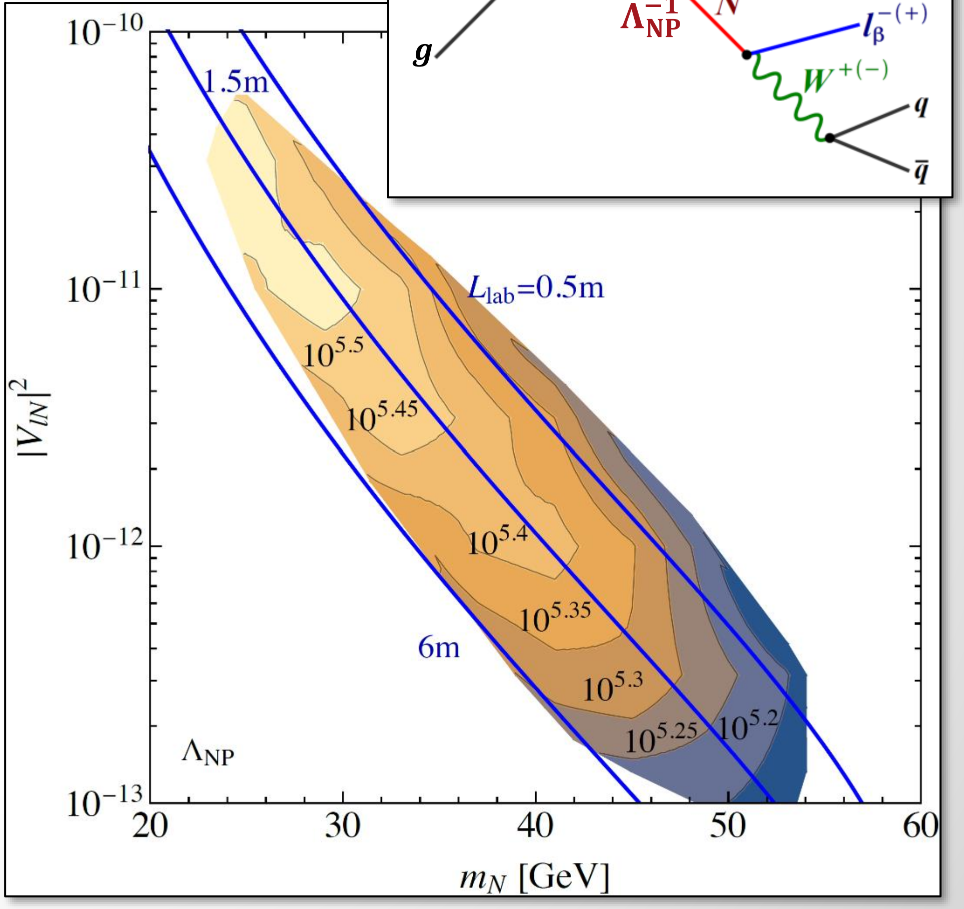
$$\Lambda_{NP}^{-1}(\overline{N^c}N)(H^+H)$$

  - Sensitivity to NP scales

$$\Lambda_{NP} \approx 100\ \text{TeV}$$

  for appropriate LLP HNLs





W. Liu, S. Kulkarni, FFD preliminary

HNL Magnetic Moments

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- N_RLEFT Transition Magnetic Moments

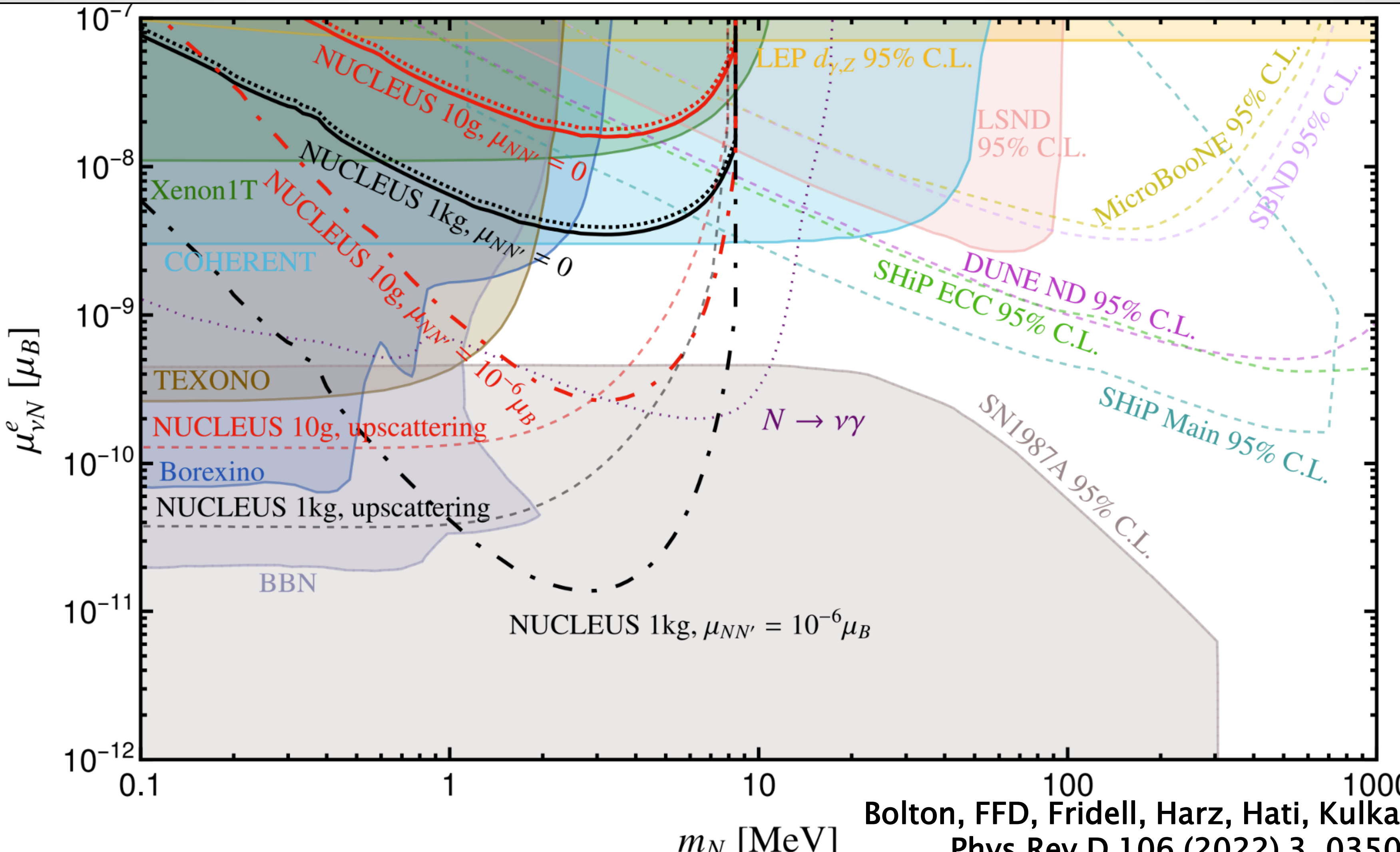
$$\mathcal{O}_{NN\gamma}^{ij} = (\bar{N}_{Ri}^c \sigma_{\mu\nu} N_{Rj}) F^{\mu\nu}\,, \quad \mathcal{O}_{\nu N\gamma}^{\alpha i} = (\bar{\nu}_{L\alpha} \sigma_{\mu\nu} N_{Ri}) F^{\mu\nu}\,,$$

- N_RSMEFT

$$\mathcal{O}_{NNB}^{(5)ij} = (\bar{N}_{Ri}^c \sigma_{\mu\nu} N_{Rj}) B^{\mu\nu}\,,$$

$$\mathcal{O}_{NB}^{(6)\alpha i} = (\bar{L}_\alpha \sigma_{\mu\nu} N_{Ri}) \tilde{H} B^{\mu\nu}\,, \quad \mathcal{O}_{NW}^{(6)\alpha i} = (\bar{L}_\alpha \sigma_{\mu\nu} N_{Ri}) \tau^I \tilde{H} W^{I\mu\nu}\,,$$

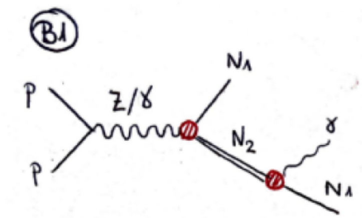
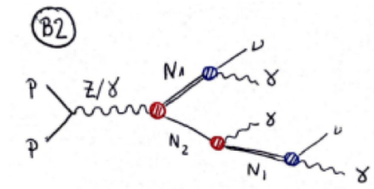
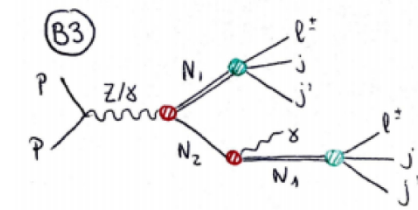
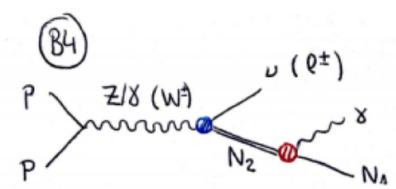
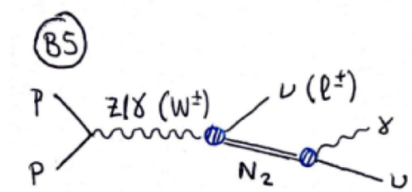
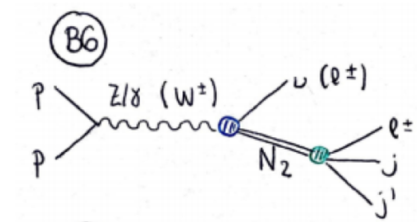
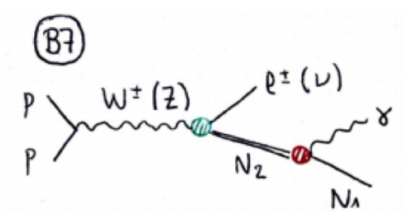
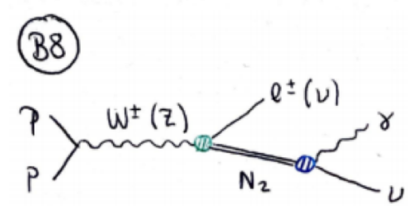
HNL Magnetic Moments



Bolton, FFD, Fridell, Harz, Hati, Kulkarni
Phys.Rev.D 106 (2022) 3, 035036

HNL Magnetic Moments

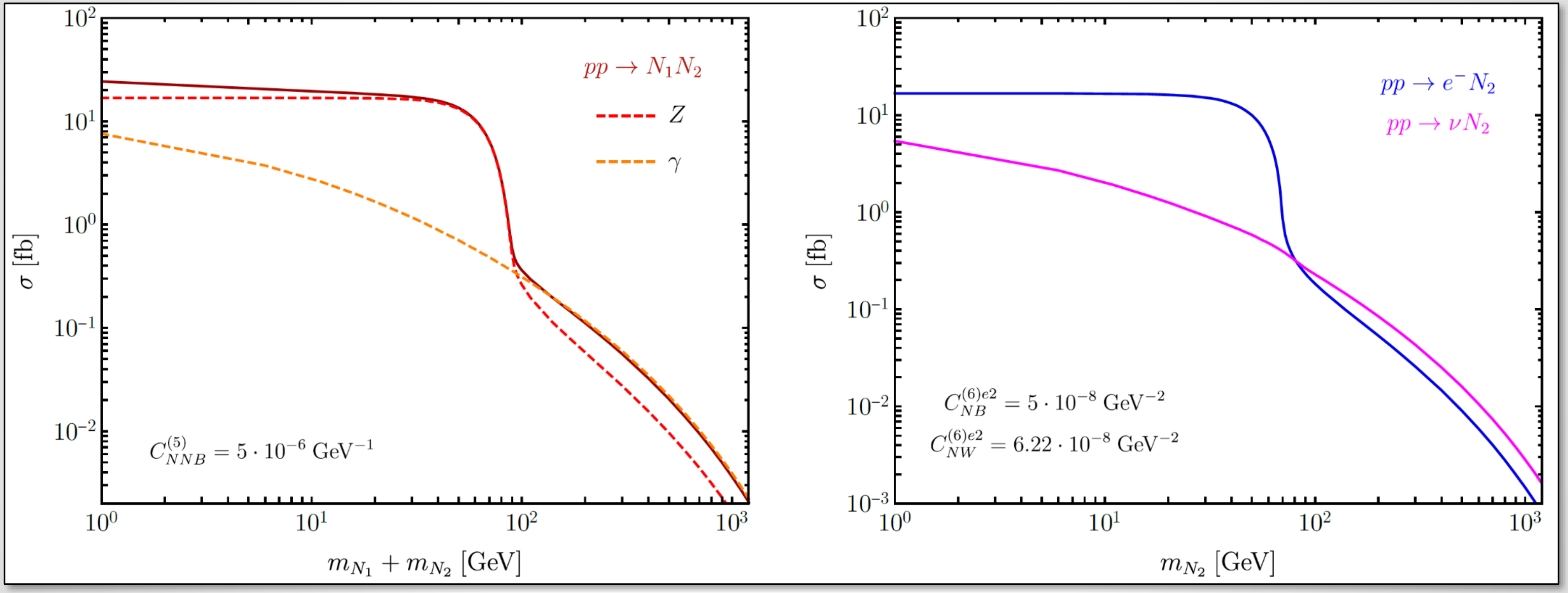
- Phenomenology at LHC

Prod. \ Dec.	$C^{(5)}_{NNB}$	$C^{(6)}_{NB}$, $C^{(6)}_{NW}$	$V_{\ell N}$
$C^{(5)}_{NNB}$			
$C^{(6)}_{NB}$, $C^{(6)}_{NW}$			
$V_{\ell N}$			Minimal scenario

Beltran, Bolton, FFD, Hati, Hirsch, JHEP 07 (2024) 153

HNL Magnetic Moments

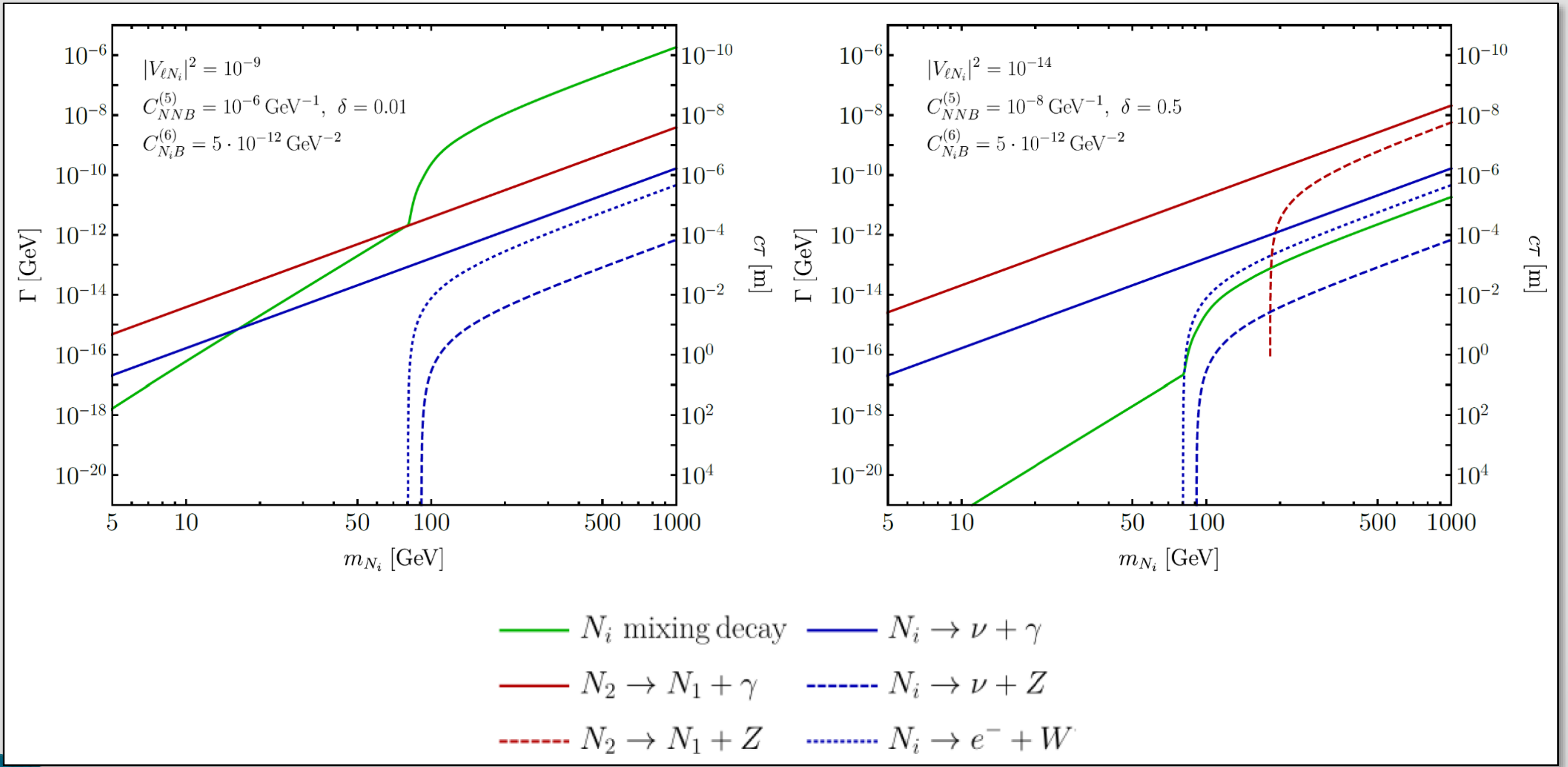
- LHC Production Cross Sections



Beltran, Bolton, FFD, Hati, Hirsch, JHEP 07 (2024) 153

HNL Magnetic Moments

- HNL Decay Modes



Beltran, Bolton, FFD, Hati, Hirsch, JHEP 07 (2024) 153

HNL Magnetic Moments

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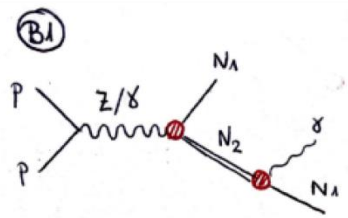
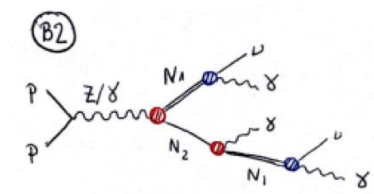
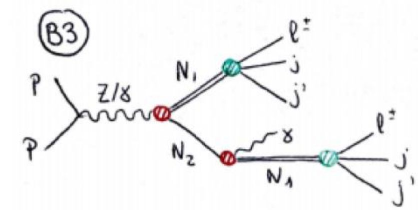
- Non-pointing photon signal in ECal

Prod. \ Dec.	$C^{(5)}_{NNB}$	$C^{(6)}_{NB}$, $C^{(6)}_{NW}$	$V_{\ell N}$
$C^{(5)}_{NNB}$			

Scenario	Signature	Selection cuts
B1	Non-pointing γ	$\lvert p_T^\gamma \rvert > 10$ GeV , $\lvert \eta^\gamma \rvert < 2.47$ $r_{\mathrm{DV}} < 1450$ mm , $\lvert z_{\mathrm{DV}} \rvert < 3450$ mm $\lvert d_{XY}^\gamma \rvert > 6$ mm
B2	Non-pointing γ $(\times 2)$ (+ prompt γ)	
B3	Displaced Vertex $(\times 2)$ (+ prompt γ)	$\lvert p_T^e \rvert > 120$ GeV, $\lvert \eta^e \rvert < 2.47$ 4 mm $< r_{\mathrm{DV}} < 300$ mm, $\lvert z_{\mathrm{DV}} \rvert < 300$ mm 4 tracks with $\lvert d_0 \rvert > 2$ mm $m_{\mathrm{DV}} > 5$ GeV

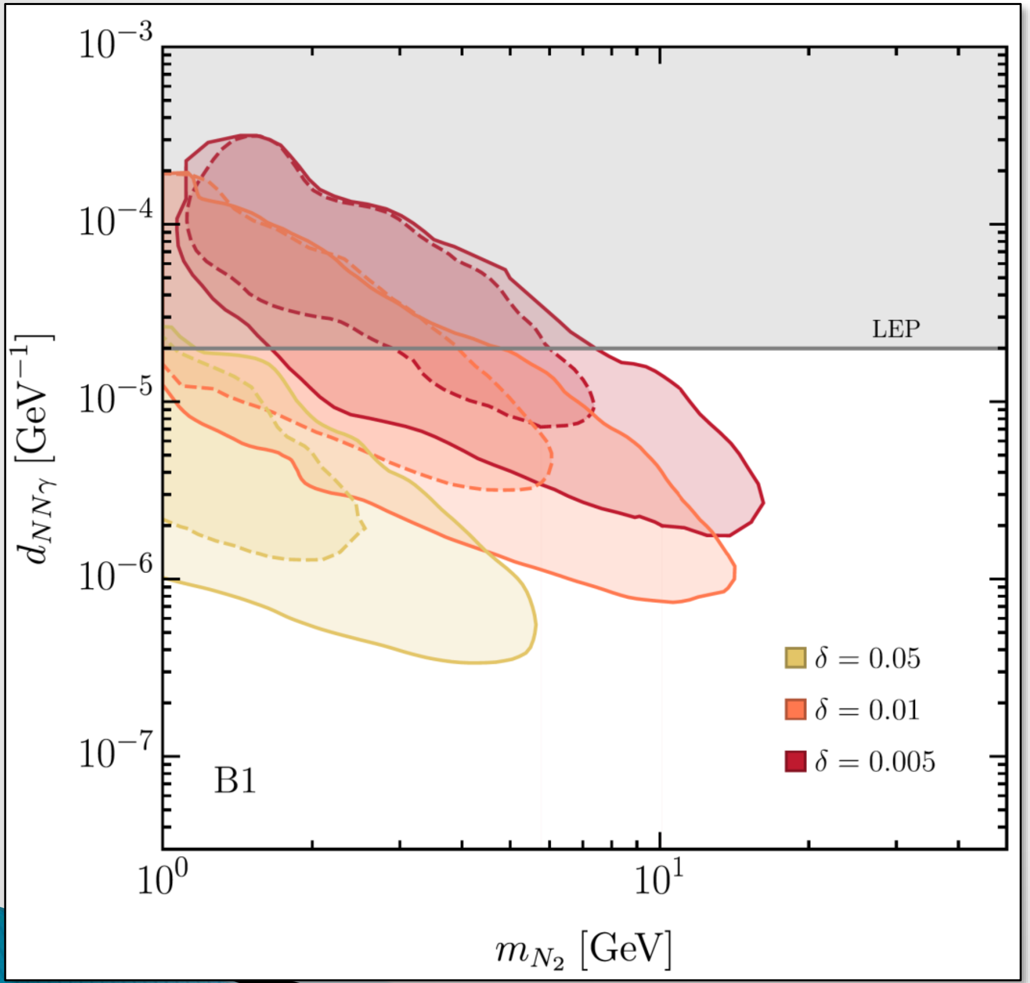
$$d_{XY} = x_{LLP}\frac{p_Y}{p_T} - y_{LLP}\frac{p_X}{p_T},$$

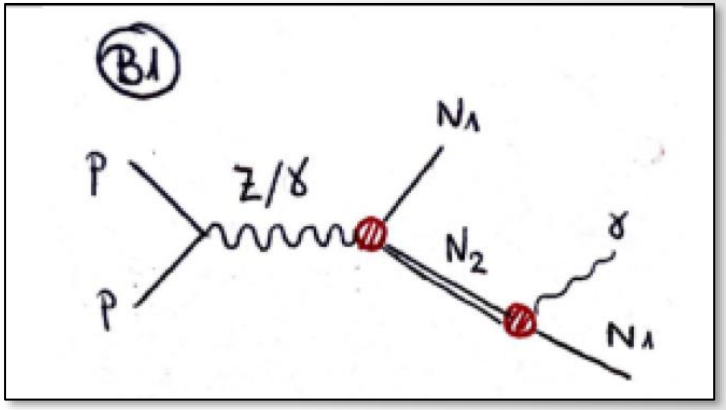
$$d_Z = \frac{z_{LLP} - (\vec{r}\cdot\vec{p})p_Z/|\vec{p}|^2}{1 - p_Z^2/|\vec{p}|^2},$$

Transverse and longitudinal location of impact parameter

HNL Magnetic Moments

- Sensitivity prospects at HL-LHC





Beltran, Bolton, FFD, Hati, Hirsch, JHEP 07 (2024) 153

HNL Magnetic Moments

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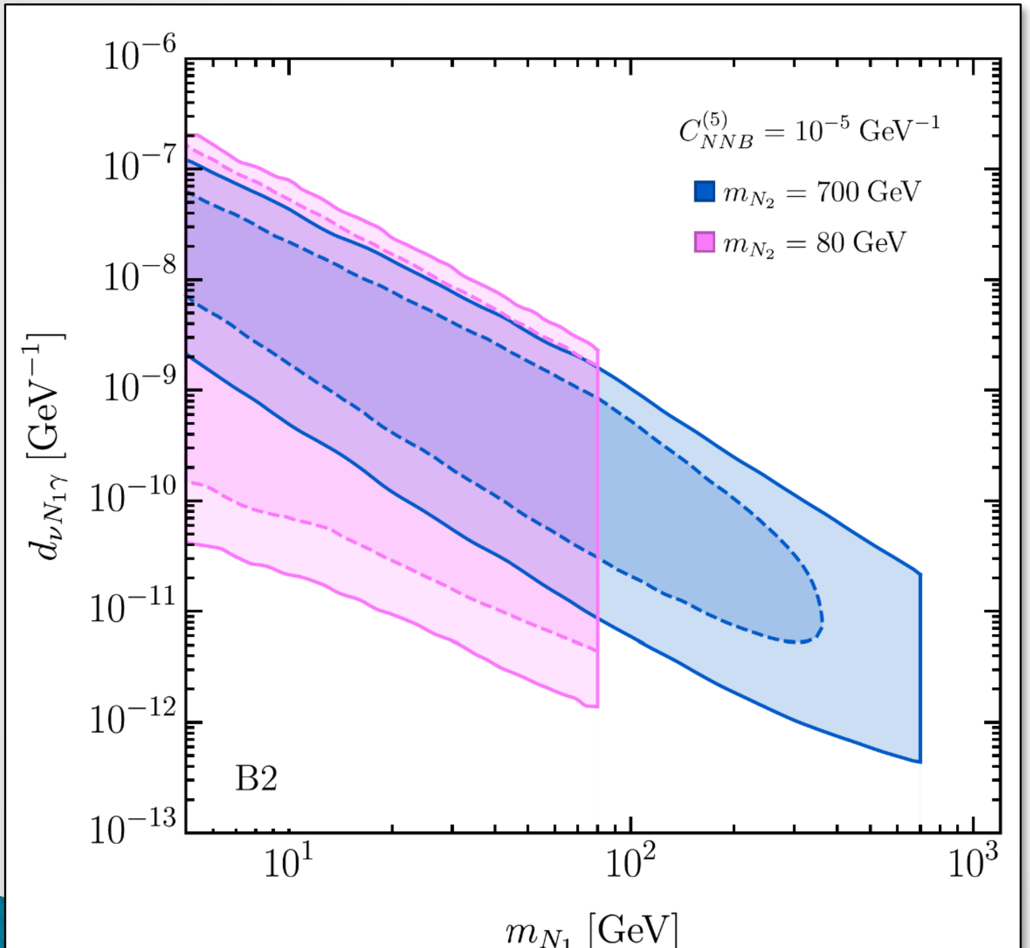

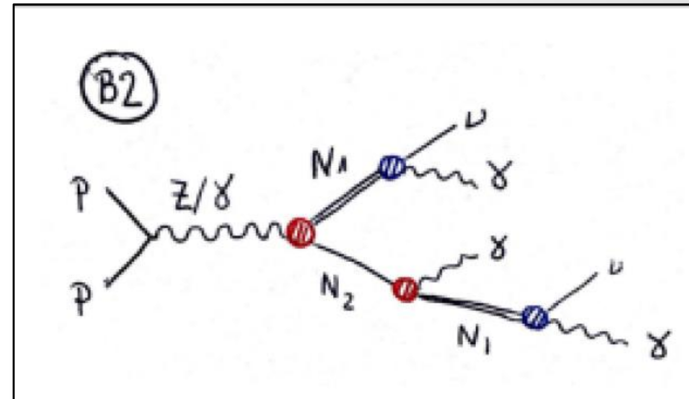

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HNL Magnetic Moments

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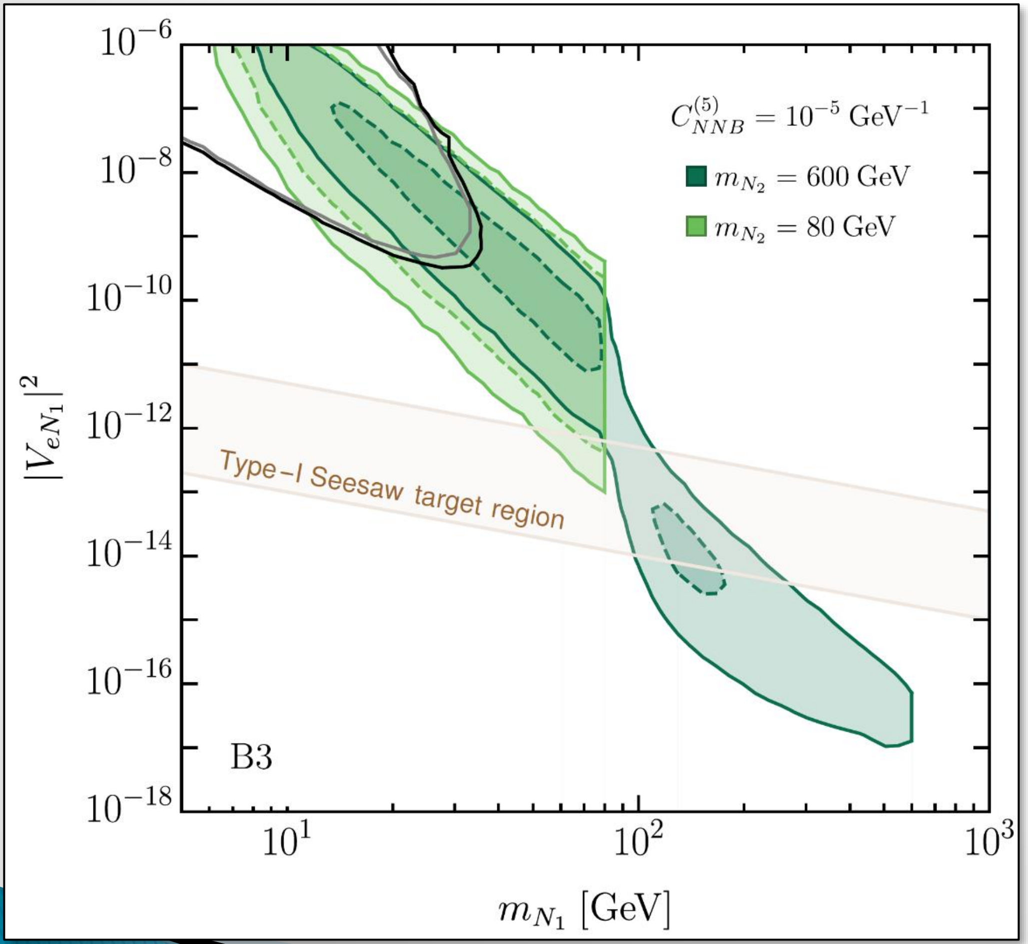

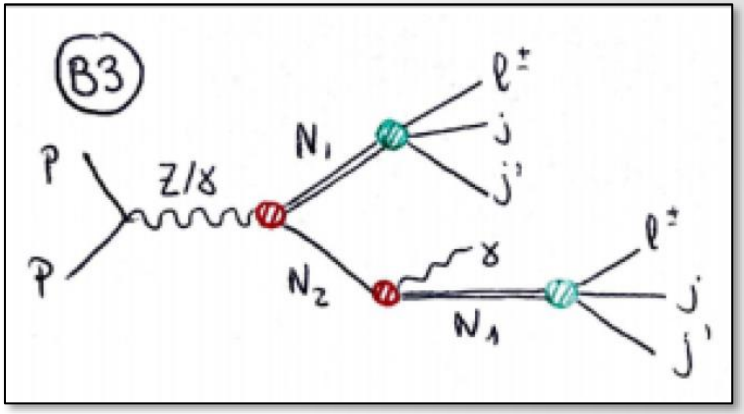

Beltran, Bolton, FFD, Hati, Hirsch,
JHEP 07 (2024) 153

Conclusion

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- **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
  - Light neutrino masses generically require small Yukawa couplings → Small active-sterile mixing → HNLs are LLPs
- **Beyond sterile: HNL portals**
  - Efficient BSM portals to produce HNLs beyond mixing
    - Gauge, Higgs and Dipole
  - Sensitivity to seesaw floor of neutrino mass generation