Long-lived heavy neutrinos from neutrinophilic charged Higgs at the HL-LHC

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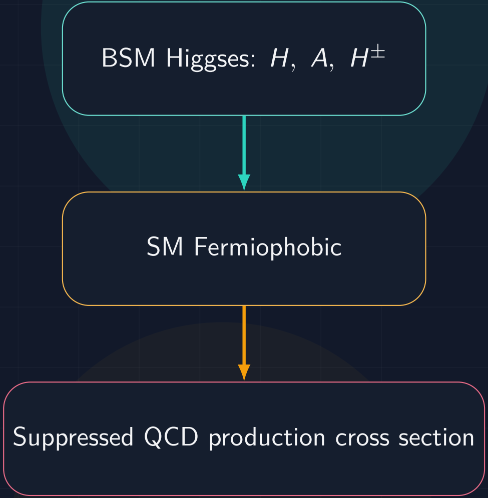
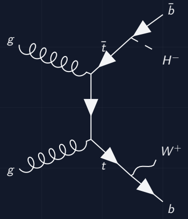
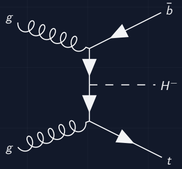
Revisiting Type-I 2HDM

- $\mathbb{Z}_2$ symmetry evades the FCNC problem, leading to four Yukawa types: **Type-I, II, X and Y**.
- $-\mathcal{L}_Y^{I} = \bar{Q}_L Y_u \tilde{H}_1 u_R + \bar{Q}_L Y_d H_1 d_R + \bar{L}_L Y_l H_1 l_R + \text{h.c.}$
- Small H_1–H_2 mixing and $v_2 \ll v_1$: $h_{SM} \in H_1$ and BSM Higgses $H^{\pm}, A, H \in H_2$.
- The mostly H_2 BSM Higgses have suppressed Yukawa couplings to SM fermions.



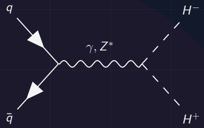


Light $H^\pm$ QCD production

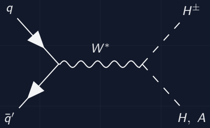


Heavy $H^\pm$ QCD production

QCD vs EW production of $H^\pm$



EW $H^\pm$ pair production



EW $H^\pm$ production in association with $H,\ A$

EW production remains sizable and can exceed the QCD induced production

Neutrinophilic Higgs doublet

- Neutrino mass matrix in canonical seesaw:

$$\mathcal{M} = \begin{pmatrix} 0 & m_D \\ m_D^T & m_N \end{pmatrix}$$

m_D : Dirac mass matrix
m_N : Majorana mass matrix
$m_D \ll m_N$: Seesaw hierarchy

- The BSM (neutrinophilic) Higgs doublet H_2 couples to the SM lepton doublets and gauge singlet right-handed neutrinos (N_R).

$$-\mathcal{L}_y \supset y_D^{ij} \bar{L}_{Li} H_2 N_{R_j} + \text{h.c.} \quad \text{and} \quad m_D = \frac{y_D}{\sqrt{2}} v_2$$

The small VEV $v_2 (\ll v_{EW})$ of the neutrinophilic Higgs doublet naturally generates small Dirac neutrino masses, even for sizable Dirac Yukawa couplings

- Diagonalization of the neutrino mass matrix gives:

$$m_\nu = -m_D m_N^{-1} m_D^T$$
$$R = m_D m_N^{-1}$$

m_ν : Light neutrino matrix
R : Light–heavy neutrino mixing matrix

$$D_\nu = U^T m_\nu U = \text{diag}(m_1, m_2, m_3); \quad m_N = \text{diag}(m_{N_1}, m_{N_2}, m_{N_3}) \ \text{ and } \ U : \text{PMNS matrix}$$

- Flavor–mass eigenstate relation:

$$\nu_\alpha = U_{\alpha i}\nu_i + R_{\alpha i} N_i \qquad \alpha: \text{ flavor index}, \quad i: \text{ mass index}$$

[A] $-\mathcal{L}_{\text{CC}} = \frac{g}{\sqrt{2}} W_\mu \bar{\ell}_\alpha \gamma^\mu P_L (U_{\alpha j}\nu_j + R_{\alpha j} N_j) + \text{h.c.}$

[B] $-\mathcal{L}_{\text{NC}} = \frac{g}{2c_W} Z_\mu [\bar{\nu}_i \gamma^\mu P_L \nu_i + \bar{N}_i \gamma^\mu P_L (R^\dagger R)_{ij} N_j + \bar{\nu}_i \gamma^\mu P_L (U^\dagger R)_{ij} N_j + \text{h.c.}]$

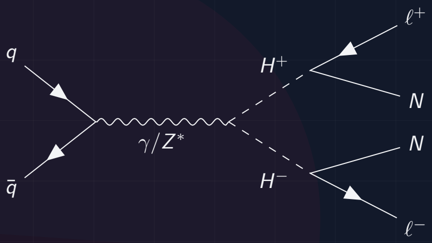
SM gauge boson induced production of heavy neutrinos is mixing suppressed

- Neutrinophilic $H^{\pm}$ decay to heavy neutrinos and SM charged lepton:

$$\Gamma(H^+ \to \ell_\alpha^+ N_i) = \frac{|m_{D\alpha i}|^2}{8\pi v_2^2} m_{H^\pm}^2 \left(1 - \frac{m_{N_i}^2}{m_{H^\pm}^2}\right)^2$$

and assuming small H_1–H_2 mixing, $H^{\pm}$ decay to heavy neutrinos is 100% if kinematically allowed.

- $\sigma_{\textbf{prod}} = \sigma(pp \to H^+ H^-) \times BR(H^\pm \to \ell^\pm N)^2$



Neutrinophilic $H^{\pm}$ pair prodcution via EW process remains sizable.

This provides an alternative production channel for gauge-singlet heavy neutrinos through $H^{\pm} \to \ell^{\pm} N$, without suppression from light–heavy neutrino mixing

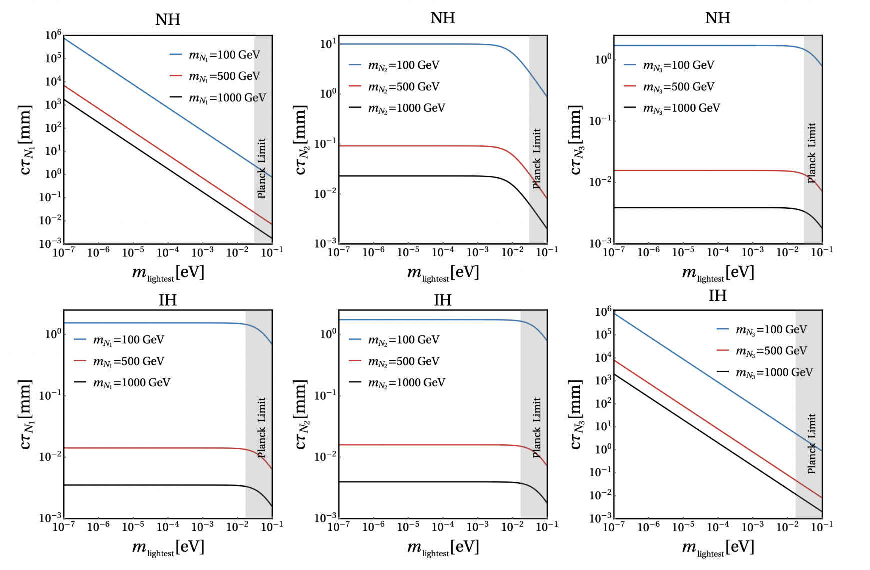
Long-lived heavy neutrinos

- $\Gamma(N_i \to \ell_\alpha W) = \frac{|R_{\alpha i}|^2}{8\pi}\frac{(m_{N_i}^2 - m_W^2)^2(m_{N_i}^2 + 2m_W^2)}{m_{N_i}^3 v^2}$ and $\Gamma(N_i \to \nu_\alpha Z) = \frac{|R_{\alpha i}|^2}{16\pi}\frac{(m_{N_i}^2 - m_Z^2)^2(m_{N_i}^2 + 2m_Z^2)}{m_{N_i}^3 v^2}$
  $v = 246$ GeV. The total decay width of N_i is: $\Gamma_{N_i} = \sum_{\alpha=e,\mu,\tau} \Gamma(N_i \to \ell_\alpha W) + \Gamma(N_i \to \nu_\alpha Z)$
- $\Gamma_{N_i} \propto \sum_{\alpha=e,\mu,\tau} |R_{\alpha i}|^2 = (R^\dagger R)_{ii}, \quad c\tau \propto 1/\Gamma_{N_i}$
- **Casas-Ibarra:** $R = m_D m_N^{-1} = U^* \sqrt{D_\nu}\mathcal{O}\sqrt{m_N^{-1}}$
  $R^\dagger R = \sqrt{m_N^{-1}}\mathcal{O}^\dagger D_\nu \mathcal{O}\sqrt{m_N^{-1}}$
- $\mathcal{O} = \mathbb{I}$: $R^\dagger R = \sqrt{m_N^{-1}} D_\nu \sqrt{m_N^{-1}} = \mathrm{diag}\left(\frac{m_1}{m_{N1}}, \frac{m_2}{m_{N2}}, \frac{m_3}{m_{N3}}\right)$

Normal hierarchy (NH): $m_1 < m_2 < m_3$
Inverted hierarchy (IH): $m_3 < m_1 < m_2$

The lightest neutrino mass becomes an independent variable

If m_{lightest} is sufficiently small, one of the heavy neutrinos can be long-lived



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How small the VEV, v_2, of the neutrinophilic Higgs doublet?

How large is the EW pair production of $H^{\pm}$ at the LHC?

- Strongest bound on v_2: $\mu \to e\gamma$ LFV process.
- For $\mathcal{O} = \mathbb{I}$, the $H^{\pm}$–N loop contribution is dominant:

$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{3\alpha_e}{16\pi G_F^2 m_{H^\pm}^4 v_2^4} \left| \sum_i^3 m_{D1i}^* m_{D2i} F\left(\frac{m_{N_i}^2}{m_{H^\pm}^2}\right) \right|^2$$

$$F(x) = \frac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x}{6(1-x)^4}$$

- **Scan:** $10^{-7} \leq m_{\text{lightest}} \leq 10^{-1}$ eV, $80 \leq m_{H^\pm} \leq 1000$ GeV, $m_{N_1} < m_{H^\pm}$ in NH and $m_{N_3} < m_{H^\pm}$ in IH. $v_2 \lesssim \mathcal{O}(1)$ MeV is excluded. $v_2 = 10$ MeV is considered throughout.
- At the LHC, $H^\pm$ pair production is γ/Z mediated EW process. For $m_{H^\pm} \gtrsim 400$ GeV, the cross section falls below 1 fb.

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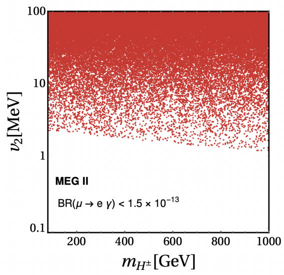
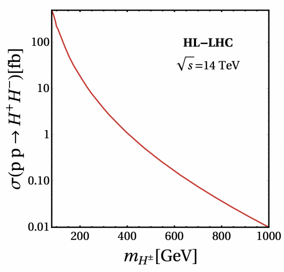
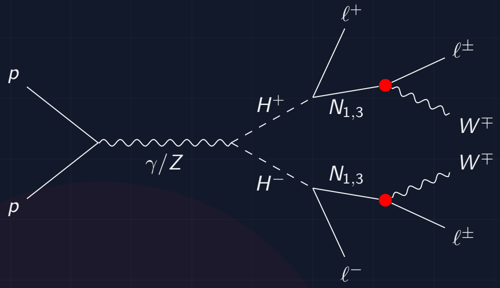




HL-LHC: $\sqrt{s} = 14$ TeV, 3000 fb^{-1} luminosity

- **N_1 (NH) and N_3 (IH)** are long-lived.



Hadraonic W decay leads $4\ell 4j$ state

Lepton number violation by two units

Displacement of leptons is measured by the transverse impact parameter $|d_0|$, defined as the distance of the closest approach of the lepton track to the primary vertex in the azimuthal plane

CMS provides $|d_0|$ dependent reconstruction efficiencies of e, μ for $|d_0| < 20$ mm

For $|d_0| > 20$ mm, a linear extrapolation, vanishing at 100 mm is adopted in MadAnalysis

Leptons (e, μ): $p_T > 10$ GeV, $|\eta| < 2.5$

Jets: $p_T > 25$ GeV, $|\eta| < 2.5$

Prompt lepton: $|d_0| < 0.1$ mm, $|d_z| < 1$ mm

Displaced lepton: $|d_0| > 2$ mm, $|d_z| < 100$ mm

Impose $|d_0|$–dependent lepton efficiency weight

1DV selection

(1) Require at least 2 jets and at least 2 leptons

(2) Require ≥ 1 prompt lepton and ≥ 1 displaced lepton

(3) Reconstruct $W \to jj$ with $|m_{jj} - m_W| < 25$ GeV

(4) Require $\Delta R(\ell^{\mathrm{disp}}, jj) < 2$

(5) If largest $|d_0|$ lepton fails, test the second-largest $|d_0|$ lepton, and so on

(6) Successful: Accepted as 1DV event

2DV selection

(1) Require at least 4 jets and at least 3 leptons

(2) Require ≥ 1 prompt lepton and 2 displaced leptons

(3) Use the 4 leading jets and form 2 dijet candidates

(4) Require $|m_{jj_1} - m_W| < 25$ GeV and $|m_{jj_2} - m_W| < 25$ GeV

(5) Require $\Delta R(\ell^{\mathrm{disp}}_{1,2}, jj_1) < 2$ and $\Delta R(\ell^{\mathrm{disp}}_{2,1}, jj_2) < 2$

(6) Successful: Accepted as 2DV event

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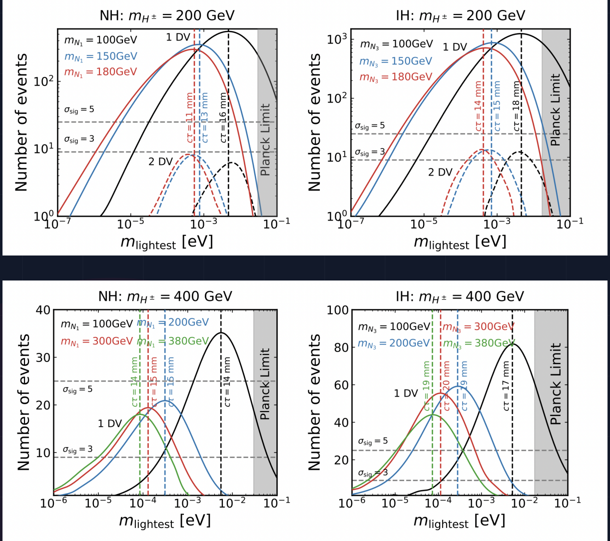

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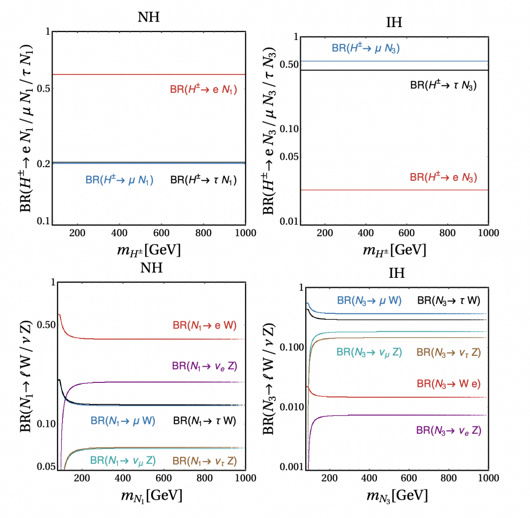
- HL-LHC: $\sqrt{s} = 14$ TeV and 3000 fb^{-1} luminosity.
- $\sigma(pp \to H^+H^-) \simeq 20\ (1)$ fb for $m_{H\pm} = 200\ (400)\ \mathrm{GeV}$.
- Signal yield peaks at $c\tau \simeq 10$–20 mm, as many events pass $|d_0| > 2$ mm while staying inside the tracker.
- **The 1DV selection yields larger signal events than the 2DV selection.**
- **Signal events in IH is higher than the signal events in NH.**



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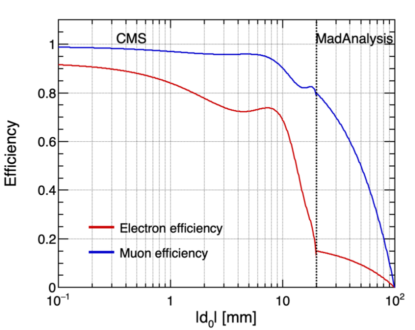

Prepared for the talk

- NH favors the electron mode, while IH favors the muon mode.
- Muons have higher $|d_0|$ efficiency than electrons.

Conclusion

BSM Higgs doublet can couple exclusively to the right-handed neutrinos and SM leptons. The small VEV of the extra Higgs doublet can generate small Dirac neutrino masses without requiring extremely small Yukawa couplings

The $H^{\pm}$ from the neutrinophilic Higgs doublet can be produced via EW process, and can decay dominantly into heavy neutrinos and charged leptons

Within the canonical seesaw, one of the heavy neutrinos can be long-lived while remaining consistent with neutrino oscillation data, and its lifetime is inversely proportional to the lightest neutrino mass

This provides a mixing unsuppressed production mechanism for SM gauge singlet long-lived heavy neutrinos.

The long-lived heavy neutrinos can give rise to displaced vertex signatures at the LHC