Neutrino Mass Models at the HL/HE-LHC

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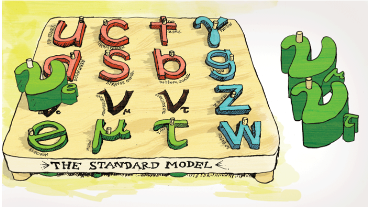
Massive neutrinos and New Physics

- Observation of ν oscillations
  $\Rightarrow$ at least 2 ν are massive
- Standard Model $L = \binom{\nu_L}{\ell_L}, \tilde{\phi} = \binom{H^{0*}}{H^-}$
  - No right-handed neutrino
    $\nu_R \to$ No Dirac mass term

$$\mathcal{L}_{\text{mass}} = -Y_\nu \bar{L} \tilde{\phi} \nu_R + \text{h.c.}$$

  - No Higgs triplet T
    $\to$ No Majorana mass term

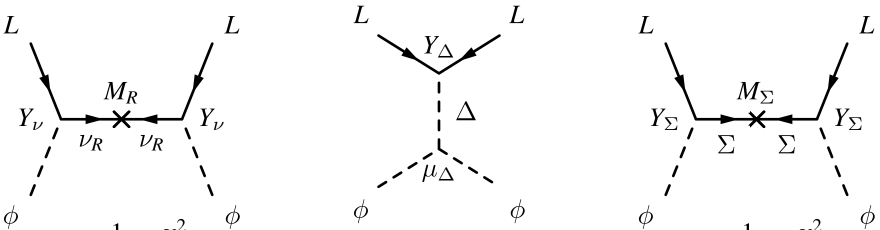
$$\mathcal{L}_{\text{mass}} = -\frac{1}{2} f \bar{L} T L^c + \text{h.c.}$$



- Necessary to go beyond the Standard Model for ν mass
  - Radiative models
  - Extra-dimensions
  - R-parity violation in supersymmetry
  - Seesaw mechanisms $\to$ ν mass at tree-level
    + BAU through leptogenesis

The seesaw mechanisms

- Seesaw mechanism: new fields + lepton number violation
  $\Rightarrow$ Generate m_ν in a renormalizable way and at tree-level
- 3 minimal tree-level seesaw models $\Rightarrow$ 3 types of heavy fields
  - type I: right-handed neutrinos, SM gauge singlets
  - type II: scalar triplets $\rightarrow \Delta^{\pm\pm}, \Delta^{\pm}, \Delta^0$
  - type III: fermionic triplets $\rightarrow \Sigma^+, \Sigma^0, \Sigma^-$



$$\mathrm{m}_\nu = -\frac{1}{2} Y_\nu \frac{\mathrm{v}^2}{M_R} Y_\nu^T \qquad \mathrm{m}_\nu = -2 Y_\Delta \mathrm{v}^2 \frac{\mu_\Delta}{M_\Delta^2} \qquad \mathrm{m}_\nu = -\frac{1}{2} Y_\Sigma \frac{\mathrm{v}^2}{M_\Sigma} Y_\Sigma^T$$

- Many variants are possible: type I + II, inverse seesaw, etc

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Collider signatures of type I seesaw and its variants

Properties of type I seesaw and variants

- Generic field content: SM + fermionic gauge singlets (a.k.a. right-handed neutrinos / sterile neutrinos)

$$\mathcal{L}_{\text{type I}} = -Y_\nu \overline{L}\tilde{\phi}\nu_R - \frac{1}{2} M_R \overline{\nu_R^c}\nu_R + \text{h.c.}$$

- After EWSB, mixing between active and sterile neutrinos

$$\begin{pmatrix} \nu_L \\ \nu_R^c \end{pmatrix}_{\text{gauge}} = \begin{pmatrix} U & V \\ W & X \end{pmatrix} P_L \begin{pmatrix} \nu \\ N \end{pmatrix}_{\text{mass}}$$

giving the relevant couplings for N production

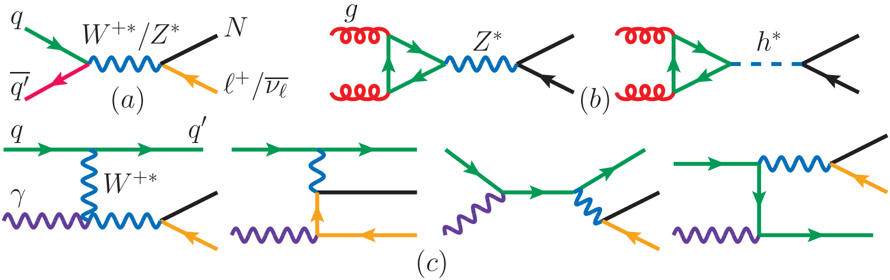
$$\begin{aligned} \mathcal{L}_{\text{Int.}} = & - \frac{g}{\sqrt{2}} W^+_\mu \, \overline{N} \, V^* \, \gamma^\mu P_L \ell^- \\ & - \frac{g}{2\cos\theta_W} Z_\mu \, \overline{N} \, V^* \, \gamma^\mu P_L \nu_\ell \\ & - \frac{g m_N}{2 M_W} h \, \overline{N} \, V^* P_L \nu_\ell + \text{h.c.}\,, \end{aligned}$$

- Theorem: $m_\nu = 0 \Leftrightarrow$ Conserved lepton number L

  [Kersten and Smirnov, 2007; Moffat, Pascoli, **CW**, 2017]

  Consequence: Large V in presence of nearly conserved L symmetry

Heavy N production: diagrams and tools



- `HeavyNnlo` FeynRules model file [Degrande et al., 2016]
- LO/NLO done with `MadGraph5_aMC@NLO` with `NNPDF3.1 NLO+LUXqed`
- $\mathrm{N^3LL}$(threshold) resummation for gluon fusion done within SCET formalism [Ruiz et al., 2017]

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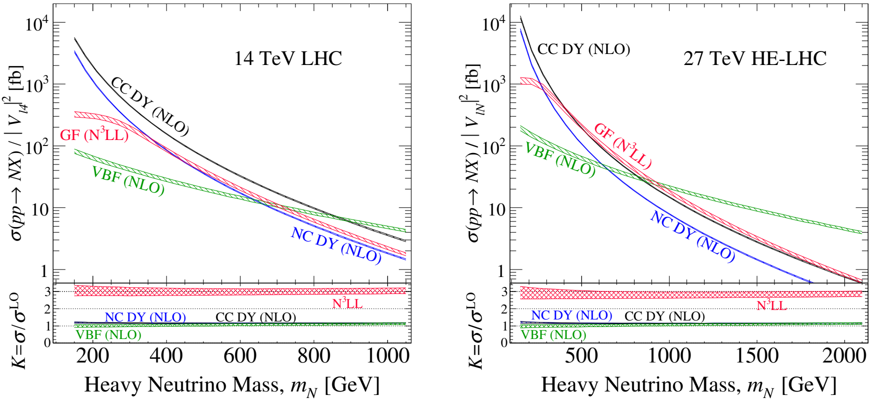
Heavy N production: cross-sections

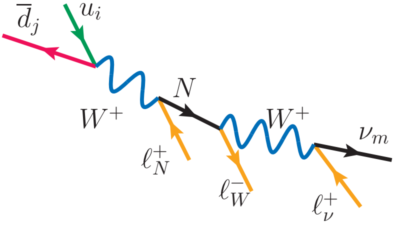
[1805.09335 and update]



- Band width = scale uncertainty ($\mu_f, \mu_r = \frac{1}{2}\sum_k E_{T,k}$)
- CC DY dominates for low masses at both LHC and HE-LHC
  VBF dominates for $m_N \geqslant 900 - 1000$ GeV at both LHC and HE-LHC
- Gluon fusion relevant at HE-LHC for $450 \leqslant m_N \leqslant 940$ GeV

Signal: tri-lepton + MET

[1805.09335]



- Focus on lepton number conserving final state
- Produced from charged-current Drell-Yan and VBF
- Specific example $|V_{eN}| = |V_{\tau N}| \neq 0$ and $|V_{\mu N}| = 0$
  Signal: $pp \to \tau_h^\pm e^\mp \ell_X +$ MET
- Purely leptonic final state → include jet veto in analysis

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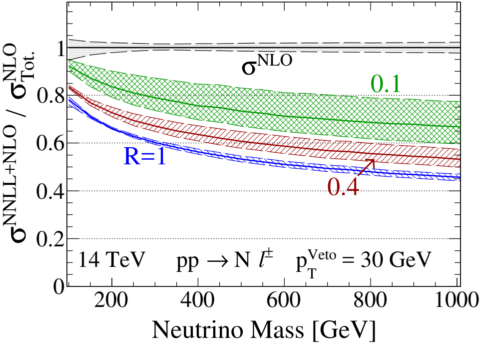
Jet veto with fixed p_T

- Jets associated with color-singlet processes mostly forward and soft
  → veto central and hard jets associated with colored backgrounds
  [Barger et al., 1990, Barger et al., 1991, Fletcher and Stelzer, 1993, Barger et al., 1995]



- Major issues:
  - Signal efficiency drops with m_N
  - $\alpha_s(p_T^{Veto}) \log(Q^2/p_T^{Veto\,2})$ corrections
- Jet veto: NLO + NNLL(veto) resummation within SCET formalism [Alwall et al., 2014, Becher et al., 2015]
- Residual scale uncertainties: $\pm 10/5/2\%$

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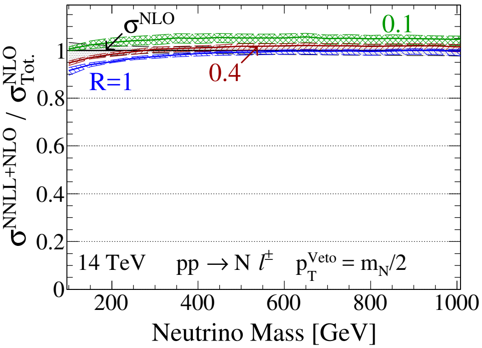
Dynamical jet veto

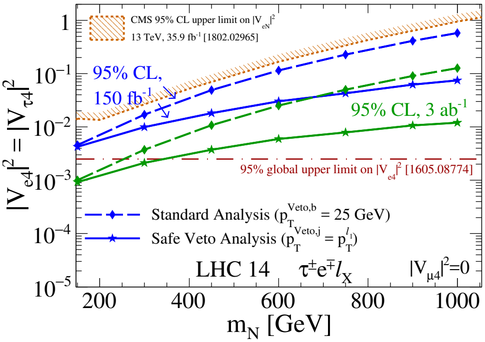
- Idea: Tie the veto scale to the hard scale
- Previously used for EW multiboson production

  [Denner et al., 2009, Nhung et al., 2013, Frye et al., 2016]



- $p_T^{\ell_W} \sim \frac{m_N}{2}(1 - M_W^2/m_N^2)$ and $p_T^{\text{Veto}} = m_N/2 \Rightarrow Q^2/p_T^{\text{Veto}\,2} \sim 4$
- Logs under control → No need for NNLL resummation anymore
- p_T^{Veto} increases with m_N → No drop in efficiency
- Mismatch here due to PDF sets used for jet veto vs no veto
- Can be used for τ at NLO since they are color-disconnected from the initial state

Tri-lepton search results at LHC and HL-LHC



- Search rebuild around the jet veto
- $p_T^{\ell\ [\tau_h]\ \{j\}} > 15\ [30]\ \{25\}$ GeV, $|\eta^{\mu,\tau_h,j}| < 2.4$, $|\eta^e| < 1.4$ or $1.6 < |\eta^e| < 2.4$
- Top background: killed by jet veto $p_T^{\text{Veto}} = p_T^{\ell_1}$
- EW triboson: $S_T > 120\,\text{GeV}$

$$S_T^{3W} \equiv \sum_\ell |\vec{p_T}^\ell| \sim 3\frac{M_W}{2} \sim 120\,\text{GeV}$$
$$S_T^N \sim \frac{m_N}{3} + \frac{m_N}{2} + \frac{m_N}{4} = \frac{13}{12} m_N .$$

- EW diboson: $M_{\ell\ell} > 10\,\text{GeV}$, $|M_{\ell\ell}\text{ or }M_{3\ell} - M_Z| < 15\,\text{GeV}$
- Fake leptons: killed by jet veto

- Proxy for m_N: multi-body transverse mass [Barger et al., 1983, Barger et al., 1988]
- Up to $10 - 11$ improvement in $|V_{\ell 4}|$ reach

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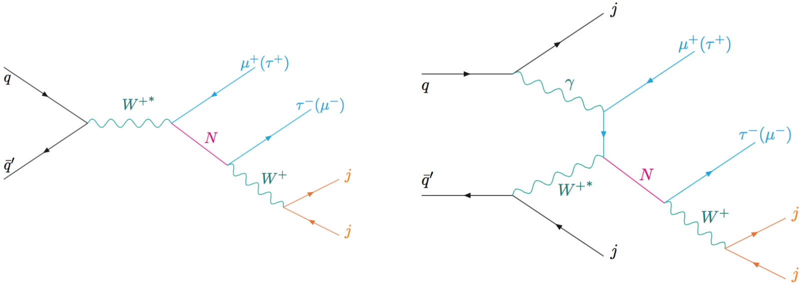
Signal: LFV dilepton

[PLB752(2016)46 and updates]

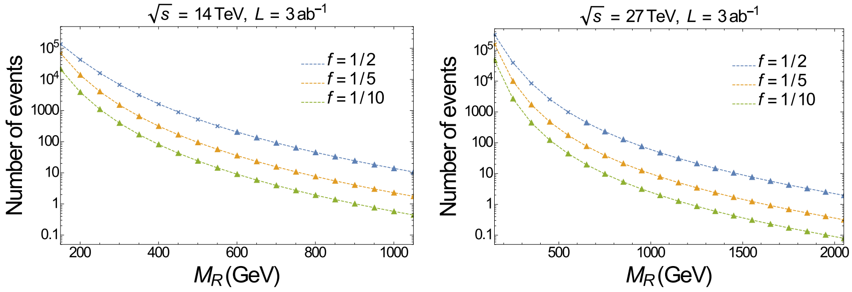


- Focus on lepton number conserving final state
- Produced from charged-current Drell-Yan and VBF
- Only lightest pseudo-Dirac neutrino accessible and use

$$Y_\nu = f \begin{pmatrix} -1 & 1 & 0 \\ 1 & 1 & 0.9 \\ 1 & 1 & 1 \end{pmatrix}$$

- Good prospect to reconstruct m_N and keep background under control

LFV dilepton results



▲ Allowed by LFV radiative decays
$\times$ Excluded by Br($\tau \to \mu\gamma$)$\geqslant 4.4 \times 10^{-8}$ [Aubert et al., 2010]

- For $m_N \approx 150$ GeV, up to 20000 events at the HL-LHC
- $\sqrt{s} = 14 \to 27$ TeV: Number of events $\times 2$ and more
- For $\mathcal{L} = 3\,\mathrm{ab}^{-1}$, more than 100 LFV events for $m_N \leqslant 700(1000)$ GeV at HL(HE)-LHC

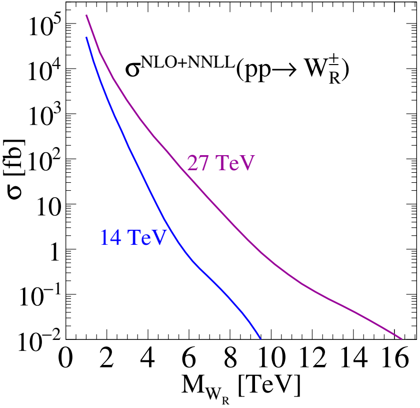
Collider signatures of left-right symmetric models

Minimal left-right symmetric model

- Gauge group: $\mathrm{SU}(3) \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$ with $g_L = g_R$
- Field content: SM + 3 ν_R + scalar triplets Δ_L, Δ_R Higgs promoted to a bidoublet $(\mathbb{1}, \mathbb{2}, \mathbb{2}, 0)$
- $\mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L} \to \mathrm{U}(1)_Y$ when Δ_R takes a vev much above EW scale
- Neutrino masses from type I + II seesaw
- When $\langle \Delta_R \rangle \gg v_{\mathrm{SM}} \gg \langle \Delta_L \rangle \to$ get the usual W_L as well as W_R with $m_{W_R} \approx g\langle \Delta_R \rangle / \sqrt{2}$

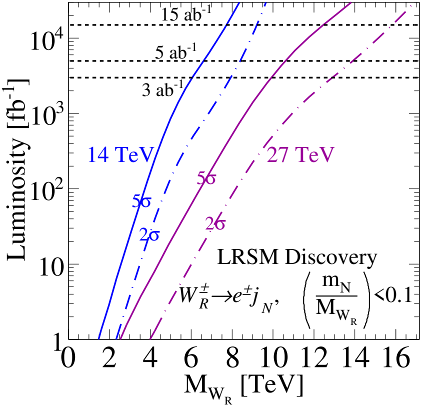
W_R production

[PRD94(2016)095016 and update]



- Manifest LRSM FeynRules model file [Roitgrund et al., 2016] set up to reproduce MLRSM
- Calculation at NLO+NNLL(threshold) using `NNPDF3.0 NLO` and cross-checked against literature and `MadGraph5_aMC@NLO`
- Resummation particularly critical when $m_{W_R} \to \sqrt{s}$ due to soft radiation
- $\sigma \geqslant 1\text{fb}$ for $m_{W_R} = 5.5(9)$ TeV at the (HE-)LHC

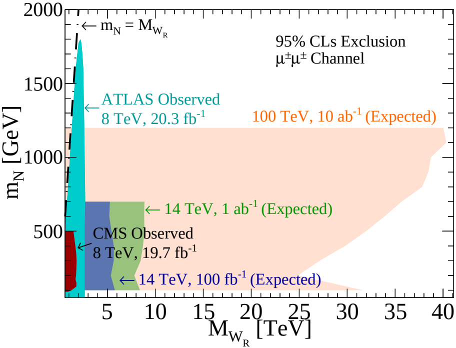
Signal: neutrino jet from on-shell W_R production



- Hierarchical $m_N \ll m_{W_R}$ $\Rightarrow$ boosted N $\Rightarrow$ collimated decay products = neutrino jet
- Signal: $pp \to W_R \to N\ell^\pm \to j_N \ell^\pm$
- HL-LHC sensitivity at 5σ: $m_{W_R} \approx 6$ TeV
  HE-LHC sensitivity at 5σ: $m_{W_R} \approx 12.5$ TeV

Signal: same-sign dilepton from non-resonant W_R

[EPJC77(2017)375]



- $pp \to W_R^* \to N\ell^\pm \to \ell^\pm\ell^\pm + 2j$
- Effective Left-Right Symmetric Model FeynRules model file [Mattelaer et al., 2016]
- Similar to searches for Majorana N in phenomenological type I seesaw
  → Can recast current searches
- Can probe $m_{W_R} \approx 8 - 9$ TeV with $1\,\mathrm{ab}^{-1}$ at 14 TeV

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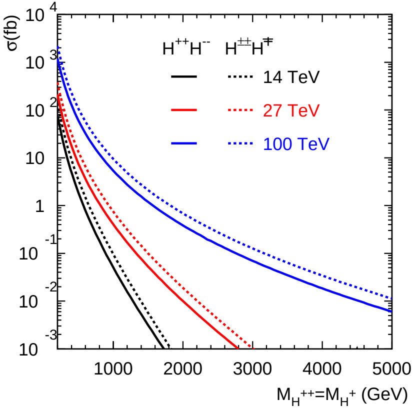
Collider signatures of type II seesaw scalars

Doubly charged scalar production

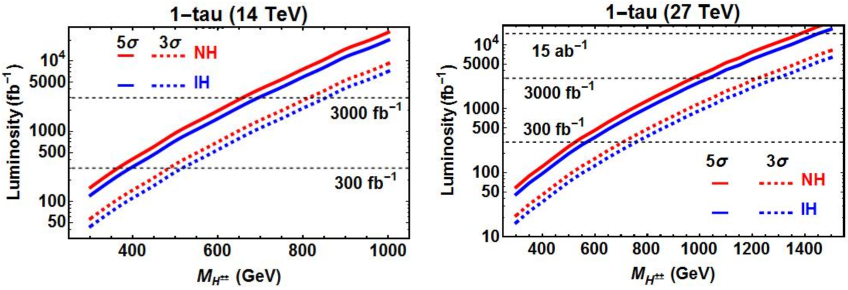
[PRD78(2008)015018, 1802.00945 and update]



- Pair production:
  $pp \to Z^*/\gamma^* \to H^{++}H^{--}$

  Single production:
  $pp \to W^* \to H^{\pm\pm}H^{\mp}$
- Make use of `LNV-Scalars_UFO` file [del Águila and Chala, 2014]
- Proceeds via weak gauge interactions → Unsuppressed by mixing
- $H^{\pm\pm}$ has striking LNV decays to two same-sign leptons

HL-LHC and HE-LHC sensitivity to $H^{\pm\pm}$



- $H^{\pm\pm}$ decays mostly $\tau^{\pm}\mu^{\pm}$ and $e^{\pm}e^{\pm}$ for inverted hierarchy (IH) or $\mu^{\pm}\mu^{\pm}$ and $\tau^{\pm}\tau^{\pm}$ for normal hierarchy (NH)
- Search built on final state $pp \to H^{++}H^{--} \to \tau^{\pm}\ell^{\pm}\ell^{\mp}\ell^{\mp}$ with τ decaying hadronically and $\ell = e, \mu$
- HL-LHC sensitivity at 5σ: 655(695) GeV for NH(IH)
  HE-LHC sensitivity at 5σ: 1380(1450) GeV for NH(IH)

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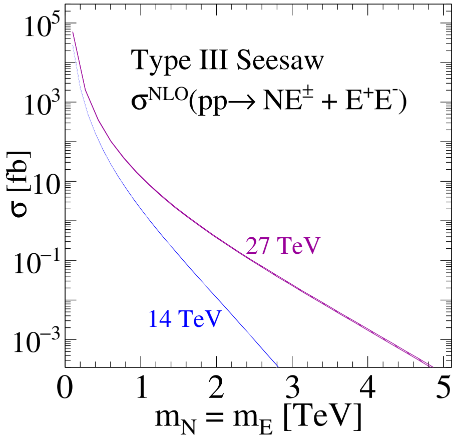
Collider signatures of type III seesaw fermions

Triplet lepton pair production

[JHEP12(2015)165 and update]



- Summed $\sigma(pp \to Z^*/\gamma^* \to E^+E^-)$ and $\sigma(pp \to W^* \to E^\pm N)$ at NLO QCD
- Degenerate limit $m_{H^\mp} = m_{H^{\mp\mp}}$
- Proceeds via weak gauge interactions → Unsuppressed by mixing
- $\sigma \sim \text{fb}$ for $m_N = m_E = 1.2(1.8)$ TeV at the (HE-)LHC
  $\sigma \sim \text{ab}$ for $m_N = m_E = 2.5(4.2)$ TeV at the (HE-)LHC

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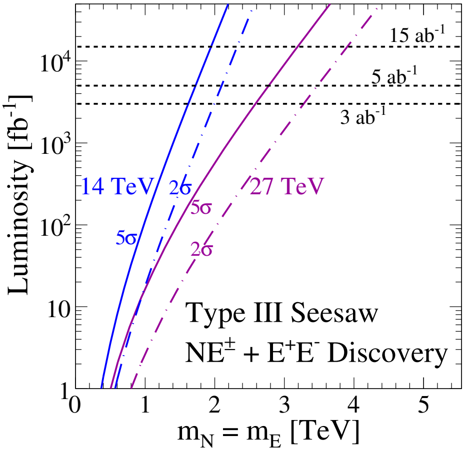
Triplet lepton sensitivity

[PRD80(2009)093003, PRD82(2010)053004 and update]



- Fully reconstructible final states

$$NE^\pm \to \ell\ell' + nj + mb$$
$$E^+E^- \to \ell\ell' + nj + mb$$

with

$$\mathrm{Br}(NE^\pm) \approx 0.115$$
$$\mathrm{Br}(E^+E^-) \approx 0.116$$

- SM background is negligible
- HL-LHC sensitivity at 5σ: 1.6 TeV
  HE-LHC sensitivity at 5σ: 3.2 TeV

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Conclusions

- Neutrino mass models have a very rich phenomenology at hadronic colliders
- Dynamical jet veto:
  - reduces QCD uncertainties
  - improve signal efficiencies
  - improve background rejection
- Type I seesaw: new search strategy using dynamical jet veto can beat indirect constraints at HL-LHC (currently preparing MC samples for 27 TeV)
- MLRSM: neutrino jets are sensitive to W_R up to 6(12.5) TeV at the HL(HE)-LHC
  Indirect searches via same-sign dilepton sensitive to 8-9 TeV at LHC
- Type II: search for $H^{\pm\pm}$ can probe masses up to 0.65(1.4) TeV at the HL(HE)-LHC
- Type III: search for $E^{\pm}$ sensitive to masses up to 1.6(3.2) TeV at the HL(HE)-LHC

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Backup slides

Theorem on Lepton number conservion

- Are lepton number violating processes suppressed in all low-scale seesaw models ?

Theorem

If: - no cancellation between different orders of the seesaw expansion[a]

- no cancellations between different radiative orders[b]

Then $m_\nu = 0$ equivalent to having the neutrino mass matrix, in the basis $(\nu_L^C, \{\nu_{R,1}^{(1)} \ldots \nu_{R,n}^{(1)}\}, \{\nu_{R,1}^{(2)} \ldots \nu_{R,n}^{(2)}\}, \{\nu_{R,1}^{(3)} \ldots \nu_{R,m}^{(3)}\})$

$$\tilde{M} = \begin{pmatrix} 0 & \alpha & \pm i\alpha & 0 \\ \alpha^T & M_1 & 0 & 0 \\ \pm i\alpha^T & 0 & M_1 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix}, \quad (1)$$

for an arbitrary number of ν_R and to all radiative orders, with M_1 and M_2 diagonal matrices with positive entries and α a generic complex matrix.

[a] This is a necessary requirement to satisfy phenomenological constraints

[b] These are highly fine-tuned solution that cannot be achieved solely by specific textures of the neutrino mass matrix

Corollary on lepton number violation

Using a unitary matrix D, let us construct

$$Q = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \pm\frac{i}{\sqrt{2}}D & \frac{1}{\sqrt{2}}D & 0 \\ 0 & \frac{1}{\sqrt{2}}D & \pm\frac{i}{\sqrt{2}}D & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

then through a change of basis

$$Q^T \tilde{M} Q = \begin{pmatrix} 0 & \pm i\sqrt{2}(D^T\alpha^T)^T & 0 & 0 \\ \pm i\sqrt{2}D^T\alpha^T & 0 & \pm iD^T M_1 D & 0 \\ 0 & \pm iD^T M_1 D & 0 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix} \sim \begin{pmatrix} 0 & M_D^T & 0 & 0 \\ M_D & 0 & M_R & 0 \\ 0 & M_R^T & 0 & 0 \\ 0 & 0 & 0 & M_2 \end{pmatrix}$$

- Similar to the L conserving limit of inverse and/or linear seesaw
- Explicitly L conserving taking the L assignment $(+1, -1, +1, 0)$

Corollary

The most general gauge-singlet neutrino extensions of the SM with no cancellation between different orders of the seesaw expansion, no fine-tuned cancellations between different radiative orders and which lead to three massless neutrinos are L conserving.