Heavy Neutrino Searches at the LHC

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PSBD, A. Pilaftsis and U.-k. Yang, arXiv:1308.2209 [hep-ph];
C.-Y. Chen, PSBD and R. N. Mohapatra, Phys. Rev. D **88**, 033014 (2013) [arXiv:1306.2342].

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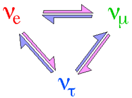
Outline

- Introduction
- Type-I seesaw and its two aspects
- Experimental constraints
- Improving the LHC sensitivity
- Left-Right seesaw
- A predictive TeV-scale L-R seesaw model
- Conclusion

Neutrino Oscillation ⇒ Physics beyond the SM

- Neutrinos oscillate between different flavors:

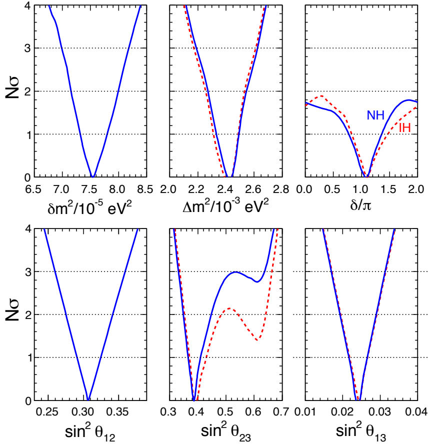


- Oscillation probability between two flavors:

$$P(\nu_i \to \nu_j) = \sin^2 2\theta_{ij} \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right)$$

- Oscillation between all three flavors ⇒ at least two non-zero neutrino masses.
- Firmly established ($> 5\sigma$ evidence) over the past decade.
- First (and so far only) conclusive *experimental* evidence for BSM Physics.

Synopsis of global 3ν oscillation analysis

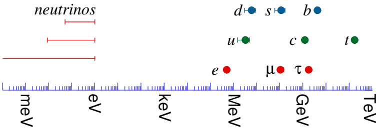


[Fogli *et al*, PRD **86**, 013012 (2012)]

Neutrino Oscillation ⇒ Physics beyond the SM

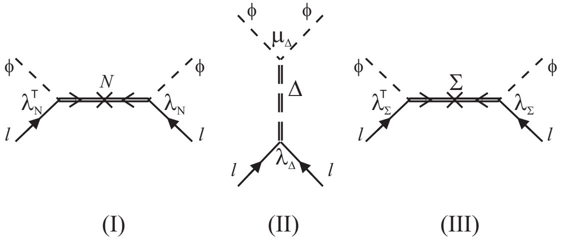
- Neutrinos are massless in the SM because
  - No right-handed counterpart (no Dirac mass unlike charged fermions).
  - ν_L part of the $SU(2)_L$ doublet ⇒ No Majorana mass term $\nu_L^T C^{-1} \nu_L$.
  - SM has an exact global $(B - L)$-symmetry. Even non-perturbative effects cannot induce neutrino mass.

- Simply adding RH neutrinos (N) requires tiny Yukawa coupling $y_\nu \lesssim 10^{-12}$ in the Dirac mass term $\mathcal{L}_{\nu,Y} = y_{\nu,ij} \bar{L}_i \Phi N_j + \mathrm{h.c.}$
- Though not unnatural, has *no* experimentally observable effects.
- Large hierarchy between neutrino and charged fermion masses might be suggesting some new distinct mechanism behind neutrino masses.



A Simple Paradigm

- A natural way to generate neutrino mass is by breaking $(B - L)$.
- Within the SM, can be parametrized through Weinberg's dimension-5 operator $\lambda_{ij}(L_i^{\mathsf{T}}\Phi)(L_j^{\mathsf{T}}\Phi)/\Lambda$. [Weinberg, PRL **43**, 1566 (1979)]
- Three tree-level realizations: Type I,II,III Seesaw mechanism.



- Majorana mass of the heavy particle (N, Δ, or Σ) breaks L by two units.
- Other profound implications: Leptogenesis, Dark Matter, Electroweak Vacuum Stability, ...
- A pertinent question in the LHC era: Is $\not{L}$ observable at the LHC?

Type-I Seesaw

- Seesaw messenger: SM singlet fermions (RH neutrinos).
- Have a Majorana mass term $M_N N^{\mathsf{T}} C^{-1} N$, in addition to the Dirac mass $M_D = v y_\nu$.
- In the flavor basis $\{\nu_L^C, N\}$, leads to the general structure

$$\mathcal{M}_\nu \quad = \quad \begin{pmatrix} 0 & M_D \\ M_D^{\mathsf{T}} & M_N \end{pmatrix}$$

[Minkowski '77; Mohapatra, Senjanović '79; Yanagida '79; Gell-Mann, Ramond, Slansky '79; Glashow '79]

- In the seesaw approximation $||\xi|| \ll 1$, where $\xi \equiv M_D M_N^{-1}$ and $||\xi|| \equiv \sqrt{\mathrm{Tr}(\xi^\dagger \xi)}$,
  - $M_\nu^{\mathrm{light}} \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$ is the light neutrino mass matrix.
  - $\xi \equiv M_D M_N^{-1}$ is the heavy-light neutrino mixing.

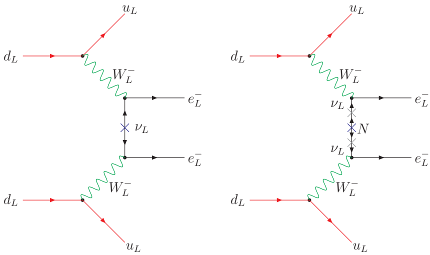
- From a bottom-up approach, we call this minimal scenario the 'SM seesaw'.
- No definite prediction for the seesaw scale: a wide range of possibilities over 20 orders of magnitude (keV - 10^{14} GeV)!

Two Key Aspects of Seesaw

Majorana Mass

⇓

Neutrinoless Double Beta Decay

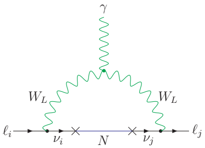


Does not necessarily probe the heavy-light mixing since the mixed diagram may not give the dominant contribution.

Heavy-light Mixing

⇓

- Lepton Flavor Violation ($\mu \to e\gamma$, $\mu \to 3e$, $\mu - e$ conversion, etc.)

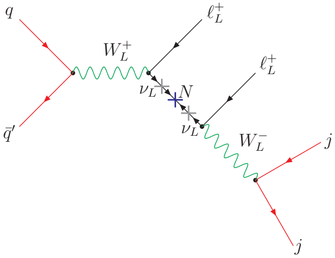


- Also deviations from the unitarity of the PMNS neutrino mixing matrix.
- Do not necessarily prove the Majorana nature since a Dirac neutrino can also give large LFV and non-unitarity effects.

Low-energy tests of Seesaw at the Intensity Frontier require a synergy between the two aspects.

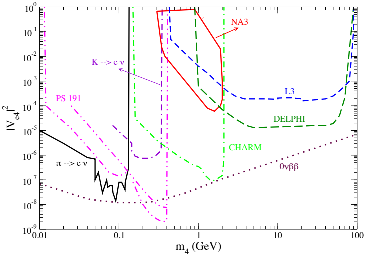
Collider Signal

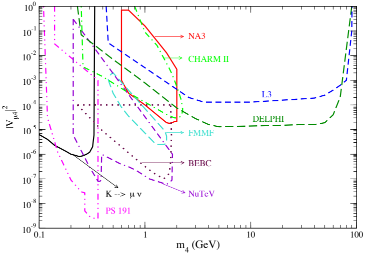
- A direct test of *both* the aspects of type-I seesaw at the Energy Frontier.
- ‘Smoking gun’ signal: $pp \to W^* \to \ell^\pm_\alpha N \to \ell^\pm_\alpha \ell^\pm_\beta jj$ with no $\not\!\!E_T$.

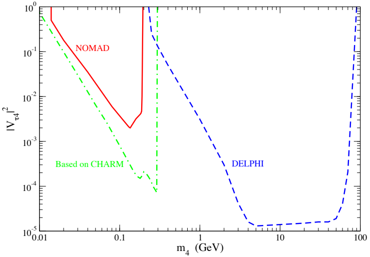


- Requires *both* the Majorana nature of N at (sub-)TeV scale and a ‘large’ heavy-light mixing to have an observable effect.
- A potential direct probe of both LNV and LFV (for $\alpha \neq \beta$) if $M_N = \mathcal{O}$(100 GeV - 1 TeV).

Pre-LHC Constraints

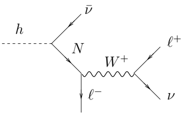


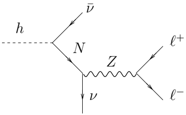


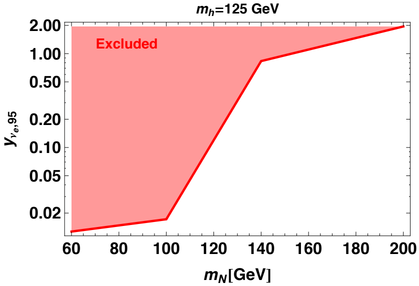


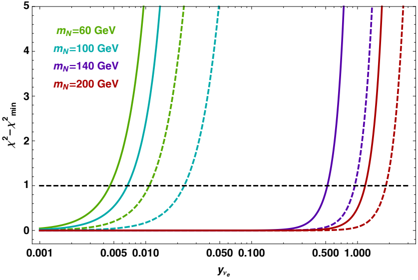
[Atre, Han, Pascoli, Zhang, JHEP **0905**, 030 (2009)]

Constraints from LHC Higgs Data



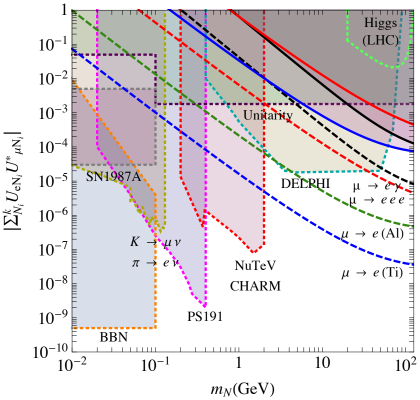






[PSBD, Franceschini, Mohapatra, PRD **86**, 093010 (2012)]

LFV Constraints

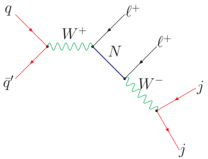


[Alonso, Dhen, Gavela, Hambye (2013)]

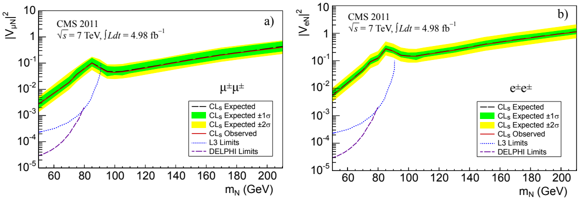
- Only constrains the product $|V_{\ell N} V^*_{\ell' N}|$ (with $\ell \neq \ell'$), and *not* the individual $|V_{\ell N}|^2$.
- A combination of direct and indirect limits important.

Direct Search Limits from LHC7

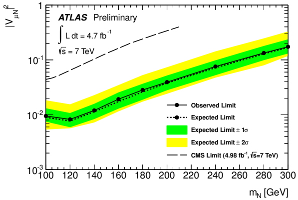
- Within SM seesaw framework, the only channel examined at the LHC so far:



$\Downarrow$



[CMS Collaboration, PLB **717**, 109 (2012)]

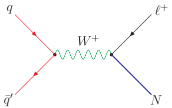


[ATLAS-CONF-2012-139]

- Signal strength depends on the largeness of $V_{\ell N}$.
- Can effectively probe heavy neutrinos only if $M_N \lesssim 300$ GeV and $|V_{\ell N}|^2 \gtrsim 10^{-3}$.
  [Datta, Guchait, Pilaftsis '93; Han, Zhang '06; del Aguila, Aguilar-Saavedra, Pittau '07;...]

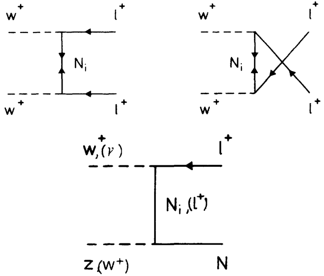
Heavy Neutrino Production at the LHC

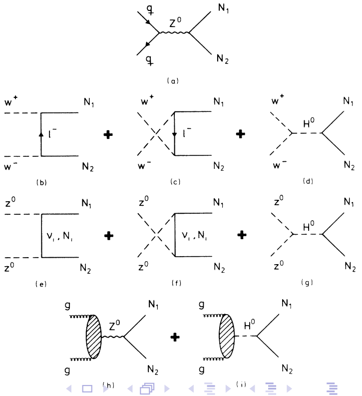
- The LHC searches considered only the *s*-channel *W*-exchange diagram:



- There exist many other production modes (even within the minimal SM seesaw), but most of these are negligible.

[Datta, Guchait, Pilaftsis, PRD **50**, 3195 (1994)]





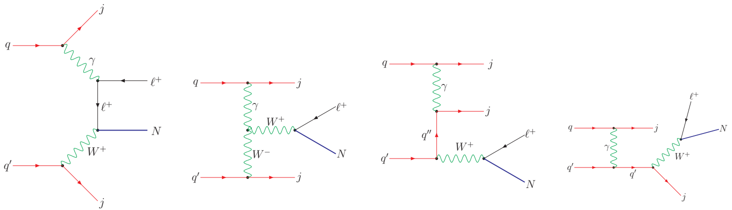
A New *Dominant* Production Channel

[PSBD, Pilaftsis, Yang, arXiv:1308.2209 [hep-ph]]

- Diagrams involving virtual photons in the *t*-channel give rise to *diffractive* processes, e.g.,

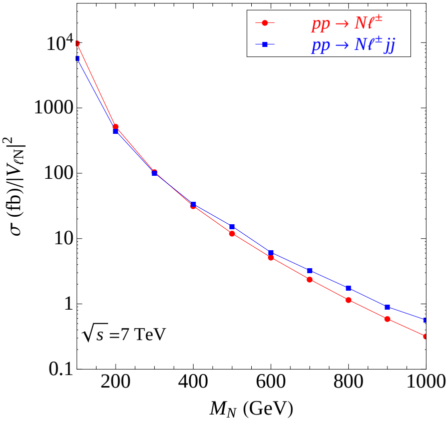
$$pp \;\to\; W^* \gamma^* jj \;\to\; \ell^\pm N jj \;,$$

  which are *not* negligible, but infrared enhanced.



- Divergent inclusive cross section due to collinear singularity caused by the photon propagator.
- A minimum p_T^j cut required to make the cross section finite.
- Collinear divergence of the low-p_T^j regime is absorbed into an effective photon structure function for the proton (analogous to the Weizsäcker-Williams equivalent photon approximation for electrons).

Comparison of the Production Cross Sections



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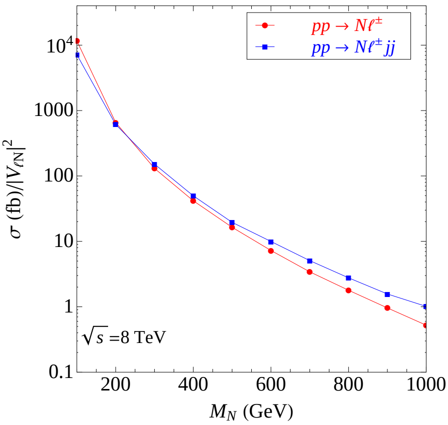

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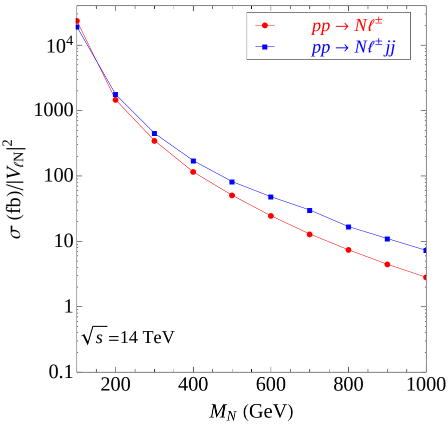
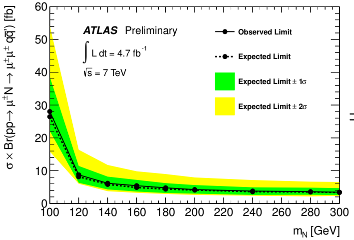


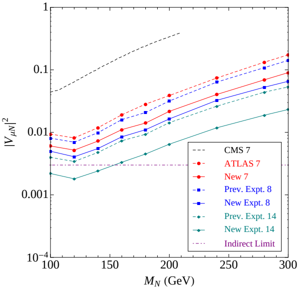
Comparison of the Production Cross Sections

- The hadronic channels for $pp \to N\ell^\pm jj$ mediated by virtual gluons and quarks give $\mathcal{O}(\alpha_s)$ corrections and drop at the same rate as the $pp \to N\ell^\pm$ cross section.
- The total electroweak $(\gamma + Z)$ contribution for $pp \to N\ell^\pm jj$ drops at a rate slower than the $pp \to N\ell^\pm$ cross section with increasing M_N.
- The production channel $N\ell^\pm jj$ dominates over the earlier considered $N\ell^\pm$ channel with increasing M_N.
- Similar behavior with increasing $\sqrt{s}$ in the pp collisions.
- The crossover point shifts towards lower M_N with increasing $\sqrt{s}$.
- Thus, the $N\ell^\pm jj$ process becomes increasingly important for $M_N \gtrsim 200$ GeV.
- Must be taken into account in present and future analyses of the LHC data.

Improved Upper Limit on Mixing



$\Longrightarrow$



[PSBD, Pilaftsis, Yang, arXiv:1308.2209]

- Improved direct limits are rather conservative since we used only the $\int Ldt = 4.7\ \text{fb}^{-1}$ data at $\sqrt{s} = 7$ TeV LHC ($\sim$ 1% of the total data expected).
- In practice, the direct limits from $\sqrt{s} = 8$ and 14 TeV LHC data could be much more stringent (if no signal is observed!).

Extension to Other Exotic Searches

- The infrared-enhanced mechanism can equally be extended to other exotic searches at the LHC.
- One example: In the context of type-II seesaw with singly and doubly-charged scalars, we have vertices of the form $H^+H^-A_\mu A_\nu$ and $H^{++}H^{--}A_\mu A_\nu$.
- Lead to diffractive processes such as

$$\begin{aligned} pp &\to \gamma^*\gamma^* jj \to H^{++}H^{--} jj \to \ell^+\ell^+\ell^-\ell^- jj \\ pp &\to \gamma^*\gamma^* jj \to H^+H^- jj \to \ell^+\nu\ell^-\bar{\nu} jj \end{aligned}$$

- Expected to dominate over the usually considered search channel

$$pp \to Z/\gamma^* \to H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-$$

- LHC exclusion limits for $M_{H^{\pm\pm}}$ can be improved significantly. [PSBD, Figy (work in progress)]

Left-Right Seesaw

- L-R gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ provides a natural embedding of the heavy neutrinos and seesaw physics. [Pati, Salam '74; Mohapatra, Pati '75; Mohapatra, Senjanović '75]
  - N is the parity partner of ν_L and required by anomaly cancellation.
  - Scale of $SU(2)_R$-breaking sets the seesaw scale.
- Basic features:
  - Fermions: $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv Q_R, \ \ \psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} N \\ e_R \end{pmatrix} \equiv \psi_R.$
  - Scalars: $\Delta_R \equiv \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix}, \quad \phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}.$
- Yukawa Lagrangian:

$$\begin{aligned} \mathcal{L}_Y \quad = \quad & h_{ij}^{q,a}\bar{Q}_{L,i}\phi_a Q_{R,j} + \tilde{h}_{ij}^{q,a}\bar{Q}_{L,i}\tilde{\phi}_a Q_{R,j} + h_{ij}^{\ell,a}\bar{L}_i\phi_a R_j \\ & + \tilde{h}_{ij}^{\ell,a}\bar{L}_i\tilde{\phi}_a R_j + f_{ij}(R_iR_j\Delta_R + L_iL_j\Delta_L) + \text{h.c.} \end{aligned}$$

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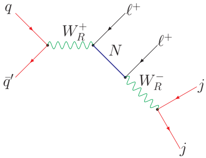
- $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ by $\langle \Delta_R^0 \rangle = v_R$. Leads to $M_{W_R} = g_R v_R$.
- $SU(2)_L \times U(1)_Y \to U(1)_{\rm em}$ by $\langle \phi \rangle = \mathrm{diag}(\kappa', \kappa)$.
- Leads to the fermion masses

$$\begin{aligned} & M_u = h^q\kappa' + \tilde{h}^q\kappa, \;\; M_d = h^q\kappa + \tilde{h}^q\kappa', \;\; M_\ell = h^\ell\kappa + \tilde{h}^\ell\kappa', \\ & M_D = h^\ell\kappa' + \tilde{h}^\ell\kappa, \;\; M_N = f v_R \end{aligned}$$

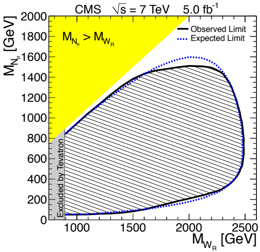
- Seesaw matrix fully determined.

L-R Seesaw at the LHC

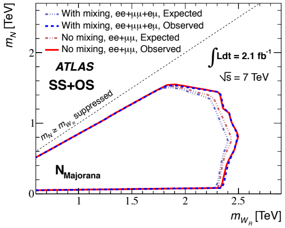
- New contribution via W_R exchange. [Keung, Senjanović, PRL **50**, 1427 (1983)]



- Independent of mixing effects. Could probe M_N up to 2-3 TeV, and M_{W_R} up to 5-6 TeV. [Ferrari *et al* '00; Nemevsek, Nesti, Senjanović, Zhang '11; Das, Deppisch, Kittel, Valle '12;...]
- Current LHC limits exclude M_{W_R} below about 2.5 TeV (depending on M_N).

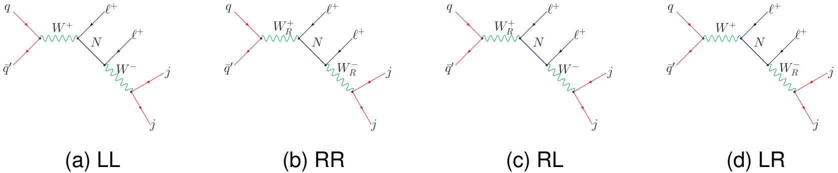


[CMS Collaboration, PRL **109**, 261802 (2012)]

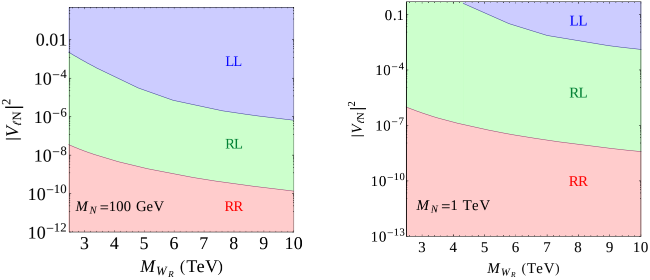


[ATLAS Collaboration, EPJC **72**, 2056 (2012)]

New Diagram including Mixing Effects



- RL diagram could dominate over LL and RR diagrams over a large range of L-R seesaw model parameter space.
- The L-R phase diagram for collider studies: [Chen, PSBD, Mohapatra, PRD **88**, 033014 (2013)]



A Unique Probe of M_D

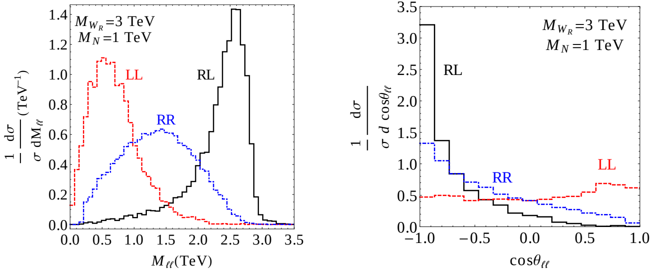
- The new RL mode is a unique probe of M_D in L-R seesaw at the LHC.
- Could have huge phenomenological impact in low-energy searches of L-R seesaw: $0\nu\beta\beta$, LFV, electron EDM, neutrino transition moment, etc. [Nemevsek, Senjanović, Tello, PRL **110**, 151802 (2013)]
- Immediate implication at high-energy: given an experimental limit on the $\ell^\pm\ell^\pm jj$ cross section ($\sigma_{\rm expt}$),
    - (M_N, M_{W_R}) plane with $\sigma_{\rm RL} \geq \sigma_{\rm expt}$ is ruled out. Complementary to that obtained from RR mode.
    - For $\sigma < \tilde{\sigma}_{\rm LL} < \sigma_{\rm expt}$ (where $\tilde{\sigma}_{\rm LL}$ is $\sigma_{\rm LL}$ normalized to $|V_{\ell N}|^2 = 1$), we can derive an improved limit on

$$|V_{\ell N}|^2 < \frac{\sigma_{\rm expt} - \sigma_{\rm RL}}{\tilde{\sigma}_{\rm LL}}$$

    - For LHC7, limits improve by about 10% at $M_N = 300$ GeV.
    - Better improvement for higher M_N and/or higher $\sqrt{s}$. Could be as high as 60%.
    - Should be included in future LHC analyses to probe a bigger range of L-R seesaw parameter space.

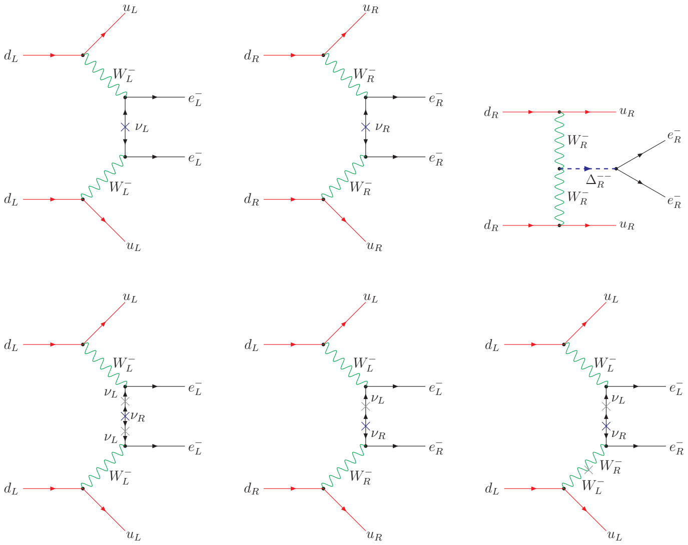
Distinguishing RR from RL and LL

- Different helicity correlations lead to distinguishing features in the kinematic and angular distributions. [Han, Lewis, Ruiz, Si, PRD **87**, 035011 (2013)]
- Can be used to pin down the dominant mode in L-R seesaw, if a signal is observed.



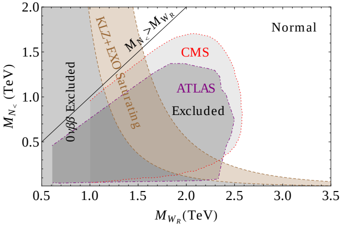
[Chen, PSBD, Mohapatra, PRD **88**, 033014 (2013)]

Neutrinoless Double Beta Decay in L-R Seesaw

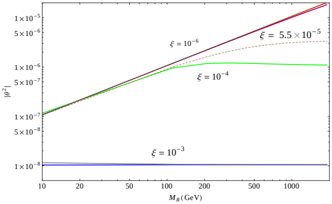


Exclusion Limits from $0\nu\beta\beta$

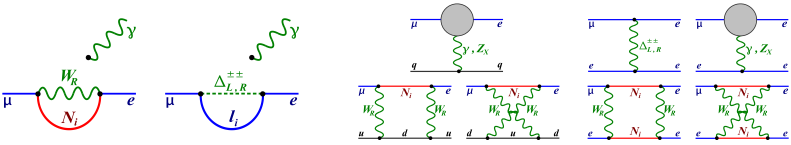
- Assuming dominance of purely RH-currents, can obtain exclusion regions complementary to those from the LHC. [Das, Deppisch, Kittel, Valle '12; PSBD, Goswami, Mitra, Rodejohann '13]

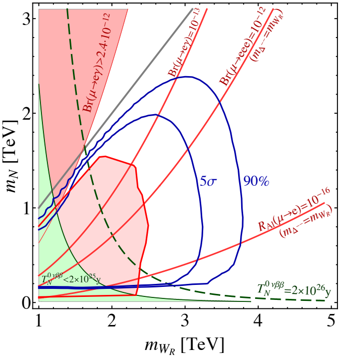


- For $M_{W_R} \lesssim 10$ TeV, the η-diagram could provide the most stringent constraint on the electron-neutrino mixing parameter $|V_{eN}|^2$. [PSBD, Goswami, Mitra (work in progress)]



Charged Lepton Flavor Violation





[Das, Deppisch, Kittel, Valle, PRD **86**, 055006 (2012)]

Large Heavy-Light Mixing with TeV-scale M_N

- In the 'vanilla' seesaw, for $M_N \gtrsim$ TeV, we expect $\xi \sim M_D M_N^{-1} \simeq (M_\nu M_N^{-1})^{1/2} \lesssim 10^{-6}$.
- Suppresses all mixing effects to an unobservable level.
- Need special textures of M_D and M_N to have 'large' mixing effects even with TeV-scale M_N.
  [Pilaftsis '92; Kersten, Smirnov '07; Ibarra, Molinaro, Petcov '10; Mitra, Senjanović, Vissani '11; ...]
- One example: [Kersten, Smirnov '07]

$$M_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \text{ and } M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix} \quad \text{with } \epsilon_i, \delta_i \ll m_i.$$

- In the limit $\epsilon_i, \delta_i \to 0$, the neutrino masses given by $M_\nu \simeq -M_D M_N^{-1} M_D^T$ vanish, although the heavy-light mixing parameters given by $\xi_{ij} \sim m_i / M_j$ can be large.

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- Can we have an L-R embedding of these textures?
- Nontrivial to find a phenomenologically viable scenario since M_D is related to M_ℓ in L-R model.
- Also need to reproduce the observed neutrino masses and mixing.
- And all other experimental constraints.

TeV-scale L-R Seesaw with Enhanced $V_{\ell N}$

- Supplement the L-R gauge group with a global discrete symmetry $D = Z_4 \times Z_4 \times Z_4$. [PSBD, Lee, Mohapatra, arXiv:1309.0774]
- The Yukawa Lagrangian invariant under this symmetry:

$$\mathcal{L}_{\ell,Y} = h_{\alpha 1}\bar{L}_\alpha \tilde{\phi}_1 R_1 + h_{\alpha 2}\bar{L}_\alpha \phi_2 R_2 + h_{\alpha 3}\bar{L}_\alpha \phi_3 R_3 + f_{12} R_1 R_2 \Delta_{R,1} + f_{33} R_3 R_3 \Delta_{R,2} + \mathrm{h.c.}$$

Field	$Z_4 \times Z_4 \times Z_4$ Transformation
L_α	$(1,\ 1,\ 1)$
R_1	$(-\mathrm{i},\ 1,\ 1)$
R_2	$(1,\ -\mathrm{i},\ 1)$
R_3	$(1,\ 1,\ -\mathrm{i})$
ϕ_1	$(-\mathrm{i},\ 1,\ 1)$
ϕ_2	$(1,\ \mathrm{i},\ 1)$
ϕ_3	$(1,\ 1,\ \mathrm{i})$
$\Delta_{R,1}$	$(\mathrm{i},\ \mathrm{i},\ 1)$
$\Delta_{R,2}$	$(1,\ 1,\ -1)$

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$\Delta_{R,1}$	$(\mathrm{i},\ \mathrm{i},\ 1)$
$\Delta_{R,2}$	$(1,\ 1,\ -1)$

- In the discrete symmetry limit, $\langle \phi_a \rangle = \begin{pmatrix} 0 & 0 \\ 0 & \kappa_a \end{pmatrix}$ (with $a = 1, 2, 3$).

$$M_\ell = \begin{pmatrix} 0 & h_{12}\kappa_2 & h_{13}\kappa_3 \\ 0 & h_{22}\kappa_2 & h_{23}\kappa_3 \\ 0 & h_{32}\kappa_2 & h_{33}\kappa_3 \end{pmatrix}, \quad M_D = \begin{pmatrix} h_{11}\kappa_1 & 0 & 0 \\ h_{21}\kappa_1 & 0 & 0 \\ h_{31}\kappa_1 & 0 & 0 \end{pmatrix}, \quad M_N = \begin{pmatrix} 0 & f_{12}v_{R1} & 0 \\ f_{12}v_{R1} & 0 & 0 \\ 0 & 0 & 2f_{33}v_{R2} \end{pmatrix}.$$

- In this limit, $m_e = 0$ and $m_{\nu,i} = 0$.

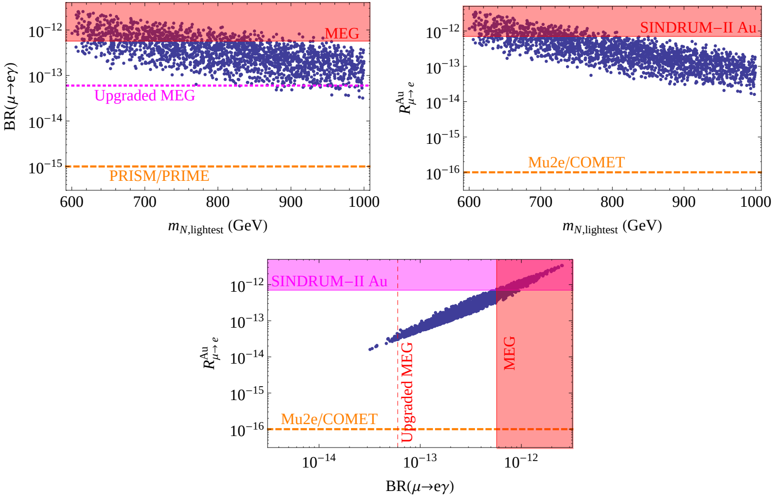
A Predictive and Testable Model

- Discrete symmetry broken by $\langle\phi_a\rangle = \begin{pmatrix} \delta\kappa_a & 0 \\ 0 & \kappa_a \end{pmatrix}$, where $\delta\kappa_a \ll \kappa_a$.
- Can be generated naturally through loop-effects.
- $\delta\kappa$'s responsible for nonzero electron mass as well as neutrino masses:

$$M_\ell = \begin{pmatrix} h_{11}\delta\kappa_1 & h_{12}\kappa_2 & h_{13}\kappa_3 \\ h_{21}\delta\kappa_1 & h_{22}\kappa_2 & h_{23}\kappa_3 \\ h_{31}\delta\kappa_1 & h_{32}\kappa_2 & h_{33}\kappa_3 \end{pmatrix}, \quad M_D = \begin{pmatrix} h_{11}\kappa_1 & h_{12}\delta\kappa_2 & h_{13}\delta\kappa_3 \\ h_{21}\kappa_1 & h_{22}\delta\kappa_2 & h_{23}\delta\kappa_3 \\ h_{31}\kappa_1 & h_{32}\delta\kappa_2 & h_{33}\delta\kappa_3 \end{pmatrix}.$$

- Can be written in an upper-triangular form: only 11 free parameters.
- Has to fit 3 charged lepton and 3 neutrino masses, 3 neutrino mixing angles, constraints on mixing $V_{\ell_i N_j}$ (unitarity, LFV, etc), and on $V^{\ell}_{R_{12}}$ (from $\mu \to 3e$).
- Hence predictive and testable!!

LFV Predictions

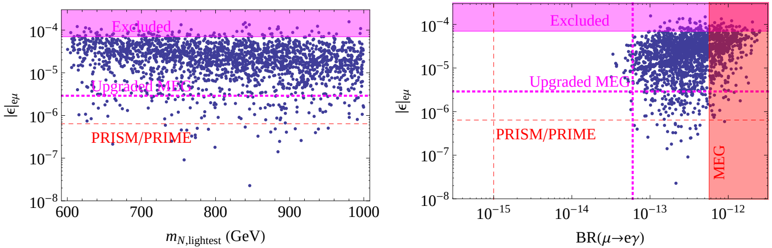


[PSBD, Lee, Mohapatra, arXiv:1309.0774]

Leptonic Non-unitarity Effects

- For large $V_{\ell N}$, the light neutrino mixing matrix could have large deviations from unitarity.
- Can be parametrized by $\epsilon = U_L^\dagger U_L$.
- Off-diagonal entries of ϵ are measures of the non-unitarity.
- Current limits (from a global fit of neutrino oscillation data, electroweak decays, universality tests, and rare charged lepton decays): [Antusch, Biggio, Fernandez-Martinez, Gavela, Lopez-Pavon, JHEP **0610**, 084 (2006); Abada, Biggio, Bonnet, Gavela, Hambye, JHEP **0712**, 061 (2007)]

$$|\epsilon|_{\rm exp} \approx \begin{pmatrix} 0.994 \pm 0.005 & < 7.0 \times 10^{-5} & < 1.6 \times 10^{-2} \\ < 7.0 \times 10^{-5} & 0.995 \pm 0.005 & < 1.0 \times 10^{-2} \\ < 1.6 \times 10^{-2} & < 1.0 \times 10^{-2} & 0.995 \pm 0.005 \end{pmatrix}.$$



[PSBD, Lee, Mohapatra, arXiv:1309.0774]

$0\nu\beta\beta$ Predictions

Parameter	Value	Current Limit [Barry, Rodejohann, arXiv:1303.6324]
$\lvert\eta_\nu^L\rvert$	8.1×10^{-11}	$\lesssim 7.1 \times 10^{-7}$
$\lvert\eta_{\nu_R}^R\rvert$	4.4×10^{-12}	$\lesssim 7.0 \times 10^{-9}$
$\lvert\eta_{\nu_R}^L\rvert$	1.2×10^{-19}	$\lesssim 7.0 \times 10^{-9}$
$\lvert\eta_{\Delta_R}\rvert$	2.1×10^{-10}	$\lesssim 7.0 \times 10^{-9}$
$\lvert\eta_\lambda\rvert$	1.5×10^{-8}	$\lesssim 5.7 \times 10^{-7}$
$\lvert\eta_\eta\rvert$	1.5×10^{-9}	$\lesssim 3.0 \times 10^{-9}$

$$\frac{1}{T_{1/2}^{0\nu}} = G_{01}^{0\nu}\Big[|\mathcal{M}_\nu^{0\nu}|^2|\eta_\nu^L|^2 + |\mathcal{M}_{\nu_R}^{0\nu}|^2(|\eta_{\nu_R}^L|^2 + |\eta_{\nu_R}^R + \eta_{\Delta_R}|^2) + |\mathcal{M}_\lambda^{0\nu}|^2|\eta_\lambda|^2 + |\mathcal{M}_\eta^{0\nu}|^2|\eta_\eta|^2$$
$$+ \text{interference terms}\Big]$$

Nucleus	Model Prediction for $T_{1/2}^{0\nu}$ (yr)	Current Limit (yr)	Future Limit (yr)
^{76}Ge	6.2×10^{25} - 6.2×10^{27}	$> 2.1\ (3.0) \times 10^{25}$ (GERDA-I)	6×10^{27} (GERDA-II, MAJORANA)
^{136}Xe	2.3×10^{25} - 4.3×10^{26}	$> 1.9\ (3.1) \times 10^{25}$ (KamLand-Zen)	8×10^{26} (EXO-1000)

Conclusion

- A simple paradigm for neutrino masses: Type-I Seesaw.
- Two key aspects: Majorana neutrino mass and Heavy-light neutrino mixing.
- Large mixing effects can be tested at the Intensity Frontier.
- Both aspects can be tested *directly* at the Energy Frontier.
- New heavy neutrino production mechanism gives improved LHC sensitivity.

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- Rich phenomenological implications for both LNV and LFV.
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THANK YOU.

Selection Efficiency

- To compare with the old limits, we use the same selection criteria as used by ATLAS for $pp \to \mu^\pm\mu^\pm jj$:

$$p_T^j > 20\ \mathrm{GeV},\ p_T^\mu > 20\ \mathrm{GeV},\ p_T^{\mu,\mathrm{leading}} > 25\ \mathrm{GeV},$$
$$|\eta^j| < 2.8,\ |\eta^\mu| < 2.5,\ \Delta R^{jj} > 0.4,\ \Delta R^{\mu j} > 0.4,$$
$$m_{\mu\mu} > 15\ \mathrm{GeV},\ E_T^{\mathrm{miss}} < 35\ \mathrm{GeV},\ m_{jj} \in [55, 120]\ \mathrm{GeV}.$$

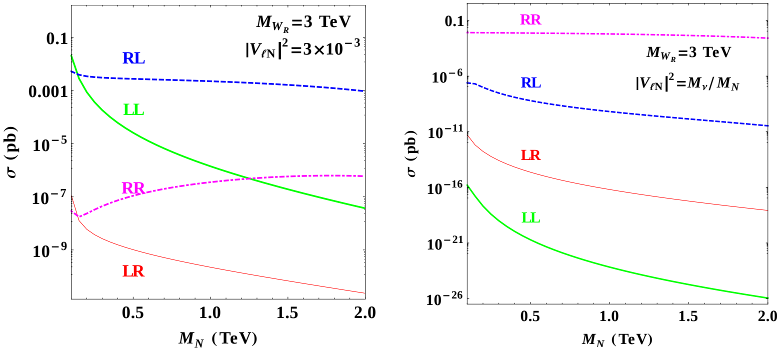
- Total selection efficiency for the $\mu^\pm\mu^\pm$ signal remains almost the same as before.

Signal m_N [GeV]	100	120	140	160	180	200	240	280	300
Selection Efficiency [%]	3.9	13.0	18.1	21.3	23.9	25.7	28.7	30.8	31.7

- SM background for di-muon+n jets (with $n \geq 2$):

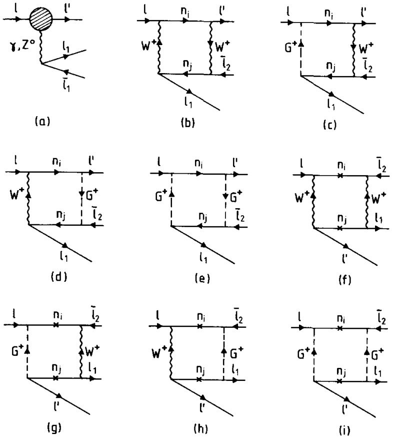
Source	$\mu^\pm\mu^\pm$
WZ	$1.0 \pm 0.2 \pm 0.3$
ZZ	$0.22 \pm 0.05\,^{+0.07}_{-0.06}$
$W^\pm W^\pm$	$0.15 \pm 0.04 \pm 0.08$
$t\bar{t} + V$	$0.23 \pm 0.04 \pm 0.12$
Charge mis-measurement	< 0.03
Non−prompt	$1.1 \pm 0.5\,^{+0.6}_{-0.5}$
Total background	$2.7 \pm 0.5\,^{+0.7}_{-0.6}$
Data	3

Comparison between LL, RL and RR Cross Sections



[Chen, PSBD, Mohapatra, PRD **88**, 033014 (2013)]

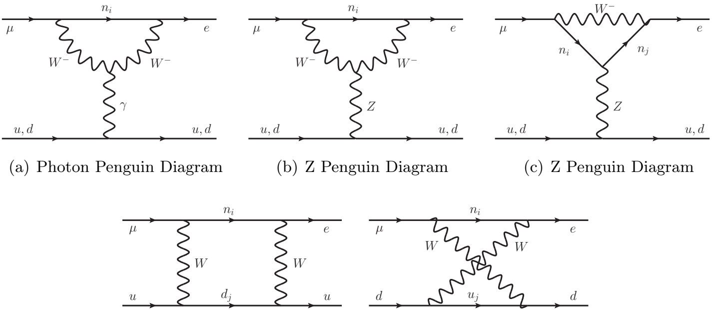
$\ell_i \to \bar{\ell}_j \ell_k \ell_m$



+ $(l_1 \leftrightarrow l')$

[Ilakovac, Pilaftsis, NPB **437**, 491 (1995)]

$\mu - e$ Conversion



(a) Photon Penguin Diagram

(b) Z Penguin Diagram

(c) Z Penguin Diagram

(d) Box Diagram

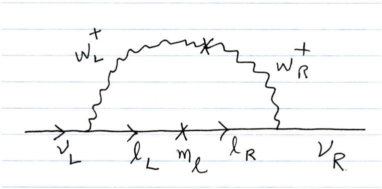
(e) Box Diagram

[Alonso, Dhen, Gavela, Hambye, JHEP **1301**, 118 (2013)]

Why $Z_4 \times Z_4 \times Z_4$?

- Choice of the product of Z_4 groups reduces possible multiple $U(1)$ symmetries of the model associated with different bi-doublets.
- Other Z_n's restrict the terms in the Higgs potential so much that the discrete group will get promoted to a continuous $U(1)$ group, whose spontaneous breaking by non-zero vevs of ϕ_a will lead to a massless Goldstone boson.
- With the Z_4 group, terms like $\lambda_a \mathrm{Tr}[(\phi_a^\dagger \tilde{\phi}_a)^2]$ break the $U(1)$ symmetry while keeping the Z_4 subgroup of it in tact (for $\lambda_a \neq 0$).
- Gives mass of order $\lambda_a \kappa_a^2$ (sub-TeV scale) to the leptophilic Higgses.
- Could also add soft D-breaking terms like $\mathrm{Tr}(\phi_a^\dagger \phi_b)$ without destabilizing the vacuum.

Generating $\delta\kappa$ through Loops



$$(\delta m_D)_{\alpha i} \simeq \frac{g^2 h_{\alpha i} \kappa}{16\pi^2} \frac{g^2 \kappa_q \kappa'_q}{M_{W_R}^2} \simeq 10^{-6} h_{\alpha i} \kappa$$

A Sample Fit

$$M_\ell = \begin{pmatrix} 0.00153973 & -0.0511895 & -1.61367 \\ 0 & 0.0961545 & -0.366453 \\ 0 & 0 & -0.647105 \end{pmatrix} \text{GeV},$$

$$M_D = \begin{pmatrix} 14.0638 & -7.5\times10^{-10} & -1.8\times10^{-4} \\ 0 & 1.4\times10^{-9} & -4.1\times10^{-5} \\ 0 & 0 & -7.2\times10^{-5} \end{pmatrix} \text{GeV},$$

$$M_N = \begin{pmatrix} 0 & 814.118 & 0 \\ 814.118 & 0 & 0 \\ 0 & 0 & -2549.95 \end{pmatrix} \text{GeV}.$$

$$V_{\ell N} = \begin{pmatrix} -0.004 & 0.004 & 7.7\times10^{-13} \\ 0.003 & -0.003 & 6.9\times10^{-11} \\ 0.011 & -0.011 & -7.7\times10^{-8} \end{pmatrix}.$$

Output Parameter	Value
m_e	0.511 MeV
m_μ	105.61 MeV
m_τ	1.777 GeV
Δm^2_{21}	7.62×10^{-5} eV^2
Δm^2_{31}	2.41×10^{-3} eV^2
θ_{12}	33.8°
θ_{23}	39.1°
θ_{13}	8.6°
m_{N_1}	814.24 GeV
m_{N_2}	−814.24 GeV
m_{N_3}	2550 GeV