TeV-scale Left-Right Seesaw

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(mostly) based on

PSBD, C. -H. Lee and R. N. Mohapatra, arXiv:1309.0774 [hep-ph];
C. -Y. Chen, PSBD and R. N. Mohapatra, Phys. Rev. D **88**, 033014 (2013) [arXiv:1306.2342].

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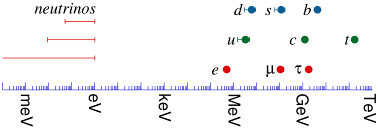
Outline

- Introduction: Type-I seesaw and its two aspects
- SM seesaw vs Left-Right seesaw
- TeV-scale L-R seesaw with large heavy-light neutrino mixing
- Experimental Signatures in LNV and LFV processes
- Conclusion

Neutrino Oscillation ⇒ Physics beyond the SM

- Oscillation between all three flavors ⇒ at least two non-zero neutrino masses.
- First (and so far only) conclusive *experimental* evidence for BSM Physics.
- 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 $\mathcal{L}_{\nu,Y} = y_{\nu,ij} \bar{L}_i \Phi N_j + \mathrm{h.c.}$ with no experimentally observable effects.
- Large hierarchy between neutrino and charged fermion masses might be suggesting some new distinct mechanism for neutrino masses.



(Type-I) Seesaw Mechanism

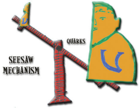
- A natural way to generate neutrino mass is by breaking $(B-L)$.
- Within the SM, can be parametrized through Weinberg's dimension-5 operator $\lambda_{ij}(L_i^{\mathsf{T}}\Phi)(L_j^{\mathsf{T}}\Phi)/\Lambda$.
- A simple tree-level realization: Type-I seesaw mechanism – RH neutrinos have a Majorana mass term $M_N N^{\mathsf{T}} C^{-1} N$, in addition to the Dirac mass term $M_D = v y_\nu$.
- In the flavor basis $\{\nu_L^C, N\}$, leads to the general structure

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

- In the seesaw approximation $||\xi|| \ll 1$, where $\xi \equiv M_D M_N^{-1}$ and $||\xi|| \equiv \sqrt{\mathrm{Tr}(\xi^\dagger \xi)}$,

$M_\nu^{\rm light} \simeq -M_D M_N^{-1} M_D^{\mathsf{T}}$ is the light neutrino mass matrix.

$\xi \equiv M_D M_N^{-1}$ is the heavy-light neutrino mixing.



[Minkowski '77; Yanagida '79; Gell-Mann, Ramond, Slansky '80; Mohapatra, Senjanović '80]

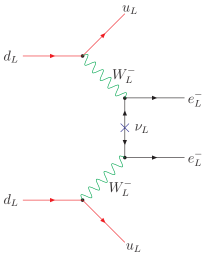
From a bottom-up approach, we call this minimal scenario the 'SM seesaw'.

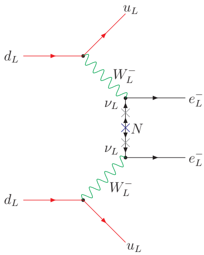
Two Key Aspects of Seesaw

Majorana Mass

$\Downarrow$

Neutrinoless Double Beta Decay



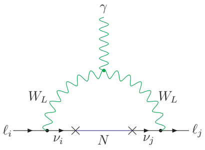


Does not necessarily probe the heavy-light mixing since the mixed diagram may not give the dominant contribution.

Heavy-light Mixing

$\Downarrow$

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

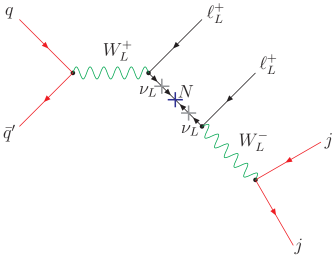


- Also deviations from the unitarity of the PMNS neutrino mixing matrix.
- Do not necessarily prove the Majorana nature since a Dirac neutrino can also give large LFV and non-unitarity effects.

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: $pp \to W^* \to \ell_\alpha^\pm N \to \ell_\alpha^\pm \ell_\beta^\pm jj$ 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 $\alpha \neq \beta$).

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 $M_\nu \simeq -M_D M_N^{-1} M_D^{\sf T}$ vanish, although the heavy-light mixing parameters given by $\xi_{ij} \sim m_i / M_j$ can be large.

- Two main points of this talk:
  1. Are there realistic models at TeV-scale with large heavy-light mixing while satisfying the tiny neutrino masses in a natural way protected by some underlying symmetry?
  2. If so, what are the tell-tale experimental signatures of such a scenario?

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: $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \equiv Q_R, \quad \psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} N \\ e_R \end{pmatrix} \equiv \psi_R.$
  - Scalars: $\Delta_R \equiv \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix}, \quad \phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}.$

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- We consider a version of the model where P and $SU(2)_R$ breaking scales are decoupled; so no Δ_L fields at low-energy. [Chang, Mohapatra, Parida, PRL **52**, 1072 (1984)]
- $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$ 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 $\langle \phi \rangle = {\rm diag}(\kappa', \kappa)$.
- Fermion masses can be derived from the Yukawa Lagrangian

$$\begin{aligned} \mathcal{L}_Y &= h_{ij}^{q,a} \bar{Q}_{L,i} \phi_a Q_{R,j} + \tilde{h}_{ij}^{q,a} \bar{Q}_{L,i} \tilde{\phi}_a Q_{R,j} + h_{ij}^{\ell,a} \bar{L}_i \phi_a R_j \\ & \quad + \tilde{h}_{ij}^{\ell,a} \bar{L}_i \tilde{\phi}_a R_j + f_{ij} (R_i R_j \Delta_R + L_i L_j \Delta_L) + {\rm h.c.} \\ \Longrightarrow & \quad M_\ell = h^\ell \kappa + \tilde{h}^\ell \kappa', \ M_D = h^\ell \kappa' + \tilde{h}^\ell \kappa \ \text{ and } M_N = f v_R \end{aligned}$$

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

- Basic strategy:
  - Appropriate textures for M_D and M_N which via type-I seesaw lead to 'large' heavy-light mixing ($V_{\ell N}$).
  - L-R embedding using a suitable family symmetry.
  - 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.

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- Our model: [PSBD, Lee, Mohapatra, arXiv:1309.0774]
  - Supplement the L-R gauge group with a global discrete symmetry $D = Z_4 \times Z_4 \times Z_4$.
  - For the scalar sector, use three leptophilic bi-doublets $\phi_{1,2,3}$ with $B - L = 0$ and two RH triplets ($\Delta_{R1,R2}$) with $B - L = 2$.

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

New L-R Model with Enhanced $V_{\ell N}$

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

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

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

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

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

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

- Minimal version with 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!!

A Sample Fit

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

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

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

$$V_{\ell N} = \begin{pmatrix} -0.004 & 0.004 & 7.7 \times 10^{-13} \\ 0.003 & -0.003 & 6.9 \times 10^{-11} \\ 0.011 & -0.011 & -7.7 \times 10^{-8} \end{pmatrix}.$$

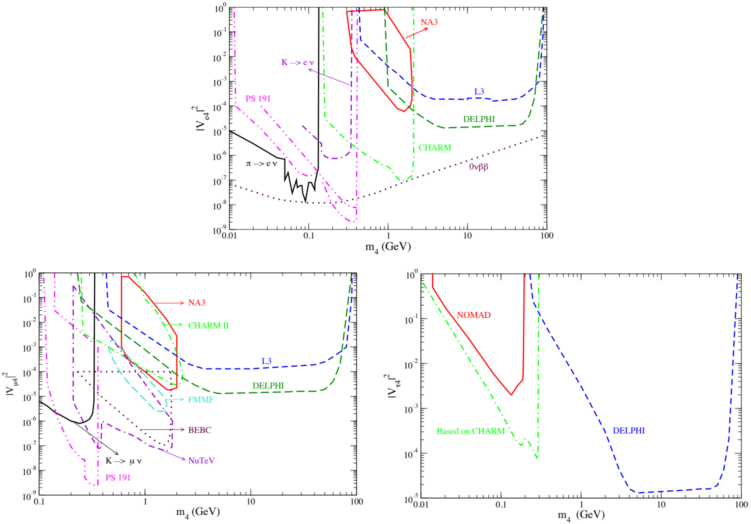
Output Parameter	Value
m_e	0.511 MeV
m_μ	105.61 MeV
m_τ	1.777 GeV
Δm^2_{21}	7.62×10^{-5} eV^2
Δm^2_{31}	2.41×10^{-3} eV^2
θ_{12}	33.8°
θ_{23}	39.1°
θ_{13}	8.6°
m_{N_1}	814.24 GeV
m_{N_2}	−814.24 GeV
m_{N_3}	2550 GeV

Using a χ^2-analysis, we found $\sim$ 2000 solutions within 3σ of experimental lepton mass and mixing parameter values.

Experimental Signatures

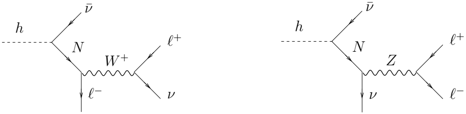
- Lepton Number Violating:
  - Collider signal ($pp \to \ell^{\pm}\ell^{\pm}jj$):
    - Important distinctions between SM seesaw and L-R seesaw.
    - For the textures considered, *no* collider signal in the SM seesaw case.
    - Observable signal in the L-R case, but only in the LFV channel with $e\mu$ final state.
  - Neutrinoless double beta decay (^{76}Ge and ^{136}Xe).
- Lepton Flavor Violating:
  - $\mu \to e\gamma$,
  - $\mu \to 3e$,
  - $\mu - e$ conversion in various nuclei (^{48}Ti, ^{197}Au, and ^{208}Pb).
- Leptonic non-unitarity effects.

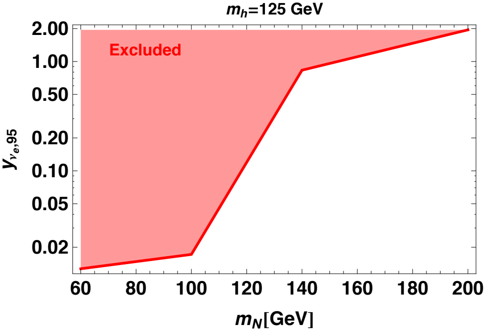
Pre-LHC Constraints on Mixing



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

Constraints from LHC Higgs Data

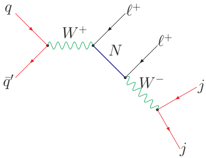




[PSBD, Franceschini, Mohapatra, PRD **86**, 093010 (2012)]

Direct Search Limits from LHC7

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



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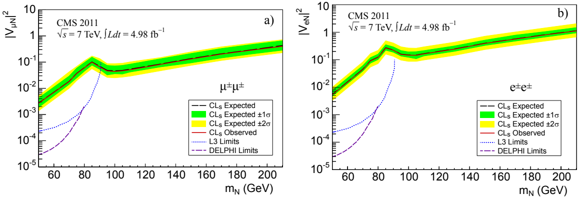
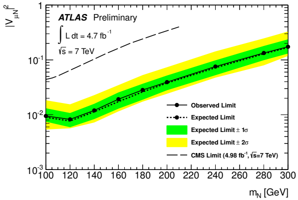




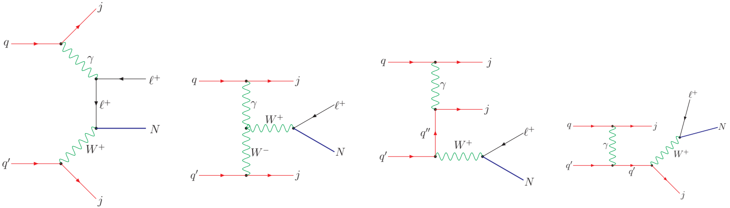
[CMS Collaboration, PLB **717**, 109 (2012)]

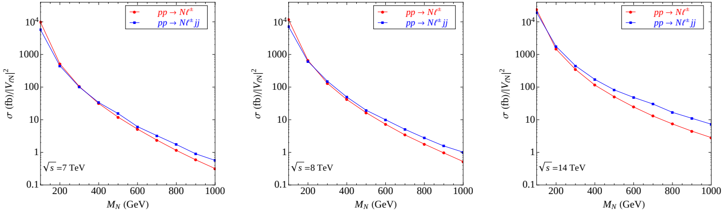
[ATLAS-CONF-2012-139]

- 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; del Aguila, Aguilar-Saavedra '08;...]

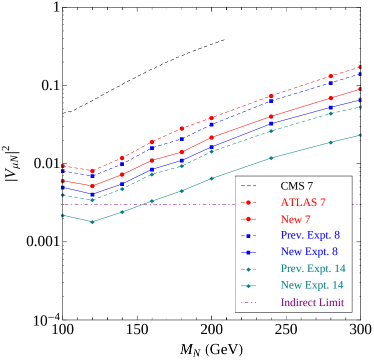
A New *Dominant* Production Channel

- There exist many other production modes, but most of these are negligible. [Datta, Guchait, Pilaftsis, PRD **50**, 3195 (1994)]
- However, *diffractive* processes, e.g., $pp \to W^*\gamma^* jj \to \ell^\pm Njj$ are *not* negligible, but infrared enhanced. [PSBD, Pilaftsis, Yang, arXiv:1308.2209]





Improved Upper Limit on Mixing

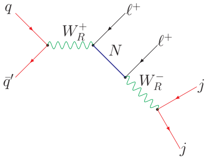


PSBD, Pilaftsis, Yang, arXiv:1308.2209

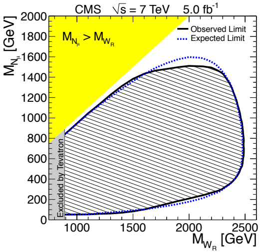
- Indirect limit was taken from the old global fit to electroweak precision data. [del Aguila, de Blas, Perez-Victoria, PRD **78**, 013010 (2008)]
- New global fit including Higgs data: $|V_{\mu N}|^2 < 9 \times 10^{-4}$. [de Blas, arXiv:1307.6173]
- However, our limits are rather conservative since we used the 95% CL upper limits on $\sigma(pp \to \mu^\pm\mu^\pm jj)$ using $\int Ldt = 4.7\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV.
- In practice, the new collider limits could be much stronger since experimental limits on σ should improve significantly with more data (if no signal is observed!).

L-R Seesaw at LHC

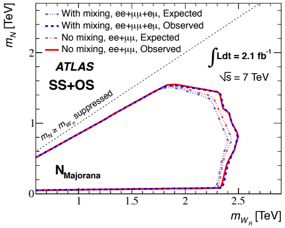
- New contribution via W_R exchange. [Keung, Senjanović, PRL **50**, 1427 (1983)]



- Independent of $V_{\ell N}$. 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).

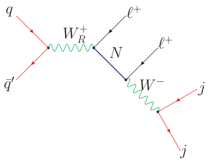


[CMS Collaboration, PRL **109**, 261802 (2012)]

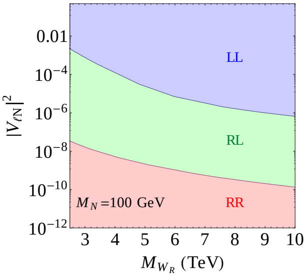


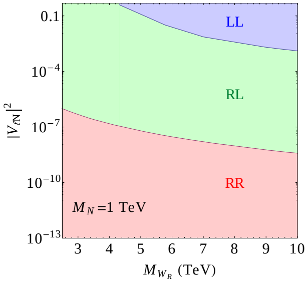
[ATLAS Collaboration, EPJC **72**, 2056 (2012)]

New Diagram for Large $V_{\ell N}$



- 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

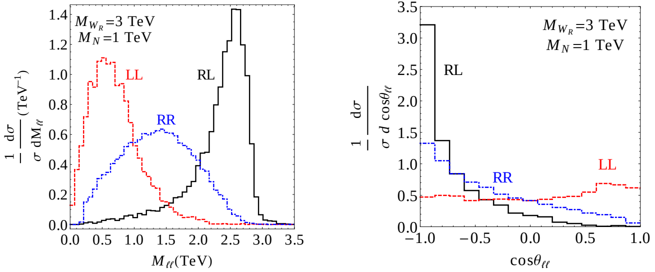
- The new RL mode is a unique probe of M_D in L-R seesaw at the LHC.
- Could have huge phenomenological impact in low-energy searches of L-R seesaw: $0\nu\beta\beta$, LFV, electron EDM, neutrino transition moment, etc. [Nemevsek, Senjanović, Tello, PRL **110**, 151802 (2013)]
- Immediate implication 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.

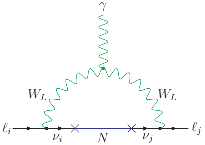
Distinguishing RR from RL and LL

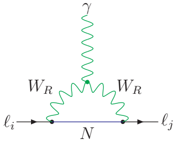
- Different helicity correlations lead to distinguishing features in the kinematic and angular distributions. [Han, Lewis, Ruiz, Si, PRD **87**, 035011 (2013)]
- Can be used to pin down the dominant mode in L-R seesaw, if a signal is observed.

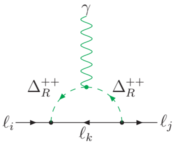


[Chen, PSBD, Mohapatra, PRD **88**, 033014 (2013)]

Charged Lepton Flavor Violation: $\mu^- \to e^- \gamma$







$$\mathrm{BR} = \frac{\alpha_W^3 s_W^2}{256\pi^2} \frac{m_\mu^4}{M_{W_L}^4} \frac{m_\mu}{\Gamma_\mu} |G_\gamma^{\mu e}|^2$$

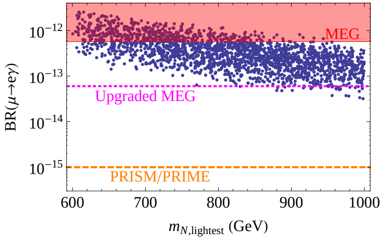
[Marciano, Sanda '77; Cheng, Li '80; Langacker, London '88; Ilakovac, Pilaftsis '94]

$$\frac{3\alpha_W}{32\pi} \left(\frac{M_{W_L}}{M_{W_R}}\right)^8 \left(s_R c_R \frac{m_{N_2}^2 - m_{N_1}^2}{M_{W_L}^2}\right)^2$$

[Riazuddin, Marshak, Mohapatra '81; Cirigliano, Kurylov, Ramsey-Musolf, Vogel '04]

$$\frac{2\alpha_W M_{W_L}^4}{3\pi g^4} \left[\frac{(ff^\dagger)_{12}}{M_{\Delta_R^{++}}^2}\right]^2$$

[Mohapatra '92; Tello, Nemevsek, Nesti, Senjanović, Vissani '10]

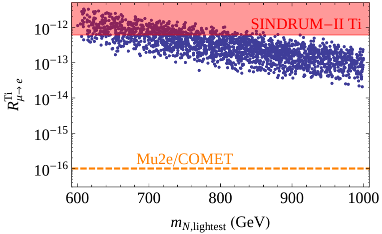


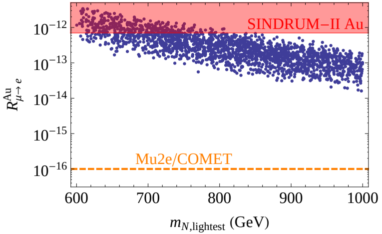
[PSBD, Lee, Mohapatra, arXiv:1309.0774]

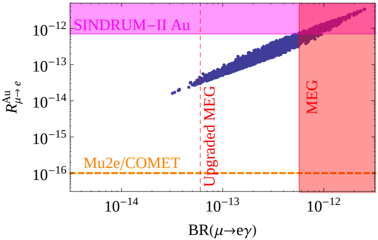
$\mu \to e$ Conversion

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

$$R_{\mu\to e} = \frac{2G_F^2\alpha_W^2 m_\mu^5}{16\pi^2\Gamma_{\rm capt}}\left|4V^{(p)}(2\tilde{F}_u^{\mu e}+\tilde{F}_d^{\mu e})+4V^{(n)}(\tilde{F}_u^{\mu e}+2\tilde{F}_d^{\mu e})+s_W^2 G_\gamma^{\mu e}\frac{D}{2e}\right|^2$$







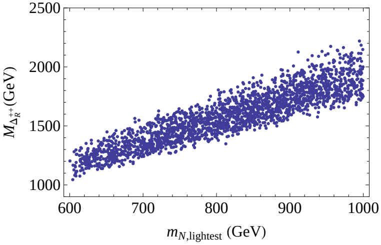
[PSBD, Lee, Mohapatra, arXiv:1309.0774]

$\mu \to 3e$

- The tree-level contribution is [Pal, NPB **227**, 237 (1983)]

$$\mathrm{BR}(\mu \to 3e) \simeq \frac{1}{2}\left(\frac{M_{W_L}}{M_{W_R}}\right)^4 \left(\frac{M_{N,12}M_{N,11}}{M^2_{\Delta_R^{++}}}\right)^2 .$$

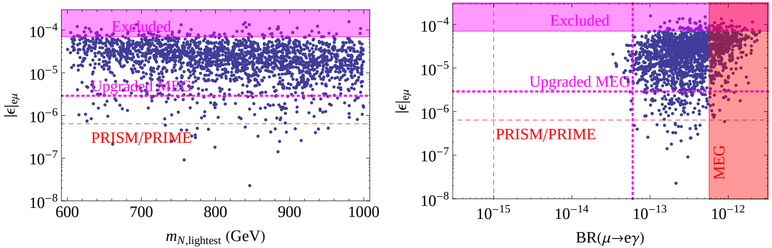
- In our model, the neutrino mass fit fixes all the parameters of the model except M_{W_R} and $M_{\Delta_R^{++}}$.
- For a given M_{W_R}, a lower limit on $M_{\Delta_R^{++}}$ to satisfy the current limit on $\mathrm{BR}(\mu \to 3e) < 1.0 \times 10^{-12}$.



Leptonic Non-unitarity Effects

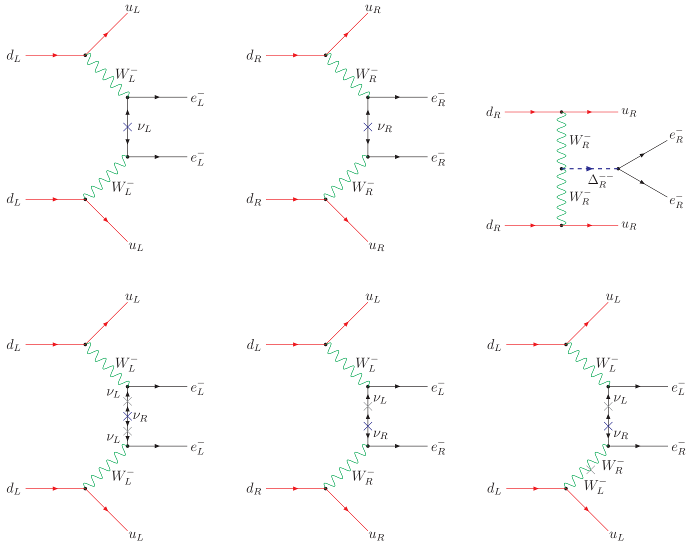
- For large $V_{\ell N}$, the light neutrino mixing matrix could have large deviations from unitarity.
- Can be parametrized by $\epsilon = U_L^\dagger U_L$.
- Off-diagonal entries of ϵ are measures of the non-unitarity.
- Current limits (from a global fit of neutrino oscillation data, electroweak decays, 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]

Neutrinoless Double Beta Decay in L-R Seesaw



$0\nu\beta\beta$ predictions in our L-R Seesaw Model

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.
- Both aspects can be tested *directly* at the Energy Frontier.
- Large mixing effects can be tested at the Intensity Frontier.
- We proposed a natural TeV-scale Left-Right seesaw model where both aspects of seesaw are in testable range.

Conclusion

- A simple paradigm for neutrino masses: Type-I Seesaw.
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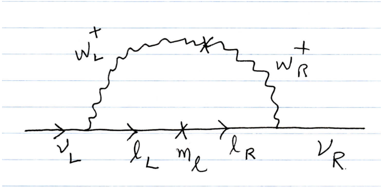
THANK YOU.

Why $Z_4 \times Z_4 \times Z_4$?

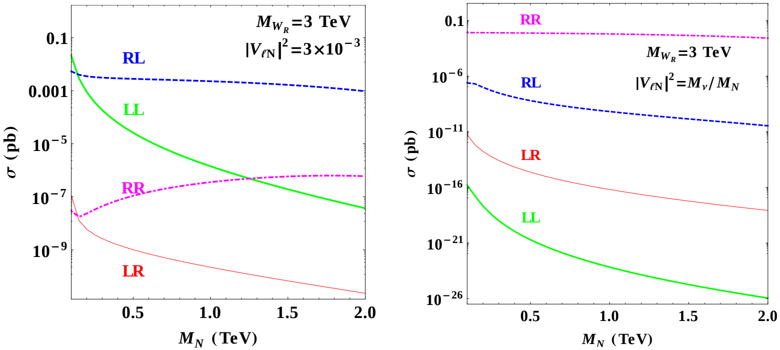
- Choice of the product of Z_4 groups reduces possible multiple $U(1)$ symmetries of the model associated with different bi-doublets.
- Other Z_n's restrict the terms in the Higgs potential so much that the discrete group will get promoted to a continuous $U(1)$ group, whose spontaneous breaking by non-zero 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



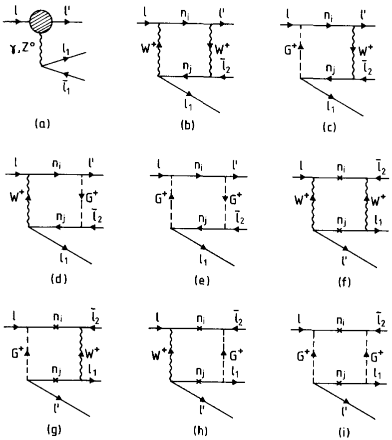
$$(\delta m_D)_{\alpha i} \simeq \frac{g^2 h_{\alpha i} \kappa}{16\pi^2} \frac{g^2 \kappa_q \kappa'_q}{M_{W_R}^2} \simeq 10^{-6} h_{\alpha i} \kappa$$

Comparison between LL, RL and RR Cross Sections



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

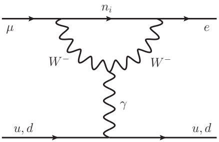
$\ell_i \to \bar{\ell}_j \ell_k \ell_m$



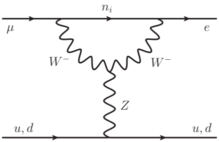
$+ \quad (l_1 \longleftrightarrow l')$

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

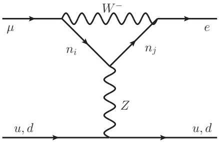
$\mu - e$ Conversion



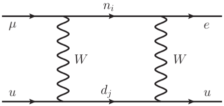
(a) Photon Penguin Diagram



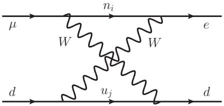
(b) Z Penguin Diagram



(c) Z Penguin Diagram



(d) Box Diagram



(e) Box Diagram

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