Neutrino Mass Models at the Intensity Frontier

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Where does neutrino mass come from ?

- For charged fermions, they come from the Higgs vev:

$$m_f = h_f v_{wk} \qquad v_{wk} = \langle h^0 \rangle$$

★ Discovery of the 125 GeV Higgs h^0 confirms this.

- For neutrinos, this formula gives too large a mass !!
- **Enter seesaw paradigm:**

(Minkowski; Gell-Mann, Ramond,Slansky;Yanagida;Glashow;Mohapatra,Senjanovic)

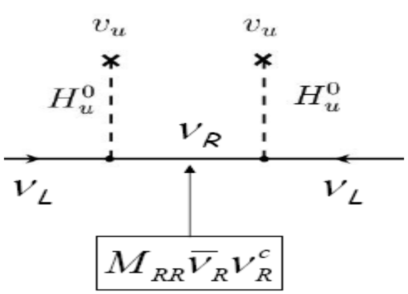
$$m_\nu = \lambda \frac{v_{wk}^2}{M}$$

- $\lambda \sim 1; M$ big $m_\nu \ll m_f$ **Physics of M ?**
- Alternative strategies: Radiative effects (Babu, Zee,....)

Unravelling Seesaw

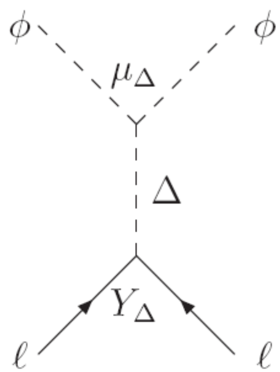
- Add New fermions **N_R** or new Higgs $\vec{\Delta}$ to SM

Type I | **Type II** | **Type III** | **Inverse**



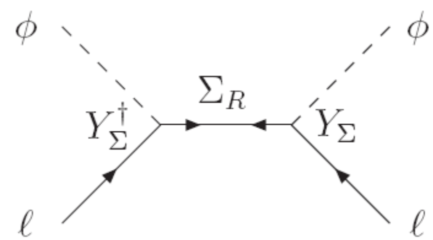
$$m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$$

Majorana N



$$m_\nu = -2Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}\,.$$

Triplet Higgs $\vec{\Delta}$



$$m_\nu = -\frac{v^2}{2} Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

Triplet N Maj.

$$\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$$

$$m_\nu \cong -m_D^T M^{-1} \mu M^{-1} m_D$$

Dirac N

Can seesaw scale be TeV ?
How do we probe it ?

- Colliders: key parameter is νN mixing $\varepsilon = \frac{h_\nu v_{wk}}{M_N}$
- Generic TeV models: h_ν small to get small mass
  hence $\varepsilon \leq 10^{-6}$; N unobservable !!
- Exceptions: sym. or Inverse seesaw: $\varepsilon \leq 0.1$

$$h_\nu = \begin{pmatrix} h_{11} & \epsilon_1 & \epsilon_2 \\ h_{21} & \epsilon_3 & \epsilon_4 \\ h_{31} & \epsilon_5 & \epsilon_2 \end{pmatrix}$$

$$M_N = \begin{pmatrix} 0 & M & 0 \\ M & 0 & 0 \\ 0 & 0 & M' \end{pmatrix}$$

Pilaftsis; Kersten, Smirnov,..

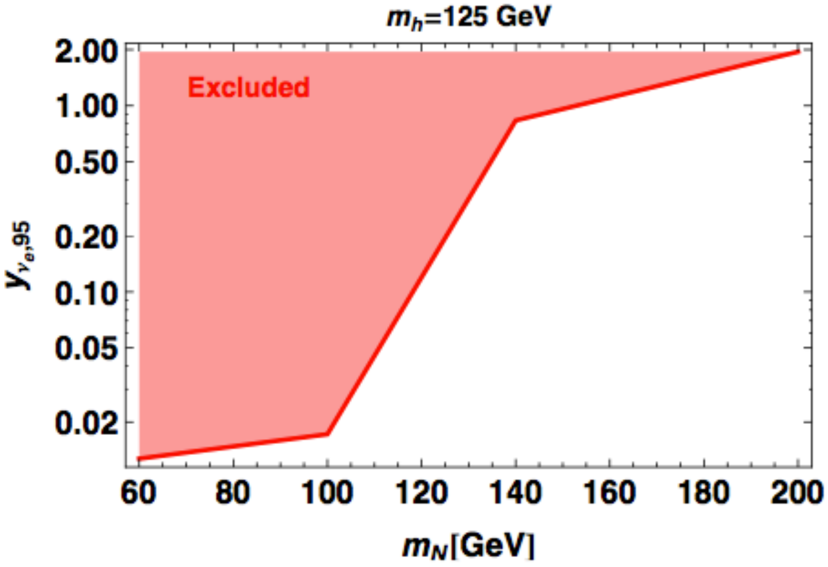
$$M_{\nu,N,S} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

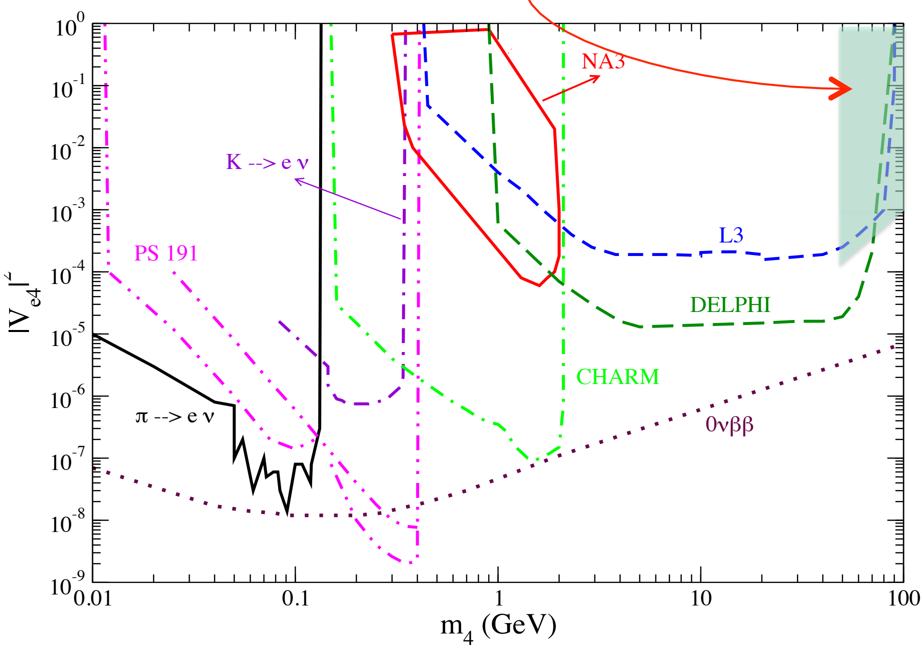
$$\mu \ll m_D, M$$

R. N. M., Valle

Higgs decay+other constraints

LHC Higgs search: final states $\rightarrow e^+e^- \not{E}_T$ (Dev, Franceschini, RNM'12)





- More collider info (Ruiz talk)

(Atre, Han, Pascoli,Zhang)

Lepton Flavor violation and minimal TeV seesaw

- Processes: (i) $\mu \to e + \gamma$ $B_{\mu \to e+\gamma} \leq 5.7 \times 10^{-13}$ MEG

  (ii) $\mu \to 3e$ $B(\mu \to 3e) \leq 10^{-12}$ Sindrum

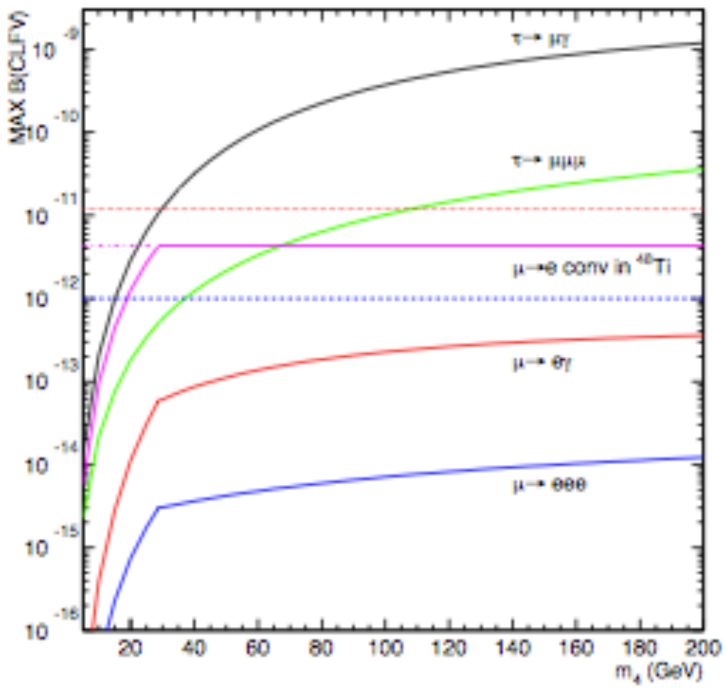
  (iii) $\mu^- \to e^-|_{Ti}$ $B(\mu^- \to e^-)|_{Ti} \leq 4.3 \times 10^{-12}$

- Generic seesaw models without SUSY and no new gauge group: effects are unobservable.

- However with symmetries to get small nu mass, they can be a useful probes of minimal sub-TeV seesaw.

Lepton Flavor Violation with special low scale seesaw

- Majorana N mediated loop graphs: (deg. RH)
- Type I with symmetries: (de Gouvea'07)



Inverse seesaw case:

$$m_N \lesssim 6000\,\mathrm{TeV}\cdot\left(\frac{10^{-18}}{R^{Ti}_{\mu\to e}}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 1000\,\mathrm{TeV}\cdot\left(\frac{10^{-16}}{R^{Al}_{\mu\to e}}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 300\,\mathrm{TeV}\cdot\left(\frac{10^{-14}}{Br(\mu\to e\gamma)}\right)^{\frac{1}{4}},$$

$$m_N \lesssim 1000\,\mathrm{TeV}\cdot\left(\frac{10^{-16}}{Br(\mu\to eee)}\right)^{\frac{1}{4}}$$

(Gavela, Alonso,Hambye,Dhen'12);

Ilakovic, Pilaftsis, Popov'12

CLFV that directly relates to neutrino Majorana mass

- $\mu \to e\gamma, \mu \to 3e, \mu^- \to e^-$ conserve L and are not true tests of Majorana nu mass.
- However $\mu^- \to e^+, \mu^- \to \mu^+$ are $\Delta L \neq 0$

$$B(\mu^- Ti \to e^+ Ca) \leq 3.6 \times 10^{-11}$$

- Flavor analog of $\beta\beta_{0\nu}$ decay
- Small in minimal type I and inverse seesaw
- Other related processes: $K^+ \to \pi^- e^+ e^+, \pi^- e^+ \mu^+$

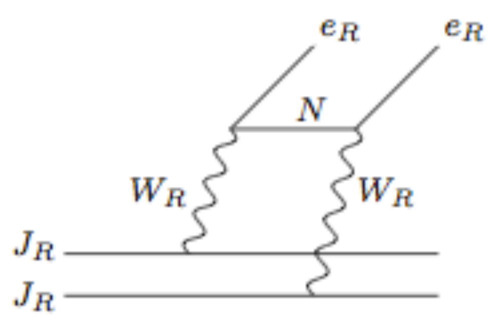
New gauge forces: a natural part of type I, ISS

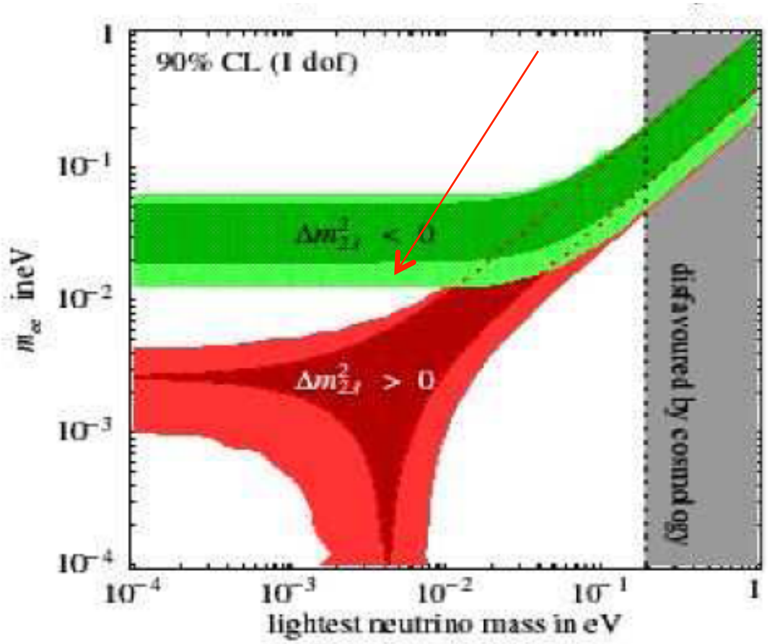
- **Type I** : why seesaw scale so far below Planck scale:
- **Inverse seesaw case**:
- **Why** $\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$ **why not** $\begin{pmatrix} 0 & hv_{wk} & h'v_{wk} \\ hv_{wk} & M' & M \\ h'v_{wk} & M & \mu \end{pmatrix}$
- **Local B-L** symmetry or **Left-Right** symmetry guarantees this !!
- New affects from W_{R}, N and new seesaw Higgs $\Delta_{L,R}$
- CMS: M_{WR}>2.9 TeV

TeV WR manifesting in $\beta\beta_{0\nu}$

- $\beta\beta_{0\nu}$ search will have deep impact on left-right seesaw

- W_R contributes to :





- Suppose long baseline → $\Delta m^2_{31} > 0$
- and nonzero signal for $\beta\beta_{0\nu}$

→could be due to few TeV WR

$$|(M_N)_{ee}| \gtrsim 10\,\text{GeV} \times \left(\frac{3.5\ \text{TeV}}{M_{W_R}}\right)^4$$

LFV in left-right seesaw

- $W_{R,}$ N contribution to CLFV for generic seesaw from in LRSM(Riazuddin, Marshak, RNM'81; Cirigliano,Kurylov,Musolf,Vogel'04)

$$B(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left(\frac{m_{W_L}^2}{m_{W_R}^2}\right)^4 \left(\sin\theta' \cos\theta' \frac{m_{N_2}^2 - m_{N_1}^2}{m_{W_L}^2}\right)^2 < 10^{-14}$$

$$M_{N_1} \ll M_{N_2} = 400\ GeV$$

- $$B(\mu^- \to e^-) = 10^{-6}\epsilon^2 \sin^2\theta' \cos^2\theta' < 10^{-12}$$

(M_2=100 GeV)

$$\epsilon = \frac{m_2^2 - m_1^2}{\sin^2\theta_W m_{W_L}^2}\left(\frac{m_{W_L}^2}{m_{W_R}^2}\right)^2 \left(\ln\frac{m_{W_R}^2}{M^2} - 2\right)$$

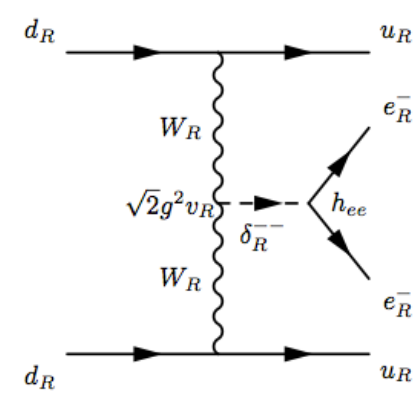
→ Can probe W_R and M_N to 10-40 TeV scale !!

New Higgs in LR seesaw and their effects

(i) Extra Higgs doublet: M_H in multi-TeV range.

(ii) Triplet Higgs: $$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}_{L,R}.$$ can be light

- Spectacular collider signature $\delta^{++} \rightarrow \ell^+ \ell^+$ CMS,ATLAS $\sim 200 GeV$
- δ^{++} in $\beta\beta_{0\nu}$ decay: (RNM, Vergados'81; piccioto, Zahir'82; lNemesvek, Nesti, Senjanovic, Tello, Vissani'12; Goswami et al;12; Awasthi,Parida,Patra'12; Barry, Rodejohann'12)



- $$\frac{M_N}{M^2_{\delta^{++}}} \leq 10^{-2}$$ GeV $^{-1}$

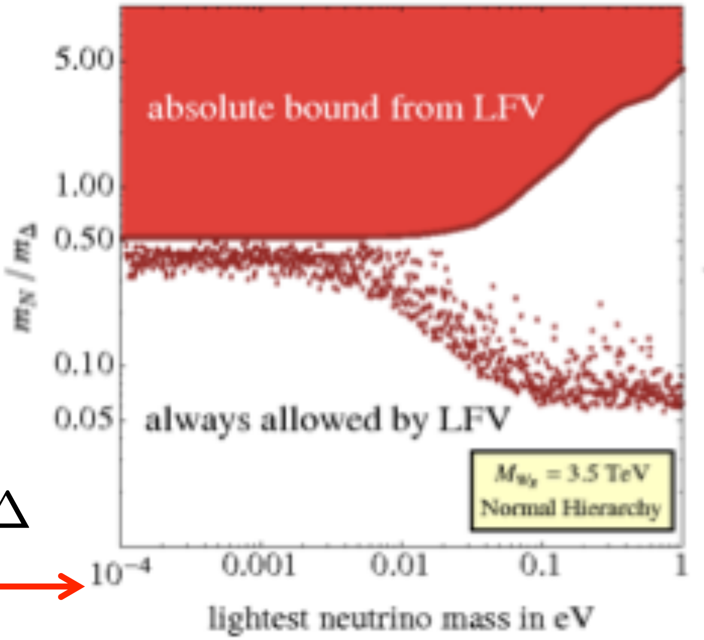
(for M_{WR} =3 TeV)

LR seesaw Higgs and CLFV

- (V. Tello,Nemevsek,Nesti,Senjanovic,Vissani'12; Cirigliano, Kurylov,Ramsey-Musolf, Vogel'04)
- Loops involving δ^{++} and δ^{+}

→ $\mu \to e|_{Au}$, $\mu \to e\gamma$

$$B(\mu Au \to eAu) \simeq 5 \times 10^{-10} \left(\frac{3.5\text{TeV}}{M_{W_R}}\right)^4 \left|\frac{M_N M_N^*}{m_\Delta^{++}}\right|^2_{e\mu}$$



- Bounds the mass ratio: M_N / M_Δ

(Tello,..)

- Muonium-anti-muonium osc.

Unique signature $G_{M-\bar{M}} \sim \frac{f_{ee} f_{\mu\mu}}{8M^2_{\Delta^{++}}}$ PSI Limit : $\leq 3G_F 10^{-3}$

Beyond left-right : Quark-lepton Unif.

- If Q-L unified at the seesaw scale, a model is

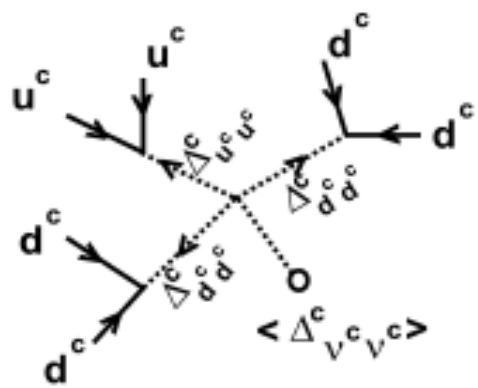
$$SU(2)_L \times SU(2)_R \times SU(4)_c \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

→SU(4) generalization of the seesaw Higgs field Δ_R has partners Δ_{qq} connecting to quarks:

→leads to neutron-anti-neutron oscillation: (Mohapatra,Marshak'80)

→No proton decay.

-Example of nu mass-NNbar connection

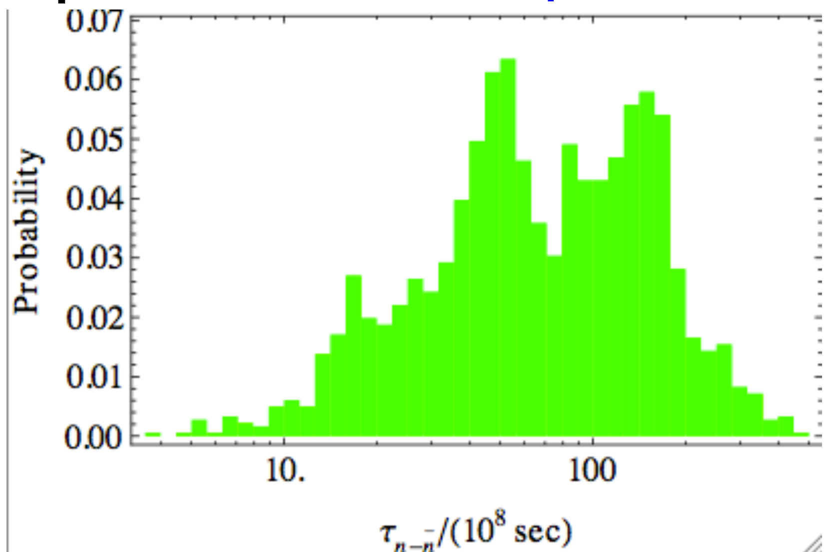


$$\frac{\lambda f^3 v_{BL}}{M_\Delta^6}$$

observable for TeV sextets

Baryogenesis constraints

- If NN-bar is observable, it will erase all pre-existing baryon asymmetry: need to generate baryons below weak scale:
- Baryogenesis via higher dim operators: Post-sphaleron baryogenesis: (Babu,Nasri, RNM'07)
- upper bound on Nnbar transition time $< 5\times10^{10}$sec. (Babu,Dev,Fortes,RNM'arXiv:1303.6918)



- Predicts ~TeV color sextet fields for LHC.

Type II seesaw

- New particles are SM non-singlets:
- **Type II**: $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$. couples to leptons $f_\nu LL\Delta$

$$m_\nu = f_\nu \frac{\mu_\Delta v_{wk}^2}{M_\Delta^2}$$

- → sub-TeV $\vec{\Delta}$ → $f_\nu \mu_\Delta \leq 10^{-9}$

- Collider searches directly probe neutrino mass matrix.
- 4-lepton signal $\ell^+\ell^+\ell^-\ell^-$ (Han, Perez,Huang, Li, Wang; Ruiz talk)

Recent interest from Higgs observation

- SM+ 125 GeV Higgs in SM→ vacuum unstable below Planck scale !
- Presence of the triplet alleviates this problem.
- It also adds new contribution to $\Gamma(h \to \gamma\gamma)$ and be of help to Higgs that way (unlike minimal type I) e.g 10% enhancement→ $M_{\Delta^{++}} \leq 450 GeV$ ★
- Current limits: 198 GeV range (CMS)(mostly $\tau\tau$) ; 265 GeV (ATLAS)(33% $\mu\mu$)

(Dev, Ghosh, Okada,Saha, arXiv:1301.3453; many earlier papers Melfo et al; Ahreib et al.)

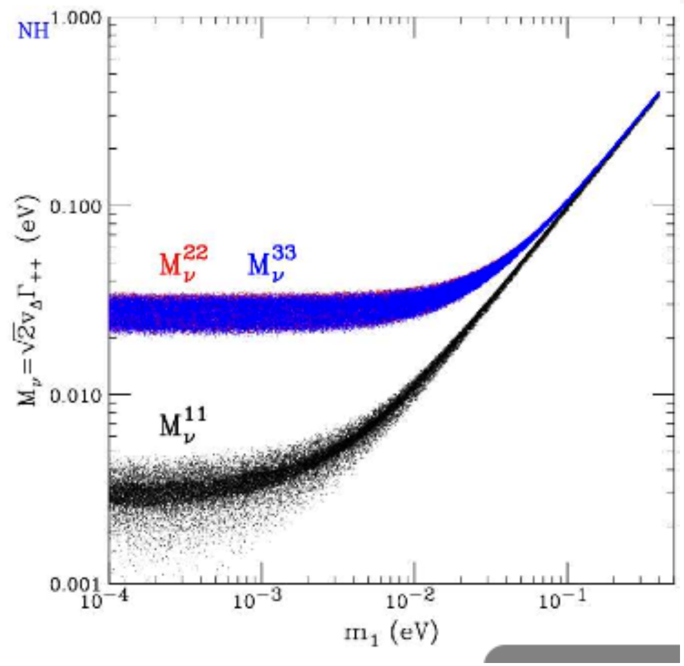
LFV constraints on Type II

- . $\mu \to 3e$ Constraints

(Han, Perez,Huang, Li, Wang'08)

$$v_\Delta^2 > 0.2 \times 10^5 \, |M_\nu^{11} M_\nu^{12}| \times \left(\frac{1 \text{ TeV}}{M_\Delta}\right)^2$$

- v_Δ^2 scales like $\sqrt{Br}$



- Muonium-anti-muonium osc:($M_\delta = 450 GeV; v_\Delta = eV$)

$$G_{M-\bar{M}} = 4 G_F 10^{-6}$$

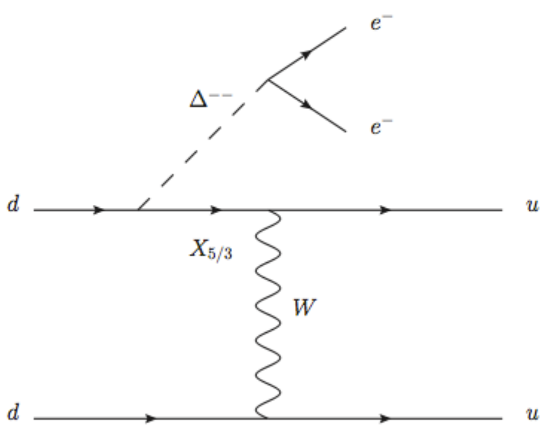
(unique to type II and LR)

Natural type II and 5/3 charge quarks

- Add vectorlike quark doublet: $Q' = \begin{pmatrix} X_{5/3} \\ t' \end{pmatrix}$

  (Franceschini, RNM'13)

- Makes μ_Δ naturally small:
- New contributions to $\beta\beta_{0\nu}$



Collider signals:

$X \to \ell^+\ell^+ + (b, s, d)$

Current search with

$X \to t + W^+$

CMS limit: $M_X \geq 645\ GeV$

This model: $M_X \geq TeV$

from searches for Δ^{++}

- Limits $f_{Xd\delta} f_{ee} \theta_{Xu} \leq 10^{-4}$

Conclusion:

- **Seesaw:** Compelling big picture for nu masses;
- Low energy CLFV expts can probe TeV scale left-right seesaw : M_{WR} to 10- 20 TeV; LHC <6 TeV.
- Observation of normal Hierarchy for nu’s and $\beta\beta_{0\nu}$ could indicate low scale WR.
- TeV seesaw+ Q-L unification→ observable $n\bar{n}$ osc.
- $M-\bar{M}$ and collider $\ell^+\ell^+$ unique to LR and type II

Extra slides

Future Sensitivities

- Experiment

No.	Observable	Upper Limit	Future Sensitivity
1.	$B(\mu \to e\gamma)$	2.4×10^{-12} [1]	$1-2 \times 10^{-13}$ [6], 10^{-14} [6]
2.	$B(\mu \to eee)$	10^{-12} [2]	10^{-16} [8], 10^{-17} [7]
3.	$R_{\mu e}^{\mathrm{Ti}}$	4.3×10^{-12} [3],	$3-7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
4.	$R_{\mu e}^{\mathrm{Au}}$	7×10^{-13} [4]	$3-7 \times 10^{-17}$ [10, 9], 10^{-18} [11, 7]
5.	$B(\tau \to e\gamma)$	3.3×10^{-8} [5]	$1-2 \times 10^{-9}$ [13, 12]
6.	$B(\tau \to \mu\gamma)$	4.4×10^{-8} [5]	2×10^{-9} [13, 12]
7.	$B(\tau \to eee)$	2.7×10^{-8} [5]	2×10^{-10} [13, 12]
8.	$B(\tau \to e\mu\mu)$	2.7×10^{-8} [5]	10^{-10} [12]
9.	$B(\tau \to \mu\mu\mu)$	2.1×10^{-8} [5]	2×10^{-10} [13, 12]
10.	$B(\tau \to \mu ee)$	1.8×10^{-8} [5]	10^{-10} [12]

Table 1: Current upper limits and future sensitivities of CLFV observables under study.

Left-right seesaw at LHC

- WR and Z' : $u\bar{d} \to W_R \to l^+ N$ $u\bar{u} \to Z' \to NN$

(Keung, Senjanovic; Han, Perez,Huang,Li, Wang; Del Aguila, Aguilar-Saavedra; de Blas, Azuelos, Nersti,Nemevsek,…)

- **type I** : W_R production source of new signal:

$$pp \to l^{\pm} l^{\pm} jj + X$$

(ATLAS, CMS bounds)

- **Inv. Seesaw** $\varepsilon > 10^{-3}$ $N \to l^- jj, l^- l^+ \nu$ $pp \to lll\nu + X$

LHC reach < 4 TeV

(Dev, Chen'11)

(Ruiz's talk)

TeV seesaw in Colliders: New particles and decays

- RH neutrino N : Dirac (Inverse) $N \to l^- W^+ \to l^- l^+ \nu$
  via $\theta_{\nu N} \equiv \varepsilon$ Majorana (Type I) $N \to l^\pm W^\mp \to l^\pm jj$
  Higgs decay: $h \to N\nu$

- Scalar triplet (Type II) $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}.$ $\delta^{++} \to l^+ l^+, W^+ W^+$
  $\delta^+ \to l^+ \overline{\nu}$ $, W^+ Z$

- Fermion triplet: (Type III) $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}.$ $\Sigma^0 \to l^+ W^-$
  $\Sigma^+ \to l^+ Z, ..$