Probing physics behind neutrino mass

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Nature of neutrino mass

- Dirac type: $\mathcal{L}^{D}_{mass} = \sum_i m_i \nu_i \nu_{s,i}$

- ν_i = mass eigenstates (contains flavor mixings)
- $\nu_{s,i}$ = sterile neutrinos (3 states)

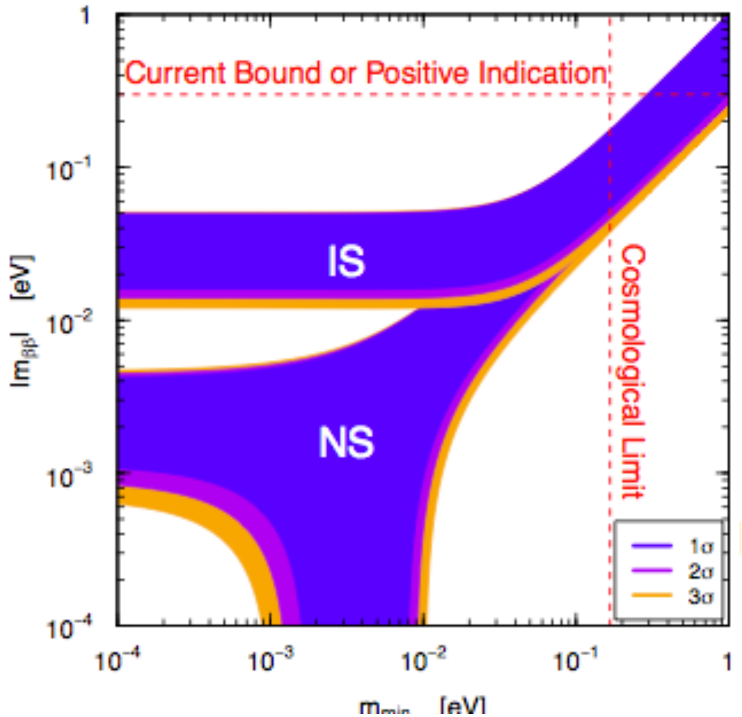
- How to disprove ? +ve $\beta\beta_{0\nu}$ decay signal or any L-violating signal e.g. colliders, rare decays etc.
- How to prove ? *inverted hierarchy in LBL expts*

  + no signal in double beta decay till < 10-15 meV.

Majorana neutrinos

- . $\mathcal{L}^{M}_{mass} = \sum_i m_i \nu_i \nu_i + h.c.$
- $\beta\beta_{0\nu}$ signal;

(normal hierarchy hard to reach)



- Other possible signals: LNV at LHC;
- $B \to \pi\mu^+\mu^+$ (LHCb,…) currently < 10^{-7} level;

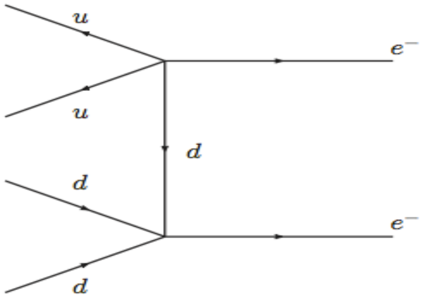
What if $\beta\beta_{0\nu}$ search comes up empty?

- If LBL finds normal hierarchy, and no $\beta\beta_{0\nu}$ signal →don't know whether Dirac or Majorana !

◆ *LBL normal hierarchy + $\beta\beta_{0\nu}$ signal→Majorana nu+ new heavy particles (more later!)*

- If all else fails, observation of nucleon decay with B-L=0 and +2 modes together→ Majorana nu.

$$p \to e^+\pi^0; n \to e^-\pi^+$$



(a)

(Babu, RNM'14)

Are there intermediate possibilities ?

(i) Generic pseudo-Dirac:

$$\mathcal{L}_{mass} = \sum_i m_i \nu_i \nu_{s,i} + \delta\ \nu_s \nu_s\ +\ h.c.$$

- Solar neutrino observations → $\delta \leq 10^{-11}\ \mathrm{eV}$

(ii) A possibility not ruled out: "Schizophrenic"

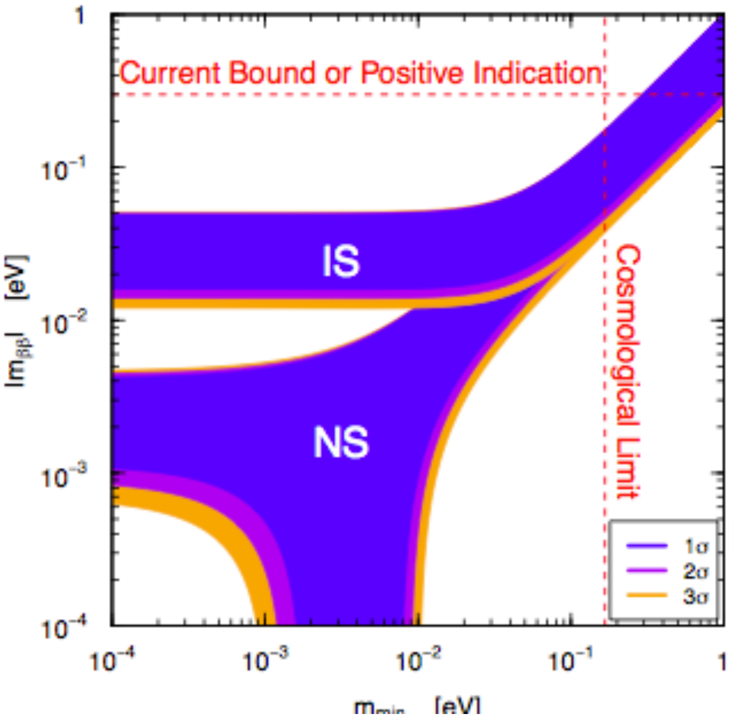
$$\mathcal{L}^{schizo}_{mass} = m_k \nu_k \nu_s + \sum_{i \neq k} m_i \nu_i \nu_i + h.c.$$

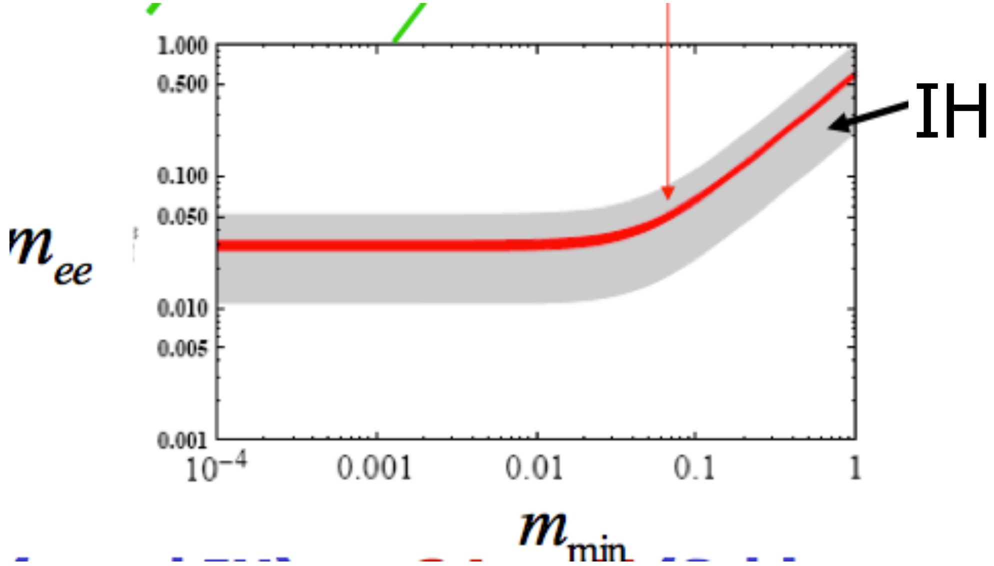
(Allaverdi, Dutta, RNM'10)

- One *mass eigenstate* Dirac type, rest Majorana type!

Double beta test of Schizo-nu

- Majorana: $\beta\beta_{0\nu}$ search: Schizophrenic
-





one mass eigenstate Dirac, rest. Maj

$$m_{min}^{IH} \geq 15meV$$

$$m_{min}^{IH} \geq 30meV$$

Now to theory: physics behind neutrino mass

- Charged fermion masses come from the Higgs vev:

$$m_f = h_f v_{wk} \qquad v_{wk} = < h^0 >$$

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

- For neutrinos, this formula gives too large a mass unless $h_\nu \leq 10^{-12}$!!

- This is an indication of new physics as source of neutrino mass !

Weinberg Effective operator as a clue to the new physics

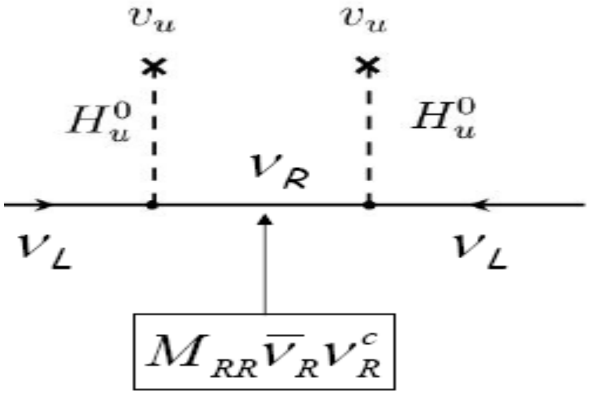
- Add effective operator to SM: $\lambda \frac{LHLH}{M}$

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

- $\lambda \sim 1; M$ big → $m_\nu \ll m_f$ naturally !
- ***It does not tell us anything else ?***
- To explore true physics, UV completion of Weinberg operator essential (build models) !!

Seesaw Mechanism

- Add SM singlet heavy Majorana neutrinos N to SM to realize Weinberg operator in UV complete theory !



→

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

$m_D = h v_{wk}$

seesaw mechanism (type I)

(Minkowski'77; Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra,Senjanovic79)

- Immediate bonus of UV theory: Can explain the origin of matter(Fukugita,Yanagida'86) (build models)

Naïve intuition about seesaw scale

- Models dictate seesaw scale→ seesaw physics
- $m_{atmos} \sim 0.05\mathrm{eV}$; if $h_{33} \sim h_t \sim 1$,

  ⇨ Seesaw → $M_N \sim 10^{14}$ GeV;
- Fits well into SO(10) theories which contain the two ingredients of seesaw i.e. N and B-L breaking naturally. Very elegant.
- Hard to test- no susy-"no test"; *where is susy ?*

- *Observation of IH will cast serious doubt on SO(10) !*

Could seesaw scale be in the TeV range ?

- Another theory that also incorporates seesaw physics automatically is the left-right extension of standard model: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- N is the parity partner of familiar neutrino;
- Seesaw scale is the scale of $SU(2)_R$ scale !!

- *Scale could be in the TeV range with plethora of experimental tests: LHC, LFV,* $\beta\beta_{0\nu}$ *etc. !*
- *Can accommodate both NH and IH.*

Choosing between SO(10) and TeV scale LR

- Are quarks leptons really similar or different ?
- Differences: a) Quarks have strong CP problem;

  leptons do not !!

  b) $m_\nu \ll m_q$ and $\theta_q \ll \theta_\ell$
- This difference could, for example, crystallize if neutrinos have inverted hierarchy !
- Proton decay, a key signal of GUTs-No evidence yet !
- No need for GUTs to understand charge quantization!
- GUTs add "nothing" to understanding origin of matter

This talk:

(i) TeV scale LR seesaw can give *naturally small* nu masses !

(ii) Collider and Low energy tests

(iii) Can explain the origin of matter !

TeV Scale Left-Right Seesaw

- LR basics: Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- Fermions

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$$L = \frac{g}{2}[\vec{J}_L^{\mu} \cdot \vec{W}_{\mu L} + \vec{J}_R^{\mu} \cdot \vec{W}_{\mu R}]$$

- Parity a spontaneously broken symmetry $M_{W_R} \gg M_{W_L}$

(R. N. M., Pati, Senjanovic'74-75)

Seesaw scale is $SU(2)_R$ breaking Scale

$$\begin{tikzcd}
SU(2)_L \times SU(2)_R \times U(1)_{B-L} \arrow[d, "v_R"] \\
SU(2)_L \times U(1)_Y \arrow[d, "\kappa"] \\
U(1)_{em}
\end{tikzcd}$$

$$M_N = f v_R$$

Seesaw

$$\xrightarrow{\quad} M_{\nu,N} = \begin{pmatrix} 0 & h\kappa \\ h\kappa & f v_R \end{pmatrix}$$

$$m_\nu \simeq -\frac{(h\kappa)^2}{M_N}$$

- Heavy-light mixing: $V_{\ell N} \simeq \dfrac{h\kappa}{f v_R}$

How plausible is a TeV seesaw in LR models ?

- · $\mathcal{L}_{\mathcal{Y}} = h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + h.c.$
- Using $\phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \rightarrow$

$$\begin{aligned} M_\ell &= h\kappa + \tilde{h}\kappa' \\ m_D &= h\kappa' + \tilde{h}\kappa \end{aligned}$$

- How to get small m_ν for TeV seesaw:

✔(i) $\kappa' = 0; \tilde{h} \sim 10^{-5.5}$ $(\sim h_e^{SM})$

$$\left.\begin{array}{l} \text{(ii) Cancellation with } \kappa', \kappa \text{ similar} \\ \text{✔ (iii) specific mass textures} \end{array}\right\} \begin{array}{c} h, \tilde{h} \\ \text{much larger} \end{array}$$

with generalized chiral sym.

Making TeV scale seesaw "natural" Case (iii)

- Consider the following mass texture:

$$m_D = \begin{pmatrix} m_1 & \delta_1 & \epsilon_1 \\ m_2 & \delta_2 & \epsilon_2 \\ m_3 & \delta_3 & \epsilon_3 \end{pmatrix} \quad M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$$

$$m_{D_{1,2,3}} \sim \ GeV \rightarrow Y_\nu \sim 10^{-2}$$

- Sym limit $\epsilon_i, \delta_i \rightarrow 0$ → $m_\nu = m_D M_R^{-1} m_D^T = 0$
- sym. Br. $\delta_i, \; \epsilon_i \ll m_i$ → for TeV M_{R}, → small m_ν
- Small δ, ϵ break generalized chiral symmetry; arise from one loop effects: (Dev, Lee, RNM'13)

NEUTRINO FIT IN LR SEESAW WITH BROKEN CHIRAL SYM.

$$M_D = \begin{bmatrix} 14.0638 & -7.51379\times10^{-10} & -0.000179257 \\ 0 & 1.41139\times10^{-9} & -0.0000407079 \\ 0 & 0 & -0.0000718846 \end{bmatrix} \quad M_e = \begin{pmatrix} 0.00153973 & -0.0511895 & -1.61367 \\ 0 & 0.0961545 & -0.366453 \\ 0 & 0 & -0.647105 \end{pmatrix}$$

$$M_R = \begin{bmatrix} 0 & 814.118 & 0 \\ 814.118 & 0 & 0 \\ 0 & 0 & -2549.95 \end{bmatrix}$$

$$V_{\mathrm{PMNS\ (fit)}} = V_e^T V_\nu = \begin{pmatrix} 0.821407 & 0.550361 & -0.149532 \\ -0.35362 & 0.697233 & 0.623538 \\ 0.447484 & -0.459255 & 0.7672 \end{pmatrix}$$

NH

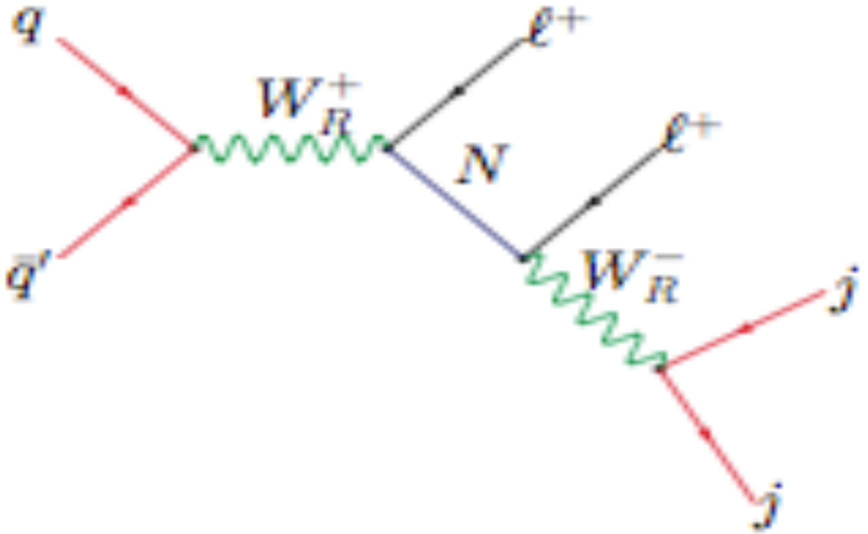
- New feature of model: $V_{\ell N} \simeq \dfrac{m_D}{M_N}$ is "large"

(Dev, Lee, RNM'13)

Experimental Probes of TeV LR seesaw

- TeV mass W_R and Z';
- Heavy Majorana neutrino: N
- $\beta\beta_{0\nu}$ process with observable lifetime
- Enhanced LFV processes

WR Signals at LHC



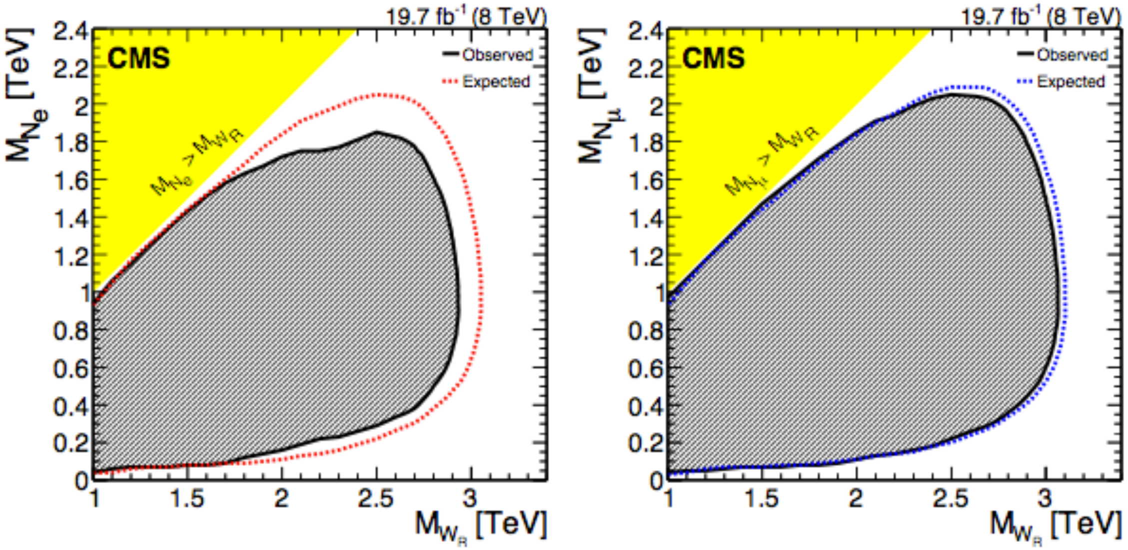
$$N \to l^{\pm} jj$$

(Keung, Senjanovic'83)

- Golden channel: $\ell_i \ell_k jj$;
- Other collider signals: (Gunion, Kayser'84 Snowmass proceedings)
- Probes RHN flavor pattern: $\boxed{A_{\ell^+\ell^+jj} \propto M^{-1}_{N,ik}}$

Current LHC analysis: only W_R graph

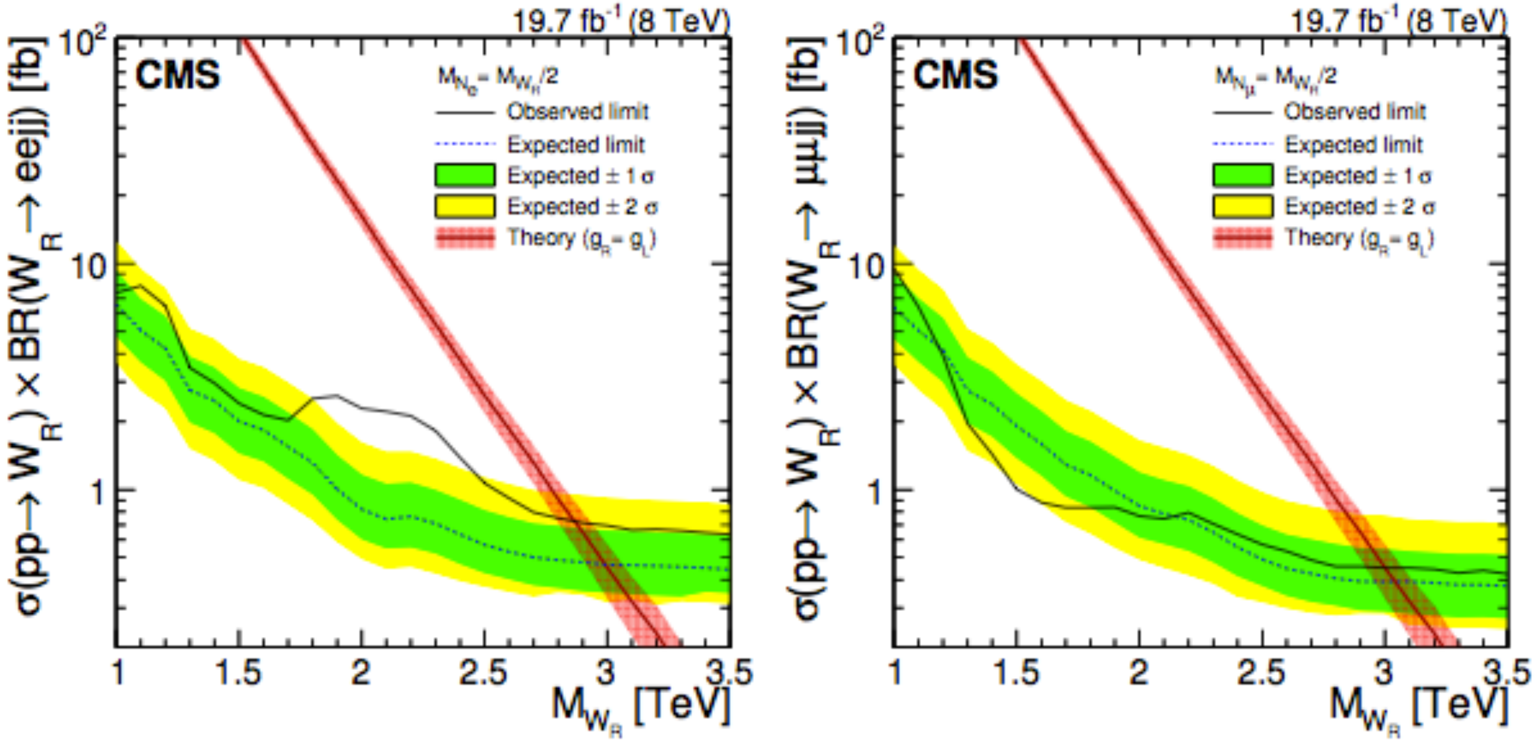
- Current W_R limits from CMS, ATLAS 2.9 TeV;



- 14-TeV LHC reach for M_{WR} 6 TeV with 300 fb^{-1}
- A recent CMS excess in ee channel (next page)

CMS Excess: possible signal

- . arXiv:1407.3683

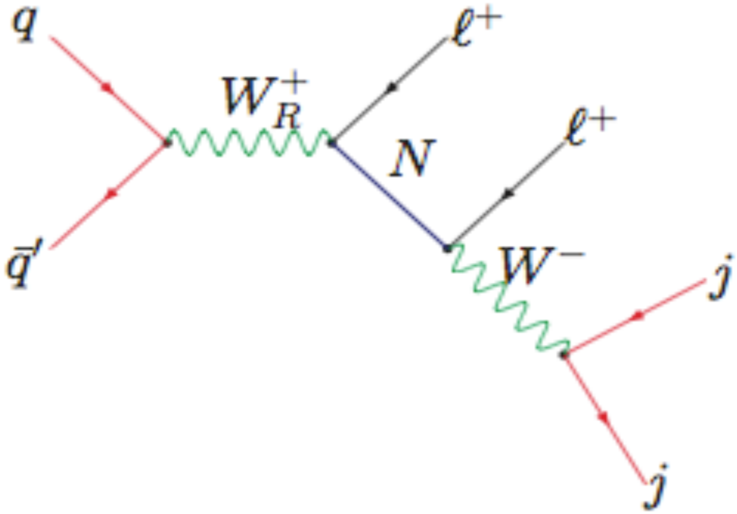


- Possible M_{WR} =2.1 TeV with g_R =.6 g_L(Deppisch et al; Heikinheimo, Raidal, Spethman; Aguilar Saavedra, Joaquim;Fowlie,Marzola)

New RL contribution to like sign dilepton signal

- If $V_{\ell N}$ is "large" i.e. $V_{\ell N} \sim 0.01 - 0.001$

(Chen, Dev, RNM' arXiv: 1306.2342- PRD)

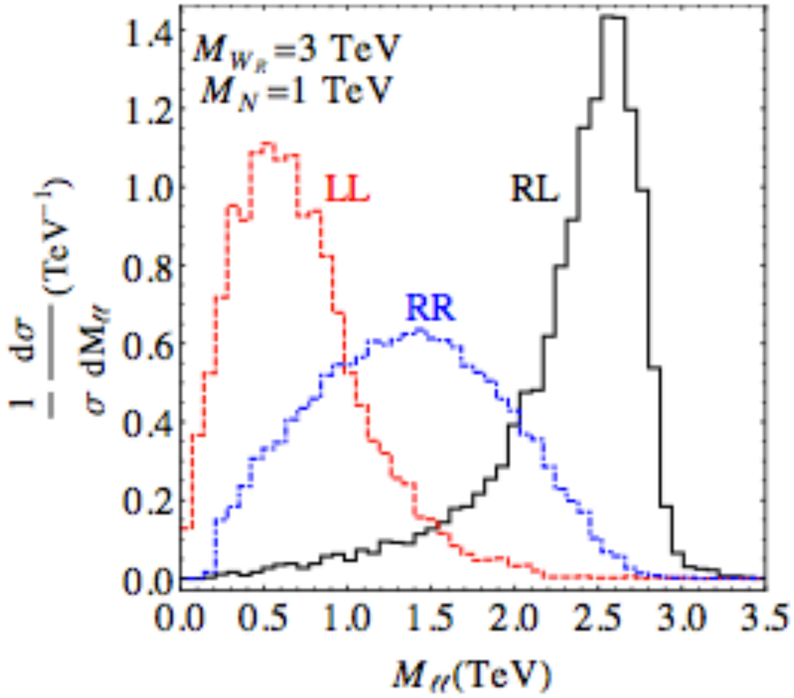


$$q\bar{q} \to W_R \to \ell + N;$$
$$N \to \ell W_L$$

- Collider signal: $A_{LR}^{LHC}(\ell^+\ell^+jj) \propto m_D M_N^{-1}$
- Flavor dependence will probe Dirac mass M_D profile:

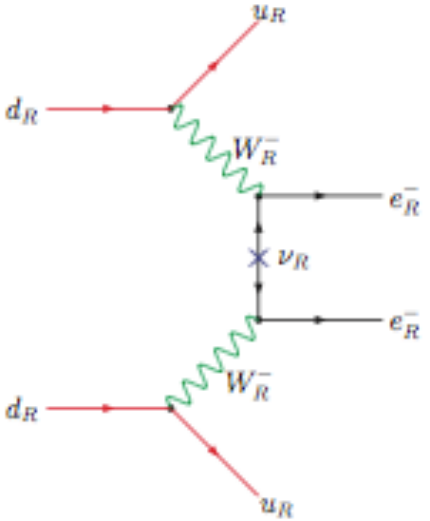
Distinguishing RR from RL

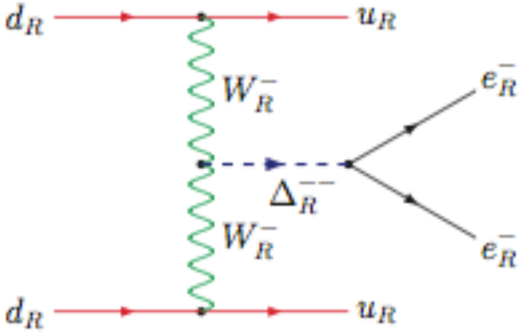
- Post-observation of W_R Dilepton invariant mass plots can distinguish RL from RR

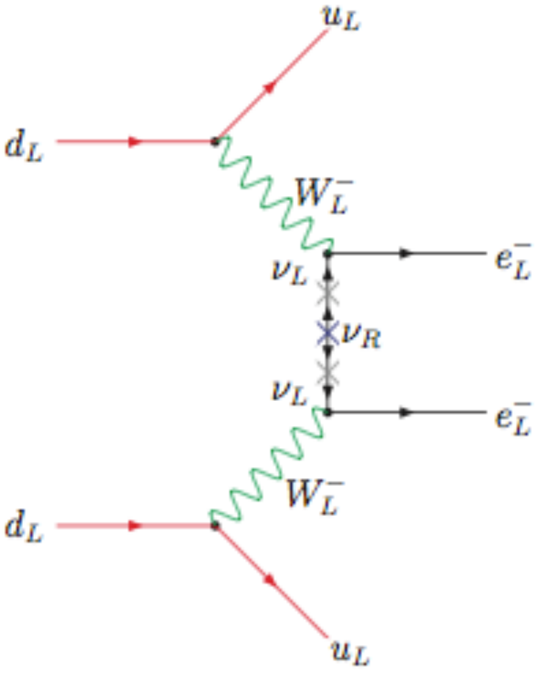


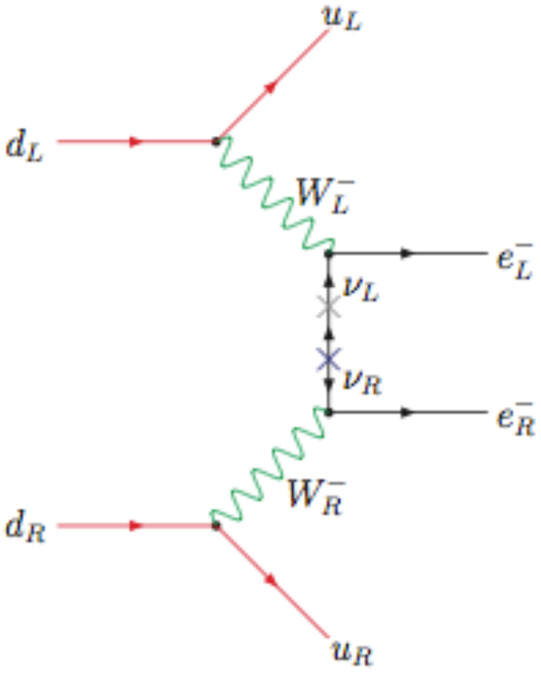
(Chen et al using Han, Lewis, Ruiz, Si)

New contributions to $\beta\beta_{0\nu}$

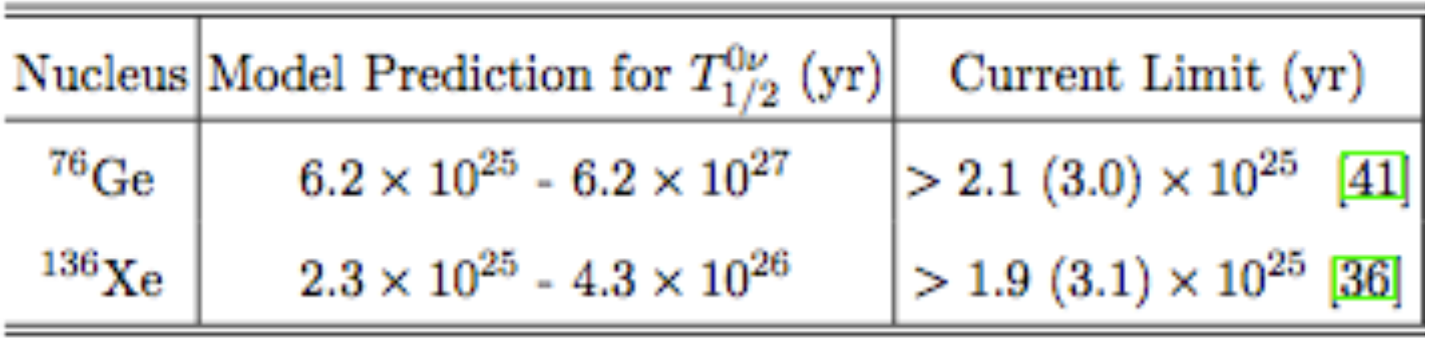








Model predictions

- 

Nucleus	Model Prediction for $T^{0\nu}_{1/2}$ (yr)	Current Limit (yr)
^{76}Ge	6.2×10^{25} - 6.2×10^{27}	$> 2.1\ (3.0) \times 10^{25}$ [41]
^{136}Xe	2.3×10^{25} - 4.3×10^{26}	$> 1.9\ (3.1) \times 10^{25}$ [36]

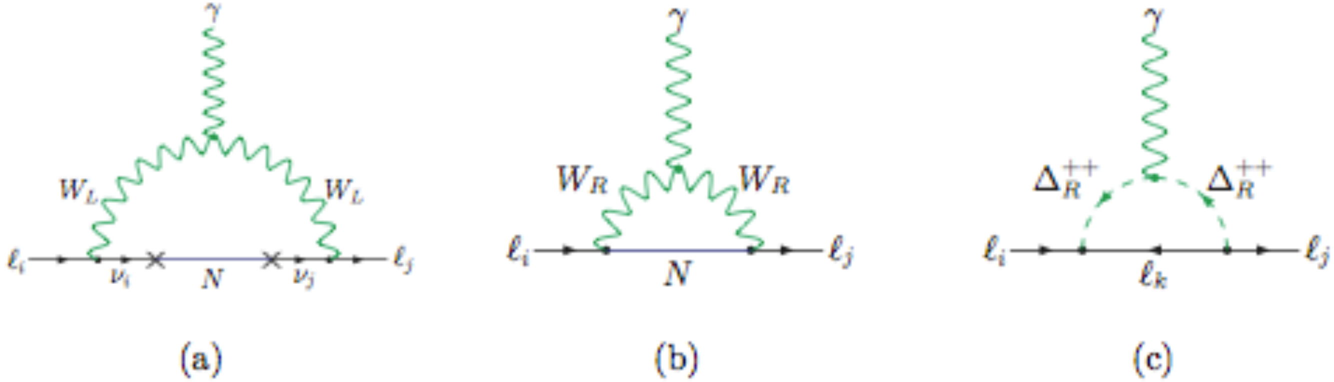
- $$\frac{M_N}{M^2_{\delta^{++}}} \leq 10^{-2}$$

- Normal hierarchy + nonzero $\beta\beta_{0\nu}$ signal

→could be due to few TeV WR

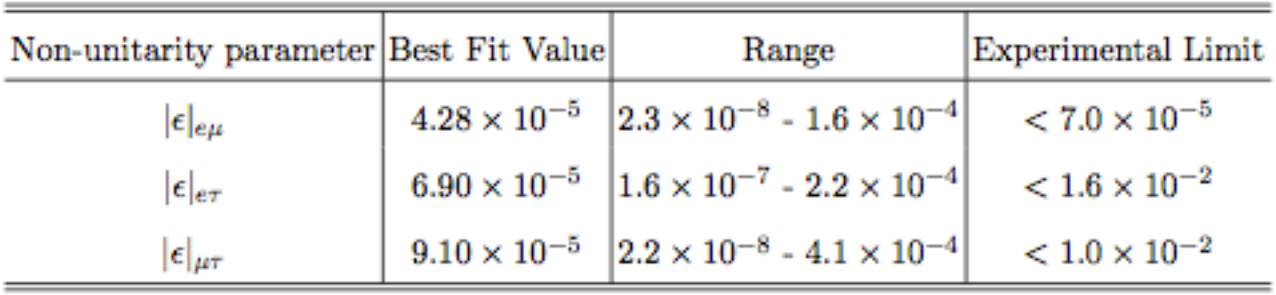
Lepton Flavor violation etc

- $\mu \rightarrow e + \gamma$



(a) (b) (c)

- W_L graph dominates Branching ratio $< 10^{-14}$
- Non-unitarity



Non-unitarity parameter	Best Fit Value	Range	Experimental Limit
$\lvert\epsilon\rvert_{e\mu}$	4.28×10^{-5}	2.3×10^{-8} - 1.6×10^{-4}	$< 7.0 \times 10^{-5}$
$\lvert\epsilon\rvert_{e\tau}$	6.90×10^{-5}	1.6×10^{-7} - 2.2×10^{-4}	$< 1.6 \times 10^{-2}$
$\lvert\epsilon\rvert_{\mu\tau}$	9.10×10^{-5}	2.2×10^{-8} - 4.1×10^{-4}	$< 1.0 \times 10^{-2}$

(B) LEPTOGENESIS WITH TEV W_R

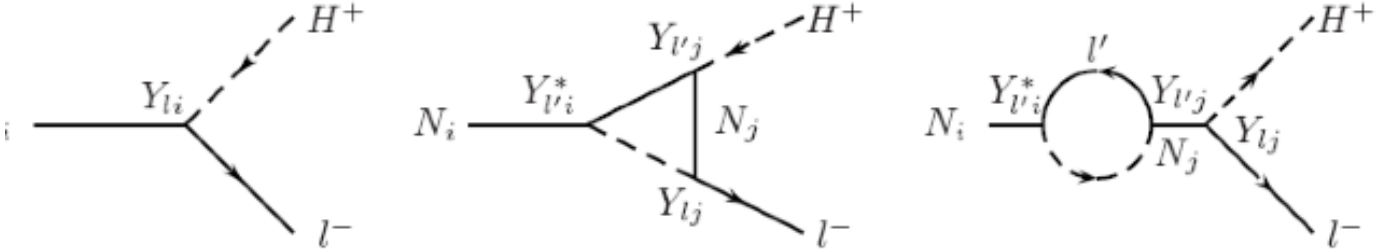
- Basic Proposal: Heavy ν_R decays:

$$\nu_R \to L + H \qquad R = (1+\varepsilon)$$

$$\nu_R \to \bar{L} + \bar{H} \qquad \bar{R} = (1-\varepsilon)$$

- Generates lepton asymmetry: **Δ L** (Leptogenesis)
- Sphalerons convert leptons to baryons

Diagrams



Leptogenesis with TeV W_R

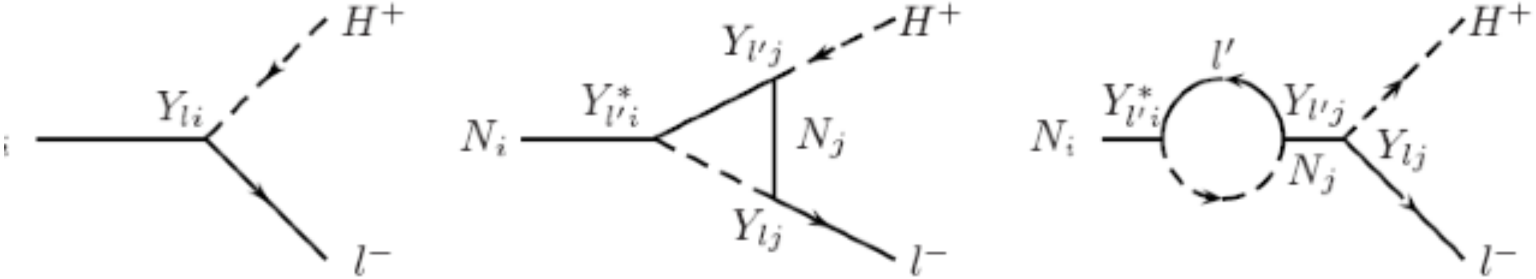
- Since $m_\nu \simeq -\frac{(Y\kappa)^2}{f v_R}$, Generic TeV ν_R →

$Y \leq 10^{-5.5}$

- Note $\epsilon_{CP} \sim \frac{Im(Y^\dagger Y)^2}{4\pi Y^\dagger Y} \sim 10^{-12}$
- since $\frac{n_B}{n_\gamma} \sim 10^{-2}\epsilon_{CP}\kappa_{eff}$ (κ_{eff}=wash out)
- need enhancement→suggest resonant leptogenesis

TeV scale Resonant leptogenesis:

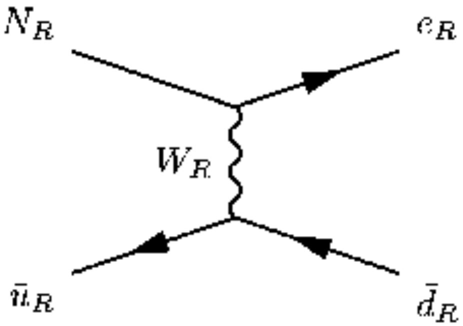
- RH neutrino mass ~ TeV scale(Flanz, Pascos, Sarkar; Pilaftsis, Underwood; Covi, Roulet, Vissan)i



- Issue here is: $\frac{n_B}{n_\gamma} \propto \frac{ImY^4}{|Y|^2} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1\Gamma_1 + M_2\Gamma_2)^2}$
- Since nu mass→ $Y \sim 10^{-5}$ for TeV M_N, generic model requires extreme degeneracy among RHNs !!

Constraint on W_R for tiny Yukawa case (i)

- Tiny Yukawa Leads to strong wash out for low WR masses: (Frere, Hambye, Vertongen'11) (for M_{WR} 3-18 TeV)



$$>> \Gamma(\nu_R \to \ell H) \rightarrow \kappa_{eff} \propto \frac{\Gamma_D/\Gamma_S}{1+\Gamma_D/\Gamma_S} \ll 1$$

- Bound: **M_{WR} > 18 TeV** assuming $\epsilon_{CP} \sim 1$; no flavor effect;

→ Discover W_R below this mass at LHC→ rules out leptogenesis for *generic* TeV scale LR seesaw!!

New TeV W_R seesaw models with texture

- Special textured seesaw has two features:

  (i) Larger Yukawas $Y_\nu \leq 10^{-2}$

  (ii) Naturally deg $N_{1,2}$ since $M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$

- Such LR models more suitable for TeV leptogenesis

Wash out effect is less !

- Here $\boxed{\frac{\Gamma_D}{\Gamma_S} \sim 1}$ enhances κ_{eff}

- Washout via inverse decay increases due to larger Yukawas; but there is a compromise situation where enough lepton asym is generated for $M_{WR} > 3$ TeV (new lower bound)

(Dev, Lee, RNM; arXiv:1408.2820)

Parameteric dependence on RH Maj. Mass parameters

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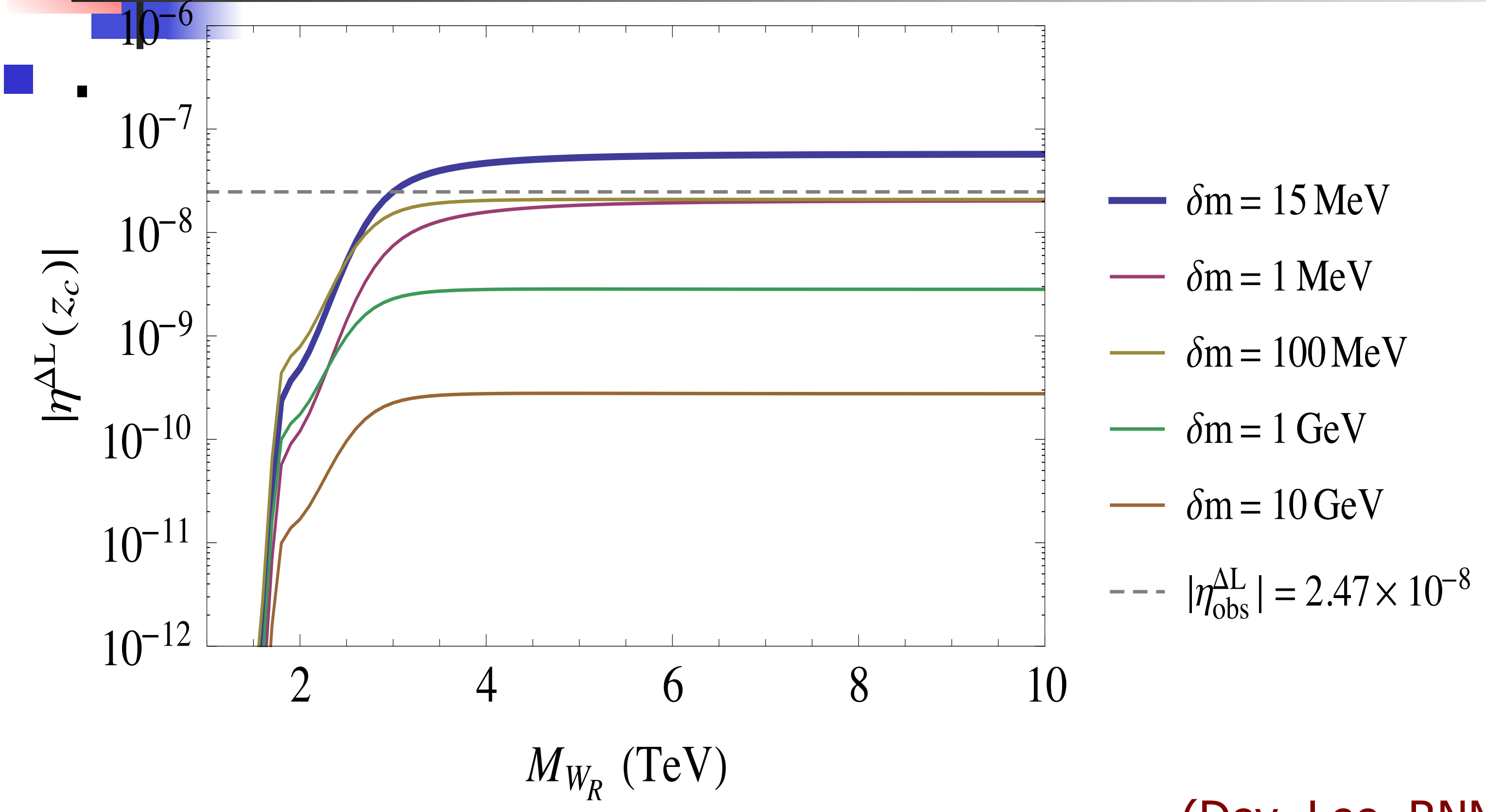


(Dev, Lee, RNM'14, 1408.2820)

- $\delta m = M_{N,11}$ → M_{WR} >3 TeV (in LHC reach)

Summary

- SO(10) is a dream picture for seesaw neutrino masses *but very hard to test* !!
- TeV scale LR model are attactive realizations since they lead to a variety of low energy tests e.g. LFV, neutrinoless D-beta decay etc.
- They are accessible at the LHC till $M_{WR} < 6$ TeV.

- They can be natural models for small neutrino masses as well as for leptogenesis.

(i) Parameter space where there is weaker bound

- A realistic model which has large Yukawas i.e. a neutrino fit via cancellation + M_N texture

$$h = \begin{pmatrix} -0.0192325 - 0.0269331\,i & -0.00141553 - 3.01252\times 10^{-10}\,i & -0.0392938 \\ 0. & 0.0025837 + 5.49862\times 10^{-10}\,i & -0.0179653 \\ 0. & 0. & -0.0240005 \end{pmatrix}$$

$$\tilde{h} = \begin{pmatrix} 0.022545 + 0.031557\,i & 0.00120812 + 3.52972\times 10^{-10}\,i & 0.0335349 \\ 0. & -0.00220512 - 6.44264\times 10^{-10}\,i & 0.0153323 \\ 0. & 0. & 0.0204829 \end{pmatrix}$$

$\kappa=112.958$

$\kappa'=132.35$

$$M_N = \begin{pmatrix} 0.015 & 1752.07 & 0 \\ 1752.07 & 0 & 0 \\ 0 & 0 & -1752.04 \end{pmatrix}$$

Advantage of this solution

- Planck scale corrections: $\frac{\bar{Q}_L \chi_L \chi_R^\dagger Q_R}{M_{Pl}}$

$$\frac{\kappa_L \kappa_R}{M_{P\ell}}$$

$$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$$

- Arg Det M not zero and < 10^{-10} →

$$\kappa_R \sim m_{\psi_t\psi_t}, \kappa_R \leq 100\ TeV$$

- M_t implies → top partner mass $M_T \sim \kappa_R$

- Planck corrections huge- destabilize the axion soln:

Questions raised by seesaw

- Where did N come from ?
- Where did the seesaw scale come from and what is its value ?
- Two theories that provide answers to these questions automatically are:

(A) SO(10) GUT where N+15 SM fermions =16 spinor

seesaw scale (*>10^{14}GeV since* $h_\nu \sim h_q$)*(hard to test)*

(B) Left-right model where N is the parity partner

of ν and seesaw scale is $SU(2)_R$ scale (*> few TeVs*)

Left-right realization: an example

- Only Lepton sector has bi-doublets with symmetry

$$\phi_\ell \to i\phi_\ell$$

$$\to <\phi_\ell> = \begin{pmatrix} 0 & 0 \\ 0 & \kappa \end{pmatrix}$$

- → Dirac mass part of neutrino seesaw and charged lepton masses;
- Loop induced by quark sector and small m_ν

$$<\phi_\ell> = \begin{pmatrix} \delta\kappa' & 0 \\ 0 & \kappa \end{pmatrix}$$

LR and Tree level masses

- .

$$M_\ell^0 = \begin{pmatrix} 0 & h_{12}\kappa & h_{13}\kappa \\ 0 & h_{22}\kappa & h_{23}\kappa \\ 0 & h_{32}\kappa & h_{33}\kappa \end{pmatrix} M_D^0 = \begin{pmatrix} h_{11}\kappa & 0 & 0 \\ h_{21}\kappa & 0 & 0 \\ h_{31}\kappa & 0 & 0 \end{pmatrix}$$

$$\mathcal{L}_\mathcal{M} = f_{12} R_1 R_2 \Delta_{1,R} + f_{33} R_3 R_3 \Delta_{3,R} + h.c.$$

- $M_R = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$ → $m_\nu^0 = 0; m_e = 0$

- → $m_{D,j1}$ can be “large” (~GeV) and still give small nu masses !

One loop and neutrino fit:

$$M_\ell = \begin{pmatrix} h_{11}\delta\kappa & h_{12}\kappa & h_{13}\kappa \\ h_{21}\delta\kappa & h_{22}\kappa & h_{23}\kappa \\ h_{31}\delta\kappa & h_{32}\kappa & h_{33}\kappa \end{pmatrix} m_D = \begin{pmatrix} h_{11}\kappa & h_{12}\delta\kappa & h_{13}\delta\kappa \\ h_{21}\kappa & h_{22}\delta\kappa & h_{23}\delta\kappa \\ h_{31}\kappa & h_{32}\delta\kappa & h_{33}\delta\kappa \end{pmatrix}$$

$$M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$$

$$m_\nu \neq 0 \ and \ small$$

- Collider signal at LHC ?

Small $\delta\kappa$ from Quark sector

- Add singlet vector like quarks to LR ($\psi^{u,d}$) and Higgs are doublets: $\chi_{L,R}$ $< \chi_R >= \kappa_R \neq v_R$
- Sym breaking→ doublet-singlet quark mass

$$M_{q\psi} = \begin{pmatrix} 0 & m_{q_L\psi} \\ m_{q_R\psi} & M_{\psi\psi} \end{pmatrix}$$

$$m_{u,d} \sim \frac{m_{q_L\psi} m_{q_R\psi}}{M_{\psi\psi}}$$

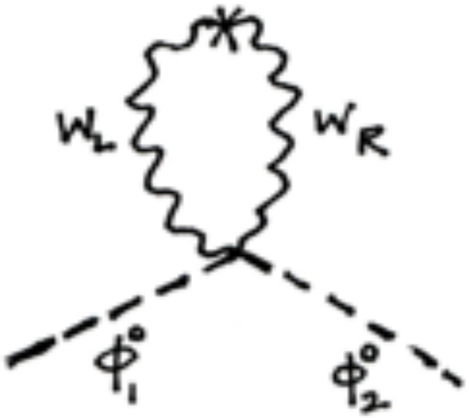
- LR→ $m_{q_L,\psi} = m^{\dagger}_{q_R,\psi}$ →Arg Det M = 0 at tree level.→ $\theta_{tree} = 0$

(Babu and RNM'90)

- *Solves strong CP without axion*

$\delta\kappa$ From loops

- small parameter $\delta\kappa$ of neutrino sector generated at one loop of quark sector:

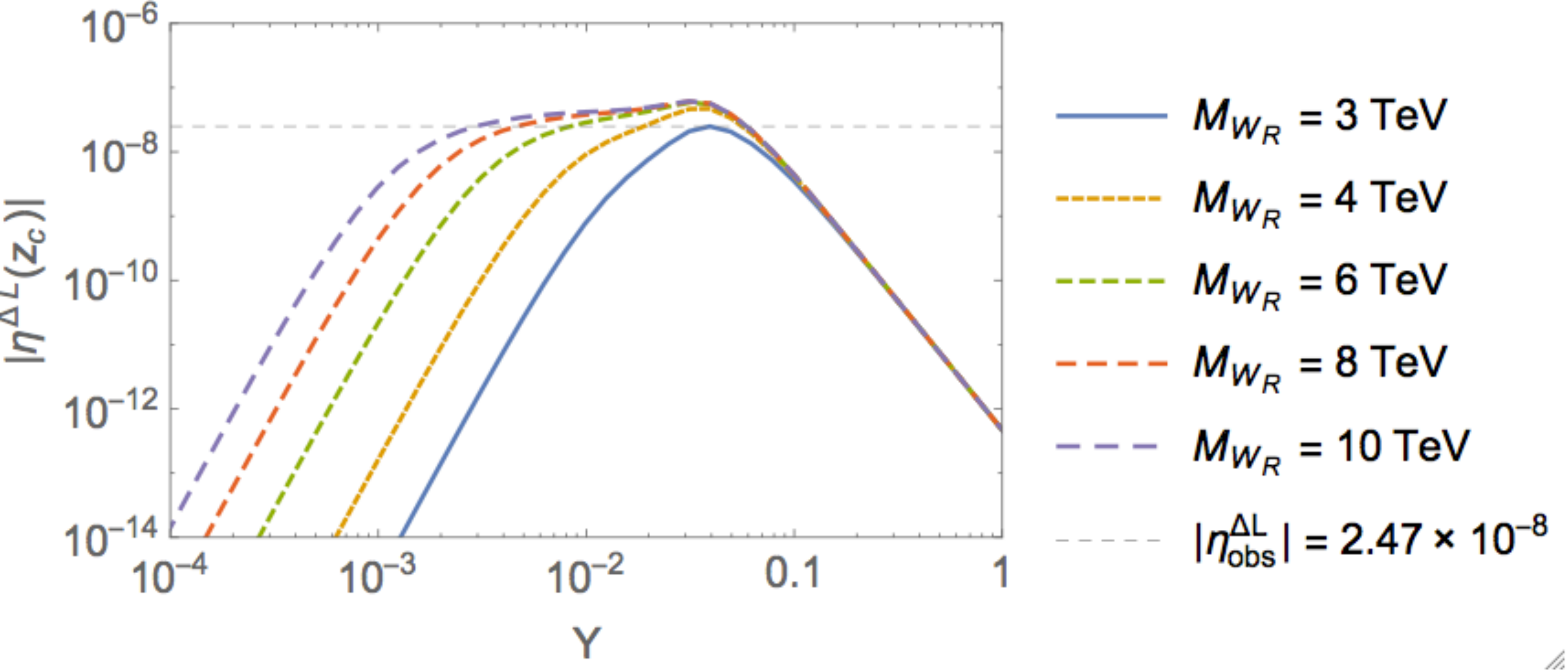


$$\to \delta\mu^2 Tr(\phi^\dagger\tilde{\phi})$$

$$\delta\mu^2 \sim \frac{\delta m^2_{W_L W_R} m^2_{\psi_T}}{v_R^2}$$

- $\delta\kappa \sim \frac{\delta\mu^2}{\kappa}$ → $v_R < 10\text{-}100$ TeV

Dependence of efficiency on Y



- Processes e.g. $\mu \to e + \gamma$ Observable !