Probing TeV LR Seesaw for Neutrino Mass and Origin of matter

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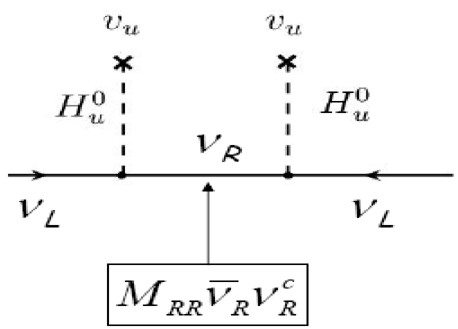
Weinberg operator and naïve lore about scale of L-violation

SM+ $\lambda \frac{LHLH}{M}$ → $m_\nu = \lambda \frac{v_{wk}^2}{M}$ → nu Majorana

- Neutrino osc data→ m_ν << eV
- Scale of L violation:$\sim 10^{14}\ \mathrm{GeV}$ for $\lambda \sim 1$
- Dimensional analysis arguments, however, can be quite misleading *(e.g. K_L –K_S mass diff.)*!!
- To explore true scale, UV completion of Weinberg operator essential (*build models*) !!

Seesaw as step towards UV completion of Weinberg Op.

- Add right handed N and a Majorana mass for it: *Seesaw mechanism*:



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

Minkowski'77, Gell-Mann, Ramond, Slansky;Yanagida; Glashow; Mohapatra,Senjanovic'79

- Majorana mass of N →Majorana nu (SM seesaw)
- Major bonus: Leptogenesis as origin of matter from N-decay in combination with sphalerons.
- Small h, lower seesaw scale: (talks by: Deppisch, Dev, Lopez-Pavon, Ruiz, Molinaro@INFO2015)

TeV seesaw beyond SM

- Search for BSM UV complete seesaw models
- Guiding principle *(assume as little as possible)*

(i) Existence of N should be predicted by theory

(ii) Seesaw scale be related to local symmetry

- Two simple theories that conform to these:

(i) Left-right model where N is the parity partner of ν_L and seesaw scale is $SU(2)_R$ scale could be TeV

(ii) SO(10) GUT where N+15 SM fermions =16 spinor and seesaw scale = GUT scale. *(Hard to test)*

This talk: TeV LR seesaw

- A "natural" TeV scale theory for neutrinos
- Minimal SUSY LR *requires* TeV scale L-violation
- How to probe this TeV scale theory in colliders
- Leptogenesis with TeV scale $\not{L}$ and constraints

Left-Right Model Basics

- LR basics: Gauge group: $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$
- Fermions $$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix} \qquad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$
-

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

- Parity a spontaneously broken symmetry: $M_{W_R} \gg M_{W_L}$ (Mohapatra, Pati, Senjanovic'74-75)

Other advantages of LR

- A more physical electric charge formula than SM

- Solves strong CP problem without the axion and limits $M_{WR} < 1000$ TeV.

- With supersymmetry, provides a naturally stable dark matter (automatic R-parity)

New Higgs fields and Yukawa couplings

- LR bidoublet: $\phi = \begin{pmatrix} \phi_1{}^0 & \phi_2{}^+ \\ \phi_1{}^- & \phi_2{}^0 \end{pmatrix}$

- Triplet to break B-L and generate seesaw: $\Delta = \begin{pmatrix} \frac{1}{\sqrt{2}}\Delta^+ & \Delta^{++} \\ \Delta^0 & -\frac{1}{\sqrt{2}}\Delta^+ \end{pmatrix}$

$$\mathcal{L}_Y = h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + fRR\Delta_R + h.c.$$

$$<\Delta_R> = \begin{pmatrix} 0 & 0 \\ v_R & 0 \end{pmatrix} \qquad \phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix}$$

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

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

$\downarrow$ v_R (ΔL=2) $\quad M_N = f v_R$

$$SU(2)_L \times U(1)_Y$$

$\downarrow$ κ $\quad\Rightarrow\quad$ Seesaw $\quad M_{\nu,N} = \begin{pmatrix} 0 & h\kappa \\ h\kappa & f v_R \end{pmatrix}$

$$U(1)_{em}$$

- If $v_R \sim$ TeV, L-violaion is TeV scale $\quad m_\nu \simeq -\frac{(h\kappa)^2}{M_N}$
- Any theoretical justification for TeV v_R ?

SUSY as theory justification for TeV W_R

- Supersymmetrize this minimal LR model
- First consequence: Tree level global minimum violates electric charge: $< \Delta^{++} > \neq 0$

(i) unless R-parity is broken (Kuchimanchi, R. N. M.'94, '95)

- +

(ii) W_R mass has an upper limit: $M_{W_R} \leq \frac{M_{SUSY}}{f}$

i.e. W_R is in TeV range !

Minimal SUSYLR with exact R-parity

- Extend with a singlet and add one loop→ RP exact !

(Babu, R. N. M.'08; Babu, Patra'14; Basso, Fuks, Krauss, Porod'15)

- *Upper bound on W_R required to conserve electric charge; M_{WR} < 7 TeV* (Porod et al., private communications)

- *Implies a light (< TeV) doubly charged Higgs*

$$M_{\Delta^{++}} \leq 2\ \mathrm{TeV}$$ (Porod et al.)

- *Neutrino masses from usual seesaw*

Seesaw formula in TeV LR models: Type II small

- Generic LR models with parity down to TeV,

→ Seesaw formula $$m_\nu \simeq f\frac{\kappa^2}{v_R} - m_D^T \frac{1}{f v_R} m_D$$

(apriori large)

Seesaw formula in TeV LR models: Type II small

- Generic LR models with parity down to TeV,

→ Seesaw formula $$m_\nu \simeq f\frac{\kappa^2}{v_R} - m_D^T \frac{1}{f v_R} m_D$$

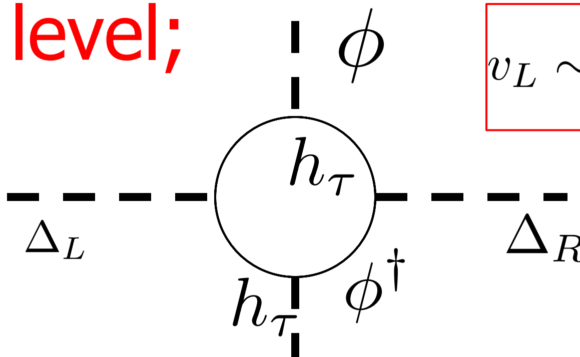
- Two theories where first term is small:

  (i) decouple P breaking from $SU(2)_R$ $\quad g_R < g_L$

  (ii) SUSYLR→ zero at tree level;

  1-loop small

$$v_L \sim \frac{h_\tau^2 f^2 \kappa^2 M_{SSB}}{16\pi^2 v_R^2}$$



Small Neutrino masses with TeV WR

- $\cdot \; \mathcal{L}_{\mathcal{Y}} = h\bar{L}\phi R + \tilde{h}\bar{L}\tilde{\phi}R + h.c.$

- Using $\phi = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \rightarrow$

$$M_\ell = h\kappa + \tilde{h}\kappa'$$

$$m_D = h\kappa' + \tilde{h}\kappa$$

- How to get small m_ν for TeV seesaw:

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

  (ii) Cancellation with κ', κ similar

  (iii) *assume texture for Dirac mass*

  } $h, \tilde{h}$ much larger

Making TeV scale seesaw "natural" Case (iii)

- Neutrino Mass texture: (for SM→ Kersten, Smirnov; Pilaftsis, Underwood)

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

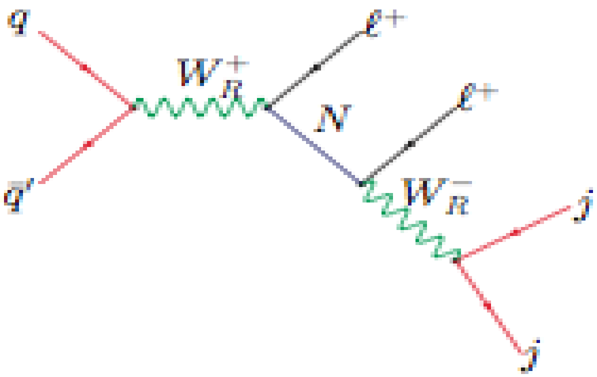
$$m_{D_{1,2,3}} \sim \ GeV \to Y_\nu \sim 10^{-2}\text{–}10^{-4}$$

- Sym limit $\epsilon_i, \delta_i \to 0$ → $m_\nu = m_D M_R^{-1} m_D^T = 0$
- sym. Br. $\delta_i, \epsilon_i \ll m_i$ → for TeV M_R, → small m_ν
- Small δ, ϵ arise from one loop SUSY breaking effects; *Good fit to neutrinos* (Dev, Lee, RNM'13)

Probing TeV LR: (i) WR Signals at LHC $\ell_i \ell_k j j$

(a) LR Seesaw signals at LHC

(b)



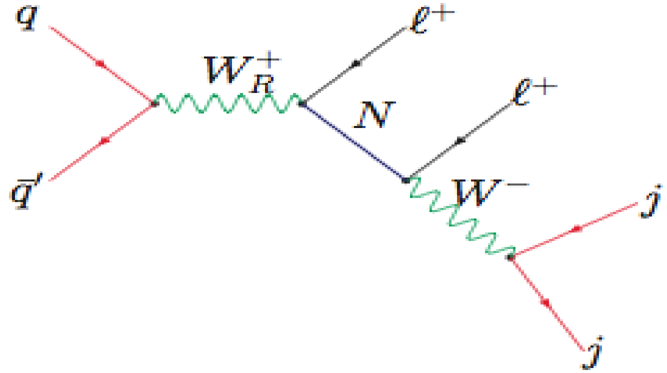
$$N \to l^{\pm} jj$$

(Keung, Senjanovic'83; Gunion, Kayser'84)

$$A_{\ell^+\ell^+jj} \propto M_{N,ik}^{-1}$$

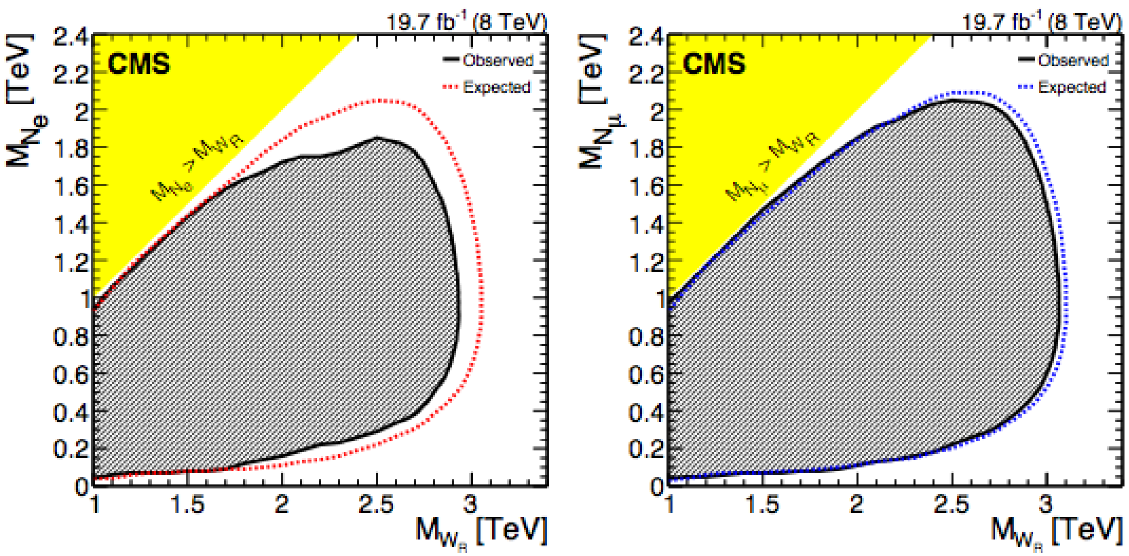
(Tello, Nemevsek, Senjanovic; Chen, Dev, RNM)

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



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}
- Higgs signals at LHC (Nemevsek@CETUP2015)

LHC anomalies ~2 TeV (W_R?)

- 3.4 σ WZ→ JJ excess (ATLAS)
- CMS JJ excess 1.8σ excess
- 2.2σ Wh excess (ATLAS)
- 2.8σ eejj excess (CMS)
- 2.6σ excess WW and ZZ channel (ATLAS)

W_R interpretation of LHC anomalies

- eejj: (Deppisch Gonzalo,Patra,sahu,Sarkar; Heikinheimo, Raidal, Spethman; Aguilar-Saavedra, Joachim;Fowlie,Marzola; Gluza, Jelinsky)
- Diboson+..: (Hisano et al. Dobrescu, Liu; Gao, Ghosh, Sinha, Yu; Cheung, Keung et al; Cao, Dong, Zhang; Bremmer,Hewett, Kopp, Rizzo, Tattersal; Krauss, Porod)
- Telling WR from W': (Han, Lewis, Ruiz, Si'12)

Does Leptogenesis work in TeV W_R models

- Since $m_\nu \simeq -\frac{(Y\kappa)^2}{f v_R}$, TeV v_R means $Y \leq 10^{-5.5}$
- or larger Y with Texture
- Either case $\epsilon_{CP} \sim \frac{Im(Y^\dagger Y)^2}{4\pi Y^\dagger Y} \sim 10^{-12} - 10^{-10}$
- since $\frac{n_B}{n_\gamma} \sim 10^{-2} \epsilon_{CP} \kappa_{eff}$ (κ_{eff}=wash out)
- need enhancement→suggest resonant leptogenesis

(II): TeV scale Resonant leptogenesis:

- RH neutrino mass ~ TeV scale

$$\frac{n_B}{n_\gamma} \propto \frac{Im Y^4}{|Y|^2} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1 \Gamma_1 + M_2 \Gamma_2)^2}$$

- Generic model requires extreme degeneracy among RHNs to get enough n_B / n_γ

Final baryon asymmetry from lepton asymmetry

- Wash out effect important: (Buchmuller, Di Bari, Pliumacher)

$$\frac{n_B}{n_\gamma} \sim 10^{-2}\epsilon_{CP}\kappa_{eff}$$

- In LR, $\kappa_{eff} \propto \frac{\Gamma_D/\Gamma_S}{1+\Gamma_D/\Gamma_S} \ll 1$ $\quad \Gamma_D \propto Y^2$ $\quad \Gamma_S \propto M_{W_R}^{-4}$
- Given Y, Washout increases as M_{WR} decreases: →lower bound on M_{WR}
- Two papers: small Y: M_{WR} >18 TeV (Frere,Hambye, Vertongen)

  Larger Y with nu fits: M_{WR} > 10 TeV (Dev, Lee, RNM.'14)
- *LHC can rule out leptogenesis idea !!*

Summary

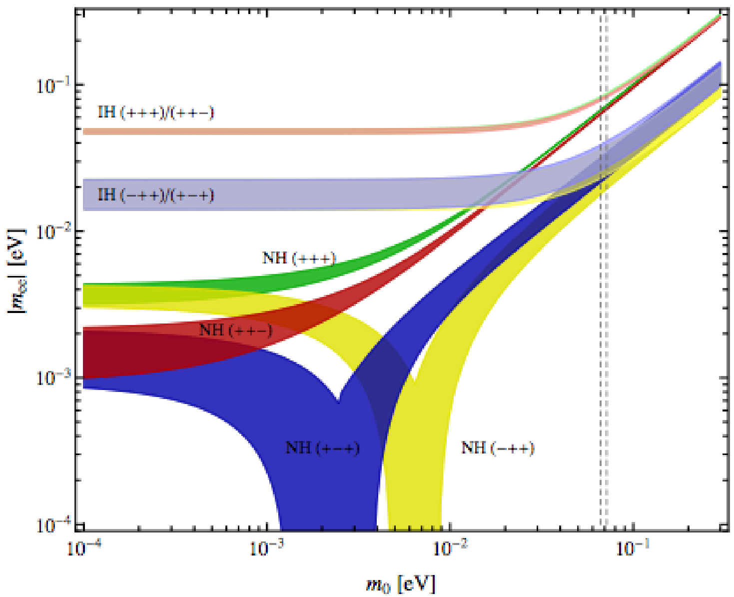
- Left-Right theories provide a simple realization of TeV scale seesaw for neutrino mass and leptogenesis with testable collider implications (W_R , Z′, N..)!

- Minimal susy LR bound on→ *M_{WR} < multi-TeV*
- Leptogenesis bound on W_R→ *M_{WR} > 10 TeV*

- If colliders find W_R with mass < 10 TeV or $M_{WR} < M_N$ leptogenesis can be ruled out.
- Another direction: Inverse seesaw in TeV LR models

$$Thank\ you\ for\ your\ attention\ !$$

Neutrino mass and $\beta\beta_{0\nu}$



(well-known IH bounds)

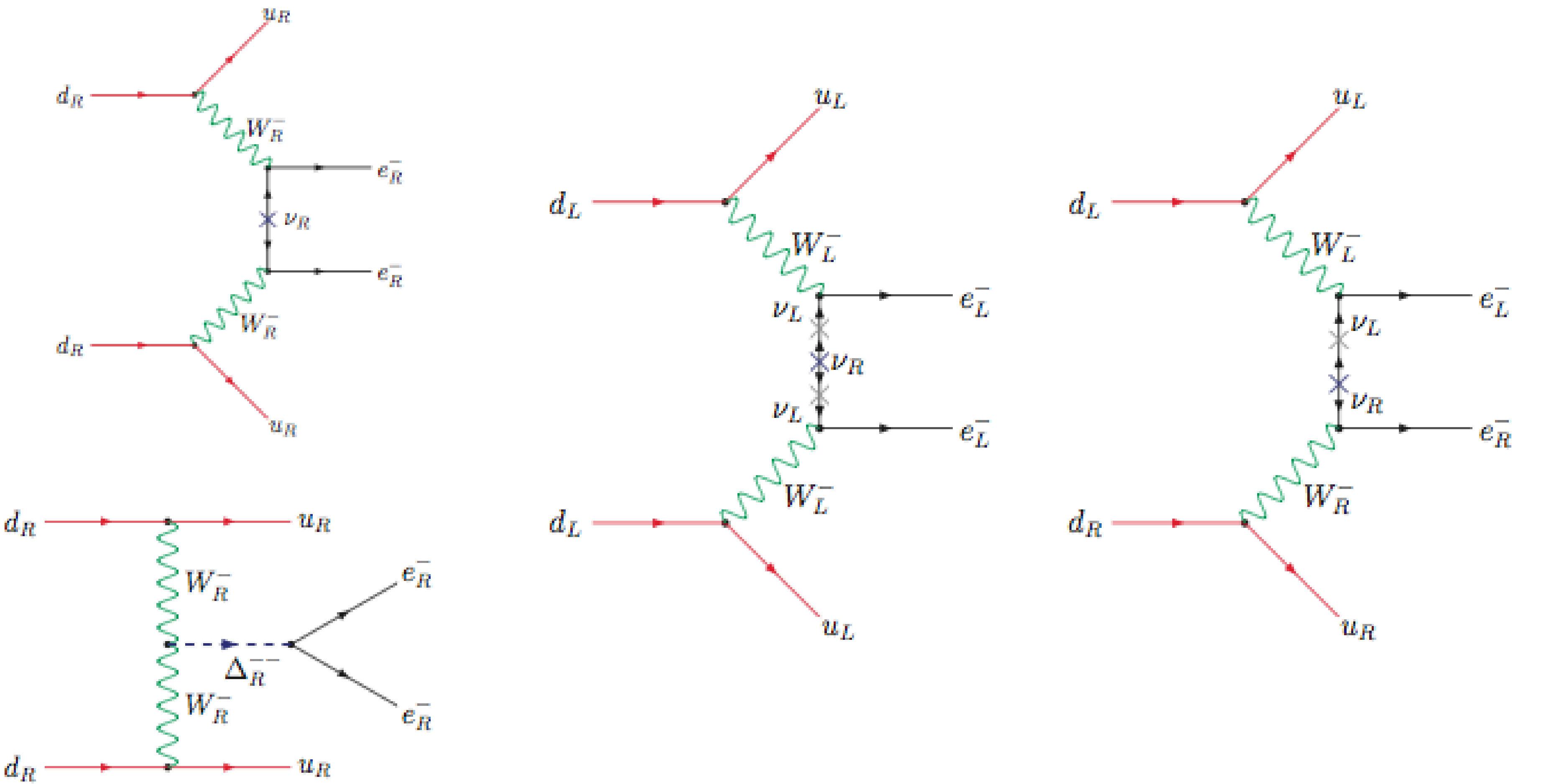
(Vissani'99; Bilenky,Pascoli,Petcov'01)

- Two points to emphasize:

(i) lower bounds even for NH with sym (RNM, Nishi; 1506.)

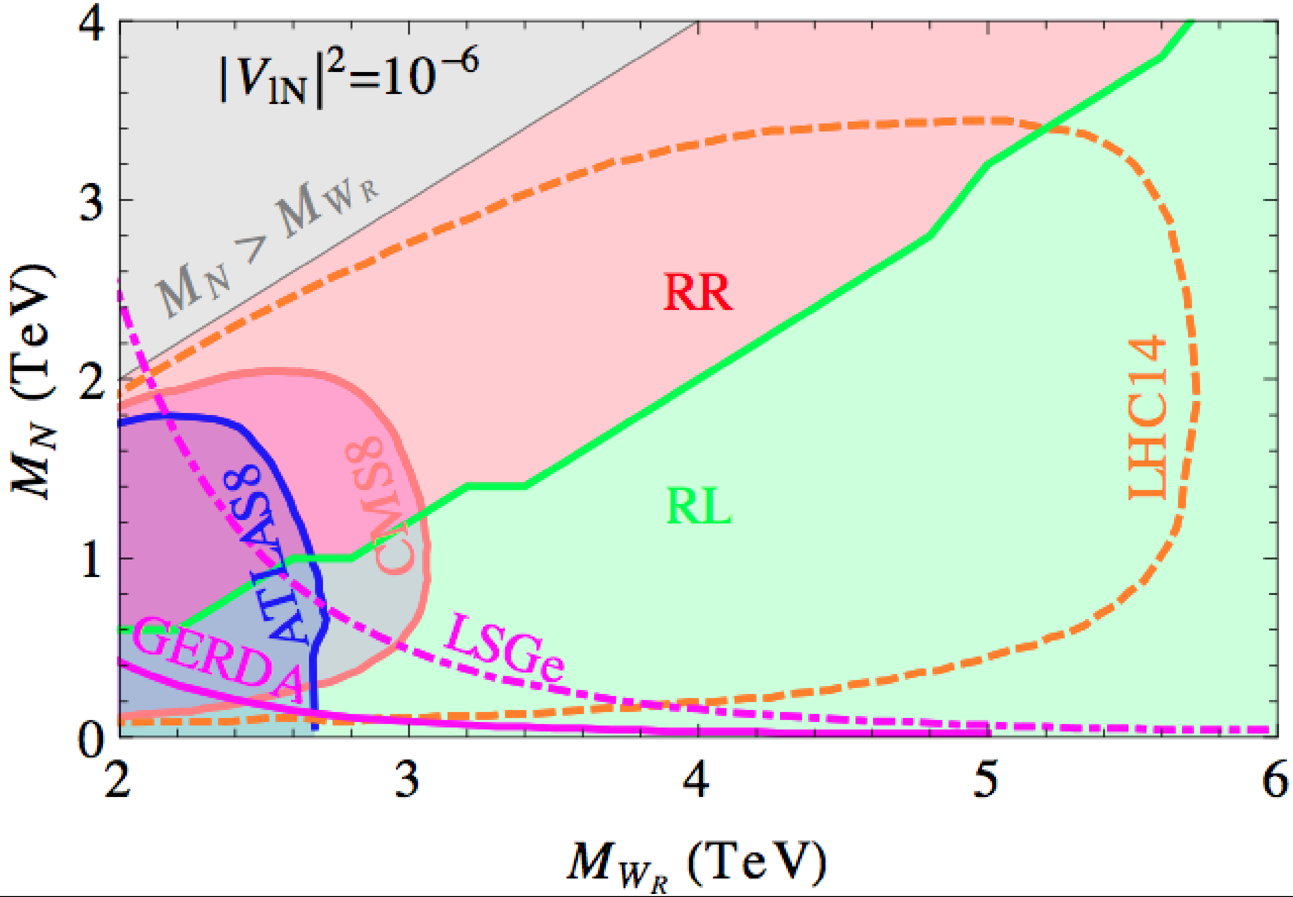
(ii) Heavy particle effects can "fake" IH (e.g. WR)

(ii) New contributions to $\beta\beta_{0\nu}$ in LR models

- 

LHC and double beta reach for W_R

Dev, et al.



(Das, Deppisch, Kittel, Valle)

Case of $M_N > M_{WR}$

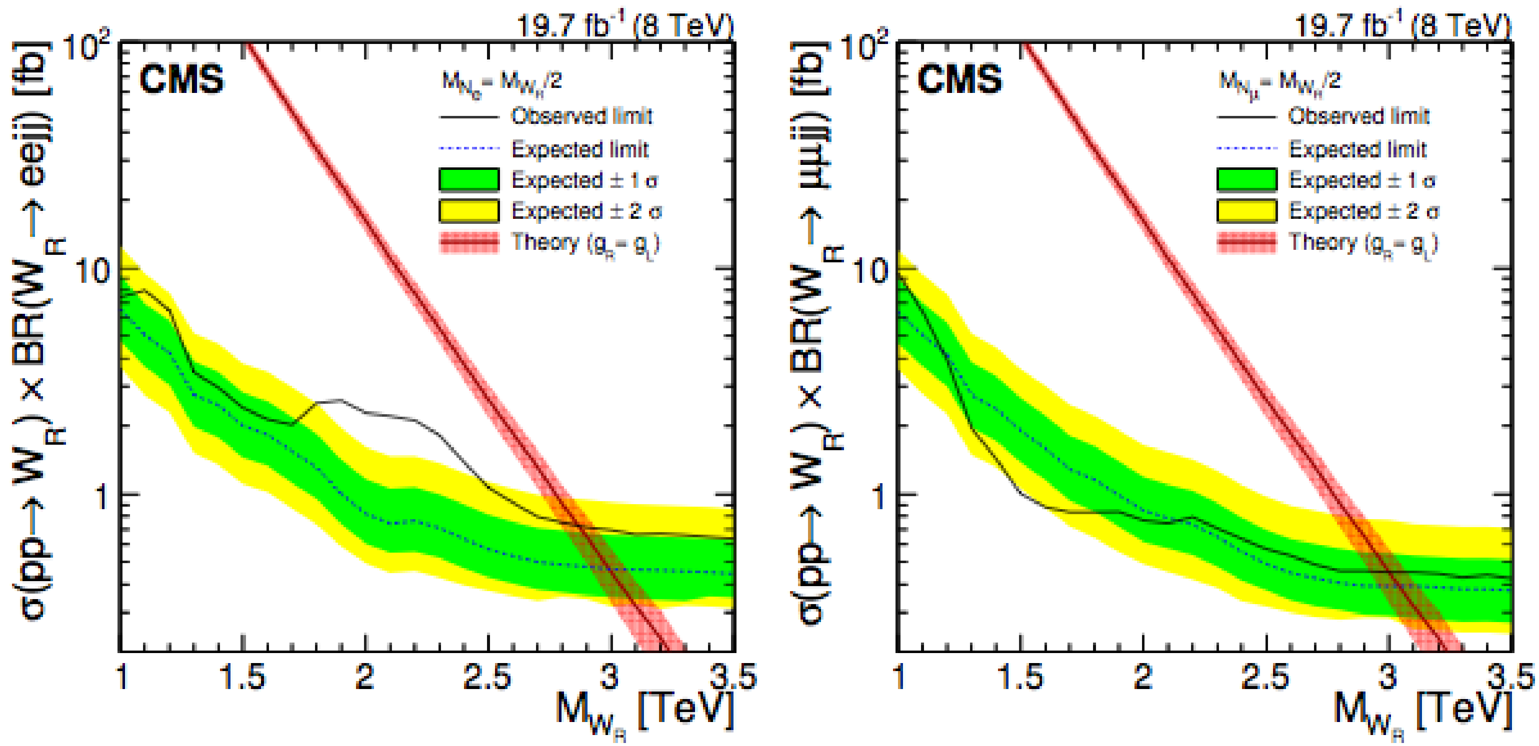
- CP conserving decay mode $N \rightarrow W_R + \ell$ dominates !

- Leptogenesis impossible (Deppisch, Harz, Hirsch'14)

- If experimentally it is found, $M_N > M_{WR}$, this by itself can rule out leptogenesis as a mechanism for origin of matter !!

Intriguing excess in CMS

- . CMS: arXiv:1407.3683



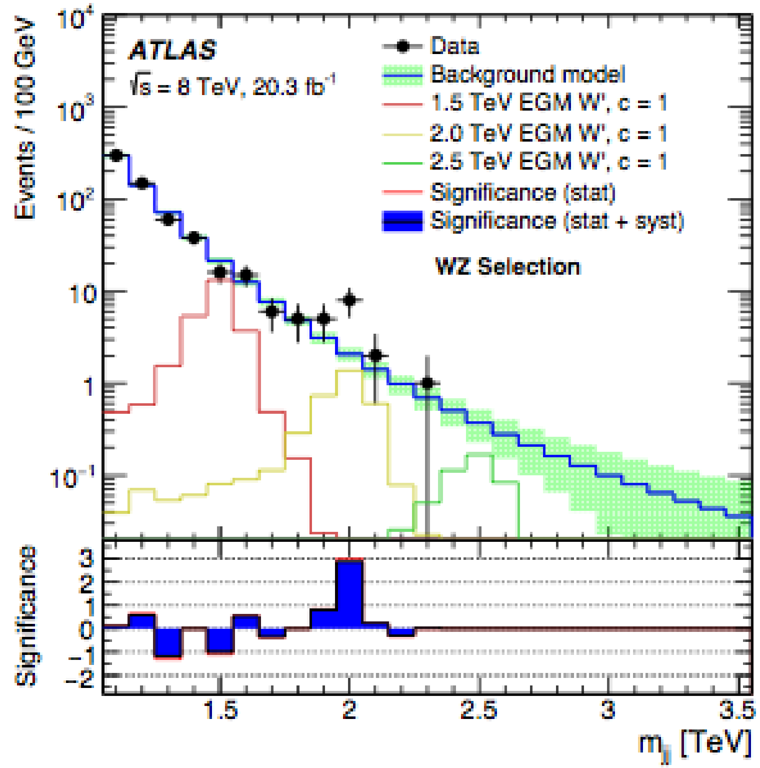
- Possible M_{WR} =2.1 TeV ? : (Deppisch Gonzalo,Patra,sahu,Sarkar; Heikinheimo, Raidal, Spethman; Aguilar-Saavedra, Joachim;Fowlie,Marzola'14; Gluza, Jelinsky'15)

ATLAS Diboson anomaly

- Another W_R decay mode: $W_R \rightarrow W_L Z$ (via WL-WR mixing)
- Could it be connected to ATLAS diboson anomaly around 2-2.3 TeV?

arXiv:1506.00962

- Possibly a CMS $W_R \rightarrow Wh$ anomaly ?



LHC anomalies and LR interpretation (~2 TeV)

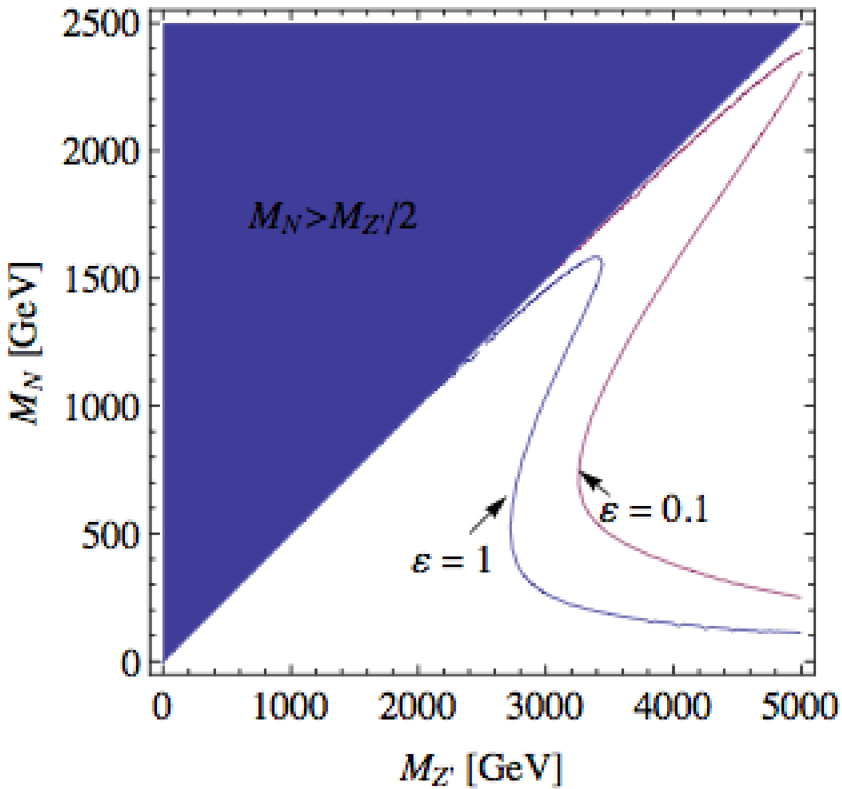
- 2 TeV W_R : $\sigma(W_R) \times B_{W_R \to WZ} \approx 600 g_R^2 B\ fb$
- If no leptons → $M_{N_{e,\mu}} \geq M_{W_R}$
- WZ channel signal at the level of 6-7 fb→ arises from W_L–W_R mixing, corresponds to $\zeta_{LR} \sim 0.01$
- *Signal fits for g_R ~ 0.5 g_L → ~8 excess events* $jjjj$
- *Predicts ~2-3 excess events in the Wh^0 channel – consistent with CMS excess for this channel.* $b\bar{b}\ell\nu$
- *Should not see any signal in WW and ZZ mode.*

Leptogenesis with $M_{Z'} << M_{WR}$

- Effective theory: $SU(2)_L \times U(1)_{I_{3R}} \times U(1)_{B-L}$
- Z′ couples also to NN and effects leptogenesis
- Origin of CP asymmetry same as in WR case via resonant leptogenesis and requires deg $N_{1,2}$: $\mathcal{E}$ can be as large as 1.
- Washout has no W_R contribution but only NN→ Z′→ qq, ll type.
- Lower the Z′, more washout in generic case

Lower bound on $M_{Z'}$

- (Blanchet, Chacko, Granor, RNM'2009, PRD)

- 

$M_{Z'} > 3$ TeV

Directly probing leptogenesis in Z' case:

- Lepton asymmetry $\mathcal{E}$ is directly related to the following collider observable:

$$\frac{N(\ell^+\ell^+) - N(\ell^-\ell^-)}{N(\ell^+\ell^+) + N(\ell^-\ell^-)} = \frac{2\sum_i \varepsilon_i}{\sum_i 1}$$

- Makes it possible to see origin of matter directly.

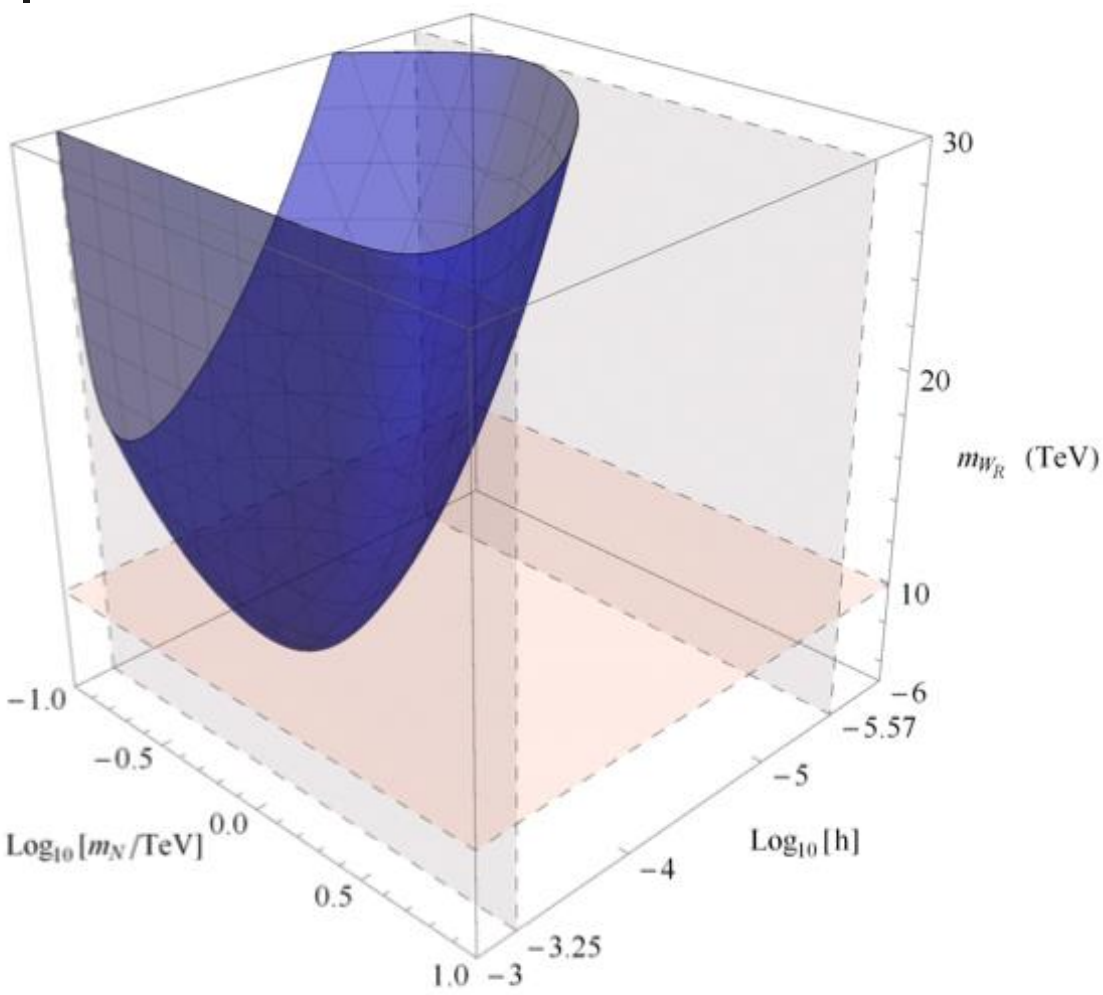
Distinguishing different mechanisms (RR vs RL)

- .Look for end points in various inv. Masses:

	RL	LL	RR	LR
m_{jj}^2	m_W^2	m_W^2	m_N^2	m_N^2
m_{ll}^2	$\frac{(m_{W_R}^2 - m_N^2)(m_N^2 - m_W^2)}{m_N^2}$	$\frac{(s - m_N^2)(m_N^2 - m_W^2)}{m_N^2}$	$m_{W_R}^2 - m_N^2$	$s - m_N^2$
${m_{jl}^{>}}^2$	$m_N^2 - m_W^2$ or	$m_N^2 - m_W^2$ or	m_N^2 or	m_N^2 or
${m_{jl}^{<}}^2$	$m_{W_R}^2 - m_N^2$	$s - m_N^2$	$m_{W_R}^2 - m_N^2$	$s - m_N^2$
m_{llj}^2	$m_{W_R}^2 - m_W^2$	$s - m_W^2$	$m_{W_R}^2$	s
${m_{ljj}^{>}}^2$	m_N^2 or	m_N^2 or	$m_{W_R}^2$	s
${m_{ljj}^{<}}^2$	$m_{W_R}^2 - m_N^2 + m_W^2$	$s - m_N^2 + m_W^2$	m_N^2	m_N^2
m_{lljj}^2	$m_{W_R}^2$	s	$m_{W_R}^2$	s

(Kim, Dev,RNM'15)

Low scale Leptogenesis Plot

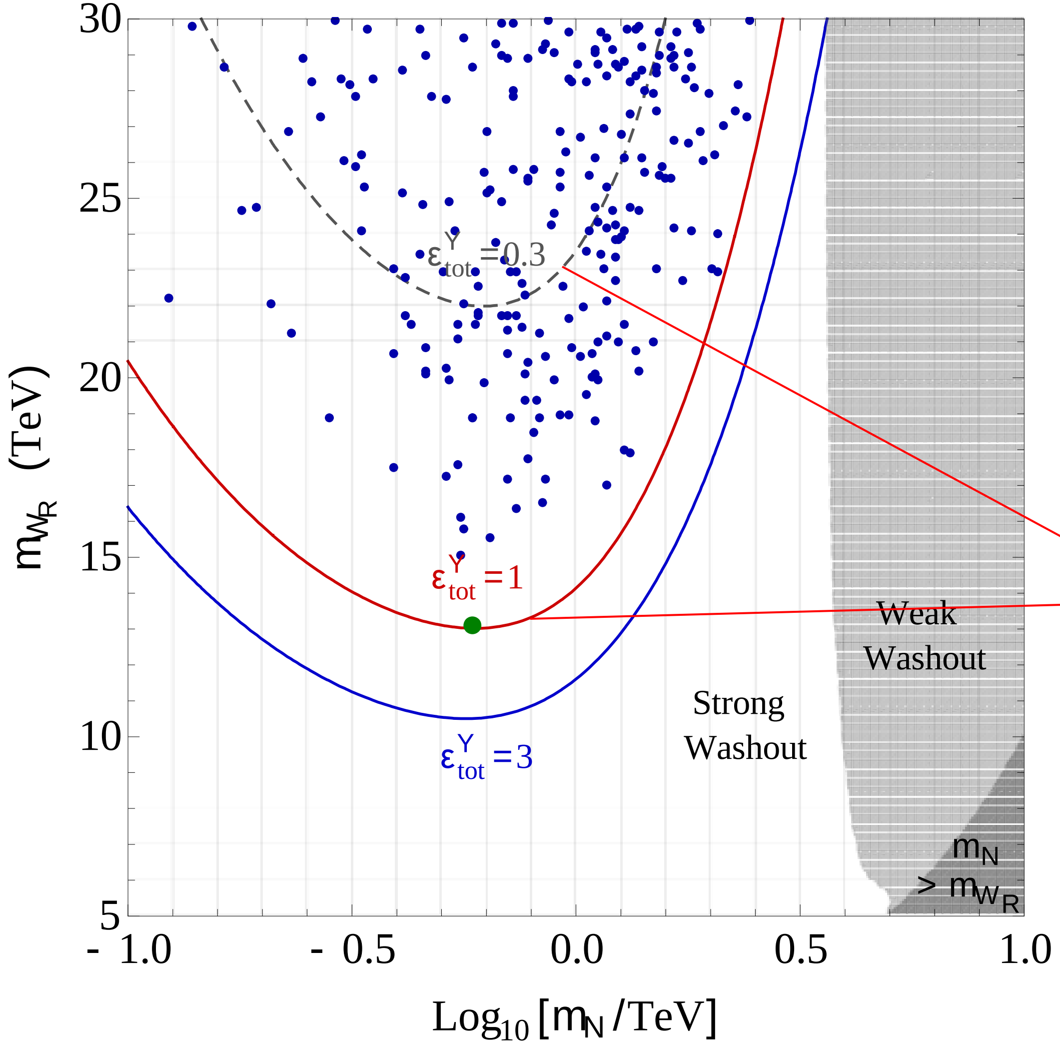


M_{WR} >10 TeV

M_N > 585 GeV

(Dev., Lee and RNM'15)

M_{WR} vs M_N Plot where leptogenesis works



(Dev, Lee, RNM'15)

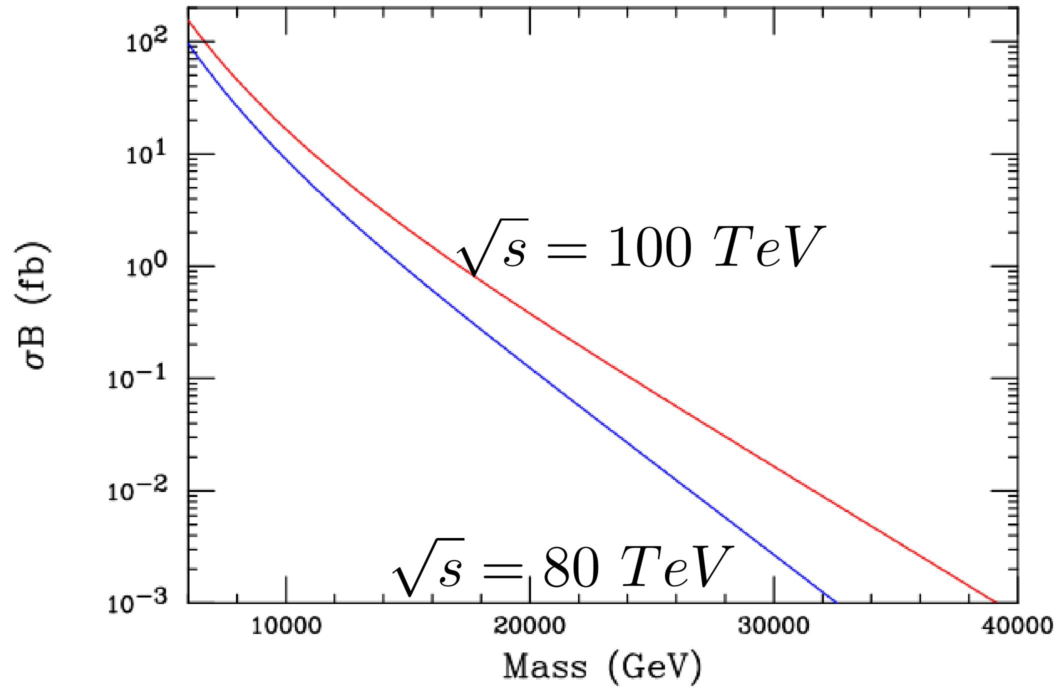
$M_{WR} > 10$ TeV

$M_N > 585$ GeV

Explicit models with nu mass fits.

Higher Mass WR probe at Future Circular colliders

- So far one study by Rizzo: $W_R \to \ell + \nu'$ channel



$M_{WR} < 30$ TeV

- For the $\ell^{\pm}\ell^{\pm}jj$ channel, see Ng, Puente,Pan'15

Right handed neutrino mass restricted by low energy obs.

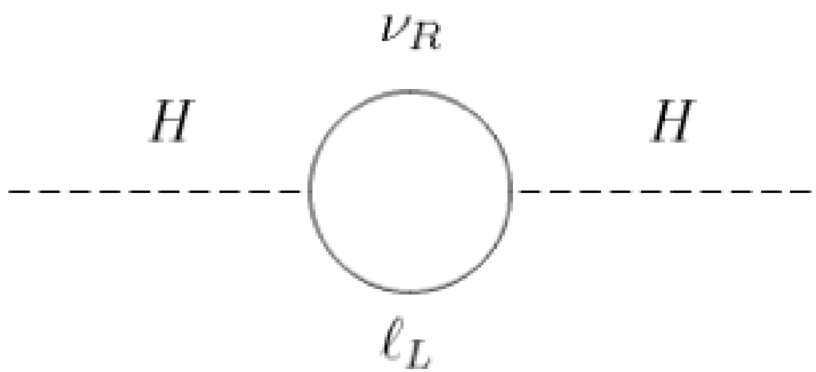
- Low scale seesaw → Δ_R masses below 10 TeV

- $\mu \to 3e, \ \mu \to e + \gamma, \ \tau \to 3e$ etc. bounds restrict flavor structure of Δ_R coupling f and hence RHN mass texture $M_N = f v_R$!!

- One (only) allowed texture: $M_N = \begin{pmatrix} 0 & M_1 & 0 \\ M_1 & 0 & 0 \\ 0 & 0 & M_2 \end{pmatrix}$

Naturalness arguments for lower Seesaw scale

- Correction to Higgs mass from RHN Yukawa



$$\leq 1 \text{ TeV}^2$$

→ $M_R < 7 \times 10^7$ GeV (not a GUT scale)

(Vissani'97; Clarke, Foot, Volkas'15)

- Explore TeV scale models !!

SUSY+Leptogenesis also prefer low scale seesaw

- For leptogenesis to occur, $M_N < T_{reheat}$;
- Gravitino overclosing prefers that $T_{reheat} < 10^6$ GeV (Kohri et al.)

→ Hence preference of leptogenesis for lower seesaw scale !!

Experimental searches for TeV W_R effects

- Collider searches for W_R and N: LHC

  (i) Direct WR production

  (ii) ν-N mixing from seesaw $V_{\ell N} = \sqrt{\frac{m_\nu}{M_N}}$

  (Han, Ruiz et al; Senjanovic, Nemevsek, Nesti, Tello,..Deppisch, Dev, Pilaftsis;..Del Aguila et al.)

- New leptophilic Higgses: Δ^{++}, Δ^{+}

  (Chakrabortty,Gluza, Bhambaniya, Zafron,..Dutta, Goa, Ghosh,Eusebii, Kamon…)

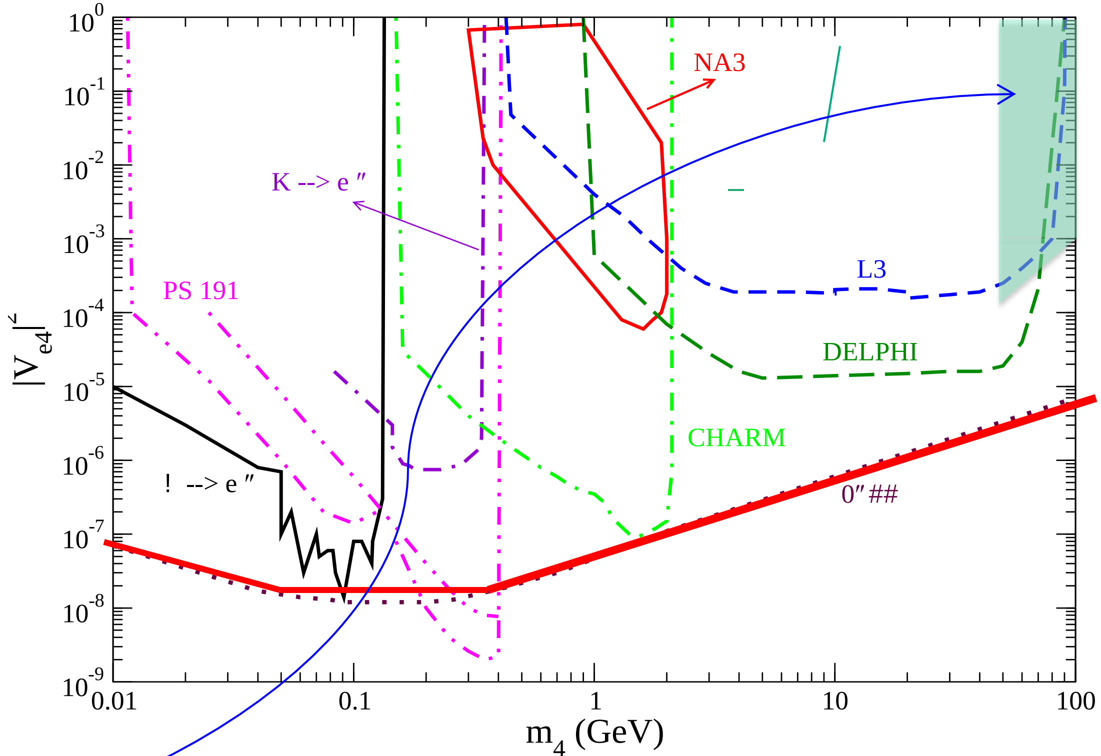
- Neutrinoless double beta decay and LFV

  (RNM'86; Hirsch, Klapdor,Kovalenko'96; Das, Deppisch, Kittel, Valle; Dev, Goswami, Mitra;….)

- Light N's and displaced vertices (Helo, Dib, Kovalenko,Ortiz,)

Lower Mass N_R

$\nu - N$ mixing $V_{\ell N}$



(Atre, Han, Pascoli, Zhang; Antusch,Fisher'14)

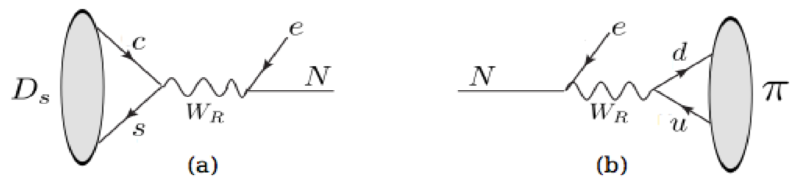
Bounds from LHC Higgs decay to $e^+e^-\not{E}_T$ from $pp \to h \to \ell N$

$N \to W^+\ell^-, Z + \nu$

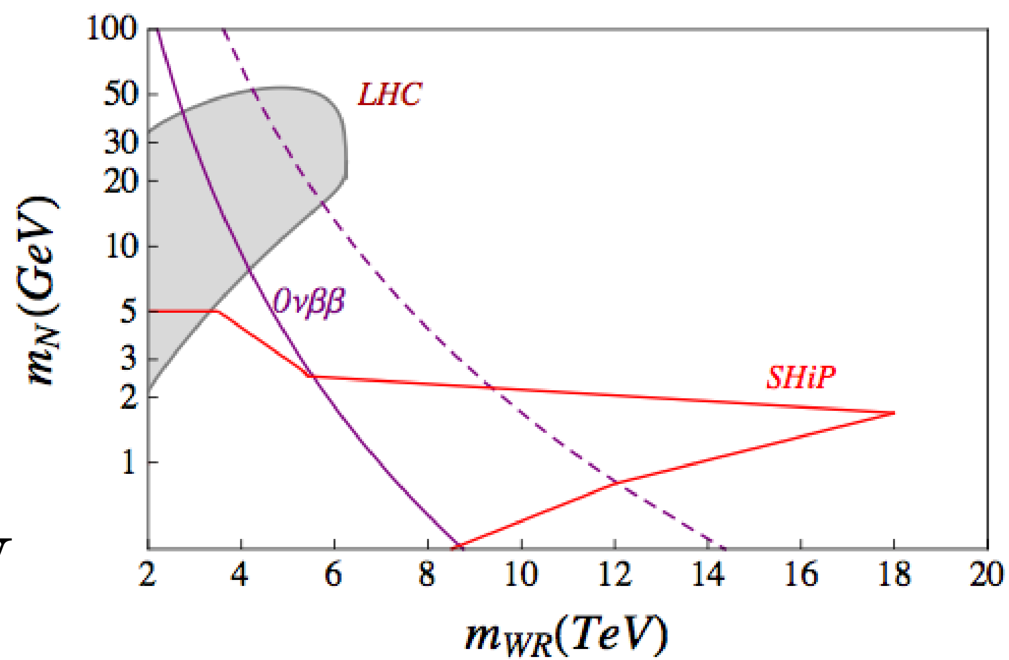
(Dev, Francischini, RNM'12 ; Gago,Hernandez,Perez,Losada,Briceno'15)

Beam Dump searches

- Displaced vertices (Castillo-Feliosela, Helo, Dib, Kovalenko, Ortiz'15)
- $M_N < 1.8$ GeV



SHIP setup



- Reach:

$$M_{W_R} \leq 18 \text{ TeV}$$