Probing TeV Scale Origin of Neutrino Mass and Baryon Excess

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Neutrino mass and BSM physics

- Neutrino are now known to have mass !
- Since $m_\nu = 0$ in SM, neutrino mass is first evidence of physics beyond SM (BSM).
- Origin of matter cannot be understood within SM: its understanding requires BSM physics.
- This talk: *Could both these problems be connected to physics at TeV scale and be accessible at colliders and in low energy searches ?*

Weinberg Effective operator as starting paradigm for m_ν

- Add effective operator to SM: $$\lambda \frac{LHLH}{M}$$
- After symmetry breaking $$m_\nu = \lambda \frac{v_{wk}^2}{M}$$
- M is BSM physics and is arbitrary; can be large
  → $M \gg v_{wk} \rightarrow \text{small } m_\nu$
- *Operator breaks lepton number !!*

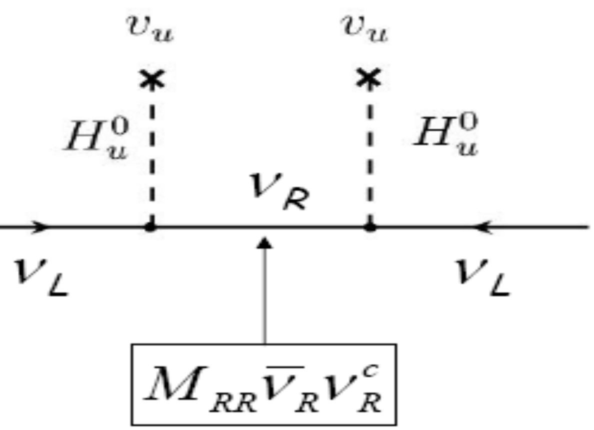
Scale of L-violation

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

- Naive lore:
- Neutrino osc data→ m_ν << eV
- So if $\lambda \sim 1; M \sim 10^{14}\ \mathrm{GeV}$ (Beyond reach!)
- Dimensional analysis arguments, however, can be quite misleading !!
- To explore true scale, UV completion of Weinberg operator essential (*build models*) !!

Seesaw as step towards UV completion of Weinberg Op.

- Add right handed nu 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 → L violation
- Could Majorana N be accessible (~TeV) ?

Bonus from Seesaw UV completion: Leptogenesis origin of matter

- Fukugita and Yanagida (1986) RH neutrino is its own anti-particle: so it can decay to both leptons and anti-leptons:
- Proposal: Heavy ν_R decays:

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

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

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

(Kuzmin, Rubakov,Schaposnikov'83)

- Related to neutrino mass and hence attractive; motivates search for CP violation in nu-oscillations !!

Can seesaw and hence leptogenesis scale be TeV's ?

- Search for explicit UV complete models
- Guiding principle in this search

(i) Existence of N should be predicted by theory

(ii) Seesaw scale should be related to symmetry

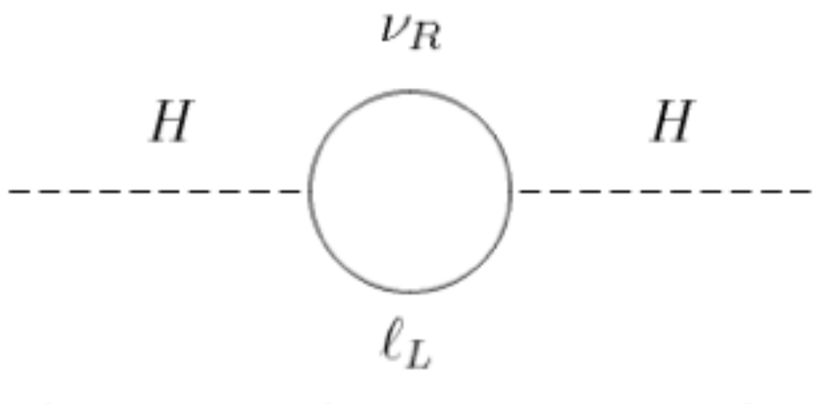
- Two simple theories that conform to these:

(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)*

Naturalness arguments for lower Seesaw scale

- Correction to Higgs mass from RHN Yukawa



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

→ $M_R < 7 \times 10^7$ 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 !!

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

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

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

Why these models are attractive ?

- New way to understanding parity violation:
- A more physical electric charge formula
- Explains small neutrino masses via seesaw:
- Solves strong CP problem:
- With supersymmetry, provides a naturally stable dark matter (automatic R-parity)
- Can explain the origin of matter (see later)

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) $\qquad M_N = f v_R$

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

$\downarrow$ κ $\quad\Longrightarrow\quad$ Seesaw

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

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

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

Minimal SUSY left-right requires low scale 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 !

However due to RPV, neutrino masses get complicated !

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;*

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

- *Neutrino masses from usual seesaw*

Seesaw formula in TeV scale LR models

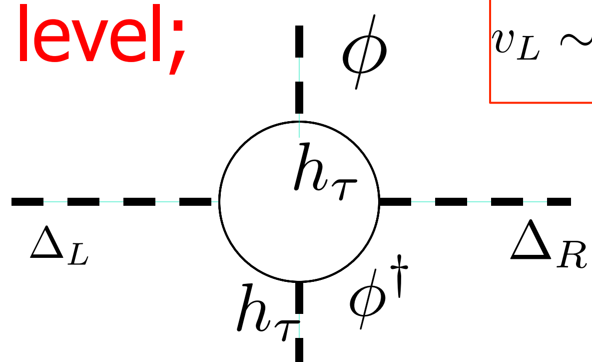
- Generic LR models with parity down to TeV,

$$< \Delta_R^0 > v_R \;\; \rightarrow < \Delta_L^0 > \simeq \frac{\kappa^2}{v_R}$$

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

- First term too large for TeV seesaw; two ways to prevent
  (i) decouple P breaking from $SU(2)_R$
  (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 (non-SUSY)

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

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

Understanding small nu mass

- Neutrino Mass texture:

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

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

- 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)

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^{+}

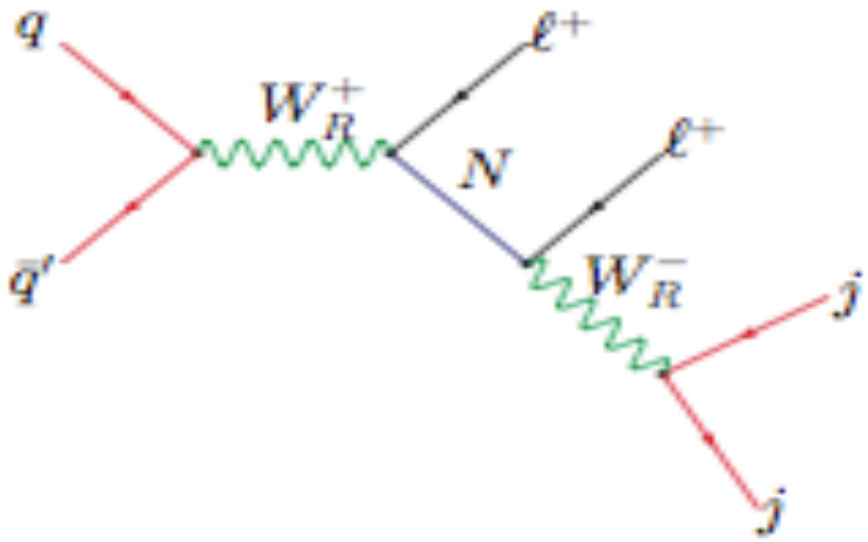
  (Chakrabortty,Gluza, Bhambaniya, Zafron,..Dutta, Goa, Ghosh,Eusebii, Kamon…)

- Neutrinoless double beta decay and LFV

  (Das, Deppisch, Kittel, Valle; Dev, Goswami, Mitra;….)

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

WR search at LHC



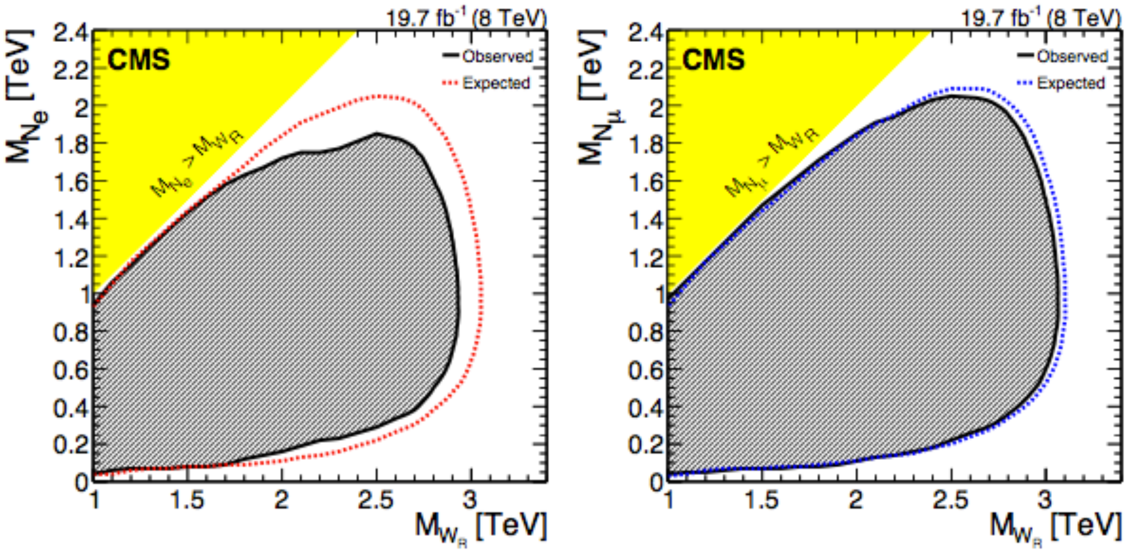
$$N \to l^{\pm} jj$$

(Keung, Senjanovic'83)

- Golden channel: $\ell_i \ell_k jj$;
- Probes RHN flavor pattern: $A_{\ell^+\ell^+jj} \propto M^{-1}_{N,ik}$

Current LHC analysis: only W_R graph

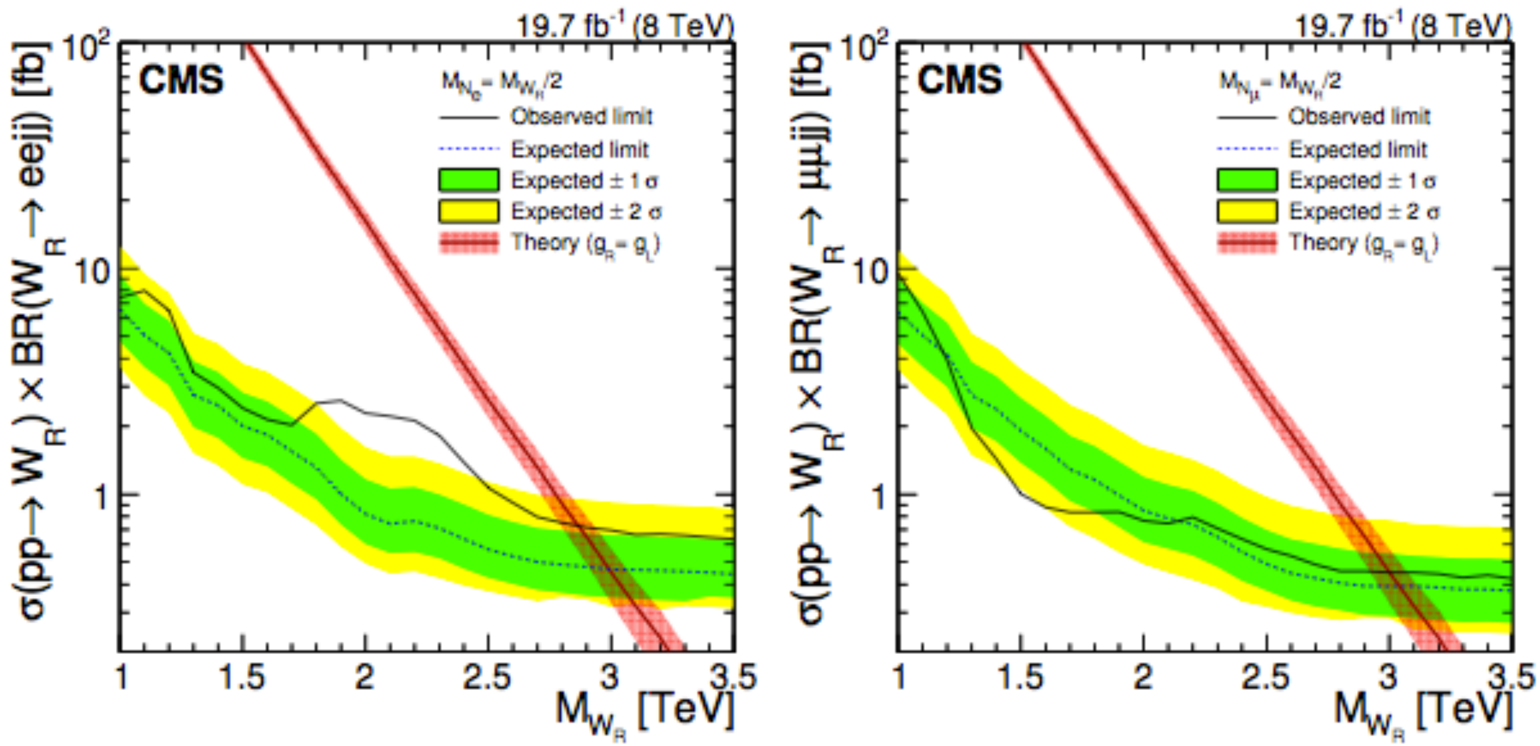
- Current W_R limits from CMS, ATLAS 2.9 TeV;



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

Intriguing excess in CMS

- . CMS: arXiv:1407.3683

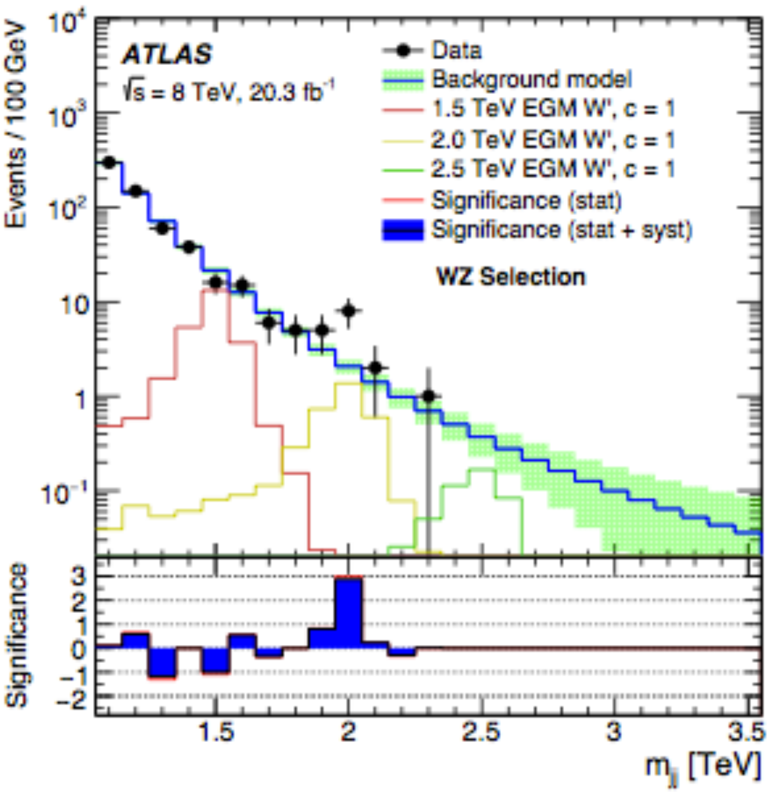


- Possible M_{WR} =2.1 TeV ? : (Deppisch Gonzalo,Patra,sahu,Sarkar; Heikinheimo, Raidal, Spethman; Aguilar-Saavedra, Joachim;Fowlie,Marzola'14; Gluza, Jelinsky'15)

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 TeV?

arXiv:1506.00962



- Anomaly in W*h* channel

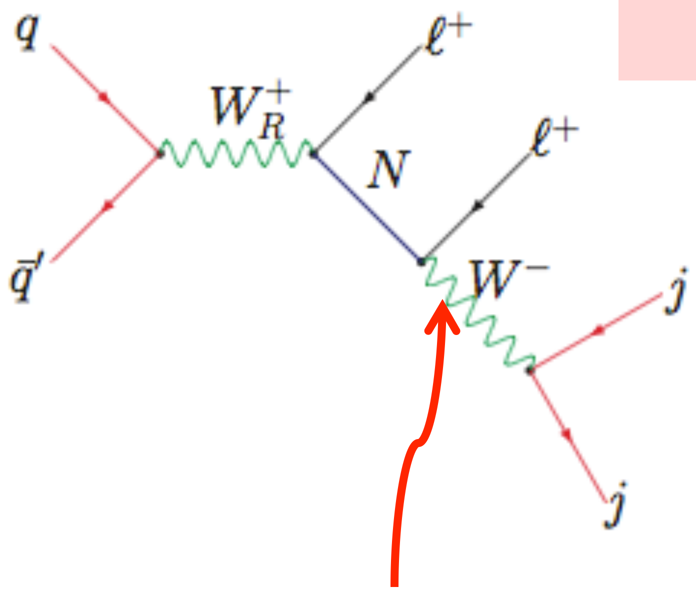
(Hisano et al. Dobrescu, Liu; Gao, Ghosh,Sinha,Yu; Cheung et al)

New (RL) contribution to like sign dilepton signal

- When $V_{\ell N} \sim 0.01 - 0.001$, new contributions:

(Nemevsek, Tello, Senjanovic'12; Chen, Dev, RNM' arXiv: 1306.2342- PRD)

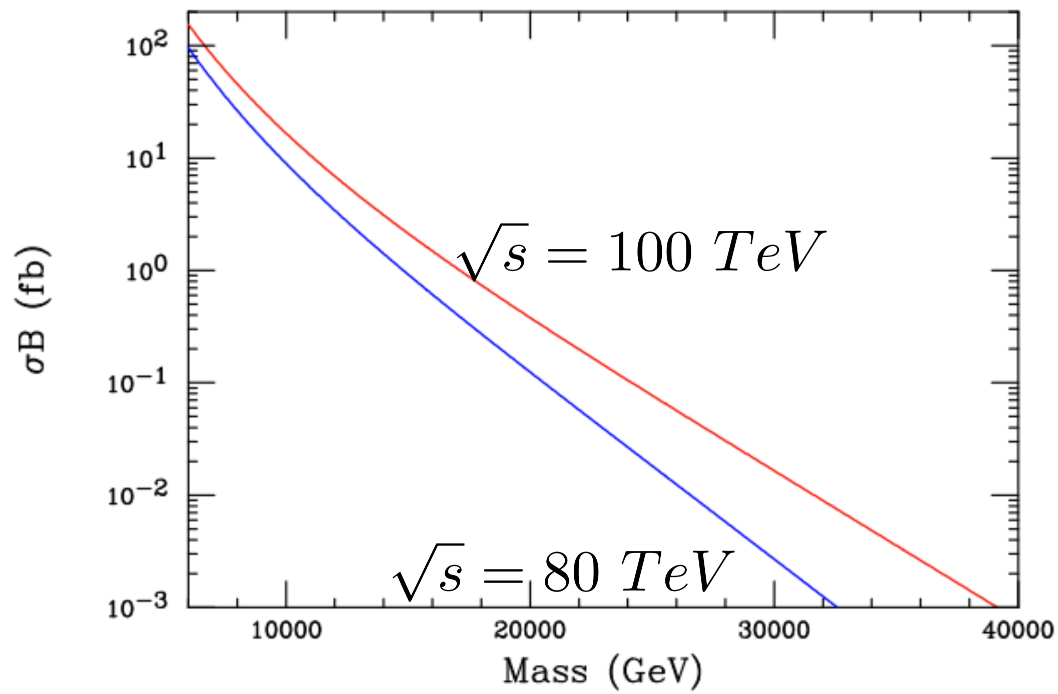
$$q\bar{q} \to W_R \to \ell + N;$$
$$N \to \ell W_L$$



- Flavor dependence will probe Dirac mass M_D profile:

Higher Mass WR probe at Future Circular colliders

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

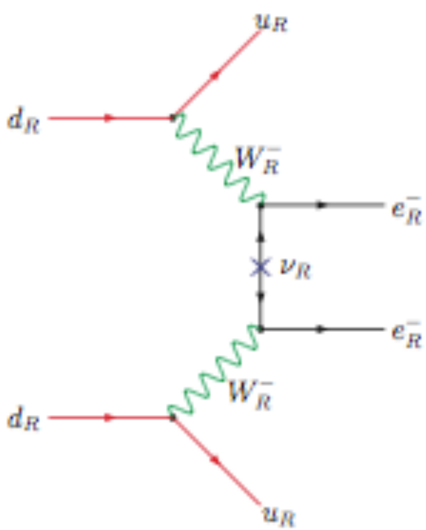


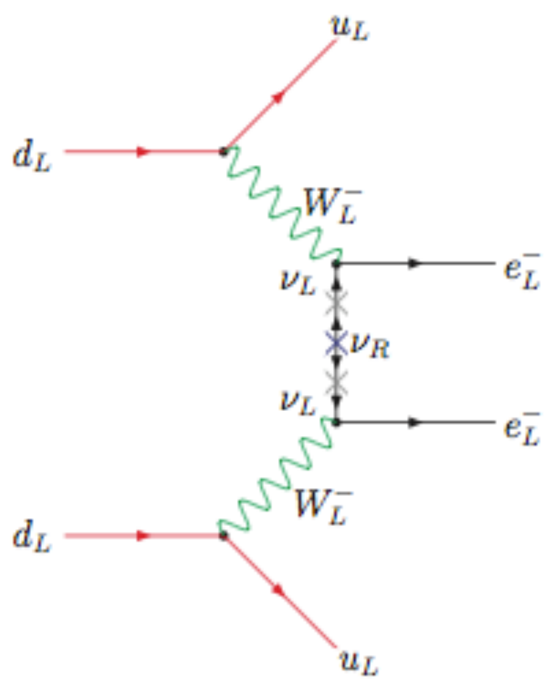
Reach:

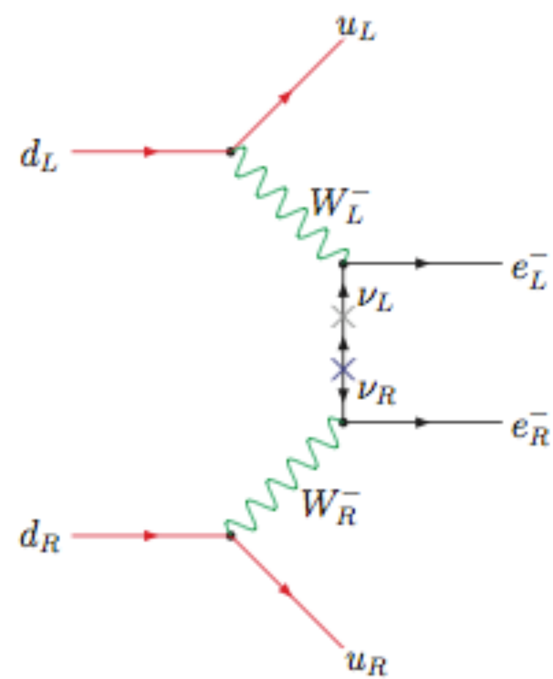
M_{WR} < 30 TeV

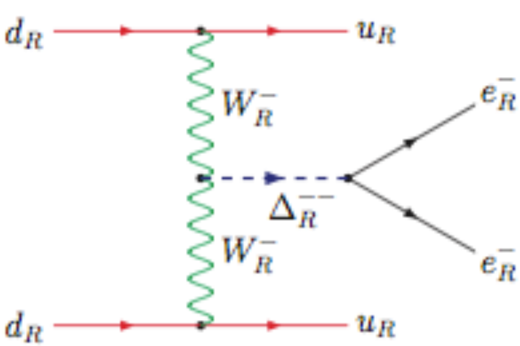
- For the $\ell^{\pm}\ell^{\pm}jj$ channel, see Ng, Puente,Pan'15

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



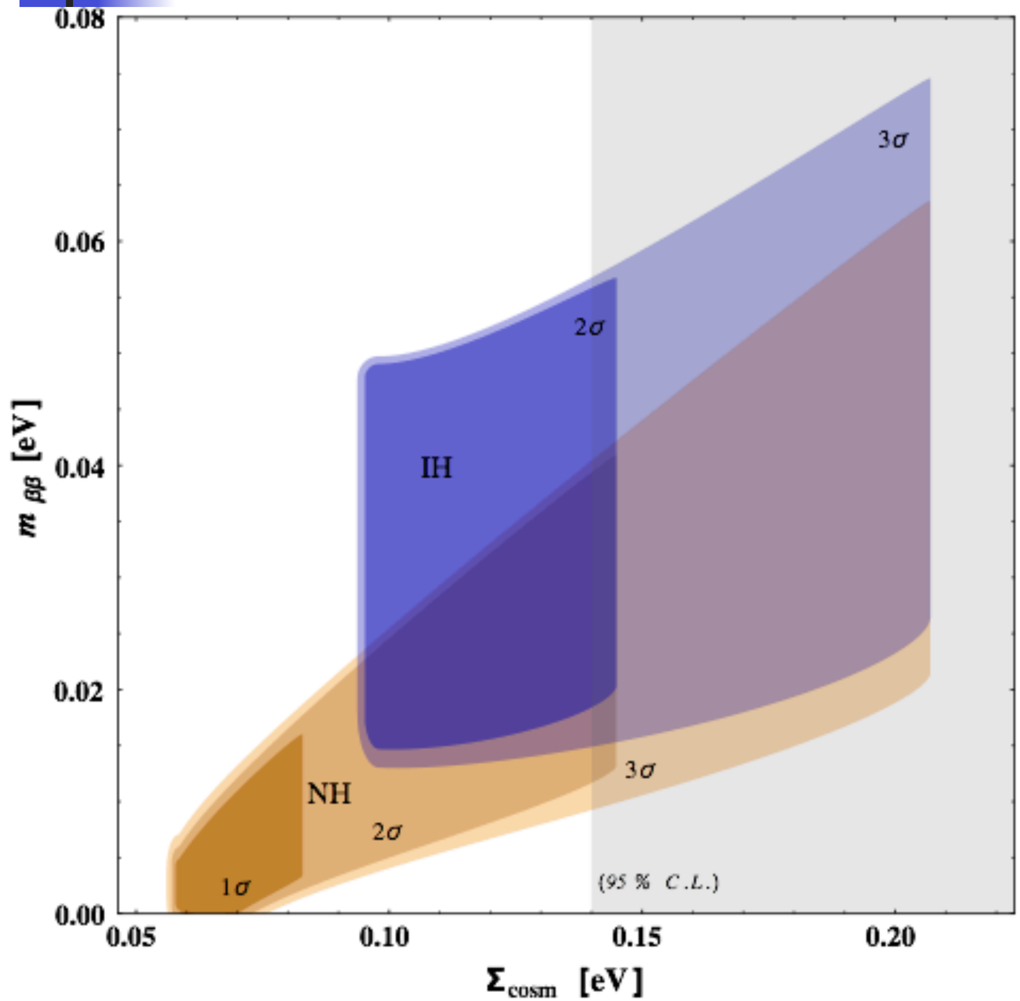






- Now $>10^{25}$ yr. Future $>10^{28}$ yr

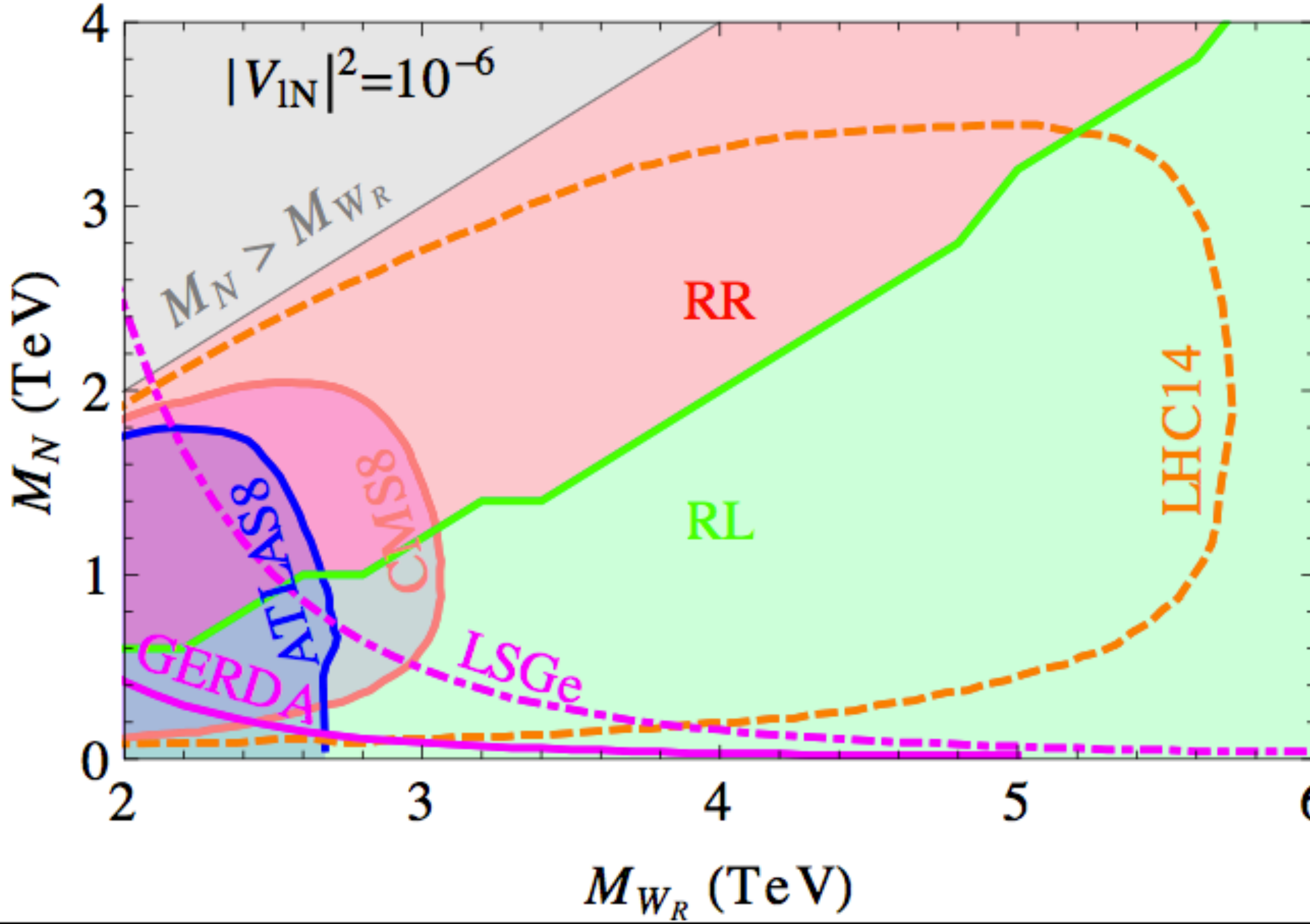
Cosmology and $\beta\beta_{0\nu}$



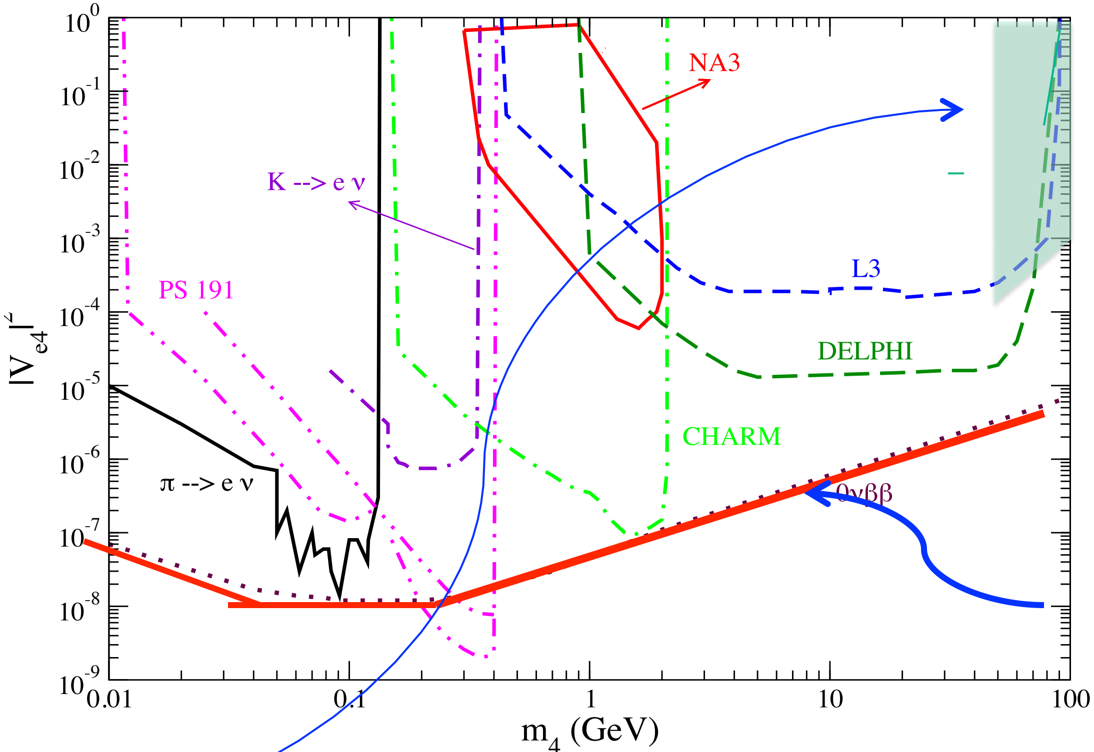
Low WR effect could fake IH or appear in in the forbidden area

LHC and double beta reach

- Dev,..



Constraints RH Neutrino M_N in the lower mass range



most relevant for seesaw

(Atre, Han, Pascoli, Zhang)

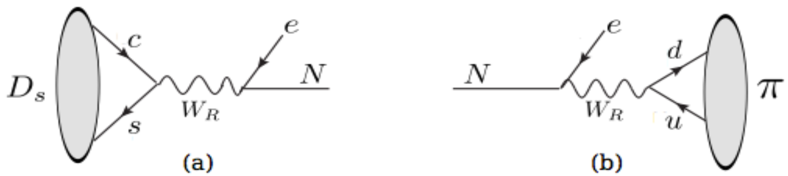
Bounds from LHC Higgs decay to $e^+e^-\not{E}_T$ from $pp \to h \to \ell N$

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

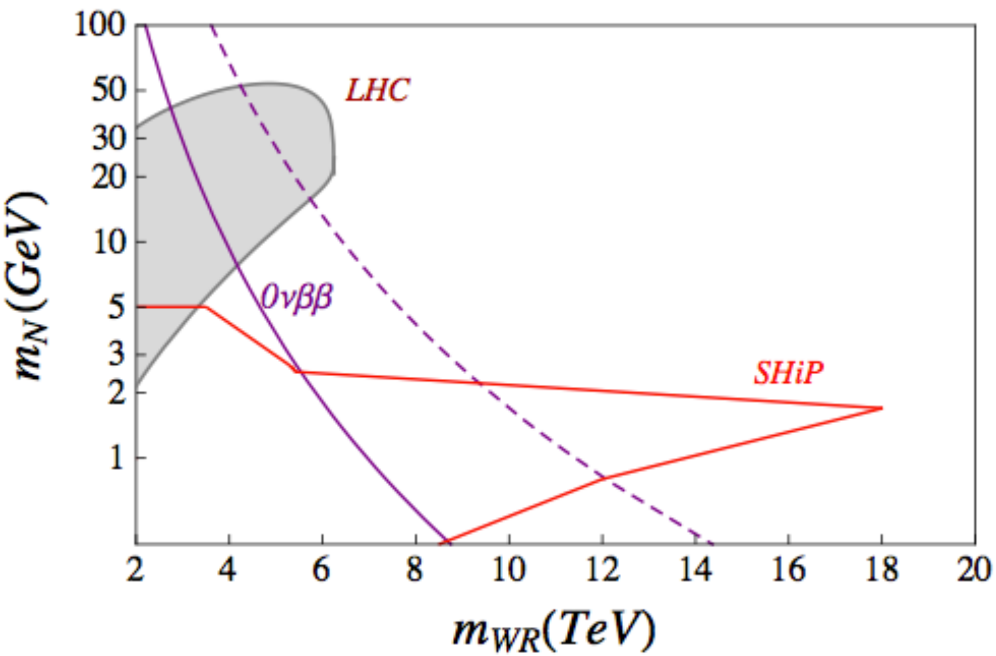
(Dev, Francischini, RNM'12 ; Gago,Hernandez,Perez,Losada,Briceno'15)

Beam Dump searches

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



SHIP setup



- Reach:

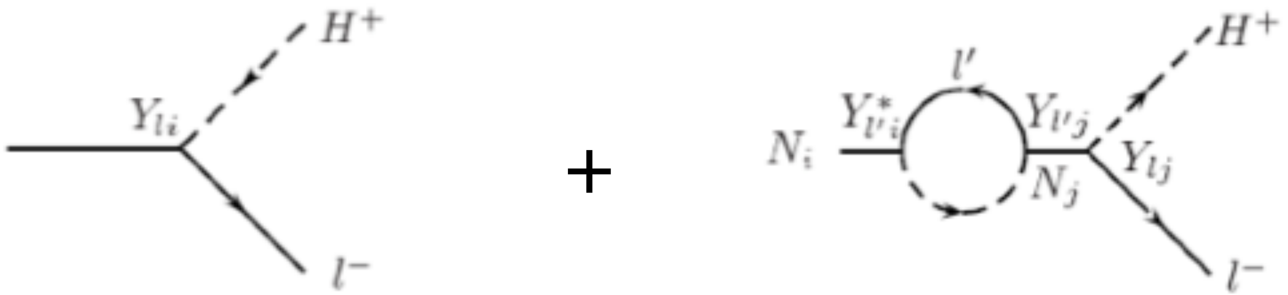
$$M_{W_R} \leq 18 \text{ TeV}$$

Understanding origin of matter with TeV scale L- violation !

Does Leptogenesis work in TeV W_R models

- Since $m_\nu \simeq -\frac{(Y\kappa)^2}{f v_R}$, TeV v_R means $Y \leq 10^{-5.5}$
- Vertex diagram $\epsilon_{CP} \sim \frac{Im(Y^\dagger Y)^2}{4\pi Y^\dagger Y} \sim 10^{-12}$
- since $\frac{n_B}{n_\gamma} \sim 10^{-2} \epsilon_{CP} \kappa_{eff}$ (κ_{eff}=wash out)
- Vertex diagram does not work→resonant leptogenesis

TeV scale Resonant leptogenesis:

- RH neutrino mass ~ TeV scale
- 

- $$\frac{n_B}{n_\gamma} \propto \frac{ImY^4}{|Y|^2} \frac{M_1 M_2 (M_2^2 - M_1^2)}{(M_2^2 - M_1^2)^2 + (M_1\Gamma_1 + M_2\Gamma_2)^2}$$
- Generic model requires degenerate RHNs to get enough n_B/n_γ
- Deg. Natural with our texture:

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

Final baryon asymmetry from lepton asymmetry

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

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

$$\Gamma_D \propto Y^2$$

$$\Gamma_S \propto M_{W_R}^{-4}$$

- In LR, $\kappa_{eff} \propto \frac{\Gamma_D/\Gamma_S}{1+\Gamma_D/\Gamma_S} \ll 1$
- 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)

Case of $M_N > M_{WR}$

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

Summary

- TeV scale seesaw is theoretically appealing, can explain neutrino masses contrary to common lore!
- Left-Right theories provide a simple realization with testable collider implications (W_R , Z', N, Δ_R^{++})!
- Minimal susy LR-rational requires→ *M_{WR} < multi-TeV*

- Leptogenesis bound on W_R→ *M_{WR}> 10 TeV*
- If colliders find W_R with mass < 10 TeV or $M_{WR} < M_N$ or light N, leptogenesis can be ruled out.
- *Further impetus to search for W_R!*

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

LHC anomalies (~2 TeV)

- 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)

LHC anomalies and LR interpretation (~2 TeV)

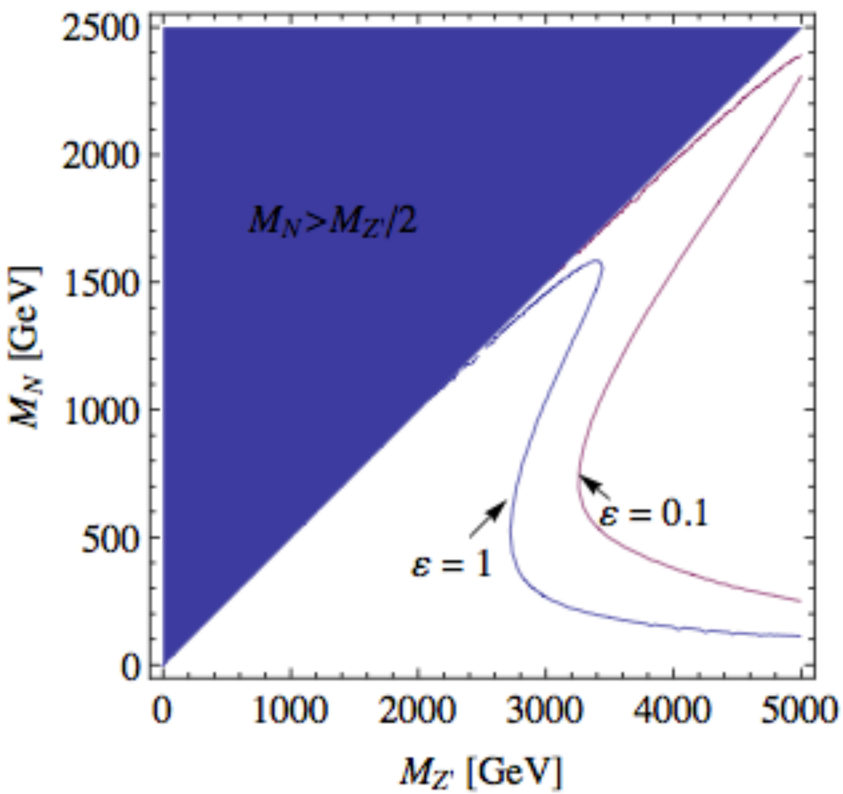
- 2 TeV W_R : $\sigma(W_R) \times B_{W_R \to WZ} \approx 600 g_R^2 B\ fb$
- If no leptons → $M_{N_{e,\mu}} \geq M_{W_R}$
- WZ channel signal at the level of 6-7 fb→ arises from W_L –W_R mixing, corresponds to $\zeta_{LR} \sim 0.01$
- *Signal fits for $g_R \sim 0.5\ g_L$ → ~8 excess events* $jjjj$
- *Predicts ~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)

M_{WR} vs M_N Plot for one model for leptogenesis

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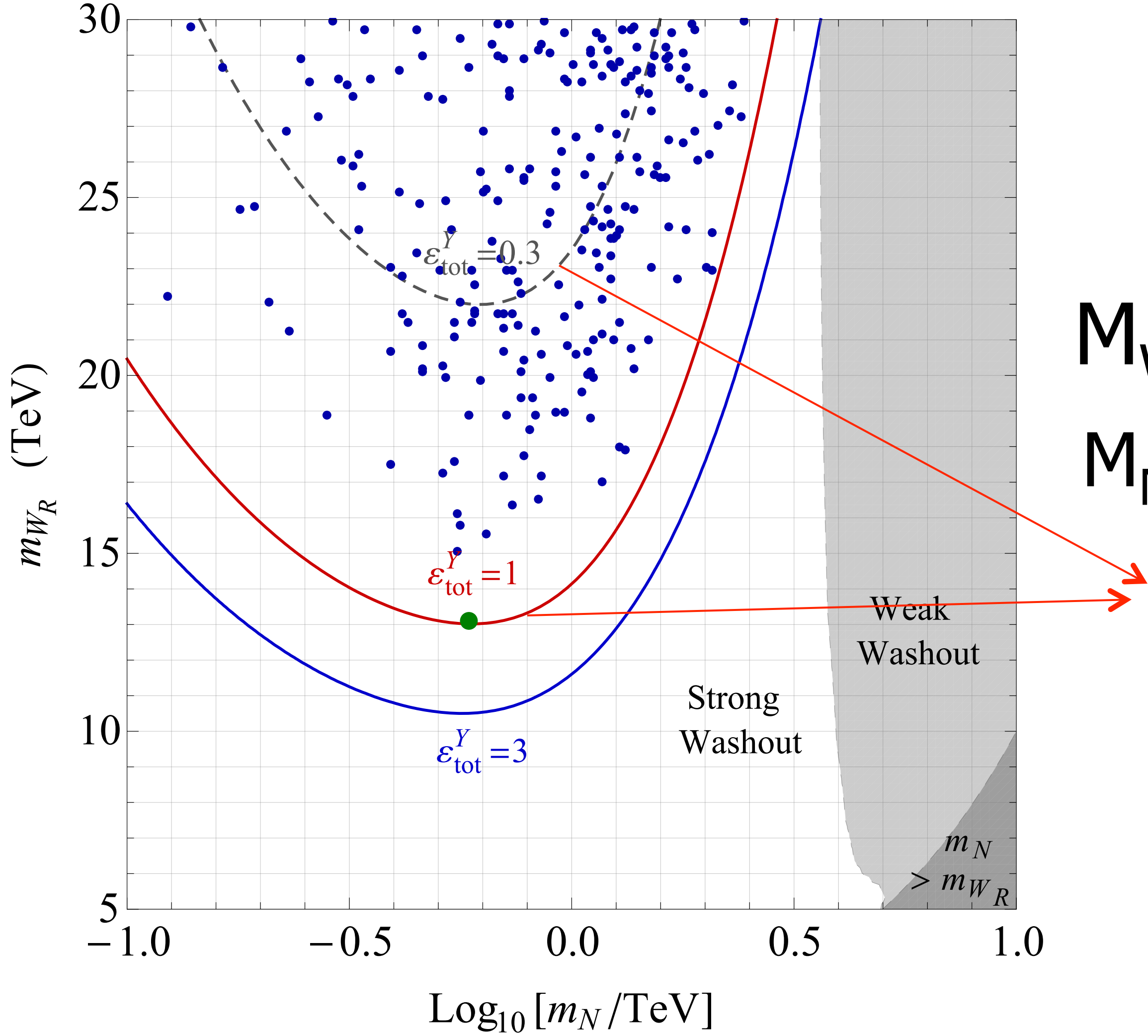
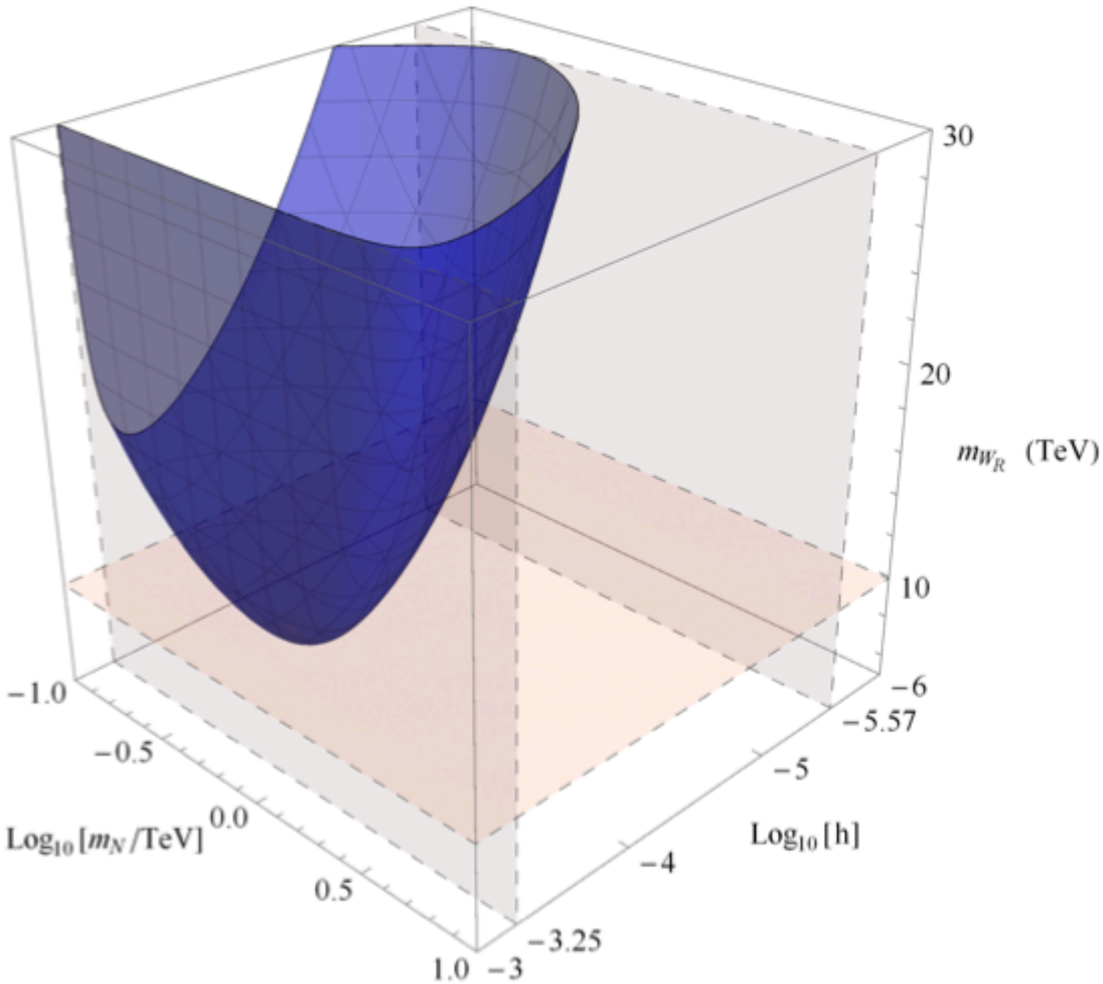


M_{WR} >10 TeV

M_N > 585 GeV

Explicit models with nu mass fits.

Low scale Leptogenesis Plot



M_{WR} >10 TeV

M_N > 585 GeV

(Dev., Lee and RNM'15)