Hints for a TeV scale W_R at the LHC and constraints on leptogenesis

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Based on
Phys. Rev. D 91, 055010 (2015),
JCAP 09, 035 (2015),
Phys. Rev. D - Rap Com 92, 031701(2015),
and arXiv:1507.08297

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The Challenge: A Cosmic Broken Symmetry

- Today: $B \equiv \#$ (Baryons) - $\#$ (Antibaryons) $\neq 0$
- $\frac{n_b}{n_\gamma} \sim 10^{-10}$ while $\frac{n_{\bar{b}}}{n_\gamma} \sim 10^{-20}$
- Standard Cosmology:
  at $t < 10^{-6}$ sec $\Rightarrow \frac{n_b - n_{\bar{b}}}{n_b} \sim 10^{-8}$

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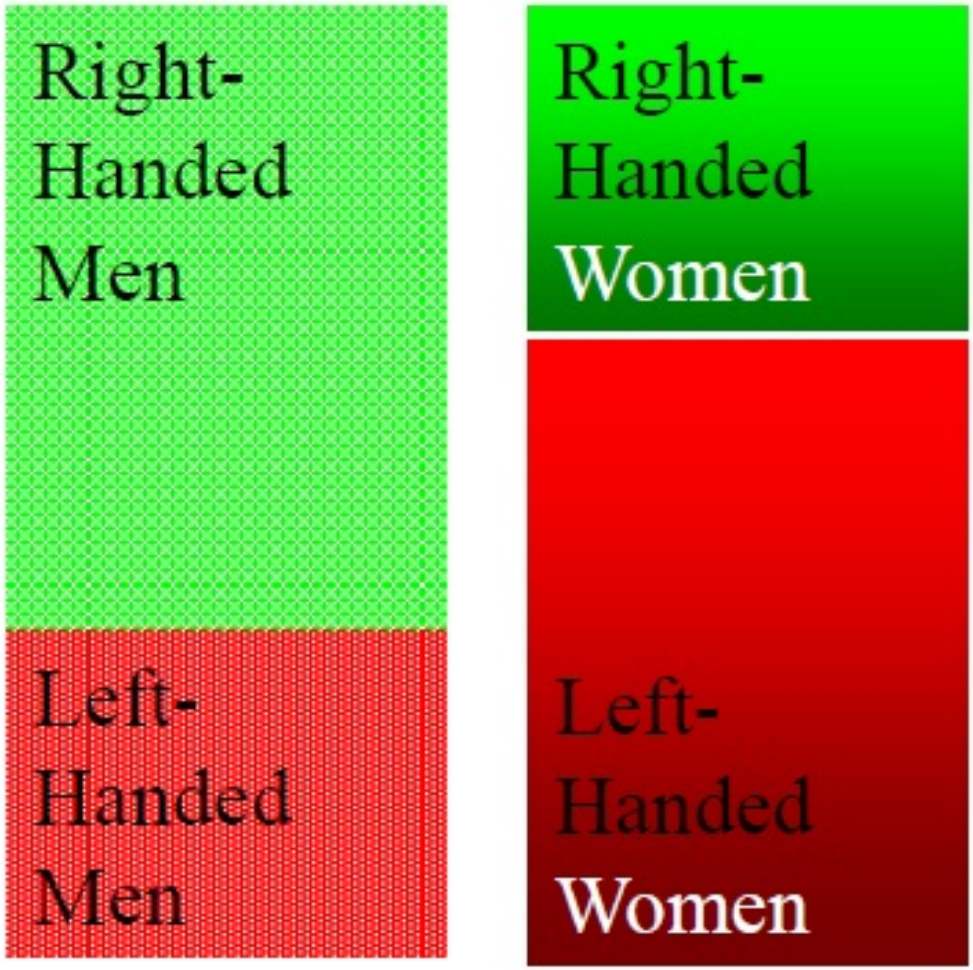
How did $B \sim 0 \Rightarrow B \neq 0$

Sakharov: three conditions to be met in order to dynamically generate of the baryon asymmetry ("baryogenesis") :

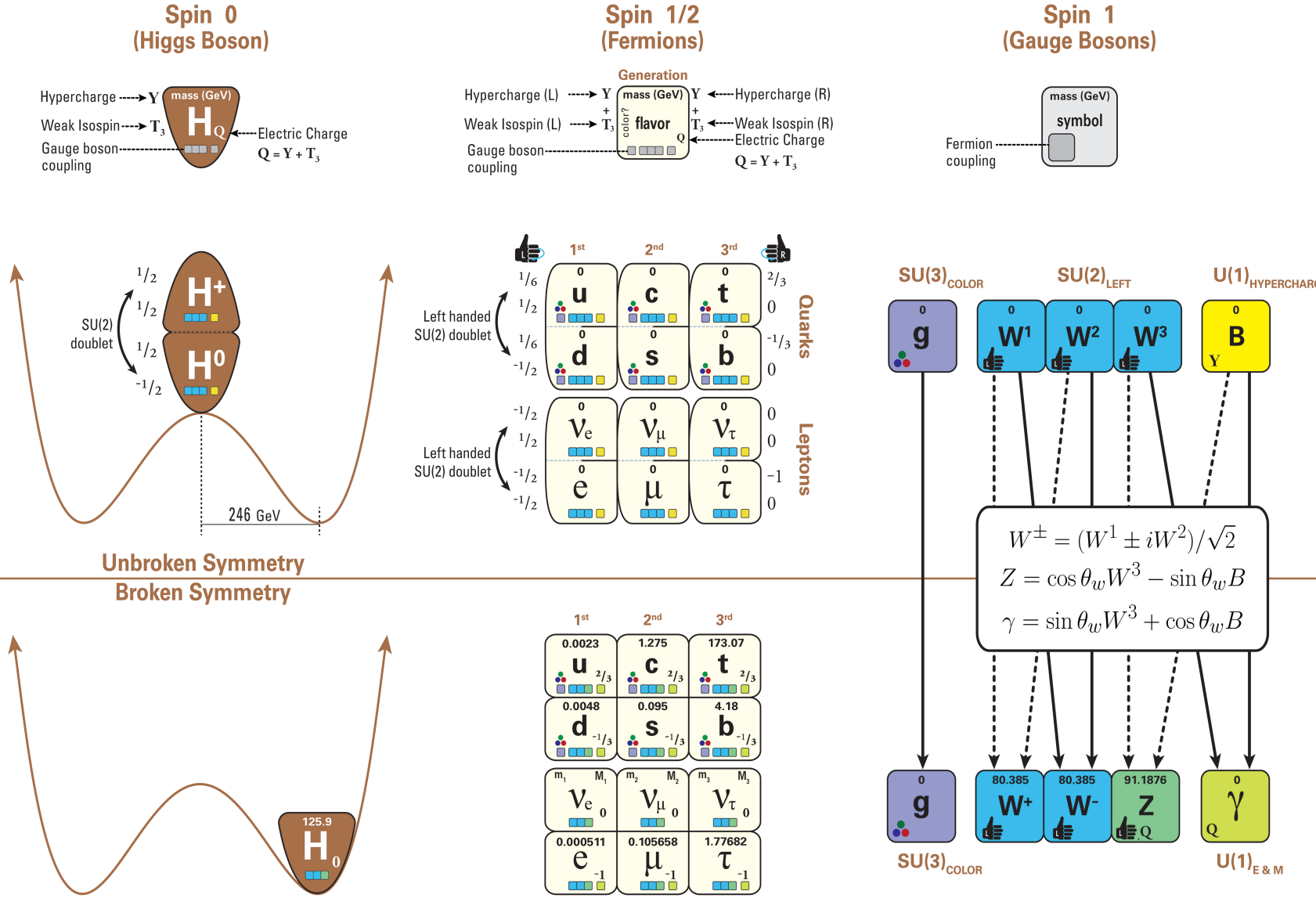
- Baryon number violation
- C and CP violation
- Departure from thermal equilibrium

A toy example

- Replace C by G (Gender): Man $\leftrightarrow$ Woman,
- Parity : Left-Handed $\leftrightarrow$ Right-Handed

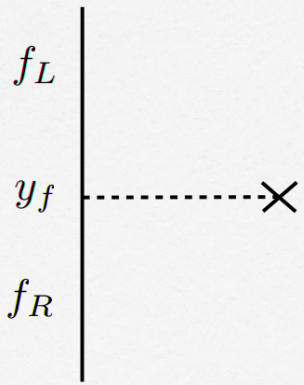


The Standard Model of Particle Physics



Neutrino masses, See-saw

Dirac mass from Dirac Yukawa couplings



$$y_f\,\phi\bar{f}_L f_R + h.c.$$

$$y_f = \frac{g}{2}\,\frac{m_f}{m_W}$$

Standard Model L-R asymmetry

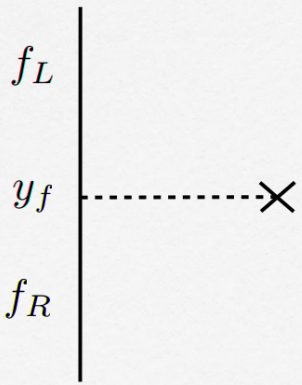
$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ e_R $\not{\nu_R}$ $\begin{pmatrix} u_L \\ d_L \end{pmatrix}$ u_R d_R

neutrino mass $\nu_L\nu_L$

forbidden by $SU(2)$ symmetry

Neutrino masses, See-saw

Dirac mass from Dirac Yukawa couplings



$$y_f\,\phi\bar{f}_L f_R + h.c.$$

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Standard Model

L-R asymmetry

$\begin{pmatrix}\nu_L\\ e_L\end{pmatrix}$ e_R ~~ν_R~~ $\begin{pmatrix}u_L\\ d_L\end{pmatrix}$ u_R d_R

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Type I Seesaw

$$y_D\,\phi\bar{\nu}_L\nu_R + M_{\nu_R}\,\nu_R^T\nu_R$$

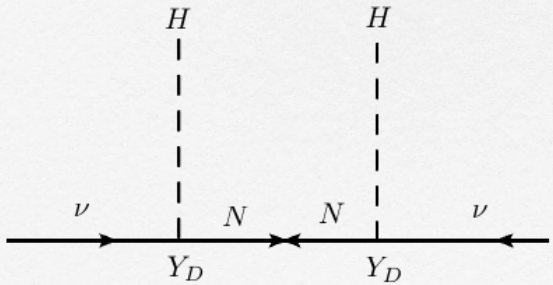
a mess

$$\begin{matrix}\nu_L\\ \nu_R\end{matrix}\begin{pmatrix}0 & M_D\\ M_D^T & M_{\nu_R}\end{pmatrix}$$

light $M_\nu = M_D^T\frac{1}{M_{\nu_R}}M_D$

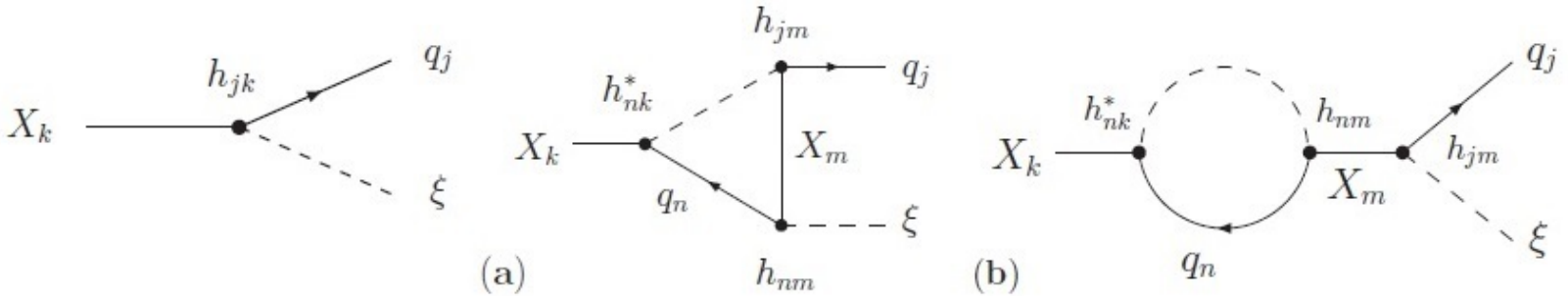
heavy $m_N = m_{\nu_R}$

simple: N heavy



Leptogenesis

- **Leptogenesis:** The lepton asymmetry generated before EW phase transition gets converted to baryon asymmetry in presence of anomalous $B + L$ violating transitions Fukugita and Yanagida (1986)



$$\Gamma = \int_{\text{phase-space}} \left| \quad + \underbrace{\quad}_{\text{1-loop graphs}} + \cdots \right|^2 ,$$

$$= \int_{\text{phase-space}} \left| \quad \right|^2 + \left(\quad \right)^\dagger \left(\quad \right) + \left(\quad \right)^\dagger \left(\quad \right) + \cdots ,$$

$$= |h_{jk}|^2 I_{\text{tree}} + h^*_{jk} h_{jm} h_{nm} h^*_{nk} I_{\text{loop}} + h_{jk} h^*_{jm} h^*_{nm} h_{nk} I^*_{\text{loop}} + \mathcal{O}\left(h^6\right)$$

$$\bar{\Gamma} = |h_{jk}|^2 I_{\text{tree}} + h_{jk} h^*_{jm} h^*_{nm} h_{nk} I_{\text{loop}} + h^*_{jk} h_{jm} h_{nm} h^*_{nk} I^*_{\text{loop}} + \mathcal{O}\left(h^6\right)$$

$$\varepsilon_{CP} = \frac{1}{\Gamma_{\text{tot}}} \left(A_h I_{\text{loop}} + A^*_h I^*_{\text{loop}} - A^*_h I_{\text{loop}} - A_h I^*_{\text{loop}} \right)$$

A dirty example of how it works

Assume we have created some lepton number

- **Initial situation:**
  $B_i = 0,\ L_i = L_0$
  $\Rightarrow (B - L)_i = -L_0 = -(B + L)_i$

- Sphalerons: conserved $B - L$, violation of $B + L$ above EWPT
  $(B + L)_f = 0,\ (B - L)_f = -L_0$
  $\Rightarrow B_f = -1/2 L_0$

- A much more sophisticated calculation gives $B_f \sim -28/79 L_0$

A framework: The Left-Right Symmetric Model

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

W_L W_R

bi-doublet

R - triplet

$$\langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}$$

- mass of N (majorana)
- mass of W_R and Z_R

$$\phi \sim (h_{\rm SM}, H_{\rm heavy})$$

$$\langle \phi \rangle = \begin{pmatrix} v & \\ & \sim v \end{pmatrix}$$

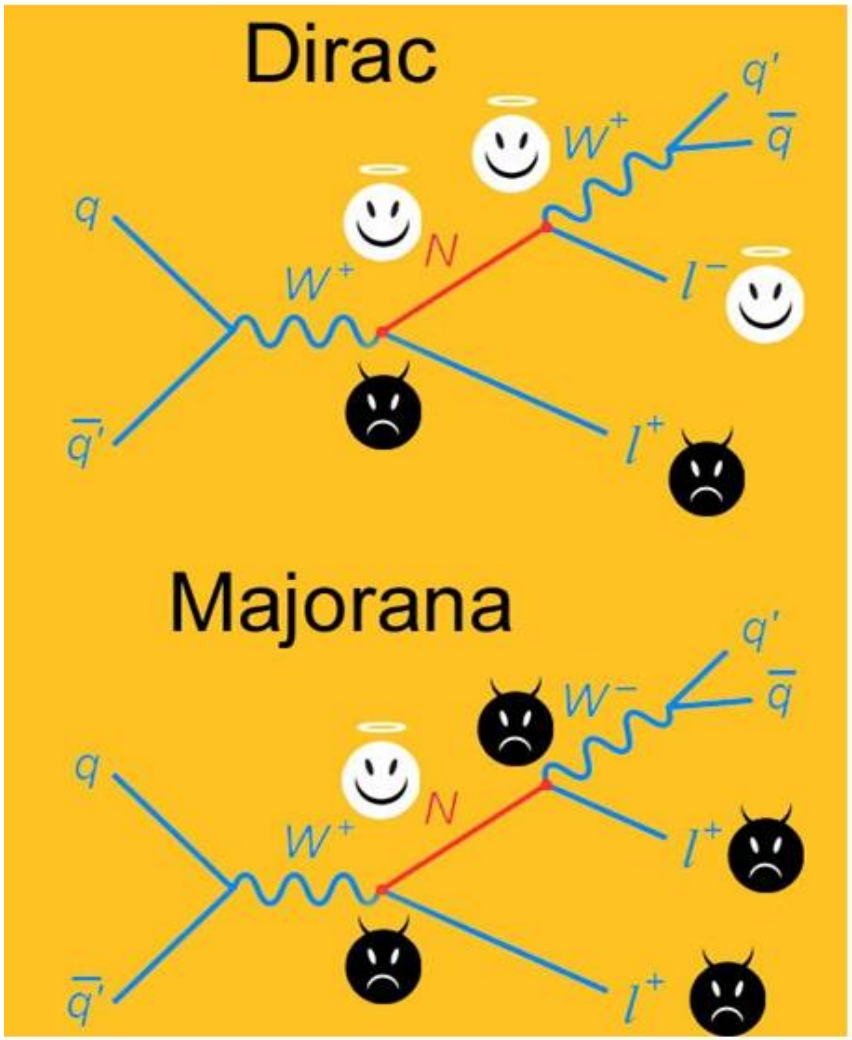
- EW symmetry breaking

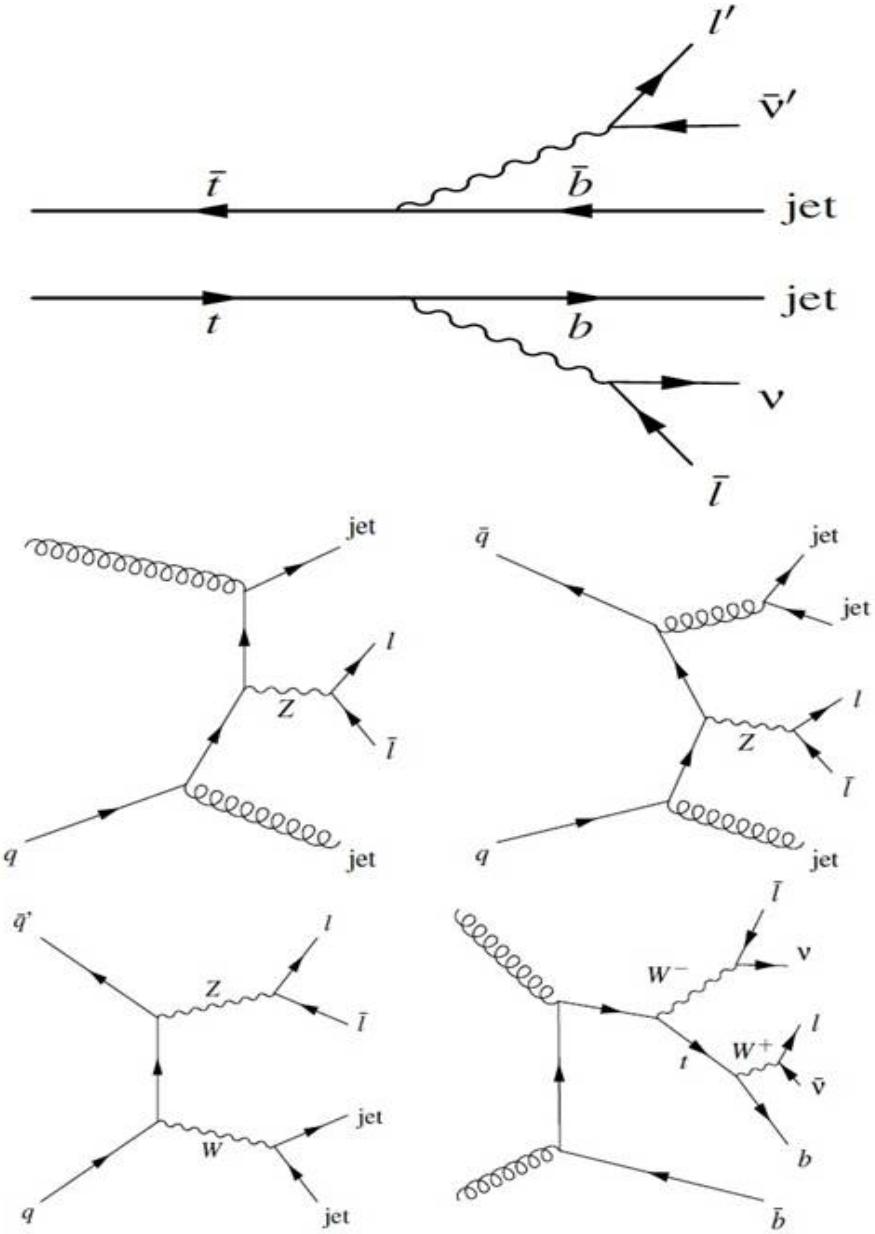
L - triplet

$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}$$

- mass of ν (majorana)

CMS W_R search using $lljj$ channel

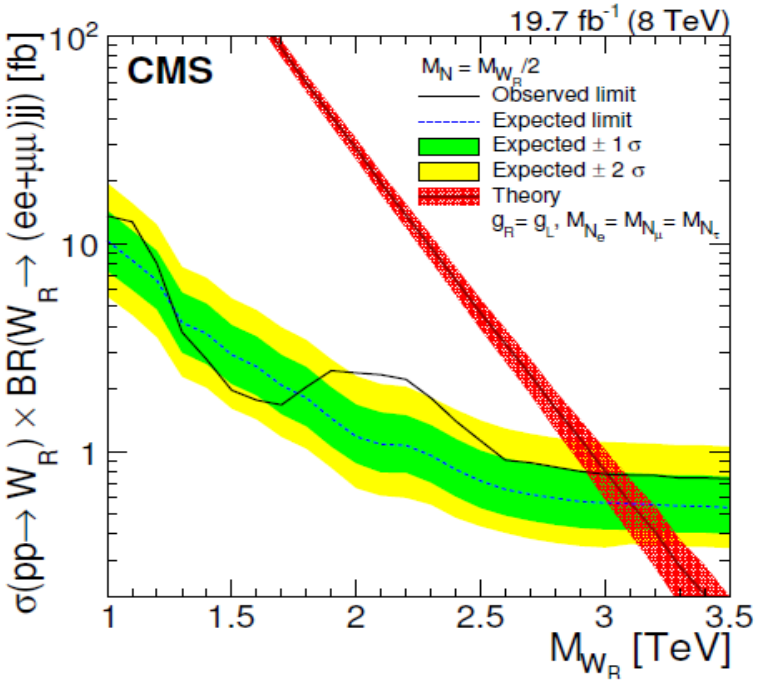


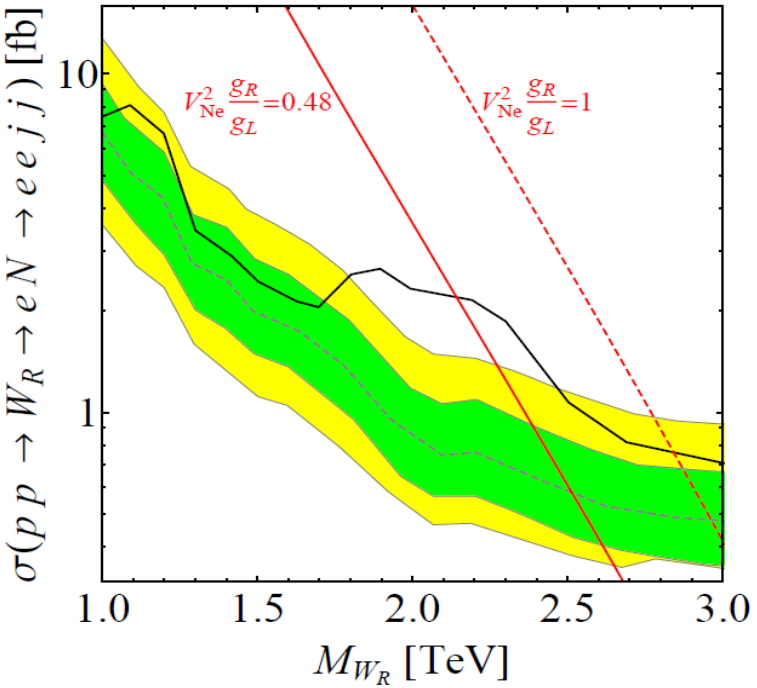


eejj Excess Signal and a possible explanation

- 14 events in the bin $1.8\,\mathrm{TeV} < M_{eejj} < 2.2\,\mathrm{TeV}$ compared to 4 expected from the SM background

$\Longrightarrow$ a 2.8σ local excess in the $pp \to ee + 2j$ channel





- The dashed red curve corresponds to the standard scenario $g_R = g_L$, $V_{Ne} = 1$ and the solid red curve to the D parity breaking scenario $g_R/g_L = 0.6$, $V_{Ne} = 0.9$

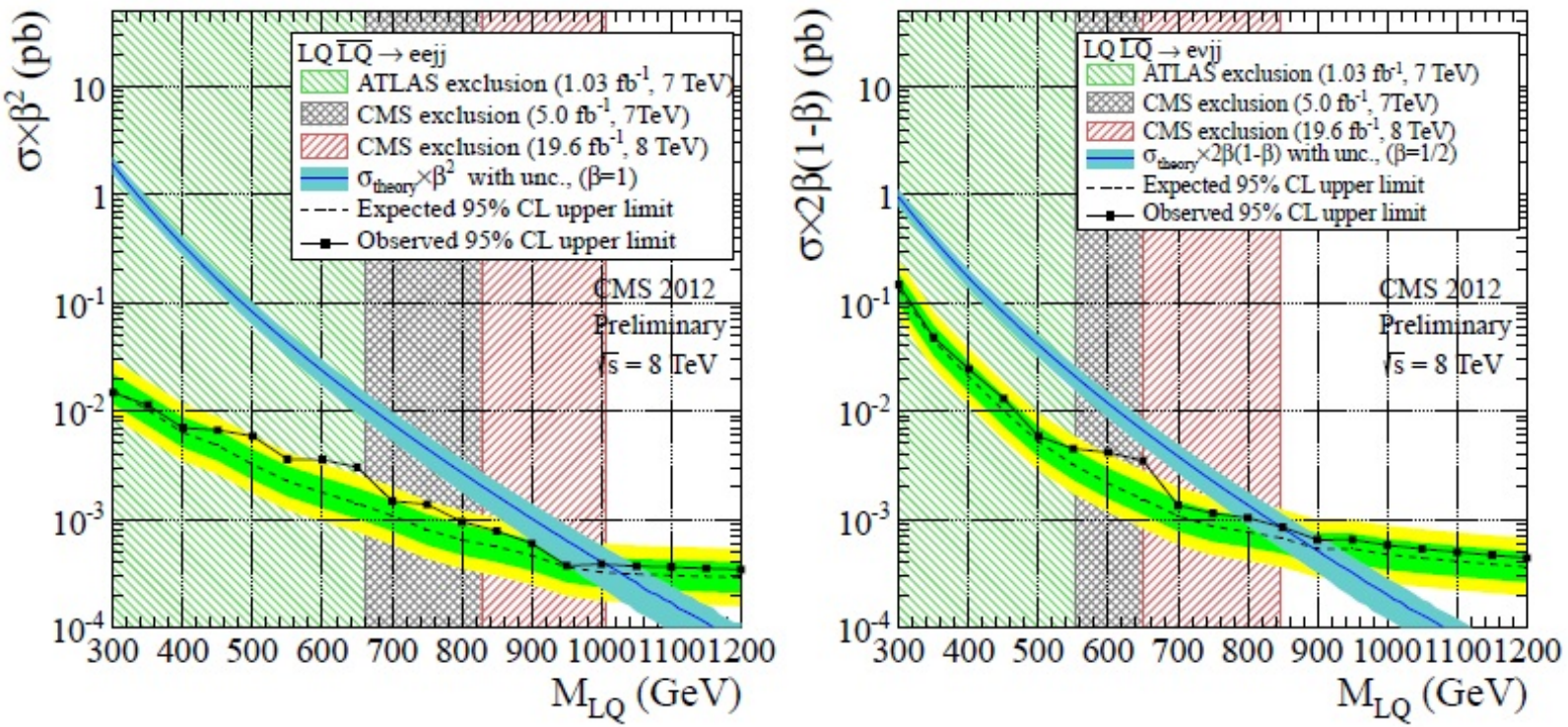
(l) V. Khachatryan *et al.* [CMS Collaboration], Eur.Phys.J. C **74** (2014) 11, 3149 [arXiv:1407.3683 [hep-ex]]

(r) F. F. Deppisch, T. E. Gonzalo, S. Patra, N. Sahu and U. Sarkar, Phys. Rev. D **90**, 053014 (2014) [arXiv:1407.5384 [hep-ph]]

The CMS search for di-leptoquark production

- $eejj$ channel: 36 obs events with $20.49 \pm 2.4 \pm 2.45$(sys.) SM bg
- $e\not{p}_T jj$ channel: 18 obs events with $7.54 \pm 1.20 \pm 1.07$(sys.) SM bg

$\Longrightarrow$ 2.4σ and 2.6σ local excesses in $eejj$ and $e\not{p}_T jj$ channels respectively



CMS Collaboration, CMS-PAS-EXO-12-041

Leptogenesis in LRSM

- In LRSM: the right-handed neutrinos must now interact with the $SU(2)_R$ gauge bosons

- To have successful leptogenesis in the case $M_N > M_{W_R}$ the condition that the process

$$e_R^- + W_R^+ \to N_R \to e_R^+ + W_R^-$$

goes out-of-equilibrium gives $M_N \gtrsim 10^{16}\,\mathrm{GeV}$ with $m_{W_R}/m_N \gtrsim 0.1$

- Now for the case $M_{W_R} > M_N$ leptogenesis can happen either at $T \simeq M_N$ or at $T > M_{W_R}$ but at less than $B - L$ breaking scale

- For $T \simeq M_N$: $M_{W_R} \gtrsim 2 \times 10^5\,\mathrm{GeV}(M_N/10^2\,\mathrm{GeV})^{3/4}$
- For $T > M_{W_R}$: $M_{W_R} \gtrsim 3 \times 10^6\,\mathrm{GeV}(M_N/10^2\,\mathrm{GeV})^{2/3}$
  Ma, Sarkar and Sarkar (1999)

Objectives

- If $1.8\,\mathrm{TeV} < M_{W_R} < 2.2\,\mathrm{TeV}$ then for hierarchical neutrino masses it is not possible to generate the required baryon asymmetry of the universe from high-scale leptogenesis

Way outs:

- A quasi-degenerate right-handed neutrinos mass spectrum?
- Just the right amount of lepton asymmetry can be produced for a W_R mass ($M_{W_R} > 3\,\mathrm{TeV}$) by considering relatively large Yukawa couplings

Frere, Hambye and Vertongen (2009)
Bhupal Dev, Lee and Mohapatra, (2014)

- Other LRSM like frameworks where constraints can be relaxed ? Can these scenarios explain the CMS excesses?

The LRSM interactions inducing LNV scattering processes mediated via N_R and Δ_R^{++}

- The CC interaction involving N_R and W_R:

$$\mathcal{L}_N = \frac{1}{2\sqrt{2}} g_R J_{R\mu} W_R^{-\mu} + h.c. \text{ where } J_{R\mu} = \bar{l}\gamma_\mu (1+\gamma_5) N_{lR}$$

- The interaction between the doubly charged Higgs triplet and the gauge boson W_R:

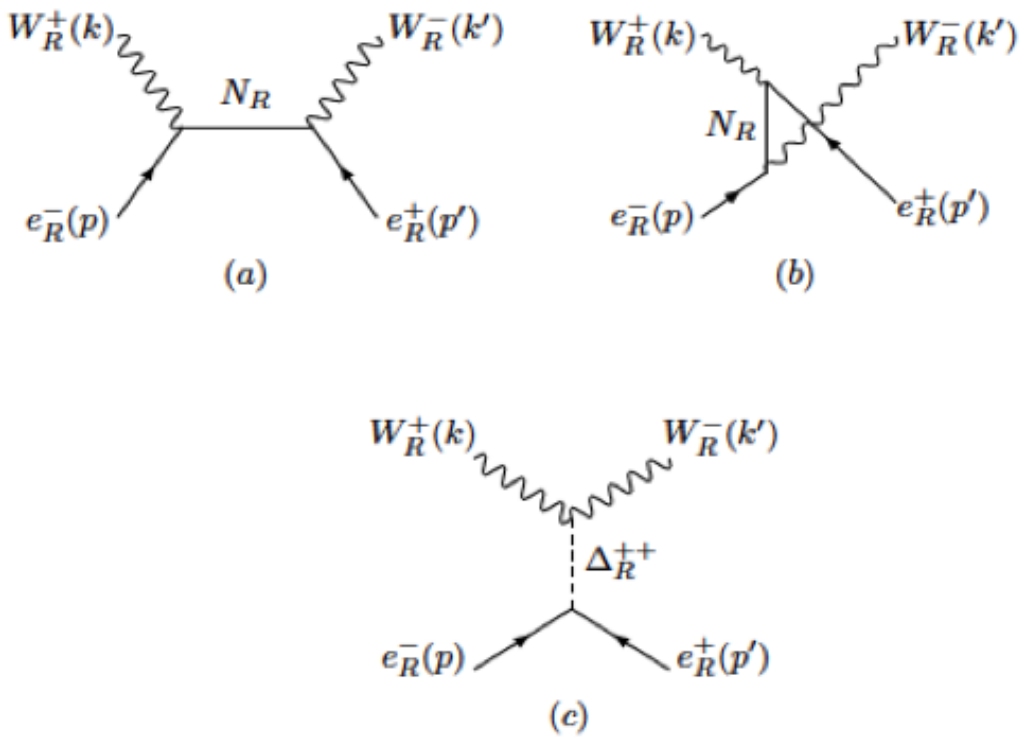
$$\mathcal{L}_{\Delta_R} \supset \left(-\frac{v_R}{\sqrt{2}}\right) g_R^2 W_{\mu R}^- W_R^{-\mu} \Delta_R^{++} + h.c.$$

- The Yukawa interaction between the lepton doublet $\psi_{eR} = (N_R, e_R)^T$ and the Higgs triplet $\vec{\Delta}_R$:

$$\mathcal{L}_Y = h_{ee}^R \overline{(\psi_{eR})^c} \left(i\tau_2 \vec{\tau}.\vec{\Delta}_R\right) \psi_{eR} + h.c.$$

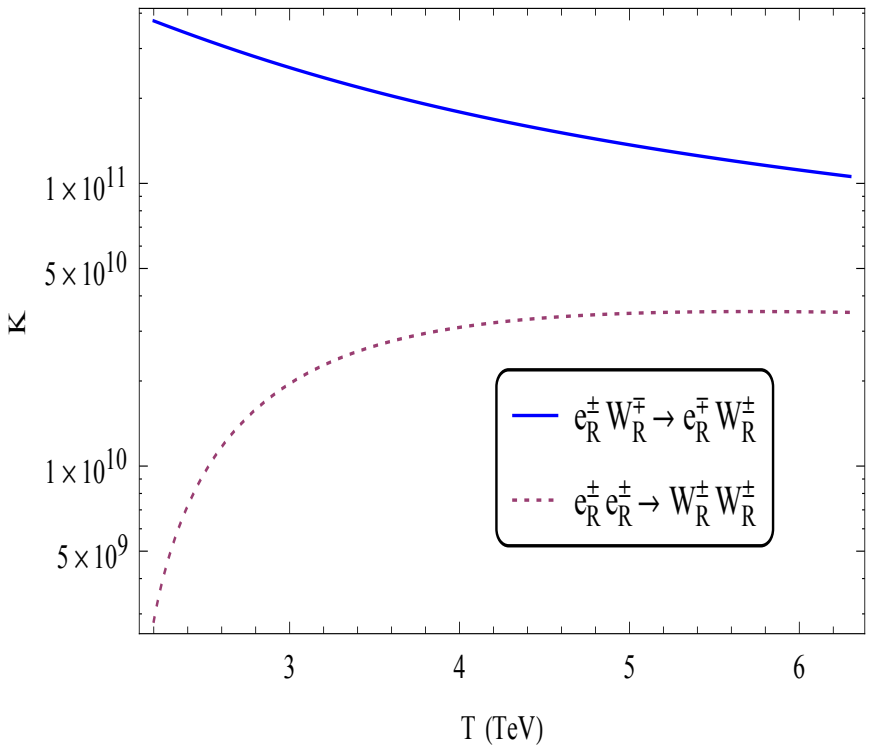
M. Dhuria, C. H, R. Rangarajan and U. Sarkar, Phys. Rev. D - Rap Com 92, 031701(2015)

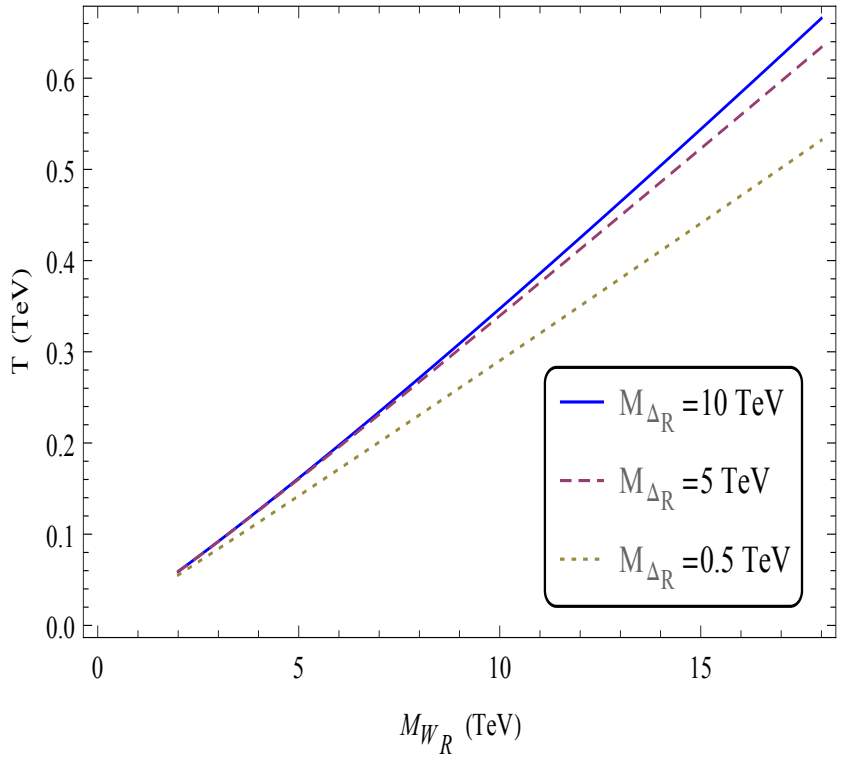
The lepton number violating scattering process $e_R^{\pm} W_R^{\mp} \to e_R^{\mp} W_R^{\pm}$ mediated via N_R and Δ_R^{++}



M. Dhuria, C. H, R. Rangarajan and U. Sarkar, Phys. Rev. D - Rap Com 92, 031701(2015)

- During the period $v_R > T > M_{W_R}$: (left) We plot $K \equiv \frac{n\langle\sigma|v|\rangle}{2H}$
- During the period $T < M_{W_R}$ the process $e_R^{\pm} e_R^{\pm} \to W_R^{\pm} W_R^{\pm}$ is doubly phase space suppressed and the process $e_R^{\pm} W_R^{\mp} \to e_R^{\mp} W_R^{\pm}$ becomes more important
- (right) we plot approximate lower bound on T till which the latter process stays in equilibrium below $T = M_{W_R}$





Playing around with $SU(2)_R$

- Both $eejj$ and $e\not{p}_T jj$ signals and high-scale leptogenesis in the context of supersymmetric low energy subgroups of E_6 in
  M. Dhuria, C. H, R. Rangarajan and U. Sarkar, Phys. Rev. D 91, 055010 (2015)
  M. Dhuria, C. H, R. Rangarajan and U. Sarkar, JCAP 09, 035 (2015)
- Under one of the maximal subgroups of E_6 given by $SU(3)_C \times SU(3)_L \times SU(3)_R$, the fundamental 27 representation reduces to

$$27 = (3, 3, 1) + (3^*, 1, 3^*) + (1, 3^*, 3)$$

$$\begin{pmatrix} u \\ d \\ h \end{pmatrix} + \begin{pmatrix} u^c & d^c & h^c \end{pmatrix} + \begin{pmatrix} E^c & \nu & \nu_E \\ N_E^c & e & E \\ e^c & N^c & n \end{pmatrix}$$

where $SU(3)_L$ operates vertically and $SU(3)_R$ operates horizontally

Case 1: Standard LRSM like Model

- The transformation of the fields under the subgroup $G = SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is given by

$$(u,d)_L : (3,2,1,\frac{1}{6}),\ (d^c,u^c)_L : (\bar{3},1,2,-\frac{1}{6}),$$
$$(\nu_e,e)_L : (1,2,1,-\frac{1}{2}),\ (e^c,N^c)_L : (1,1,2,\frac{1}{2}),$$
$$h_L : (3,1,1,-\frac{1}{3}),\ h_L^c : (\bar{3},1,1,\frac{1}{3}),$$
$$\begin{pmatrix} \nu_E & E^c \\ E & N_E^c \end{pmatrix}_L : (1,2,2,0),\ n_L : (1,1,1,0)$$

- Among the five neutral fermions only ν_e and N^c carry nonzero $B-L$
- Successful leptogenesis can not be obtained

Case 2: Alternative LRSM

- the assignments of fields transforming under the subgroup $G = SU(3)_c \times SU(2)_L \times SU(2)_{R'} \times U(1)_{Y'}$ are given as

$$(u,d)_L : (3,2,1,\frac{1}{6}),\ (h^c,u^c)_L : (\bar{3},1,2,-\frac{1}{6}),$$
$$(\nu_E,E)_L : (1,2,1,-\frac{1}{2}),\ (e^c,n)_L : (1,1,2,\frac{1}{2}),$$
$$h_L : (3,1,1,-\frac{1}{3}),\ d_L^c : (\bar{3},1,1,\frac{1}{3}),$$
$$\begin{pmatrix} \nu_e & E^c \\ e & N_E^c \end{pmatrix}_L : (1,2,2,0),\ N_L^c : (1,1,1,0)$$

- In this case $W_{R'}^-$ carries a leptonic charge $L = 1$
- This scenario has an appealing feature of allowing high-scale leptogenesis
- However the $W_{R'}$ decay can not give rise to the $ee + 2j$ signal

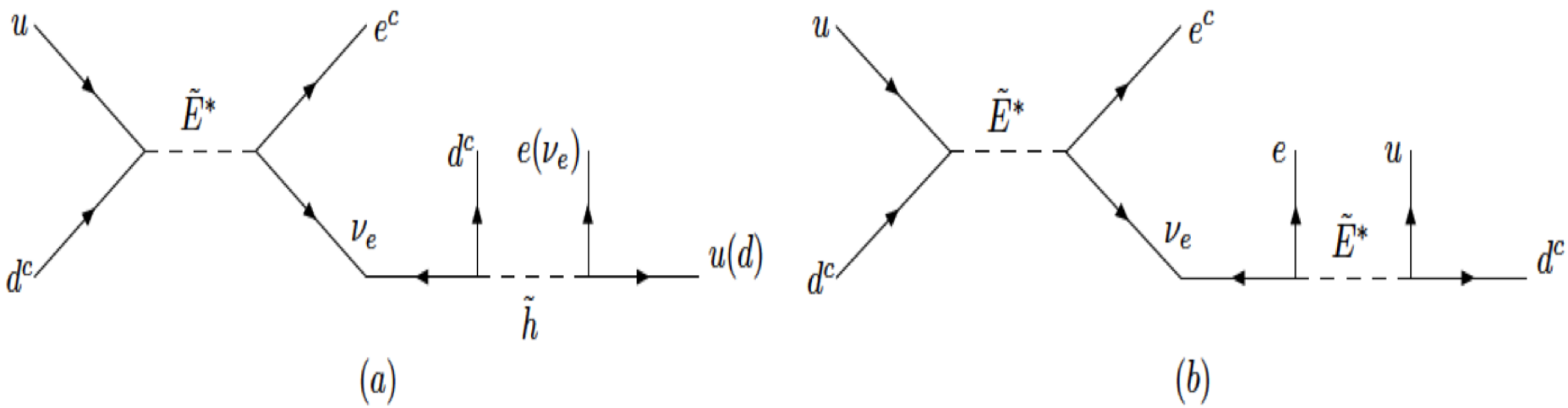
Case 3: Model with Neutral $SU(2)_{(R)}$

- $SU(2)_{(R)}$ does not contribute to the electric charge equation and we will represent it by $SU(2)_N$
- The fields transform under the subgroup $G = SU(3)_c \times SU(2)_L \times SU(2)_N \times U(1)_Y$ as

$$(u, d)_L : (3, 2, 1, \frac{1}{6}),\ (h^c, d^c)_L : (\bar{3}, 1, 2, \frac{1}{3}),$$
$$(E^c, N_E^c)_L : (1, 2, 1, \frac{1}{2}),\ (N^c, n)_L : (1, 1, 2, 0),$$
$$h_L : (3, 1, 1, -\frac{1}{3}),\ u_L^c : (\bar{3}, 1, 1, -\frac{2}{3}),$$
$$\begin{pmatrix} \nu_e & \nu_E \\ e & E \end{pmatrix}_L : (1, 2, 2, -\frac{1}{2}),\ e_L^c : (1, 1, 1, 1)$$

- In this scenario also W_N has nonzero leptonic charge
- $ee + 2j$ signal can not be obtained from the decay of W_N

A R-parity conserving scenario explaining the excesses



- In Case 2, the relevant interaction terms are

$$W_2 = -\lambda_1 \left(u h^c e - d h^c \nu_e\right) + \lambda_2 u d^c E - \lambda_5 E e^c \nu_e,$$

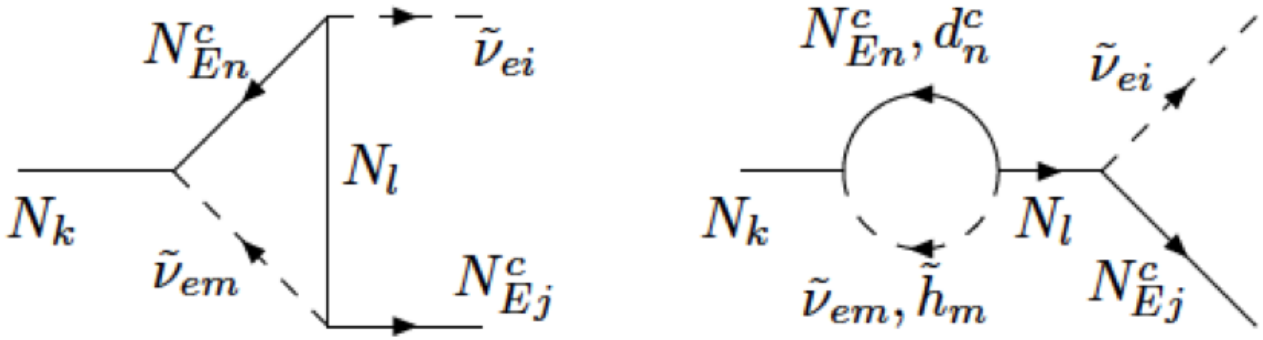
- In Case 3, the relevant interaction terms are

$$W_3 = \lambda_5' \left(\nu_e e^c E + e e^c \nu_E\right) + \lambda_6' \left(u d^c E + u h^c e + d h^c \nu_e\right).$$

High scale leptogenesis in ALRSM (Case 2)

- Amongst the five neutral fermions, only ν_e and N^c carry nonzero $B-L$
- N_k^c decays to $B-L=-1$ final states $\nu_{e_i}\tilde{N}^c_{E_j}, \tilde{\nu}_{e_i}N^c_{E_j}, e_i\tilde{E}^c_j, \tilde{e}_i, E^c_j$ and $d_i\tilde{h}_j, \tilde{d}^c_i\tilde{h}_j$ and to their conjugate states

- $W \supset \lambda_4 h d^c N^c_L + \lambda_6\left(\nu_e N^c_L N^c_E - e E^c N^c_L\right)$



Conclusions

- For the high-scale leptogenesis scenario ($T \gtrsim M_{W_R}$), in the LRSM the lepton number violating scattering processes ($e_R^{\pm} e_R^{\pm} \to W_R^{\pm} W_R^{\pm}$ and $e_R^{\pm} W_R^{\mp} \to e_R^{\mp} W_R^{\pm}$) are very efficient in wiping out the lepton asymmetry

- For a TeV scale resonant leptogenesis scenario the latter process will stay in equilibrium till the electroweak phase transition, slowing down the creation of lepton asymmetry for $T < M_{W_R}$

- Amongst all low energy subgroups of E_6 considered, only ALRSM allows high-scale leptogenesis and it can explain both $eejj$ and $e\not{p}_T jj$ excess signals.

Thank You.

"LHC" STARTED RUNNING
Particle Physicist
OH Darling! You again started Your colliding Business.
Gaurav Tomar