TeV Scale B-L extension of the Standard Model

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Introduction

- The SM, based on the gauge symmetry $SU(3)_C$ x $SU(2)_L$ x $U(1)_Y$, is in excellent agreement with experimental results.

- Three firm observational evidences of new physics beyond the Standard Model :

    1. Neutrino Masses.
    2. Dark Matter.
    3. Baryon Asymmetry.

- These three problems **may be solved by introducing right-handed neutrinos.**

TeV Scale B-L

- The tremendous success of gauge symmetry in describing the SM indicates that any extension of the SM should be through the extension of its gauge symmetry.

- **The minimal extension is based on the gauge group**

$$G_{B-L} \equiv SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

- **This model accounts for the exp. results of the light neutrino masses**

- **New particles are predicted:**
  - Three SM singlet fermions (right handed neutrinos) (cancellation of gauge anomalies)
  - Extra gauge boson corresponding to B−L gauge symmetry
  - Extra SM singlet scalar (heavy Higgs)

- **These new particles have Interesting signatures at the LHC**

$U(1)_{B-L}$ Model

- **Under $U(1)_{B-L}$ we demand:** $\psi_L \rightarrow e^{iY_{B-L}\theta(x)}\psi_L, \qquad \psi_R \rightarrow e^{iY_{B-L}\theta(x)}\psi_R,$
- **Derivatives are covariant if a new gauge field C_μ is introduced:**

$$D_\mu\psi_L \equiv (\partial_\mu - \frac{ig}{2}W_\mu^r\tau_r - \frac{ig'}{2}YB_\mu - \frac{ig''}{2}Y_{B-L}C_\mu)\psi_L, \qquad D_\mu\psi_R \equiv (\partial_\mu - \frac{ig'}{2}YB_\mu - \frac{ig''}{2}Y_{B-L}C_\mu)\psi_R$$

- **Lagrangian: fermionic and kinetic sectors**

$$L_{B-L} = i\bar{l}D_\mu\gamma^\mu l + i\bar{e}_R D_\mu e_R + i\bar{\nu}_R D_\mu\gamma^\mu\nu_R - \frac{1}{4}W_{\mu\nu}^r W^{r\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}C_{\mu\nu}C^{\mu\nu}$$

Lagrangian: Higgs and Yukawa sectors

$$L_{\text{Higgs+Yukawa}} = (D_\mu\phi)(D^\mu\phi) + (D_\mu\chi)(D^\mu\chi) - V(\phi,\chi) - (\lambda_e\bar{l}\phi e_R + \lambda_\nu\bar{l}\tilde{\phi}\nu_R + \frac{1}{2}\lambda_{\nu_R}\bar{\nu}_R^c\chi\nu_R + h.c.)$$

	l	ν_R	e_R	q	u_R	d_R	ϕ	χ
$SU(1)_L \times U(1)_Y$	(2,-1/2)	(1,0)	(1,-1)	(2,1/6)	(1,2/3)	(1,1/3)	(2,1/2)	(1,0)
$U(1)_{B-L}$	-1	-1	-1	1/3	1/3	1/3	0	2

$U(1)_{B-L}$ Symmetry Breaking

- The $U(1)_{B-L}$ gauge symmetry can be spontaneously broken by a SM singlet complex scalar field χ:

$$|\langle \chi \rangle| = v'/\sqrt{2}$$

- The $SU(2)_L \times U(1)_Y$ gauge symmetry is broken by a complex *SU(2)* doublet of scalar field φ:

$$|\langle \phi \rangle| = v/\sqrt{2}$$

- Most general Higgs potential:

$$V(\phi,\chi) = m_1^2 \phi^+ \phi + m_2^2 \chi^+ \chi + \lambda_1 (\phi^+ \phi)^2 + \lambda_2 (\chi^+ \chi)^2 + \lambda_3 (\phi^+ \phi)(\chi^+ \chi)$$

- For $V(\varphi,\chi)$ bounded from below, we require: $\lambda_3 > -2\sqrt{\lambda_1 \lambda_2}, \quad \lambda_2, \lambda_1 \geq 0$

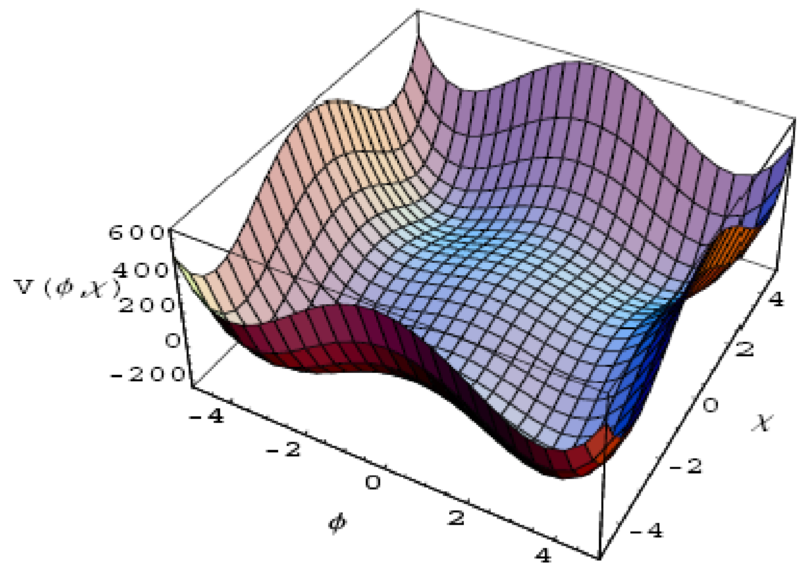
- For non-zero local minimum, we require $\lambda_3^2 < 4\lambda_1 \lambda_2$

$U(1)_{B-L}$ Symmetry Breaking (Cont.)

- **Non-zero minimum:**

$$v^2 = \frac{4\lambda_2 m_1^2 - 2\lambda_3 m_2^2}{\lambda_3^2 - 4\lambda_1\lambda_2},$$

$$v'^2 = \frac{-2(m_1^2 + \lambda_1 v^2)}{\lambda_3}$$



- **Interesting scale:** $0 > \lambda_3 > -2\sqrt{\lambda_1\lambda_2}$

- **After the *B−L* gauge symmetry breaking, the gauge field C_μ acquires mass:**

$$M_{z'}^2 = 4g''^2 v'^2$$

- **Strongest Limit comes from LEP II:** $\frac{M_{z'}}{g''} \approx O(TeV),\ g'' \approx O(1)\ \Rightarrow v' > O(TeV)$

B-L symmetry breaking scale.

- The scale of B- L symmetry breaking is unknown, ranging from TeV to much higher scales (GUT or Planck NP).

- In SUSY, the electroweak and SUSY breaking scale are nicely correlated through the mechanism of radiative breaking of the EW symmetry.

- Radiative corrections may drive the squared Higgs mass from positive initial values at the GUT scale to negative values at the EW scale.

- The size of the Higgs VEV responsible for the EW breaking is determined by the size of the top Yukawa coupling and of the soft SUSY breaking terms.

- Analogously, in a SUSY see-saw scheme it is possible to radiatively induce the breaking of B−L having the scale of such breaking directly linked to the soft SUSY breaking scale.

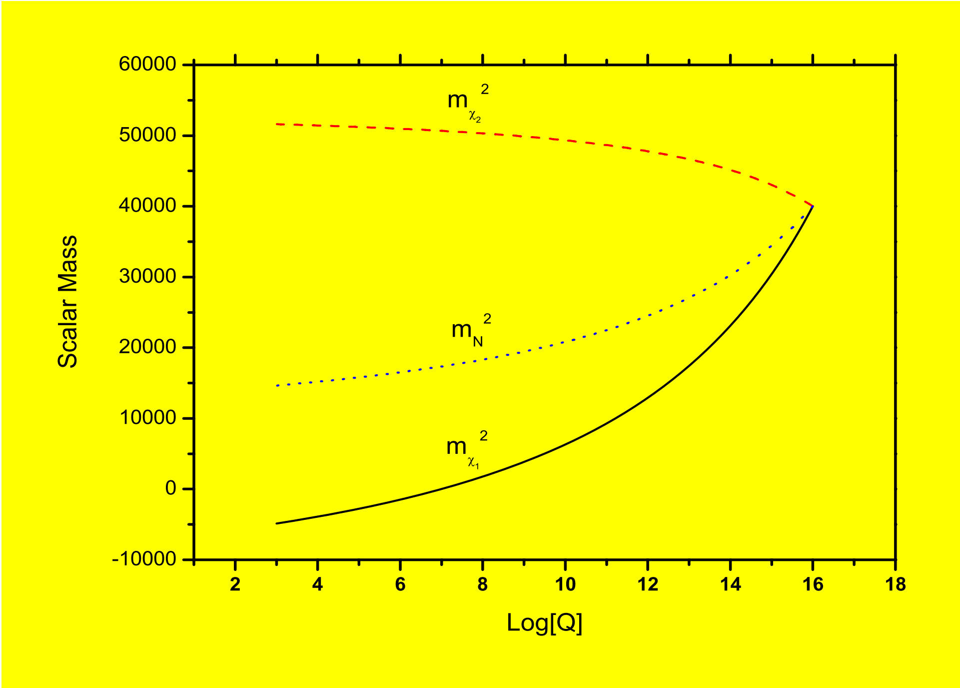
SUSY and B-L radiative symmetry breaking.

S.K., A. Masiero, 2007

$$W = (h_U)_{ij} Q_i H_2 U_j^c + (h_D)_{ij} Q_i H_1 D_j^c + (h_L)_{ij} L_i H_1 E_j^c + (h_\nu)_{ij} L_i H_2 N_j^c$$
$$+ (h_N)_{ij} N_i^c N_j^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2 .$$

$$\frac{dm^2_{\chi_1}}{dt} = 6\tilde{\alpha}_{B-L} M^2_{B-L} - 2\tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right),$$
$$\frac{dm^2_{N_3}}{dt} = \frac{3}{2}\tilde{\alpha}_{B-L} M^2_{B-L} - \tilde{Y}_{N_3}\left(m^2_{\chi_1} + 2m^2_{N_3} + A^2_{N_3}\right).$$

$$\mu'^2 = \frac{m^2_{\chi_2} - m^2_{\chi_1}\tan^2\theta}{\tan^2\theta - 1} - \frac{1}{4} M^2_{Z_{B-L}} .$$
$$\sin 2\theta = \frac{2\mu_3^2}{\mu_1^2 + \mu_2^2} .$$



TeV scale B-L from GUT

- G_{B-L} can be obtained from SO(10) in the following branching rule:

$$SO(10)$$

$$\Downarrow$$

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

$$\Downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

$$\Downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

AT scale ~ GUT though (1,1,1) in 54_H or $210_{H.}$

Below GUT scale (15,1,3) Higgs

At TeV scale via (1,1,0,2) Higgs

TeV scale B-L through SU(5)

- Another way to get (modified) G_{B-L} is to have the following breaking of SO(10) :

$$SO(10)$$

$$\Downarrow$$

$$SU(5) \times U(1)_\chi$$

$$\Downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\chi$$

$$\Downarrow$$

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

AT scale ~ GUT though 1 in 45_H

$U(1)_\chi = 5\ U(1)_{B-L} + 4\ U(1)_Y$

Below GUT scale (1,1) in 24_H

At TeV scale via (1,1,0,2) Higgs

Neutrino masses and mixing

- **Left and right-handed neutrino form 2x2 mass matrix:**

$$\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

- ***M_R* Majorana mass (*$U(1)_{B-L}$* symmetry breaking)**

$$M_R = \lambda_{\nu_R} v'$$

$$v' \sim O(TeV),\ \lambda_{\nu_R} \sim O(1) \Rightarrow M_R \approx O(TeV)$$

- ***m_D* Dirac mass (Electroweak symmetry breaking)**

$$m_D = h_\nu v$$

$$h_\nu \sim O(1) \Rightarrow m_D \approx O(100) GeV, h_\nu \sim h_e \Rightarrow m_D \approx O(10^{-4}) GeV$$

Neutrino Masses (Cont.)

- **we adopt the basis where the charged lepton mass matrix and the Majorana mass matrix *MR* are both diagonal.**

$$M_R = M_{R_3} \begin{pmatrix} r_1 & 0 & 0 \\ 0 & r_2 & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

Where

$$M_{R_3} = |\lambda_{\nu_{R_3}}| \frac{v'}{\sqrt{2}}$$

And

$$r_{1,2} = \frac{M_{R_{1,2}}}{M_{R_3}} = \left| \frac{\lambda_{\nu_{R_{1,2}}}}{\lambda_{\nu_{R_3}}} \right| .$$

M_R is parameterized by 3 parameters (*v'* ~ TeV,) & m_D is given by 9 parameters.

$U(1)_{B-L}$ can not impose any constraint to reduce the number of these parameters

Neutrino Masses (Cont.)

- The solar & atmospheric neutrino oscillation experiments imply at the 3¾ level:

$$
\begin{aligned}
\Delta m_{12}^2 &= (7.9 \pm 0.4) \times 10^{-5}\mathrm{eV}^2, \\
|\Delta m_{32}^2| &= (2.4 + 0.3) \times 10^{-3}\mathrm{eV}^2, \\
\theta_{12} &= 33.9^\circ \pm 1.6^\circ, \\
\theta_{23} &= 45^\circ, \\
\sin^2\theta_{13} &\leq 0.048.
\end{aligned}
$$

- An interesting parameterization for the m_D is: $m_D = U_{MNS}\sqrt{m_\nu^{diag}}R\sqrt{M_R},$

- In order to fix the angles of R, one needs a favor symmetry.

Neutrino Masses (Cont.)

From the measured values of the quark and lepton masses:

$$\frac{m_u}{m_c} \sim \frac{m_e}{m_\mu} \sim O(10^{-3}),$$

$$\frac{m_c}{m_t} \sim \frac{{m_\mu}^2}{{m_\tau}^2} \sim O(10^{-3})$$

In the event of a favor symmetry that explains these ratios, the down quark and neutrino sectors may also be subjected to this symmetry.

If the scale of this favor symmetry breaking (v_F) is below seesaw scale

$$\frac{m_d}{m_s} \sim \frac{m_{\nu_1}}{m_{\nu_2}} \sim O(10^{-2})$$

$$\frac{m_s}{m_b} \sim \frac{m_{\nu_2}^2}{m_{\nu_3}^2} \sim O(10^{-2}).$$

If the scale of the favor symmetry breaking is above the seesaw mechanism scale

$$\frac{m_d}{m_s} \sim \frac{m_{D_1}}{m_{D_2}} \sim O(10^{-2}) \qquad \frac{m_s}{m_b} \sim \frac{m_{D_2}^2}{m_{D_3}^2} \sim O(10^{-2})$$

In case v_F <v'

$$m_\nu \simeq 0.05\, eV \begin{pmatrix} 10^{-3} & 0 & 0 \\ 0 & 0.16 & 0 \\ 0 & 0 & 1 \end{pmatrix} .$$

Consistent with the hierarchal ansatz with m_{ν_1}~10^{-4}

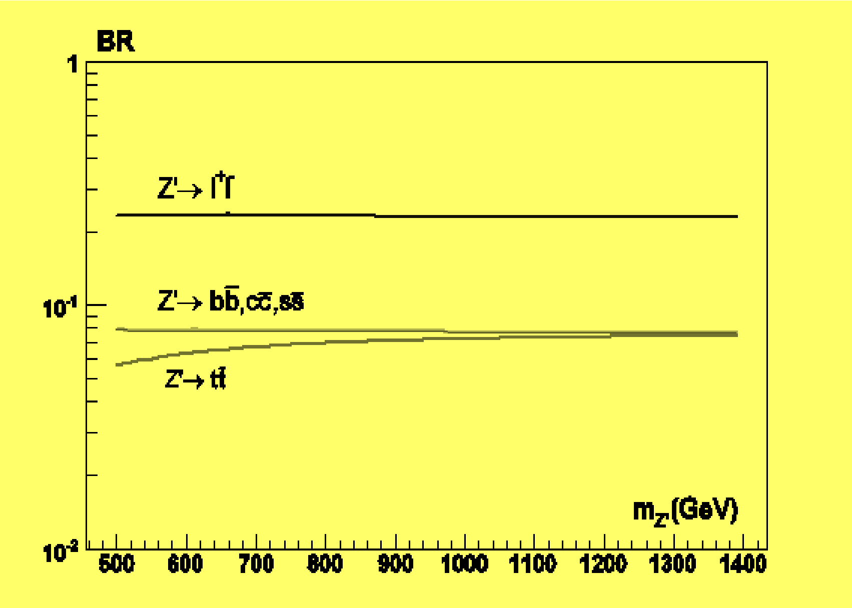
The Dirac neutrino mass matrix (for r_1~ r_2 ~ 0.1, M_{R3} = 5 TeV, and order one angles/phases of *R*-matrix) is given by:

$$m_D \simeq 10^{-3} \begin{pmatrix} 0.16+0.23\,i & -0.25+0.16\,i & -0.19-0.26\,i \\ -0.22-0.34\,i & 0.37-0.24\,i & 0.30+0.38\,i \\ -0.14+0.47\,i & -0.53-0.15\,i & 0.16-0.68\,i \end{pmatrix} .$$

$Z_{B\text{-}L}$ Decay

- The interactions of the *Z′* boson with the SM fermions are described by

$$\sum_f Y_{B-L} g'' C_\mu \bar{f} \gamma^\mu f$$



- **Branching ratios**

$$\Gamma(Z' \to l^+ l^-) \approx \frac{Y_l^2 g''^2}{24\pi} M_{Z'}$$

$$\Gamma(Z' \to b\bar{b}, c\bar{c}, s\bar{s}) \approx \frac{Y_q^2 g''^2}{8\pi} M_{Z'} (1 + \frac{\alpha_s}{\pi})$$

$$\Gamma(Z' \to t\bar{t}) \approx \frac{Y_q^2 g''^2}{8\pi} M_{Z'} (1 - \frac{m_t^2}{M_{Z'}^2})(1 - \frac{4m_t^2}{M_{Z'}^2})^{1/2} [1 + \frac{\alpha_s}{\pi} + O(\frac{\alpha_s m_t^2}{M_{Z'}^2})]$$

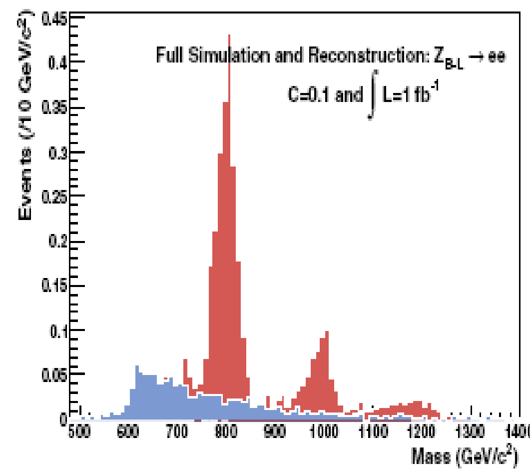
- Branching ratios of $Z' \to l^+ l^-$ are relatively high compared to $Z' \to qq$.
- Search for Z' at LHC via dilepton channels are accessible at LHC.

$$Z' \to l^+ l^- \quad \text{BR} = 30\%$$

$$Z' \to q\bar{q} \quad \text{BR} = 10\%$$

Z_{B-L} Discovery at LHC

Emam, Mine, 2008



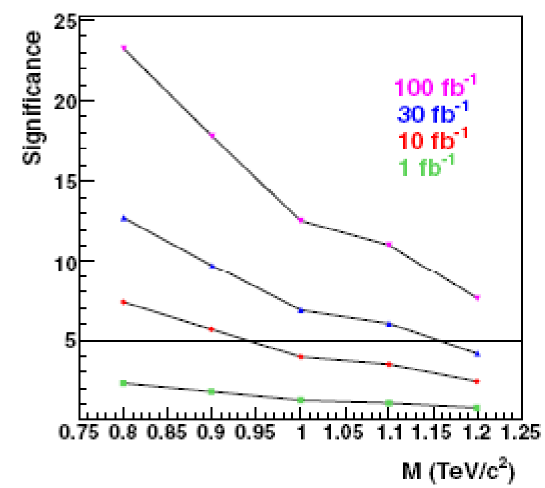
In case of g" ~ O(0.1) then $M_{Z_{B-L}}$ ~ O(600) GeV

In LHC, the neutral gauge boson Z_{B-L} can be produced through $q\bar{q} \rightarrow Z_{B-L}$

The SM background for this production consists mostly of the Drell-Yan process

$$q\bar{q} \rightarrow \gamma / Z^0 \rightarrow e^+ e^-$$

Therefore, one expects a clear peak at $M_{Z_{B-L}}$ boson in the M_{e+e-} distribution



Z_{B-L} boson could be discovered in the e+e− decay channel in the mass region 800<M_Z < 1000 GeV with an integrated luminosity of 10 fb^{-1}.

Higgs Sector

- One complex $SU(2)_L$ doublet and one complex scalar singlet
  - Six scalar degrees of freedom
  - Four are eaten by $C, Z^0, W^\pm$ after symmetry breaking
  - Two physical degrees of freedom: φ, χ
- Mass matrix:

$$\frac{1}{2}M^2(\phi,\chi) = \begin{pmatrix} \lambda_1 v^2 & \lambda_3 v v'/2 \\ \lambda_3 v v'/2 & \lambda_2 v'^2 \end{pmatrix}$$

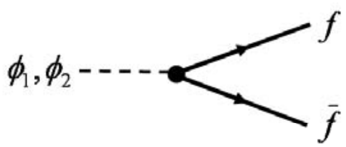
- Mass eigenstates:

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} \phi \\ \chi \end{pmatrix}, \qquad \tan 2\theta = \frac{|\lambda_3| v v'}{\lambda_1 v^2 - \lambda_2 v'^2}$$

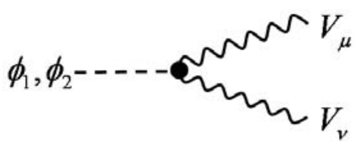
- Masses: $m_{1,2}^2 = \lambda_1 v^2 + \lambda_2 v'^2 \mp \sqrt{(\lambda_1 v^2 - \lambda_2 v'^2)^2 + \lambda_3^2 v^2 v'^2}$
- Mixing is controlled by λ_3: $\lambda_3 = 0 \rightarrow m_\phi = \sqrt{\lambda_1}\, v, \quad m_\psi = \sqrt{\lambda_2}\, v'$

Higgs Sector (Cont.)

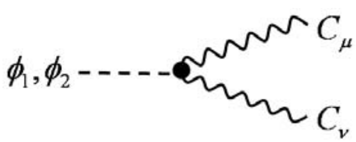
- **Couplings to fermions and gauge bosons**



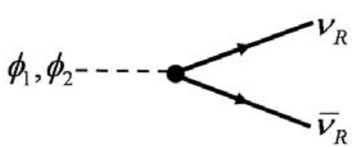
$$g_{\phi_1 ff} = i\frac{m_f}{v}\cos\theta, \qquad g_{\phi_2 ff} = i\frac{m_f}{v}\sin\theta$$



$$g_{\phi_1 VV} = -2i\frac{m_V^2}{v}\cos\theta, \qquad g_{\phi_2 VV} = -2i\frac{m_V^2}{v}\sin\theta$$



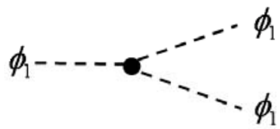
$$g_{\phi_1 CC} = 2i\frac{m_C^2}{v'}\sin\theta, \qquad g_{\phi_2 CC} = -2i\frac{m_C^2}{v'}\cos\theta$$



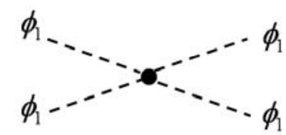
$$g_{\phi_1 \nu_R \nu_R} = -i\frac{m_{\nu_R}}{v'}\sin\theta, \qquad g_{\phi_2 \nu_R \nu_R} = i\frac{m_{\nu_R}}{v'}\cos\theta$$

Higgs Sector (Cont.)

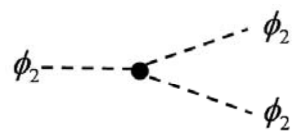
- **Self-couplings**



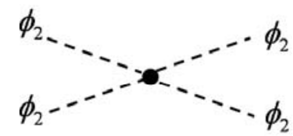
$$g_{\phi_1^3} = 6i(\lambda_1 v \cos^3\theta - \lambda_3 v' \cos^2\theta \sin\theta / 2)$$



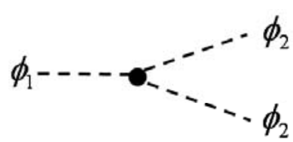
$$g_{\phi_1^4} = 6i\lambda_1 \cos^4\theta$$



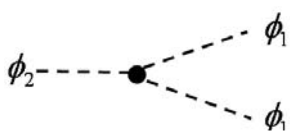
$$g_{\phi_2^3} = 6i(\lambda_2 v' \cos^3\theta + \lambda_3 v \cos^2\theta \sin\theta / 2)$$



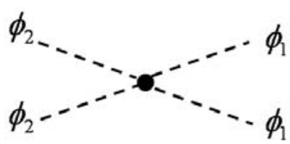
$$g_{\phi_2^4} = 6i\lambda_2 \cos^4\theta$$



$$g_{\phi_1\phi_2^2} = 2i(\lambda_3 v \cos^3\theta / 2 + \lambda_3 v' \cos^2\theta \sin\theta - 3\lambda_2 v' \cos^2\theta \sin\theta)$$



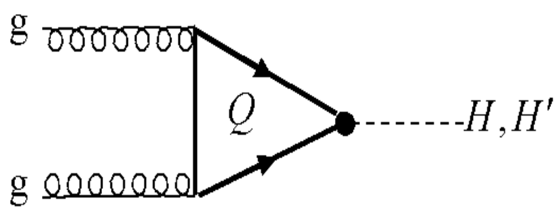
$$g_{\phi_1^2\phi_2^1} = 2i(\lambda_3 v' \cos^3\theta / 2 - \lambda_3 v \cos^2\theta \sin\theta + 3\lambda_1 v \cos^2\theta \sin\theta)$$

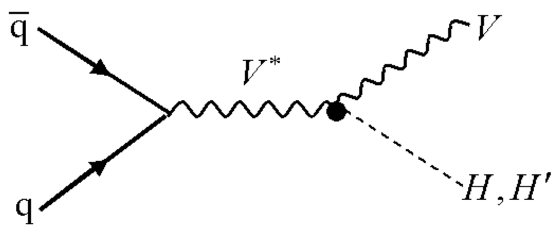


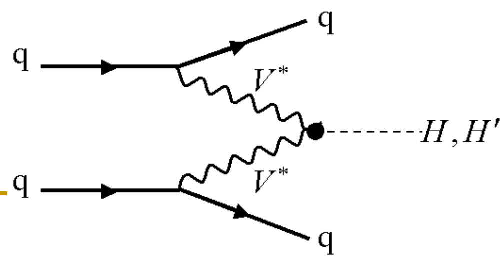
$$g_{\phi_1^2\phi_2^2} = i\lambda_3 \cos^4\theta$$

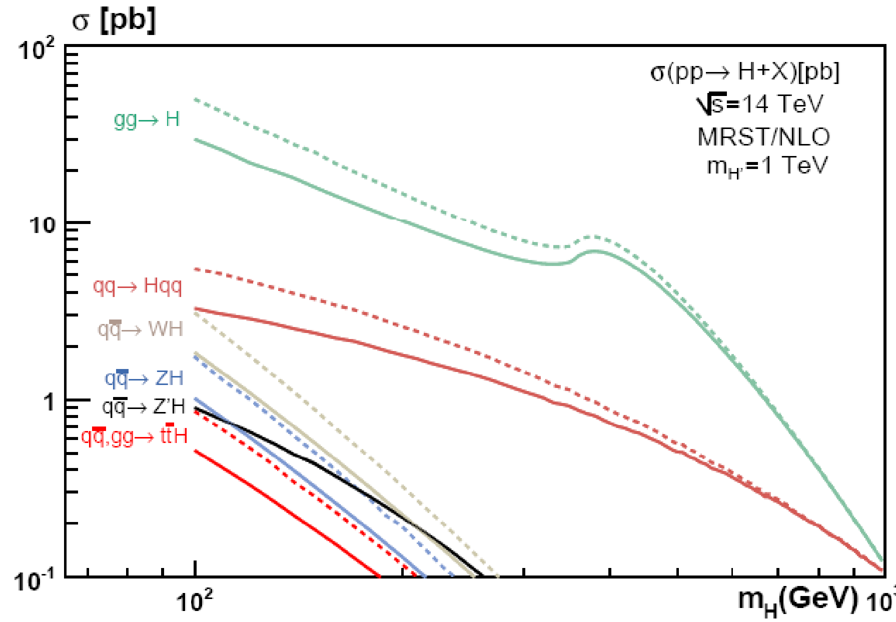
Higgs Production

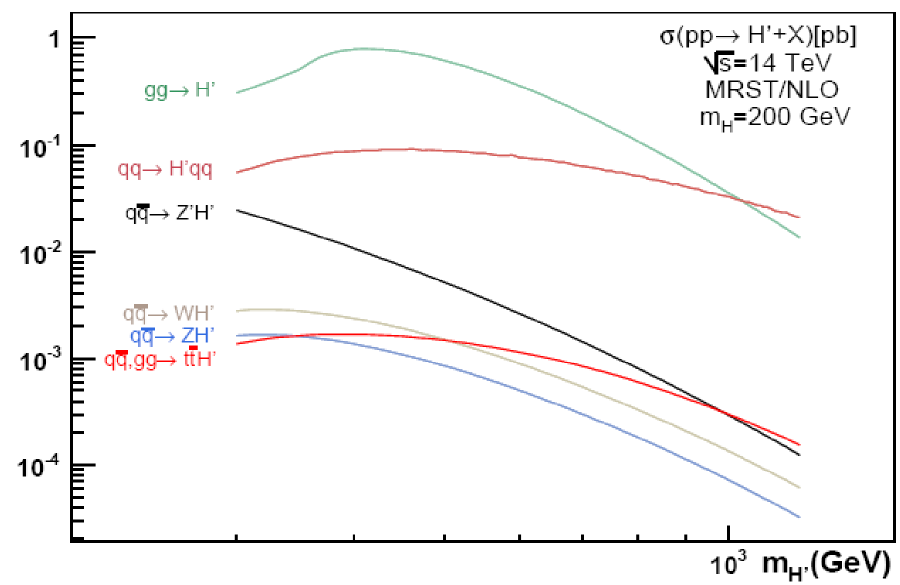
- **Heavy and light Higgses are produced through same processes:**
  - **gluon-gluon fusion**
  - **vector boson fusion**
  - **associated production with *W/Z/Z'***
  - **associated production with heavy quarks**











Higgs Decay

BR

- **Branching Ratios of Light Higgs are very close to those of SM**
  - **Couplings are cancelled in the ratio**
  - **Decay width of *H→Z'Z' is very tiny***
  - **Low mass range M_H < 130 GeV:**

$$H \to b\bar{b} \quad \mathrm{BR} = 60\text{-}90\%$$

$$H \to \tau^+\tau^-, c\bar{c}, gg \quad \mathrm{BR} = \text{a few } \%$$

$$H \to \gamma\gamma, \gamma Z \quad \mathrm{BR} = \text{a few } \%$$

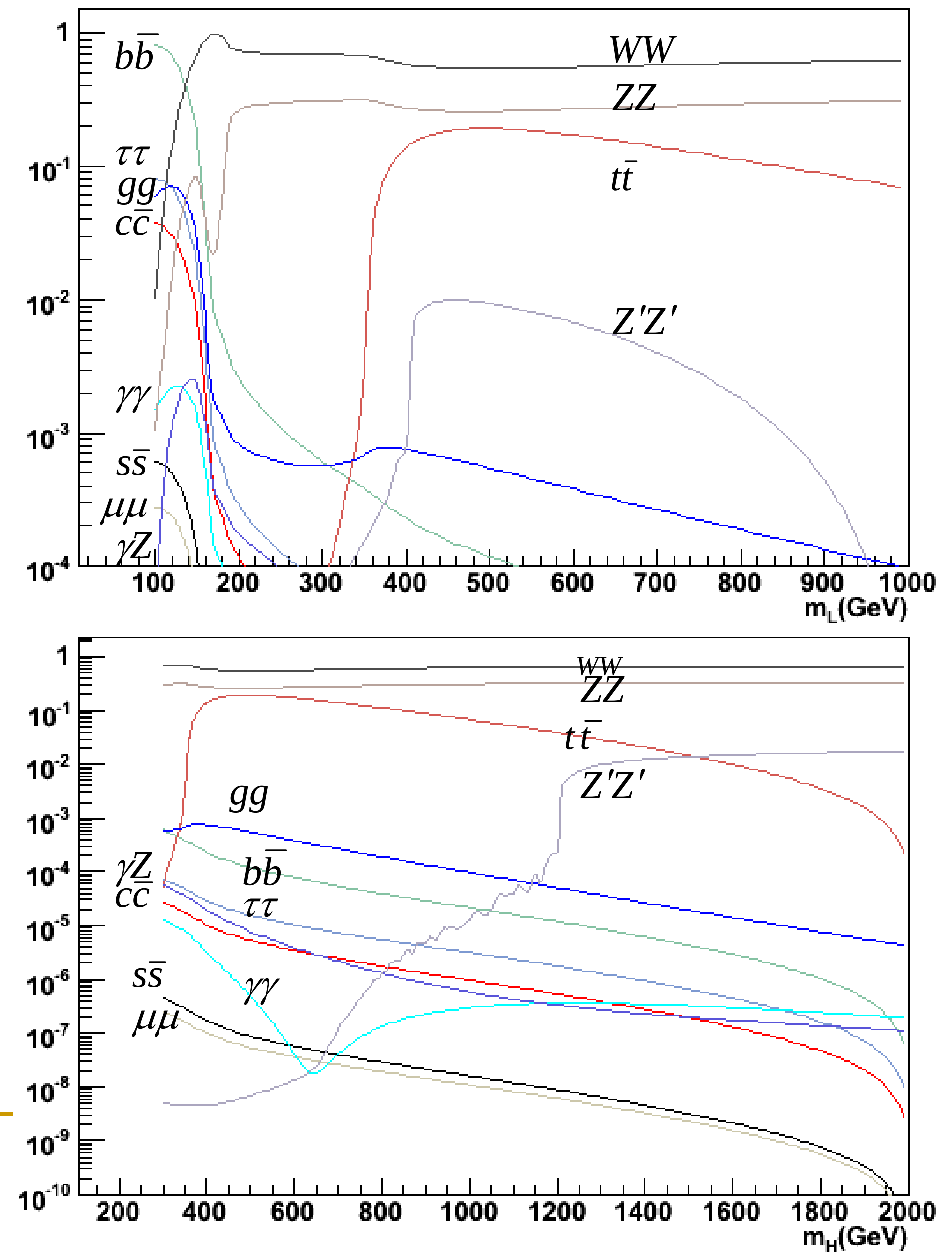
  - **High mass range M_H > 130 GeV:**

$$H \to WW, ZZ \, (\mathrm{BR} = \frac{2}{3}, \frac{1}{3})$$

$$H \to t\bar{t} \quad \mathrm{BR} \leq 20\%$$

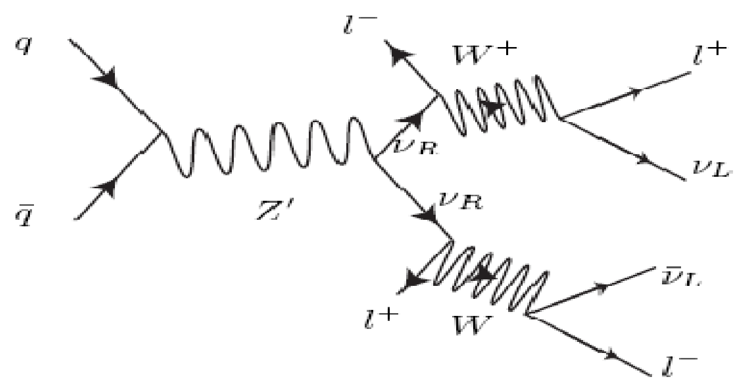
Interesting mass range of Heavy Higgs (200<$m_{H'}$):

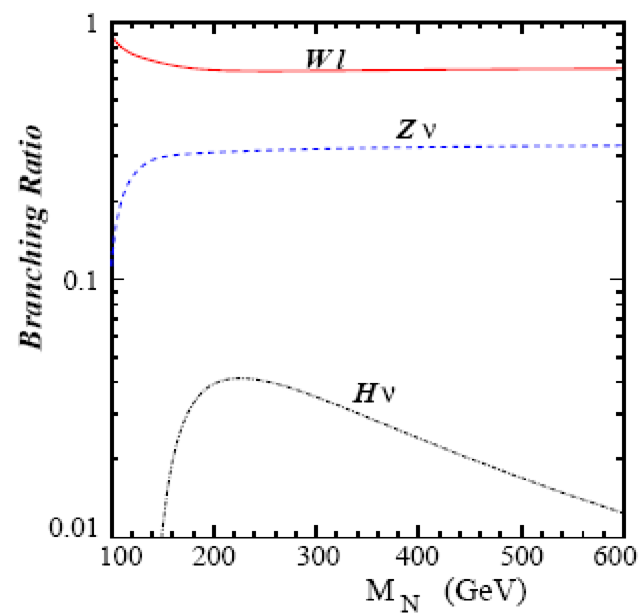
- ***H'→WW/ZZ* channel is dominant**



Signatures for ν_R at the LHC

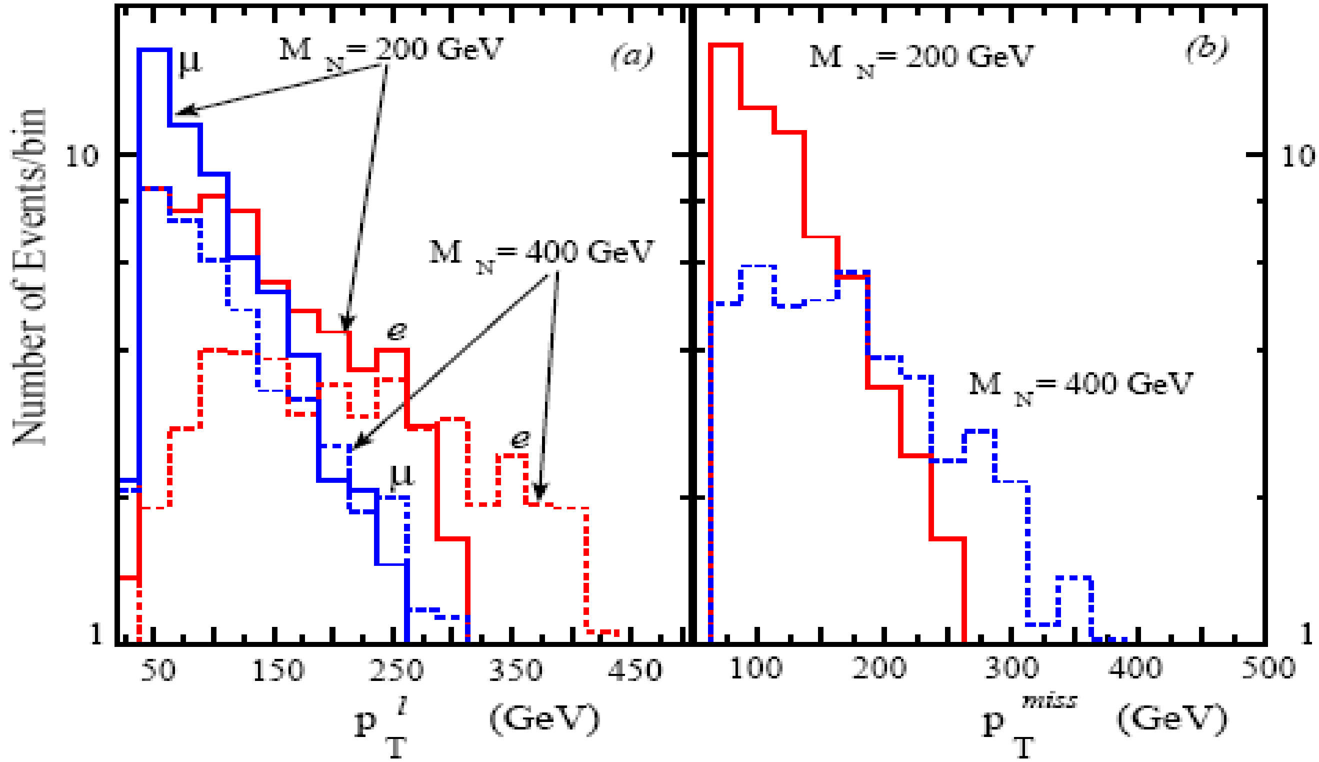
$$\mathcal{L}_{int.} \sim -g" C_\mu [(\overline{\nu_R})_i \gamma^\mu (\nu_R)_i + b_{ij} \overline{(\nu_L)^c}_i \gamma^\mu (\nu_R)_j + h.c.] + \frac{g_2}{\sqrt{2}} [W_\mu^- l_i^+ \gamma^\mu U_{ij} (\nu_L)_j + b_{ij} W_\mu^- l_i^+ \gamma^\mu (\nu_R)_j^c + h.c.],$$





The decay modes, which go through the Higgs H or H' and Z boson, can be neglected compared to the main mode $\nu_R \rightarrow W\, l$.

These decays are very clean with four hard leptons in the final states and large missing energy due to the associated neutrinos.



The transverse momentum distribution for the charged leptons and the missing transverse momentum, for the $4l + \not{E}_T$ signal at the LHC for M_N = 200 GeV and M_N = 400 GeV.

Integrated luminosity ~ 300 fb^{-1} gives 71 events for the right handed neutrino mass of 200 GeV while it gives 46 events for the right handed neutrino mass of 400 GeV.

Leptogenesis in B-L Extension

- **The recent observations lead to the following baryon asymmetry in the Universe**

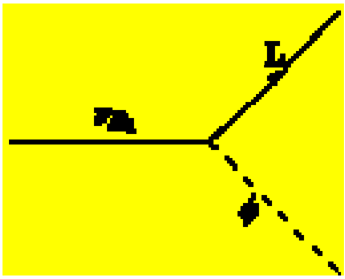
$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = \frac{n_B}{s} = (6.3 \pm 0.3) \times 10^{-10},$$

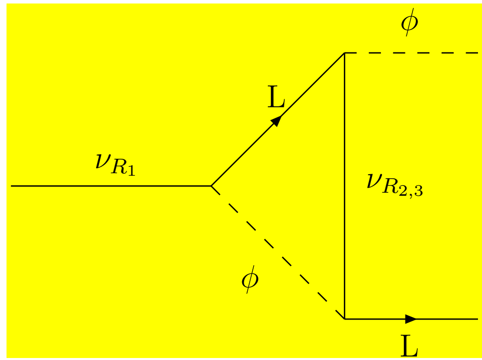
- **This asymmetry may be originate through the CP violating decay of the heavy right-handed neutrino is an interesting mechanism known as Leptogenesis**

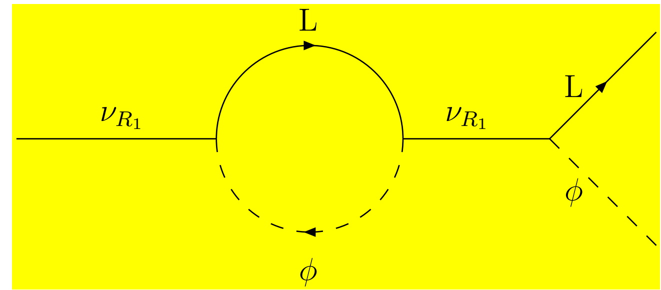
$$\nu_{R_i} \longrightarrow \phi + l_\alpha$$

- **The lepton asymmetry is usually dominated by ν_{R1}**

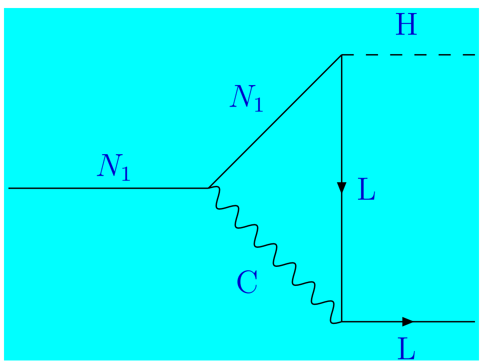
$$\varepsilon_1 = \frac{\sum_\alpha \left(\left| A(\nu_{R_1} \to \phi\, l_\alpha) \right|^2 - \left| A(\nu_{R_1} \to \bar{\phi}\, \bar{l}_\alpha) \right|^2 \right)}{\sum_\alpha \left(\left| A(\nu_{R_1} \to \phi\, l_\alpha) \right|^2 + \left| A(\nu_{R_1} \to \bar{\phi}\, \bar{l}_\alpha) \right|^2 \right)},$$

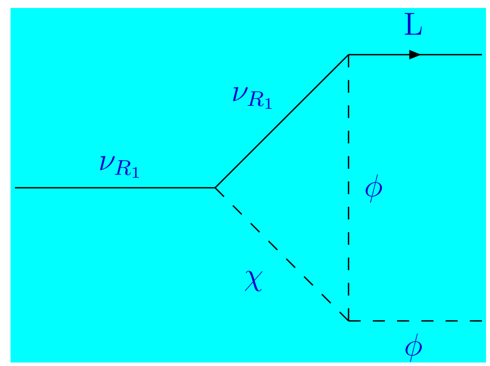






SM like right-handed neutrino decay through tree, vertex, and self-energy diagrams





B-L new contributions through diagrams mediated by extra Higgs and extra gauge boson.

The tree level contribution is given by

$$A_0(\nu_{R_1} \to \phi\, l_\alpha) = -i(\lambda_\nu)_{\alpha 1}\Big(\bar{u}(p)\; P_R\; u^c(q)\Big),$$

The contribution to the decay amplitude from the vertex correction is given by

$$A_V(\nu_{R_1} \to \phi\, l_\alpha) = \frac{i}{16\pi^2}\sum_i (\lambda_\nu)_{\alpha i}(\lambda_\nu^\dagger \lambda_\nu)_{1i}\Big(\bar{u}(p)\; P_R\; u^c(q)\Big)\; F_V\left(\frac{M_{R_i}^2}{M_{R_1}^2}\right).$$

- The self-energy diagram leads to the following contribution:

$$A_S(\nu_{R_1} \to \phi\, l_\alpha) = \frac{i}{16\pi^2}\sum_i (\lambda_\nu)_{\alpha i}(\lambda_\nu^\dagger \lambda_\nu)_{1i}\Big(\bar{u}(p)\; P_R\; u^c(q)\Big)\; F_S\left(\frac{M_i^2}{M_{R_1}^2}\right),$$

- The extra Higgs contribution is given by

$$A_\chi(\nu_{R_1} \to \phi\, l_\alpha) = \frac{1}{16\pi^2 M_{R_1}}(\lambda_{\nu R})_{11}(\lambda_\nu)_{1\alpha}\; g_{\phi^2\chi}\;\; (\bar{u}(p)\; P_R\; u^c(q))\;\; F_\chi\left(\frac{M_\chi^2}{M_{R_1}^2}\right).$$

- Finally, the extra gauge boson contribution is

$$A_{Z'}(\nu_{R_1} \to \phi\, l_\alpha) = \frac{1}{4\pi^2} g''^2 (\lambda_\nu)_{\alpha 1}\Big(\bar{u}(p) P_R u^c(q)\Big)\; F_{Z'}\left(\frac{M_{z'}^2}{M_{R_1}^2}\right),$$

Some Remarks:

1- The loop functions F_V & F_S are complex while F_χ & $F_{Z'}$ are real. New Contributions interface with SM one loop amplitudes only, so their impacts are small.

2-

$$\mathrm{Im}\ F_S(x) = \frac{\sqrt{x}}{1-x}.$$

In the limit of quasi-degenerate right-handed neutrinos, x ~1, a resonant enhancement for the lepton asymmetry is obtained.

3- The coupling $g_{\phi^2\chi}$ is real since $g_{\phi^2\chi} = \sqrt{2} v' \lambda_3.$

However,

$$(\lambda_{\nu_R})_{11} = \frac{2\sqrt{2} M_{R_1}}{v'}\ e^{i\phi_1}.$$

4- Since the coupling g' is real the Z' contribution can be considered as correction to the tree level contribution.

If the new contributions are neglected, the lepton asymmetry is given by

$$\varepsilon_1^{\rm SM} \simeq \frac{1}{8\pi}\frac{1}{(\lambda_\nu^\dagger\lambda_\nu)_{11}}\sum_{i=2,3}{\rm Im}\{(\lambda_\nu^\dagger\lambda_\nu)^2_{1i}\}\left[{\rm Im}\ F_V\left(\frac{M^2_{R_i}}{M^2_{R_1}}\right)+{\rm Im}\ F_S\left(\frac{M^2_{R_i}}{M^2_{R_1}}\right)\right].$$

- **Therefore, the necessary condition for leptogenesis is**

$${\rm Im}\left(\lambda_\nu^\dagger\lambda_\nu\right)_{1i} \neq 0 \Rightarrow {\rm Im}\left(\sqrt{M_R}\ R\ m_\nu^{\rm diag} R^+\sqrt{M_R}\right) \neq 0,\ \ i=2,3.$$

- **Due to the unitarity of U_{MNS}, leptogenesis does not depend on low energy phase appears in the leptonic mixing matrix.**

- **If the matrices *R* and M_R are real the ϵ_1 =0**

- **In B-L extension of the SM, the lepton asymmetry is given by**

$$\varepsilon_1 \simeq \frac{1}{8\pi(\lambda_\nu^\dagger\lambda_\nu)_{11}}\sum_{i=2,3}\left[\frac{{\rm Im}\{(\lambda_\nu^\dagger\lambda_\nu)^2_{1i}\}}{\left(1-\frac{1}{4\pi^2}g''^2F_{Z'}\left(\frac{M^2_{Z'}}{M^2_{R_1}}\right)-\frac{1}{4\pi^2}\lambda_3\ F_\chi\left(\frac{M^2_\chi}{M^2_{R_1}}\right)\right)}\right]$$

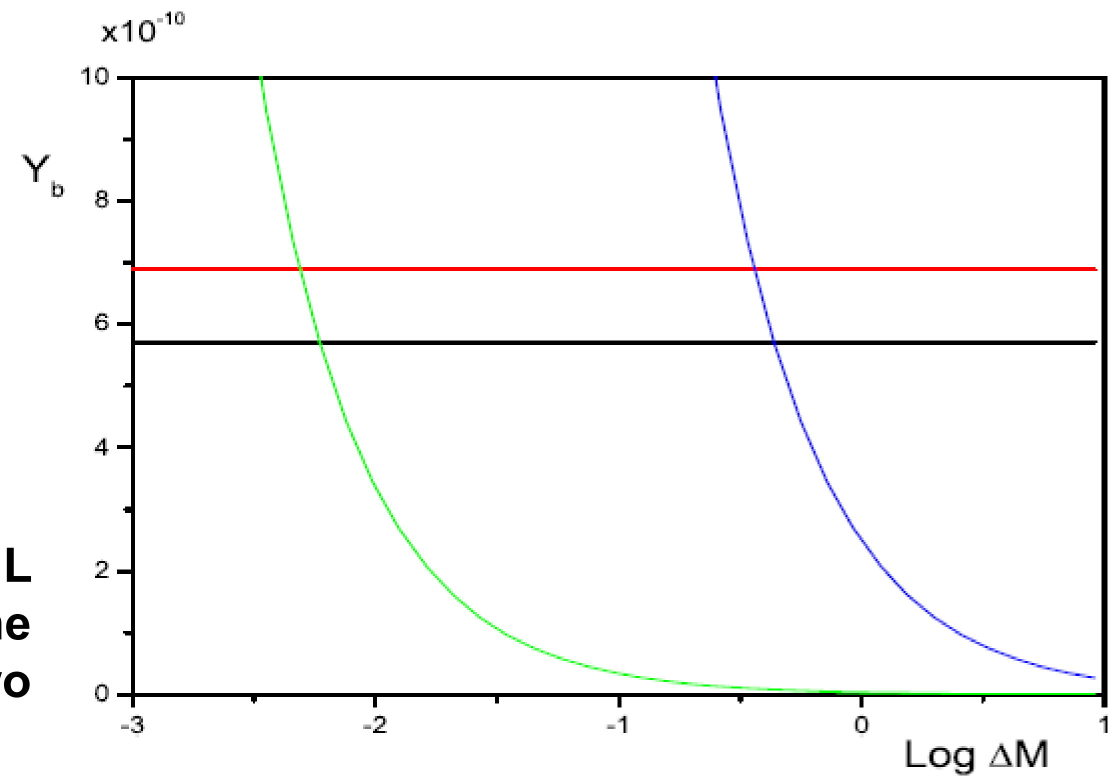
$$\left[{\rm Im}\ F_V\left(\frac{M^2_{R_i}}{M^2_{R_1}}\right)+{\rm Im}\ F_S\left(\frac{M^2_{R_i}}{M^2_{R_1}}\right)\right].$$

Thermal leptogenesis is realized by the out of equilibrium of ν_{R1} at temperature below its mass scale.

To avoid washing out the asymmetry ϵ_1 by inverse decay and scattering processes, the total width of ν_{R1} decay should be smaller than the expansion rate of the universe at temperature $T = M_{R1}$.

$$Y_B = \frac{c}{c-1} Y_L \simeq -1.4 \times 10^{-3} \eta\, \varepsilon_1$$

η is the efficiency factor which parameterizes the amount of washing out by inverse decay and scattering processes



Baryon asymmetry in B − L extension of the SM versus the mass difference of the first two right-handed neutrinos.

Summary

- The SM gauge group can be minimally extended by adding $U(1)_{B-L}$
- G_{B-L} contains three right handed neutrinos, extra gauge boson, and extra scalar Higgs.
- Neutrino masses and mixing can be accommodate in this type of models.
- Search for Z' at LHC via dilepton channels is promising.
- Extra Higgs phenomenology at LHC has been studied.
  - Only production is affected, cross-sections are reduced by about 25-40 % at the interesting mass range of $100<m_H<250$.
  - Decay Branching ratios are not affected.
- We explore the signature for a right handed neutrino at the LHC.
- We computed the new contributions to the CP violating decay of right handed neutrino to Higgs and leptons, due to the extra Higgs and extra gauge boson.
- Successful baryogenesis can be obtained by resonance leptogenesis.