# Resonant leptogenesis in minimal U(1)x extensions of the Standard Model

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arXiv:2407.05644

Collaborator: Arindam Das

# Introduction

U(1)x model

- Leptogenesis
- collider

# U(1) models

# Model

Minimum SM + 3 right-handed neutrinos:

$$q_L, u_R, d_R, l_L, e_R + N$$

Gauge-Gravitational anomaly free U(1):

$$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y + U(1)$$

A scalar boson breaks the U(1):

$$H + \Phi$$

# Anomaly

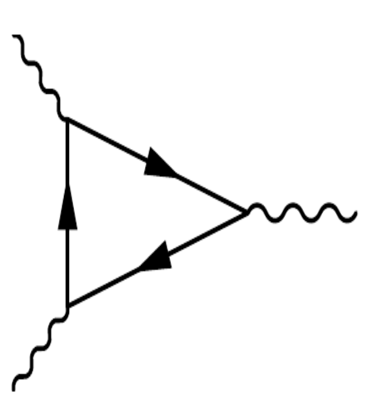
## Yukawa interactions

$$\mathcal{L}^{\text{Yukawa}} = -Y_u^{\alpha\beta}\overline{q_L^\alpha}Hu_R^\beta - Y_d^{\alpha\beta}\overline{q_L^\alpha}\tilde{H}d_R^\beta - Y_e^{\alpha\beta}\overline{\ell_L^\alpha}\tilde{H}e_R^\beta - Y_D^{\alpha\beta}\overline{\ell_L^\alpha}HN_R^\beta - Y_N^\alpha\Phi\overline{(N_R^\alpha)^c}N_R^\alpha + \text{H.c.}$$

$$-\frac{1}{2}x_H = -x_q + x_u = x_q - x_d = x_\ell - x_e = -x_\ell + x_\nu \ ; \ 2x_\Phi = -2x_\nu$$

$x_f$: U(1) charges for f

## Mixed gauge-gravity anomaly cancellation conditions



$$\begin{aligned}
\text{U}(1)_X \otimes [\text{SU}(3)_C]^2 &: & 2x_q - x_u - x_d &= 0, \\
\text{U}(1)_X \otimes [\text{SU}(2)_L]^2 &: & 3x_q + x_\ell &= 0, \\
\text{U}(1)_X \otimes [\text{U}(1)_Y]^2 &: & x_q - 8x_u - 2x_d + 3x_\ell - 6x_e &= 0, \\
[\text{U}(1)_X]^2 \otimes \text{U}(1)_Y &: & {x_q}^2 - 2{x_u}^2 + {x_d}^2 - {x_\ell}^2 + {x_e}^2 &= 0, \\
[\text{U}(1)_X]^3 &: & 6{x_q}^3 - 3{x_u}^3 - 3{x_d}^3 + 2{x_\ell}^3 - {x_\nu}^3 - {x_e}^3 &= 0, \\
\text{U}(1)_X \otimes [\text{grav.}]^2 &: & 6x_q - 3x_u - 3x_d + 2x_\ell - x_\nu - x_e &= 0,
\end{aligned}$$

# U(1)x model

| Fields | $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ | $U(1)_X$ |
|---|---|---|
| $q_L^i$ | $(3, 2, \frac{1}{6})$ | $\frac{1}{6}x_H + \frac{1}{3}$ |
| $u_R^i$ | $(3, 1, \frac{2}{3})$ | $\frac{2}{3}x_H + \frac{1}{3}$ |
| $d_R^i$ | $(3, 1, -\frac{1}{3})$ | $-\frac{1}{3}x_H + \frac{1}{3}$ |
| $\ell_L^i$ | $(1, 2, -\frac{1}{2})$ | $-\frac{1}{2}x_H - 1$ |
| $e_R^i$ | $(1, 1, -1)$ | $-x_H - 1$ |
| $H$ | $(1, 2, -\frac{1}{2})$ | $-\frac{1}{2}x_H$ |
| $N^j$ | $(1, 1, 0)$ | $-1$ |
| $\Phi$ | $(1, 1, 0)$ | $2$ |

$$(F_Y)^2 + (F_{B-L})^2$$

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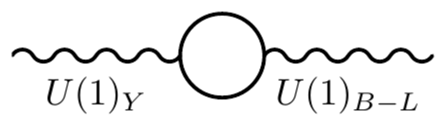
$+$



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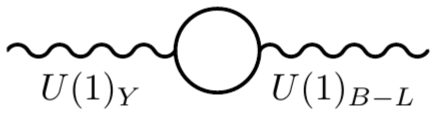


$$\Rightarrow \quad (F_Y)^2 + (F_{B-L})^2 + \epsilon F_Y F_{B-L}$$

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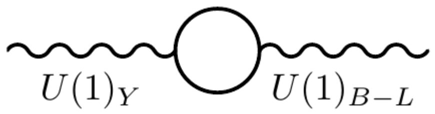
$$(F_Y)^2 + (F_{B-L})^2$$

+




$$\Rightarrow \quad (F_Y)^2 + (F_{B-L})^2 + \epsilon F_Y F_{B-L}$$

Diagonalize

$$(F_Y)^2 + (F_X)^2$$

# Setup

- U(1) breaking scale is TeV scale
  - Z' and N masses are around TeV
    - It is testable in collider experiments
- 3rd generation of right-handed neutrino is a DM candidate
  - One of neutrino masses is zero
- Scalar mixing is zero
  - $\Phi$ couples to only Z' and N

# Leptogenesis

# Boltzman Equations

$$\frac{dY_{N_i}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\left(\frac{Y_{N_i}}{Y_{N_i}^{eq}} - 1\right)(\gamma_{D_i} + 2\gamma_{h,s} + 4\gamma_{h,t}) + \left(\left[\frac{Y_{N_i}}{Y_{N_i}^{eq}}\right]^2 - 1\right)\gamma_{Z'}\right.$$
$$\left. + \left(\left[\frac{Y_{N_i}}{Y_{N_1}^{eq}}\right]^2 - \left[\frac{Y_{\Phi}}{Y_{N_1}^{eq}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi})\right],$$

$$\frac{dY_{\Phi}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\left[\frac{Y_{\Phi}}{Y_{N_1}^{eq}}\right]^2 - \left[\frac{Y_{N_i}}{Y_{N_1}^{eq}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi}) + \left(\left[\frac{Y_{\Phi}}{Y_{N_1}^{eq}}\right]^2 - 1\right)\gamma_{Z',h}\right],$$

$$\frac{dY_{B-L}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\frac{1}{2}\frac{Y_{B-L}}{Y_{\ell}^{eq}} + \epsilon_i\left(\frac{Y_{N_i}}{Y_{N_i}^{eq}} - 1\right)\right)\gamma_{D_i} + \frac{Y_{B-L}}{Y_{\ell}^{eq}}\left(2(\gamma_N + \gamma_{N,t} + \gamma_{h,t}) + \sum_{i=1}^{2}\frac{Y_{N_i}}{Y_{N_i}^{eq}}\gamma_{h,s}\right)\right].$$

# Boltzman Equations

$$\frac{dY_{N_i}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}}-1\right)(\gamma_{D_i}+2\gamma_{h,s}+4\gamma_{h,t})+\left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_i}}\right]^2-1\right)\gamma_{Z'}\right.$$
$$\left.+\left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2-\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2\right)(\gamma_{Z',\Phi}+\gamma_{N,\Phi})\right],$$

$$\frac{dY_{\Phi}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2-\left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2\right)(\gamma_{Z',\Phi}+\gamma_{N,\Phi})+\left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2-1\right)\gamma_{Z',h}\right],$$

$$\frac{dY_{B-L}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\frac{1}{2}\frac{Y_{B-L}}{Y^{eq}_{\ell}}+\epsilon_i\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}}-1\right)\right)\gamma_{D_i}+\frac{Y_{B-L}}{Y^{eq}_{\ell}}\left(2\left(\gamma_N+\gamma_{N,t}+\gamma_{h,t}\right)+\sum_{i=1}^{2}\frac{Y_{N_i}}{Y^{eq}_{N_i}}\gamma_{h,s}\right)\right].$$

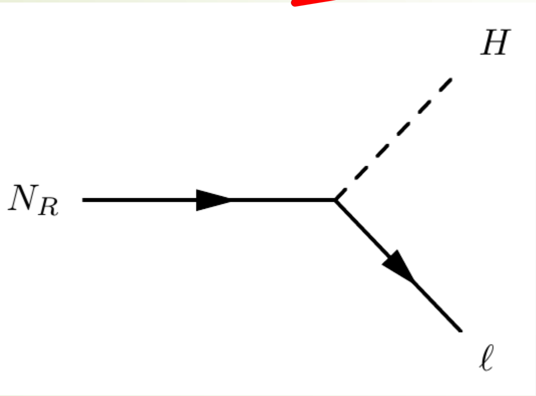
# Boltzman Equations

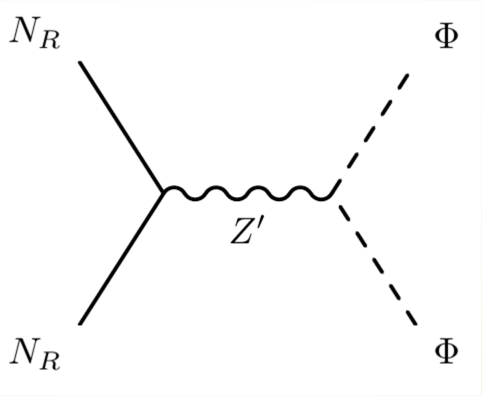
$$\frac{dY_{N_i}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right)(\gamma_{D_i} + 2\gamma_{h,s} + 4\gamma_{h,t}) + \left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_i}}\right]^2 - 1\right)\gamma_{Z'}\right.$$

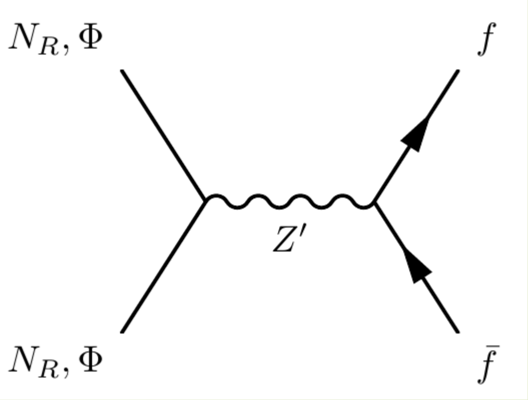
$$\left. + \left(\left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2 - \left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi})\right],$$

$$\frac{dY_{\Phi}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2 - \left[\frac{Y_{N_i}}{Y^{eq}_{N_1}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi}) + \left(\left[\frac{Y_{\Phi}}{Y^{eq}_{N_1}}\right]^2 - 1\right)\gamma_{Z',f}\right],$$

$$\frac{dY_{B-L}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\frac{1}{2}\frac{Y_{B-L}}{Y^{eq}_{\ell}} + \epsilon_i\left(\frac{Y_{N_i}}{Y^{eq}_{N_i}} - 1\right)\right)\gamma_{D_i} + \frac{Y_{B-L}}{Y^{eq}_{\ell}}\left(2(\gamma_N + \gamma_{N,t} + \gamma_{h,t}) + \sum_{i=1}^{2}\frac{Y_{N_i}}{Y^{eq}_{N_i}}\gamma_{h,s}\right)\right].$$



# Boltzman Equations

$$\frac{dY_{N_i}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\left(\frac{Y_{N_i}}{Y_{N_i}^{eq}} - 1\right)(\gamma_{D_i} + 2\gamma_{h,s} + 4\gamma_{h,t}) + \left(\left[\frac{Y_{N_i}}{Y_{N_i}^{eq}}\right]^2 - 1\right)\gamma_{Z'} + \left(\left[\frac{Y_{N_i}}{Y_{N_1}^{eq}}\right]^2 - \left[\frac{Y_\Phi}{Y_{N_1}^{eq}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi})\right],$$

$$\frac{dY_\Phi}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\left[\frac{Y_\Phi}{Y_{N_1}^{eq}}\right]^2 - \left[\frac{Y_{N_i}}{Y_{N_1}^{eq}}\right]^2\right)(\gamma_{Z',\Phi} + \gamma_{N,\Phi}) + \left(\left[\frac{Y_\Phi}{Y_{N_1}^{eq}}\right]^2 - 1\right)\gamma_{Z',h}\right],$$

$$\frac{dY_{B-L}}{dz} = -\frac{z}{sH(m_{N_1})}\left[\sum_{i=1}^{2}\left(\frac{1}{2}\frac{Y_{B-L}}{Y_\ell^{eq}} + \epsilon_i\left(\frac{Y_{N_i}}{Y_{N_i}^{eq}} - 1\right)\right)\gamma_{D_i} + \frac{Y_{B-L}}{Y_\ell^{eq}}\left(2(\gamma_N + \gamma_{N,t} + \gamma_{h,t}) + \sum_{i=1}^{2}\frac{Y_{N_i}}{Y_{N_i}^{eq}}\gamma_{h,s}\right)\right].$$

# resonant-leptogenesis

If two right-handed neutrinos have mass differences comparable to their decay widths $\left(M_2^2 - M_1^2 \sim M_1 \Gamma_2\right)$ , self-energy contribution becomes dominant.

$$\epsilon_1 \sim \frac{Im[Y^2]_{12}^2}{|Y^2|_{11}|Y^2|_{22}} \frac{M_1 \Gamma_2 \left(M_2^2 - M_1^2\right)}{\left(M_2^2 - M_1^2\right)^2 + M_1^2 \Gamma_2^2}$$

$$\sim \frac{1}{2} \frac{Im[Y^2]_{12}^2}{|Y^2|_{11}|Y^2|_{22}}$$

$\epsilon_1$ can be even $O(1)$ .

We fix the second right-handed neutrino mass

$$M_2^2 = M_1^2 + M_1 \Gamma_2$$

# Casas-Ibarra parametrization

J. A. Casas, A. Ibarra, NPB618 (2001)

$$m_\nu \simeq m_D m_N^{-1} m_D^T$$

$$U_{\rm PMNS}^T \, m_\nu \, U_{\rm PMNS} = diag(m_1, m_2, m_3)$$

⇒

$$m_D = U^*_{PMNS} \begin{pmatrix} \sqrt{m_1} & 0 & 0 \\ 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} O \begin{pmatrix} \sqrt{M_{N_1}} & 0 & 0 \\ 0 & \sqrt{M_{N_2}} & 0 \\ 0 & 0 & \sqrt{M_{N_3}} \end{pmatrix}$$

We assume third generation of right-handed neutrino is DM candidate

⇒ Active neutrinos have one massless state

**NH case**

$$m_1 = 0, m_2 = m_{2NH}, m_3 = m_{3NH},$$
$$O = \begin{pmatrix} 0 & 0 & 1 \\ \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \end{pmatrix},$$

**IH case**

$$m_1 = m_{1IH}, m_2 = m_{2IH}, m_3 = 0,$$
$$O = \begin{pmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{pmatrix},$$

# Maximal CP asymmetry

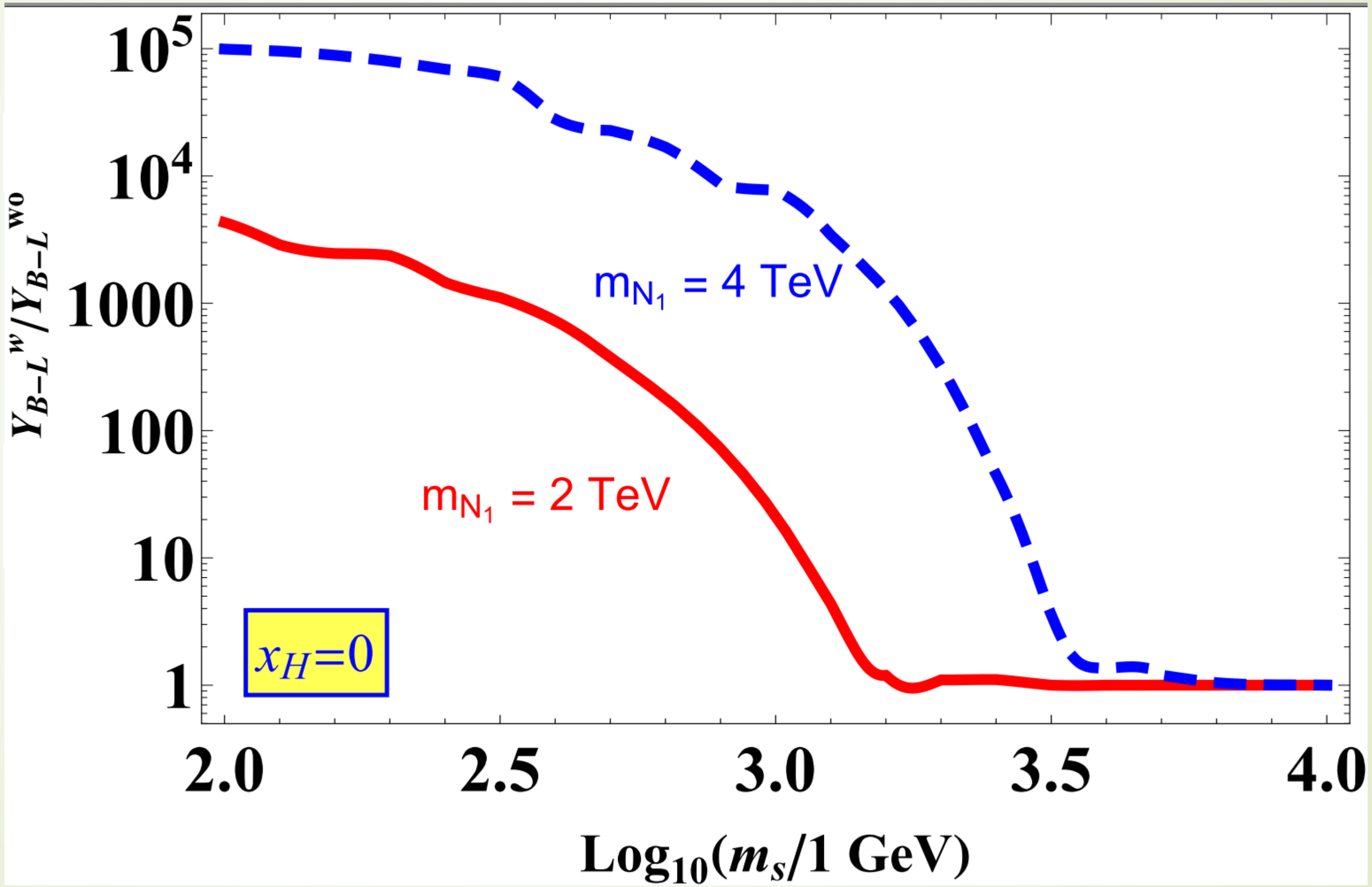
## NH case

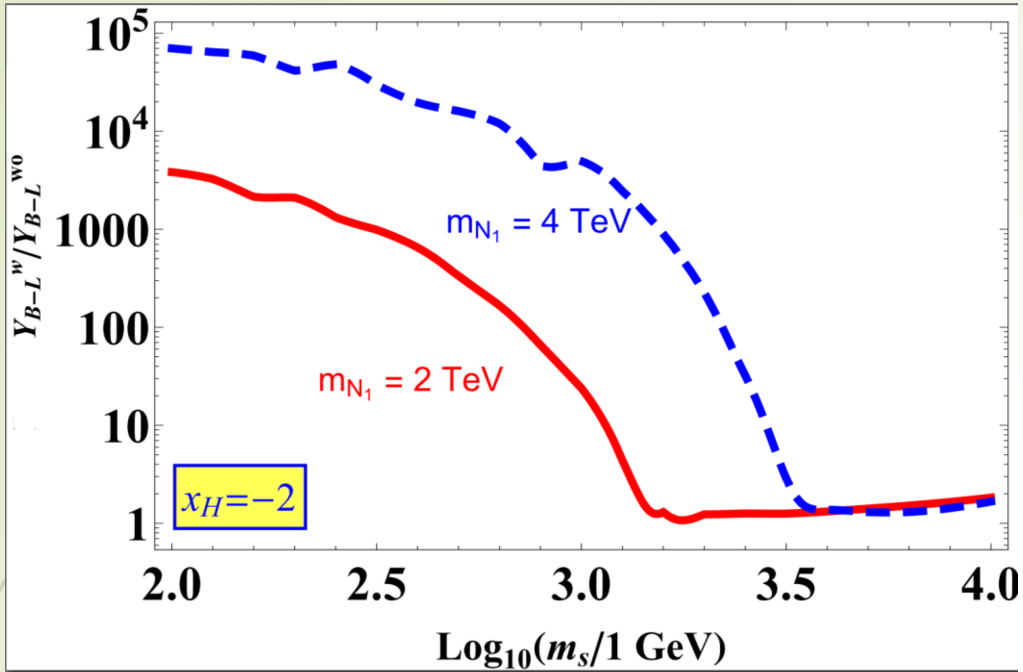
$$
\begin{aligned}
|\epsilon_1| &= \left| \frac{1}{2} \frac{\mathrm{Im}\left[\left(m_D m_D^\dagger\right)_{ij}^2\right]}{\left(m_D m_D^\dagger\right)_{ii}\left(m_D m_D^\dagger\right)_{jj}} \right| \\
&= \left| \frac{(m_{2NH}^2 - m_{3NH}^2)\sin(2\alpha_r)\sinh(2\alpha_i)}{(m_{2NH} - m_{3NH})^2\cos(2\alpha_r)^2 - (m_{2NH} + m_{3NH})^2\cosh(2\alpha_i)^2} \right| \\
&\leq \frac{m_{3NH} - m_{2NH}}{2(m_{3NH} + m_{2NH})} \qquad \alpha = \pm\frac{\pi}{4} + \frac{i}{2}\log(1+\sqrt{2}) \\
&= 0.353, \qquad m_{2NH} = 0.00861\ \mathrm{eV}, m_{3NH} = 0.0502\ \mathrm{eV}
\end{aligned}
$$

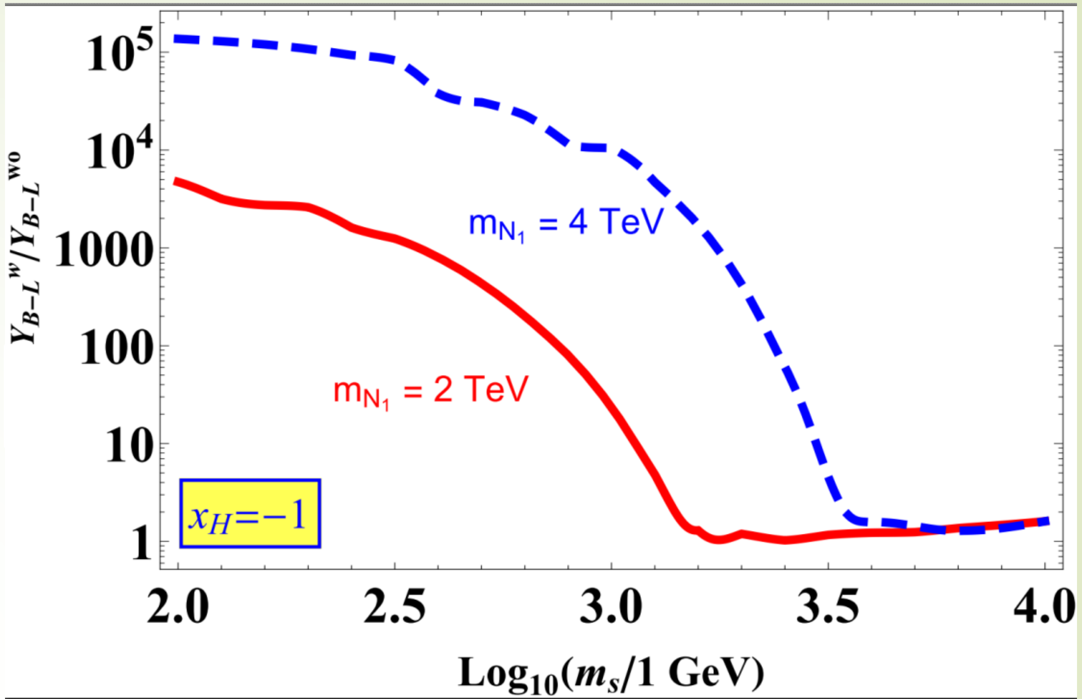
## IH case

$$
\begin{aligned}
|\epsilon_1| &= \left| \frac{(m_{1IH}^2 - m_{2IH}^2)\sin(2\alpha_r)\sinh(2\alpha_i)}{(m_{1IH} - m_{2IH})^2\cos(2\alpha_r)^2 - (m_{1IH} + m_{2IH})^2\cosh(2\alpha_i)^2} \right| \\
&\leq \frac{m_{2IH} - m_{1IH}}{2(m_{2IH} + m_{1IH})} = 0.00377, \qquad m_{1IH} = 0.0492\ \mathrm{eV}, m_{2IH} = 0.0500\ \mathrm{eV}
\end{aligned}
$$

# Scalar contribution




$Y_{B-L}^{w}/Y_{B-L}^{wo}$
$10^5$
$10^4$
1000
100
10
1
2.0
2.5
3.0
3.5
4.0
$\mathrm{Log}_{10}(m_s/1\ \mathrm{GeV})$
$m_{N_1}$ = 4 TeV
$m_{N_1}$ = 2 TeV
$x_H=-2$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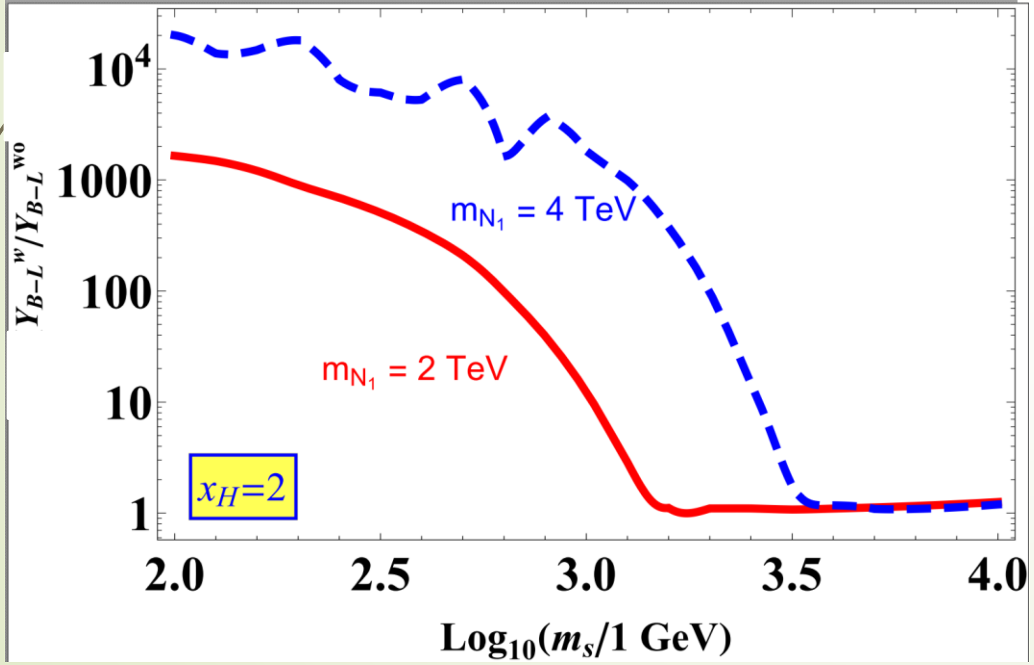
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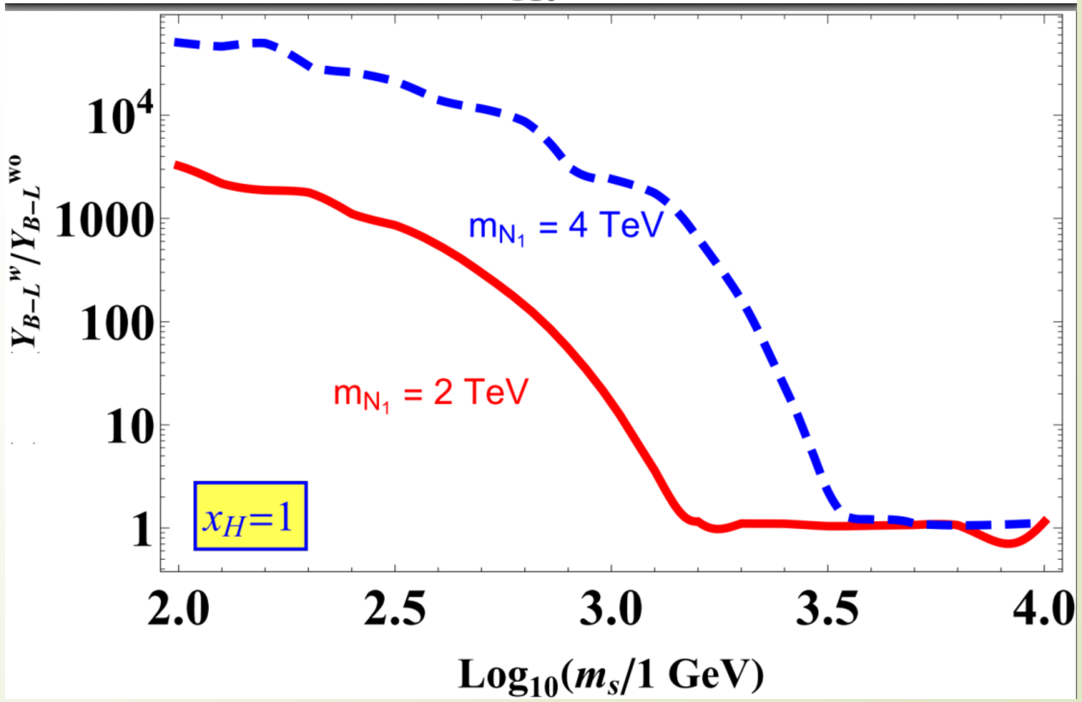
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$m_{N_1}$ = 4 TeV
$m_{N_1}$ = 2 TeV
$x_H=1$

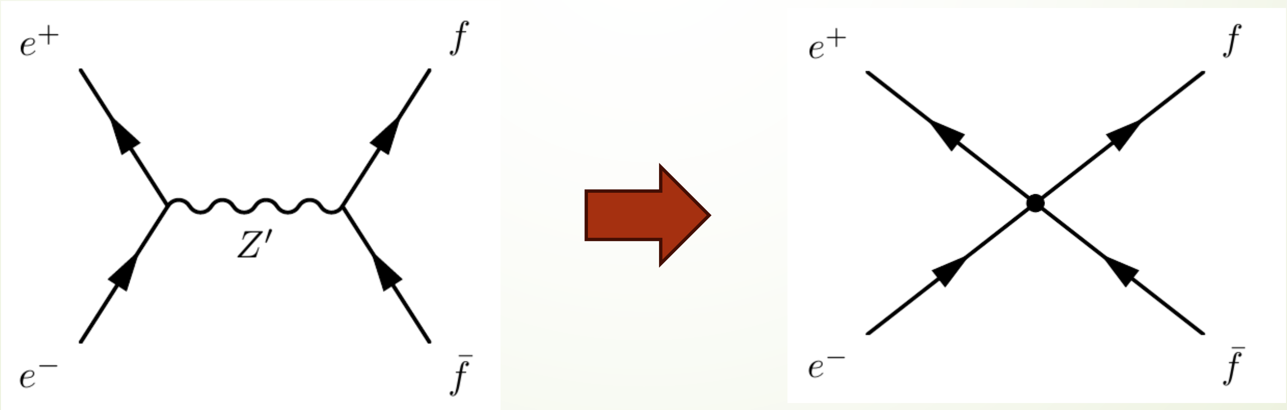
# Collider

# Electron-Positron colliders

LEP II experiment provide the bound of the following ΛAB

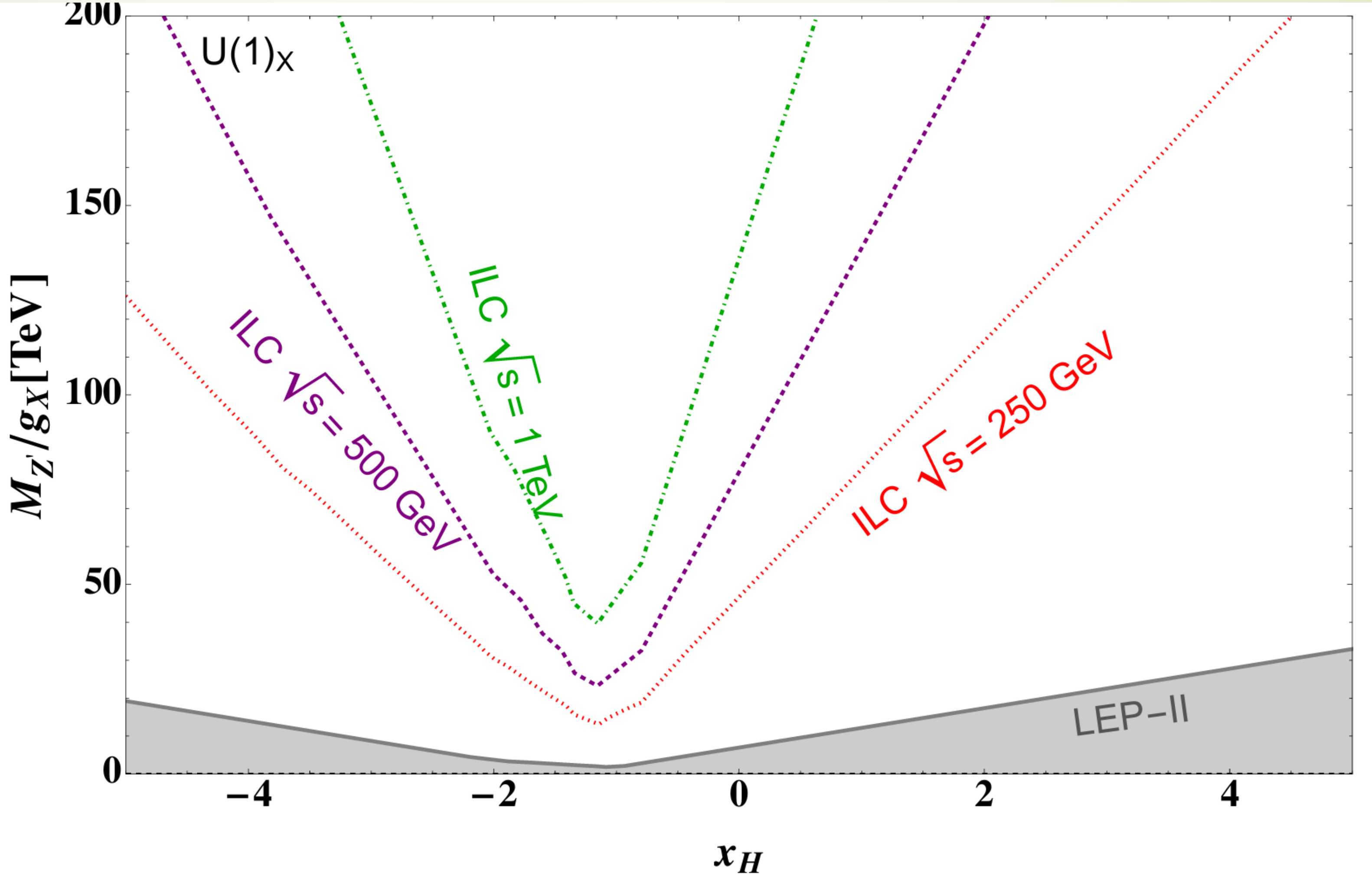
$$\mathcal{L}_{\text{eff}} = \frac{g_X^2}{(1+\delta_{ef})(\Lambda_{AB}^{f\pm})^2} \sum_{A,B=L,R} \eta_{AB}(\bar{e}\gamma^\mu P_A e)(\bar{f}\gamma_\mu P_B f)$$

ΛAB in U(1) models




$$\frac{g_X^2}{{M_{Z'}}^2 - s}[\bar{e}\gamma^\mu(x_\ell P_L + x_e P_R)e][\bar{f}\gamma_\mu(x_{f_L} P_L + x_{f_R} P_R)f]$$

$$M_{Z'}^2 \gtrsim \frac{{g_X}^2}{4\pi}|x_{e_A} x_{f_B}|(\Lambda_{AB}^{f\pm})^2$$



U(1)X
ILC √s = 500 GeV
ILC √s = 1 TeV
ILC √s = 250 GeV
LEP–II
M_Z'/g_X [TeV]
x_H
200
150
100
50
0
−4
−2
0
2
4

# Hadron collider

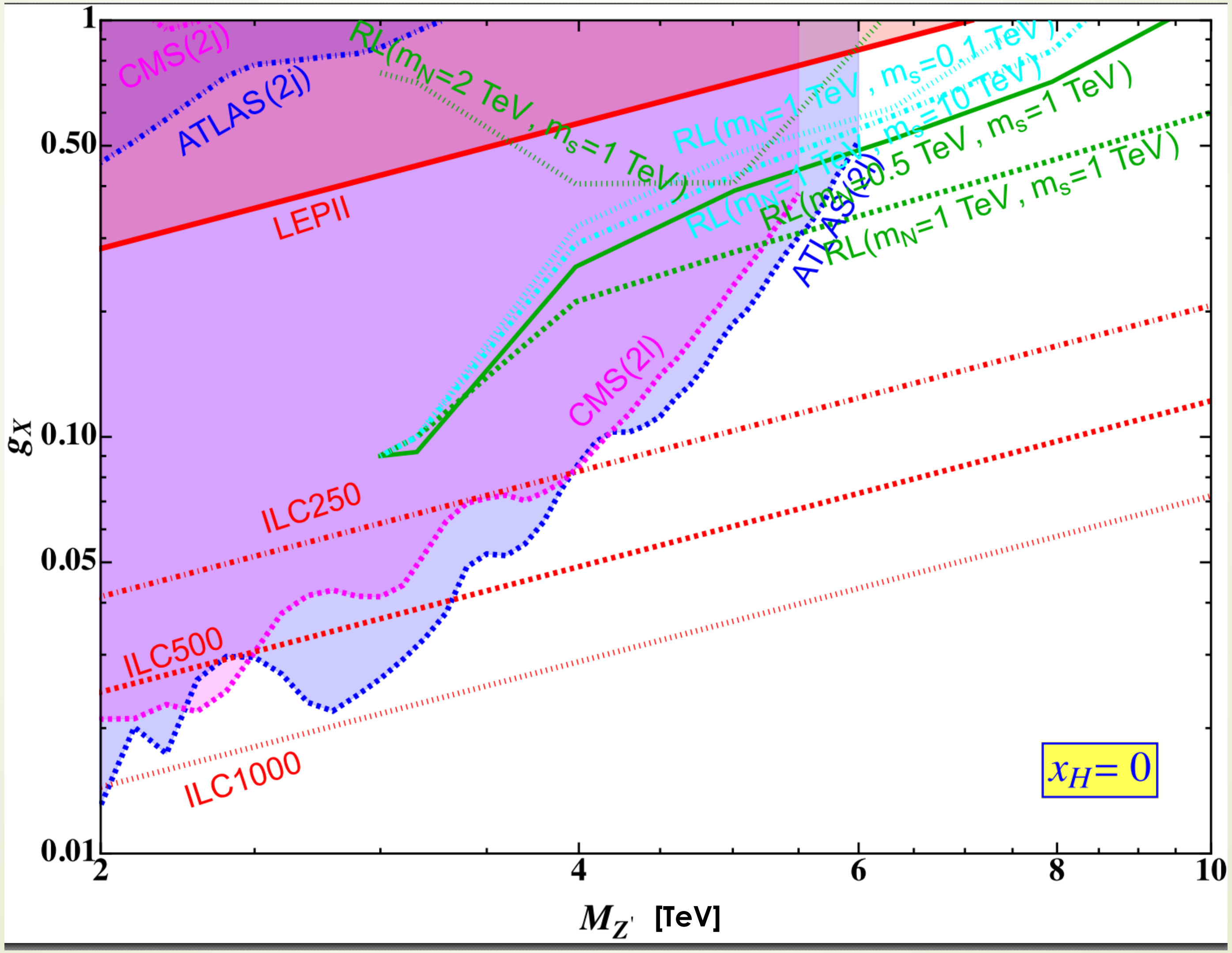
- LHC uses Sequential Standard Model(SSM)
- We compare the production cross section of dilepton mode in our model with that of CMS and ATLAS experiments

$$g_X = g^{\rm model}\sqrt{\frac{\sigma^{\rm CMS/ATLAS}}{\sigma^{\rm model}}}$$

Trial value : $g_{\rm model}$

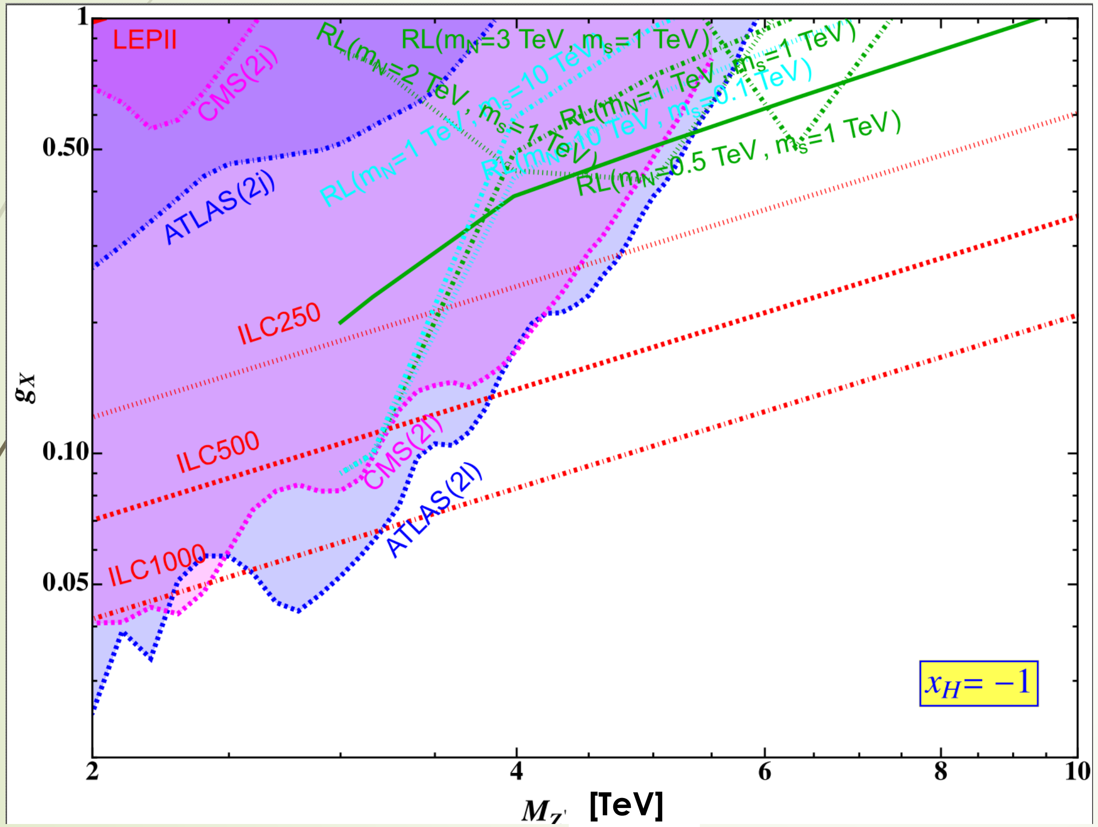
$$\sigma^{\rm model} = \frac{8\pi^2}{3}\sum_{q,\bar{q}}\int dx\int dy\; q(x,Q),\bar{q}(x,Q)\times\frac{\Gamma(Z'\to q\bar{q})}{M_{Z'}}\delta(\hat{s}-M_{Z'})\times {\rm BR}({\rm Z}'\to 2\ell)$$

# Result

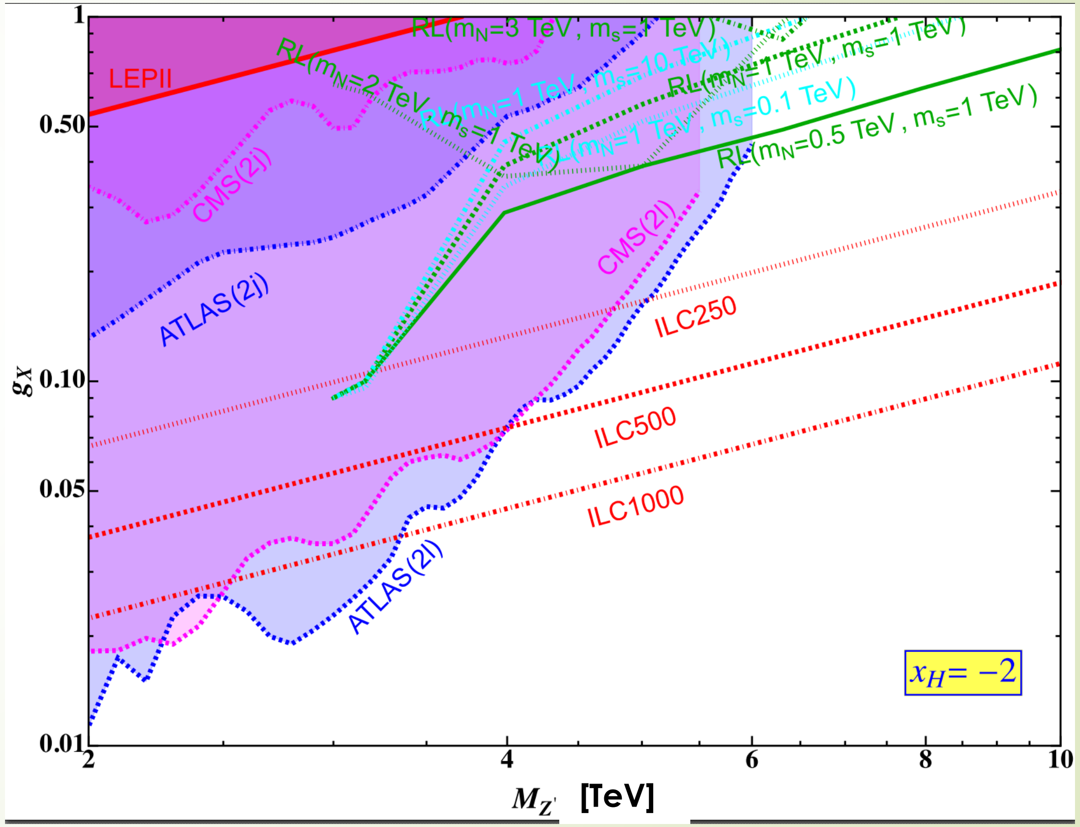


CMS(2j)
ATLAS(2j)
LEPII
ILC250
ILC500
ILC1000
CMS(2l)
ATLAS(2l)
RL(m_N=2 TeV, m_s=1 TeV)
RL(m_N=1 TeV, m_s=0.1 TeV)
RL(m_N=1 TeV, m_s=10 TeV)
RL(m_N=0.5 TeV, m_s=1 TeV)
RL(m_N=1 TeV, m_s=1 TeV)
x_H = 0
g_X
M_Z' [TeV]
1
0.50
0.10
0.05
0.01
2
4
6
8
10

# Results

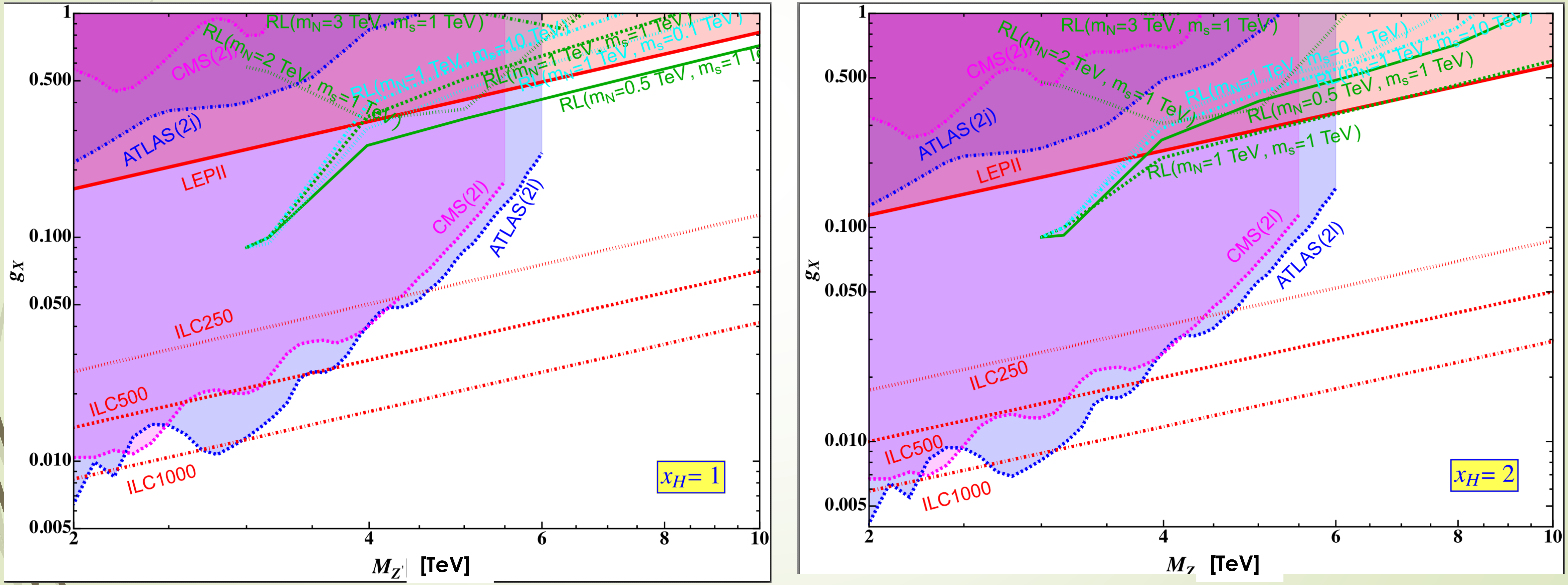


LEPII
CMS(2j)
ATLAS(2j)
ILC250
ILC500
ILC1000
CMS(2l)
ATLAS(2l)
$x_H = -1$
$g_X$
$M_{Z'}$ [TeV]

LEPII
CMS(2j)
ATLAS(2j)
ILC250
ILC500
ILC1000
CMS(2l)
ATLAS(2l)
$x_H = -2$
$g_X$
$M_{Z'}$ [TeV]

# Results



RL($m_N$=3 TeV, $m_s$=1 TeV)
RL($m_N$=2 TeV, $m_s$=1 TeV)
RL($m_N$=1 TeV, $m_s$=10 TeV)
RL($m_N$=1 TeV, $m_s$=1 TeV)
RL($m_N$=1 TeV, $m_s$=0.1 TeV)
RL($m_N$=0.5 TeV, $m_s$=1 TeV)
CMS(2j)
ATLAS(2j)
LEPII
CMS(2l)
ATLAS(2l)
ILC250
ILC500
ILC1000
$x_H$= 1
$x_H$= 2
$g_X$
$M_{Z'}$ [TeV]

# Conclusion

- We consider $U(1)_X$ scenario
- We estimate the bound on $m_{Z'}$-$g_X$ plane from resonant leptogenesis
- And from LHC and LEPII
- Resonant leptogenesis provide stronger bound compared to those obtained from LHC

  for $m_{Z'} > 5.8$ TeV

# Back-up

# U(1) models

| Fields | $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ | $U(1)_X$ | $U(1)_{xq-\tau_R^3}$ | $U(1)_{q+xu}$ |
|---|---|---|---|---|
| $q_L^i$ | $(3, 2, \frac{1}{6})$ | $x_q = \frac{1}{6}x_H + \frac{1}{3}x_\Phi$ | $x$ | $\frac{1}{3}$ |
| $u_R^i$ | $(3, 1, \frac{2}{3})$ | $x_u = \frac{2}{3}x_H + \frac{1}{3}x_\Phi$ | $-1 + 4x$ | $\frac{x}{3}$ |
| $d_R^i$ | $(3, 1, -\frac{1}{3})$ | $x_d = -\frac{1}{3}x_H + \frac{1}{3}x_\Phi$ | $1 - 2x$ | $\frac{2-x}{3}$ |
| $\ell_L^i$ | $(1, 2, -\frac{1}{2})$ | $x_\ell = -\frac{1}{2}x_H - x_\Phi$ | $-3x$ | $-1$ |
| $e_R^i$ | $(1, 1, -1)$ | $x_e = -x_H - x_\Phi$ | $1 - 6x$ | $-(\frac{2+x}{3})$ |
| $H$ | $(1, 2, -\frac{1}{2})$ | $-\frac{1}{2}x_H$ | $1 - 3x$ | $\frac{1-x}{3}$ |
| $N^j$ | $(1, 1, 0)$ | $x_N = -x_\Phi$ | $-1$ | $\frac{-4+x}{3}$ |
| $\Phi$ | $(1, 1, 0)$ | $2\ x_\Phi$ | $2$ | $-2(\frac{-4+x}{3})$ |

$U(1)_X$: Linear combination of Y and B-L

$U(1)_{xq-\tau_R^3}$: x=-1: $U(1)_\chi$ from SO(10) GUT, x=4-3$g_R^2/g_Y^2$: $(U(1)_R \times U(1)_{B-L})/U(1)_Y$

$U(1)_{q+xu}$: x=0: $u_R$ zero, x=2: $d_R$ zero, x=-2: $e_R$ zero

# U(1)X and U(1)xq-τR3

| Fields | $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ | $U(1)_X$ | $U(1)_{xq-\tau^3_R}$ | $U(1)_{q+xu}$ |
|---|---|---|---|---|
| $q^i_L$ | $(3, 2, \frac{1}{6})$ | $\frac{1}{6}x_H + \frac{1}{3}x_\Phi$ | $x$ | $\frac{1}{3}$ |
| $u^i_R$ | $(3, 1, \frac{2}{3})$ | $\frac{2}{3}x_H + \frac{1}{3}x_\Phi$ | $-1 + 4x$ | $\frac{x}{3}$ |
| $d^i_R$ | $(3, 1, -\frac{1}{3})$ | $-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$ | $1 - 2x$ | $\frac{2-x}{3}$ |
| $\ell^i_L$ | $(1, 2, -\frac{1}{2})$ | $-\frac{1}{2}x_H - x_\Phi$ | $-3x$ | $-1$ |
| $e^i_R$ | $(1, 1, -1)$ | $-x_H - x_\Phi$ | $1 - 6x$ | $-(\frac{2+x}{3})$ |
| $H$ | $(1, 2, -\frac{1}{2})$ | $-\frac{1}{2}x_H$ | $1 - 3x$ | $\frac{1-x}{3}$ |
| $N^j$ | $(1, 1, 0)$ | $-x_\Phi$ | $-1$ | $\frac{-4+x}{3}$ |
| $\Phi$ | $(1, 1, 0)$ | $2\ x_\Phi$ | $2$ | $-2(\frac{-4+x}{3})$ |

$$U(1)_X \to U(1)_{xq-\tau^3_R}$$

$$x_\Phi \to 1$$

$$x_H \to 6x - 2$$

# U(1)$_X$ and U(1)$_{q+xu}$

| Fields | $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ | $U(1)_X$ | $U(1)_{xq-\tau_R^3}$ | $U(1)_{q+xu}$ |
|---|---|---|---|---|
| $q_L^i$ | $(3,2,\frac{1}{6})$ | $\frac{1}{6}x_H+\frac{1}{3}x_\Phi$ | $x$ | $\frac{1}{3}$ |
| $u_R^i$ | $(3,1,\frac{2}{3})$ | $\frac{2}{3}x_H+\frac{1}{3}x_\Phi$ | $-1+4x$ | $\frac{x}{3}$ |
| $d_R^i$ | $(3,1,-\frac{1}{3})$ | $-\frac{1}{3}x_H+\frac{1}{3}x_\Phi$ | $1-2x$ | $\frac{2-x}{3}$ |
| $\ell_L^i$ | $(1,2,-\frac{1}{2})$ | $-\frac{1}{2}x_H-x_\Phi$ | $-3x$ | $-1$ |
| $e_R^i$ | $(1,1,-1)$ | $-x_H-x_\Phi$ | $1-6x$ | $-(\frac{2+x}{3})$ |
| $H$ | $(1,2,-\frac{1}{2})$ | $-\frac{1}{2}x_H$ | $1-3x$ | $\frac{1-x}{3}$ |
| $N^j$ | $(1,1,0)$ | $-x_\Phi$ | $-1$ | $\frac{-4+x}{3}$ |
| $\Phi$ | $(1,1,0)$ | $2\ x_\Phi$ | $2$ | $-2(\frac{-4+x}{3})$ |

$$U(1)_X \to U(1)_{q+xu}$$

$$x_\Phi \to \frac{1}{3}(x-4)$$

$$x_H \to \frac{2}{3}(x-1)$$

# U(1)x model

| Fields | $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ | $U(1)_X$ | $U(1)_{xq-\tau^3_R}$ | $U(1)_{q+xu}$ |
|---|---|---|---|---|
| $q^i_L$ | $(3,2,\frac{1}{6})$ | $\frac{1}{6}x_H + \frac{1}{3}x_\Phi$ | $x$ | $\frac{1}{3}$ |
| $u^i_R$ | $(3,1,\frac{2}{3})$ | $\frac{2}{3}x_H + \frac{1}{3}x_\Phi$ | $-1+4x$ | $\frac{x}{3}$ |
| $d^i_R$ | $(3,1,-\frac{1}{3})$ | $-\frac{1}{3}x_H + \frac{1}{3}x_\Phi$ | $1-2x$ | $\frac{2-x}{3}$ |
| $\ell^i_L$ | $(1,2,-\frac{1}{2})$ | $-\frac{1}{2}x_H - x_\Phi$ | $-3x$ | $-1$ |
| $e^i_R$ | $(1,1,-1)$ | $-x_H - x_\Phi$ | $1-6x$ | $-(\frac{2+x}{3})$ |
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| $\Phi$ | $(1,1,0)$ | $2\ x_\Phi$ | $2$ | $-2(\frac{-4+x}{3})$ |

# Baryon Asymmetry

There are baryon asymmetry in universe.

$$5.8\ 10^{-10} < \frac{n_b - n_{\bar{b}}}{n_\gamma} < 6.5\ 10^{-10}$$

The origin of baryon asymmetry is mystery.

# Sakharov’s condition

THE BARYON ASYMMETRY CAN BE DYNAMICALLY GENERATED (‘BARYOGENESIS’) PROVIDED THAT

1. B VIOLATION
2. C AND CP VIOLATION
3. OUT OF THERMAL EQUILIBRIUM

# Baryogenesis in SM

## Electroweak baryogenesis

- B violation

  sphaleron process
- C and CP violation

  CKM matrix
- Out of thermal equilibrium

  1st order phase transition

# Can electroweak baryogenesis in SM generate a sufficiently large asymmetry?

↓

NO!

The SM fails on two aspects:

1. The Higgs sector does not give a strongly first order PT.

Requirement: $m_H < 70 GeV$ LHC: $m_H = 125.25$ GeV

2. CP Violation in CKM is not enough.

Requirement: $Y_B \sim 10^{-10}$ CKM: $\frac{n_B - n_{\bar{B}}}{n_B + n_{\bar{B}}} \sim 10^{-20}$

# Baryogenesis Via Leptogenesis

SM + right-handed Majorana neutrinos

- B violation

  L violation by majorana neutrinos decay

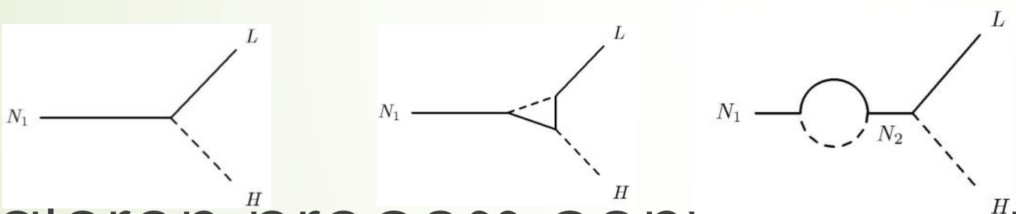
  Sphaleron process
- C and CP violation

  Neutrino mixing matrix (complex)
- Out of thermal equilibrium

  Out of equilibrium decay of right-handed neutrino

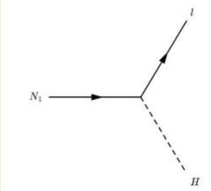
# Baryogenesis Via Leptogenesis

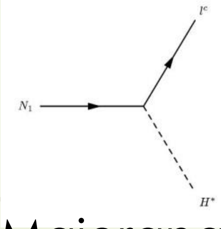
- L asymmetry is generated due to CP asymmetry that arises through interference of tree level and one-loop diagrams.




- Sphaleron process converts L asymmetry into B asymmetry.

# CP Asymmetry



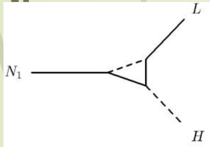

Right-handed Majorana neutrino can decay into lepton and anti-lepton.

$$\epsilon_1 \equiv \frac{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) - \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) + \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}$$

$$= -\sum_{j=2,3} \frac{M_1}{M_j}\frac{\Gamma_j}{M_j}\left(\frac{V_j}{2} + S_j\right)\frac{\mathrm{Im}\left[(Y_D^2)_{1j}^2\right]}{\left|Y_D^2\right|_{11}\left|Y_D^2\right|_{jj}}$$

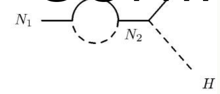
$$\frac{\Gamma_j}{M_j} = \frac{\left|Y_D^2\right|_{jj}}{8\pi}$$

## Vertex contribution




$$V_j = 2\frac{M_j^2}{M_1^2}\left[\left(1 + \frac{M_j^2}{M_1^2}\right)\log\left(1 + \frac{M_1^2}{M_j^2}\right) - 1\right]$$

## Self-energy contribution




$$S_j = \frac{M_j^2 \Delta M_{1j}^2}{\left(\Delta M_{1j}^2\right)^2 + M_1^2 \Gamma_j^2}$$

$$\Delta M_{1j}^2 = M_j^2 - M_1^2$$

# Hierarchical case

If right-handed neutrinos have a hierarchical mass spectrum $(M_{2,3} \gg M_1)$, we can write a CP asymmetry parameter as

$$\epsilon_1 \sim \frac{3}{16\pi}\frac{m_\nu M_1}{v^2}\sin\delta \sim 10^{-6}\frac{m_\nu}{0.05eV}\frac{M_1}{10^{10}GeV}\sin\delta$$

The present Baryon asymmetry $Y_B \sim \kappa\frac{\epsilon_1}{g_*} \sim 10^{-10}$

$g_* = \mathcal{O}(100)$ is the number of relativistic degrees of freedom.

The efficiency factor (due to wash out)

In the SM $\kappa \sim 2 \times 10^{-2}\left(\frac{0.05eV}{m_\nu}\right)^{1.1}$

# Majorana mass bound

$$Y_B \sim 10^{-10} \left(\frac{0.05eV}{m_\nu}\right)^{0.1} \frac{M_1}{10^{10}GeV} \sin\delta \sim 10^{-10}$$

$$m_\nu \sim \sqrt{m_{atm}^2} \sim 0.05eV$$

**The lightest Majorana mass is heavier than $10^{10}$ $GeV$**

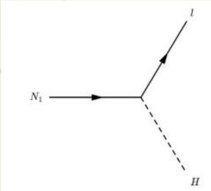
# Resonant Leptogenesis

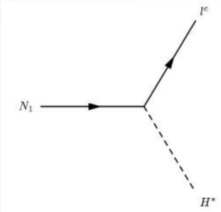
- The Majorana masses is heavier than $10^{10} GeV$ , if the spectrum of Majorana masses has hierarchy.
- If the Majorana mass of right-handed neutrino is smaller than a few TeV, general leptogenesis can not work.

⬇

Resonant-Leptogenesis

# CP Asymmetry



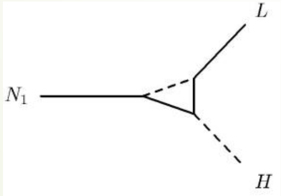




Right-handed Majorana neutrino can decay into lepton and anti-lepton.

$$\epsilon_1 \equiv \frac{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) - \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}{\sum_j \left[\Gamma\left(N_1 \to \ell_j h\right) + \Gamma\left(N_1 \to \ell_j^C h^*\right)\right]}$$

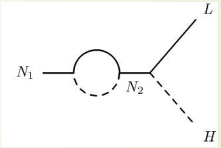
$$= -\sum_{j=2,3} \frac{M_1}{M_j}\frac{\Gamma_j}{M_j}\left(\frac{V_j}{2} + S_j\right)\frac{\mathrm{Im}\left[(Y_D^2)_{1j}^2\right]}{\left|Y_D^2\right|_{11}\left|Y_D^2\right|_{jj}} \qquad \frac{\Gamma_j}{M_j} = \frac{\left|Y_D^2\right|_{jj}}{8\pi}$$

Vertex contribution




$$V_j = 2\frac{M_j^2}{M_1^2}\left[\left(1 + \frac{M_j^2}{M_1^2}\right)\log\left(1 + \frac{M_1^2}{M_j^2}\right) - 1\right]$$

Self-energy contribution




$$S_j = \frac{M_j^2 \Delta M_{1j}^2}{\left(\Delta M_{1j}^2\right)^2 + M_1^2 \Gamma_j^2}$$

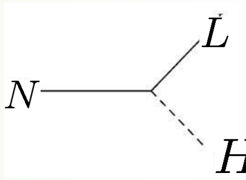
$$\Delta M_{1j}^2 = M_j^2 - M_1^2$$

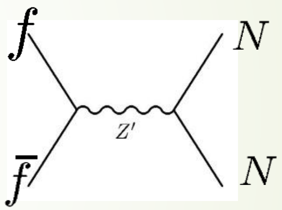
# Thermal Leptogenesis

Baryon asymmetry is evaluated by Boltzmann equations with TeV scale Z' boson.

Number density of neutrino

$$\frac{dY_N}{dz} \sim -\frac{z}{sH}\left[\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\gamma_D + \left(\left(\frac{Y_N}{Y_N^{eq}}\right)^2 - 1\right)\gamma_{Z'}\right]$$




$$z = \frac{m_1}{T}$$

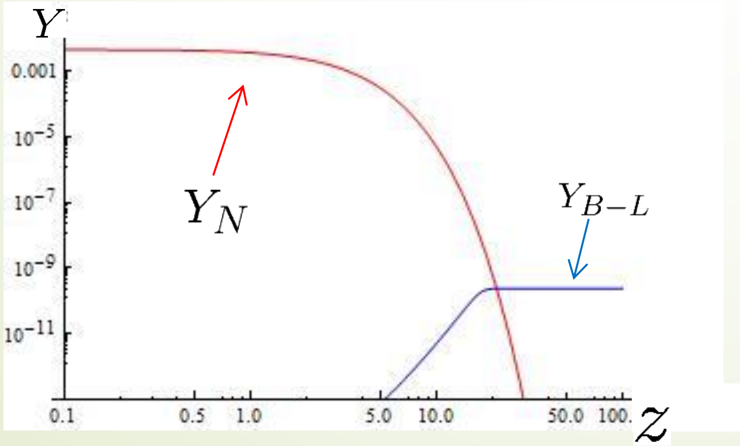
Bryon number generation via neutrino decay

$$\frac{dY_{B-L}}{dz} \sim -\frac{z}{sH}\left[\frac{1}{2}\frac{Y_{B-L}}{Y_l^{eq}} + \epsilon\left(\frac{Y_N}{Y_N^{eq}} - 1\right)\right]\gamma_D$$

Initial condition

$$Y_{B-L}(z=0) = 0$$

$$Y_N(z=0) = Y_N^{eq}$$



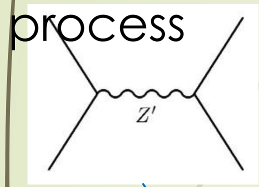
# TeV scale Leptogenesis

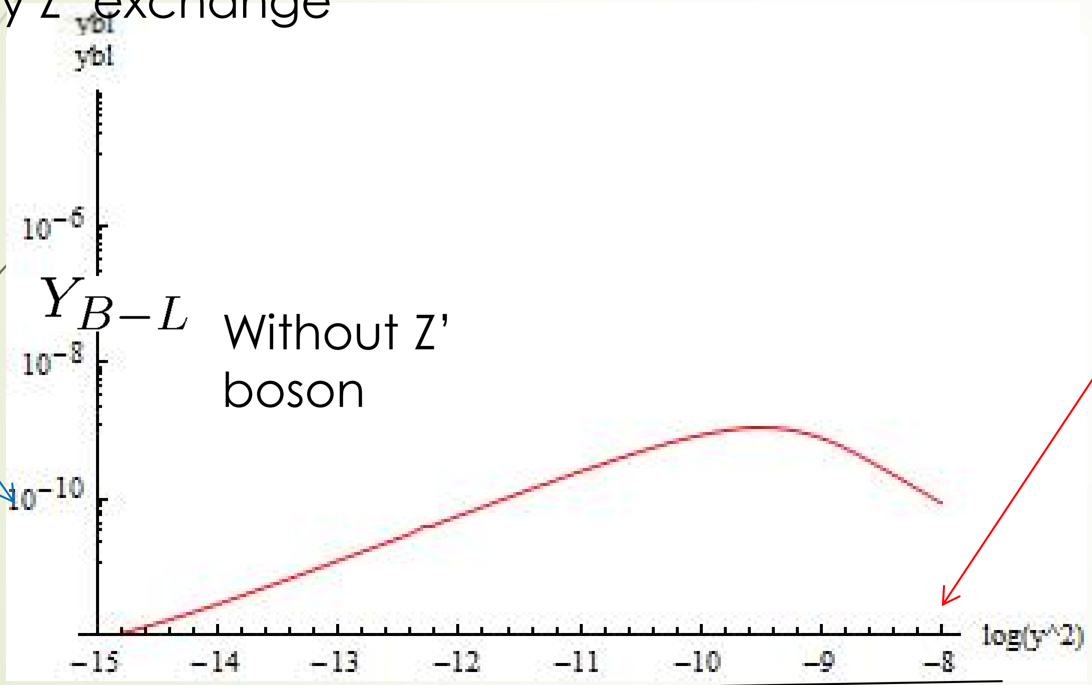
$$\begin{cases} \frac{dY_N}{dz} \sim -\frac{z}{sH}\left[\left(\frac{Y_N}{Y_N^{eq}}-1\right)\gamma_D\right] \\ \frac{dY_{B-L}}{dz} \sim -\frac{z}{sH}\left[\frac{1}{2}\frac{Y_{B-L}}{Y_l^{eq}}+\epsilon\left(\frac{Y_N}{Y_N^{eq}}-1\right)\right]\gamma_D \end{cases}$$

$$\gamma_D = n^{eq}\frac{K_1(z)}{K_2(z)}\Gamma_1$$

$$\Gamma_1 = \frac{\left|Y_D^2\right|_{11} M_1}{8\pi}$$

suppressed by Z' exchange process



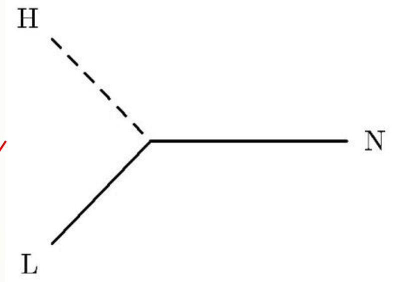




$Y_{B-L}$

Without Z' boson

With Z' boson

Wash out for inverse decay




Initial condition

$Y_B(z=0) = 0$

$Y_N(z=0) = Y_N^{eq}$

$m_{Z'} = 2.5TeV$

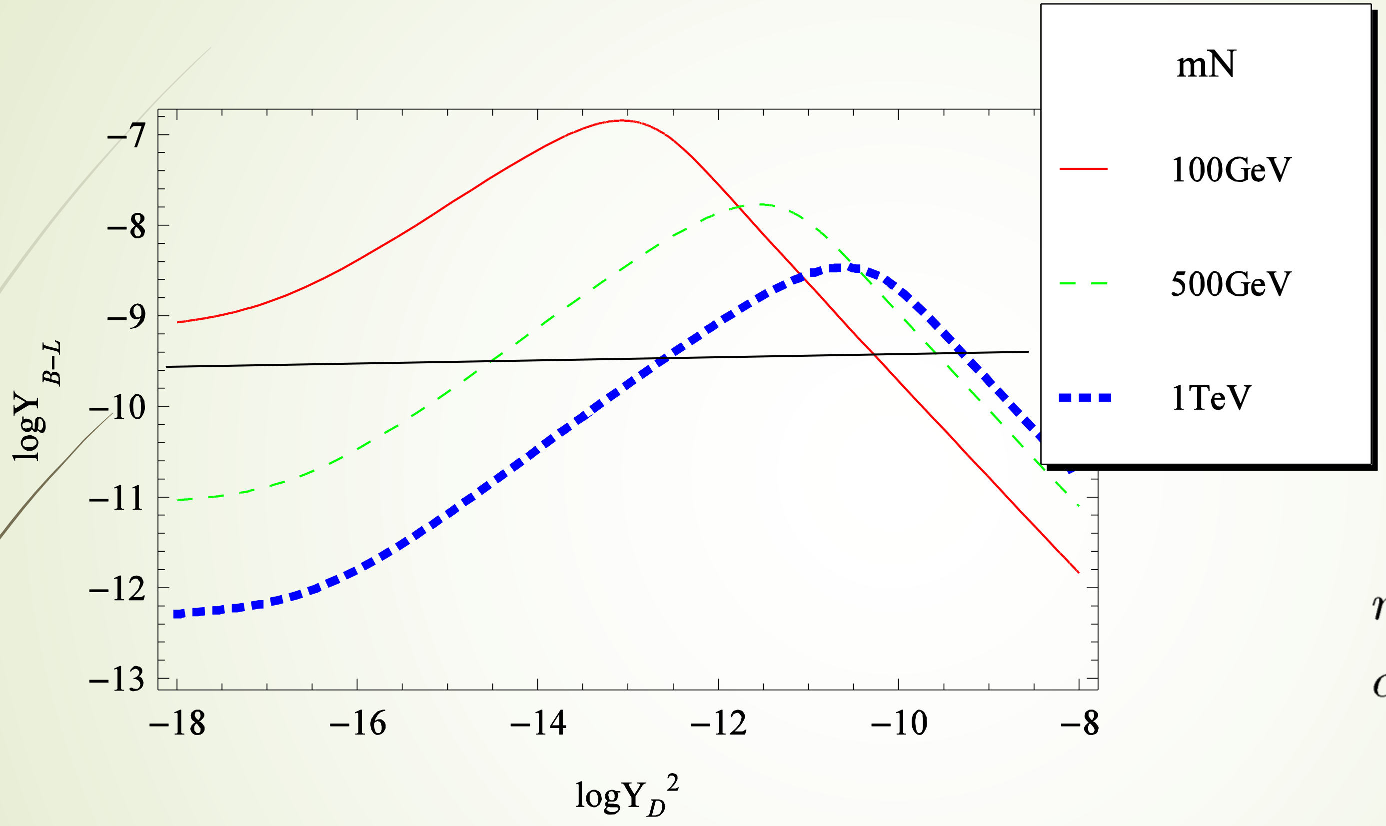
$m_N = 1TeV$

$\alpha_{B-L} = 0.008$

$\log_{10} Y_D^2$

ε=0.01

# Different Majorana Mass




$m_{Z'} = 2.5 TeV$

$\alpha_{B-L} = 0.008$

ε=0.01