RESONANT LEPTOGENESIS IN B-L EXTENDED STANDARD MODEL AT TEV SCALE

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CONTENTS

- RESONANT LEPTOGENESIS
- FLAVOR SYMMETRY

RESONANT LEPTOGENESIS

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 VIA LEPTOGENESIS

SM + right-handed Majorana neutrinos

- B violation

  L violation by majorana neutrinos decay

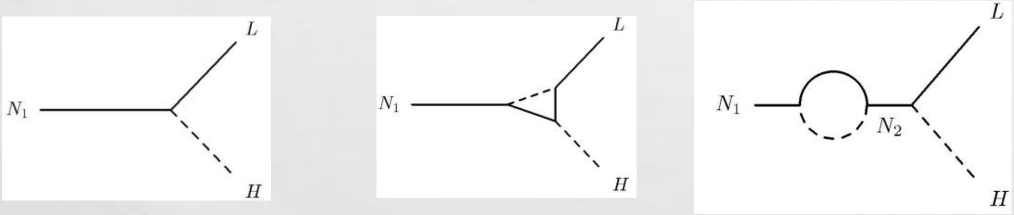
  Sphaleron process
- C and CP violation

  Neutrino mixing matrix (complex)
- Out of thermal equilibrium

  Out of equilibrium decay of right-handed neutrino

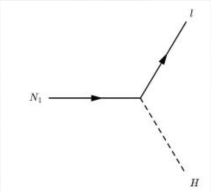
BARYOGENESIS VIA LEPTOGENESIS

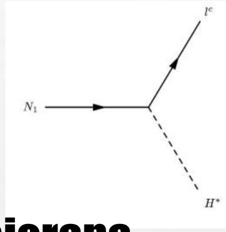
- L ASYMMETRY IS GENERATED DUE TO CP ASYMMETRY THAT ARISES THROUGH INTERFERENCE OF TREE LEVEL AND ONE-LOOP DIAGRAMS.



- SPHALERON PROCESS CONVERTS L ASYMMETRY INTO B ASYMMETRY.

CP ASYMMETRY





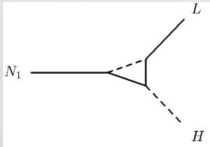
Right-handed Majorana neutrino can decay into lepton and anti-lepton.

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

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

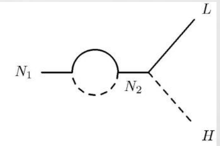
$$\frac{\Gamma_j}{M_j} = \frac{\left|Y_D^2\right|_{jj}}{8\pi}$$

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.

In the SM $\kappa \sim 2\times 10^{-2}\left(\frac{0.05eV}{m_\nu}\right)^{1.1}$ The efficiency factor (due to wash out)

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.

$\Downarrow$

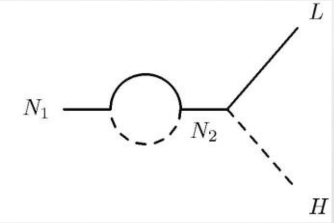
Resonant-Leptogenesis

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 correction dominate.

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

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



ϵ_1 **can be even** $O(1)$.

$$\frac{M_2^2 - M_1^2}{M_1^2} \sim 10^{-12}, \qquad M_1 \sim TeV$$

DEGENERATE MASSES

$M_1 = M_2$ @ $High\ scale$

RG evolution

$$M_2^2 - M_1^2 \quad \propto \quad Y_\nu^\dagger Y_\nu \ (y v_{B-L})^2$$
$$\propto \Gamma M$$

Flavor symmetry

S_4 Modular symmetry

FLAVOR SYMMETRY

MODEL

3 Right-Handed Neutrinos $\Rightarrow$ Resonant Leptogenesis

+

Dark Matter candidate

U(1) B-L Gauge Symmetry $\Rightarrow$ Thermal Production of Neutrinos

S_4 Modular Symmetry $\Rightarrow$ Resonant Leptogenesis

MODEL

	Fermions					Bosons		
	$\bar{L}_L \equiv (\bar{L}_{L_e}, \bar{L}_{L_\mu}, \bar{L}_{L_\tau})^T$	e_{R_e}	$\ell_R \equiv (e_{R_\mu}, e_{R_\tau})^T$	N_{R_1}	$N_R \equiv (N_{R_2}, N_{R_3})^T$	H_u	H_d	ϕ
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{2}$	-1	-1	0	0	$-\frac{1}{2}$	$\frac{1}{2}$	0
$U(1)_{B-L}$	1	-1	-1	-1	-1	0	0	2
S_4	$\mathbf{3'}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$-k$	-1	-1	-1	-3	0	-3	0	0

Yukawa

$$\mathcal{L}_Y = \alpha \bar{L}_L Y_{\mathbf{3'}}^{(2)} e_{R_e} H_d + \beta \bar{L}_L Y_{\mathbf{3'}}^{(2)} \ell_R H_d + \bar{L}_L \left(\gamma_1 Y_{\mathbf{3}}^{(4)} + \gamma_2 Y_{\mathbf{3'}}^{(4)} \right) N_R H_u + \delta \bar{N}_{R_1}^c Y_{\mathbf{1}}^{(6)} N_{R_1} \phi + y \bar{N}_R^c N_R \phi$$

MODULAR SYMMETRY

$$\tau \longrightarrow \gamma\tau = \frac{a\tau + b}{c\tau + d}\ , \quad \text{where} \quad a, b, c, d \in \mathbb{Z} \quad \text{and} \quad ad - bc = 1, \quad \mathrm{Im}[\tau] > 0$$

Generators

$$S : \tau \longrightarrow -\frac{1}{\tau}\ , \qquad T : \tau \longrightarrow \tau + 1$$

$$S^2 = I, (ST)^3 = I$$

Infinite normal group

$$\Gamma(N) = \left\{ \begin{pmatrix} a & b \\ c & d \end{pmatrix} \in SL(2, \mathbb{Z})\ , \quad \begin{pmatrix} a & b \\ c & d \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \quad (\mathrm{mod} N) \right\}$$

$$T^N = I$$

$$\Gamma(4) \approx S_4$$

MODULAR SYMMETRY

Holomorphic function (Yukawa couplings)

$$f(\gamma\tau) = (c\tau + d)^k f(\tau)\ , \quad \gamma \in \Gamma(N)$$

K : **Modular weight**

$$a = d = -1, b = c = 0$$
$$f(\tau) = (-1)^k f(\tau)$$

Odd modular weight ⇒ Vanish

Modular Weight	Representation
2	2, 3'
4	1, 2, 3, 3'
6	1, 1', 2, 3, 3'

Field

$$\phi^{(I)} \to (c\tau + d)^{-k_I} \rho^{(I)}(\gamma)\phi^{(I)},$$

$\rho^{(I)}(\gamma)$: **Unitary representation matrix of** S_4

MODEL

Yukawa

$$\mathcal{L}_Y = \alpha \bar{L}_L Y_{\mathbf{3'}}^{(2)} e_{R_e} H_d + \beta \bar{L}_L Y_{\mathbf{3'}}^{(2)} \ell_R H_d + \bar{L}_L \left(\gamma_1 Y_{\mathbf{3}}^{(4)} + \gamma_2 Y_{\mathbf{3'}}^{(4)} \right) N_R H_u + \delta \bar{N}_{R_1}^c Y_{\mathbf{1}}^{(6)} N_{R_1} \phi + y \bar{N}_R^c N_R \phi$$

Vanishing terms

$\bar{L}_L N_{R_1} H_u$

$\bar{N}_R^c N_{R_1} \phi$

→ **Yukawa coupling with odd modular weight**

N_{R_1} **is stable** → **Dark Matter Candidate**

	Fermions					Bosons		
	$\bar{L}_L \equiv (\bar{L}_{L_e}, \bar{L}_{L_\mu}, \bar{L}_{L_\tau})^T$	e_{R_e}	$\ell_R \equiv (e_{R_\mu}, e_{R_\tau})^T$	N_{R_1}	$N_R \equiv (N_{R_2}, N_{R_3})^T$	H_u	H_d	ϕ
$SU(2)_L$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{2}$	$\mathbf{1}$
$U(1)_Y$	$\frac{1}{2}$	-1	-1	0	0	$-\frac{1}{2}$	$\frac{1}{2}$	0
$U(1)_{B-L}$	1	-1	-1	-1	-1	0	0	2
S_4	$\mathbf{3'}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$-k$	-1	-1	-1	-3	0	-3	0	0

MODEL

Boundary conditions

$$Y_M(m_0) = \begin{pmatrix} y & 0 \\ 0 & y \end{pmatrix}$$

m_0: **Breaking scale of the flavor symmetry**

$$Y_\nu(m_0) = \begin{pmatrix} \gamma_2 y_1' & -\gamma_1 y_1 \\ \frac{\sqrt{3}}{2}\gamma_1 y_2 - \frac{1}{2}\gamma_2 y_3' & \frac{1}{2}\gamma_1 y_3 + \frac{\sqrt{3}}{2}\gamma_2 y_2' \\ \frac{\sqrt{3}}{2}\gamma_1 y_3 - \frac{1}{2}\gamma_2 y_2' & \frac{1}{2}\gamma_1 y_2 + \frac{\sqrt{3}}{2}\gamma_2 y_3' \end{pmatrix}$$

$$Y_{\mathbf{3}}^{(4)} = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix}, \quad Y_{\mathbf{3'}}^{(4)} = \begin{pmatrix} y_1' \\ y_2' \\ y_3' \end{pmatrix}$$

$$Y_\nu(m_{EW}) \sim U_{MNS}^* \begin{pmatrix} 0 & 0 \\ \sqrt{m_1} & 0 \\ 0 & \sqrt{m_2} \end{pmatrix} O \sqrt{Y_M(m_{EW})}\,\frac{\sqrt{v_{B-L}}}{v}$$

$$O = \begin{pmatrix} cos\alpha & sin\alpha \\ -sin\alpha & cos\alpha \end{pmatrix}, \alpha \in \mathbb{C}$$

RESULT

parameters

Guage

$$v_{B-L} = 17\ TeV$$
$$g_{B-L} = 0.20$$

Modular

$$\tau = 0.25 + 2.5\ i$$

Yukawa

$$\alpha = i$$
$$y = 0.5$$

predictions

Baryon number

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} = 5.93\ 10^{-10}$$

Active neutrino

$$m_1 = 8.46\ 10^{-3}\ eV$$
$$m_2 = 4.93\ 10^{-2}\ eV$$

Majorana neutrino

$$M_1 = 7.79\ TeV$$
$$\frac{M_2^2 - M_1^2}{M_1^2} = 9.92\ 10^{-12}$$

Gauge boson

$$M_{Z'} = 6.90\ TeV$$

Observed values

$5.8\ 10^{-10} < \frac{n_b - n_{\bar{b}}}{n_\gamma} < 6.5\ 10^{-10}$ **(95 % CL)**

$8.26\ 10^{-3}\ eV < m_1 < 8.97\ 10^{-3}\ eV$ **(3 σ)**

$4.93\ 10^{-2}\ eV < m_2 < 5.10\ 10^{-2}\ eV$ **(3 σ)**

CONCLUSIONS

- THE RESONANT LEPTOGENESIS SCENARIO IN THE TEV SCALE B-L MODEL
- S_4 MODULAR SYMMETRY NATURALLY REALIZES DEGENERATE MASSES
- RG EVOLUTIONS GENERATE A SPLITTING OF THE MAJORANA MASSES
- THE CP ASYMMETRY PARAMETERS ARE AUTOMATICALLY ENHANCED BY RESONANCE
- THE RIGHT AMOUNT OF BARYON NUMBER CAN BE OBTAINED

FUTURE WORK

- SEARCH WIDE REGION
- QUARK AND CHARGED LEPTON SECTOR

BACK UP

S_4 SYMMATRY

Representations : 1, 1', 2, 3, 3'

Tensor Products

$$1' \otimes 1' = 1$$
$$1' \otimes 2 = 2$$
$$1' \otimes 3 = 3'$$
$$1' \otimes 3' = 3$$

$$2 \otimes 2 = 1 \oplus 1' \oplus 2$$
$$2 \otimes 3 = 3 \oplus 3'$$
$$2 \otimes 3' = 3 \oplus 3'$$
$$3 \otimes 3 = 3' \otimes 3' = 1 \oplus 2 \oplus 3 \oplus 3'$$
$$3 \otimes 3' = 1' \oplus 2 \oplus 3 \oplus 3'$$

YUKAWA COUPLINGS

$$Y_{\mathbf{2}}^{(2)} = i\begin{pmatrix} Y^{(4)}(1,1,-1/2,-1/2,-1/2,-1/2|\tau) \\ Y^{(4)}(0,0,\sqrt{3}/2,-\sqrt{3}/2,\sqrt{3}/2,-\sqrt{3}/2|\tau) \end{pmatrix}$$

$$Y_{\mathbf{3'}}^{(2)} = i\begin{pmatrix} Y^{(4)}(1,-1,0,0,0,0|\tau) \\ Y^{(4)}(0,0,-1/\sqrt{2},i/\sqrt{2},1/\sqrt{2},-i/\sqrt{2}|\tau) \\ Y^{(4)}(0,0,-1/\sqrt{2},-i/\sqrt{2},1/\sqrt{2},i/\sqrt{2}|\tau) \end{pmatrix}$$

$$Y_{\mathbf{3}}^{(2)} = 0$$

$$Y^{(4)}(a_1,\ldots,a_6|\tau) = \frac{\mathrm{d}}{\mathrm{d}\tau}\left[a_1 \log\eta\left(\tau+\frac{1}{2}\right) + a_2\log\eta\,(4\tau) + a_3\log\eta\left(\frac{\tau}{4}\right) + a_4\log\eta\left(\frac{\tau+1}{4}\right) + a_5\log\eta\left(\frac{\tau+2}{4}\right) + a_6\log\eta\left(\frac{\tau+3}{4}\right)\right]$$

Dedekind eta function

$$\eta(\tau) = q^{1/24}\prod_{n=1}^{\infty}(1-q^n)\,, \qquad q = e^{2\pi i\tau}$$

Multiplets of higher weight can be obtained from those of lowest weight via tensor products.

MODULAR FORM

$$Y_{\mathbf{2}}^{(4,2)}(\tau) = -3\pi \begin{pmatrix} b_1^{(4)}(\tau)/8 + 3\,b_5^{(4)}(\tau) \\ -\sqrt{3}\,b_3^{(4)}(\tau) \end{pmatrix},$$

$$Y_{\mathbf{3'}}^{(4,2)}(\tau) = -\pi \begin{pmatrix} -b_1^{(4)}(\tau)/4 + 2\,b_5^{(4)}(\tau) \\ \sqrt{2}\,b_2^{(4)}(\tau) \\ 4\sqrt{2}\,b_4^{(4)}(\tau) \end{pmatrix}.$$

$$\begin{aligned}
b_1^{(4)} &= 1 + 24q_4^8 + 24q_4^{16} + 96q_4^{24} + 24q_4^{32} + 144q_4^{40} + \dots\,, \\
b_2^{(4)} &= q_4 + 6q_4^5 + 13q_4^9 + 14q_4^{13} + 18q_4^{17} + 32q_4^{21} + 31q_4^{25} + 30q_4^{29} + 48q_4^{33} + 38q_4^{37} + \dots\,, \\
b_3^{(4)} &= q_4^2 + 4q_4^6 + 6q_4^{10} + 8q_4^{14} + 13q_4^{18} + 12q_4^{22} + 14q_4^{26} + 24q_4^{30} + 18q_4^{34} + 20q_4^{38} + \dots\,, \\
b_4^{(4)} &= q_4^3 + 2q_4^7 + 3q_4^{11} + 6q_4^{15} + 5q_4^{19} + 6q_4^{23} + 10q_4^{27} + 8q_4^{31} + 12q_4^{35} + 14q_4^{39} + \dots\,, \\
b_5^{(4)} &= q_4^4 + 4q_4^{12} + 6q_4^{20} + 8q_4^{28} + 13q_4^{36} + \dots\,,
\end{aligned}$$

$$q_4 \equiv e^{2\pi i\tau/4} = e^{\pi i\tau/2}$$