A Lepton Specific Universal Seesaw Model with Left Right Symmetry

In collaboration with Santosh Kumar Rai (arXiv:1711.00627)

Ayon Patra
Indian Institute of Science, Bangalore

SUSY 2017
TIFR, Mumbai

OUTLINE

- LEFT-RIGHT SYMMETRY
- LEPTON SPECIFIC LRS UNIVERSAL SEESAW MODEL
  - MODEL AND LAGRANGIAN
  - PHENOMENOLOGICAL IMPLICATION
  - NEW COLLIDER SIGNALS
- CONCLUSION

LEFT-RIGHT SYMMETRY

- Gauge group extended to
  $$SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$
- Quarks and leptons are all doublets.
- Origin of Parity violation as a spontaneously broken symmetry.
- Solve the strong CP problem.
- Can naturally generate light neutrino mass.

LEPTON SPECIFIC LRS UNIVERSAL SEESAW MODEL

- Gauge group extended to $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$.
- Electric charge defined as $Q = I_{3L} + I_{3R} + \frac{B-L}{2}$.
- The $SU(2)_R \times U(1)_{B-L}$ symmetry is broken spontaneously at a high scale leading to observed parity asymmetry at low scale.
- Additional Z_2 symmetry for lepton specific interactions.
- All fermions get their masses through seesaw mechanism.

MODEL AND LAGRANGIAN

- Quark and Lepton doublets $Q_{L/R}$, $l_{L/R}$.
- Higgs Doublets only H_{LQ}, H_{Ll}, H_{RQ}, H_{Rl} .
- No bidoublet - fermion singlets are needed to generate their masses.
- Fermion singlets $U_{L/R}$, $D_{L/R}$, $E_{L/R}$, $N_{L/R}$.
- Extra Z_2 symmetry under which $E_{L/R}$, $N_{L/R}$, H_{Ll}, H_{Rl} are odd and other fields are even.

Field	$SU(3)_C$	$SU(2)_L$	$SU(2)_R$	$U(1)_{B-L}$	Z_2
$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	1	$\frac{1}{3}$	+
$Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R$	3	1	2	$\frac{1}{3}$	+
$l_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L$	1	2	1	-1	+
$l_R = \begin{pmatrix} \nu \\ e \end{pmatrix}_R$	1	2	1	-1	+
U_L, U_R	3	1	1	$\frac{4}{3}$	+
D_L, D_R	3	1	1	$-\frac{2}{3}$	+
E_L, E_R	1	1	1	-2	-
N_L, N_R	1	1	1	0	-
$H_{RQ} = \begin{pmatrix} H_{RQ}^+ \\ H_{RQ}^0 \end{pmatrix}$	1	1	2	1	+
$H_{LQ} = \begin{pmatrix} H_{LQ}^+ \\ H_{LQ}^0 \end{pmatrix}$	1	2	1	1	+
$H_{Rl} = \begin{pmatrix} H_{Rl}^+ \\ H_{Rl}^0 \end{pmatrix}$	1	1	2	1	-
$H_{Ll} = \begin{pmatrix} H_{Ll}^+ \\ H_{Ll}^0 \end{pmatrix}$	1	2	1	1	-

- Non-zero VEVs are given as

$$\langle H^0_{RQ} \rangle = v_{RQ}, \ \langle H^0_{Rl} \rangle = v_{Rl}, \ \langle H^0_{LQ} \rangle = v_{LQ}, \ \langle H^0_{Ll} \rangle = v_{Ll}$$

  with $v_{RQ}, v_{Rl} >> v_{LQ} > v_{Ll}$.

- v_{RQ}, v_{Rl} responsible for $SU(2)_R \times U(1)_{B-L} \to U(1)_Y$.
- v_{LQ}, v_{Ll} breaks EW symmetry.

Charged gauge boson masses are given as

$$M_{W_R^\pm}^2 = \frac{1}{2} g_R^2 (v_{RQ}^2 + v_{Rl}^2), \quad M_{W^\pm}^2 = \frac{1}{2} g_L^2 (v_{LQ}^2 + v_{Ll}^2).$$

Neutral gauge boson masses

$$M_{Z_R}^2 \simeq \frac{1}{2} \left[(g_R^2 + g_V^2)(v_{RQ}^2 + v_{Rl}^2) + \frac{g_V^4 (v_{LQ}^2 + v_{Ll}^2)}{g_R^2 + g_V^2} \right], \quad M_Z^2 \simeq \frac{1}{2} (g_L^2 + g_Y^2)(v_{LQ}^2 + v_{Ll}^2),$$

where

$$g_Y = \frac{g_L g_V}{\sqrt{g_L^2 + g_V^2}}.$$

The Yukawa Lagrangian is given as

$$\mathcal{L}_Y = \Big(Y_{uL}\overline{Q}_L\widetilde{H}_{LQ}U_R + Y_{uR}\overline{Q}_R\widetilde{H}_{RQ}U_L + Y_{dL}\overline{Q}_L H_{LQ}D_R + Y_{dR}\overline{Q}_R H_{RQ}D_L$$
$$+ \; Y_{\nu L}\bar{l}_L\widetilde{H}_{Ll}N_R + Y_{\nu R}\bar{l}_R\widetilde{H}_{Rl}N_L + Y_{eL}\bar{l}_L H_{Ll}E_R + Y_{eR}\bar{l}_R H_{Rl}E_L + M_U\overline{U}_L U_R + M_D\overline{D}_L D_R$$
$$+ \; M_E\overline{E}_L E_R + M_N\overline{N}_L N_R + H.C.\Big) + M_L N_L N_L + M_R N_R N_R$$

Quark and charged lepton masses arise through Type-I seesaw like matrix.

$$\mathcal{L}_u = \left(\bar{u} \;\; \bar{U}\right)\left(M_u P_L + M_u^T P_R\right)\begin{pmatrix} u \\ U \end{pmatrix}$$

with

$$M_u = \begin{pmatrix} 0 & Y_{uR} v_{RQ} \\ Y_{uL}^T v_{LQ} & M_U \end{pmatrix}$$

Diagonalizing requires bi-unitary transformation

$$M_u^{diag} = V_{uL} M_u V_{uR}^{\dagger}$$

Up sector Y_{uL}, Y_{uR} and M_U are taken diagonal so CKM generated from down sector.

$$U_L^{CKM} = U_{uL}^{\dagger} U_{dL}, \; U_R^{CKM} = U_{uR}^{\dagger} U_{dR}$$

These are 6X6 matrices with the top-left 3X3 corresponding to the SM-like quark CKM.

Charged lepton

$$M_e = \begin{pmatrix} 0 & Y_{eR} v_{Rl} \\ Y_{eL}^T v_{Ll} & M_E \end{pmatrix}$$

Neutrino mass matrix in the basis $(\nu_L^*, N_R, \nu_R, N_L^*)$

$$\begin{pmatrix} 0 & Y_{\nu L} v_{Ll} & 0 & 0 \\ Y_{\nu L}^T v_{Ll} & M_R & 0 & M_N^T \\ 0 & 0 & 0 & Y_{\nu R}^T v_{Rl} \\ 0 & M_N & Y_{\nu R} v_{Rl} & M_L \end{pmatrix}$$

Depending on M_N two possible cases

1. Majorana case with $M_N \neq 0$: 3 light neutrinos satisfying mass-squared relations and PMNS mixings, 3 neutrinos in the EW breaking scale, 6 heavy neutrinos of TeV scale.
2. Pseudo-Dirac case with $M_N = 0$: Pseudo-Dirac like 3 light neutrinos, 3 heavy neutrinos.

The scalar potential is

$$V(H)=\sum_{i=1}^{4}\mu_{ii}H_i^\dagger H_i+\sum_{\substack{i,j=1\\ i\le j}}^{4}\lambda_{ij}H_i^\dagger H_i H_j^\dagger H_j+\Big(\alpha_1 H_{LQ}^\dagger H_{Ll}H_{RQ}^\dagger H_{Rl}$$

$$+\alpha_2 H_{LQ}^\dagger H_{Ll}H_{Rl}^\dagger H_{RQ}+\mu_{12}^2 H_{LQ}^\dagger H_{Ll}+\mu_{34}^2 H_{RQ}^\dagger H_{Rl}+H.C.\Big)$$

where $H_1=H_{LQ}$, $H_2=H_{Ll}$, $H_3=H_{RQ}$, $H_4=H_{Rl}$.

Minimizing this potential and diagonalizing the CP-even, CP-odd and charged Higgs mass-squared matrices. This gives us 4 CP-even neutral scalars, 2 pseudo-scalar and 2 charged Higgs bosons.

Particle	Mass (GeV)	Eigenstate
H_1	125.5	$0.996\ \mathrm{Re}(H^0_{LQ}) - 0.010\ \mathrm{Re}(H^0_{RQ}) + 0.080\ \mathrm{Re}(H^0_{Ll}) + 0.027\ \mathrm{Re}(H^0_{Rl})$
H_2	2543.9	$-0.0289\ \mathrm{Re}(H^0_{LQ}) - 0.381\ \mathrm{Re}(H^0_{RQ}) + 0.001\ \mathrm{Re}(H^0_{Ll}) + 0.924\ \mathrm{Re}(H^0_{Rl})$
H_3	4229.0	$0.001\ \mathrm{Re}(H^0_{LQ}) - 0.924\ \mathrm{Re}(H^0_{RQ}) + 0.005\ \mathrm{Re}(H^0_{Ll}) - 0.381\ \mathrm{Re}(H^0_{Rl})$
H_4	7127.5	$0.080\ \mathrm{Re}(H^0_{LQ}) - 0.005\ \mathrm{Re}(H^0_{RQ}) - 0.997\ \mathrm{Re}(H^0_{Ll}) + 0.003\ \mathrm{Re}(H^0_{Rl})$
A_1	217.0	$0.001\ \mathrm{Im}(H^0_{LQ}) - 0.707\ \mathrm{Im}(H^0_{RQ}) - 0.008\ \mathrm{Im}(H^0_{Ll}) + 0.707\ \mathrm{Im}(H^0_{Rl})$
A_2	7127.7	$-0.080\ \mathrm{Im}(H^0_{LQ}) - 0.006\ \mathrm{Im}(H^0_{RQ}) + 0.997\ \mathrm{Im}(H^0_{Ll}) + 0.006\ \mathrm{Im}(H^0_{Rl})$
H_1^+	225.8	$-0.707 H^+_{RQ} + 0.707 H^+_{Rl}$
H_2^+	7127.5	$0.080 H^+_{LQ} - 0.997 H^+_{Ll}$

$\alpha_1 = -0.3,\ \alpha_2 = 0.1,\ \lambda_{11} = 0.172,\ \lambda_{12} = 0.8,\ \lambda_{13} = 0.05,\ \lambda_{14} = -0.1,\ \lambda_{22} = 0.5,\ \lambda_{23} = 0.1,$
$\lambda_{24} = 0.1,\ \lambda_{33} = 0.2,\ \lambda_{34} = 0.1,\ \lambda_{44} = 0.1,\ \mu_{12}^2 = 2.5\times 10^4,\ \mu_{34}^2 = 2.5\times 10^4$

PHENOMENOLOGICAL IMPLICATIONS

Values of the VEVs

$$v_{RQ} = v_{Rl} = 4.5 \text{ TeV}, \; v_{LQ} = 173.4 \text{ GeV}, \; v_{Ll} = 14 \text{ GeV}$$

Unlike SM Yukawa couplings range can be much smaller, here from 10^{-3} to 1.

$$Y^{11}_{u(L/R)} \sim Y^{11}_{d(L/R)} \sim Y^{11}_{e(L/R)} \approx 10^{-2}, \; Y^{22}_{u(L/R)} \sim Y^{22}_{dR} \sim Y^{22}_{e(L/R)} \approx 10^{-1}, \; Y^{33}_{u(L/R)} \sim Y^{33}_{dL} \sim Y^{33}_{e(L/R)} \approx 1$$

Off-diagonal elements $Y^{ij}_{dL} \sim 10^{-3}$.

Left-handed CKM matrix consistent with the experimental values.

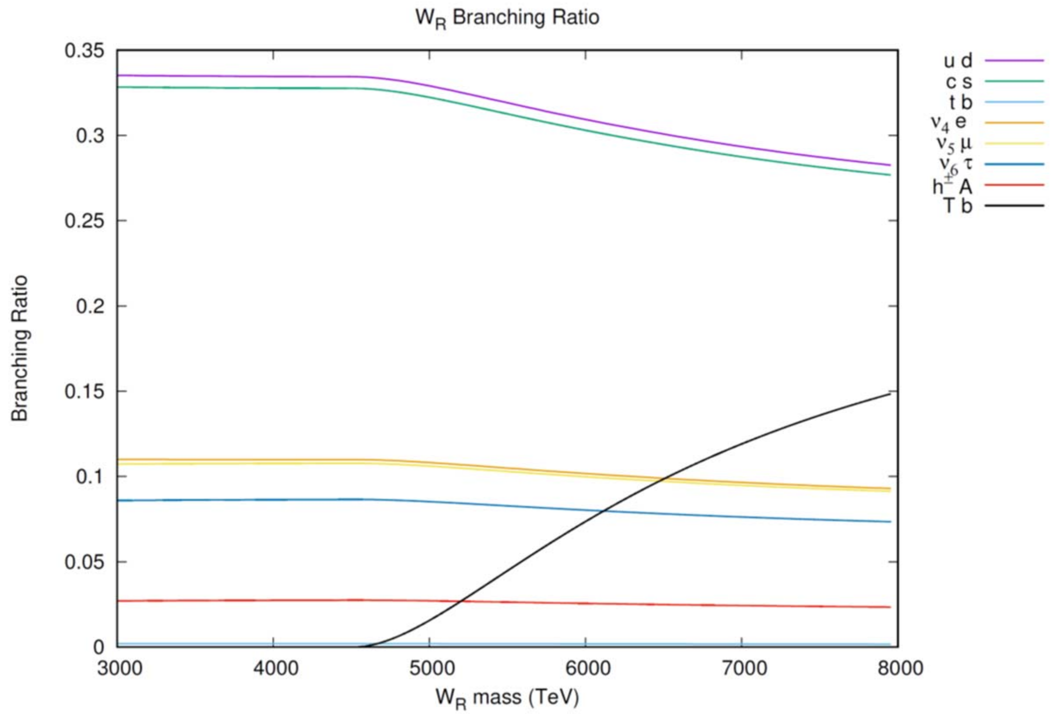
Right-handed CKM is almost identity matrix as Y_{dR} is diagonal.

Heavy quarks and charged leptons have an inverted mass hierarchy compared to SM case.

Mixing between SM and heavy states very small except top quark.

Right-handed component of top quark almost entirely from singlet.

Effect is clearly seen in W_R branching ratio plot.



Up-type Quark	Down-type Quark	Charged Lepton	Neutrino	
			Majorana	Pseudo-Dirac
$M_T = 4.51$ TeV, $M_C = 6.17$ TeV, $M_U = 30.0$ TeV	$M_B = 3.97$ TeV, $M_S = 10.4$ TeV, $M_D = 17.2$ TeV	$M_{E_3} = 6.13$ TeV, $M_{E_2} = 9.92$ TeV, $M_{E_1} = 12.3$ TeV	$M_{\nu_4} = 136$ GeV, $M_{\nu_5} = 258$ GeV, $M_{\nu_6} = 317$ GeV, $M_{\nu_7} = 9.07$ TeV, $M_{\nu_8} = 9.13$ TeV, $M_{\nu_9} = 9.16$ TeV, $M_{\nu_{10}} = 11.06$ TeV, $M_{\nu_{11}} = 11.1$ TeV, $M_{\nu_{12}} = 11.2$ TeV	$M_{\nu_4} = 200.0$ GeV, $M_{\nu_5} = 300.0$ GeV, $M_{\nu_6} = 400.0$ GeV

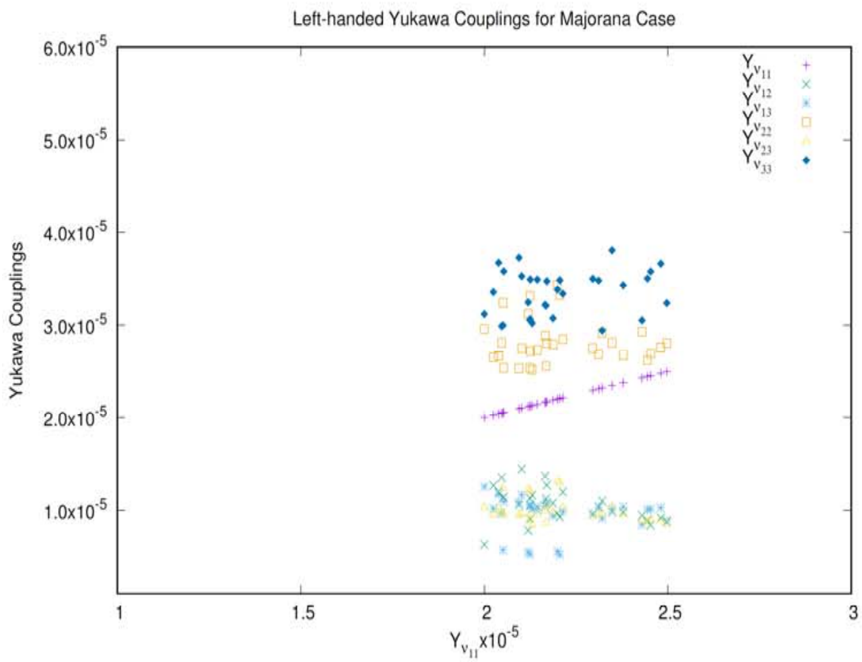
Majorana neutrino case

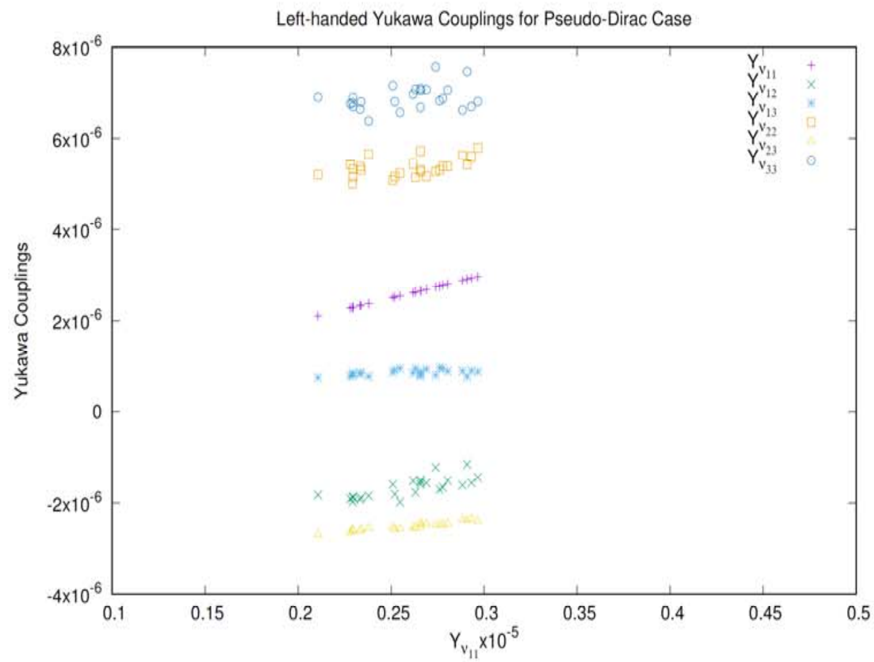
$$M_R = M_L = Diag(10^4, 10^4, 10^4),\ M_N = Diag(10^3, 10^3, 10^3),\ Y_{\nu R_{ii}} \sim 0.1,\ Y_{\nu L_{ij}} \sim 10^{-5}$$

Pseudo-Dirac neutrino case

$$M_R = M_L = Diag(200, 300, 400),\ M_N = 0,\ Y_{\nu R_{ij}} = \frac{v_{Ll}}{v_{Rl}} Y_{\nu L_{ij}}$$

Correct light neutrino mass $Y_{\nu L_{ij}} \sim 10^{-6}$ which leads to $Y_{\nu R_{ij}} \sim 10^{-9}$.





Normal hierarchy is considered here.

Most of the points show $Y_{\nu 33}$ is largest while $Y_{\nu 13}$ is the smallest.

NEW COLLIDER SIGNALS

- The light charged Higgs is linear combination of right-handed doublets.
- Majorana neutrinos of mass at the EW scale are part of the right-handed doublet and decay mainly into charged Higgs and leptons.
- They can be pair produced through the Z_R exchange DY processes leading to a very interesting final state

$$p\,p \to \nu_4\nu_4 \to e^-\,e^-\,H^+\,H^+ \to 2e^- + 2t + 2\bar{b}$$

when charged Higgs is heavier than top mass.

- If charged Higgs is heavier than the heavy neutrinos we get an entirely different signature

$$p\,p \to H^+\,H^- \to \nu_j\nu_j\ell_i^+\ell_i^-$$

CONCLUSION

- We propose a LR symmetric model with fermion mass generation through universal seesaw mechanism.
- Lepton specific interaction due to additional Z_2 symmetry.
- Soft breaking the Z_2 symmetry avoids domain wall problems.
- Neutrinos can be either Majorana or Pseudo-Dirac like.
- Lepton specific interactions lead to unique collider signals which we are studying for an upcoming work.

THANK YOU

◆ Origin of parity violation

- Gauge group of Standard Model is $SU(3)_c \times SU(2)_L \times U(1)_Y$.
- Parity is explicitly broken.
- It would be desirable to understand the origin of parity violation as spontaneous.

Strong CP Problem

- CP violation is seen in the weak forces sector (e.g. $K^0 - \overline{K}^0$ mixing) but not in strong forces.
- One can write CP and P violating term in the QCD Lagrangian

$$\mathscr{L}_{QCD} = \frac{\theta g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

- Actual physical observable is

$$\bar{\theta} = \theta + \text{Arg}(\text{Det } M_q) \,, \qquad M_q \to \text{quark mass matrix}$$

- Experimental limit from neutron electric dipole moment measurements constraints $\bar{\theta} < 10^{-10}$.
- This is the Strong CP problem.

Neutrino Oscillation

- Neutrinos of different flavor (ν_e, ν_μ, ν_τ) can oscillate into one another due to non-zero neutrino mass and mixing angles.
- Flavor eigenstates of neutrinos are linear combination of field of three (or more) neutrinos (ν_j) with non-zero mass.

$$\nu_{lL}(x) = \sum_j U_{lj}\nu_{jL}(x) \qquad l = e, \mu, \tau$$

- From current experimental results, defining $\Delta m_{ij}^2 = m_i^2 - m_j^2$

$$\Delta m_{21}^2 = 7.59^{+0.20}_{-0.18} \times 10^{-5}\ eV^2$$

$$\Delta m_{31}^2 = \begin{cases} (2.45 \pm 0.09) \times 10^{-3}\ eV^2, & \text{for } m_1 < m_2 < m_3 \\ -(2.34^{+0.10}_{-0.09}) \times 10^{-3}\ eV^2, & \text{for } m_3 < m_1 < m_2 \end{cases}$$

- Extension of Standard Model with a right-handed neutrino (N^C) which is a singlet under $SU(2)_L$ will have terms

$$\mathcal{L}_{\nu-mass} = m_D \nu_L N^C + \frac{1}{2} m_R N^C N^C , \qquad m_D = Y_\nu \mathrm{v}$$

- Solving for the light neutrino mass gives

$$m_\nu \simeq \frac{m_D^2}{m_R}$$

We can get $m_\nu \sim 0.1\ \mathrm{eV}$ with $m_R \sim 10^4\ \mathrm{GeV}$ and $Y_\nu \sim 10^{-5}$.

- This is the **Seesaw** mechanism.