Small Neutrino Masses in a TeV Scale Seesaw Model with a Z'

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Introduction

- Conventional Seesaw mechanism: High (GUT) scale physics
  - With SM particle content:

$$C\,\frac{HH\overline{\ell}^c_L\ell_L}{\Lambda} \quad \text{small } \nu \text{ masses} \Rightarrow \Lambda \sim 10^{14}\ \text{GeV} \quad \text{with} \quad C \sim \mathcal{O}(1)$$

  - $\exists$ gauge singlet fermions ν_R

$$H\overline{\ell}_L\nu_R \quad \rightarrow \quad m_D$$

$$M_R\overline{\nu}^c_R\nu_R$$

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

$$\text{intergrating out} \quad \nu_R : \qquad M_{eff} \sim M_D M_R^{-1} M_D^T$$

$$y^2\,\frac{HH\ell\ell}{M_R} \qquad \Rightarrow \quad M_R \sim 10^{14}\ \text{GeV} \ \sim M_{GUT}$$

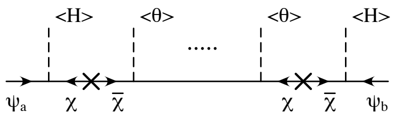
- Can small neutrino masses due to low (TeV) scale physics?
  - new EW models (littel Higgs, Higgsless models, etc): $\Lambda \sim$ TeV
  - can be tested at colliders

An Alternative

- gauge symmetry SM x non-anomalous U(1)ν + N ν_R
- SM particles & ν_R : all charged under U(1)
- U(1) forbids dim-4, dim-5 operators
- To get $m_\nu \neq 0$: ~~$U(1)_\nu$~~ $\langle \phi \rangle$: SM singlet breaks $U(1)_\nu$

  $\frac{HH\ell\ell}{M}\left(\frac{\langle\phi\rangle}{\Lambda}\right)^p$, p large $\langle \phi \rangle < \Lambda,$ $\frac{\langle\phi\rangle}{\Lambda} \sim 10^{-1}$

  Λ ~ TeV!



- non-anomalous U(1)ν
  - anomaly cancellation conditions ⇒ constraints on U(1) charges
  - generation dependent charges ⇒ U(1) flavor symmetry

    ⇒ mixing pattern & mass hierarchy (FN)
  - light sterile neutrinos: DM candidate
  - TeV scale Z': probing flavor sector at colliders
- c.f. anomalous U(1): mixed anomaly cancelled by Green-Schwarz mechanism
  - U(1) broken at fundamental string scale
  - $[U(1)]^3$ anomaly cancelled by other exotics

constraints not as stringent

The Model

SM x U(1)ν + N ν_R

- generation independent quark charges ⇒ no FCNC in quark sector

$$q_L^i : z_q \qquad u_R^i : z_u \qquad d_R^i : z_d$$

- generation dependent lepton charges ⇒ neutrino mixing

$$\ell_L^i : z_{\ell_i} \qquad e_R^i : z_{e_i} \qquad \nu_R^k : z_{n_k}$$

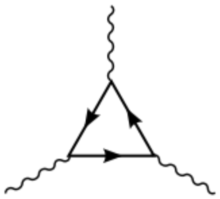
- scalar charges:

$$H : z_H \qquad \phi : \quad \text{SM singlet} \quad +1, \quad \langle\phi\rangle \text{ breaks } U(1)_\nu$$

- N = 1, 2: always terms allowed at dime-4
  ⇒ high seesaw scale
- lowest value for N to get TeV scale seesaw: N=3
- with N=3: (9+N) charges

Anomaly Cancellation

SU(3) x SU(2)$_L$ x U(1)$_Y$ x U(1)$_\nu$



- 4 mixed anomalies not involving ν_R

$$[SU(3)]^2 U(1)_\nu : \quad z_d = 2z_q - z_u$$
$$U(1)_\nu [SU(2)_L]^2 : \quad \sum_{i=1}^3 z_{\ell_i} = -9 z_q$$
$$U(1)_\nu [U(1)_Y]^2 : \quad \sum_{i=1}^3 z_{e_i} = -3(2z_q + z_u)$$
$$U(1)_Y [U(1)_\nu]^2 : \quad \sum_{i=1}^3 (z_{\ell_i}^2 - z_{e_i}^2) = 3(z_q - z_u)(5z_q + z_u)$$

- 2 anomaly conditions involving ν_R

$$U(1)_\nu - \text{graviton} : \quad \sum_{k=1}^N z_{n_k} = -3(4z_q - z_u)$$
$$[U(1)_\nu]^3 : \quad \sum_{i=1}^3 z_{n_k}^3 = (2z_{\ell_i}^3 - z_{e_i}^3) - 54 z_q (z_q - z_u)^2$$

- additional constraints:
  - top mass generated at dim-4: $z_H = z_u - z_q$
    (all quark masses allowed at dim-4)
  - diagonal elements in M$_e$ allowed at dim-4

$$\lambda_e^{ii} \overline{\ell}_L^i e_R^i H \qquad m_e \sim \begin{pmatrix} \lambda_{11} & * & * \\ * & \lambda_{22} & * \\ * & * & \lambda_{33} \end{pmatrix}$$

- charged fermion sector: 4 independent charges
- neutrino sector: (N-2) independent charges

Neutrino Mass Terms

U(1)ν forbids $H\bar{\ell}_L\nu_R$, $\frac{HH\bar{\ell}^c_L\ell_L}{\Lambda}$, $M_R\bar{\nu}^c_R\nu_R$; after its breaking:

- LH Majorana mass terms:

$$\sum_{i,j}\frac{c^{ij}_\ell}{\Lambda}\left(\frac{g_\phi}{\Lambda}\phi\right)^{q_{ij}}\overline{\ell^c}^i_L\ell^j_L HH \qquad q_{ij} = 2(z_q - z_u) - z_{\ell_i} - z_{\ell_j}$$

- Dirac mass terms:

$$\sum_{i,k}\lambda^{ik}_\nu\left(\frac{g_\phi}{\Lambda}\phi\right)^{p_{ik}}\bar{\ell}^i_L n^k_R\tilde{H} \qquad p_{ik} = z_u - z_q + z_{\ell_i} - z_{n_k}$$

- RH Majorana mass terms:

$$\sum_{k,k'}c^{kk'}_n\Lambda\left(\frac{g_\phi}{\Lambda}\phi\right)^{r_{kk'}}\overline{n^c}^k_R n^{k'}_R \qquad r_{kk'} = -z_{n_k} - z_{n_{k'}}$$

- resulting neutrino mass matrix:

$$M_\nu \sim \left(\begin{array}{c|c}\frac{v^2}{\Lambda}\epsilon^{|q|} & v\epsilon^{|p|} \\ \hline v(\epsilon^{|p|})^\top & \Lambda\epsilon^{|r|}\end{array}\right)$$

- pure type-I seesaw unattainable

$q_{ij} = -p_{ik} - p_{jk'} + r_{kk'}$ = integer

-- Pure Dirac

-- Type-II sesaw

Charged Lepton Sector

- charged lepton masses:

$$\sum_{ij} \lambda_e^{ij} \left(\frac{g_\phi}{\Lambda} \phi \right)^{s_{ij}} \overline{\ell}_L^i e_R^j H \qquad\qquad s_{ij} = z_{\ell_i} - z_{\ell_j}$$

- generation-dependent U(1) charges:

$$s_{ij} \neq 0 \quad \text{for} \quad i \neq j \quad \Rightarrow \quad \text{tree-level FCNC mediated by} \quad Z'$$

$$\overline{f} V^\dagger \gamma_\mu \begin{pmatrix} z_{\ell_1} & & \\ & z_{\ell_2} & \\ & & z_{\ell_3} \end{pmatrix} V f$$

- flavor changing processes

$$\mu \to e, \quad \mu^+ \to e^+ e^- e^+, \quad \tau \to \ell \ell' \ell''$$

$$\text{decay rate:} \quad \Gamma \propto \left(\frac{\epsilon^{|s_{ij}|}}{\langle \phi \rangle^2} \right)^2, \quad \epsilon^{|s_{ij}|} < 1$$

Leptocratic Models

- with N=3: 5 independent charges z_q, , z_{ℓ_1}, z_{ℓ_2}, $2z_{n_k}$
- Cubic equation: rational solutions non-trivial [Fermat's Last Theorem]

$$z_{\ell_1} \equiv -3z_q - 2a \ , \quad z_{\ell_2} \equiv -3z_q + a + a' \ , \quad z_{\ell_3} = -3z_q + a - a' \ ,$$

$$z_{e_1} \equiv -6z_q + \frac{c}{2} - 2a \ , \quad z_{e_2} \equiv -6z_q + \frac{c}{2} + a + a' \ , \quad z_{e_3} = -6z_q + \frac{c}{2} + a - a' \ .$$

$$z_{n_1} \equiv -\frac{c}{2} - 2b \ , \quad z_{n_2} \equiv -\frac{c}{2} + b + b' \ , \quad z_{n_3} = -\frac{c}{2} + b - b' \ ,$$

- $[U(1)_\nu]^3$: general class of rational solutions

$$c = -2\,\frac{a\left(a^2 - a'^2\right) - b\left(b^2 - b'^2\right)}{3a^2 + a'^2 - 3b^2 - b'^2}$$

Leptocratic Models

- resulting mass matrices
  - Dirac neutrino mass matrix

$$p = \begin{pmatrix} -2(a-b) & -(2a+b+b') & -(2a+b-b') \\ a+a'+2b & a+a'-b-b' & a+a'-b+b' \\ a-a'+2b & a-a'-b-b' & a-a'-b+b' \end{pmatrix}$$

  - LH Majorana mass matrix

$$q = \begin{pmatrix} c+4a & c+a-a' & c+a+a' \\ c+a-a' & c-2\,(a+a') & c-2a \\ c+a+a' & c-2a & c-2\,(a-a') \end{pmatrix}$$

  - RH Majorana mass matrix

$$r = \begin{pmatrix} c+4b & c+b-b' & c+b+b' \\ c+b-b' & c-2\,(b+b') & c-2b \\ c+b+b' & c-2b & c-2\,(b-b') \end{pmatrix}$$

  - Charged lepton mass matrix

$$s = \begin{pmatrix} 0 & -3a-a' & -3a+a' \\ 3a+a' & 0 & 2a' \\ 3a-a' & -2a' & 0 \end{pmatrix}$$

Orwellian Leptocratic Model

- all $U(1)_{NA}$ charges for SM fermions are generation independent:
  - a = a' = b'= 0; c = -2b/3
  - no charged lepton flavor violating FCNC mediated by Z' at tree level
  - $Q(N_2) = Q(N_3) \neq Q(N_1)$
  - bi-large mixing through anarchy

- three active neutrinos: can either be Dirac or Majorana fermions

(I) Dirac neutrinos: b = integer, but not (3n) ⇒ c = non-int, only M_D allowed

$$M_D = v\,\epsilon^{|b|} \begin{pmatrix} \lambda_\nu^{11}\,\epsilon^{|b|} & \lambda_\nu^{12} & \lambda_\nu^{13} \\ \lambda_\nu^{21}\,\epsilon^{|b|} & \lambda_\nu^{22} & \lambda_\nu^{23} \\ \lambda_\nu^{31}\,\epsilon^{|b|} & \lambda_\nu^{32} & \lambda_\nu^{33} \end{pmatrix} \qquad \Lambda \sim 1 \text{ TeV}$$

$$\lambda \sim 10^{-4} - 10^{-5} : \quad b = \pm 2$$

$$\lambda \sim 1 : \quad b = \pm 13$$

Orwellian Leptocratic Model

- (II) Majorana neutrinos: b = (3n) ⇒ M_D, M_{LL}, M_{RR} all allowed

$$M_L = \frac{v^2}{\Lambda}\,\epsilon^{2|b|/3}\,c_\ell \qquad M_R = \Lambda\,\epsilon^{|b|/3}\begin{pmatrix} c_n^{11}\epsilon^{3|b|} & c_n^{12} & c_n^{13} \\ c_n^{12} & c_n^{22}\epsilon^{7|b|/3} & c_n^{23}\epsilon^{7|b|/3} \\ c_n^{13} & c_n^{23}\epsilon^{7|b|/3} & c_n^{33}\epsilon^{7|b|/3} \end{pmatrix}$$

- if $\lambda \sim c$: $M_{LL} > M_D$ ⇒ inverted seesaw
- for $\lambda \sim 10^{-5},\ \epsilon \sim 10^{-4},\ |b| = 3$

$$\Rightarrow \text{ light sterile } m_{\nu_4} \sim \Lambda\epsilon^{4|b|/3}\left(\frac{\lambda_\nu^2}{c_\ell}\right) \sim 10^{-9}\text{ eV} \qquad \Theta_{\text{active}-\text{light}} \sim \epsilon\,\frac{\Lambda}{v} \sim 10^{-3}$$

$$\Rightarrow\ 2 \text{ heavy sterile } m_{\nu_{5,6}} \sim \Lambda\epsilon^{|b|/3}c_n \sim 1\text{ keV} \qquad \Theta_{\text{active}-\text{heavy}} \sim \epsilon^2\,\frac{v}{\Lambda} \sim 10^{-9}$$

- for $\lambda \sim 1,\ \epsilon \sim 0.1,\ |b| = 18$

$$\text{light sterile: } m_{\nu_4} \sim 10^{-12}\text{ eV} \qquad \Theta_{\text{active}-\text{light}} \sim \epsilon^6\,\frac{\Lambda}{v} \sim 10^{-5}$$

$$\text{heavy sterile: } m_{\nu_{5,6}} \sim 1\text{ MeV} \qquad \Theta_{\text{active}-\text{heavy}} \sim \epsilon^{12}\,\frac{v}{\Lambda} \sim 10^{-13}$$

(2+1) Leptocratic Model

- generation dependent charged lepton charges

$$z_{\ell_1} \neq z_{\ell_2} = z_{\ell_3}$$
$$z_{e_1} \neq z_{e_2} = z_{e_3}$$
$$z_{n_1} \neq z_{n_2} = z_{n_3}$$

- a’ = b’ = 0; a, b ≠ 0 $c = -\frac{2}{3}\left(\frac{a^2+ab+b^2}{a+b}\right)$

- large neutrino mixing from U(1) symmetry

- a = 25/3, b = -11/3, ε ~ 0.1 ⇒ pure Dirac

$$M_D = v\,\epsilon^{12}\begin{pmatrix} \mathcal{O}(\epsilon^{12}) & \mathcal{O}(\epsilon) & \mathcal{O}(\epsilon) \\ \mathcal{O}(\epsilon^{13}) & \mathcal{O}(1) & \mathcal{O}(1) \\ \mathcal{O}(\epsilon^{13}) & \mathcal{O}(1) & \mathcal{O}(1) \end{pmatrix}$$

- LFV in charged lepton sector?

  $|s_{12}| = |s_{23}| = 3a = 25$: suppressed by 10^{-25} Safe!

  $z_{\ell_2} = z_{\ell_3}$: no tree-level FCNC

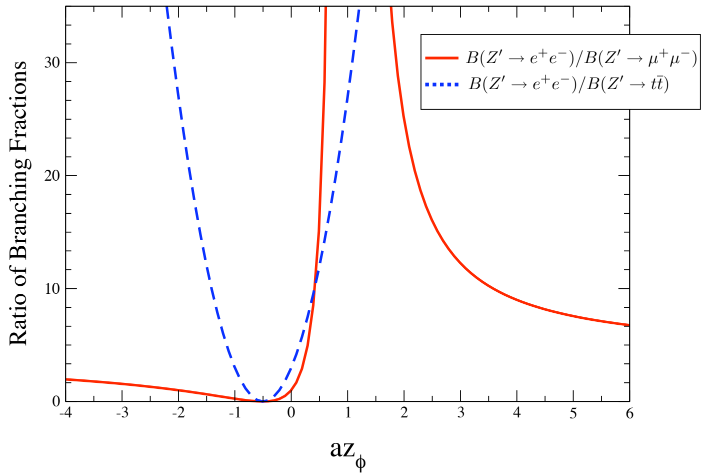
TeV Scale Seesaw

- probing the flavor sector at the colliders
- (2+1) leptocratic models:

$$\frac{B\left(Z' \to e^+e^-\right)}{B\left(Z' \to \mu^+\mu^-\right)} = \left(\frac{1+2az_\phi}{1-az_\phi}\right)^2$$

$$\frac{B\left(Z' \to e^+e^-\right)}{B\left(Z' \to t\bar{t}\right)} = 3\left(1+2az_\phi\right)^2$$

$$z_\phi = -\frac{3(a+b)}{a^2+ab+b^2}$$



- invisible decays of Z’: distinguish different U(1)
  - $U(1)_{B-L}$: B(Z’ ⟶ invisible) = 3/8
  - Orwellian Z’: B(Z’ ⟶ invisible) = 6/7

    [z_{n1} = 5, z_{n2} = z_{n3} = -4]

Conclusion

- TeV scale seesaw:
  - required in new EW models; testability at colliders

- SM x non-anomalous U(1), in presence of RH neutrinos
- anomaly cancellations: constraints on charges, predict flavor structure
- TeV scale seesaw possible with 3 RH neutrinos
- neutrinos can either be Dirac or Majorana fermions
- Orwellian leptocratic models: generation independent charged lepton charges
- (2+1) leptocratic models: generation dependent charged lepton charges
- GUT extension: SU(5) x $U(1)_{NA}$ [MCC, Jones, Rajaraman, Yu, arXiv:0801.4228]
  - family symmetry
  - proton stability