Minimal Textures in Seesaw Mass Matrices and their low and high Energy Phenomenology

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Neutrino Mass Models

- Neutrinos are mass less in Standard Model ($SU(2)_L \times U(1)_Y$).
- Experiments established that neutrinos have tiny mass (indication of Physics Beyond Standard Model).
- Challenges to theoretician to formulate a theory of neutrino mass origin.
- Possibilities are: (a) Modifying the exiting theory (b) Construction of new theory (like Left-Right Symmetric Model, $SO(10)$ GUT).
- Modifying the exiting theory.
- $$2 \times 2 = 3 + 1$$

3	3	1	1
fermion	scalar	fermion	scalar
↓	↓	↓	↓
Type III	Type II	Type I	Not possible

- Adding these heavy particles to SM will generate small neutrino mass.

Type I See-saw Mechanism

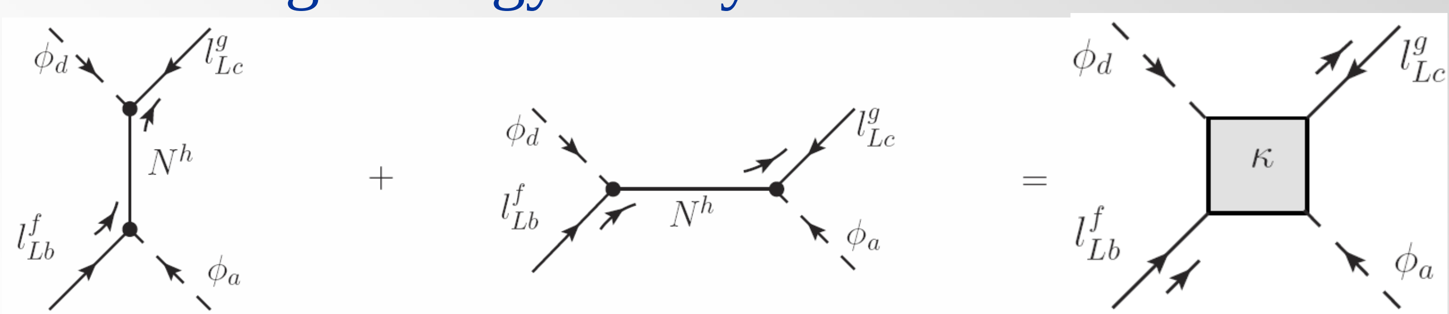
- Lagrangian with additional right-handed singlet neutrino

$$-\mathcal{L} = (Y_\nu)_{fg}\overline{N}^g\tilde{\phi}^\dagger l_L^f + (Y_e)_{fg}\overline{e}_R^g\phi^\dagger l_L^f + \frac{1}{2}\overline{N^c}_f(M_R)_{fg}N_g + \text{h.c}$$

- The mass matrix for the neutral fermions after EWSM

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

- Diagonalization, assuming $M_R >> m_D$, gives light neutrino mass matrix $\boxed{\mathcal{M}_\nu = -m_D M_R^{-1} m_D^T}$
- Arises in high energy theory



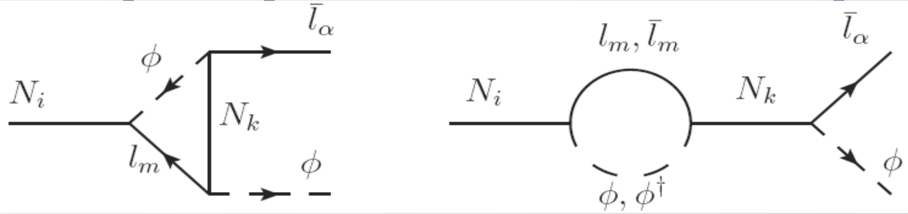
- M_ν is diagonalized as

$$V_\nu^T \mathcal{M}_\nu V_\nu = D_\nu = \text{diag}(m_1, m_2, m_3)$$

m_1, m_2, m_3 are the light neutrino masses

CP Violation and Leptogenesis

- In the decay process of heavy right-handed neutrino, the CP asymmetry generates through the interference between tree level and one loop heavy Majorana neutrino decay diagrams.



- The CP asymmetry is given by

$$\varepsilon_i = \sum_\alpha \varepsilon_i^\alpha \equiv \frac{\sum_\alpha \left[\Gamma(N_i \to \phi\,\bar{l}_\alpha) - \Gamma(N_i \to \phi^\dagger\, l_\alpha)\right]}{\sum_\beta \left[\Gamma(N_i \to \phi\,\bar{l}_\beta) + \Gamma(N_i \to \phi^\dagger\, l_\beta)\right]} = \frac{1}{8\pi\, v^2} \frac{1}{(\tilde{m}_D^\dagger\, \tilde{m}_D)_{ii}} \sum_{j\neq i} \sum_\alpha \left(\mathcal{I}_{ij}^\alpha\, f(M_j^2/M_i^2) + \mathcal{J}_{ij}^\alpha \frac{1}{1 - M_j^2/M_i^2} \right)$$

$$\mathcal{I}_{ij}^\alpha = \mathrm{Im}\Big[(\tilde{m}_D^\dagger)_{i\alpha} (\tilde{m}_D)_{\alpha j} (\tilde{m}_D^\dagger \tilde{m}_D)_{ij} \Big] \qquad \mathcal{J}_{ij}^\alpha = \mathrm{Im}\Big[(\tilde{m}_D^\dagger)_{i\alpha} (\tilde{m}_D)_{\alpha j} (\tilde{m}_D^\dagger \tilde{m}_D)_{ji} \Big]$$

$$f(x) = \sqrt{x}\big(1 - (1+x)\ln[(1+x)/x]\big)$$

- CP violation at low energy

$$J_{CP} = \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos\theta_{13} \sin\delta$$

θ_{ij}'s are the mixing angles and δ is the CP violating phase

5 zero in m_D with diagonal M_R and 4 zero in M_R

- In the high energy there are 24 parameters.

$$\mathcal{M}_\nu = -\underbrace{m_D}_{}\underbrace{M_R^{-1}}_{} m_D^T$$

(18-3) + (12-3) = 24

- In order to reduce the number of parameters, one successful scheme is texture zero.
- For the minimal number of parameters in M_R, maximum number of zeros, allowed in m_D, is five.
- Total number of different possible form of m_D, with 5 vanishing entry, is ${}^9C_5 = 126$
- For 4 zeros in M_R there are total 15 possibilities. But among them only 3 have non-vanishing determinant.
- These three together with diagonal M_R there are total 504 candidates.
- Only 18 (with diagonal M_R) are consistent with low energy data.

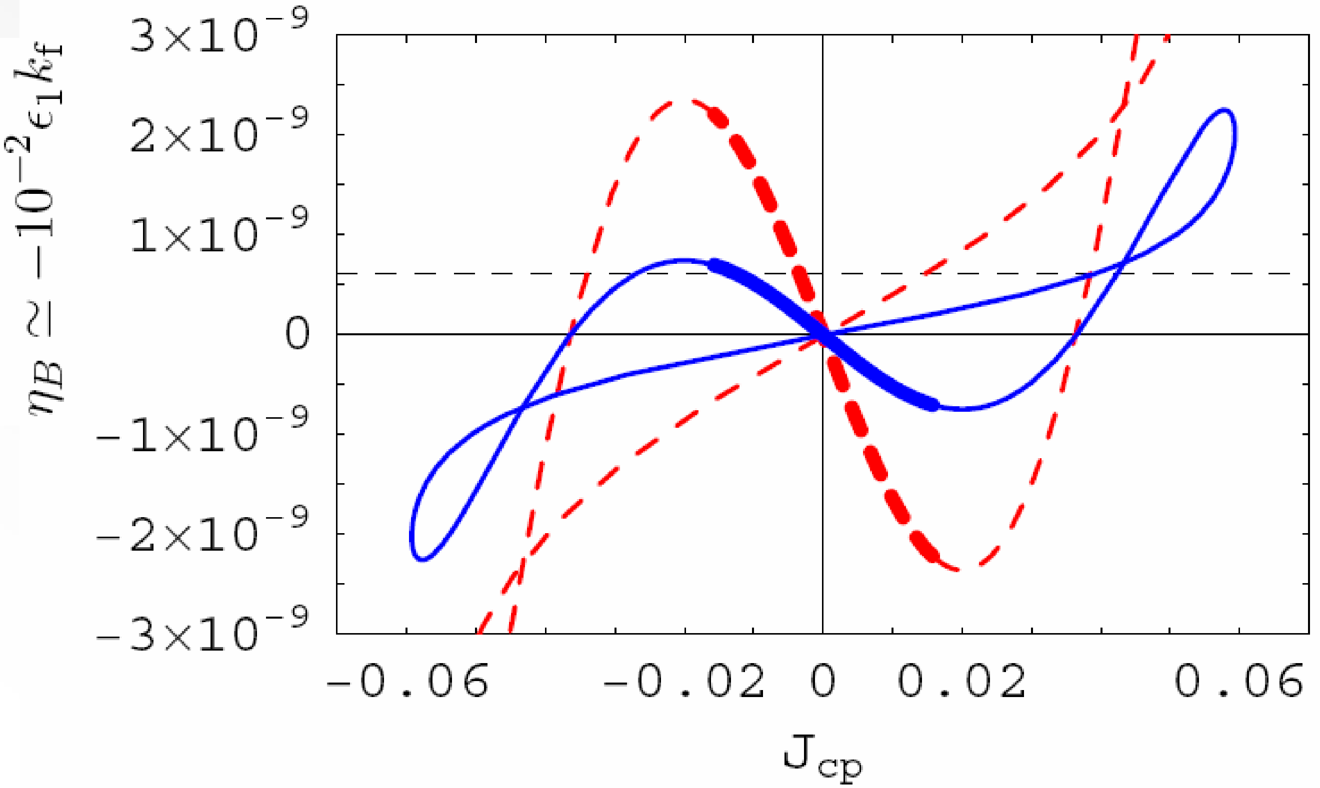
5 zero in m_D with diagonal M_R and 4 zero in M_R

- <u>Diagonal M_R</u>
- ➢ The cases with a vanishing $e\mu$ or $e\tau$ element in M_ν, the invariant J_{CP}, responsible for low energy CP violation is non-zero.
- ➢ This is proportional to the same phase factor as in I_{ij} .
- ➢ When scaling (the ratio between second column, third column and the ratio between second row and third row is some constant) in M_ν is present, there is no CP violation.
- <u>Non-diagonal M_R</u>
- ➢ For minimal non-diagonal form of M_R (four zero in M_R), one gets two zero textures in M_ν.
- ➢ Only four of the seven allowed two zero textures can be obtained for each of the three non-diagonal form of M_R.
- ➢ None of them are consistent with the experiments.

S. Goswami, SK, W. Rodejohann; arXiv:0905.2739 (accepted in Phys. Lett. B)

Hybrid Scenarios

- Another scheme is, imposing equalities among the matrix elements in addition to the texture zero with two right-handed neutrinos (it can reduce the number of parameters up to two undetermined).
- Six patterns are consistent but only in one case there is correlation between low and high energy CP violation.



$-0.02 < J_{CP} < 0.02$

S. Goswami, SK, A. Watanabe; arXiv:0905.2739

Summary and Conclusions

- Implications of Dirac mass matrices with 5 zeros for seesaw model containing three heavy right-handed neutrinos has been investigated with both diagonal and non-diagonal forms of M_R.
- For m_D with 5 zeros and diagonal M_R there are 18 allowed textures.
- All these 18 cases have one zero mass eigenvalue.
- Simultaneous presence of equalities and texture zero in the elements of Dirac and Majorana mass matrices in the context of the minimal seesaw model containing two heavy right-handed neutrinos reduce the number of parameters up to two undetermined.
- Only 6 textures (out of around 400) stand out to be consistent experiments.