Phenomenology of Minimal Seesaw Model with S_4 Symmetry

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high Energy

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Based on the work in collaboration with John Ng, Arnab Dasgupta

Introduction

- Current situation of neutrino physics :
  - We have determined three neutrino mixing angles, $\theta_{12}, \theta_{23}, \theta_{13}$.
  - Recent measurements of not-so-small θ_{13} open up new window to probe leptonic CPV.
  - No compelling evidence for LCPV yet, but there is a fit to neutrino data narrows down the allowed non-trivial values of Dirac-type CP phase $\delta_{CP} \sim 1.5\pi$

  - Tri-Bimaximal neutrino mixing is ruled out.

Introduction

- What we have done in this work
  - Since the deviation from TBM is not substantial, we consider the modification of TBM matrix by regarding it as a leading order
  - a minimal modification of TBM, $U_{TBM}U_{13}(\theta,\xi)$, is consistent with experiments and originates in a minimal seesaw model with S4 sym.
  - we show that this model is very predictive, (M_1, δ_M) are the only unknown parameters in lepton sector.
  - we show how Dirac CP phase in PMNS matrix is predicted in terms of neutrino mixing angles.
  - we study how leptogenesis, LFV processes and neutrinoless double beta decay are predicted.

Minimal Seesaw Model

(Frampton, Glashow, Yanagida, Phys. Lett. B (2002)
Endo. SK, Kaneko, Morozumi,Tanimoto, Phys.Rev.Lett. (2002)

- Only 2 heavy RH neutrinos are added to the SM

$$L = \overline{\nu_{Li}} m_{Dij} N_{Rj} + \frac{1}{2} \overline{(N_{Rj})^c} M_j N_{Rj}$$

$$(i = 1-3;\ j = 1,2)$$

- a δ_D, *and* *a* δ_{Maj} exist in ν mixing matrix
- one light neutrino mass is zero

→ Very predictive model !

- Impose **additional simple theoretical assumptions** to reduce free parameters:

- From the seesaw mechanism, we get light neutrino mass matrix

$$m_{eff} = m_D \frac{1}{M} m_D^T \qquad \text{where } M = \text{Diag.}[M_1, M_2]$$

- Dirac Yukawa mass matrix m_D should be 3x2 matrix .

- The light neutrino mass matrix m_{eff} is diagonalized by PMNS mixing matrix

$$m_{eff} = U^*_{\text{PMNS}} m_\nu^D U^\dagger_{\text{PMNS}}$$

$$m_\nu^D = \text{Diag.}[m_1, m_2, m_3]$$

- For normal hierarchy (NH), $m_1 = 0$, whereas $m_3 = 0$ for inverted hierarchy(IH)

- The following relation holds in general

$$m_D \frac{1}{\sqrt{M}} O^T = U^*_{\rm PMNS} \sqrt{m^D_\nu}$$

$$\sqrt{m_\nu^D} = \begin{pmatrix} 0 & 0 \\ \sqrt{m_2} & 0 \\ 0 & \sqrt{m_3} \end{pmatrix} \text{ for NH}$$

$$= \begin{pmatrix} \sqrt{m_1} & 0 \\ 0 & \sqrt{m_2} \\ 0 & 0 \end{pmatrix} \text{ for IH}$$

$$1/\sqrt{M} = Dia[1/\sqrt{M_1},\ 1/\sqrt{M_2}\ ]$$

- O is a 2x2 complex orthogonal matrix

$$O = \begin{pmatrix} x & y \\ -y & x \end{pmatrix} \qquad x^2 + y^2 = 1$$

- Imposing S_4 symmetry, the elements of m_D and O can be presented in terms of U_{PMNS}, $m_{1,2(2,3)}$, $M_{1,2}$.

Minimal seesaw with S_4 model

- Introducing new SU(2) doublet scalar fields ϕ_i triplet under S_4
- 3 light neutrinos → a triplet under S_4
- 2 heavy neutrinos → a doublet under S_4
- Yukawa interactions :

$$y[\phi_1(\nu_2 N_{R_1} + \nu_3 N_{R_2}) + \phi_2(\nu_3 N_{R_1} + \nu_1 N_{R_2}) + \phi_3(\nu_1 N_{R_1} + \nu_2 N_{R_2}).$$

- When ϕ_i get VEV, the above Yukawa terms lead to

$$m_D = \begin{pmatrix} c & b \\ a & c \\ b & a \end{pmatrix} \qquad a = y < \phi_1 >, b = y < \phi_2 >, c = y < \phi_3 >$$

$$m_D \frac{1}{\sqrt{M}} O^T = \begin{pmatrix} \frac{cx}{\sqrt{M_1}} + \frac{by}{\sqrt{M_2}} & -\frac{cy}{\sqrt{M_1}} + \frac{bx}{\sqrt{M_2}} \\ \frac{ax}{\sqrt{M_1}} + \frac{cy}{\sqrt{M_2}} & -\frac{ay}{\sqrt{M_1}} + \frac{cx}{\sqrt{M_2}} \\ \frac{bx}{\sqrt{M_1}} + \frac{ay}{\sqrt{M_2}} & -\frac{by}{\sqrt{M_1}} + \frac{ax}{\sqrt{M_2}} \end{pmatrix} = U^*_{\mathrm{PMNS}} \sqrt{m^D_\nu} \equiv U$$

$$\frac{x}{y} = \frac{U_{13} + qU_{22}}{U_{12} - qU_{23}} = \frac{U_{23} + qU_{32}}{U_{22} - qU_{33}} = \frac{U_{33} + qU_{12}}{U_{32} - qU_{13}} \qquad q = \sqrt{M_2/M_1}.$$

- q is determined from the above eq. in terms of a Majorana phase
- Then, (a,b,c) depend on a Majorana phase and M_1

⇨ Only a Majorana phase and M_1 are independent parameters in this minimal seesaw model

$$
\begin{aligned}
a^2 = \frac{M_1}{1+q^6} \{ & q^6 [U_{32}(U_{12} - qU_{23}) + U_{33}(U_{13} + qU_{22})] \\
& -q^4 [U_{32}(U_{22} - qU_{33}) + U_{33}(U_{23} + qU_{32}] \\
& +q^2 [U_{32}(U_{32} - qU_{13}) + U_{33}(U_{33} + qU_{12}] \} \,, \\
b^2 = \frac{M_1}{1+q^6} \{ & q^6 [U_{12}(U_{22} - qU_{33}) + U_{13}(U_{23} + qU_{32}] \\
& -q^4 [U_{12}(U_{32} - qU_{13}) + U_{23}(U_{33} + qU_{12}] \\
& +q^2 [U_{12}(U_{12} - qU_{23}) + U_{13}(U_{13} + qU_{22})] \} \,, \\
c^2 = \frac{M_1}{1+q^6} \{ & q^6 [U_{22}(U_{32} - qU_{13}) + U_{23}(U_{33} + qU_{12})] \\
& -q^4 [U_{22}(U_{12} - qU_{23}) + U_{23}(U_{13} + qU_{22}] \\
& +q^2 [U_{22}(U_{22} - qU_{33}) + U_{23}(U_{23} + qU_{32})] \} \,,
\end{aligned}
$$

Neutrino Mixing Matrix

- Before the measurements of θ_{13} , Tri-Bimaximal mixing has attracted much attention.

$$U^{TBM} = \begin{pmatrix} -\sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

(Harrison, Perkins, Scott, 2002)

$$\begin{cases} \nu_2 = -\frac{1}{\sqrt{3}}\nu_e + \frac{1}{\sqrt{3}}\nu_\mu + \frac{1}{\sqrt{3}}\nu_\tau \\ \nu_3 = -\frac{1}{\sqrt{2}}\nu_\mu + \frac{1}{\sqrt{2}}\nu_\tau \end{cases}$$

$$\theta_{12} = \sin^{-1}\left(\frac{1}{\sqrt{3}}\right) \approx 35.3°$$

$$\theta_{23} = 45° \qquad \theta_{13} = 0°, \qquad \delta_{CP} = 0$$

Neutrino Mixing Matrix

- TBM is theoretically well motivated, but challenged by the current experimental data.
- Modifying Tri-Bimaximal mixing matrix (SK, C.S.Kim, 2012)

  - Simple possible forms deviated from Tri-Bimaximal :

$$\begin{cases} U^{TBM} \cdot U_{ij}(\theta, \xi) \\ {U_{ij}}^{+}(\theta, \xi) \cdot U^{TBM} \end{cases}$$

- θ possibly gives rise to non-zero θ_{13} and possible deviation from maximal for θ_{23}.
- We call those forms modified TBM parameterization.

Neutrino Mixing Matrix

- Among possible forms, we show that $U_{TBM}U_{13}(\theta,\xi)$ originates in a minimal seesaw model with S4.

$$U_0^{\mathrm{TBM}}U_{13}(\theta,\xi)=\begin{pmatrix}\sqrt{\frac{2}{3}}c_\theta & \frac{1}{\sqrt{3}} & -\sqrt{\frac{2}{3}}s_\theta e^{i\xi}\\ -\frac{1}{\sqrt{6}}c_\theta+\frac{1}{\sqrt{2}}(s_\theta e^{-i\xi}) & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}c_\theta+\frac{1}{\sqrt{6}}(s_\theta e^{i\xi})\\ \frac{1}{\sqrt{6}}c_\theta+\frac{1}{\sqrt{2}}(s_\theta e^{-i\xi}) & -\frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}}c_\theta-\frac{1}{\sqrt{6}}(s_\theta e^{i\xi})\end{pmatrix}\equiv V.$$

$$P_\phi U_0^{\mathrm{TBM}}U_{13}(\theta,\xi)P_\alpha\equiv U_{\mathrm{PMNS}},$$

Predicting LCPV

- Any forms of neutrino mixing matrix should be equivalent to the PMNS matrix presented in the (PDG) standard parameterization :

- $U_{PMNS} = U_{23}(\theta_{23})U_{13}(\theta_{13}, \delta_D)U_{12}(\theta_{12})P_\phi$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_D} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_D} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_D} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_D} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_D} & c_{23}c_{13} \end{pmatrix} P_\phi .$$

$= P_\alpha \cdot V(\theta, \xi) \cdot P_\beta$: neutrino mixing matrix proposed before

➡ $V_{ij}e^{i(\alpha_i+\beta_j)} = (U_{PMNS})_{ij}$

Predicting LCPV

- For $V = U_0^{TBM} U_{13}(\theta, \xi)$

- We get $\sin\theta = \sqrt{\frac{3}{2}} s_{13}$, $\cos\xi = \frac{c_{13}^2 (s_{23}^2 - c_{23}^2)}{s_{13} \sqrt{2 - 3\, s_{13}^2}}$

- From the explicit form of V given above, we see that

$$\frac{V_{21} - V_{31}}{V_{23} - V_{33}} = \frac{V_{11}}{V_{13}} \quad \text{and} \quad V_{22} = -V_{32}$$

Predicting LCPV

- Using $V_{ij}e^{i(\alpha_i+\beta_j)} = (U_{PMNS})_{ij}$, we finally get

$$\frac{(U_{\rm PMNS})_{11}}{(U_{\rm PMNS})_{13}} = \frac{(U_{\rm PMNS})_{21}(U_{\rm PMNS})_{32} + (U_{\rm PMNS})_{31}(U_{\rm PMNS})_{22}}{(U_{\rm PMNS})_{23}(U_{\rm PMNS})_{32} + (U_{\rm PMNS})_{33}(U_{\rm PMNS})_{22}}$$

- Plugging the explicit form of $(U_{PMNS})_{ij}$,

$$\cos\delta_D = -\frac{1}{2\tan 2\theta_{23}} \cdot \frac{1-2{s_{13}}^2}{s_{13}\sqrt{2-3{s_{13}}^2}}$$

- Leptonic Jarlskog invariant :

$$\begin{aligned} {J_{CP}}^2 &= (\mathrm{Im}[U_{11}\ {U_{12}}^*\, U_{21}\ {U_{11}}^*\,])^2 \\ &= \frac{1}{12^2}(8{s_{13}}^2(1-3{s_{13}}^2) - \cos 2\theta_{23}\, {s_{13}}^2) \end{aligned}$$

Input for Numerical Results

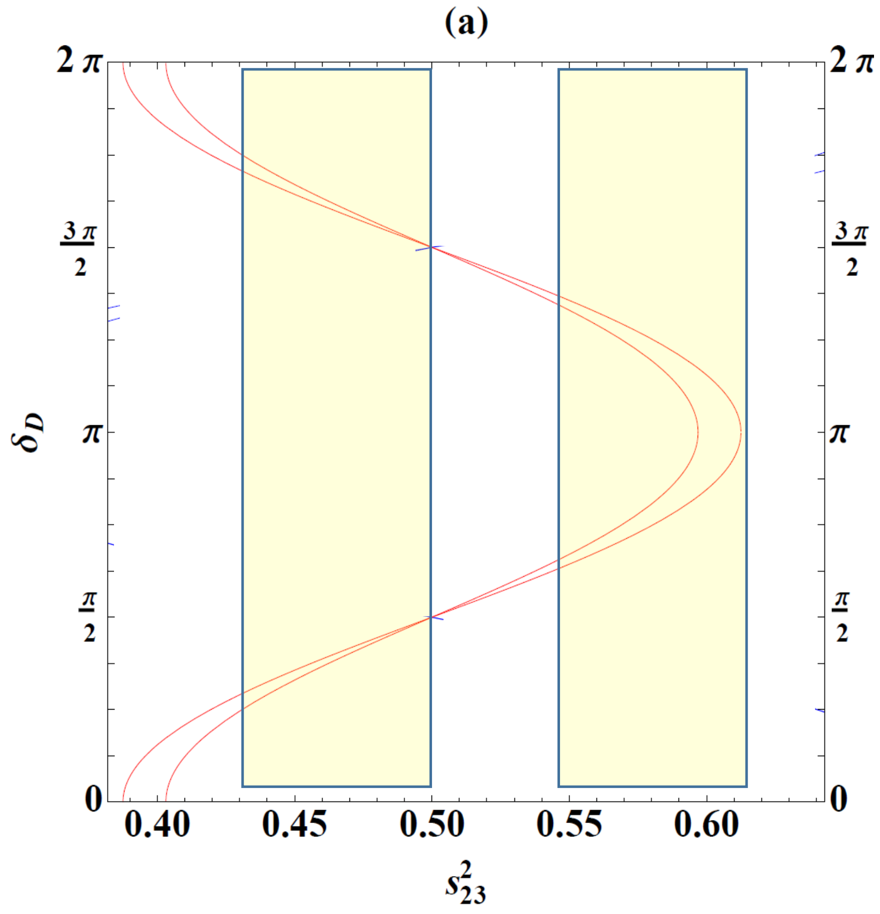
(Gonsalez-Garcia, Maltoni, Schwetz, arXiv:1512.06856)

	Normal Ordering ($\Delta\chi^2 = 0.97$)		Inverted Ordering (best fit)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.304^{+0.013}_{-0.012}$	$0.270 \to 0.344$	$0.270 \to 0.344$
$\theta_{12}/^\circ$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$33.48^{+0.78}_{-0.75}$	$31.29 \to 35.91$	$31.29 \to 35.91$
$\sin^2\theta_{23}$	$0.452^{+0.052}_{-0.028}$	$0.382 \to 0.643$	$0.579^{+0.025}_{-0.037}$	$0.389 \to 0.644$	$0.385 \to 0.644$
$\theta_{23}/^\circ$	$42.3^{+3.0}_{-1.6}$	$38.2 \to 53.3$	$49.5^{+1.5}_{-2.2}$	$38.6 \to 53.3$	$38.3 \to 53.3$
$\sin^2\theta_{13}$	$0.0218^{+0.0010}_{-0.0010}$	$0.0186 \to 0.0250$	$0.0219^{+0.0011}_{-0.0010}$	$0.0188 \to 0.0251$	$0.0188 \to 0.0251$
$\theta_{13}/^\circ$	$8.50^{+0.20}_{-0.21}$	$7.85 \to 9.10$	$8.51^{+0.20}_{-0.21}$	$7.87 \to 9.11$	$7.87 \to 9.11$
$\delta_{CP}/^\circ$	306^{+39}_{-70}	$0 \to 360$	254^{+63}_{-62}	$0 \to 360$	$0 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.02 \to 8.09$	$7.02 \to 8.09$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.457^{+0.047}_{-0.047}$	$+2.317 \to +2.607$	$-2.449^{+0.048}_{-0.047}$	$-2.590 \to -2.307$	$\begin{bmatrix} +2.325 \to +2.599 \\ -2.590 \to -2.307 \end{bmatrix}$

	Quark	**Lepton**
θ_{12}	13°	33°
θ_{23}	2°	45°
θ_{13}	0.2°	8.5°
δ	65°	270°

Plot of δ_D

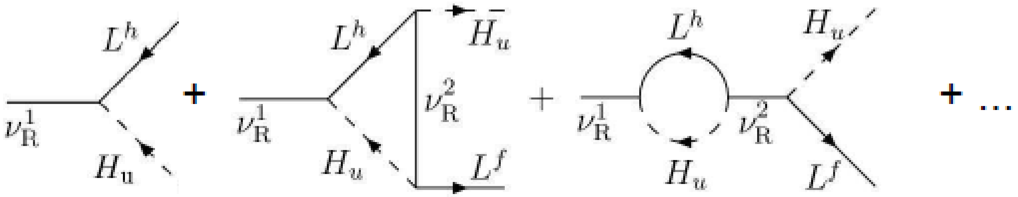
- Imposing data at 3 σ



Phenomenology

- Leptogenesis

-Generate $\not L$ from the direct CP violation in RH neutrino decay



-CP asymmetry

$$\epsilon_1 = \frac{1}{8\pi v^2}\frac{(c^*b + a^*c + b^*a)^2}{|a|^2 + |b|^2 + |c|^2} g(|q|^4)$$

$$g(x) = \sqrt{x}(1/(1-x) + 1 - (1+x)\ln((1+x)/x)) \text{ with } x = M_2/M_1$$

-$\not L$ gets converted to B via EW anomaly:

$$\boxed{Y_{B-L}^{SM} = -\eta\varepsilon_1 Y_{N_1}^{eq}}$$

$$Y_{N_1}^{eq} \approx \frac{45}{\pi^4}\frac{\varsigma(3)}{g_*\kappa_B}\frac{3}{4}$$

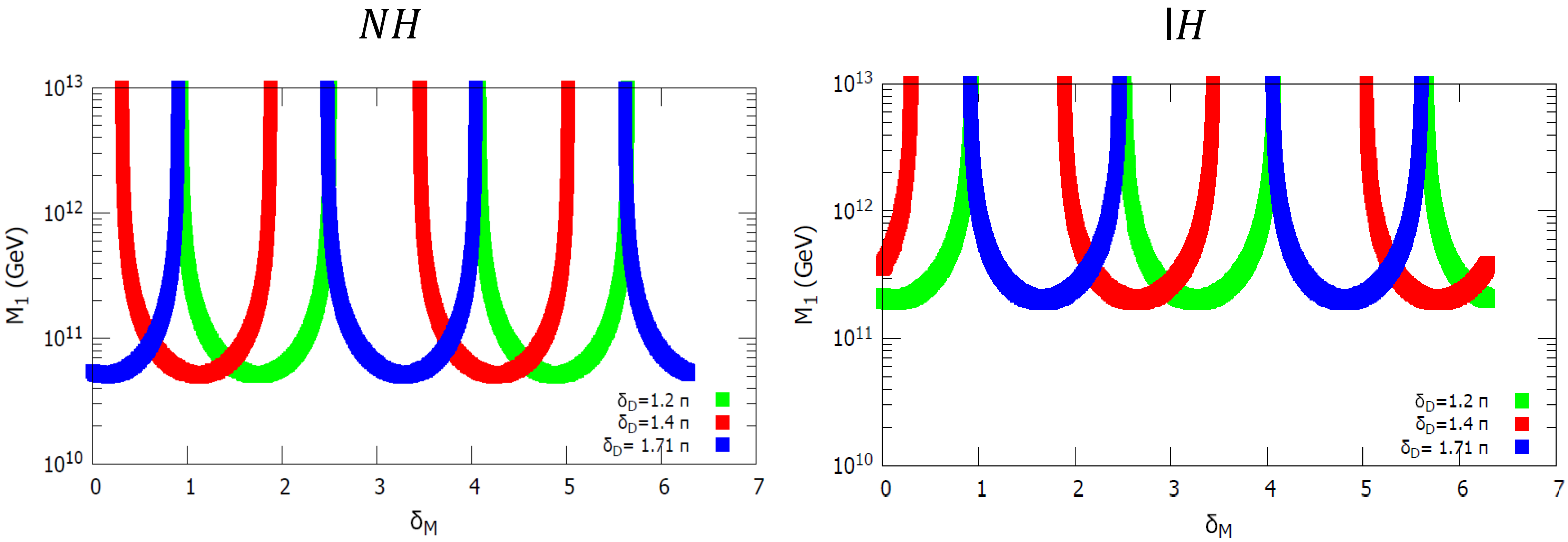
$$\frac{n_{\mathcal{B}}}{s} = \frac{24+4n_H}{66+13n_H}\frac{n_{\mathcal{B}-\mathcal{L}}}{s} = -1.38\times 10^{-3}\epsilon_{N_1}\eta$$

$$\frac{1}{\eta} \approx \frac{3.3\times 10^{-3}\ \text{eV}}{\tilde{m}_1} + \left(\frac{\tilde{m}_1}{0.55\times 10^{-3}\ \text{eV}}\right)^{1.16}$$

Giudice et al., 2004)

$$\tilde{m}_1 = (m_D m_D^{+})_{11}/M_1$$

$$\frac{n_{\mathcal{B}}}{n_\gamma} = (6.15\pm 0.25)\times 10^{-10}$$



NH
IH
10^{13}
10^{12}
10^{11}
10^{10}
M_1 (GeV)
0 1 2 3 4 5 6 7
δ_M
δ_D=1.2 π
δ_D=1.4 π
δ_D= 1.71 π

Resonant Leptogenesis :

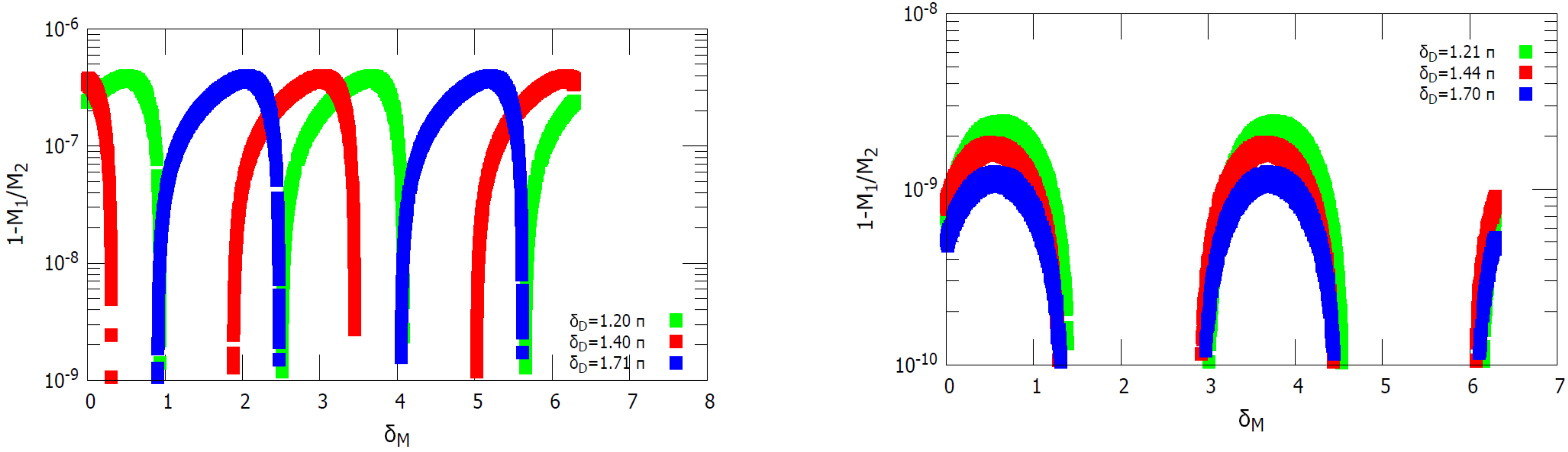
when the mass splitting between M_1 *and* M_2 is equal to the decay rate of heavy majorana neutrino, ϵ_1 can be resonantly enhanced.

(Pilaftsis and Underwood, 2004)

$$\epsilon_1 = \frac{\sum_{i\neq 1} \mathrm{Im}[(m_D^\dagger m_D)_{1i}]^2}{(m_D^\dagger m_D)_{11}(m_D^\dagger m_D)_{22}} \frac{(M_2^2 - M_1^2)M_1\Gamma_2}{(M_2^2 - M_1^2)^2 + M_1^2\Gamma_2^2}$$

$$\Gamma_2 = \frac{M_2}{4\pi v^2}(m_D^\dagger m_D)_{22}$$

NH IH



$For\ \ M_1 = 10\,TeV$

Phenomenology

- Lepton Flavor Violation $l_i \to l_j\gamma$
  -

$$\mathrm{Br}(l_i \to l_j\gamma) = \frac{\alpha_W^3 s_W^2}{256\pi^2}\frac{m_{l_i}^4}{M_W^4}\frac{m_{l_i}}{\Gamma_{l_i}}\left|\Omega_{l_i l_j} G_\gamma\left(\frac{M_1^2}{M_W^2}\right)\right|^2$$

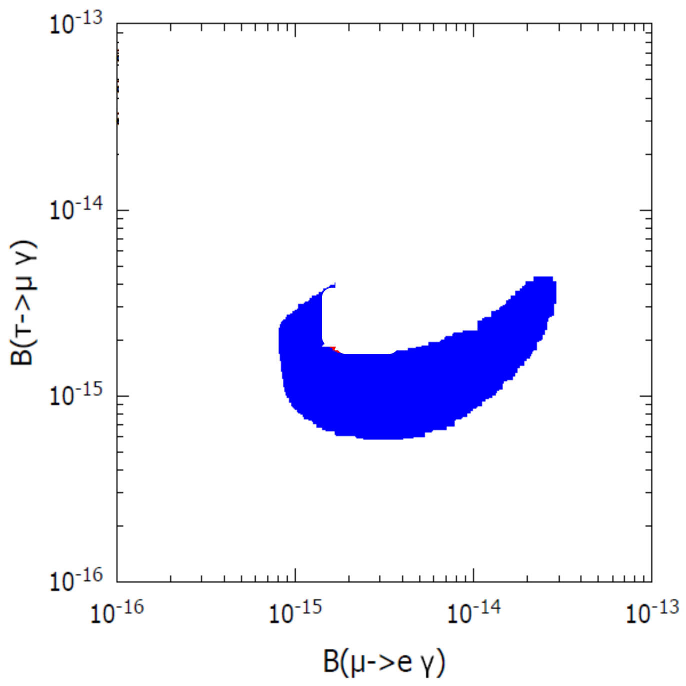
$$\Omega_{l_i l_j} = (m_D m_D^\dagger)_{l_i l_j}/(2M^2)$$

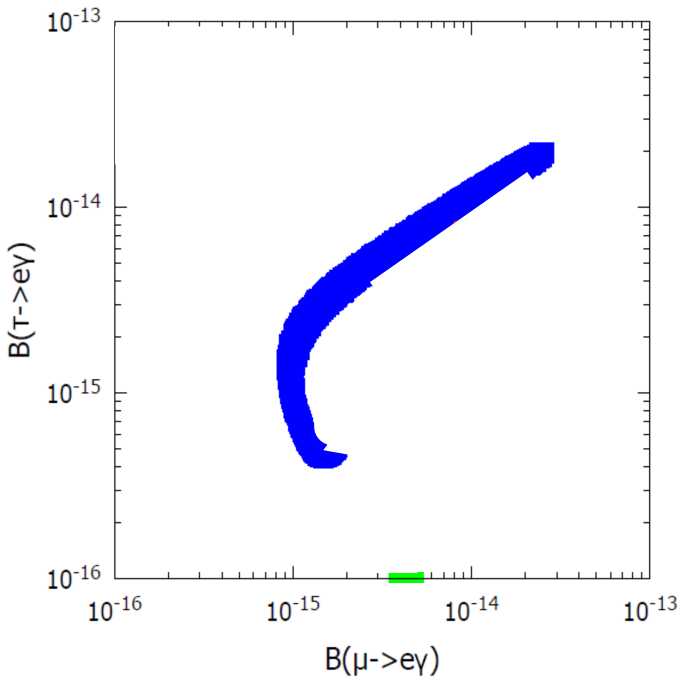
$$\Gamma_\mu = 2.997 \times 10^{-19}\ \mathrm{GeV}$$

$$\Gamma_\tau = 2.158 \times 10^{-12}\ \mathrm{GeV}$$

(Deppisch and Pilaftsis, 2011)

For the allowed parameter space for the resonant leptogenesis with $M_1 = 10$ TeV,





If newly designed experiment, MEG II, would achieve the sensitivity to 5×10^{-14} in future, we can exclude some of parameter space

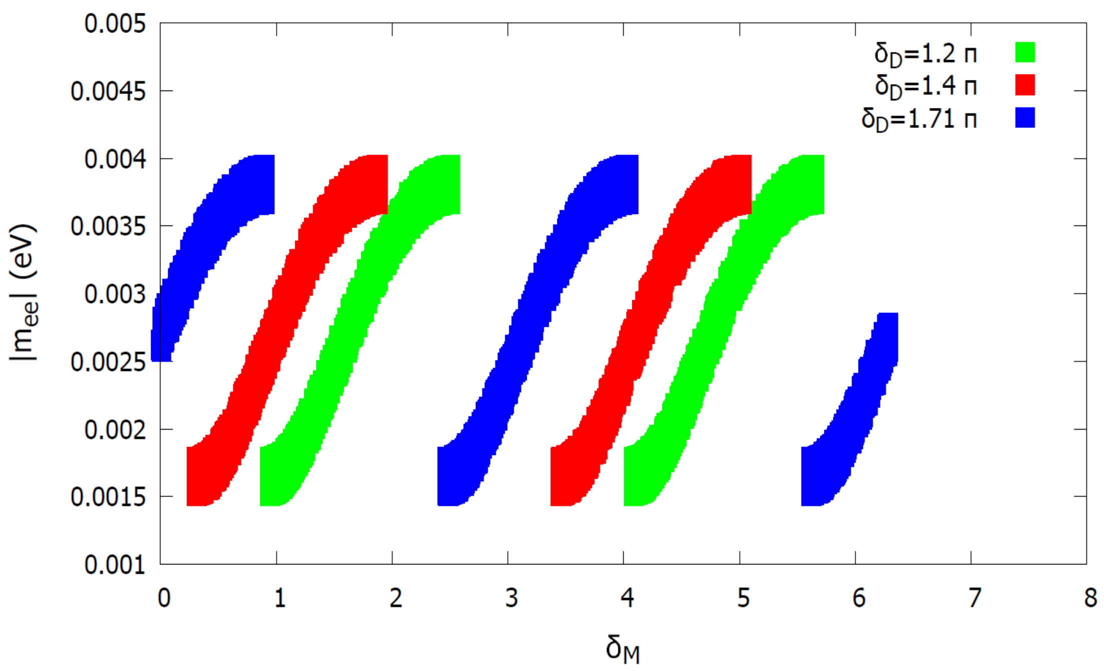
Phenomenology

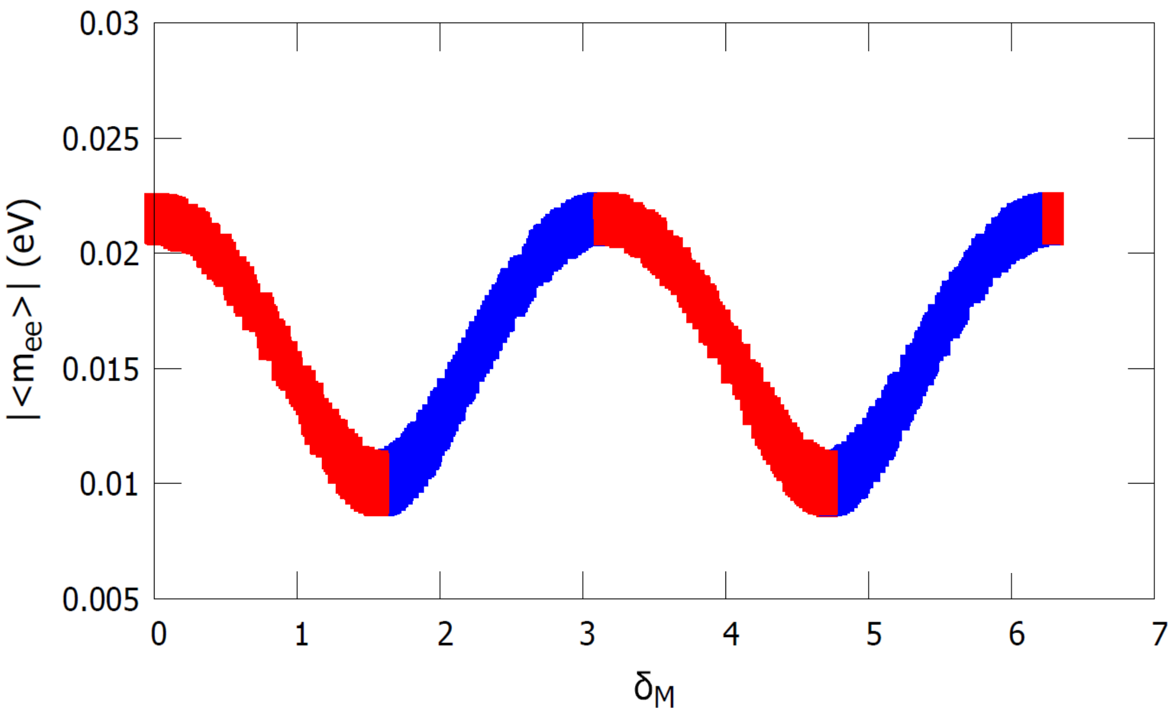
- Neutrinoless double beta decay
  -

$$|\sum_i U_{ei}^2 m_i| \equiv |< m_{ee} >| = \begin{cases} \left|m_2 s_{12}^2 c_{13}^2 + m_3 s_{13}^2 e^{-2i(\delta_D+\delta_M)}\right| & \text{for NH} \\ c_{13}^2 \left|m_1 c_{12}^2 + m_2 s_{12}^2 e^{2i\delta_M}\right| & \text{for IH} \end{cases}$$

  - For NH, $|\langle m_\nu \rangle|$ depends on both δ_D, δ_{Maj}
  - For IH, $|\langle m_\nu \rangle|$ depends on δ_{Maj}

For the allowed parameter space for the resonant leptogenesis with $M_1 = 10$ TeV,





Conclusion

- We have shown that the modification of TBM, $U_{TBM}U_{13}(\theta, \xi)$,

  can be derived in a minimal seesaw model with S4 symmetry.
- We have shown that the model is very predictive and .the Dirac type CP phase can be estimated in terms of neutrino mixing angles in the standard parameterization of the PMNS mixing matrix.
- A Majorana phase and M_1 are unknown parameters in lepton sector.
- We can study how leptogenesis, LFVs and neutrinoless deouble beta are predicted in terms of those two unknown parameters.