Nonzero θ_{13} and Leptogenesis with A_4 symmetry

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Outline

- **Introduction:**

Neutrino oscillation data before 2011 was suggestive of a low energy lepton mixing matrix that could be described by tribimaximal (TB) pattern (with $\theta_{13} = 0$) at the zeroth order;
A_4 is the simplest symmetry to realize TB pattern.

Ma,Rajasekharan PRD64; Babu,Valle,Ma PLB512

Altarelli,Feruglio NPB741, Varzielas,King,Ross PLB648; ....

After Double-Chooz, T2K, RENO, Daya Bay, $\theta_{13} \neq 0$ & hence deviation from TB is necessary.

- **The set-up:**

a) particle contents and symmetries
b) light neutrino mass generated by Type-I see-saw
c) parameters involved and their correlations with Majorana phases involved in lepton mixing matrix

- **Leptogenesis:**

Baryon asymmetry can be realized with next-to-leading-order contribution to the neutrino Yukawa matrix and its dependence on Majorana phases and θ_{13}.

- **Conclusions**

Neutrino Oscillation Parameters

- Neutrino flavour and mass eigenstates are related by $\Rightarrow |\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$.

Pontecorvo-Maki-Nakagawa-Sakata parametrization

$$U_{PMNS} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{13}S_{23}e^{i\delta} & C_{12}C_{23} - S_{12}S_{13}S_{23}e^{i\delta} & C_{13}S_{23} \\ S_{12}S_{23} - C_{12}S_{13}C_{23}e^{i\delta} & -C_{12}S_{23} - S_{12}S_{13}C_{23}e^{i\delta} & C_{13}C_{23} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_{21}/2} & 0 \\ 0 & 0 & e^{i\alpha_{31}/2} \end{bmatrix}$$

here $C_{ij} = \cos\theta_{ij}$ and $S_{ij} = \sin\theta_{ij}$.

Summary of Neutrino Parameters[Forero,Tortola,Valle, PRD86 (2012)]

Parameter	Best Fit	1σ range	3σ range
$\Delta m^2_\odot$ $[\times 10^{-5} eV^2]$	7.62	7.43 — 7.81	7.12 — 8.20
$\lvert\Delta m^2_A\rvert$ $[\times 10^{-3} eV^2]$	2.55 2.43	2.46 — 2.61 2.37 — 2.50	2.31 — 2.74 2.21 — 2.64
$\sin^2\theta_{12}$	0.320	0.303 — 0.336	0.27 — 0.37
$\sin^2\theta_{23}$	0.613 (0.427) 0.600	0.400 — 0.461 & 0.573 — 0.635 0.569 — 0.626	0.36 — 0.68 0.37 — 0.67
$\sin^2\theta_{13}$	0.0246 0.0250	0.0218 — 0.0275 0.0223 — 0.0276	0.017 — 0.033
δ	0.80π -0.30π	$0 - 2\pi$	$0 - 2\pi$

Tribimaximal (TBM) mixing:

Global analysis of neutrino oscillation data (before 2011) was suggestive of TBM form, $\sin^2\theta_{12} = 1/3$ and $\sin^2\theta_{23} = 1/2$ along with $\theta_{13} = 0$; the lepton mixing matrix takes the form

$$U_{TB} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}$$

Measurement of θ_{13}

- Important discovery in 2011-12 apart from Higgs
  T2K : $\sin^2 2\theta_{13} = 0.140^{+0.038}_{-0.032}(0.170^{+0.045}_{-0.037})$, arXiv:1106.2822; arXiv:1311.4750
  DOUBLE-CHOOZ: $\sin^2 2\theta_{13} = 0.109 \pm 0.030(stat.) \pm 0.025(syst.)$, arXiv:1112.6353
  Daya Bay : $\sin^2 2\theta_{13} = 0.089 \pm 0.010(stat.) \pm 0.005(syst.)$, arXiv:1203.1669
  RENO : $\sin^2 2\theta_{13} = 0.113 \pm 0.013(stat.) \pm 0.019(syst.)$, arXiv:1204.0626
  hence $\theta_{13} \approx 9^o$

Structure of the Model

Modified Altarelli-Feruglio (AF) [arXiv:hep-ph/0512103] model with $A_4 \times Z_3$

	e^c	μ^c	τ^c	L	N^c	H_u	H_d	ϕ_S	ϕ_T	ξ	ξ'	ϕ_0^S	ϕ_0^T	ξ_0
SU(2)	1	1	1	2	1	2	2	1	1	1	1	1	1	1
A_4	1	$1''$	$1'$	3	3	1	1	3	3	1	$1'$	3	3	1
Z_3	ω	ω	ω	ω	ω^2	1	ω	ω^2	1	ω^2	ω^2	ω^2	1	ω^2
$U(1)_R$	1	1	1	1	1	0	0	0	0	0	0	2	2	2

Also in Shimizu,Tanimoto,Watanabe PTP126; King,Luhn JHEP1109

- Vacuum expectation values (vev) of the scalar fields
$\langle\phi_T\rangle = (v_T, 0, 0)$, $\langle\phi_S\rangle = (v_S, v_S, v_S)$, $\langle H_{u,d}\rangle = v_{u,d}$, $\langle\xi\rangle = u$, $\langle\xi'\rangle = u_N$.
- This alignments are ensured by the driving fields ϕ_0^S, ϕ_0^T and ξ_0.

Superpotential and Coupling Matrices (at Leading Order)

- Charged Leptons:

$$w_L = \left[y_e e^c(\phi_T L) + y_\mu \mu^c(\phi_T L)' + y_\tau \tau^c(\phi_T L)''\right]\left(\frac{H_d}{\Lambda}\right) \rightarrow Y_L = \frac{v_T}{\Lambda}\begin{bmatrix} y_e & 0 & 0 \\ 0 & y_\mu & 0 \\ 0 & 0 & y_\tau \end{bmatrix}$$

- Dirac mass terms for neutrinos:

$$w_\nu = y(N^c L)H_u \rightarrow Y_{\nu 0} = y\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix}$$

Superpotential and Coupling Matrices

Majorana Mass Matrix (without ξ')

$$w_N = x_A \xi (N^c N^c) + x_B \phi_S (N^c N^c)$$

$$M_R = \begin{bmatrix} a + 2b/3 & -b/3 & -b/3 \\ -b/3 & 2b/3 & a - b/3 \\ -b/3 & a - b/3 & 2b/3 \end{bmatrix}$$

where $a = 2x_A u$, $b = 2x_B v_S$

- It can be diagonalized by U_{TB}, having the form

$$U_{TB} = \begin{bmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{bmatrix}.$$

- Light neutrino masses obtained through **seesaw mechanism**, $m_\nu = -m_D^T M_R^{-1} m_D$.
- Diagonalizing matrix is U_ν, $m_\nu^{diag} = U_\nu^T m_\nu U_\nu$,

where $U_\nu = U_{TB} diag(1, e^{i\alpha_{21}/2}, e^{i\alpha_{31}/2})$.

- Exact TBM mixing has been extensively studied in [arXiv:hep-ph/0512103v2, 0511133v3, 0905.0620, 0908.0240 etc.] literature. Here, we will study the deviation of this TBM mixing.

Deviation from TBM mixing

- To make $\theta_{13} \neq 0$, introduce new scalar singlet ξ', which contributes in the heavy Majorana neutrino sector through $x_N \xi' (N^c N^c)$
- Mojarana mass matrix is then given by

$$M_{Rd} = \begin{bmatrix} a + 2b/3 & -b/3 & -b/3 \\ -b/3 & 2b/3 & a - b/3 \\ -b/3 & a - b/3 & 2b/3 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d \\ 0 & d & 0 \\ d & 0 & 0 \end{bmatrix},$$

where $d = 2x_N u_N$.

- Above structure of RH neutrino mass matrix is no longer diagonalizable by U_{TB} only.
- Additional rotation is required. Let us consider a matrix U_1 (parametrized by angle θ and phase ψ), which do this job.
- Then RH neutrino mass matrix can be diagonalized by

$$\mathrm{diag}(M_1 e^{i\varphi_1}, M_2 e^{i\varphi_2}, M_3 e^{i\varphi_3}) = (U_{TB} U_1)^T M_{Rd} U_{TB} U_1.$$

Here, $M_{1,2,3}$ all are real, positive eigenvalues of M_{Rd}.

RH-Neutrino masses and phases associated

- Majorana neutrino mass eigenvalues and phases associated can be given by

$$\begin{aligned} M_1 &= |b+\sqrt{a^2+d^2-ad}| = |a|\left|\alpha_2 e^{i\phi_{ba}} + \sqrt{1+\alpha_1^2 e^{2i\phi_{da}} - \alpha_1 e^{i\phi_{da}}}\right| \\ M_2 &= |a+d| = |a|\left|1+\alpha_1 e^{i\phi_{da}}\right|, \\ M_3 &= |b-\sqrt{a^2+d^2-ad}| = |a|\left|\alpha_2 e^{i\phi_{ba}} - \sqrt{1+\alpha_1^2 e^{2i\phi_{da}} - \alpha_1 e^{i\phi_{da}}}\right|, \end{aligned}$$

$$\begin{aligned} \varphi_1 &= \arg(b+\sqrt{a^2+d^2-ad}) \\ \varphi_2 &= \arg(a+d) \\ \varphi_3 &= \arg(b-\sqrt{a^2+d^2-ad}) \end{aligned}$$

where $\alpha_1 = |d/a|$ and $\alpha_2 = |b/a|$, also $\phi_{da} = \phi_d - \phi_a$ and $\phi_{ba} = \phi_b - \phi_a$ are phase difference between (d, a) and (b, a) respectively.

- Without loss of generality we will work with $\boxed{\phi_{da} = 0}$ and say $\mathrm{K} = \sqrt{1-\alpha_1+\alpha_1^2}$, then we have

$$\begin{aligned} M_1 &= |a|\left|\alpha_2 e^{i\phi_{ba}} + \mathrm{K}\right| & \varphi_1 &= \arg(b+a\mathrm{K}), \\ M_2 &= |a|\,|1+\alpha_1| & \varphi_2 &= \arg(a+d), \\ M_3 &= |a|\left|\alpha_2 e^{i\phi_{ba}} - \mathrm{K}\right| & \varphi_3 &= \arg(b-a\mathrm{K}). \end{aligned}$$

Light neutrino masses and mixings

- Light neutrino masses obtained via $m_\nu = m_D^T M_{Rd}^{-1} m_D = U_\nu^* m_\nu^{diag} U_\nu^\dagger$, here

$$U_\nu = \frac{m_D^T}{y v_u} U_{TB} U_1^* \,\mathrm{diag}(e^{i\varphi_1/2}, e^{i\varphi_2/2}, e^{i\varphi_3/2}).$$

King, Luhn JHEP1109

- Light neutrino masses given by

$$m_i = \frac{(y v_u)^2}{M_i},$$

where m_i's are real and positive.

- We find a general sum rule for light neutrino masses as given by,

$$\frac{1}{m_1} - \frac{2\mathrm{K} e^{i\alpha_{21}}}{m_2(1+\alpha_1)} = \frac{e^{i\alpha_{31}}}{m_3}.$$

- When, $\mathrm{K}\left(= \sqrt{1 - \alpha_1 + \alpha_1^2}\right) \rightarrow 1$ (i.e. with $\alpha_1 = 0$), the sum rule is reduced to the one found in Altarelli,Meloni JPG36 and Hagedorn,Molinaro,Petcov JHEP0909.

Light neutrino masses and mixings

- Final form of unitary matrix that diagonalizes m_ν is given by

$$U_\nu = \frac{m_D^T}{y v_u} U_{TB} \begin{bmatrix} \cos\theta & 0 & -\sin\theta e^{-i\psi} \\ 0 & 1 & 0 \\ \sin\theta e^{+i\psi} & 0 & \cos\theta \end{bmatrix} diag(1, e^{i\phi_2/2}, e^{i\phi_3/2})$$

$$= \begin{bmatrix} \sqrt{\frac{2}{3}}\cos\theta & 1/\sqrt{3} & -\sqrt{\frac{2}{3}}\sin\theta e^{-i\psi} \\ -\frac{\cos\theta}{\sqrt{6}} + \frac{\sin\theta}{\sqrt{2}} e^{i\psi} & 1/\sqrt{3} & \frac{\cos\theta}{\sqrt{2}} + \frac{\sin\theta}{\sqrt{6}} e^{-i\psi} \\ -\frac{\cos\theta}{\sqrt{6}} - \frac{\sin\theta}{\sqrt{2}} e^{i\psi} & 1/\sqrt{3} & -\frac{\cos\theta}{\sqrt{2}} + \frac{\sin\theta}{\sqrt{6}} e^{-i\psi} \end{bmatrix} . \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\phi_2/2} & 0 \\ 0 & 0 & e^{i\phi_3/2} \end{bmatrix} .$$

here we have parametrized the extra U_1 matrix by θ and ψ as mentioned earlier.

- We can now remove one common phase by setting $\varphi_1 = 0$ and we find the Majorana phases as

$$\varphi_2 = \alpha_{21}$$
$$\varphi_3 = \alpha_{31}$$

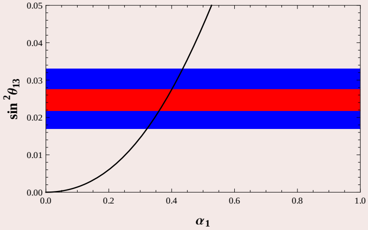
Generation of nonzero θ_{13} and effect on other mixing angles

- Comparing U_{PMNS} and U_ν we get

$$\sin\theta_{13} = \sqrt{\frac{2}{3}}\sin\theta, \qquad \delta_{CP} = \psi + \pi \qquad \sin^2\theta_{12} = \frac{1}{3(1-\sin^2\theta_{13})},$$

$$\sin^2\theta_{23} = \frac{1}{2} + \frac{1}{\sqrt{2}}\sin\theta_{13}\cos\psi \quad \text{and with} \quad \psi = 0, \qquad \tan 2\theta = \frac{\sqrt{3}\alpha_1}{(2-\alpha_1)}..$$

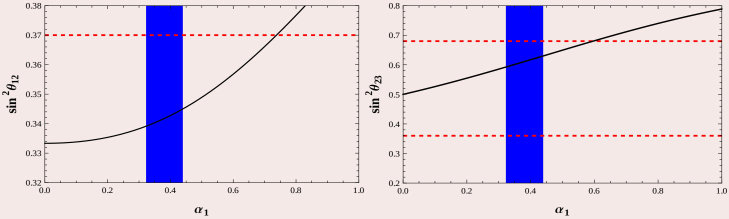
• $\sin^2\theta_{13}$ vs α_1



- Here $\psi = 0$. Now, for 3σ (blue patch) and 1σ (red patch) range of $\sin^2\theta_{13}$ we get $\alpha_1 = 0.32 - 0.44$ and $\alpha_1 = 0.36 - 0.40$ respectively. Best-fit value of $\sin^2\theta_{13}$ makes $\alpha_1 = 0.38$.

Non-zero θ_{13} and effect on other mixing angles

• $\sin^2\theta_{12}$ vs α_1 $\sin^2\theta_{23}$ vs α_1



•Here, vertical blue patch indicates allowed value for α_1 corresponding to 3σ range of $\sin^2\theta_{13}$ and horizontal red dashed line represents 3σ allowed range for $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$

• Summary:

Range of α_1 obtained from Fig.1	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$
$0.36 \leq \alpha_1 \leq 0.40$	0.341-0.343	0.38-0.40
$0.32 \leq \alpha_1 \leq 0.44$	0.339-0.345	0.37-0.41

Table : Allowed regions of $\sin^2\theta_{12}$ and $\sin^2\theta_{23}$ depending on α_1 in our set-up

Correlation of parameters involved

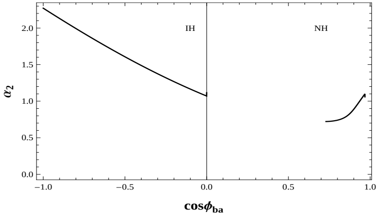
- Parameters involved Majorana neutrino masses: $\boxed{\alpha_1,\ \alpha_2,\ \phi_{ba},\ |a|.}$
- First three can be constrained by low energy neutrino oscillation data through ratio of solar and atmospheric mass squared difference defined as

$$r = \frac{\Delta m^2_\odot}{|\Delta m^2_A|},\ \ \Delta m^2_\odot = \Delta m^2_{21} \equiv m^2_2 - m^2_1,\ \ |\Delta m^2_A| = |\Delta m^2_{31}| \equiv |\Delta m^2_{32}|.$$

- Hence using above relations we get

$$r = \frac{(\alpha_2^2 + 2\alpha_2 \mathrm{K}\cos\phi_{ba} - \alpha_1)(\alpha_2^2 - 2\alpha_2\mathrm{K}\cos\phi_{ba} + \mathrm{K}^2)}{4(1+\alpha_1)^2\alpha_2\mathrm{K}|\cos\phi_{ba}|}.$$

- Variation of $\cos\phi_{ba}$ with α_2 for $r = 0.03$ and $\alpha_1 = 0.38$



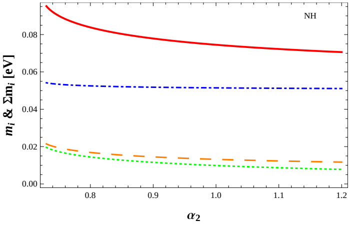
- From the above plot for NH $\cos\phi_{ba} > 0$ ($\alpha_2 = 0.73 - 1.2$) and for IH $\cos\phi_{ba} < 0$ ($\alpha_2 = 1.1 - 2.3$) .

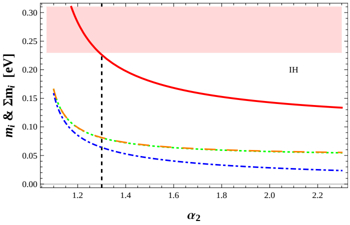
Constraints on Light Neutrino Mass

- Using $r = \frac{\Delta m^2_\odot}{|\Delta m^2_A|}$ and neutrino mass eigenvalues we obtain

$$m_1^2 = |\Delta m_A^2| r \frac{(1+\alpha_1)^2}{(\alpha_2^2 + 2\alpha_2 \mathrm{K} \cos\phi_{ba} + \mathrm{K}^2 - 1 - 2\alpha_1 - \alpha_1^2)}.$$

- Using the best fit value of $|\Delta m_A^2| = 2.55 \times 10^{-3}\mathrm{eV}^2$ [NH] ($2.43 \times 10^{-3}\mathrm{eV}^2$ [IH]), $r = 0.03$ and $\alpha_1 = 0.38$, we can estimate m_i's from the above relation for both the NH (and IH) as follows





- Here in the right panel horizontal shaded region indicated disfavored region as $\sum_i m_{\nu_i} < 0.440$ eV (95% CL) [WMAP Collaboration, arXiv:1212:5225]; so we have,

$$0.07 \text{ eV} \le \sum m_i \le 0.10 \text{ eV} \, (\text{NH}, \alpha_2 = 0.73 - 1.20), \quad (1)$$

$$0.13 \text{ eV} \le \sum m_i \le 0.23 \text{ eV} \, (\text{IH}, \alpha_2 = 1.30 - 2.30). \quad (2)$$

Constraints on Majorana phases

- Majorana phases are insensitive to neutrino oscillation experiments.
- They can an be constrained using parameters appearing in mass eigenvalues.
- With ϕ_{da}=0, we found Majorana phases $\alpha_{21,31}$ as [arXiv: 0908.0240]

$$\tan \alpha_{21} = -\frac{\alpha_2 \sin \phi_{ba}}{\mathrm{K} + \alpha_2 \cos \phi_{ba}}, \qquad \tan \alpha_{31} = \frac{2\mathrm{K}\alpha_2 \sin \phi_{ba}}{\alpha_2^2 - \mathrm{K}^2}.$$

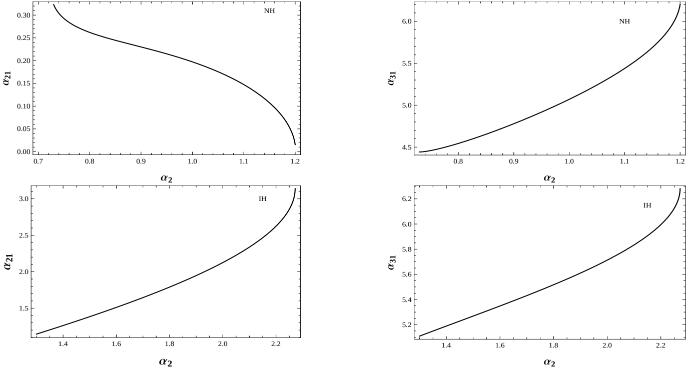


Figure : Majorana phases $\alpha_{21,31}$ as function of α_2 for NH (upper row with $\cos \phi_{ba} > 0$ and $\sin \phi_{ba} < 0$) and IH (lower row with $\cos \phi_{ba} < 0$ and $\sin \phi_{ba} < 0$) respectively.

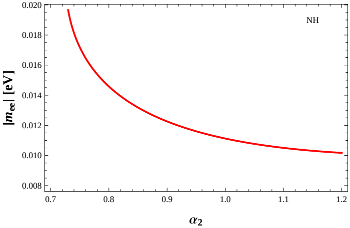
Bound on neutrinoless double beta decay:

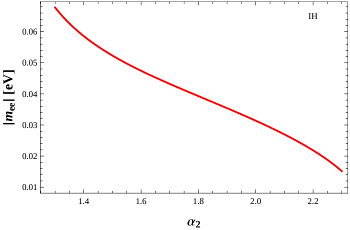
Effective neutrino mass parameter $|m_{ee}|$

$$|m_{ee}| = \left| \frac{2}{3} m_1 \cos^2\theta + \frac{1}{3} m_2 e^{i\alpha_{21}} + \frac{2}{3} m_3 \sin^2\theta e^{i\alpha_{31}} \right|.$$

with $\delta_{CP} = \pi$

- For $\alpha_1 = 0.38$





Leptogenesis

$$Y_B = \frac{n_B - n_{\bar{B}}}{s} = (8.77 \pm 0.24) \times 10^{-11}$$

where $n_B - n_{\bar{B}}$ is the difference between baryon and anti-baryon number and 's' stands for entropy density[WMAP, arXiv:1212:5225].

- Out of equilibrium decay of heavy Majorana neutrinos can produce lepton asymmetry (in one flavor approximation) in the basis where RH Majorana neutrinos are diagonal as

$$\epsilon_i = \frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}\left[\left((\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ji}\right)^2\right]}{(\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ii}} f\left(\frac{m_i}{m_j}\right)$$

where $\hat{Y}_\nu = \mathrm{diag}(1, e^{-i\alpha_{21}/2}, e^{-i\alpha_{31}/2}) U_R^T Y_\nu$.

- The loop factor $f(x)$ in above expression with $x = m_i/m_j$:

$$f(x) \equiv -x\left(\frac{2}{x^2-1} + \log\left(1 + \frac{1}{x^2}\right)\right)$$

- $Y_B \approx \sum Y_{Bi}$; where $Y_{Bi} \simeq -1.48 \times 10^{-3} \epsilon_i \eta_{ii}$; the efficiency factor η_{ii}

$$\frac{1}{\eta_{ii}} \approx \frac{3.3 \times 10^{-3}\ \mathrm{eV}}{\tilde{m}_i} + \left(\frac{\tilde{m}_i}{0.55 \times 10^{-3}\ \mathrm{eV}}\right)^{1.16},$$

where washout mass parameter, $\tilde{m}_i = \frac{(\hat{Y}_\nu \hat{Y}_\nu^\dagger)_{ii} v_u^2}{M_i}$.

Leptogenesis

• At LO, $\hat{Y}_{\nu 0}\hat{Y}_{\nu 0}^{\dagger} \propto |y^2|\mathbf{I}$: vanishing asymmetry [Jenkins, Manohar PLB668]
• NLO correction in Yukawa sector; [Jenkins, Manohar PLB668, Hagedorn,Molinaro,Petcov JHEP0909]
•such contributions in our set-up are :

$$y(LN^c)H_u + x_C N^c(L\phi_T)_{3_S} H_u/\Lambda + x_D N^c(L\phi_T)_{3_A} H_u/\Lambda$$

• Yukawa matrix and $\hat{Y}_\nu \hat{Y}_\nu^\dagger$:

$$\begin{aligned} Y_\nu &= Y_{\nu 0} + \delta Y_\nu \\ &= y\begin{bmatrix}1&0&0\\0&0&1\\0&1&0\end{bmatrix} + \frac{x_C v_T}{\Lambda}\begin{bmatrix}2&0&0\\0&0&-1\\0&-1&0\end{bmatrix} + \frac{x_D v_T}{\Lambda}\begin{bmatrix}0&0&0\\0&0&-1\\0&1&0\end{bmatrix}, \end{aligned}$$

• From definition

$$\epsilon_1 = \frac{-1}{2\pi}\left(\frac{v_T}{\Lambda}\right)^2\left[\sin\alpha_{21}\left(2\mathrm{Re}(x_C)^2\cos^2\theta + \frac{2\mathrm{Re}(x_D)^2}{3}\sin^2\theta + \frac{2\mathrm{Re}(x_C)\mathrm{Re}(x_D)}{\sqrt{3}}\sin 2\theta\right) f\left(\frac{m_1}{m_2}\right)\right.$$
$$\left. + \sin\alpha_{31}\left(\mathrm{Re}(x_C)^2\sin^2 2\theta + \frac{\mathrm{Re}(x_D)^2}{3}\cos^2 2\theta + \frac{\mathrm{Re}(x_C)\mathrm{Re}(x_D)}{\sqrt{3}}\sin 4\theta\right) f\left(\frac{m_1}{m_3}\right)\right]$$

(similar expressions for ϵ_2 and ϵ_3).
• $y >> (\mathrm{Re}(x_{C,D})v_T/\Lambda)$ is considered, $\mathrm{Re}(x_{C,D})$ are of same order of y and $(v_T/\Lambda) << 1$. Small value of (v_T/Λ) is required to reproduce $|\epsilon_i| \gtrsim 10^{-6}$ for generating baryon asymmetry of proper order. With this consideration, the washout mass parameters becomes identic to light neutrino masses (i.e $\tilde{m}_i \approx m_i$).

Leptogenesis

$$Y_B = \sum_{i=1}^{3} Y_{Bi} \simeq -1.48 \times 10^{-3} \left(\epsilon_1 \eta_{11} + \epsilon_2 \eta_{22} + \epsilon_3 \eta_{33}\right).$$

Baryon Asymmetry

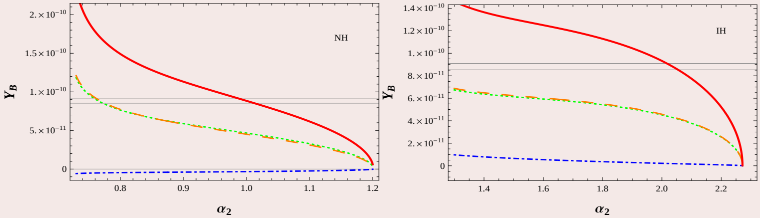


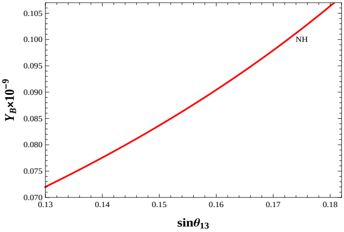
Figure : Green, orange and blue dashed lines stands for Y_{B1}, Y_{B2} and Y_{B3} respectively and red line for total baryon asymmetry Y_B.

Parameters involved and their contribution:

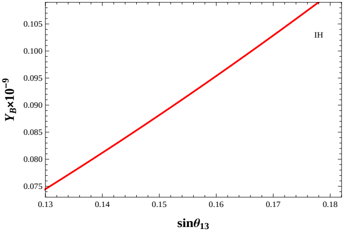
- $\frac{v_T}{\Lambda} \sim 10^{-2}$, and typical magnitude of lepton asymmetry $|\epsilon_i| \gtrsim 10^{-6}$
- $\alpha_1 = 0.38$ for best fit value of $\sin^2\theta_{13}$.
- $x_C = 0.2$, $x_D = 0.2$ for NH and $x_C = 0.03$, $x_D = 0.2$ for IH.

Leptogenesis and $\sin\theta_{13}$

- Y_B vs $\sin\theta_{13}$ for NH ($\alpha_2 = 1$)



- Y_B vs $\sin\theta_{13}$ for IH ($\alpha_2 = 2$)



Conclusion

- We have modified the original A_4 symmetry model of AF by extending the flavon sector with additional scalar singlet.
- Modified neutrino mass matrix (through Type-I seesaw) generates adequate θ_{13}; other mixing angles are in desired range
- A new sum rule for the model is obtained.
- Correlation among entries in mass parameters and Majorana phases are studied.
- Able to generate required matter-antimatter asymmetry of the universe, where Majorana phases play important role.
- The vacuum alignment of the flavon vevs are studied.