Flavour and CP Symmetries for Leptogenesis

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Combining flavour and CP symmetries

Approach: lepton mixing originates from the breaking of a discrete (non-abelian and finite) flavour symmetry

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charged lepton sector

G_e : abelian subgroup of G_f, e.g. Z_3

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$G_\nu \subseteq Z_2 \times Z_2 \subset G_f$

U_ν

$$U_{\mathrm{PMNS}} = U_e^\dagger U_\nu$$

this framework does not constrain lepton masses

drawback: Majorana phases cannot be predicted

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Feruglio, Hagedorn, Ziegler, 2012
Holthauser, Lindner, Schmidt, 2012
M.-C. Chen et al., 2014
also
Harrison, Scott, 2002
Grimus, Lavoura, 2004
Farzan, Smirnov, 2007
Mohapatra, Nishi, 2012
Branco,G.Felipe,Joachim,2012

$$G_f \quad \text{and} \quad \mathrm{CP}$$

$$(X_{\mathbf{r}}^{-1} g_{\mathbf{r}} X_{\mathbf{r}})^* = g'_{\mathbf{r}} \text{ for all } g,\ g' \in G_f$$

X_r is a class-inverting automorphism of G_f

$$\phi'(x) = X_r \phi^*(x_{CP})$$

charged lepton sector

$$G_e = Z_3$$

$$U_e$$

neutrino sector

$$G_\nu = Z_2 \times CP$$

$$U_\nu$$

$$U_{\mathrm{PMNS}} = U_e^\dagger U_\nu$$

all the PMNS phases are constrained by the residual flavour and CP symmetries up to a real parameter θ

Seesaw extension of the SM with G_f and CP

seesaw Lagrangian generated after the breaking of G_f and CP

$$\mathcal{L}_l = -Y_l \, \bar{l} \, H \, \alpha_R - Y_D \, \bar{l} \, H^c N - \frac{1}{2} \overline{N^c} M_R N + \text{h.c.}$$

$$\boxed{\text{Under } G_f \qquad \begin{array}{rcl} l & \sim & \mathbf{3} \\ N & \sim & \mathbf{3} \\ \alpha_R & \sim & \mathbf{1} \end{array}}$$

complex and faithful irrep of G_f

RH charged leptons α_R are distinguished by an auxiliary symmetry $Z_3^{(\mathrm{aux})}$

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2 possibilities @ LO in the flavon insertions:

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1. Y_D invariant under the full flavour group G_f and generated at renormalizable level; M_R invariant under the residual flavour and CP symmetry G_ν

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Lepton mixing pattern

$m_l = Y_l\, v = \mathrm{diag}\,(m_e, m_\mu, m_\tau)$ invariant under G_e

$m_D = Y_D\, v = y_0\, v\, \mathbb{I}_{3\times 3}$ invariant under G_f and CP

M_R invariant under $Z_2 \times$ CP

given $X \equiv X_{\mathbf{3}}$ (CP transformation) and Z (generator of Z_2 in $\mathbf{3}$)

$$Z^T M_R Z = M_R\,, \qquad X M_R X = M_R^*$$

consistency condition: $X Z^\star - Z X = 0$

Feruglio, Hagedorn, Ziegler, 2012
Holthauser, Lindner, Schmidt, 2012

$$U_R^T\, M_R\, U_R = \mathrm{diag}\,(M_1, M_2, M_3)$$

$$X = \Omega \Omega^T$$

$$U_R = \Omega\, R_{ij}(\theta)\, K_\nu \quad , \qquad K_\nu = \begin{pmatrix} 1 & 0 & 0 \\ 0 & i^{k_1} & 0 \\ 0 & 0 & i^{k_2} \end{pmatrix}$$

the matrix Ω is determined by X and Z

X is an automorphism of G_f of order two (involution): $X X^\dagger = X X^* = \mathbf{1}$

Lepton mixing pattern

Neutrino mass matrix:

$$m_\nu = -m_D \, M_R^{-1} \, m_D^T = -y_0^2 \, v^2 \, M_R^{-1}$$

$$U_\nu^\dagger \, m_\nu \, U_\nu^\star = \mathrm{diag}\,(m_1, m_2, m_3) \quad \text{with} \quad U_\nu = U_R$$

$$m_i = -\frac{y_0^2 \, v^2}{M_i}$$

Lepton mixing matrix:

$$U_{PMNS} = U_e^\dagger \, U_\nu = U_R = \Omega \, R_{ij}(\theta) \, K_\nu$$

PMNS mixing matrix fixed by G_f, G_e and G_ν up to a free real parameter θ

There is a strong correlation of all mixing angles and CP phases

Thermal leptogenesis

Fukugita, Yanagida, 1986

Consider leptogenesis realized at a scale **10^{12} GeV $\lesssim$ *$T \sim M_i$* $\lesssim$ 10^{14} GeV**

(lepton flavour dynamics is not resolved)

Since the RH neutrino mass spectrum is not strongly hierarchical, all the 3 RH neutrinos contribute to the generation of the baryon asymmetry:

$$Y_B = \sum_{i=1}^{3} Y_{Bi} \qquad \text{with} \qquad Y_{Bi} \approx 1.38 \times 10^{-3} \epsilon_i \sum_{j=1}^{3} \eta_{ij} \approx 10^{-10}$$

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CP asymmetries in N_i decays:

$$\epsilon_i = -\frac{\sum_\alpha [\Gamma(N_i \to H l_\alpha) - \Gamma(N_i \to H^\star \bar{l}_\alpha)]}{\sum_\alpha [\Gamma(N_i \to H l_\alpha) + \Gamma(N_i \to H^\star \bar{l}_\alpha)]}$$

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CP asymmetries in N_i decays:

$$\epsilon_i = -\frac{1}{8\pi} \sum_{j \neq i} \frac{\mathrm{Im}\left((\hat{Y}_D^\dagger \hat{Y}_D)^2_{ij} \right)}{(\hat{Y}_D^\dagger \hat{Y}_D)_{ii}} f(M_j/M_i) \gtrsim 10^{-6} \qquad \text{with} \qquad \hat{Y}_D = Y_D\, U_R$$

ϵ_i vanish in the limit of an exact flavour symmetry in the neutrino sector

Jenkins, Manohar, 2008

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The efficiency factors are diagonal at LO in the RH neutrino family space:

$$\eta_{ij} \approx \eta_{ii}\, \delta_{ij} \qquad \text{with} \qquad 10^{-3} \lesssim \eta_{ii} \lesssim 0.5$$

Thermal leptogenesis

Fukugita, Yanagida, 1986

In a specific model the neutrino Yukawa matrix receives contributions from flavour symmetry breaking fields:

$$Y_D = y_0 \, \mathbb{I} \, + \, \delta Y_D \, + \, \ldots$$

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δY_D has a residual symmetry $G_e = Z_3^{(D)}$

$$\delta Y_D = \begin{pmatrix} \frac{2}{\sqrt{3}} z_1 & 0 & 0 \\ 0 & -\frac{1}{\sqrt{3}} z_1 - z_2 & 0 \\ 0 & 0 & -\frac{1}{\sqrt{3}} z_1 + z_2 \end{pmatrix} \kappa$$

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The relevant combination in the CP asymmetries at LO in κ is

$$\hat{Y}_D^\dagger \hat{Y}_D \approx y_0 \, U_R^\dagger \left(y_0 \, \mathbb{I} + (\delta Y_D)^\dagger + \delta Y_D \right) U_R$$

the CP asymmetries at LO <u>do not depend</u> on the phases of z_1 and z_2

Hagedorn, EM, Petcov, 2009
Bertuzzo, Di Bari, Feruglio, Nardi, 2009

One particular example

Let's consider the case of a generic lepton mixing:

$$U_R \equiv U_{PMNS} = \tilde{U}\mathrm{diag}\left(1, e^{i\alpha/2}, e^{i(\beta/2+\delta)}\right)$$

If the correction z_2 is equal to zero in a specific model, then the CP asymmetries do not depend on the Dirac phase δ in the PMNS matrix:

$$\epsilon_1 \approx -\frac{3\,\tilde{\kappa}^2}{2\,\pi}\left[I_1\,f\left(\frac{m_1}{m_2}\right) + I_2\,f\left(\frac{m_1}{m_3}\right)\right]$$

$\tilde{\kappa} \equiv |\mathrm{Re}(z_1)|\,\kappa$

$$\epsilon_2 \approx \frac{3\,\tilde{\kappa}^2}{2\,\pi}\left[I_1\,f\left(\frac{m_2}{m_1}\right) - I_3\,f\left(\frac{m_2}{m_3}\right)\right]$$

the sign of the CP asymmetries is determined by the Majorana phase(s)

$$\epsilon_3 \approx \frac{3\,\tilde{\kappa}^2}{2\,\pi}\left[I_2\,f\left(\frac{m_3}{m_1}\right) + I_3\,f\left(\frac{m_3}{m_2}\right)\right]$$

no dependence on θ_{23} and δ

CP invariants:

$$I_1 = \mathrm{Im}[U^2_{PMNS,12}(U^*_{PMNS,11})^2] = s^2_{12}c^2_{12}c^4_{13}\sin\alpha$$
$$I_2 = \mathrm{Im}[U^2_{PMNS,13}(U^*_{PMNS,11})^2] = s^2_{13}c^2_{12}c^2_{13}\sin\beta$$
$$I_3 = \mathrm{Im}[U^2_{PMNS,13}(U^*_{PMNS,12})^2] = c^2_{13}s^2_{13}s^2_{12}\sin(\beta-\alpha)$$

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no dependence on θ_{23} and δ

CP invariants: $I_1 \approx (0.19 \div 0.22)\,\sin\alpha$ $\quad I_2 \approx (1.2 \div 1.8)\,\times 10^{-2}\,\sin\beta$

$I_3 \approx (4.9 \div 8.4)\,\times 10^{-3}\,\sin(\beta - \alpha)$

$$\boxed{\kappa,\ \tilde{\kappa} \gtrsim 10^{-3} \quad \text{for} \quad \epsilon_i \gtrsim 10^{-6}}$$

Lepton mixing from $\Delta(3n^2)$ and $\Delta(6n^2)$ and CP

Good fit of lepton mixing angles is realised in scenarios with $G_f = \Delta(3n^2)$ or $\Delta(6n^2)$ and **CP**

The generator of $G_e = Z_3$ is $Q = a = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix}$ $\omega = e^{\frac{2\pi i}{3}}$

All the viable mixing patterns are reduced to one of the following cases:

Hagedorn, Meroni, EM, 2014
also Ding, King, Neder, 2014

$\Delta(3\,n^2)\,,\ \Delta(6\,n^2)$	case 1)	$Z = c^{n/2}$	$X = a\,b\,c^s\,d^{2s}\,P_{23}$
$\Delta(3\,n^2)\,,\ \Delta(6\,n^2)$	case 2)	$Z = c^{n/2}$	$X = c^s\,d^t\,P_{23}$
$\Delta(6\,n^2)$	case 3 a) and case 3 b.1)	$Z = b\,c^m\,d^m$	$X = b\,c^s\,d^{n-s}\,P_{23}$

$0 \leq s, t, m \leq n-1$; a, c and d (and b) generators of $\Delta(3\,n^2)$ (and $\Delta(6\,n^2)$)

$P_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$ $\boldsymbol{X = P_{23}}$: μ-τ reflection symmetry ($|\sin(\delta)|=1$, $\theta_{23} = \pi/4$)

Lepton mixing and CP invariants in case 3b.1)

Lepton mixing angles:

$$\sin^2\theta_{13} = \frac{1}{3}\left(1 + \cos 2\,\phi_m \sin^2\theta + \sqrt{2}\cos\phi_m \cos 3\,\phi_s \sin 2\theta\right)$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1 + \frac{2\sqrt{3}\sin\phi_m \sin\theta\,[\sqrt{2}\cos 3\,\phi_s \cos\theta - \cos\phi_m \sin\theta]}{2 - \cos 2\,\phi_m \sin^2\theta - \sqrt{2}\cos\phi_m \cos 3\,\phi_s \sin 2\theta}\right)$$

$$\sin^2\theta_{12} = 1 - \frac{2\sin^2\phi_m}{2 - \cos 2\,\phi_m \sin^2\theta - \sqrt{2}\cos\phi_m \cos 3\,\phi_s \sin 2\theta}$$

CP invariants:

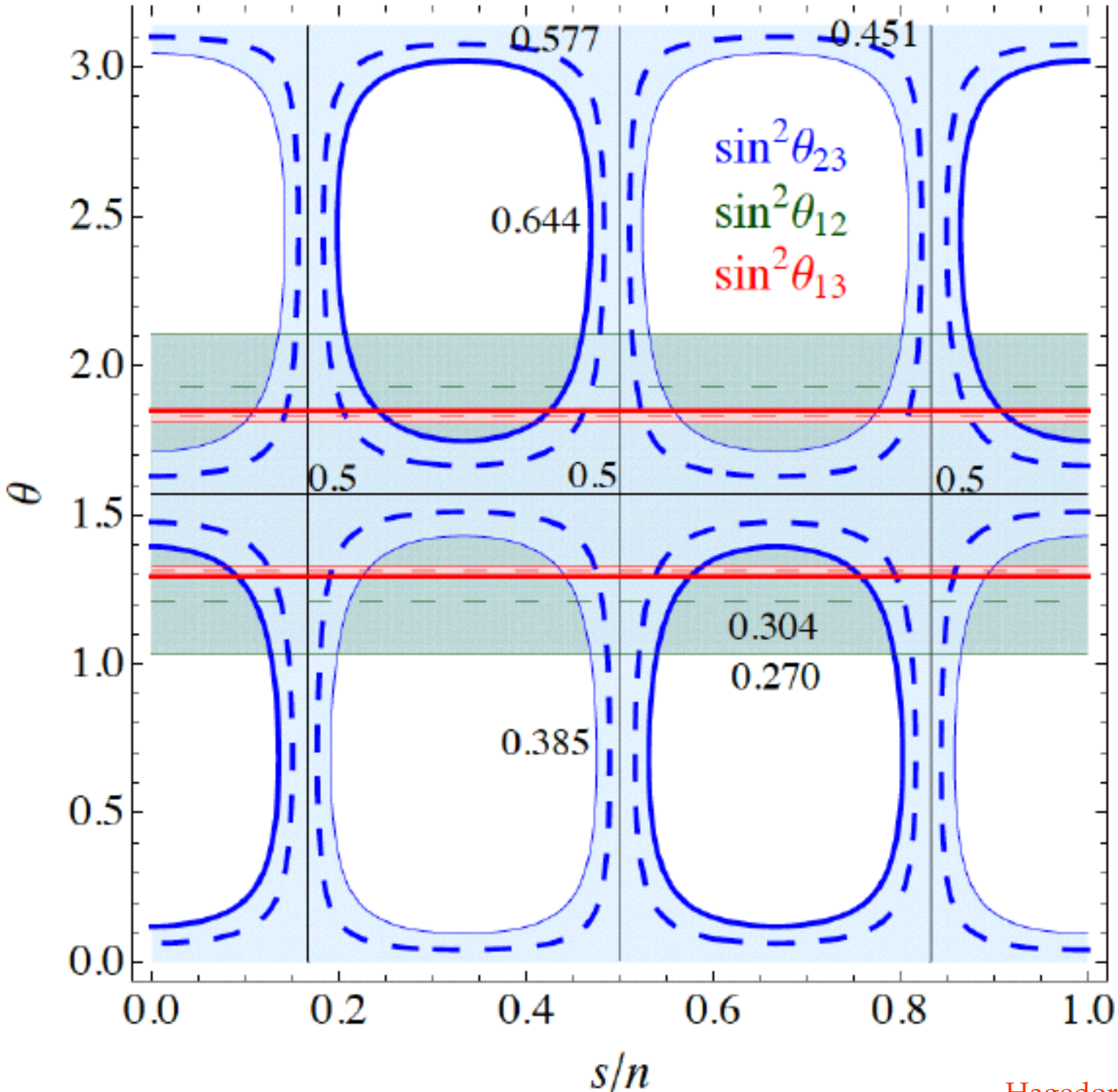
$$J_{CP} = -\frac{1}{6\sqrt{6}}\,\sin 3\,\phi_m \sin 3\,\phi_s \sin 2\theta$$

$$I_1 = \frac{4}{9}(-1)^{k_2+1}\,\sin^2\phi_m \sin 3\,\phi_s \sin\theta\,\left(\cos 3\,\phi_s \sin\theta - \sqrt{2}\cos\phi_m \cos\theta\right)$$

$$I_2 = \frac{4}{9}(-1)^{k_1+k_2+1}\,\sin^2\phi_m \sin 3\,\phi_s\,\cos\theta\,\left(\cos 3\,\phi_s \cos\theta + \sqrt{2}\cos\phi_m \sin\theta\right)$$

$$\phi_m \equiv \frac{\pi\,m}{n} \text{ and } \phi_s \equiv \frac{\pi\,s}{n}$$

Lepton mixing in case 3b.1) for $m=n/2$



Hagedorn, Meroni, EM, 2014

Lepton mixing in case 3b.1) with $m=n/2$

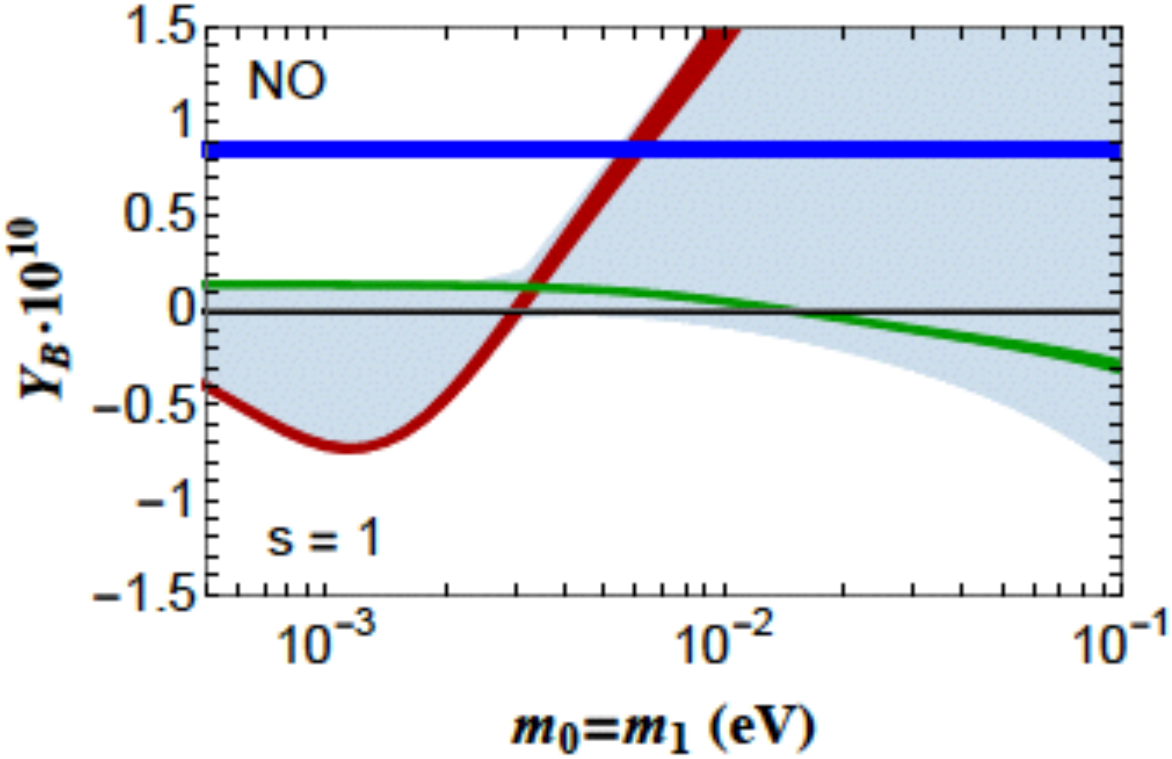
$$\sin\alpha = (-1)^{k_2+1} \sin 6\,\phi_s \;\;,\;\; \sin\beta = (-1)^{k_1+k_2+1} \sin 6\,\phi_s \;\;,\;\; |\sin\delta| \gtrsim 0.71$$

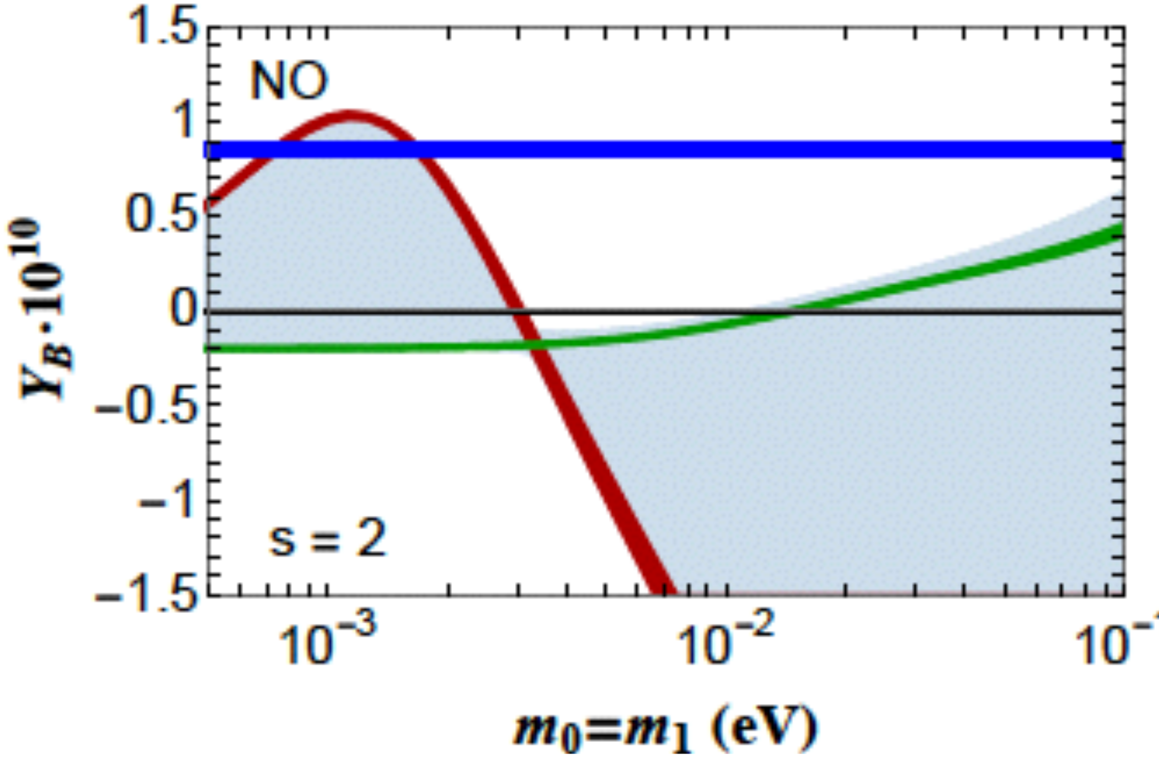
Explicit example: ***n*=8, *m*=4** and **k_1=k_2=0**

n	8		
m	4		
$\sin^2\theta_{12}$	$0.316 \div 0.321$		
$\sin^2\theta_{13}$	$0.0186 \div 0.0250$		
s	1	2	4
θ	$1.29 \div 1.33$	$1.81 \div 1.82$	$1.29 \div 1.33$
$\sin^2\theta_{23}$	$0.416 \div 0.427$	$0.635 \div 0.643$	$1/2$
$\sin\alpha = \sin\beta$	$-1/\sqrt{2}$	1	0
$\sin\delta$	$0.934 \div 0.937$	$0.734 \div 0.738$	-1

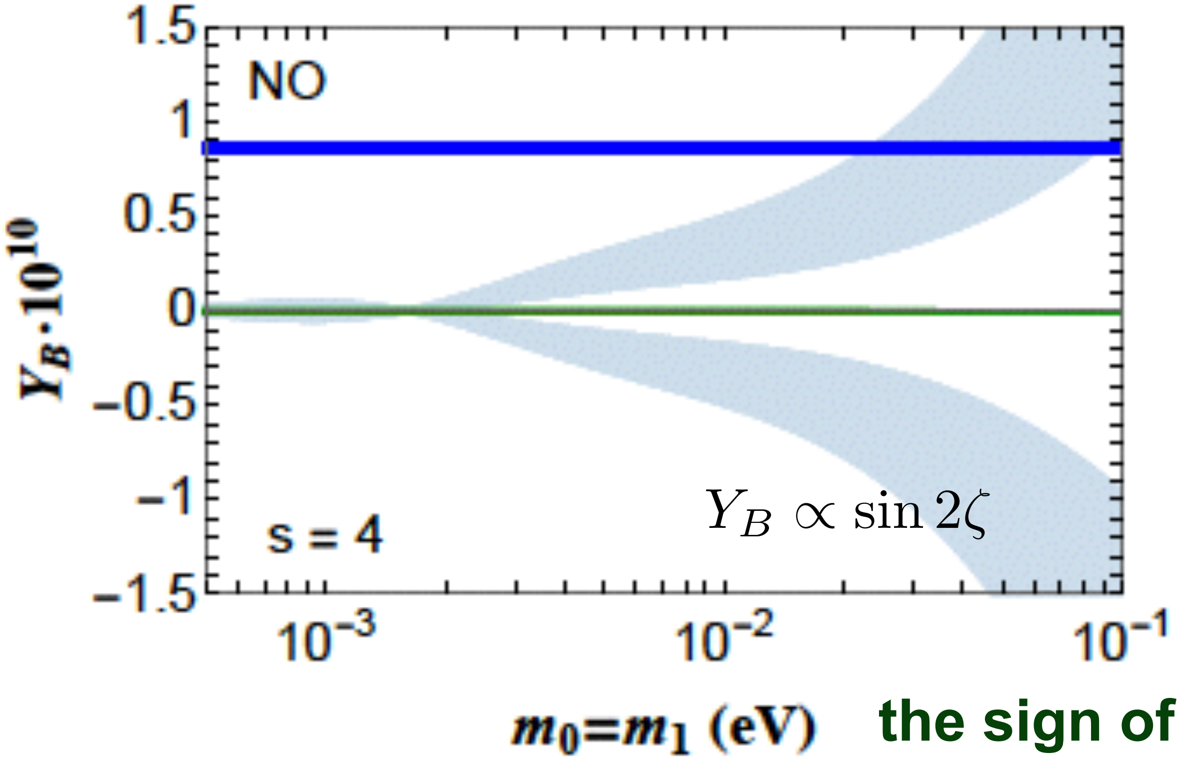
Baryon asymmetry in case 3b.1) with $m=n/2$

the sign of Y_B can be fixed by the knowledge of the Majorana phases





$$\tilde{\kappa} = 4 \times 10^{-3}$$



$$\begin{array}{lcll} \mathrm{Re}(z_2) & = & 0 & \text{red areas} \\ \mathrm{Re}(z_1) & = & 0 & \text{green areas} \\ |\mathrm{Re}(z_{1,2})| \in [1/2, 2] & & & \text{blue-shaded areas} \end{array}$$

$$\mathrm{Re}(z_1) = z \cos\zeta \quad \text{and} \quad \mathrm{Re}(z_2) = z \sin\zeta$$

Hagedorn, EM, 2016

the sign of Y_B is not determined if CPV comes only from δ

Most general neutrino Yukawa matrix

$$\mathcal{L}_l = -Y_l\, \bar{l}\, H\, \alpha_R - Y_D\, \bar{l}\, H^c N - \frac{1}{2}\overline{N^c} M_R N + \text{h.c.}$$

Y_D and M_R invariant under G_ν :

$$Z^\dagger Y_D Z = Y_D \quad \text{and} \quad X^\star Y_D X = Y_D^\star$$

$$Y_D = \Omega\, R_{ij}(\theta_L) \begin{pmatrix} y_1 & 0 & 0 \\ 0 & y_2 & 0 \\ 0 & 0 & y_3 \end{pmatrix} R_{ij}(-\theta_R)\, \Omega^\dagger$$

- 5 real parameters ($y_{1,2,3}$, $\theta_{L/R}$) not constrained by G_ν
- U_{PMNS} depends on a new continuous parameter $\vartheta(\theta,\theta_L,\theta_R)$
- flavoured CP asymmetries:

$$\epsilon_k^\alpha \propto y_i y_j (y_i^2 - y_j^2) \sin 2(\theta - \theta_R), \quad \epsilon_k^\alpha = 0 \quad \text{for} \quad k \neq i, j$$

- unflavoured CP asymmetries $\epsilon_k = 0$, unless corrections δY_D are included

Some realizations in scenarios with residual flavour and CP symm. and hierarchical RH neutrinos discussed, e.g., in Mohapatra, Nishi, 2015; Chen, Ding, King, 2016

Summary

$$G_f = \Delta(3n^2) \text{ or } \Delta(6n^2) \text{ and CP}$$

$$G_e = Z_3 \qquad\qquad G_\nu = Z_2 \times \text{CP}$$

$$Q^\dagger m_l^\dagger m_l Q = m_l^\dagger m_l \qquad\qquad Z^T m_\nu Z = m_\nu \text{ and } X m_\nu X = m_\nu^*$$

★ The lepton mixing angles and CP phases depend on the group theoretical indices and one free parameter θ

✤ In the "unflavoured" regime CP asymmetries are non-zero only if the residual symmetry G_ν is broken at higher orders ($\epsilon_k \propto \kappa^2 \gtrsim 10^{-6}$)

✳ non-zero CP asymmetries are possible if the CP phases of the PMNS matrix are non-trivial

✦ The correct sign and value of the baryon asymmetry can be easily explained in "unflavoured" leptogenesis (sign of Y_B related to the sign of the Majorana phase α)

❖ The sign of Y_B is unconstrained if the dominant source of CP violation in leptogenesis is given by the Dirac phase δ or flavour effects are dynamical

BACKUP SLIDES

Group theory of $\Delta(3n^2)$ and $\Delta(6n^2)$

Generators of $\Delta(3n^2) \sim (Z_n \times Z'_n) \rtimes Z_3$

$$a = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \omega & 0 \\ 0 & 0 & \omega^2 \end{pmatrix} \qquad \text{with } \omega = e^{\frac{2\pi i}{3}} \text{ and } \phi_n = \frac{2\pi}{n}$$

$$c = \frac{1}{3}\begin{pmatrix} 1+2\cos\phi_n & 1-\cos\phi_n-\sqrt{3}\sin\phi_n & 1-\cos\phi_n+\sqrt{3}\sin\phi_n \\ 1-\cos\phi_n+\sqrt{3}\sin\phi_n & 1+2\cos\phi_n & 1-\cos\phi_n-\sqrt{3}\sin\phi_n \\ 1-\cos\phi_n-\sqrt{3}\sin\phi_n & 1-\cos\phi_n+\sqrt{3}\sin\phi_n & 1+2\cos\phi_n \end{pmatrix}$$

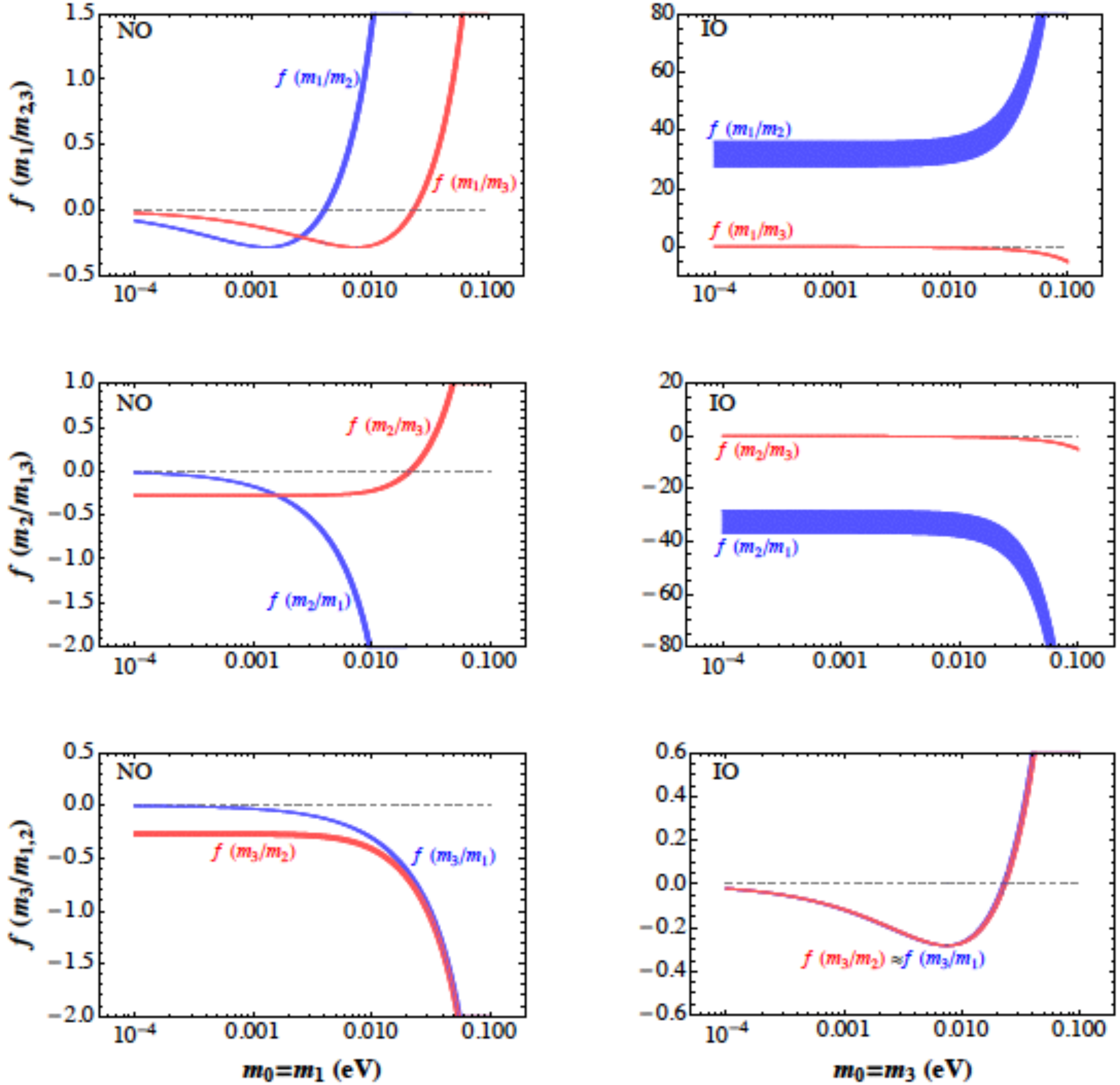
$$a^3 = e \;, \quad c^n = e \;, \quad d^n = e \;,$$
$$c\,d = d\,c \;, \quad a\,c\,a^{-1} = c^{-1}d^{-1} \;, \quad a\,d\,a^{-1} = c$$

Generators of $\Delta(6n^2) \sim (Z_n \times Z'_n) \rtimes S_3$

$$b = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & \omega^2 \\ 0 & \omega & 0 \end{pmatrix}$$

$$b^2 = e \;, \quad (a\,b)^2 = e \;, \quad b\,c\,b^{-1} = d^{-1} \;, \quad b\,d\,b^{-1} = c^{-1}$$

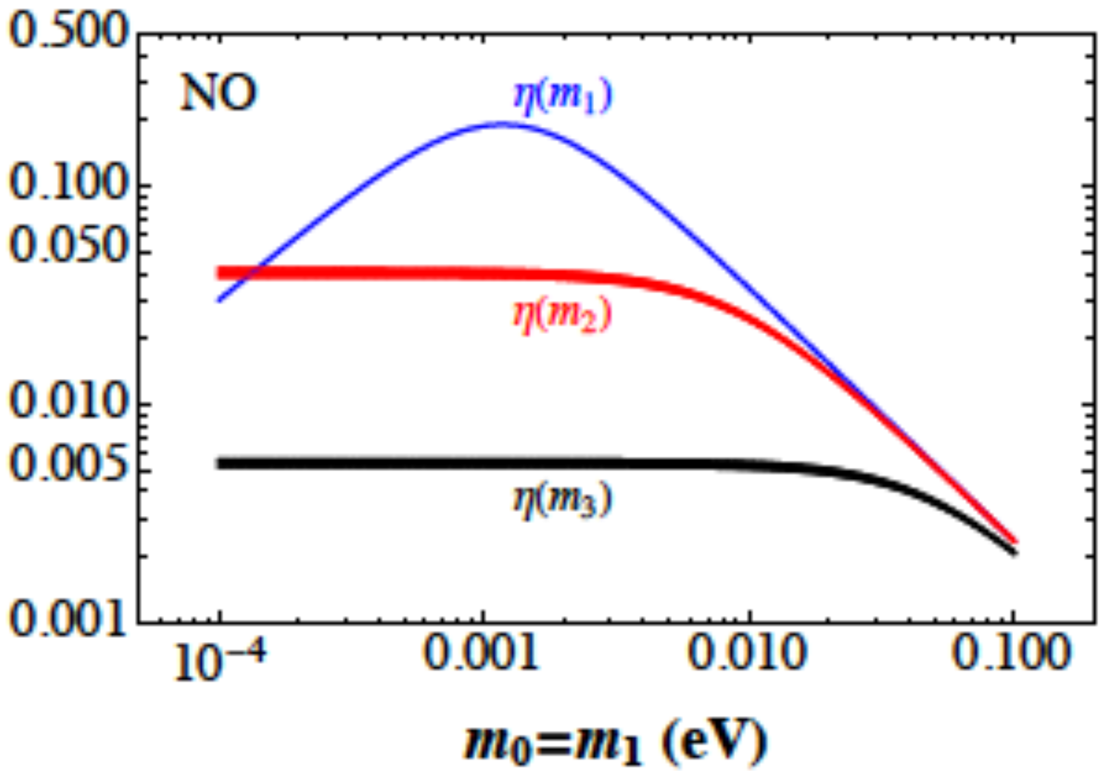
Loop functions $f(M_i/M_j) \approx f(m_j/m_i)$

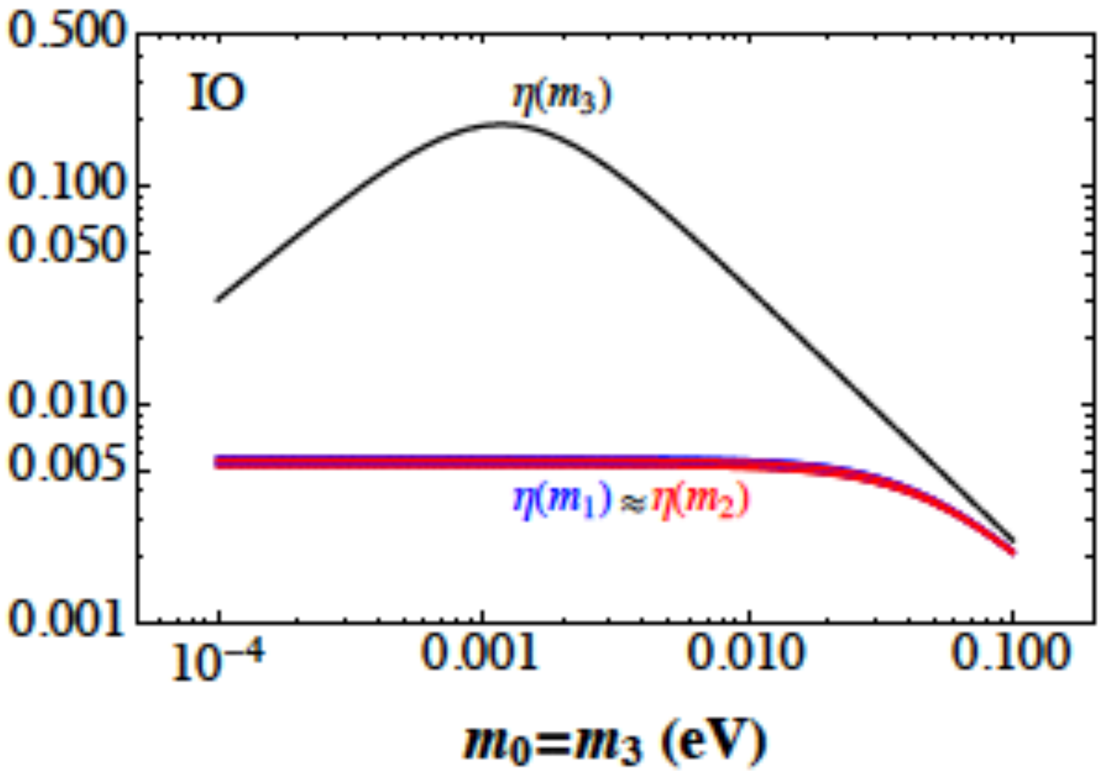


$$f(x) = x\left[\frac{1}{1-x^2} + 1 - (1+x^2)\log\left(1+\frac{1}{x^2}\right)\right]$$

Covi, Roulet, Vissani, 1996

Efficiency factors





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

with $\tilde{m}_i \equiv v^2 \frac{(\hat{Y}_D^\dagger \hat{Y}_D)_{ii}}{M_i} \approx m_i$

NO: maximum efficiency in the production of Y_{B1}. Strongest washout effects are expected for $\boldsymbol{Y_{B3}}$.

IO: the strong washout of $\boldsymbol{Y_{B1}}$ and $\boldsymbol{Y_{B2}}$ is compensated by the enhancement of the corresponding CP asymmetries.

Lepton mixing matrix in case 2)

Lepton mixing angles:

$$\sin^2\theta_{13} = \frac{1}{3}\left(1 - \cos\phi_u \cos 2\theta\right)$$

$$\sin^2\theta_{12} = \frac{1}{2 + \cos\phi_u \cos 2\theta}$$

$$\sin^2\theta_{23} = \frac{1}{2}\left(1 + \frac{\sqrt{3}\sin\phi_u \cos 2\theta}{2 + \cos\phi_u \cos 2\theta}\right)$$

CP invariants:

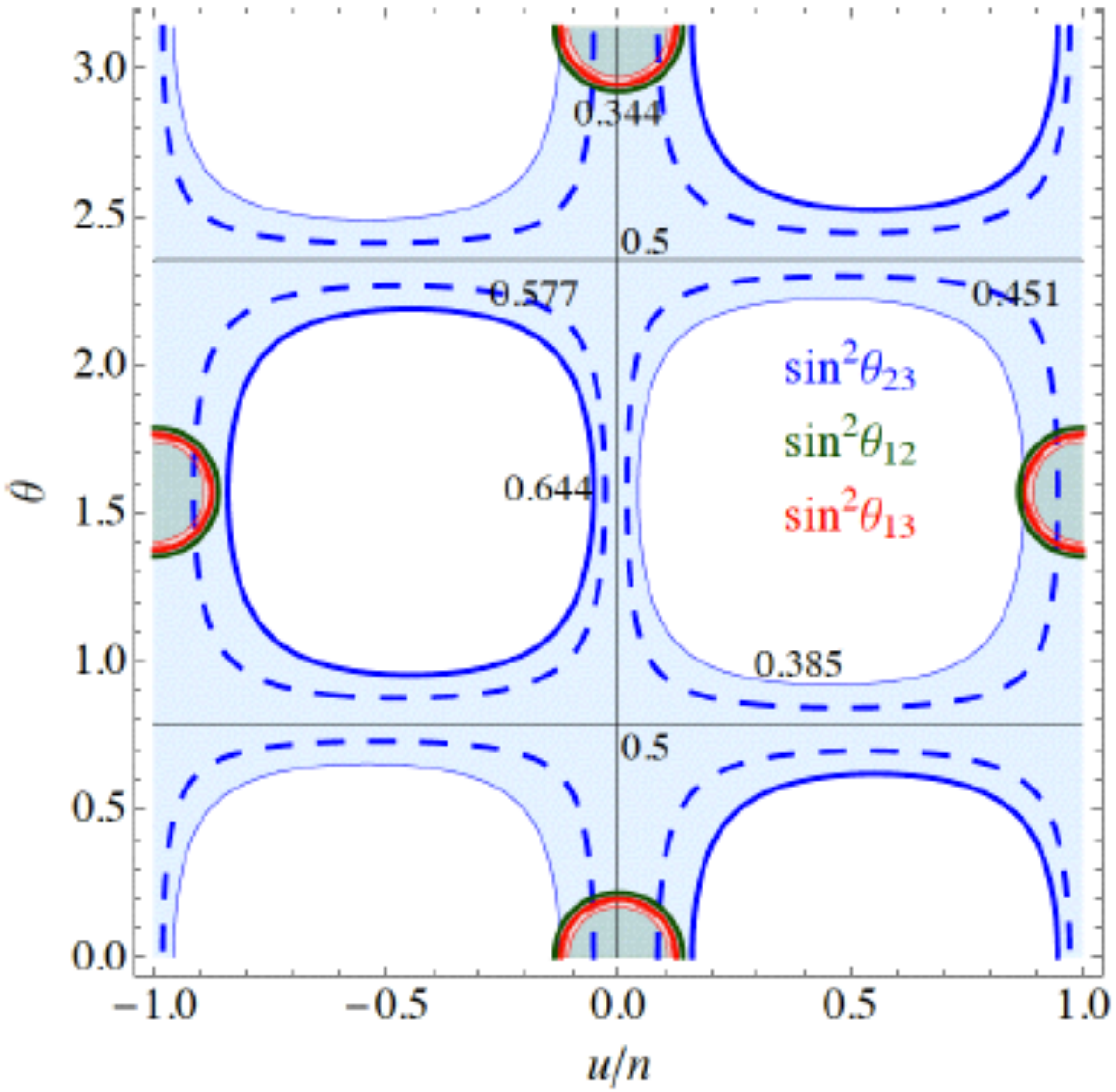
$$J_{CP} = -\frac{\sin 2\theta}{6\sqrt{3}}$$

$$I_1 = \frac{1}{9}(-1)^{k_1+1}\left(\left[\cos\phi_u + \cos 2\theta\right]\sin\phi_v - \sin\phi_u \cos\phi_v \sin 2\theta\right)$$

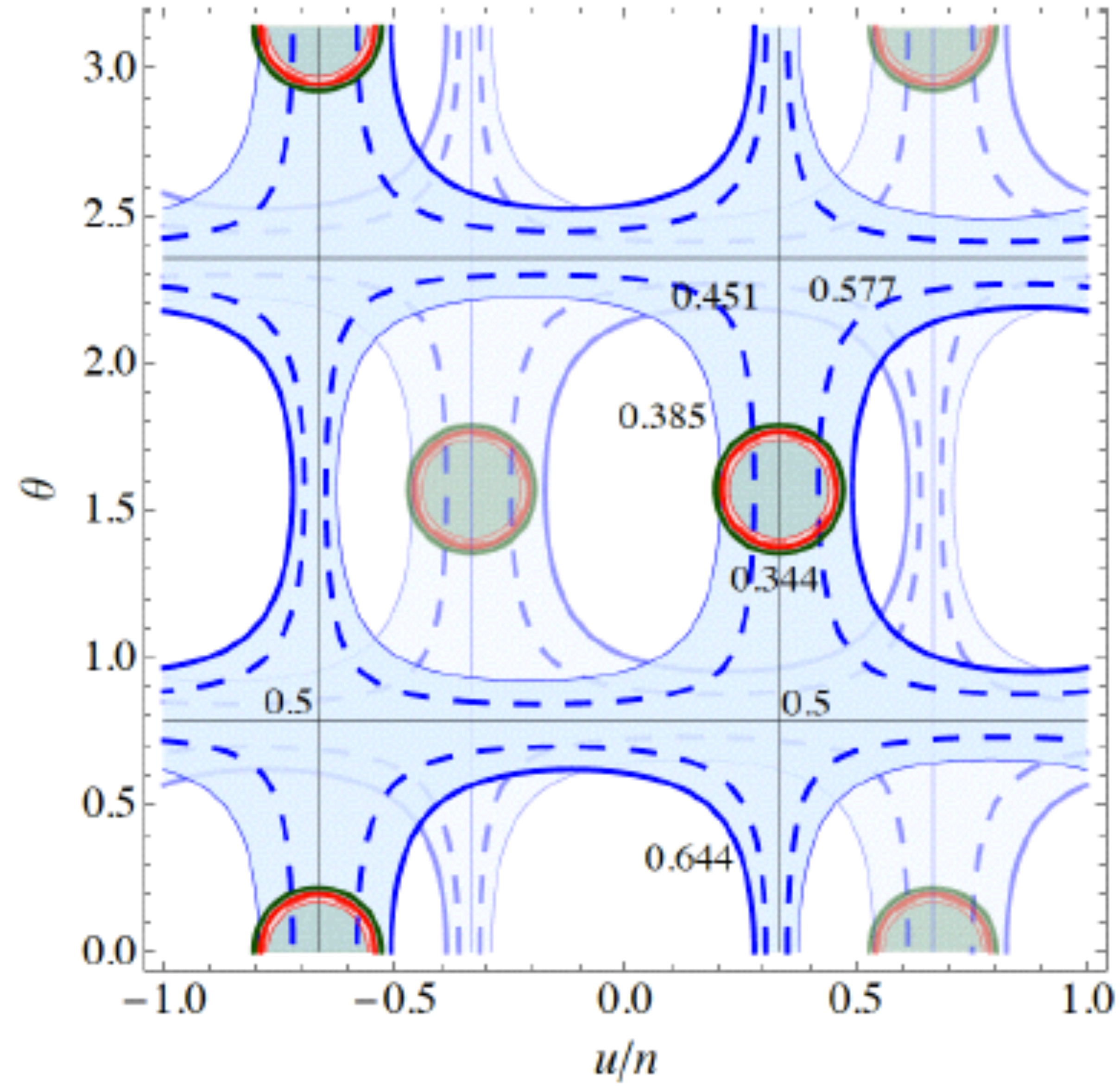
$$I_2 = \frac{1}{9}(-1)^{k_2}\sin 2\phi_u \sin 2\theta$$

$$I_3 = \frac{1}{9}(-1)^{k_1+k_2}\left(\left[\cos\phi_u - \cos 2\theta\right]\sin\phi_v + \sin\phi_u \cos\phi_v \sin 2\theta\right)$$

Lepton mixing matrix in case 2)



$$u \rightarrow u - \frac{n}{3}\ ,\ \theta \rightarrow \frac{\pi}{2} - \theta \ \text{ and } \ k_1 \rightarrow k_1 + 1$$



Hagedorn, Meroni, EM, 2014

Lepton mixing in case 2)

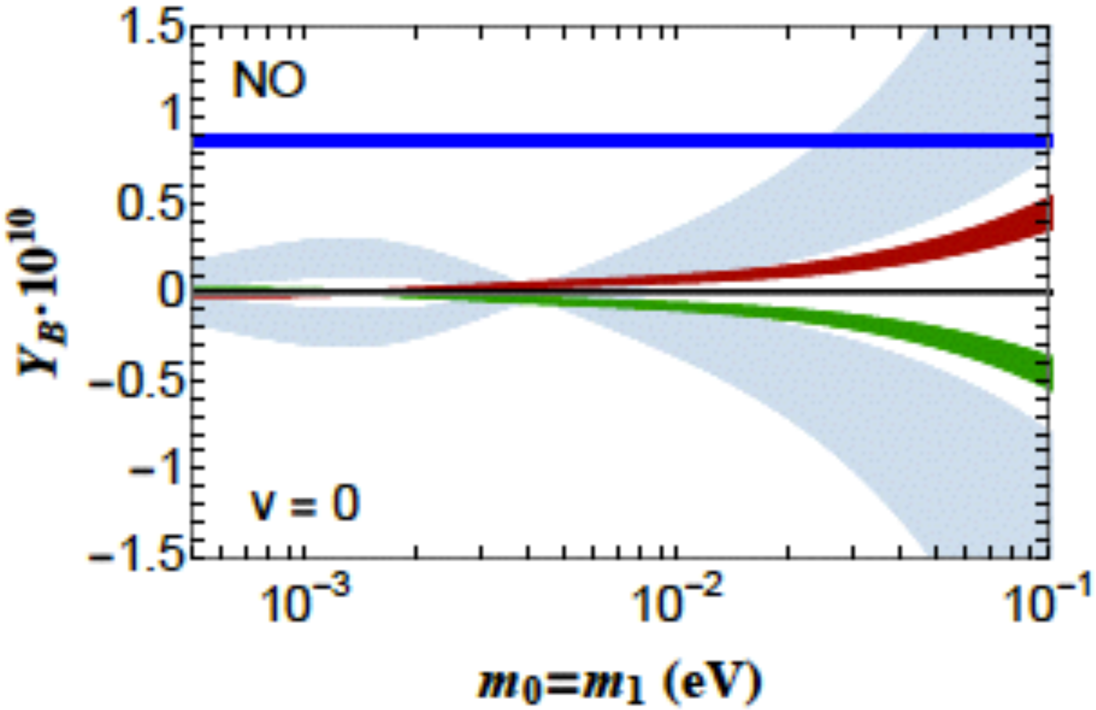
$$\sin\alpha = (-1)^{k_2+1}\,\sin 6\,\phi_s \quad , \quad \sin\beta = (-1)^{k_1+k_2+1}\,\sin 6\,\phi_s \quad , \quad |\sin\delta| \gtrsim 0.71$$

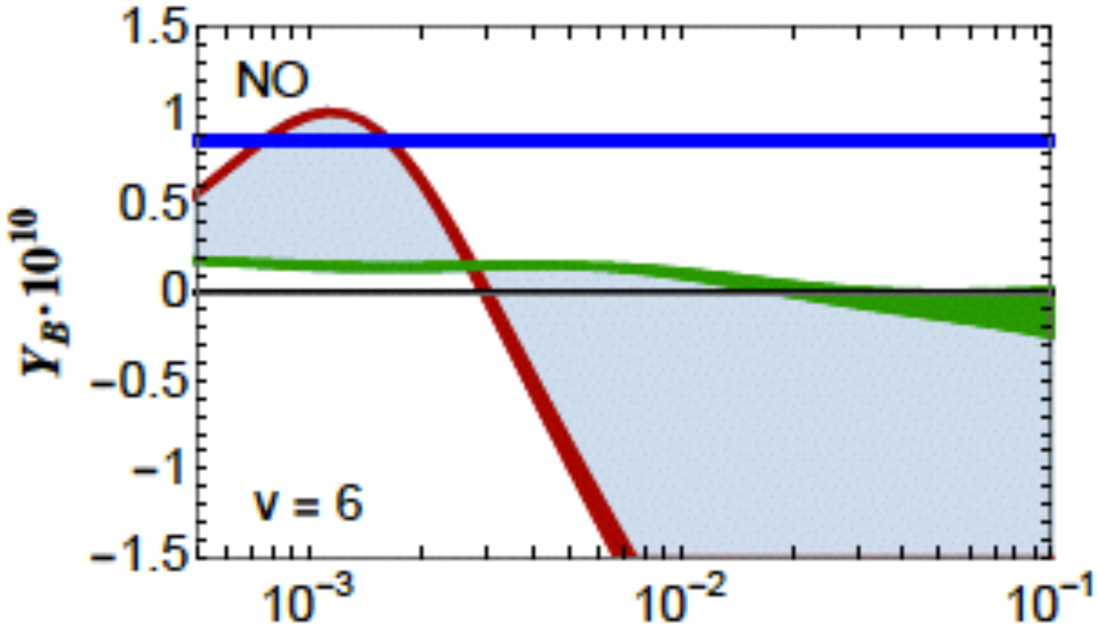
Explicit example: ***n*=10, *u*=4** and ***k*₁=*k*₂=0**

<table>
<tr><td>n</td><td colspan="3">10</td></tr>
<tr><td>u</td><td colspan="3">4</td></tr>
<tr><td>θ</td><td colspan="3">$1.40 \div 1.44$</td></tr>
<tr><td>$\sin^2\theta_{12}$</td><td colspan="3">$0.340 \div 0.342$</td></tr>
<tr><td>$\sin^2\theta_{13}$</td><td colspan="3">$0.0187 \div 0.0250$</td></tr>
<tr><td>$\sin^2\theta_{23}$</td><td colspan="3">$0.558 \div 0.559$</td></tr>
<tr><td>$\sin\beta$</td><td colspan="3">$-0.94 \div -0.83$</td></tr>
<tr><td>$\sin\delta$</td><td colspan="3">$0.80 \div 0.86$</td></tr>
<tr><td>v</td><td>0</td><td>6 , 24</td><td>12 , 18</td></tr>
<tr><td>$\sin\alpha$</td><td>$0.028 \div 0.035$</td><td>$0.94 \div 0.96$</td><td>$-0.62 \div -0.56$</td></tr>
</table>

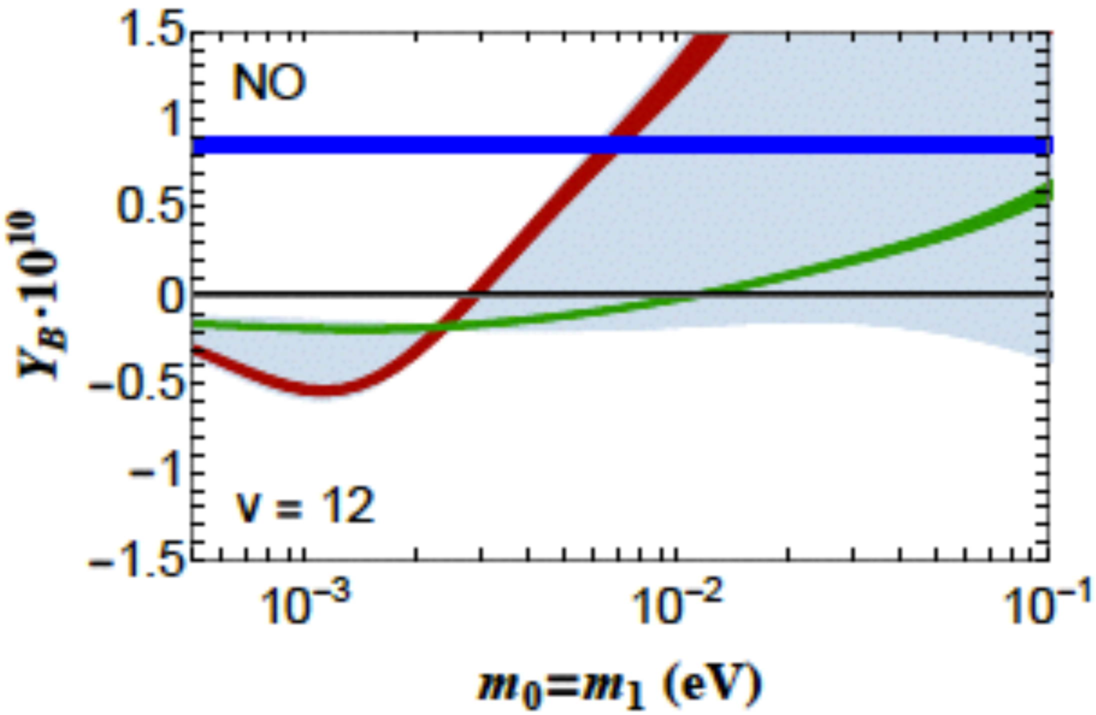
Baryon asymmetry in case 2) with n=10, u=4

the sign of Y_B is fixed the Majorana phase α





$$\tilde{\kappa} = 4 \times 10^{-3}$$



$$\begin{array}{lll} \mathrm{Re}(z_2) & = 0 & \text{red areas} \\ \mathrm{Re}(z_1) & = 0 & \text{green areas} \\ |\mathrm{Re}(z_{1,2})| & \in [1/2, 2] & \text{blue-shaded areas} \end{array}$$

$$\mathrm{Re}(z_1) = z \cos\zeta \quad \text{and} \quad \mathrm{Re}(z_2) = z \sin\zeta$$

Hagedorn, EM, 2016