Connecting α, β, δ and Y_B with flavor and CP symmetries

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Outline

- underlying scenario for leptonic CP phases α, β, δ
- framework for leptogenesis
  - some generalities
  - correlations between α, β, δ and Y_B via leptogenesis
- conclusions

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- generations of LH leptons are assigned to $\mathbf{3}$
- impose flavor and CP symmetry in fundamental theory

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- leptonic mixing arises from mismatch of residual symmetries G_e and G_ν
- features: ***(Feruglio/H/Ziegler ('12,'13))***
  - prediction of Majorana phases becomes possible, if neutrino sector is invariant under CP
  - at the same time lepton mixing angles are less constrained and non-trivial Dirac phase possible, if neutrinos are invariant under residual flavor Z_2 only

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  $\phi_i \to X_{ij}\, \phi_j^\star$ and $XX^\dagger = XX^\star = 1$ ***(Grimus/Rebelo ('95))***
- leptonic mixing arises from mismatch of residual symmetries G_e and G_ν
- in a theory with G_f and CP certain conditions have to be fulfilled

(Feruglio/H/Ziegler ('12,'13), Holthausen et al. ('12), Chen et al. ('14))

Scenario for CP phases α, β, δ

(Feruglio/H/Ziegler ('12,'13))

G_f and CP

$\swarrow$ $\searrow$

charged leptons	neutrinos
G_e	$G_\nu = Z_2 \times$ CP
U_e	$U_\nu = \Omega_\nu R(\theta) K_\nu$

$\searrow$ $\swarrow$

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

[Masses do not play a role in this approach.]

Scenario for CP phases α, β, δ

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

- 3 unphysical phases are removed by $U_e \rightarrow U_e K_e$
- U_{PMNS} contains one free parameter θ
- permutations of rows and columns of U_{PMNS} possible

$$\Downarrow$$

Predictions

Mixing angles and all CP phases are predicted
in terms of one free parameter θ only,
up to permutations of rows/columns

Scenario for CP phases α, β, δ

(H/Meroni/Molinaro ('14); see also Ding et al. ('14))

$\Delta(3\,n^2), \Delta(6\,n^2)$ and CP

$\swarrow$ $\searrow$

charged leptons	neutrinos
$G_e = Z_3$	$G_\nu = Z_2 \times$ CP
U_e	$U_\nu = \Omega_\nu R(\theta) K_\nu$

$\searrow$ $\swarrow$

$$U_{PMNS} = U_e^\dagger \Omega_\nu R(\theta) K_\nu$$

four different types of mixing patterns with different characteristics

Scenario for CP phases α, β, δ

Case 1)

(H/Meroni/Molinaro ('14))

- one column is trimaximal, i.e. $\sin^2\theta_{12} \gtrsim \frac{1}{3}$
- Dirac phase is trivial, i.e. $\delta = 0, \pi$
- one of the Majorana phases β is also trivial, i.e. $\sin\beta = 0$
- value of Majorana phase α depends on choice of CP transformation $X = X(s)$

$$|\sin\alpha| = |\sin 6\,\phi_s| \quad \text{with} \quad \phi_s = \frac{\pi s}{n} \quad \text{and} \quad s = 0, ..., n-1$$

Scenario for CP phases α, β, δ

Case 1) and $n = 4$: all choices of s are viable

- fixing $\theta \approx 0.18$ or $\theta \approx 2.96$, we find

$$\sin^2\theta_{13} \approx 0.0219 \quad , \quad \sin^2\theta_{12} \approx 0.341 \quad \text{and} \quad \sin^2\theta_{23} \approx \begin{cases} 0.605 \\ 0.395 \end{cases}$$

so, lepton mixing angles are compatible with global fit data

- non-trivial Majorana phase α is predicted

s	0	1	2	3
$\sin\alpha$	0	1	0	-1

Scenario for CP phases α, β, δ

Case 3 b.1) *(H/Meroni/Molinaro ('14))*

- first column is fixed via choice of residual Z_2 symmetry $Z_2(m)$ in neutrino sector
- in particular, solar mixing angle constrains m to be $m \approx \frac{n}{2}$
- free parameter θ is fixed by reactor mixing angle
- for $m = \frac{n}{2}$ we find lower limit on CP violation via Dirac phase

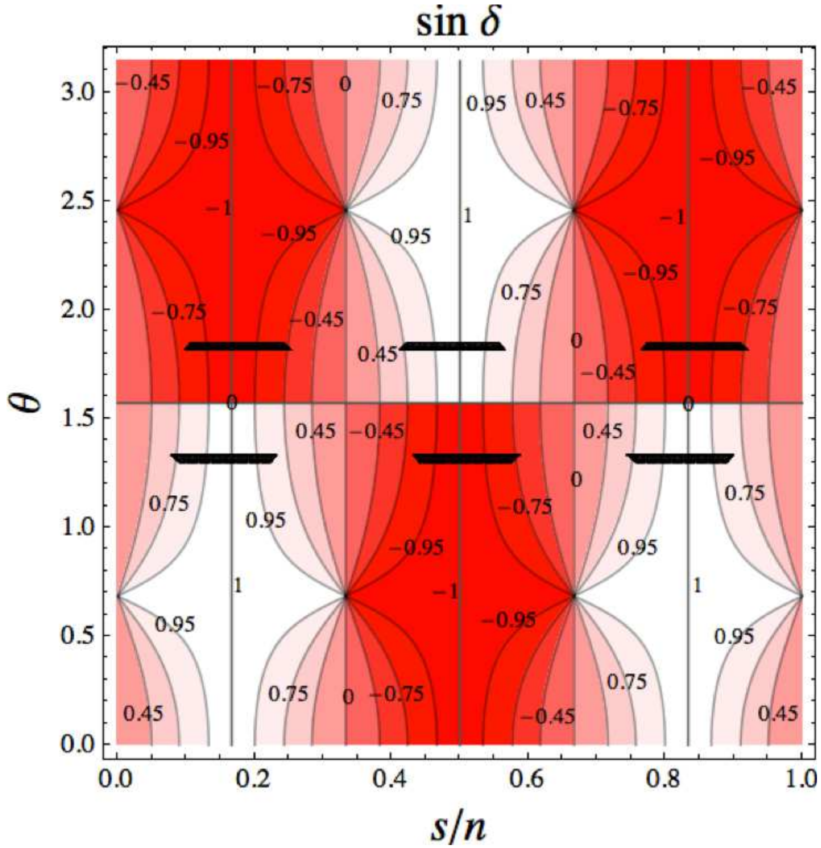
$$|\sin\delta| \gtrsim 0.71$$

and both Majorana phases α, β depend on $X = X(s)$ only

$$|\sin\alpha| = |\sin\beta| = |\sin 6\,\phi_s| \quad \text{with} \quad \phi_s = \frac{\pi s}{n} \quad \text{and} \quad s = 0, ..., n-1$$

Scenario for CP phases α, β, δ

Results for Dirac phase δ for $m/n = 1/2$ and $n = 20$



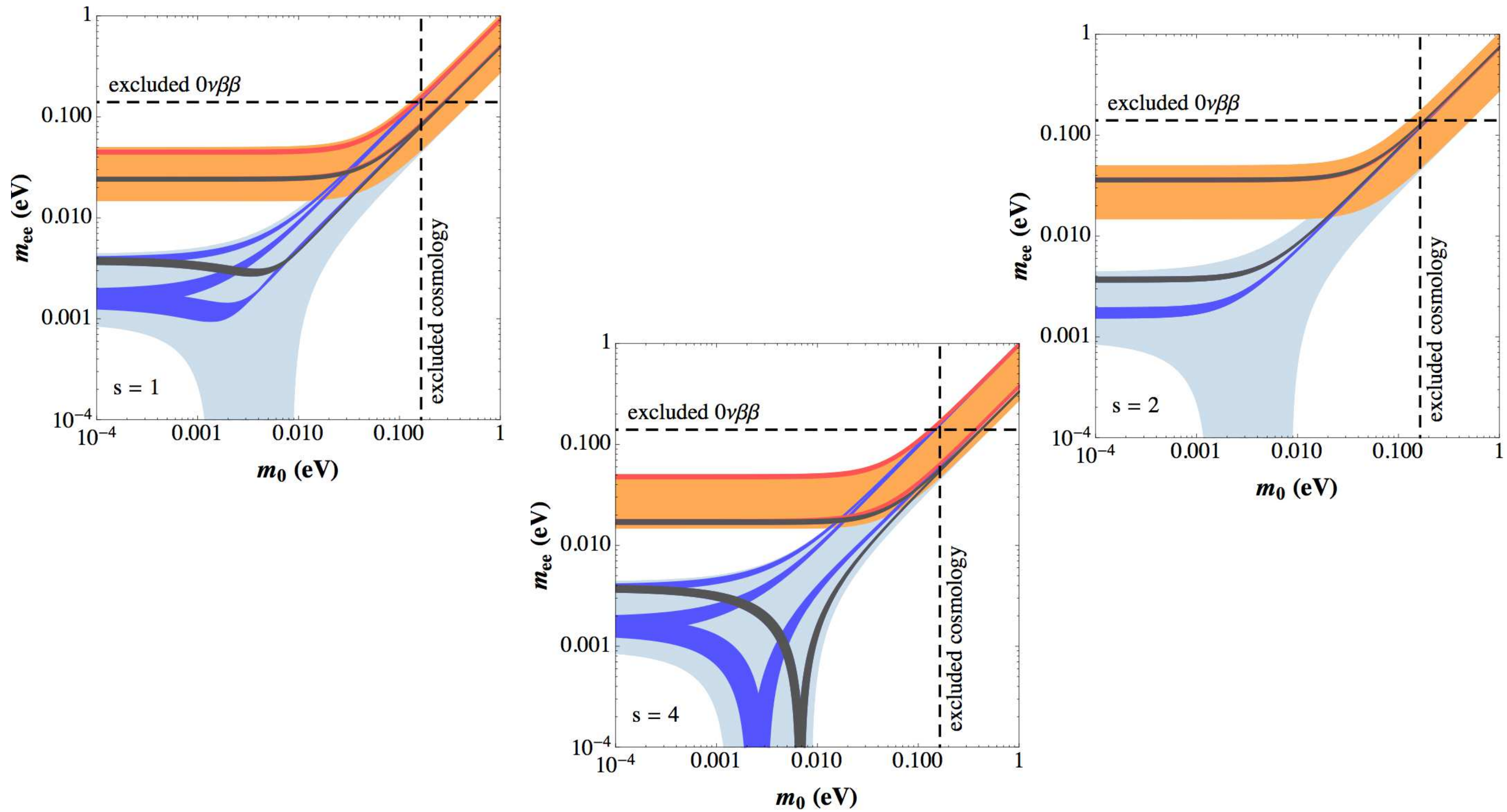
Scenario for CP phases α, β, δ

Case 3 b.1) and $n = 8$, $m = 4$:
some viable choices of s

s	$\sin^2\theta_{13}$	$\sin^2\theta_{12}$	$\sin^2\theta_{23}$	$\sin\delta$	$\sin\alpha = \sin\beta$
$s = 1$	0.0220	0.318	0.579	0.936	$-1/\sqrt{2}$
	0.0220	0.318	0.421	-0.936	$-1/\sqrt{2}$
$s = 2$	0.0216	0.319	0.645	-0.739	1
$s = 4$	0.0220	0.318	0.5	∓ 1	0

Scenario for CP phases α, β, δ

Case 3 b.1) and $n = 8$, $m = 4$ ***(H/Molinaro ('16))***



See also works by ***Ding, King, Neder***.

Framework for leptogenesis

- type-1 seesaw mechanism
- three RH neutrinos N_i forming $\mathbf{3}$
- explain $Y_B = (8.65 \pm 0.09) \times 10^{-11}$ ***(Planck ('15))***
- leptogenesis mechanism: unflavored leptogenesis

(Fukugita/Yanagida ('86))

Framework for leptogenesis

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$$10^{12}\ \text{GeV} \lesssim M_i \lesssim 10^{14}\ \text{GeV}$$

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$$10^{12}\,\text{GeV} \lesssim M_i \lesssim 10^{14}\,\text{GeV}$$

- all RH neutrinos N_i can be relevant for baryon asymmetry

$$Y_B = \sum_{i=1}^{3} Y_{Bi}$$

Framework for leptogenesis

- relation of Y_{Bi} to lepton asymmetry

$$Y_{Bi} \approx 1.38 \times 10^{-3}\, \epsilon_i \sum_{j=1}^{3} \eta_{ij}$$

with ϵ_i: CP asymmetry from N_i decays

η_{ij}: efficiency factor with $10^{-3} \lesssim \eta_{ij} \lesssim 1$

- computation of ϵ_i

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

which should be of order $10^{-4} \gtrsim \epsilon_i \gtrsim 10^{-7}$

Framework for leptogenesis

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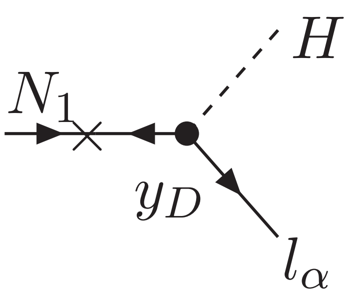
- diagrammatically:
the CP asymmetry arises from interference of tree-level diagram



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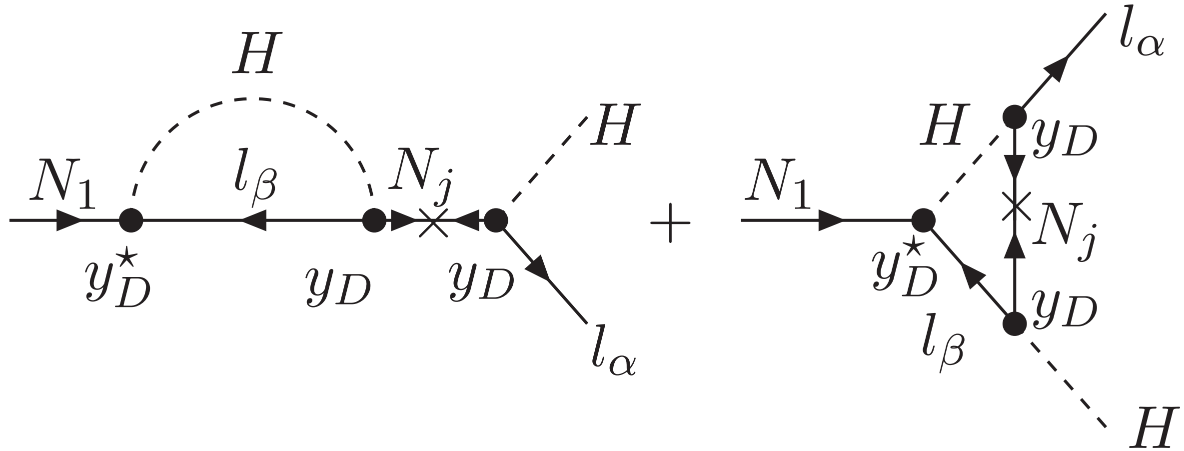
- diagrammatically:
and one-loop diagrams



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- in formula:

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

with $\hat{Y}_D$ Dirac Yukawa coupling of neutrinos in RH neutrino mass basis
and $f(\cdot)$ loop function

Framework for leptogenesis

(H/Molinaro ('16))

- charged lepton mass matrix m_e invariant under $G_e = Z_3$ and thus flavor diagonal in the chosen basis
  (no change with respect to study above)

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Framework for leptogenesis

(H/Molinaro ('16))

- charged lepton mass matrix m_e invariant under $G_e = Z_3$ and thus flavor diagonal in the chosen basis (no change with respect to study above)
- light neutrino mass matrix invariant under $G_\nu = Z_2 \times CP$ in context of type-1 seesaw mechanism
  - Dirac Yukawa coupling of neutrinos invariant under G_f and CP

$$Y_D = y_0 \, 1$$

  - lepton mixing encoded in RH neutrino mass matrix M_R, i.e. M_R is most general Majorana mass matrix invariant under $G_\nu = Z_2 \times CP$

$$U_R^T \, M_R \, U_R = \text{diag} \, (M_1, M_2, M_3) \quad \text{with} \quad U_R = \Omega_\nu \, R_{ij}(\theta) \, K_\nu$$

Framework for leptogenesis

(H/Molinaro ('16))

- charged lepton mass matrix m_e invariant under $G_e = Z_3$ and thus flavor diagonal in the chosen basis
  (no change with respect to study above)
- light neutrino mass matrix invariant under $G_\nu = Z_2 \times CP$ we find
  - seesaw relation of light and heavy neutrino masses

$$m_i \propto \frac{1}{M_i}$$

  - PMNS mixing matrix is given by

$$U_{PMNS} = U_\nu = U_R = \Omega_\nu \, R_{ij}(\theta) \, K_\nu$$

Framework for leptogenesis

- however, CP asymmetries ϵ_i vanish, since

$$\hat{Y}_D^\dagger \hat{Y}_D \propto 1$$

known in flavor symmetry-only context ***(Jenkins/Manohar ('08), Bertuzzo et al. ('09), H/Molinaro/Petcov ('09), Aristizabal Sierra et al. ('09)))***

Framework for leptogenesis

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  since
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  known in flavor symmetry-only context ***(Jenkins/Manohar ('08), Bertuzzo et al. ('09), H/Molinaro/Petcov ('09), Aristizabal Sierra et al. ('09)))***
- in order to achieve non-zero ϵ_i further symmetry breaking is needed,
  in particular
  $$\hat{Y}_D = Y_D \, U_R$$
  should get corrections,
  i.e.
  $$\hat{Y}_D = Y_D \, U_R = \left(Y_D^0 + \delta Y_D\right) \, \left(U_R^0 \, \delta U_R\right)$$

Framework for leptogenesis

- notice δU_R can only be effective, if there is also δY_D
- we focus on $\delta Y_D \neq 0$
- we get then

$$\hat{Y}_D^\dagger \hat{Y}_D \approx U_R^\dagger \left((Y_D^0)^\dagger Y_D^0 + (\delta Y_D)^\dagger Y_D^0 + (Y_D^0)^\dagger \delta Y_D \right) U_R$$

- the first term is irrelevant, since $(Y_D^0)^\dagger Y_D^0 \propto 1$
- the second and third term depend in general not only on CP phases contained in U_R,
  but also on phases encoded in correction δY_D
- four instances in which phases of δY_D become irrelevant ...

Framework for leptogenesis

- four instances in which phases of δY_D become irrelevant ...

  i) $(Y_D^0)^\dagger \delta Y_D$ is real

  ii) $(Y_D^0)^\dagger \delta Y_D$ is imaginary

  iii) $(Y_D^0)^\dagger \delta Y_D$ is complex and symmetric

  iv) $(Y_D^0)^\dagger \delta Y_D$ is complex and antisymmetric

Framework for leptogenesis

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- condition iii) can naturally be realized
  - $Y_D^0 \propto 1$ at leading order
  - δY_D flavor diagonal, since invariant under $G_e = Z_3$
    δY_D has two (in general complex) parameters

Framework for leptogenesis

- comment on size of ϵ_i:
  for $\delta Y_D \propto \kappa$ (κ symmetry breaking parameter) we find

$$\epsilon_i \propto \kappa^2$$

that fits for $\kappa \sim 10^{-(2\div3)}$ the needed order of magnitude for ϵ_i

Framework for leptogenesis

First, assume U_R to be of general form of PMNS mixing matrix

- we use parametrization for δY_D

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

- formulae become simple, if we assume $z_2 = 0$, i.e. we get

$$\begin{aligned}
\epsilon_1 &\approx -\frac{3\,z^2}{2\,\pi}\,\kappa^2\left[I_1\,f\left(\frac{m_1}{m_2}\right) + I_2\,f\left(\frac{m_1}{m_3}\right)\right] \\
\epsilon_2 &\approx \frac{3\,z^2}{2\,\pi}\,\kappa^2\left[I_1\,f\left(\frac{m_1}{m_2}\right) - I_3\,f\left(\frac{m_2}{m_3}\right)\right] \\
\epsilon_3 &\approx \frac{3\,z^2}{2\,\pi}\,\kappa^2\left[I_2\,f\left(\frac{m_3}{m_1}\right) + I_3\,f\left(\frac{m_3}{m_2}\right)\right]
\end{aligned}$$

Framework for leptogenesis

- form of I_i

$$\begin{aligned} I_1 &= \mathrm{Im}[U^2_{PMNS,12}(U^\star_{PMNS,11})^2] = \sin^2\theta_{12}\cos^2\theta_{12}\cos^4\theta_{13}\sin\alpha \\ I_2 &= \mathrm{Im}[U^2_{PMNS,13}(U^\star_{PMNS,11})^2] = \sin^2\theta_{13}\cos^2\theta_{12}\cos^2\theta_{13}\sin\beta \\ I_3 &= \mathrm{Im}[U^2_{PMNS,13}(U^\star_{PMNS,12})^2] = \cos^2\theta_{13}\sin^2\theta_{13}\sin^2\theta_{12}\sin(\beta-\alpha) \end{aligned}$$

- using experimental constraints for lepton mixing angles

$$\begin{aligned} I_1 &\approx (0.18 \div 0.22)\ \sin\alpha \\ I_2 &\approx (1.2 \div 1.8)\ \times 10^{-2}\ \sin\beta \\ I_3 &\approx (4.9 \div 8.4)\ \times 10^{-3}\ \sin(\beta-\alpha) \end{aligned}$$

- so, term with I_1 dominates, if $\sin\alpha$ is not suppressed

Framework for leptogenesis

- we also consider $z_1 = 0$ with

$$\beta = k_\beta\, \pi \quad , \quad \delta = k_\delta\, \pi \quad \text{with} \quad k_{\beta,\delta} = 0, 1$$

- we find

$$\begin{aligned}
\epsilon_1 \quad &\approx \quad -\frac{z^2}{2\,\pi}\, \kappa^2\, \sin\alpha \left[\frac{1}{2}\, \left(1 + \sin^2\theta_{13}\right)\, \sin 2\theta_{12}\, \cos 2\theta_{23} \right. \\
&\qquad \left. + (-1)^{k_\delta}\, \sin\theta_{13}\, \cos 2\theta_{12}\, \sin 2\theta_{23}\right]^2 f\left(\frac{m_1}{m_2}\right) \\
\epsilon_3 \quad &\approx \quad \frac{z^2}{2\,\pi}\, \kappa^2\, (-1)^{k_\beta + 1}\, \sin\alpha\, \cos^2\theta_{13} \left[\cos\theta_{12}\, \sin 2\theta_{23} \right. \\
&\qquad \left. + (-1)^{k_\delta}\, \sin\theta_{13}\, \sin\theta_{12}\, \cos 2\theta_{23}\right]^2 f\left(\frac{m_3}{m_2}\right)
\end{aligned}$$

Framework for leptogenesis

- we also consider $z_1 = 0$ with

$$\beta = k_\beta \, \pi \quad , \quad \delta = k_\delta \, \pi \quad \text{with} \quad k_{\beta,\delta} = 0, 1$$

- as well as

$$\epsilon_2 = -\epsilon_1 \, f\left(\frac{m_2}{m_1}\right)\left(f\left(\frac{m_1}{m_2}\right)\right)^{-1} - \epsilon_3 \, f\left(\frac{m_2}{m_3}\right)\left(f\left(\frac{m_3}{m_2}\right)\right)^{-1}$$

Framework for leptogenesis

- we consider $z_1 = 0$ instead with

$$\alpha = k_\alpha \, \pi \quad , \quad \beta + 2\delta = k_\beta \, \pi \quad \text{with} \quad k_{\alpha,\beta} = 0, 1 \; ,$$

we get e.g.

$$\epsilon_3 \propto \frac{z^2}{\pi} \, \kappa^2 \, (-1)^{k_\beta} \; \sin\delta \; \sin\theta_{13} \; \cos^2\theta_{13} \; \cos 2\theta_{23} \; (...)$$

Framework for leptogenesis

Second, we discuss the results for Case 1)

- remember Case 1) leads to only α non-trivial
- for $\epsilon_{1,3}$ we find

$$\epsilon_1 \approx (-1)^{k_1} \frac{z^2}{3\,\pi} \kappa^2 \cos^2(\theta + \zeta) \; f\left(\frac{m_1}{m_2}\right) \sin 6\,\phi_s$$

and

$$\epsilon_3 \approx (-1)^{k_1+k_2} \frac{z^2}{3\,\pi} \kappa^2 \sin^2(\theta + \zeta) \; f\left(\frac{m_3}{m_2}\right) \sin 6\,\phi_s$$

Framework for leptogenesis

Third, we discuss the results for Case 3 b.1)

- in general, the analytic formulae are lengthy ...

Framework for leptogenesis

Third, we discuss the results for Case 3 b.1)

- in general, the analytic formulae are lengthy ...
- for this reason I only show them for $m = n/2$ and $s = n/2$ (n even)

$$\epsilon_1 \approx \frac{z^2\,\kappa^2}{6\,\sqrt{2}\,\pi}\,(-1)^{k_2}\left[f\left(\frac{m_1}{m_2}\right) + (-1)^{k_1+1} f\left(\frac{m_1}{m_3}\right)\right]\sin 2\zeta\ \sin 2\theta$$

$$\epsilon_2 \approx -\frac{z^2\,\kappa^2}{6\,\sqrt{2}\,\pi}\,(-1)^{k_2}\left[f\left(\frac{m_2}{m_1}\right) + (-1)^{k_1+k_2} f\left(\frac{m_2}{m_3}\right)\right]\sin 2\zeta\ \sin 2\theta$$

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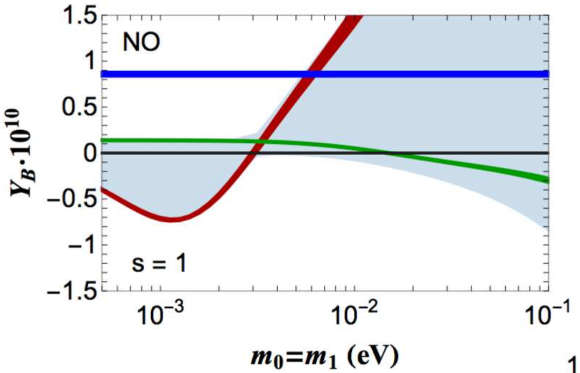
(remember in this case only the CP phase δ is non-trivial)

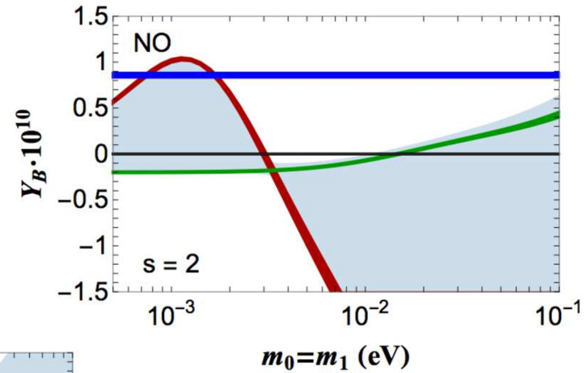
Framework for leptogenesis

Case 3 b.1) and $n = 8$, $m = 4$

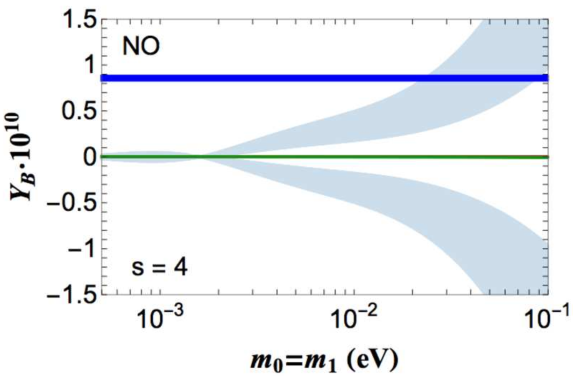
(H/Molinaro ('16))



only sinδ
non-zero



sinα<0



sinα>0

Comments on flavored leptogenesis

- we observe two major changes
  - change in relation between ϵ_i^α and κ

$$\epsilon_i^\alpha \propto \kappa$$

  - in general the sign of Y_B cannot only depend anymore on sine of CP phases and light neutrino mass spectrum, e.g. for Case 1) we find

$$\epsilon_1^\alpha \approx (-1)^{k_1+1} \frac{y_0 \, z}{6\sqrt{3}\,\pi} \kappa \cos(\theta+\zeta) \cos\left(\theta+\rho_\alpha \tfrac{\pi}{3}\right) \sin 6\,\phi_s \, f\left(\frac{m_1}{m_2}\right)$$

$$\epsilon_3^\alpha \approx (-1)^{k_1+k_2+1} \frac{y_0 \, z}{6\sqrt{3}\,\pi} \kappa \sin(\theta+\zeta) \sin\left(\theta+\rho_\alpha \tfrac{\pi}{3}\right) \sin 6\,\phi_s \, f\left(\frac{m_3}{m_2}\right)$$

with $\rho_e = 3$, $\rho_\mu = 1$ and $\rho_\tau = -1$

Comments on flavored leptogenesis

- you can also consider Y_D invariant under $G_\nu = Z_2 \times CP$ only
- then CP asymmetries do not vanish – even without δY_D
- however, there is in general no one-to-one correspondence between α, β, δ and sign of Y_B, e.g. we find for Case 2)

$$\epsilon^{\alpha}_{1\,(3)} = \frac{y_1\, y_3\, (y^2_{1\,(3)} - y^2_{3\,(1)})\, \sin 2\,(\theta - \theta_R)\, \sin\left(\phi_u - \rho_\alpha\, \frac{\pi}{3}\right)}{48\,\pi \left(y^2_{1\,(3)}\, \cos^2(\theta - \theta_R) + y^2_{3\,(1)}\, \sin^2(\theta - \theta_R)\right)} \times \left[(-1)^{k_2}\, f\left(\frac{M_{3\,(1)}}{M_{1\,(3)}}\right) + g\left(\frac{M_{3\,(1)}}{M_{1\,(3)}}\right)\right]$$

and ϵ^{α}_{2} vanish

For further studies of flavored leptogenesis in theories with flavor & CP symmetry see *Mohapatra/Nishi ('15), Chen et al. ('16), Yao/Ding ('16)*.

Conclusions

- flavor and CP symmetries can be powerful in constraining lepton mixing parameters, in particular leptonic CP phases
- series of $\Delta(3\,n^2)$ and $\Delta(6\,n^2)$, $n \geq 2$, and CP are very interesting
- strong correlation of α, β, δ and Y_B possible in unflavored leptogenesis framework

Thank you for your attention.