Connections between low-energy CP violation, lepton number violating collider signals and genesis mechanisms

C. Hagedorn

CP^3-Origins, University of Southern Denmark, Odense, Denmark

The 19th International Workshop on Neutrinos
from Accelerators (NuFact2017),
25.09-30.09.2017, Uppsala, Sweden

Overview

- flavor symmetry with CP for low-energy CP phases δ, α, β
- correlation between δ, α, β and baryon asymmetry Y_B
- possible connection to lepton number violating signals at LHC

Low-energy CP phases in the lepton sector

Parametrization

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

with

$$\tilde{U} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

and $s_{ij} = \sin\theta_{ij}$, $c_{ij} = \cos\theta_{ij}$

Experimental status

- first indications for Dirac phase $\delta \sim \frac{3}{2}\pi$

  (Capozzi et al. ('16), Esteban et al. ('16), de Salas et al. ('17))

- no constraints on Majorana phases α and β

Prediction of CP phases with a flavor and a CP symmetry

Prediction of CP phases with a flavor and a CP symmetry

- framework: 3 copies of charged leptons & Majorana neutrinos
- impose flavor symmetry G_f on space of 3 lepton generations
- G_f is non-abelian, finite and discrete
- impose also CP symmetry

Prediction of CP phases with a flavor and a CP symmetry

- framework: 3 copies of charged leptons & Majorana neutrinos
- impose flavor symmetry G_f on space of 3 lepton generations
- G_f is non-abelian, finite and discrete
- impose also CP symmetry
- G_f and CP must be broken at low energies and we assume residual symmetries G_e (G_ν) in the charged lepton (neutrino) sector
  $\hookrightarrow$ form of charged lepton mass matrix m_e & Majorana mass matrix m_ν is restricted by G_e and G_ν

Prediction of CP phases with a flavor and a CP symmetry

- framework: 3 copies of charged leptons & Majorana neutrinos
- impose flavor symmetry G_f on space of 3 lepton generations
- G_f is non-abelian, finite and discrete
- impose also CP symmetry
- G_f and CP must be broken at low energies and we assume residual symmetries G_e (G_ν) in the charged lepton (neutrino) sector
  $\hookrightarrow$ form of charged lepton mass matrix m_e & Majorana mass matrix m_ν is restricted by G_e and G_ν
  in particular, G_ν contains CP, described by CP transformation X

$$X \, m_\nu \, X = m_\nu^\star$$

$\hookrightarrow$ contributions U_e & U_ν to lepton mixing U_{PMNS} are fixed

Prediction of CP phases with a flavor and a CP symmetry

(Harrison/Scott ('02), Grimus/Lavoura ('03), Feruglio/H/Ziegler ('12), Holthausen/Lindner/Schmidt ('12), Chen et al. ('14), Grimus/Rebelo ('95))

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.]

Prediction of CP phases with a flavor and a CP symmetry

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

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

Prediction of CP phases with a flavor and a CP symmetry

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

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

$$\Downarrow$$

Predictions

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

Example

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

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

$\swarrow$ $\searrow$

charged leptons

$G_e = Z_3$

U_e

neutrinos

$G_\nu = Z_2 \times$ CP

$U_\nu = \Omega_\nu R(\theta) K_\nu$

$\searrow$ $\swarrow$

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

four different types of mixing patterns with different characteristics

Example

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

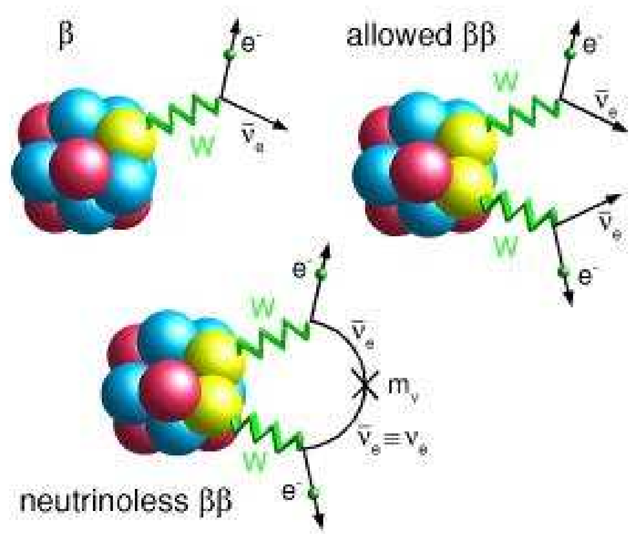
$$|\sin\alpha| = |\sin\beta| = |\sin 6\,\phi_s| \quad \text{with} \quad \phi_s = \frac{\pi s}{n} \quad \text{and} \quad s = 0, ..., n-1$$

Example

Case 3 b.1) and $n = 8$, $m = 4$: (H/Meroni/Molinaro ('14))
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

Low-energy CP phases in neutrinoless double beta decay



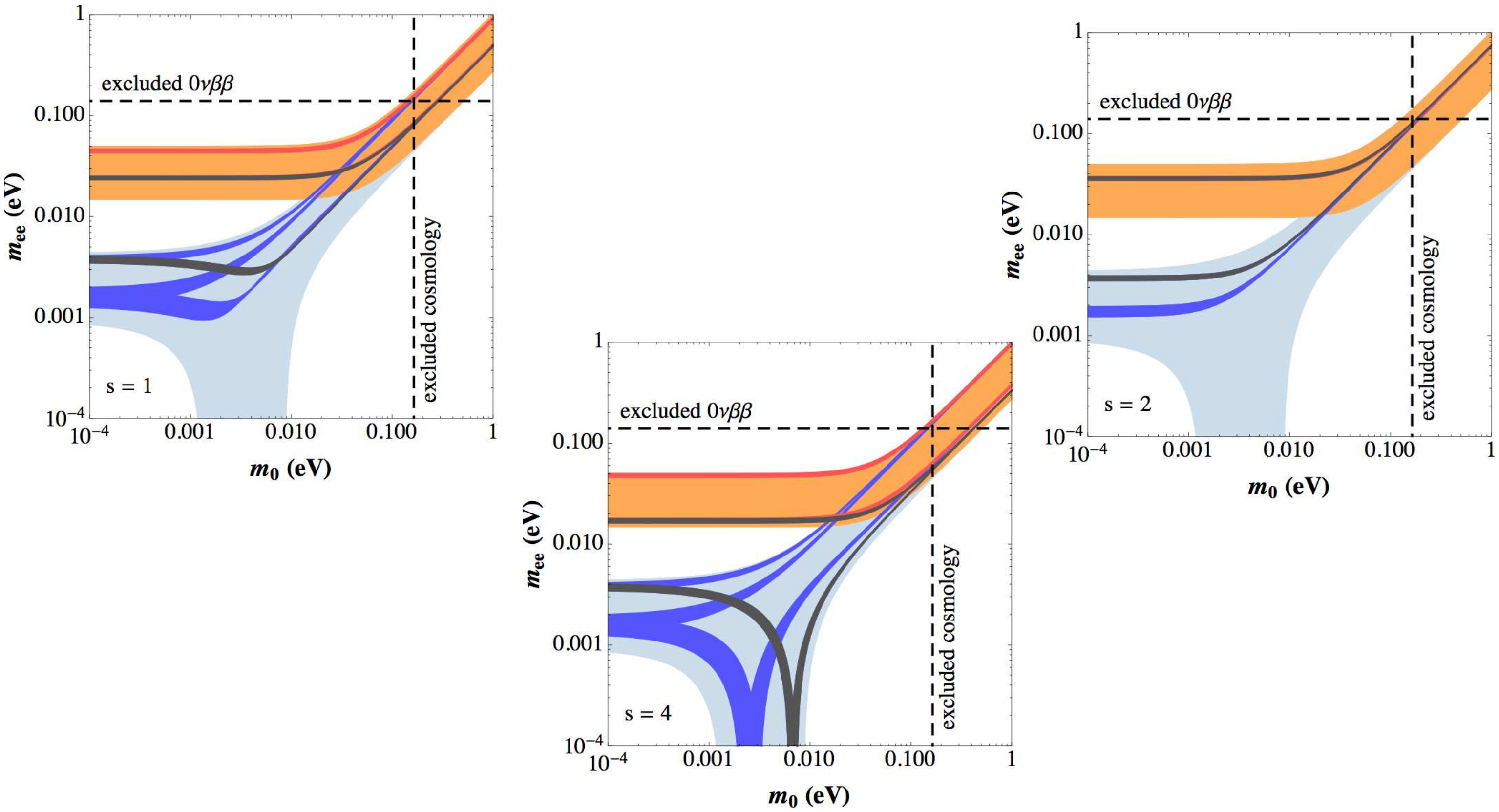
Dependence of neutrinoless double beta decay on Majorana phases α, β

$$m_{ee} = \left| \cos^2\theta_{12}\, \cos^2\theta_{13}\, m_1 + \sin^2\theta_{12}\, \cos^2\theta_{13}\, e^{i\alpha}\, m_2 + \sin^2\theta_{13}\, e^{i\beta}\, m_3 \right|$$

Low-energy CP phases in neutrinoless double beta decay

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

(H/Molinaro ('16))



Further approaches with CP symmetries

- many more flavor symmetries have been combined with CP

  (Di Iura/H/Meloni ('15), Li/Ding ('15), Ballett et al. ('15), Rong ('16), Yao/Ding ('16), ...)
- study of more general CP symmetries *(Everett et al. ('15))*
- two CP symmetries in neutrino sector *(Chen et al. ('14))*
- textures of CP transformations *(Chen et al. ('16))*
- considerable efforts in building models in recent past

  (Altarelli, Antusch, Branco, Chen, de Medeiros Varzielas, Ding, Everett, Feruglio, Gehrlein, Girardi, Gonzalez Felipe, Grimus, H, He, Joaquim, King, Lavoura, Luhn, Mahanthappa, Meloni, Meroni, Mohapatra, Nishi, Päs, Pascoli, Petcov, Rodejohann, Smirnov, Spinrath, Tanimoto, Valle, ...)

Correlation between low-energy CP phases and Y_B

Correlation between low-energy CP phases and Y_B

- type-I seesaw mechanism with 3 right-handed (RH) neutrinos N
- Lagrangian

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

Correlation between low-energy CP phases and Y_B

- type-I seesaw mechanism with 3 right-handed (RH) neutrinos N
- Lagrangian

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

- leptogenesis (flavored, unflavored, resonant) can explain the measured baryon asymmetry of the Universe
  $Y_B = (8.65 \pm 0.09) \times 10^{-11}$ *(Planck ('15))*
  through decay of RH neutrinos
- one of the Sakharov conditions is C and CP violation
- rule of thumb

$Y_B \sim 10^{-3} \, \epsilon \, \eta$ with ϵ CP asymmetry , η efficiency factor

Correlation between low-energy CP phases and Y_B

- type-I seesaw mechanism with 3 right-handed (RH) neutrinos N
- Lagrangian

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

- three possibilities to realize G_ν

Correlation between low-energy CP phases and Y_B

- type-I seesaw mechanism with 3 right-handed (RH) neutrinos N
- Lagrangian

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

- three possibilities to realize G_ν

  a) M_R invariant under G_ν, Y_D invariant under G_f and CP

  b) M_R invariant under G_f and CP, Y_D invariant under G_ν

  c) M_R and Y_D invariant under G_ν

Correlation between low-energy CP phases and Y_B

- type-I seesaw mechanism with 3 right-handed (RH) neutrinos N
- Lagrangian

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

- three possibilities to realize G_ν

  a) M_R invariant under G_ν, Y_D invariant under G_f and CP

  b) M_R invariant under G_f and CP, Y_D invariant under G_ν

  c) M_R and Y_D invariant under G_ν

Correlation between low-energy CP phases and Y_B

a) M_R invariant under G_ν, Y_D invariant under G_f and CP

(H/Molinaro ('16))

- scenario with unflavored leptogenesis
- CP phases are constrained by G_ν
- light and heavy neutrino masses are strongly correlated

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

- mixing among RH neutrinos gives PMNS mixing matrix

$$U_{PMNS} = U_\nu = U_R = \Omega_\nu R(\theta) K_\nu$$

Correlation between low-energy CP phases and Y_B

a) M_R invariant under G_ν, Y_D invariant under G_f and CP

(H/Molinaro ('16))

- scenario with unflavored leptogenesis
- CP phases are constrained by G_ν
- light and heavy neutrino masses are strongly correlated

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

- mixing among RH neutrinos gives PMNS mixing matrix

$$U_{PMNS} = U_\nu = U_R = \Omega_\nu R(\theta) K_\nu$$

- however, CP asymmetry ϵ vanishes

Correlation between low-energy CP phases and Y_B

a) M_R invariant under G_ν, Y_D invariant under G_f and CP

(H/Molinaro ('16))

- scenario with unflavored leptogenesis
- CP phases are constrained by G_ν
- light and heavy neutrino masses are strongly correlated

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

- mixing among RH neutrinos gives PMNS mixing matrix

$$U_{PMNS} = U_\nu = U_R = \Omega_\nu R(\theta) K_\nu$$

- crucial ingredient: corrections $\mathcal{O}(\kappa)$ to Y_D

(Jenkins/Manohar ('08), Bertuzzo et al. ('09), H/Molinaro/Petcov ('09), Aristizabal Sierra et al. ('09))

Correlation between low-energy CP phases and Y_B

a) M_R invariant under G_ν, Y_D invariant under G_f and CP

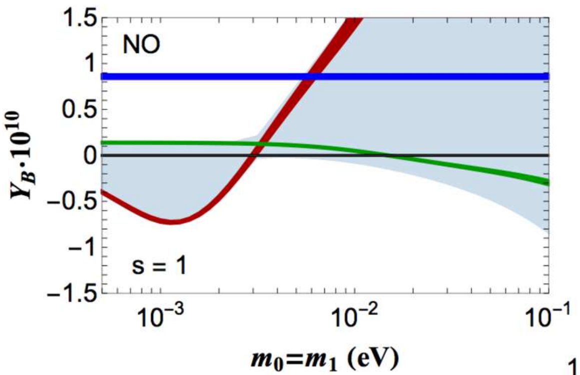
(H/Molinaro ('16))

- scenario with unflavored leptogenesis
- CP phases are constrained by G_ν
- crucial ingredient: corrections $\mathcal{O}(\kappa)$ to Y_D
- then: size of ϵ is small, since $\epsilon \propto \kappa^2$,
  sign of ϵ can be fixed, since CP phases are constrained

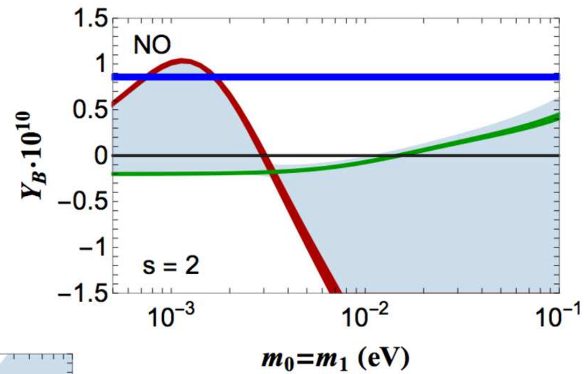
Example

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

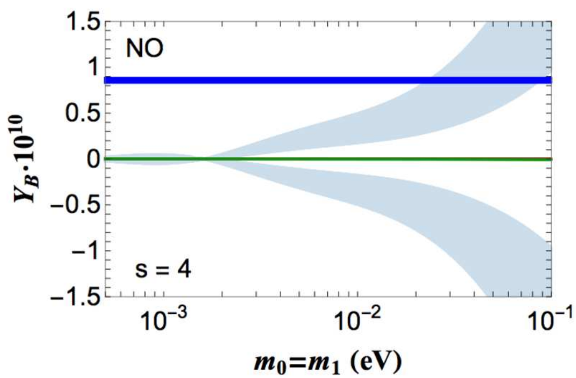
(H/Molinaro ('16))



only $\sin\delta$ non-zero



$\sin\alpha < 0$



$\sin\alpha > 0$

for light neutrinos with normal ordering

Correlation between low-energy CP phases and Y_B

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- scenario suitable for resonant leptogenesis, since RH neutrino masses are degenerate
- CP phases are constrained by G_ν
- light neutrino masses depend on Yukawa couplings

Correlation between low-energy CP phases and Y_B

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- scenario suitable for resonant leptogenesis, since RH neutrino masses are degenerate
- CP phases are constrained by G_ν
- light neutrino masses depend on Yukawa couplings
- however, CP asymmetry ϵ vanishes

Correlation between low-energy CP phases and Y_B

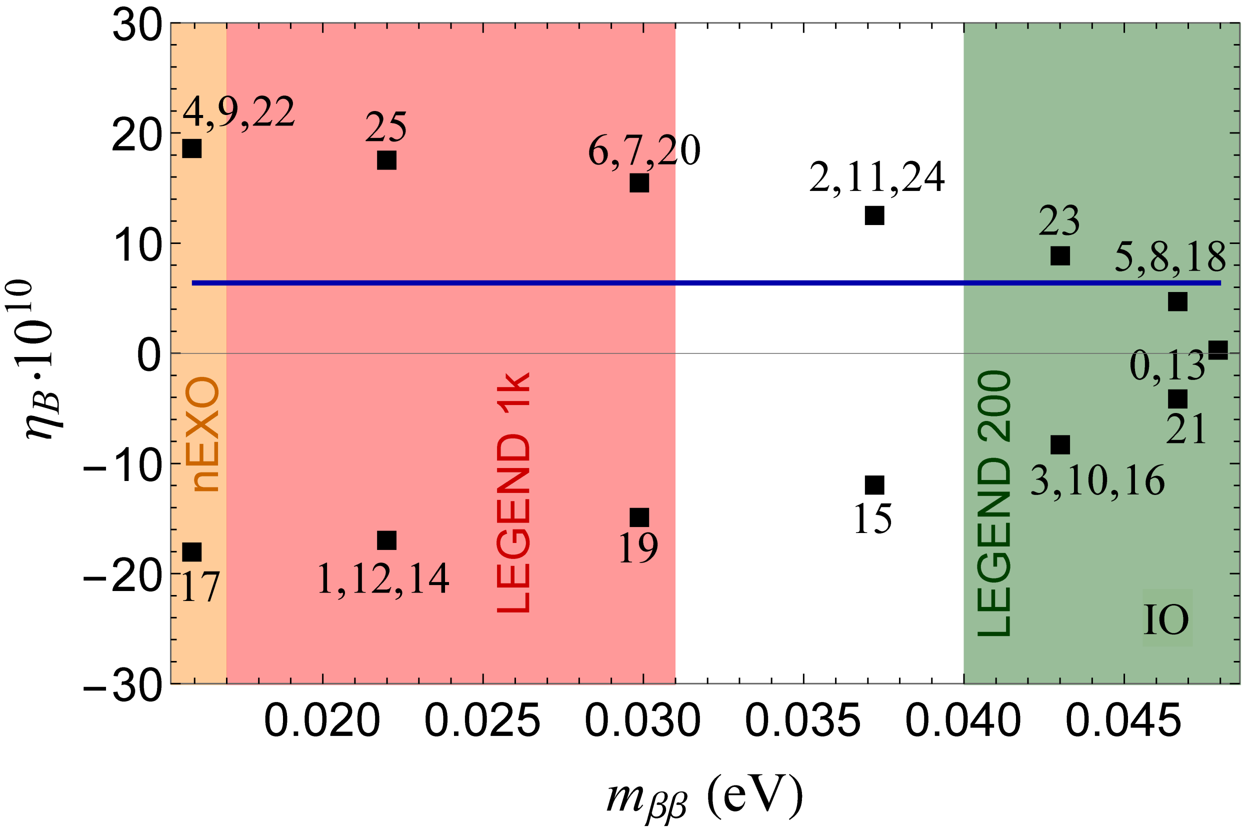
b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- scenario suitable for resonant leptogenesis, since RH neutrino masses are degenerate
- CP phases are constrained by G_ν
- light neutrino masses depend on Yukawa couplings
- crucial ingredient: corrections $\mathcal{O}(\kappa)$ to M_R
  in order to split RH neutrino masses
  for non-vanishing CP asymmetry

Example

Case 1) and $n = 26$ *(Dev/H/Molinaro (in preparation))*



for light neutrinos with inverted ordering and $m_0 = m_3 = 0$

Correlation between low-energy CP phases and Y_B

c) M_R and Y_D invariant under G_ν

- suitable scenario for flavored leptogenesis
- examples can be found in literature

  (Mohapatra/Nishi ('15), Chen et al. ('16), Yao/Ding ('16))
- in such scenarios corrections of $\mathcal{O}(\kappa)$ are not needed for non-vanishing CP asymmetries
- however, correlation between low-energy CP phases and Y_B is not as strong as in other scenarios

Possible connection to lepton number violating signals at LHC

Possible connection to lepton number violating signals at LHC

We consider

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

Possible connection to lepton number violating signals at LHC

We consider

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- RH neutrino masses M_N can be in range of few 100 GeV

Possible connection to lepton number violating signals at LHC

We consider

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- RH neutrino masses M_N can be in range of few 100 GeV
- problem:
  production at LHC is too small, since it depends on small Yukawa couplings $y \lesssim 10^{-6}$

Possible connection to lepton number violating signals at LHC

We consider

b) M_R invariant under G_f and CP, Y_D invariant under G_ν

(Dev/H/Molinaro (in preparation))

- RH neutrino masses M_N can be in range of few 100 GeV
- problem:
  production at LHC is too small, since it depends on small Yukawa couplings $y \lesssim 10^{-6}$
- solution:
  extension by $U(1)$ gauge symmetry, e.g. $B - L$ symmetry
  then production via Z' gauge boson becomes possible

$$pp \to Z' \to N_i N_j$$

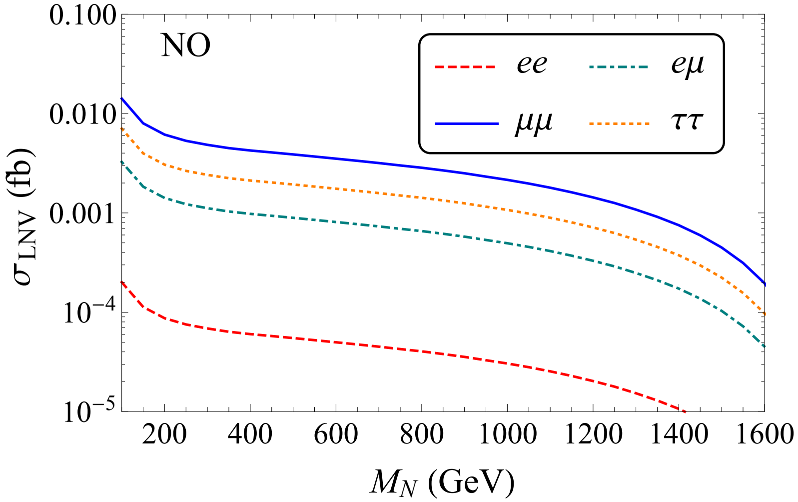
(e.g. Deppisch/Desai/Valle ('13), Helo/Hirsch/Kovalenko ('13), Blanchet et al. ('09), Blanchet/Dev/Mohapatra ('10))

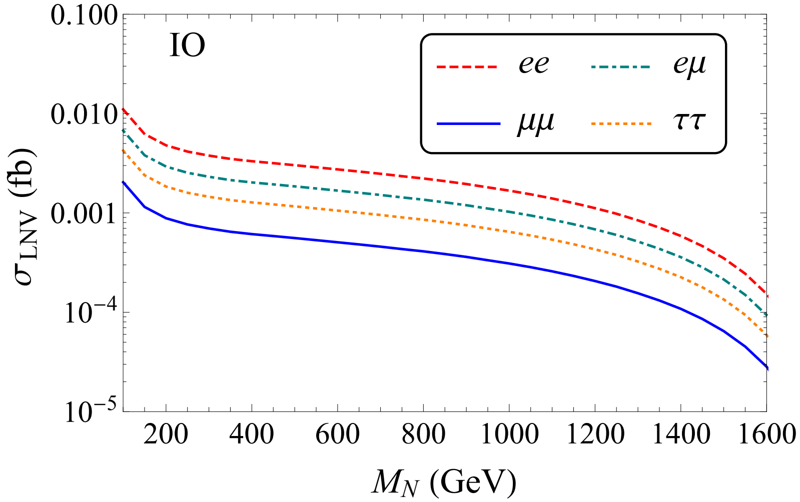
Possible connection to lepton number violating signals at LHC

(Dev/H/Molinaro (in preparation))

Study of lepton number violating process

$$pp \to Z' \to N_i N_i \to \ell_\alpha^\pm \ell_\beta^\pm + 4j$$





ratio of $\sigma_{\rm LNV}^{\alpha\beta}$ can distinguish between normal and inverted ordering

Conclusions

- flavor and CP symmetry can constrain low-energy CP phases δ, α, β
- in scenarios with RH neutrinos we can correlate δ, α, β with the sign of the baryon asymmetry Y_B of the Universe
- connection to lepton number violating signals at LHC exists

Thank you for your attention.