Large lepton mixing originating from the right-handed sector

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in collaboration with H. Päs

[Phys.Rev. D89:096010, 2014]

Overview

1. Motivation
2. The model
3. Leptogenesis
4. Analysis & predictions

Motivation

- [T2K, RENO, Daya Bay, Double CHOOZ, 2012/13]:

$$\theta_{13} \approx 0.15 \quad \Rightarrow \quad \cancel{U_{\text{TBM}} = \begin{pmatrix} -\frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \end{pmatrix}}$$

- Many approaches to explain θ_{13}
  1. Anarchy?
  2. Larger symmetry groups that accommodate all mixing parameters (e.g., $\Delta(96)$)
  3. Smaller groups yielding specific mixing patterns (TBM, GR,...) with perturbations to generate θ_{13} (e.g., S_4, A_5)

- Here: TBM+Perturbations
  Extension of: [P. Leser, H. Päs, Phys.Rev., D84:017303, 2011]

Motivation

- Where do large θ_{ij} in the neutrino sector come from?
- Ansatz: difference in CKM and PMNS mixing arises from additional heavy ν_R with Majorana mass terms

$$M_R \to \theta_{23},\, \theta_{12}$$

$$m_D \to \theta_{13}$$

- Develop a Seesaw Type I model with a diagonal Dirac sector inspired by hierarchical structure of V_{CKM}

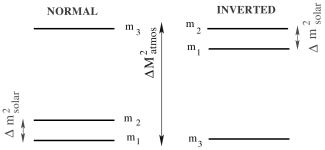
$$m_\nu = m_D^T\, M_R^{-1}\, m_D$$

Outline of the model

1. Determine the structure of M_R sector which yields tribimaximal mixing: $M_R^{-1} = (m_D^T)^{-1}\, U_{\text{TBM}}\, m'_\nu\, U_{\text{TBM}}^T\, m_D^{-1}$

$$m_D = \text{diag}(q, r, s)$$
$$m'_\nu = \text{diag}(m_1, m_2, m_3)$$

[Gonzalez-Garcia et al, Phys.Rept., 460:1-129, 2008]



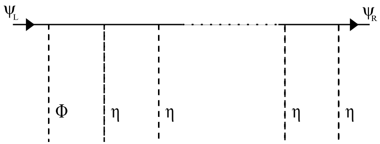
2. Assign $\epsilon \in \mathbb{C}$ ($\rightarrow$ Source of CP violation) to m_D to generate $\theta_{13} \neq 0$ independently of M_R

3. Obtain the parameter space which reproduces neutrino masses and mixing $\rightarrow$ make predictions on physical observables (CP phases, mass hierarchy, effective Majorana mass,...)

GUT embedding

- Idea: embedding in an $SU(5)$ GUT with additional flavor symmetries $U(1)_{\mathrm{FN}} \times \mathbb{Z}_2' \times \mathbb{Z}_2'' \times \mathbb{Z}_2'''$
  [McKeen et al, Phys.Rev., D76:073014, 2007]

- $U(1)_{\mathrm{FN}} \times \mathbb{Z}_2$ factors are used to suppress non-diagonal elements making use of a Froggatt-Nielson mechanism



- Suppression factor in the fermion mass term $\epsilon_i^n = \left(\frac{v_i}{\Lambda}\right)^n \simeq \lambda^n$ for each additional scalar field η_i ($\lambda \approx 0.22$)

GUT embedding

- SM particles are assigned to the irreducible $SU(5)$ representations $\mathbf{5}, \mathbf{10}$ and $\mathbf{1}$:

$$\mathbf{10} \; : \; \overline{d}_R, \; Q_L, \; l_R; \qquad \overline{\mathbf{5}} \; : \; l_L, \; d_R; \qquad \mathbf{1} \; : \; \nu_R$$

$$\Rightarrow \quad \begin{array}{lcl} \mathbf{10}_i \otimes \mathbf{10}_j & \sim & Y_u, \\ \mathbf{10}_i \otimes \overline{\mathbf{5}}_j & \sim & Y_d, \end{array} \qquad \begin{array}{lcl} \overline{\mathbf{5}}_i \otimes \mathbf{1}_j & \sim & Y_\nu^D, \\ \mathbf{1}_i \otimes \mathbf{1}_j & \sim & Y_\nu^R \end{array}$$

- $U(1)_{\mathrm{FN}}$ charges should reproduce fermion mass relations:

$$\begin{aligned} m_u : m_c : m_t &\approx \lambda^8 : \lambda^4 : 1\,, \\ m_d : m_s : m_b &\approx \lambda^4 : \lambda^2 : 1\,, \\ m_e : m_\mu : m_\tau &\approx \lambda^4 : \lambda^2 : 1\,. \end{aligned}$$

GUT embedding

- Dirac sector ($l_L \in \overline{\mathbf{5}}, \nu_R \in \mathbf{1} \Rightarrow \overline{\mathbf{5}}_i \otimes \mathbf{1}_j$):

$$Y^D \propto \begin{pmatrix} \lambda^{3+e_1} & \lambda^{3+e_2+\rho_1} & \lambda^{3+e_3+\rho_1} \\ \lambda^{3+e_1+\rho_2} & \lambda^{3+e_2} & \lambda^{3+e_3+\rho_2} \\ \lambda^{3+e_1+\rho_3} & \lambda^{3+e_2+\rho_3} & \lambda^{3+e_3} \end{pmatrix},$$

$$Y^D \propto \lambda^3 \cdot \begin{pmatrix} \lambda & \lambda^2 & \lambda \\ \lambda^2 & \lambda & \lambda \\ \lambda^2 & \lambda^2 & 1 \end{pmatrix} \approx \lambda^3 \cdot \begin{pmatrix} \lambda & 0 & \epsilon \\ 0 & \lambda & \gamma \\ 0 & 0 & 1 \end{pmatrix}$$

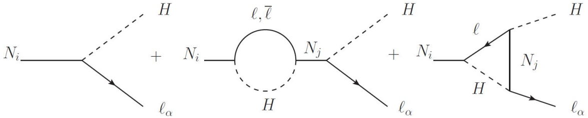
with $\quad e_3 = 0, \quad e_{1,2} = 1, \quad \rho_{1,2,3} = 1,$

and $\quad U(1)_{\text{FN}}^{\mathbf{10}} \ : \ (4,2,0), \quad U(1)_{\text{FN}}^{\mathbf{5}} \ : \ (3,3,3).$

- $SU(5)$ assignments motivate hierarchical structure of m_D with two perturbation parameters $\epsilon = |\epsilon| e^{i\phi}$ and $\gamma \in \mathbb{R}$
[H. Päs, E. Schumacher, Phys. Rev. D 89, 096010, 2014]

Baryo- and Leptogenesis

- Origin of matter asymmetry $\rightarrow$ Baryogenesis
- 'Sakharov conditions'
  1. Baryon number violation
  2. C and CP violation
  3. Thermal non-equilibrium
- Leptogenesis: L asymmetry from $N_i \rightarrow l_\alpha + \phi$ is converted to B asymmetry through $B + L$ violating sphaleron processes in the early universe [Yanagida, Fukugita, PhysRevLett.89.131602, 2002]



[Fong et al, Advances in High Energy Physics, 2012]

Leptogenesis

$$Y_{\Delta B}^{CMB} = (8.79 \pm 0.44) \cdot 10^{-11}$$

$$Y_{\Delta B}^{th} \cong \kappa_i \, \sigma_{i\alpha} \cdot 10^{-3}$$

$$\sigma_{i\alpha} = \frac{1}{8\pi} \frac{1}{(Y^{D\dagger} Y^D)_{ii}} \sum_{j \neq i} \left\{ \mathrm{Im}[(Y^{D\dagger} Y^D)_{ji} Y^D_{\alpha i} Y^{D*}_{\alpha j}] \cdot g\left(\frac{M_j^2}{M_i^2}\right) + (\ldots) \right\}$$

[Davidson et al, Phys.Rept. 466:105-177, 2008]

$$\text{with} \quad Y^D = \begin{pmatrix} \lambda & 0 & \epsilon \\ 0 & \lambda & \gamma \\ 0 & 0 & 1 \end{pmatrix} \quad \Rightarrow$$

$$\sigma_1 = \sum_i \sigma_{i1} = \frac{|\epsilon|^2 \sin(2\phi)}{8\pi} \left(\lambda^2 \cdot g\left(\frac{M_1^2}{M_3^2}\right) - g\left(\frac{M_3^2}{M_1^2}\right) \right)$$

Fit to experimental data

- Fit parameters γ, ϵ and ϕ to experimental data (3σ)

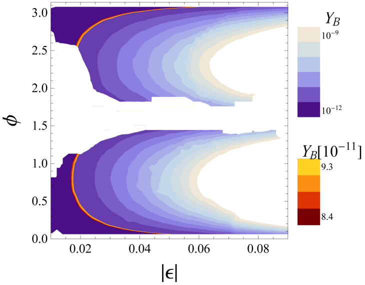
$$Y_{\Delta B}^{\mathrm{CMB}} = (8.79 \pm 0.44) \cdot 10^{-11}$$

$$|U_{\mathrm{exp}}| = \begin{pmatrix} [0.795, 0.846] & [0.513, 0.585] & [0.126, 0.178] \\ [0.205, 0.543] & [0.416, 0.730] & [0.579, 0.808] \\ [0.215, 0.548] & [0.409, 0.725] & [0.567, 0.800] \end{pmatrix}$$

$$\theta_{12} \in [0.543, 0.626]$$
$$\theta_{23} \in [0.743, 0.855]$$
$$\theta_{13} \in [0.125, 0.173]$$

Extract θ_{ij} and phases from U_{PMNS}
+ Consider RG running between Seesaw/GUT and EW scale

Numerical analysis



(a) $Y_{\Delta B}(|\epsilon|, \phi)$, NH (b) $Y_{\Delta B}(|\epsilon|, \phi)$, IH

NH:	$m_0 \in [0.00, 0.05]$ eV,	$n = 46250$,	$n_L = 19$,
IH:	$m_0 \in [0.00, 0.05]$ eV,	$n = 3768$,	$n_L = 229$,
deg:	$m_0 \in [0.05, 0.10]$ eV,	$n = 189$,	$n_L = 0$.

Numerical analysis

	m_0	$\lvert\epsilon\rvert$	ϕ	γ
NH	$[0.018, 0.050]$	$[0.018, 0.060]$	$[0.063, 0.565] \cup [2.639, 3.079]$	$[0.02, 0.20]$
IH	$[0.002, 0.044]$	$[0.034, 0.076]$	$[0.251, 1.445] \cup [1.696, 2.890]$	$[-0.38, 0.00]$
		δ	α	β
NH		$[0.016, 0.083]$	$[0.039, 0.192] \cup [3.118, 3.133]$	$[0.003, 0.157]$
IH		$[0.205, 1.293]$	$[0.448, 3.112]$	$[0.009, 2.404]$

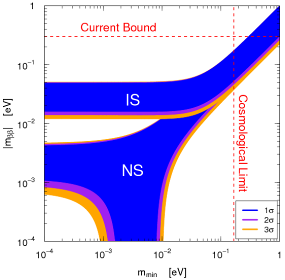
- Majorana phases α and β can affect the the effective Majorana mass relevant for $0\nu\beta\beta$

$$m_{\beta\beta} = \sum_i U_{ei}^2 \, m_i ,$$

- Upper bound from EXO-200:
  $m_{\beta\beta} \lesssim 0.19 - 0.45\,\text{eV}$
  [EXO-200 Collaboration (2014), 1402.6956.]

$$m_{\beta\beta}^{\text{NH}} \in [0.048, 0.063]\ \text{eV},$$

$$m_{\beta\beta}^{\text{IH}} \in [0.026, 0.050]\ \text{eV}.$$



[Bilenky, Giunti, Mod.Phys.Lett. A27 (2012) 1230015]

Summary

Objective:

- Construct model with large mixing originating from the right-handed sector with correct value of θ_{13}

Conclusions:

- Structures can be motivated by an $SU(5)$ embedding
- The models are consistent with current experimental bounds on θ_{ij} and accommodate the new θ_{13} in all hierarchies, but...
- neutrino mixing parameters are best reproduced with NH; IH is favored if successful leptogenesis is required
- The CP phases δ, α and β are predicted to be small in NH ($\rightarrow$ no cancellation) but large in IH
- $m_{\beta\beta}$ is accessible by Next-Gen $0\nu\beta\beta$ experiments

Thank you!

Back up

Washout-Regime

$$\left.\begin{array}{lll} \widetilde{m} < m_* \ \cap \ m_i < m_* : & \kappa_i \approx \dfrac{m_i \widetilde{m}}{m_*^2} & \text{weak} \\ \widetilde{m} > m_* \ \cap \ m_i < m_* : & \kappa_i \approx \dfrac{m_i}{m_*} & \text{intermediate} \\ \widetilde{m} > m_* \ \cap \ m_i > m_* : & \kappa_i \approx \dfrac{m_*}{m_i} & \text{strong} \end{array}\right\} \text{washout regime},$$

with $m_* \equiv \frac{16\pi^2 v^2}{3M_{pl}} \sqrt{\frac{g_* \pi}{5}} \approx 10^{-3}\,\text{eV}$ and $\widetilde{m} = \sum_i m_i$

- $\widetilde{m} > m_*$ is equivalent to $\Gamma > H$
  $\Rightarrow$ Washout regime connected to departure from thermal equlibrium

Yukawa structures

$$\mathbf{10}_i \otimes \mathbf{10}_j \quad : \quad Y_u \propto \begin{pmatrix} \lambda^8 & \lambda^{6+\rho_1+\rho_2} & \lambda^{4+\rho_1+\rho_3} \\ \lambda^{6+\rho_1+\rho_2} & \lambda^4 & \lambda^{2+\rho_3+\rho_2} \\ \lambda^{4+\rho_1+\rho_3} & \lambda^{2+\rho_3+\rho_2} & 1 \end{pmatrix}, \quad (1)$$

$$\mathbf{10}_i \otimes \bar{\mathbf{5}}_j \quad : \quad Y_d \propto \begin{pmatrix} \lambda^7 & \lambda^{7+\rho_1+\rho_2} & \lambda^{7+\rho_1+\rho_3} \\ \lambda^{5+\rho_1+\rho_2} & \lambda^5 & \lambda^{5+\rho_3+\rho_2} \\ \lambda^{3+\rho_1+\rho_3} & \lambda^{3+\rho_3+\rho_2} & \lambda^3 \end{pmatrix}. \quad (2)$$

Yukawa structures

$$Y^D \propto \lambda^3 \cdot \begin{pmatrix} \lambda & \lambda^2 & \lambda \\ \lambda^2 & \lambda & \lambda \\ \lambda^2 & \lambda^2 & 1 \end{pmatrix}, \qquad Y_R \propto \begin{pmatrix} \lambda^2 & \lambda^2 & \lambda \\ \lambda^2 & \lambda^2 & \lambda \\ \lambda & \lambda & 1 \end{pmatrix}.$$

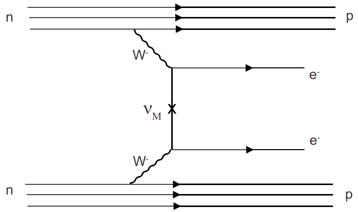
$$m_D = \mathrm{diag}(\lambda, \lambda, 1) \cdot v$$

$$\begin{aligned} M_R^{-1} &= (m_D^T)^{-1}\, U_{\mathrm{TBM}}\, m_\nu'\, U_{\mathrm{TBM}}^T\, m_D^{-1} \\ &= \frac{1}{3v^2} \begin{pmatrix} \frac{2m_1+m_2}{\lambda^2} & \frac{-m_1+m_2}{\lambda^2} & \frac{-m_1+m_2}{\lambda} \\ \frac{-m_1+m_2}{\lambda^2} & \frac{m_1+2m_2+3m_3}{2\lambda^2} & \frac{m_1+2m_2-3m_3}{2\lambda} \\ \frac{-m_1+m_2}{\lambda} & \frac{m_1+2m_2-3m_3}{2\lambda} & \frac{m_1+2m_2+3m_3}{2} \end{pmatrix} \quad \text{and} \end{aligned}$$

$$M_R = \frac{v^2}{3} \begin{pmatrix} \frac{\lambda^2(m_1+2m_2)}{m_1 m_2} & \frac{\lambda^2(m_1-m_2)}{m_1 m_2} & \frac{\lambda(m_1-m_2)}{m_1 m_2} \\ \frac{\lambda^2(m_1-m_2)}{m_1 m_2} & \frac{1}{2}\lambda^2\left(\frac{1}{m_1}+\frac{2}{m_2}+\frac{3}{m_3}\right) & \frac{1}{2}\lambda\left(\frac{1}{m_1}+\frac{2}{m_2}-\frac{3}{m_3}\right) \\ \frac{\lambda(m_1-m_2)}{m_1 m_2} & \frac{1}{2}\lambda\left(\frac{1}{m_1}+\frac{2}{m_2}-\frac{3}{m_3}\right) & \frac{1}{2}\left(\frac{1}{m_1}+\frac{2}{m_2}+\frac{3}{m_3}\right) \end{pmatrix}$$

Experimental test

- Neutrino type can be determined in neutrinoless double-beta decay experiments
- Lepton number violating process which is very hard to detect
- Only allowed if $\nu = \nu^c$



- Next-Gen experiments: GERDA, NEXT, SNO+, SuperNEMO, MAJORANA,...

Fit to experimental data

- Fit parameters γ, ϵ and ϕ to experimental data (3σ)

$$U_{\text{PMNS}} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \text{diag}(e^{i\alpha}, e^{i\beta}, 1)$$

$$|U_{\text{exp}}| = \begin{pmatrix} [0.795, 0.846] & [0.513, 0.585] & [0.126, 0.178] \\ [0.205, 0.543] & [0.416, 0.730] & [0.579, 0.808] \\ [0.215, 0.548] & [0.409, 0.725] & [0.567, 0.800] \end{pmatrix}$$

$\theta_{12} \in [0.543, 0.626]$

$\theta_{23} \in [0.625, 0.956]$

$\theta_{13} \in [0.125, 0.173]$

Problem: Various ways to parametrize U! How do we extract the mixing angles and phases?

Rephasing invariants

Rephasing invariant properties

- Jarlskog-invariant

$$J = \text{Im}\left[U_{\alpha k}\, U^*_{\alpha j}\, U^*_{\beta k}\, U_{\beta j}\right]$$
$$= \frac{1}{8}\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\cos\theta_{13}\sin\delta$$

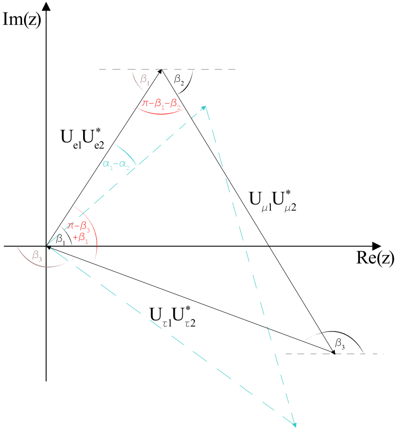
- Unitarity triangles with common area $A = \frac{1}{2}|\,J\,|$

$$U_{ei}U^*_{ej} + U_{\mu i}U^*_{\mu j} + U_{\tau i}U^*_{\tau j} = 0$$

- Define so-called Majorana-type phases to extract the physical parameters [Branco, Rebelo, Phys.Rev., D79:013001, 2009]

$$\beta_\alpha \equiv \text{Arg}(U_{\alpha 1}U^*_{\alpha 2}) \qquad \gamma_\alpha \equiv \text{Arg}(U_{\alpha 1}U^*_{\alpha 3})$$

Majorana phases



Majorana phases rotate the Majorana triangles in the complex plane $\rightarrow$ deduce expressions for the phases α and β from the rotation angle

Extract mixing angles and phases

$$\tan^2\theta_{12} = \frac{|\sin(\gamma_1-\gamma_2)||\sin(-\beta_2+\gamma_2+\beta_3-\gamma_3)||\sin(\gamma_1-\gamma_3)|}{|\sin(-\beta_1+\gamma_1+\beta_2-\gamma_2)||\sin(\gamma_2-\gamma_3)||\sin(-\beta_1+\gamma_1+\beta_3-\gamma_3)|},$$

$$\tan^2\theta_{23} = \frac{|\sin(\gamma_1-\gamma_3)||\sin(-\beta_1+\gamma_1+\beta_3-\gamma_3)||\sin(\beta_1-\beta_2)|}{|\sin(-\beta_1+\gamma_1+\beta_2-\gamma_2)||\sin(\gamma_1-\gamma_2)||\sin(\beta_1-\beta_3)|},$$

$$\tan^2\theta_{13} = \frac{|\sin(\gamma_2-\gamma_3)||\sin(\beta_1-\beta_3)||\sin(\beta_1-\beta_2)|}{|\sin(\gamma_1-\gamma_3)||\sin(\gamma_1-\gamma_2)||\sin(\beta_2-\beta_3)|}\cdot\sin^2\theta_{12},$$

$$|\sin\delta| = 8\cdot\frac{|\cos\theta_{12}\cos\theta_{13}\sin\theta_{13}|^2|\sin(\gamma_1-\gamma_3)||\sin(\gamma_1-\gamma_2)|}{|\sin(2\theta_{12})\sin(2\theta_{13})\sin(2\theta_{23})\cos\theta_{13}||\sin(\gamma_2-\gamma_3)|}.$$

[Branco, Rebelo, Phys.Rev., D79:013001, 2009]

$$\mathrm{Arg}\left(\frac{U_{P11}U^*_{P13}}{U_{11}U^*_{13}}\right)=\alpha,\quad \mathrm{Arg}\left(\frac{U_{P12}U^*_{P13}}{U_{12}U^*_{13}}\right)=\beta,\quad \mathrm{Arg}\left(\frac{U_{P11}U^*_{P12}}{U_{11}U^*_{12}}\right)=\alpha-\beta.$$

Boltzmann-Equations

$$\frac{dY_{N_1}}{dz} = -D_1(Y_{N_1} - Y_{N_1}^{eq}),$$
$$\frac{dY_{\Delta L}}{dz} = \epsilon_1 D_1(Y_{N_1} - Y_{N_1}^{eq}) - W_1 Y_{\Delta L} \quad \text{with} \quad z = M_1/T$$
$$W_1(z) = \frac{1}{2} D_1(z) \frac{Y_{N_1}^{eq}}{Y_l^{eq}}(z)$$
$$D_1(z) \propto z \frac{K_1 z}{K_2 z}, \quad K_n : \text{ nth order Bessel function}$$