Leptonic CP violation in the minimal type-I seesaw model

Bottom-up phenomenology & top-down model-building

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3rd July 2017

IMPRS-Seminar

based on

TR & K.Schmitz - arXiv:1611.05857[hep-ph], JHEP 1703 (2017) 158

TR, K.Schmitz, T.Yanagida - arXiv:1612.08878[hep-ph]

Outline

Massive neutrinos

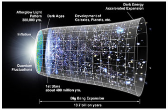
Bottom up: Yukawa hierarchies from measured CP violation

Top down: Minimal seesaw with approximate discrete symmetry

Massive neutrinos

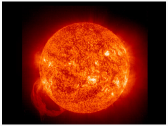
Neutrinos everywhere!

One of the most abundant particles in the universe!



[NASA]

$T_{C\nu B} \sim 1.95\,K$

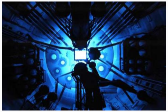


[NASA]

$\Phi_{\oplus} \sim 6.5 \times 10^{10}\,\frac{\nu_e}{\mathbf{cm}^2\,\mathbf{s}^1}$

[spacetelescope.org]

$\Delta E_G \sim 99\%\,\nu' s$



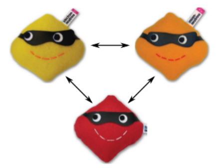
[nuclear-energy.net]

$P \sim 200\,\frac{\text{kW}}{\mathbf{m}^2}$

In the standard model:

- neutral electric charge → W. Pauli 1930
- weakly interacting → discoveries - (1952, 1962, 2000)
- $SU(2)_L$ partners of charged leptons → Wu & Goldhaber

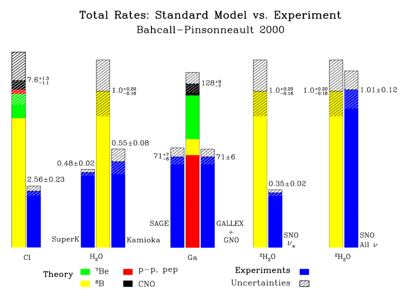
NO RH neutrinos → massless!



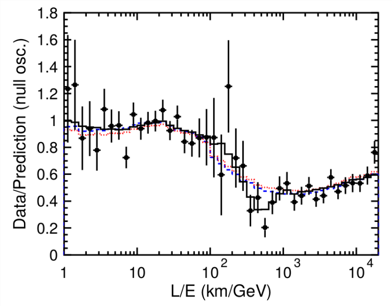
[https://www.particlezoo.net]

Why do we need massive neutrinos?

→ Neutrino flux deficits!



[de Gouvea, 2004]



[Ishitsuka, 2004]

- finite lifetime
- stronger absorption in matter
- B field induced $\nu_L \rightarrow \bar{\nu}_L, \nu_R$
- exotica (~~*equivalence principle*~~, ~~U~~, ~~L_L~~)
- flavor conversion during propagation → oscillations

⟹ flavor oscillations only convincing explanation, but non-zero Δm required!

Neutrino oscillations

[particlezoo.net]

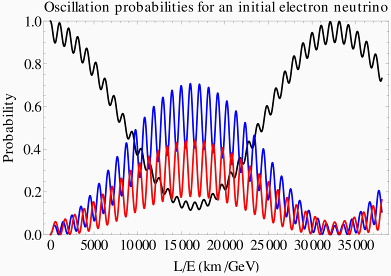
- mismatch between flavor and mass eigenstates: $|\nu_\alpha\rangle \neq |\nu_i\rangle$
- neutrino mixing incorporated in PMNS matrix: $|\nu_\alpha\rangle = U^*_{\alpha i}\,|\nu_i\rangle$

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}c_{13}s_{23}e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta} & c_{13}c_{23} \end{pmatrix} \times \text{diag}\left(1, e^{i\sigma}, e^{i\tau}\right)$$

with $s_{ij} \equiv \sin\theta_{ij}, c_{ij} \equiv \cos\theta_{ij},\ \theta_{ij} \in \left[0, \frac{\pi}{2}\right]$ and $\delta \in [0, 2\pi),\ \sigma, \tau \in [0, \pi)$

- transition probability

$$\mathcal{P}(\nu_\alpha \to \nu_\beta; t)$$
$$= \langle \nu_\beta | \nu_\alpha(t) \rangle\,| = U_{\beta j} U^*_{\alpha j} e^{-iE_j t}|^2$$
$$\simeq \sin^2 2\theta \sin^2\left(1.27\Delta m^2 \frac{L[\text{m}]}{E[\text{MeV}]}\right)$$



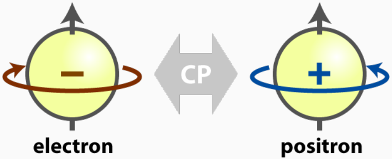
black - ν_e, blue - ν_μ, red - ν_τ

[wikipedia.org]

Leptonic CP violation

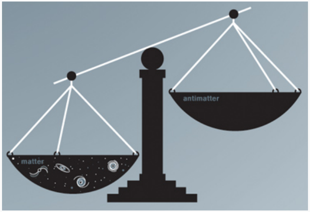
- Dirac phase δ through oscillations

$$\Delta\mathcal{P} = \mathcal{P}(\nu_\alpha \to \nu_\beta; t) - \mathcal{P}(\bar{\nu}_\alpha \to \bar{\nu}_\beta; t) \propto \sin \delta$$



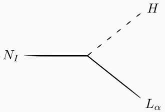
- Majorana phases through $0\nu\beta\beta$

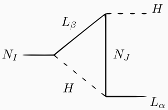
$$m_{ee}^2 = |\sum_i U_{ei}^2 m_i|$$

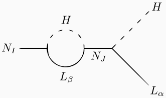


[quantumdiaries.org]

- high-E CP violation $\epsilon \to$ Leptogenesis!







Current experimental status

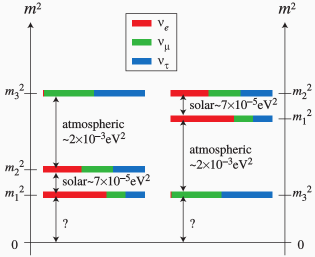
What we know:

- two non-zero mass-squared differences

$$\Delta m^2_{sol} \simeq 7.4 \cdot 10^{-5} \mathrm{eV}^2$$
$$\Delta |m^2_{atm}| \simeq 2.5 \cdot 10^{-3} \mathrm{eV}^2$$

- two large and one small mixing angle

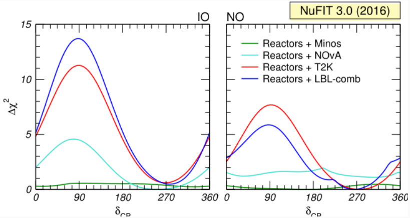
$$\theta_{12} = \theta_{sol} \sim (31...36)^\circ$$
$$\theta_{23} = \theta_{atm} \sim (38...53)^\circ$$
$$\theta_{13} = \theta_{reac} \sim (8...9)^\circ$$



[Nucciotti, 2016]

Still open questions:

- mass hierarchy - normal or inverted?
- absolute mass scale $min\{m_i\} = ?$
- fermion type - Dirac/Majorana
- octant-problem: 45° ($<$ **or** $>$) θ_{23}
- non-zero CP violating phases - δ, σ, τ



Neutrino mass models

- natural emergence of neutrino masses in many BSM theories: GUTs, Left-Right-symmetry, etc.
- rich phenomenology: $\not{L}$, BAU, etc.
- models strongly depend on neutrino's fermionic nature!

Majorana neutrino: $\nu = \nu^c$

- seesaw models
- radiative mass generation

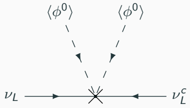
Dirac neutrino: $\nu \neq \nu^c$

- Dirac seesaw + radiative mass generation
- extra dimensions

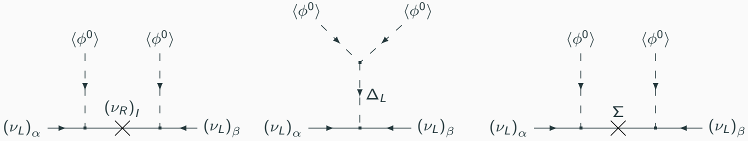
Most popular approach: realizations of eff. dim-5 operator [Weinberg, 1979]

$$\mathcal{L}_5 = \frac{1}{2}\frac{g}{\Lambda}\left(\bar{L}_L\tilde{\phi}\right)\left(\phi^* L_L^c\right)$$

$\rightarrow \Delta L = 2$



Tree level realization of Weinberg operator:

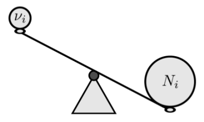


(a) seesaw type-I **(b)** seesaw type-II **(c)** seesaw type-III

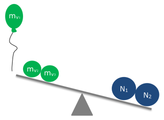
Generic feature: SM neutrino mass is suppressed by mass scale of intermediate particle/new physics scale $m_\nu \propto \Lambda^{-1}$

simplest: type-I scenario - 3 heavy RH Majorana neutrino $\rightarrow$ 18 real parameters!

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



Minimal type-I seesaw model



Predictions demand reduction of parameter space:

$$\mathcal{L}_{seesaw} = -y_{\alpha I} L_\alpha \phi N_I - \frac{1}{2} N_I N_I + \text{h.c.}, \quad \alpha = e, \mu, \tau \quad {\color{red} I = 1, 2}$$

[King, 1998, King, 1999, King, 2000, Frampton et al., 2002]

- only two N_I's:
  - three complex Yukawa couplings
  - one Majorana mass M_I

  $\rightarrow$ 11 real parameters, but one ν exactly massless!

- zero-texture ansatz (flavor symmetry, xDim, ...)
  - one zero - trivial
  - three zeros - inconsistent with data

$$A_1: \begin{pmatrix} 0 & 0 \\ \times & \times \\ \times & \times \end{pmatrix}, \quad A_2: \begin{pmatrix} \times & \times \\ 0 & 0 \\ \times & \times \end{pmatrix}, \quad A_3: \begin{pmatrix} \times & \times \\ \times & \times \\ 0 & 0 \end{pmatrix}$$

$$B_1: \begin{pmatrix} 0 & \times \\ \times & 0 \\ \times & \times \end{pmatrix}, \quad B_2: \begin{pmatrix} 0 & \times \\ \times & \times \\ \times & 0 \end{pmatrix}, \quad B_3: \begin{pmatrix} \times & \times \\ 0 & \times \\ \times & 0 \end{pmatrix}$$

$$B_4: \begin{pmatrix} \times & 0 \\ 0 & \times \\ \times & \times \end{pmatrix}, \quad B_5: \begin{pmatrix} \times & 0 \\ \times & \times \\ 0 & \times \end{pmatrix}, \quad B_6: \begin{pmatrix} \times & \times \\ \times & 0 \\ 0 & \times \end{pmatrix}$$

$$C_1: \begin{pmatrix} 0 & \times \\ 0 & \times \\ \times & \times \end{pmatrix}, \quad C_2: \begin{pmatrix} 0 & \times \\ \times & \times \\ 0 & \times \end{pmatrix}, \quad C_3: \begin{pmatrix} \times & \times \\ 0 & \times \\ 0 & \times \end{pmatrix}$$

$$C_4: \begin{pmatrix} \times & 0 \\ \times & 0 \\ \times & \times \end{pmatrix}, \quad C_5: \begin{pmatrix} \times & 0 \\ \times & \times \\ \times & 0 \end{pmatrix}, \quad C_6: \begin{pmatrix} \times & \times \\ \times & 0 \\ \times & 0 \end{pmatrix}$$

$\rightarrow$ two-zero textures: only $B_{1,4}$ and $B_{2,5}$ for IH are allowed, NH completely forbidden!

Precise predictions for CP phases $\rightarrow$ maximal CP violation!

$$\frac{(\delta, \sigma)}{\pi} \simeq \begin{cases} (0.51, 0.94) \quad \textit{or} \quad (1.49, 0.06) \quad (B_{1,4}) \\ (0.50, 0.04) \quad \textit{or} \quad (1.50, 0.96) \quad (B_{2,5}) \end{cases}$$

Bottom up: Yukawa hierarchies from measured CP violation

Motivation & Framework

Driving questions:

1. What can we learn about high-energy sector if CP violation is measured? $\rightarrow$ DUNE 2020's
2. Compatibility of (broken) flavor symmetry with data? $\rightarrow$ theoretical errors to exact zero-textures
3. Stability against experimental uncertainties?

$\rightarrow$ data-driven, "bottom-up" approach to theoretical top-down approaches!

Motivation & Framework

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Framework:

- rescale Yukawa and PMNS matrix: $\kappa_{\alpha I} = \sqrt{\frac{v_{EW}}{M_I}} y_{\alpha I}, \qquad V_{\alpha i} = i\sqrt{\frac{m_i}{v_{EW}}} U^*_{\alpha i}$
- minimal set of DOFs:

9 free parameters at low energies:

+ 6 complex Yukawa coupling $y_{\alpha I}$
+ 2 Majorana phases M_I, $I = 1, 2$
- 3 charged-lepton phases
- 2 rescaling, $M/y^2 = const.$

7 observables at low energies:

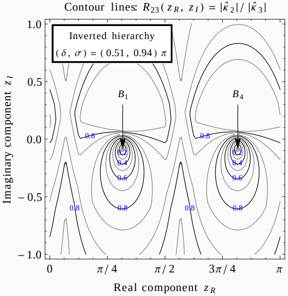
- 2 mass-squared differences $\Delta m^2_{atm}, \Delta m^2_{sol}$
- 3 mixing angles, $\theta_{atm}, \theta_{reactor}, \theta_{sol}$
- 1 Dirac CP phase δ
- 1 Majorana phase σ

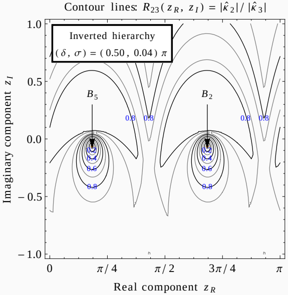
- Casas-Ibarra parametrization [Casas and Ibarra, 2001] $\rightarrow$ captures excess DOFs

$$\kappa_{\alpha 1} = \frac{1}{\sqrt{2}}\left(V^+_\alpha e^{-iz} + V^-_\alpha e^{+iz}\right) \quad \kappa_{\alpha 2} = \frac{i}{\sqrt{2}}\left(V^-_\alpha e^{+iz} - V^+_\alpha e^{-iz}\right), \quad V^\pm_\alpha = \frac{1}{\sqrt{2}}\left(V_{\alpha k} \pm iV_{\alpha l}\right)$$

Accessing hierarchies within Yukawa matrices:

- for each (δ, σ): two DOFs - real and imaginary part of complex rotation angle, z_R and z_I
  $\rightarrow$ label for all possible Yukawa matrices $y_{\alpha I}$





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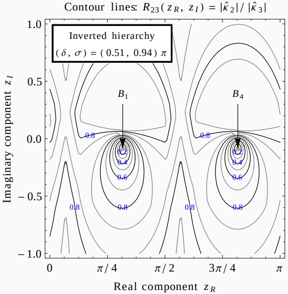
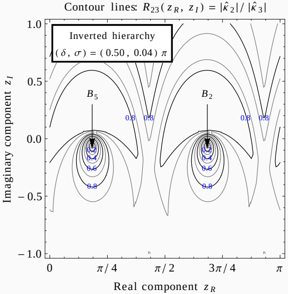
- @ each point of the complex z plane: sort Yukawa according to their abs. values
  $\kappa_{\alpha I} \rightarrow \hat{\kappa} = (\hat{\kappa}_1, \hat{\kappa}_2, \hat{\kappa}_3, \hat{\kappa}_4, \hat{\kappa}_5, \hat{\kappa}_6)$
- **Hierarchy parameter** $R_{23} \equiv \frac{|\hat{\kappa}_2|}{|\hat{\kappa}_3|}$
  - $R_{23} = 0 \rightarrow$ exact two-zero texture
  - $0 < R_{23} \ll 1 \rightarrow$ approximate texture
- Minimization of auxiliary parameter z:

$$H_{23} = min_z R_{23}$$





General approach and hierarchy parameter R_{23}

Accessing hierarchies within Yukawa matrices:

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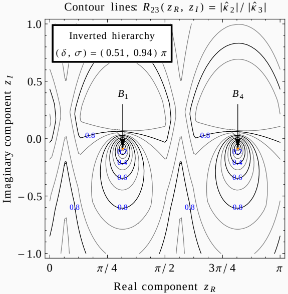
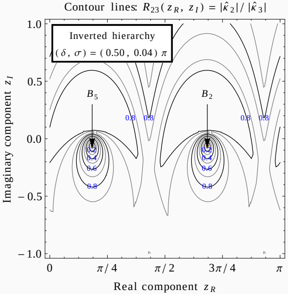
- Minimization of auxiliary parameter z:

$$H_{23} = min_z R_{23}$$

$\min_z \equiv$ scan over all UV flavor models of the minimal type-I seesaw model
$\rightarrow$ upper hierarchy bounds $H_{23}(\delta, \sigma)$!





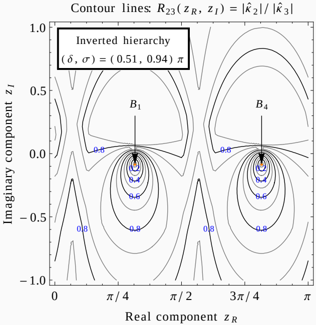
R_{23} **has useful properties:**

- probe actual Yukawa coupling if RH masses are degenerate or at least of some order of magnitude; otherwise simple rescaling

$$R_{23}(\delta,\sigma;z) = \frac{|\hat{\kappa}_2|}{|\hat{\kappa}_3|} = \left(\frac{\hat{M}_3}{\hat{M}_2}\right)^{\frac{1}{2}} \frac{|\hat{y}_2|}{|\hat{y}_3|} \simeq \frac{|\hat{y}_2|}{|\hat{y}_3|}$$

- periodic behavior:
  $R_{23}(\delta,\sigma;z) = R_{23}\left(\delta,\sigma;z+n\frac{\pi}{2}\right), \quad n\in\mathbb{Z}$
  $\Longrightarrow z\to z+\frac{\pi}{2} : \kappa_{\alpha 1}\to\kappa_{\alpha 1},\ \kappa_{\alpha 2}\to -\kappa_{\alpha 1}$
- reflection symmetry:
  $R_{23}(2\pi-\delta,\sigma;z) = R_{23}(\delta,\pi-\sigma;z)^*$
  invariance under $\delta\to-\delta, \quad \sigma\to-\sigma, \quad z\to z^*$
- independence of z in flavor-aligned limit:

$$z_I\to\pm\infty \Rightarrow R_{23}\to R_{23}^{\pm} = \left|\frac{V_{\alpha_1 k}\pm iV_{\alpha_1 l}}{V_{\alpha_2 k}\pm iV_{\alpha_2 l}}\right|$$



Flavor-alignment

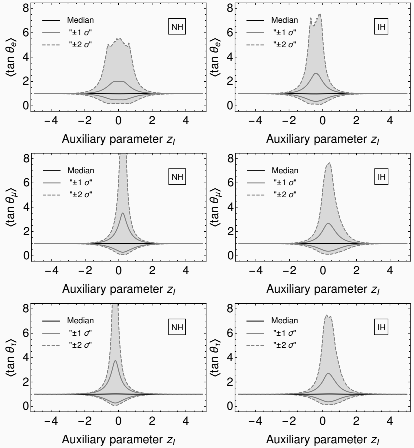
Observation:

- for large z_I: $\kappa_{\alpha 1} \simeq \kappa_{\alpha 2}$
- special configuration in flavor space, inconsistent with data
- systematic study of transition to alignment
  [TR, K.Schmitz, T.Yanagida, 2016]

$$y_{\alpha I} = \begin{pmatrix} \epsilon \cos\theta_e e^{i\phi_e} & \epsilon \sin\theta_e e^{i(\phi_e + \Delta\phi_e)} \\ \cos\theta_\mu e^{i\phi_\mu} & \sin\theta_\mu e^{i(\phi_\mu + \Delta\phi_\mu)} \\ c_{\mu\tau} \cos\theta_\tau e^{i\phi_\tau} & c_{\mu\tau} \sin\theta_\tau e^{i(\phi_\tau + \Delta\phi_\tau)} \end{pmatrix} y_0$$

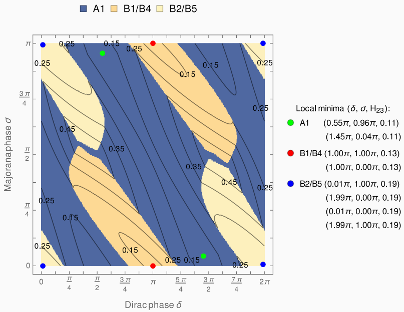
$\rightarrow$ flavor alignment for $|z_I| \gg 1$!

- separated study of aligned and un-aligned parameter space regions
  [TR, K.Schmitz, 2016]

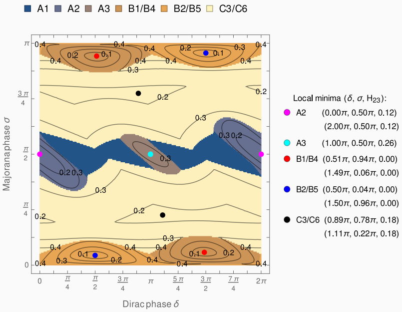


Minimized hierarchy parameter H_{23}:

Normal hierarchy



Inverted hierarchy



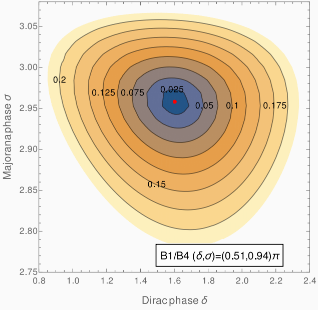
- Exact zero-textures are recovered: $B_{1,4}$ and $B_{2,5}$
- Maximal hierarchies for different flavor texture
- New approximate solution for NH and IH!

$\longrightarrow$ NH A_1 predicts max. CP violation with $\delta \sim 270^\circ \Longrightarrow$ UV origin?

Theoretical error bars and robustness study

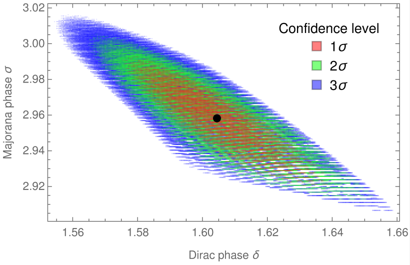
Perturbations around exact predictions:

- exact textures may receive correction by loops, gravity, etc.
- quantifications of maximally allowed perturbations
- complementary to experimental uncertainties owing to experimental error bars



Stability against experimental uncertainties:

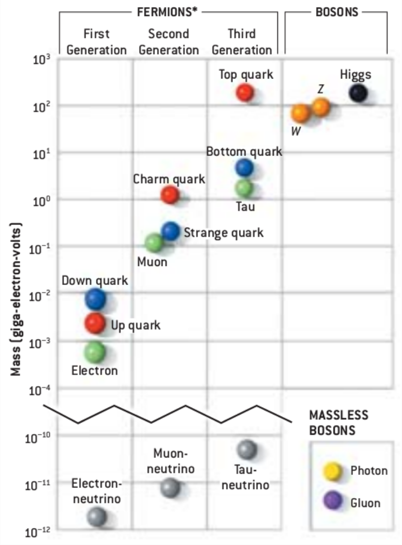
- naive χ^2 analysis as first estimate
- negligible shifts of CP phases if best-fit values vary



Top down: Minimal seesaw with approximate discrete symmetry

Generation of Yukawa textures

Flavor physics provide useful tools!



[scienceblogsl.com]

- Radiative generation [Georgi and Glashow, 1972]
- Extra dimensions [Grossman and Neubert, 2000]
- Compositeness [Kaplan, 1991]
- Froggatt-Nielsen [Froggatt and Nielsen, 1979]

Aim:
Yukawa matrix with A1 texture yielding NH at $\delta \simeq \frac{\pi}{2}, \frac{3\pi}{2}$

$$\kappa_{\alpha I} \sim \begin{pmatrix} 0.1 & 0.1 \\ 1 & 1 \\ 1 & 1 \end{pmatrix}$$

$\rightarrow SU(5)$ Froggatt-Nielsen mechanism [Buchmuller and Yanagida, 1999]

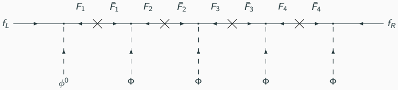
Froggatt-Nielsen mechanism [Froggatt and Nielsen, 1979]

Dynamical generation of Yukawa coupling through a globally/locally conserved charge Q_{FN}!

0. Generate heavy fermion masses at Λ_{FN}

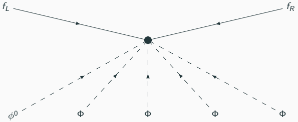
$$M_{ij} = a_{ij}\Lambda_{FN}, a_{ij} \sim \mathcal{O}(1)$$

1. Introduce "spaghetti" interactions at high scale through flavon fields Φ (charge assignment according to chain length)



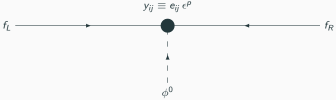
$$\mathcal{L} \supset b_{ij}\Phi f_i F_j + c_{ij}\Phi F_i F_j + d_{ij}\phi f_i F_j + M_{ij} F_i F_j + \text{h.c.}$$

2. Integrate out heavy fields F_i



$$\mathcal{L}_{eff} \supset e_{ij}\left(\frac{\Phi}{\Lambda_{FN}}\right)^{\Delta Q_{Fn}} f_i f_j \phi$$

3. SSB of FN symmetry $\Phi \rightarrow \langle\Phi\rangle$



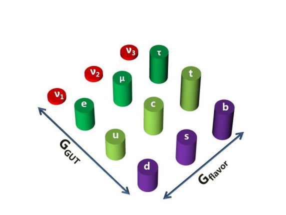
$$\mathcal{L}_{eff} \supset e_{ij}\,\epsilon^{\Delta Q_{FN}}\, f_i f_j \phi\,, \epsilon \equiv \left(\frac{\langle\Phi\rangle}{\Lambda_{Fn}}\right)$$

$SU(5) \times U(1)_5$ GUT [Georgi and Glashow, 1972], etc.

- "smallest" group containing the SM gauge group

$$SU(5) \xrightarrow{m_X} SU(3)_C \times SU(2)_L \times U(1)_Y$$
$$\xrightarrow{m_{W,Z}} SU(3)_C \times U(1)_Q$$

- unify one generation in a $(\bar{\mathbf{5}} + \mathbf{10})$-representation
- additional $U(1)$ requires RH singlets for anomaly cancellation $\psi_\mathbf{1} \simeq N$ $\rightarrow S_\mathbf{1}$ to break $U(1)$
- nice features, but common problems (proton decay, etc.) $\rightarrow SO(10) \subset SU(5) \times U(1)$



[http://theophys.kth.se/tepp/]

$$H_\mathbf{5} = \left(h_1, h_2, h_3, h^+, -h^0\right)^T = (3,1) + (1,2)$$

$$\psi_\mathbf{5} = \left(d_1, d_2, d_3, e^c, \nu^c\right)^T_R = (3,1) + (1,2)$$

$$X_\mathbf{10} = \begin{pmatrix} 0 & u_3^c & -u_2^c & -u_1 & -d_1 \\ -u_3^c & 0 & u_1^c & -u_2 & -d_2 \\ u_2^c & -u_1^c & 0 & -u_3 & -d_3 \\ u_1 & u_2 & u_3 & 0 & -e^+ \\ d_1 & d_2 & d_3 & e^+ & 0 \end{pmatrix}_L$$
$$= (3,2) + (\bar{3},1) + (1,1)$$

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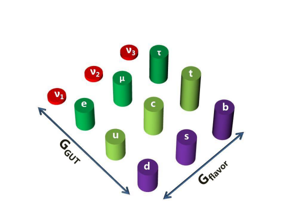

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$$= (3,2) + (\bar{3},1) + (1,1)$$

SU(5) Froggatt-Nielsen mechanism $\rightarrow$ one generation has same FN charge!

$$\mathcal{L}^5_{Yuk} = h^u_{ij}\epsilon^{\Delta Q}(X_{\mathbf{10}})_i(X_{\mathbf{10}})_j H_{\mathbf{5}} + h^d_{ij}\epsilon^{\Delta Q}(\psi_{\mathbf{5}})^*_i(X_{\mathbf{10}})_j H^*_{\mathbf{5}}$$
$$+ h^\nu_{ij}\epsilon^{\Delta Q}(\psi_{\mathbf{5}})^*_i(\psi_{\mathbf{1}})_j H_{\mathbf{5}} + h^s_{ij}\epsilon^{\Delta Q}(\psi_{\mathbf{1}})_i(\psi_{\mathbf{1}})_j S_{\mathbf{1}}$$

Modified Buchmuller-Yanagida-model

- Parametrize SM mass pattern
  → for $\epsilon_0 \simeq 0.17$ SM mass pattern is recovered!

$$m_t : m_c : m_u \simeq 1 : \epsilon^2 : \epsilon^4$$
$$m_b : m_s : m_d \simeq m_\tau : m_\mu : m_e \simeq 1 : \epsilon : \epsilon^3$$

$SU(5)$ multiplet	$\mathbf{10}_1$	$\mathbf{10}_2$	$\mathbf{10}_3$	$\mathbf{5}^*_1$	$\mathbf{5}^*_2$	$\mathbf{5}^*_3$	$\mathbf{1}_1$	$\mathbf{1}_2$	$\mathbf{1}_3$	Φ
Minimal seesaw embedding	2	1	0	2	1	1	q	q	$\diagdown$	-1

- heavy neutrino mass spectrum also generated via FN mechanism

$$m_R \sim \begin{pmatrix} \epsilon_0^{q_1} & 0 \\ 0 & \epsilon_0^{q_2} \end{pmatrix} m_0, \qquad q_i = 2\, Q_{FN}(N_i)$$

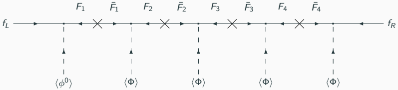
- resulting neutrino Yukawa couplings

$$y_{\alpha I} \sim \begin{pmatrix} \epsilon_0 & \epsilon_0 \\ 1 & 1 \\ 1 & 1 \end{pmatrix} y_0, \qquad y_0 \equiv \epsilon_0^q$$

Minimal seesaw model + discrete heavy-neutrino exchange symmetry

Ingredients:

- Yukawa structures generated through Froggatt-Nielsen flavor symmetry at high energy



$$\mathcal{L}_{eff} \supset \left(\frac{\Phi}{\Lambda}\right)^{q_i+q_j} \psi_i\psi_j\phi$$

- Charge assignment inspired by $SU(5)$ GUT

$$[L_e] = 2, \qquad [L_{\mu,\tau}] = 1, \qquad [N_{1,2}] = q$$

- Discrete exchange symmetry

Yukawa interaction $\quad N_1 \leftrightarrow iN_2$

mass term $\quad N_1 \leftrightarrow N_2$

$$\mathcal{L}_{seesaw} \sim -y_0\left(\epsilon l_e + l_\mu + c_{\mu\tau} l_\tau\right)\left(N_1 + iN_2\right)\phi - \frac{1}{2}M(N_1N_1 + N_2N_2)$$

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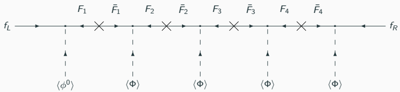

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All desired properties are reproduced:

- minimal[3] model: only two N's, appox. two-zero texture, flavor alignment
- Casas-Ibarra parametrization: in flavor-aligned regions independence of z
- Yukawa hierarchies fixed by FN model → CP phase predictions

Open questions: Origin of discrete symmetry (orbifolds?)

Generic set of parameters

Benchmark model:

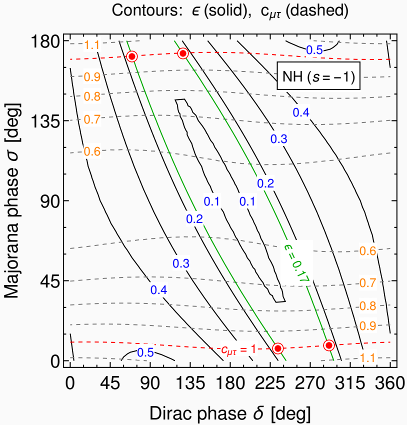
$$\mathcal{L}_{seesaw} \sim -y_0\,(\epsilon l_e + l_\mu + c_{\mu\tau} l_\tau)\,(N_1 + iN_2)\,\phi - \frac{1}{2} M (N_1 N_1 + N_2 N_2)$$

Assume "natural" hierarchies in Yukawa matrix:

- *SU*(5) FN flavor model: $\epsilon \simeq 0.17 \rightarrow \frac{|y_e|}{|y_{\mu,\tau}|}$
- equal muon and tauon Yukawa couplings: $c_{\mu,\tau} \simeq 1 \rightarrow \frac{|y_\mu|}{|y_\tau|}$

→ NH with maximal CP violation!

$$(\delta, \sigma) \simeq \begin{cases} (234^\circ, 7^\circ) \\ (291^\circ, 9^\circ) \\ (69^\circ, 171^\circ) \\ (126^\circ, 173^\circ) \end{cases}$$

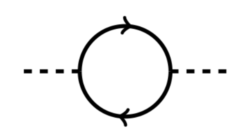


Heavy neutrino mass scale & theoretical arguments

Absolute neutrino mass scale of the constructed model: $M \simeq 4.6\, \epsilon_0^{-2q} e^{2z_I}\, 10^{15}$ GeV

Application of further theoretical arguments:

- electroweak naturalness ['t Hooft, 1980]



$$\delta\mu^2 = \approx \frac{M^3}{4\pi^2 v_{EW}^2} \cosh 2z_i \sum_i m_i$$

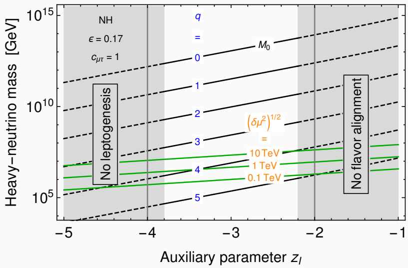
[Bambhaniya et al., 2016]

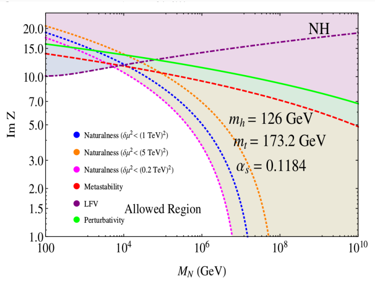
- successful (resonant) leptogenesis [Pilaftsis, 1997]

$$Y_{BAU} \propto \epsilon_{\alpha\alpha}\eta_\alpha \overset{!}{\simeq} 10^{-10...-11}$$

[Bambhaniya et al., 2016]

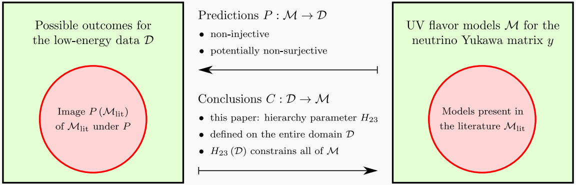
→ constrain last free parameters!





Summary and outlook - Minimal type-I seesaw investigation

Bottom-Up: Yukawa textures in term of CP phases δ, σ



- general method for assessing Yukawa structures
- maximal hierarchies for **approximate** two-zero textures consistent with data
- theoretical uncertainties for **exact** two-zero textures & robustness of results

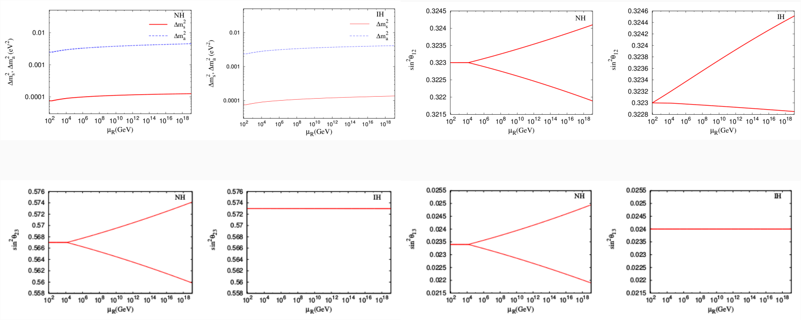
Top-Down: Benchmark model

- reproduction of current data sets
- embedding of minimal seesaw model in broader UV context
- prediction: NH A1 texture - $\delta \sim 270^\circ$!

Thank you for your attention!

RGE of neutrino mass parameters

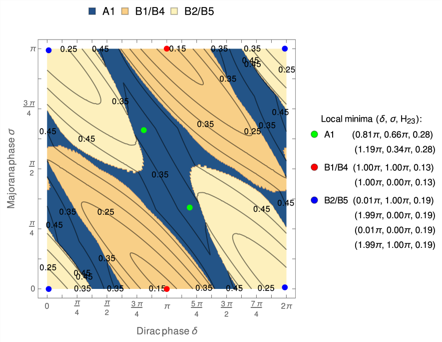
RGE can safely be neglected

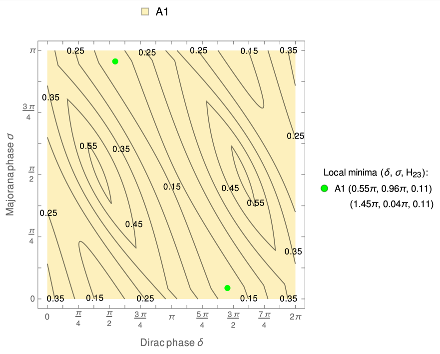


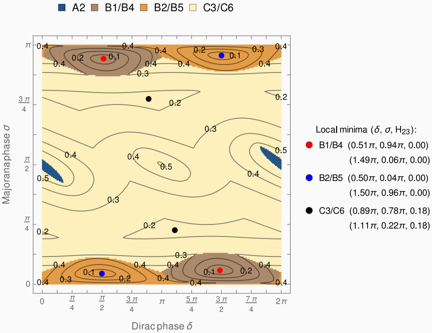
[Bambhaniya et al., 2016]

→ Experimental uncertainties outweigh RGE effects!

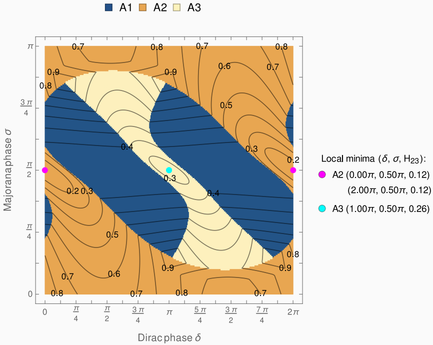
Normal hierarchy - flavor-(un)aligned regions







A2 B1/B4 B2/B5 C3/C6
Majorana phase σ
Dirac phase δ
Local minima (δ, σ, H23):
B1/B4 (0.51π, 0.94π, 0.00)
(1.49π, 0.06π, 0.00)
B2/B5 (0.50π, 0.04π, 0.00)
(1.50π, 0.96π, 0.00)
C3/C6 (0.89π, 0.78π, 0.18)
(1.11π, 0.22π, 0.18)



A1 A2 A3
Majorana phase σ
Dirac phase δ
Local minima (δ, σ, H23):
A2 (0.00π, 0.50π, 0.12)
(2.00π, 0.50π, 0.12)
A3 (1.00π, 0.50π, 0.26)

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