Fermion Masses and Mixing in Non-supersymmetric SO(10)

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SO(10) Models of Fermion Masses and Mixing

- $SO(10)$ GUT which unify strong and electroweak interactions also provide constrained and unified description of the fermion masses and mixing angles.
- All the known SM fermions plus three right-handed neutrinos fit into three copies of 16-dimensional spinorial representation of $SO(10)$.
- It predicts the existence of right-handed neutrinos and offers an appealing explanation for the smallness of neutrino masses through seesaw mechanisms.
- In renormalizable theories based on $SO(10)$ group, only three Yukawa coupling matrices Y_{10}, $Y_{\overline{126}}$, Y_{120} and relative strengths between them determine the entire spectrum of fermion masses and mixing angles.
- Because of the success of SUSY unification, most of the attention in recent years has been focused on supersymmetric $SO(10)$.

INTRODUCTION

Unification with Supersymmetry

- The minimal version of SUSY SO(10) constructed with $10 + 126 + \overline{126} + 210$ Higgs fields was found to be very predictive and studied in great details. [Aulakh, Bajc, Melfo, Senjanovic, Vissani (2004)]
- It has been shown recently that there is an inherent tension between
  - the need for relatively large atmospheric mass-squared difference in the neutrino sector
    (indicating $M_{B-L} \sim 10^{13}$GeV quite below $M_{GUT} \sim 10^{16}$GeV) and
  - the requirements of the gauge coupling convergence
    (preferring M_{B-L} close to M_{GUT})
- This issue is absent in the Non-Supersymmetric case because the separation between the GUT scale and intermediate scales is necessary for successful gauge coupling unification.

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Non-Supersymmetric $SO(10)$

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  [Bertolini, Luzio, Malinsky (2009, 2010)]

  - Two or three steps breaking of $SO(10)$ to the Standard Model can be achieved through vev of $\mathbf{45}_H$ and $\overline{\mathbf{126}}_H$ (or $\overline{\mathbf{16}}_H$). The presence of intermediate scale allows the gauge coupling unification.
  - The required pattern of the Higgs vevs for the gauge symmetry breaking can emerge from the minimization of the 1-loop corrected Higgs potential.
- This observation opens the option of considering the minimal non-susy $SO(10)$ model as a reference framework for model building.
- A complete and consistent model of this kind must also reproduce the viable and realistic fermion mass spectrum. Thus it is worth looking at detail fits to fermion masses in non-susy theory.
- A preliminary simplified two generation analytical study has been done in this direction but **Complete and systematic three generation analysis is not carried out so far.**

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Fermion Masses in SO(10)

The masses of $\mathbf{16}_F$ fermions arise from the renormalizable couplings with Higgs fields belonging to $\mathbf{10}_H$,$\overline{\mathbf{126}}_H$ and $\mathbf{120}_H$, since

$$\mathbf{16}\times\mathbf{16}=\mathbf{10}+\mathbf{126}+\mathbf{120}$$

Identifying the Minimal Higgs fields for Realistic Fermion Spectrum

- Decomposition under Pati-Salam ($SU(4)_{PS}\times SU(2)_L\times SU(2)_R$)

$$\begin{aligned}\mathbf{16} &= (4,2,1)+(\bar{4},1,2)\\ \mathbf{10} &= (1,2,2)+(6,1,1)\\ \mathbf{120} &= (1,2,2)+(6,3,1)+(6,1,3)+(15,2,2)+(10,1,1)+(\overline{10},1,1)\\ \overline{\mathbf{126}} &= (10,1,3)+(\overline{10},3,1)+(15,2,2)+(6,1,1)\end{aligned}$$

- VEV of $SU(2)_R(SU(2)_L)$ triplet $\in\overline{\mathbf{126}}$ generates light neutrino masses by type-I(type-II) seesaw mechanism.
  This makes the representation $\overline{\mathbf{126}}$ indispensable.

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\mathbf{120} &= (1,2,2) + (6,3,1) + (6,1,3) + (15,2,2) + (10,1,1) + (\overline{10},1,1) \\
\overline{\mathbf{126}} &= (10,1,3) + (\overline{10},3,1) + (15,2,2) + (6,1,1)
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The Minimal Higgs Sector

1. $\mathbf{10}_H + \overline{\mathbf{126}}_H$
2. $\mathbf{120}_H + \overline{\mathbf{126}}_H$

The Simplest Version: real $\mathbf{10}_H/\mathbf{120}_H$

- The most economical possibility would be to assume a real $\mathbf{10}_H/\mathbf{120}_H$.
- It is argued that a real $\mathbf{10}_H/\mathbf{120}_H$ cannot fit even two generation case. (as they predict $m_t/m_b \approx \mathcal{O}(1)$) [Bajc, Melfo, Senjanovic, Vissani (2006)]
- Thus both the cases require complexifying the Higgs fields $\mathbf{10}_H/\mathbf{120}_H$.

Complex $\mathbf{10}_H/\mathbf{120}_H$: Call for $U(1)_{PQ}$ symmetry

- This introduces an extra set of Yukawa couplings since both the real and imaginary parts of $\mathbf{10}_H/\mathbf{120}_H$ can independently couple to fermions.
- This can be avoided by assigning a Peccei-Quinn (PQ) charge

$$\mathbf{16}_F \to e^{i\alpha}\mathbf{16}_F \quad \text{and} \quad (\mathbf{10}_H, \overline{\mathbf{126}}_H, \mathbf{120}_H) \to e^{-2i\alpha}(\mathbf{10}_H, \overline{\mathbf{126}}_H, \mathbf{120}_H)$$

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Minimal Model: $10_H + \overline{126}_H$ Higgs

In this case, the most general Yukawa interaction is

$$\mathcal{L}_Y = \mathbf{16}_F\ [Y_{10}\mathbf{10}_H + Y_{126}\overline{\mathbf{126}}_H]\mathbf{16}_F + h.c.$$

After EWSB, the final fermion mass relations can suitably written as

$$\begin{aligned} M_d &= H + \ F \quad , \quad M_u = r(H + \ s\ F), \\ M_l &= H - 3F \quad , \quad M_D = r(H - 3s\ F), \\ M_L &= r_L\ F \quad , \quad M_R = r_R^{-1}\ F, \end{aligned}$$

The light neutrino mass matrix is given by,

$$\mathcal{M}_\nu = r_L F - r_R M_D F^{-1} M_D^T$$

- The model has 18 real parameters (compared to 56 in SM + RH neutrinos) which have to explain 20 observables of fermion masses and mixing angles. (16 measured at low energy + 4 predictions)
- Similar model was studied in great detail in context of SUSY $SO(10)$ and found to be consistent with low energy fermion mass spectrum.

Numerical Study of Model: χ^2 Analysis

- We do the χ^2 fitting to check the viability of the model.
- We construct

$$\chi^2(\alpha_j) = \sum_i \left(\frac{X_i(\alpha_j) - O_i}{\sigma_i} \right)^2$$

  Where,
  X_i are the fermion masses and mixing as complex nonlinear functions of parameters α_j calculated from the given model at GUT scale.
  O_i (σ_i) are the input mean values(1σ errors) of respective masses and mixing angles evaluated at M_{GUT}=2×10^{16} GeV.
- We assume normal hierarchy in neutrino masses and consider two separate cases corresponding to the individual dominance of type-I and type-II seesaw mechanism.
- Then the data are fitted by minimizing the χ^2 function with respect to parameters α_j using an algorithm based on the downhill simplex method.

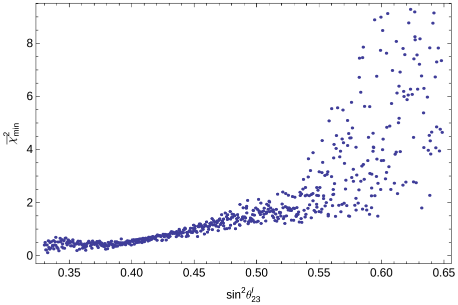
Minimal Model: Numerical Analysis

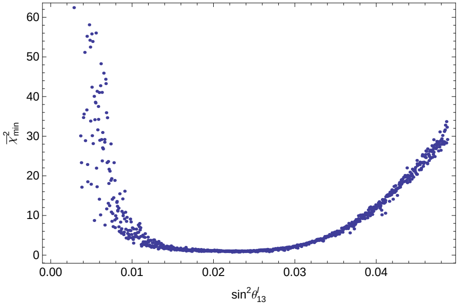
Results of χ^2 minimization

	Type-I		Type-II	
Observables	Fitted value	pull	Fitted value	pull
m_d	0.000810163	−0.687161	0.00101285	−0.264898
m_s	0.0208099	−0.198354	0.0225915	0.0844982
m_b	0.999667	−0.00831657	1.08201	2.05031
m_u	0.000495023	0.0751133	0.000507336	0.13668
m_c	0.237348	0.0670883	0.237096	0.0598882
m_t	73.9427	−0.0154941	74.3006	0.075144
m_e	0.000469652	–	0.000469652	–
m_μ	0.0991466	–	0.0991466	–
m_τ	1.68558	–	1.68558	–
$\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right)$	0.030526	0.127968	0.0297114	−0.235285
$\sin\theta^q_{12}$	0.224651	0.0464044	0.224499	−0.0916848
$\sin\theta^q_{23}$	0.0420499	0.0392946	0.0421308	0.103004
$\sin\theta^q_{13}$	0.00349369	−0.0974312	0.00353053	0.0389979
$\sin^2\theta^l_{12}$	0.323245	0.148134	0.3108	−0.610792
$\sin^2\theta^l_{23}$	0.435096	−0.369178	0.113306	−7.02461
$\sin^2\theta^l_{13}$	**0.0244287**	–	**0.0176863**	–
$\delta_{CKM}[^\circ]$	69.5262	−0.0314447	69.2051	−0.128759
$\delta_{MNS}[^\circ]$	**318.465**	–	**14.5386**	–
$\alpha_1[^\circ]$	**21.5053**	–	**345.645**	–
$\alpha_2[^\circ]$	**215.128**	–	**141.905**	–
χ^2_{min}		**0.710777**		**54.1197**

Minimal Model: Numerical Analysis

Results & Predictions





- There is no definite prediction for θ_{23} angle and very good fits are possible with values of θ_{23} in the whole range allowed by the data.
- There is a clear prediction for reactor angle $\sin^2\theta_{13}$ in the range of (0.005 - 0.035).
- We also found that the model allows whole range for CP violating Dirac phase in lepton sector δ_{PMNS}.

Minimal Model: Numerical Analysis

Failure of Type-II seesaw: An Analytical Understanding

- In the case of type-II dominance, the neutrino mass matrix can be written as

$$\mathcal{M}_\nu = r_L F \propto M_d - M_l \simeq m_b \begin{pmatrix} \epsilon & \epsilon \\ \epsilon & \frac{m_b - m_\tau}{m_b} \end{pmatrix}$$

- It has been shown that the above relation offers an interesting connection between $b - \tau$ unification and the large atmospheric mixing angle.

[Bajc, Senjanovic, Vissani (2004)]

- In SUSY version, the extrapolated data at the GUT scale shows $m_b \simeq m_\tau$ which generates large atmospheric angle.
- In NON-SUSY version, $b - \tau$ unification fails badly ($m_\tau \simeq 1.6 m_b$) at GUT scale and it generates small atmospheric mixing angle.

Non-unification of $b - \tau$ masses in non-susy spectrum disfavors type-II dominance in the minimal model.

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Minimal Model: Numerical Analysis

Fitted Structure of Mass Matrices

- The fitted fermion mass matrices can approximately be parametrized as

$$M_f \approx m_{f3} \begin{pmatrix} (1+\epsilon^f_{11})\lambda^4 & (1+\epsilon^f_{12})\lambda^3 & (1+\epsilon^f_{13})\lambda^2 \\ (1+\epsilon^f_{12})\lambda^3 & (1+\epsilon^f_{22})\lambda^2 & (1+\epsilon^f_{23})\lambda \\ (1+\epsilon^f_{13})\lambda^2 & (1+\epsilon^f_{23})\lambda & 1. \end{pmatrix} \quad \text{where } f = d, u, l, D, R$$

- Phenomenological consequences of such structure has been studied earlier by Dorsner & Smirnov (2004) and it was found that it generates correct hierarchy of the quark masses and mixings.
- After seesaw mechanism, the light neutrino mass matrix takes the form

$$\mathcal{M}_\nu \approx m_0 \begin{pmatrix} (1+\epsilon_{11})\lambda^2 & (1+\epsilon_{12})\lambda^2 & (1+\epsilon_{13}) \\ (1+\epsilon_{12})\lambda^2 & (1+\epsilon_{22}) & (1+\epsilon_{23}) \\ (1+\epsilon_{13}) & (1+\epsilon_{23}) & 1 \end{pmatrix}$$

- Such structure generally predicts hierarchical neutrinos, near maximal atmospheric mixing and large 13 mixing angle.
- **Such structure provides hint into possible flavor structure of fermions and can be a starting point to uncover the underlying flavor symmetries.**

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Minimal Model-II: $120_H + \overline{126}_H$ Higgs

In this case, the final fermion mass relations can suitably written as

$$M_d = G + F \quad , \quad M_u = t_u\, G + s\, F,$$
$$M_l = t_l\, G - 3F \quad , \quad M_D = t_D\, G - 3s\, F,$$

where G is an anti-symmetric matrix. The light neutrino mass matrix is given by,

$$\mathcal{M}_\nu = r_L F - r_R M_D F^{-1} M_D^T$$

- We studied the viability of above relations through detailed numerical analysis.
- This model is found to be highly inconsistent with all the data extrapolated at the GUT scale and show poor fits:
  - $\chi^2_{min} \sim$ **60** (in case of type-I seesaw)
  - $\chi^2_{min} \sim$ **72** (in case of type-II seesaw)

So the model with $120_H + \overline{126}_H$ Higgs fields is unable to reproduce the fermion spectrum and can be ruled out.

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An Extended Model: $10_H + \overline{126}_H + 120_H$

- The other model (studied extensively in SUSY context) is constructed with all three Higgs fields which has 28 real parameters in general.
- Considerable reduction in parameters can be achieved by restricting to the Hermitian mass matrices which can be achieved by assuming Spontaneous CP Violation (SCPV).
- In this case, the fermion mass relations can be written as

$$M_d = H + F + iG \quad , \quad M_u = r(H + sF + it_u G),$$
$$M_l = H - 3F + it_l G \quad , \quad M_D = r(H - 3sF + it_D G)$$

where H, F are real symmetric and G is real anti-symmetric matrices. r, s, t_f are real dimensionless parameters. The light neutrino mass matrix is given by,

$$\mathcal{M}_\nu = r_L F - r_R M_D F^{-1} M_D^T \equiv \mathcal{M}_\nu^{II} + \mathcal{M}_\nu^{I}$$

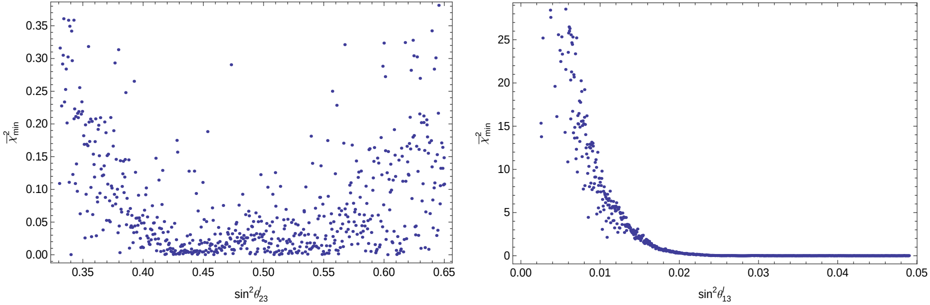
- This model has 17 real parameters (one less compared to minimal model) and provide predictive framework for fermion spectrum.

Extended Model: Numerical Analysis

Results of χ^2 minimization

	Type-I		Type-II	
Observables	Fitted value	pull	Fitted value	pull
m_d	0.00113968	−0.000676838	0.00108711	−0.110189
m_s	0.0219909	−0.00150966	0.0142689	−1.28852
m_b	1.	0.0000376219	1.19665	4.9162
m_u	0.000480133	0.000666686	0.000486627	0.0331338
m_c	0.235007	0.000211758	0.240819	0.166268
m_t	73.9997	−0.0000888053	77.4295	0.857367
m_e	0.000469652	0	0.000469652	0
m_μ	0.0991466	0	0.0991466	0
m_τ	1.68558	0	1.68558	0
$\left(\frac{\Delta m^2_{sol}}{\Delta m^2_{atm}}\right)$	0.0302402	0.000545016	0.0260106	−1.88556
$\sin\theta^q_{12}$	0.224601	0.00105776	0.224567	−0.0304356
$\sin\theta^q_{23}$	0.0420001	0.0000431604	0.0431393	0.897068
$\sin\theta^q_{13}$	0.00351992	−0.000308192	0.00338234	−0.509862
$\sin^2\theta^l_{12}$	0.320821	0.000292661	0.278093	−2.6052
$\sin^2\theta^l_{23}$	0.453034	0.000947066	0.343286	−2.26804
$\sin^2\theta^l_{13}$	**0.0306736**	–	**0.00538748**	–
$\delta_{\rm CKM}[^\circ]$	69.6278	−0.000660788	72.7155	0.935014
$\delta_{\rm MNS}[^\circ]$	**355.719**	–	**46.8148**	–
$\alpha_1[^\circ]$	**60.079**	–	**60.6202**	–
$\alpha_2[^\circ]$	**214.691**	–	**250.978**	–
χ^2_{min}		$\sim 10^{-6}$		**44.0801**

Results & Predictions



- Like minimal model, there is no definite prediction for θ_{23} angle and very good fits are possible with values of θ_{23} in the whole range allowed by the data.
- Model predicts relatively large values for reactor angle $\sin^2\theta_{13} \gtrsim 0.01$.
- It also allows whole range for CP violating Dirac phase in lepton sector δ_{PMNS}.

SUMMARY

- We studied the fit of quark and lepton masses and mixing data within a class of non-supersymmetric $SO(10)$ models.
- Among the various possible options for constructing a predictive model, we found the minimal model with $\mathbf{10}_H + \overline{\mathbf{126}}_H$ Higgs fields and an additional $U(1)_{PQ}$ symmetry can reproduce the entire fermion spectrum if neutrinos get their masses through type-I seesaw mechanism.
- It predicts the value of atmospheric angle $\sin^2\theta_{13} \sim$(0.005-0.035) which can be tested by current generation of neutrino oscillation experiments.
- This minimal model together with $\mathbf{45}_H$ Higgs may provide the platform for exploring the possibility of a realistic and predictive GUT, along the lines of the recent efforts in the SUSY context.
- We also found that an alternative model with extended Higgs sector and with the assumption of spontaneous CP violation can also provide a predictive and viable scenario for fermion spectrum in non-susy $SO(10)$.

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