Minimal Non-SUperSYmmetric Unified Model

Saki Khan

Oklahoma State University

saki.khan@okstate.edu

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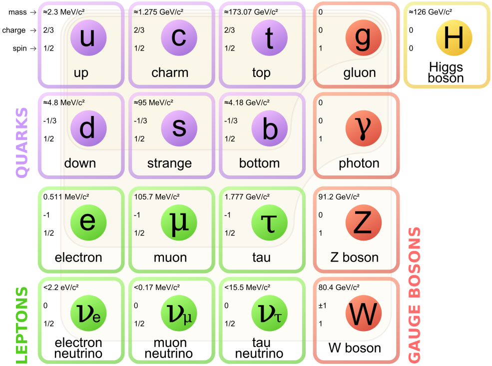
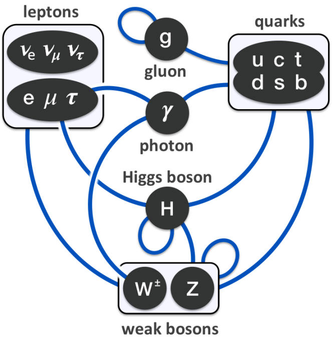
Work done with Prof. Kaladi S. Babu

Overview

Standard Model of Particle Physics



Standard Model of Elementary Particles(by MissMJ - Wikipedia);



Elementary particle interactions in the SM(by Eric Drexler);

Unanswered Questions:

- **Charge Equality** : $|1 + \frac{Q_e}{Q_p}| < 10^{-21}$
- **Strong CP Problem**: Strong interaction sector admits a CP violating term, leading to a physical observable $\overline{\theta}$. Neutron Electric Dipole Moment limits $\overline{\theta} < 10^{-10}$.
- **Dark Matter**: The total massenergy of the known universe contains 4.9% ordinary matter, 26.8% dark matter (arXiv:1303.5062). Yet SM does not have any candidate for Dark Matter.
- **Neutrino Oscillation**: Neutrinos of different flavor $(\nu_e, \nu_\mu, \nu_\tau)$ can oscillate into each other due to non-zero neutrino mass and mixing angles. Flavor eigenstates of neutrinos are linear combination of field of three (or more) neutrinos (ν_j) with non-zero mass.
- **Stability of Higgs potential**: In SM, the Higgs Quartic Coupling becomes negative around 10^{11} GeV. This instabity in the electro-weak vacuum indicates that we might be living in a metable universe.

$SO(10)$ Grand Unification

- $SO(10)$ is a group of rank 5 with the extra diagonal generator of $SO(10)$ being $B-L$ as in the left-right symmetric groups. So, the gauge interactions of $SO(10)$ conserve parity thus making parity a part of a continuous symmetry.
- 16-dimensional spinor representation of $SO(10)$ can accommodate **ALL** fermions of one generation

$u_r: \{-++\ +-\}$	$d_r: \{-++\ -+\}$	$u_r^c: \{+--\ ++\}$	$d_r^c: \{+--\ --\}$
$u_b: \{+-+\ +-\}$	$d_b: \{+-+\ -+\}$	$u_b^c: \{-+-\ ++\}$	$d_b^c: \{-+-\ --\}$
$u_g: \{++-\ +-\}$	$d_g: \{++-\ -+\}$	$u_g^c: \{--+\ ++\}$	$d_g^c: \{--+\ --\}$
$\nu: \{---\ +-\}$	$e: \{---\ -+\}$	$\nu^c: \{+++\ ++\}$	$e^c: \{+++\ --\}$

The first 3 indicates color spin and last two weak spin.

$$Y = \frac{1}{3}\sum(C) - \frac{1}{2}\sum(W)$$

- Unification of three couplings (α_s, α_{2L} and α_Y) into one coupling constant α_{GUT} even in Non-SUSY scenario with the help of an intermediate scale.
- Existence of ν_R and thus neutrino mass via seesaw.
- Baryon asymmetry.

Motivation

Looking for a Minimal Realistic Unified Model with the properties:

- Unification of the coupling happens at large enough energy scale which is compatible with the proton-lifetime
- Some kind of particle spectrum which can modify the higgs quartic coupling so that stability issue of the electroweak vacuum can be addressed
- A realistic Yukawa sector which can generate realistic fermion masses and Mixings including neutrino data
- Can also generate the baryon asymmetry (most probably via leptogenesis)
- An axion suitable to solve Strongs CP problem and account for the observed Dark Matter.

G. Altarelli and D. Meloni, 2013
Malinsky et al, 2011, 2012, 2013

Possible Higgs Sector

Let's try:

- 45 + 16 $\rightarrow$ wants to breaks via $SU(5)$, which is ruled out by proton lifetime. Also, disfavored by Neutrino oscillation data, as effective $B - L$ scale is suppressed and the light neutrino masses are overshoot.

- 54 + 16 $\rightarrow$ 54 and 16 do not have any nontrivial cross couplings, so the global symmetry is SO(10) x SO(10). When this symmetry breaks down, there is a Goldstone, belonging to (3,2,1/6)+ h.c.

- 45 + 126 $\rightarrow$ tends to go through $SU(5)$ breaking channel. If it is forced to go through L-R symmetric channel, one gets tachyonic masses.(1) It has been claimed that one can remove that issue by quantum corrections.(2)

  (1) Yasue 1981, Anastaze, Buccella 1983, Babu,Ma 1985, (2) Bertolini,Luzio, Malinsky 2010

- 54 + 126 $\rightarrow$ possible candidate!!!

The Model

$$SO(10)$$

$\longrightarrow$ Real 54

$$SU(4)_C \times SU(2)_L \times SU(2)_R \times D$$

$\longrightarrow$ Complex 126

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$\longrightarrow$ Complex 10

$$SU(3)_C \times U(1)_Q$$

Higgs Mass Scale

Extended Survival Hypothesis(ESH): At any scale, the only scalar multiplets present are those that develop VEVs at smaller scales.
To get realistic prediction, one may need to extend ESH.

- $54 = (1,3,3)_{PS} + (20',1,1)_{PS} + (6,2,2)_{PS} + (1,1,1)_{PS}$
  - $<54>$ breaks $SO(10)$ $\Rightarrow$ All the components of 54 @ M_U.
- $126 = (10,1,3)_{PS} + (\overline{10},3,1)_{PS} + (15,2,2)_{PS} + (6,1,1)_{PS}$
  - $<(10,1,3)>$ breaks $PS \times D$ $\Rightarrow$ $(10,1,3)$ @ M_i.
  - D-parity $\Rightarrow$ $(\overline{10},3,1)$ @ M_i.
  - Realistic fermion mass spectrum $\Rightarrow$ $(15,2,2)$ @ M_i.
  - Detailed potential analysis $\Rightarrow$ $(6,1,1)$ @ M_i.
- $10 = (1,2,2)_{PS} + (6,1,1)_{PS} = (1,2,+1/2)_{SM} + (1,2,-1/2)_{SM} + (3,1,-1/3)_{SM} + (\overline{3},1,+1/3)_{SM}$
  - $<(1,2,-1/2)>$ breaks EW $\Rightarrow$ $(1,2,-1/2)$ @ M_w
  - ESH $\Rightarrow$ all other @ Higher Scale

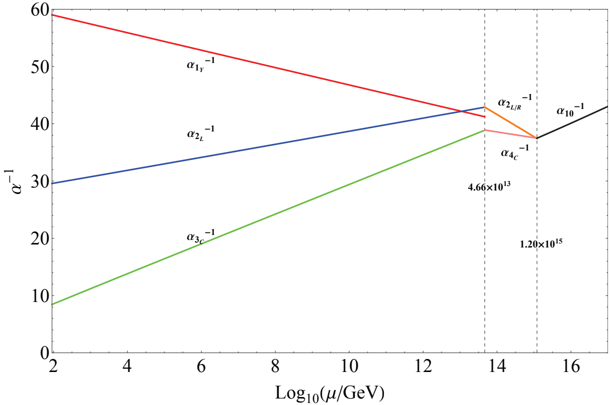
The Higgs Sector

SO(10)	$SU(4)_C \times SU(2)_L \times SU(2)_R$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Scale
10	$H_1(6,1,1)$	$T_1(3,1,-\frac{1}{3})$	M_u
		$T_2(\overline{3},1,+\frac{1}{3})$	M_u
	$H_2(1,2,2)$	$R_1(1,2,+\frac{1}{2})$	M_i
		$R_2(1,2,-\frac{1}{2})$	M_w
54	$\zeta_1(1,3,3)$	$\phi_1(1,3,+1)$	M_u
		$\phi_2(1,3,0)$	M_u
		$\phi_3(1,3,-1)$	M_u
	$\zeta_2(6,2,2)$	$\phi_4(3,2,+\frac{1}{6})$	M_u
		$\phi_5(3,2,-\frac{5}{6})$	M_u
		$\phi_6(\overline{3},2,+\frac{5}{6})$	M_u
		$\phi_7(\overline{3},2,-\frac{1}{6})$	M_u
	$\zeta_3(20',1,1)$	$\phi_8(\overline{6},1,+\frac{2}{3})$	M_u
		$\phi_9(6,1,-\frac{2}{3})$	M_u
		$\phi_{10}(8,1,0)$	M_u
	$\zeta_0(1,1,1)$	$\phi_0(1,1,0)$	M_u

Contd...

SO(10)	$SU(4)_C \times SU(2)_L \times SU(2)_R$	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Scale
126	$\Sigma_1(6,1,1)$	$\Sigma_{11}(3,1,-\frac{1}{3})$	M_u
		$\Sigma_{12}(\bar{3},1,+\frac{1}{3})$	M_u
	$\Sigma_2(10,3,1)$	$\Sigma_{21}(1,3,-1)$	M_i
		$\Sigma_{22}(3,3,-\frac{1}{3})$	M_i
		$\Sigma_{23}(6,3,+\frac{1}{3})$	M_i
	$\Sigma_3(\overline{10},1,3)$	$\Sigma_{31}(1,1,0)$	M_i
		$\Sigma_{32}(1,1,+1)$	M_i
		$\Sigma_{33}(1,1,+2)$	M_i
		$\Sigma_{34}(\bar{3},1,+\frac{4}{3})$	M_i
		$\Sigma_{35}(\bar{3},1,+\frac{1}{3})$	M_i
		$\Sigma_{36}(\bar{3},1,-\frac{2}{3})$	M_i
		$\Sigma_{37}(\bar{6},1,-\frac{4}{3})$	M_i
		$\Sigma_{38}(\bar{6},1,-\frac{1}{3})$	M_i
		$\Sigma_{39}(\bar{6},1,+\frac{2}{3})$	M_i
	$\Sigma_4(15,2,2)$	$\Sigma_{41}(1,2,+\frac{1}{2})$	M_i
		$\Sigma_{42}(1,2,-\frac{1}{2})$	M_i
		$\Sigma_{43}(3,2,+\frac{7}{6})$	M_i
		$\Sigma_{44}(3,2,+\frac{1}{6})$	M_i
		$\Sigma_{45}(\bar{3},2,-\frac{1}{6})$	M_i
		$\Sigma_{46}(\bar{3},2,-\frac{7}{6})$	M_i
		$\Sigma_{47}(8,2,+\frac{1}{2})$	M_i
		$\Sigma_{48}(8,2,-\frac{1}{2})$	M_i

Evolution of Gauge Couplings

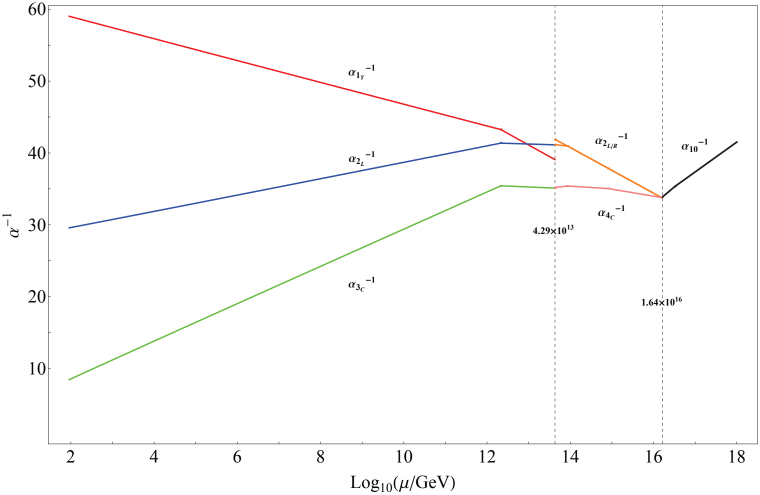


$$\tau_P \approx 5 \times 10^{29} yrs$$

Current Limit on proton life time:

$$\tau_P > 1.29 \times 10^{34} yrs$$

Threshold Corrections are Important!



Proton Lifetime (Revisited)

$$\tau_P \approx \frac{\pi}{4} R_L^2 (1+F+D) \frac{|\alpha|^2}{f_\pi^2} m_p \alpha_G^2 \left[A_{SR}^2 \left(\frac{1}{M_{(X,Y)}^2} + \frac{1}{M_{(X',Y')}^2} \right)^2 + \frac{4A_{SL}^2}{M_{(X,Y)}^4} \right]^{-1}$$

Here,

$$A_{SL(R)} = \prod_{i=1}^{n} \prod_{sc}^{Mz \leq m_{sc} < M_G} \left[\frac{\alpha_i(m_{sc+1})}{\alpha_i(m_{sc})} \right]^{\frac{\gamma_{L(R)i(sc)}}{b_i(m_{sc+1} - m_{sc})}}$$

where,

$$\gamma_{L(sm)} = \left\{ \frac{23}{20}, \frac{9}{4}, 2 \right\}; \quad \gamma_{R(sm)} = \left\{ \frac{11}{20}, \frac{9}{4}, 2 \right\}; \quad \gamma_{L/R(ps)} = \left\{ \frac{15}{4}, \frac{9}{4}, \frac{9}{4} \right\}$$

Proton Lifetime

$$\begin{aligned} \Gamma^{-1}(p \to e^+ \pi^0) &\approx (8.2 \times 10^{34} \text{yr}) \\ &\times \left(\frac{\alpha_H}{0.0122 \text{GeV}^3} \right)^{-2} \left(\frac{\alpha_G}{1/34.7} \right)^{-2} \left(\frac{A_R}{3.35} \right)^{-2} \left(\frac{M_X}{10^{16} \text{GeV}} \right)^4 \end{aligned}$$

Scalar Potential

The most general potential for the 54 and 126 representation can be written as

$$
\begin{aligned}
V(\phi,\Sigma) \quad = \quad & -\frac{\mu^2}{2}\Phi_{i,j}\Phi_{i,j} + \frac{c}{3}\Phi_{i,j}\Phi_{j,k}\Phi_{k,i} + \frac{a}{4}\Phi_{i,j}\Phi_{i,j}\Phi_{k,l}\Phi_{k,l} + \frac{b}{2}\Phi_{i,j}\Phi_{j,k}\Phi_{k,l}\Phi_{l,i} \\
& -\frac{\nu^2}{2\cdot 5!}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,m} + \frac{\lambda_0}{(2)^2\,(5!)^2}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,m}\Sigma_{n,o,p,q,r}\Sigma^*_{n,o,p,q,r} \\
& +\frac{\lambda_2}{(4!)^2}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,n}\Sigma_{o,p,q,r,m}\Sigma^*_{o,p,q,r,n} \\
& +\frac{\lambda_4}{(3!)^2\,(2!)^2}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,n,o}\Sigma_{p,q,r,l,m}\Sigma^*_{p,q,r,n,o} \\
& +\frac{\lambda'_4}{(3!)^2}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,n,o}\Sigma_{p,q,r,l,n}\Sigma^*_{p,q,r,m,o} \\
& +\frac{\alpha}{2\,(5!)}\Phi_{i,j}\Phi_{i,j}\Sigma_{p,q,r,l,m}\Sigma^*_{p,q,r,l,m} + \frac{\beta}{3!}\Phi_{i,j}\Phi_{k,l}\Sigma_{m,n,o,i,k}\Sigma^*_{m,n,o,j,l}
\end{aligned}
$$

Scalar Potential(Contd...)

The interaction part of the potential with the 10 can be written as

$$\begin{aligned} V(\Phi,\Sigma,\phi) &= -\xi_0^2\phi_i\phi_i^* + \xi_1\phi_i\phi_i^*\phi_j\phi_j^* + \xi_2\phi_i\phi_i\phi_j^*\phi_j^* + \xi_3\Phi_{i,j}\phi_i\phi_j^* \\ &+ \frac{\gamma_1}{4!}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,n}\phi_m\phi_n^* + + \frac{\gamma_2}{4!}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,n}\phi_n\phi_m^* \\ &+ \frac{\eta_0}{2}\Phi_{i,j}\Phi_{i,j}\phi_k\phi_k^* + \frac{\eta_1}{(3!)^2(2!)^2}\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,p,q}\Sigma^*_{l,m,p,q,n}\phi_n \\ &+ \frac{\eta_1}{(3!)^2(2!)^2}\Sigma^*_{i,j,k,l,m}\Sigma_{i,j,k,p,q}\Sigma_{l,m,p,q,n}\phi_n^* \\ &+ \eta_2\Phi_{i,j}\Phi_{i,k}\phi_j\phi_k^* + \frac{\eta_3}{4!}\Sigma_{i,j,k,l,m}\Sigma_{i,j,k,l,n}\phi_m\phi_n \\ &+ \frac{\eta_3}{4!}\Sigma^*_{i,j,k,l,m}\Sigma^*_{i,j,k,l,n}\phi_m^*\phi_n^* \end{aligned}$$

Let us introduce a PQ symmetry whose natural scale will be M_i. Under this PQ symmetry $\mathbf{10} \to e^{-2i\alpha}\mathbf{10}$; $\mathbf{126} \to e^{2i\alpha}\mathbf{126}$; $\mathbf{S} \to e^{-4i\alpha}\mathbf{S}$

Part of the potential with the Singlet S can be written as

$$\begin{aligned} V(S) &= -\mu_s^2 SS^* + \chi_1(SS^*)^2 + \chi_2\Sigma_{i,j,k,l,m}\Sigma^*_{i,j,k,l,m}SS^* + \chi_3\Phi_{i,j}\Phi_{i,j}SS^* \\ &+ \frac{\chi_4}{4!}\Sigma_{i,j,k,l,m}\Sigma_{i,j,k,l,n}\Phi_{i,j}S + \frac{\chi_4}{4!}\Sigma^*_{i,j,k,l,m}\Sigma^*_{i,j,k,l,n}\Phi_{i,j}S^* \\ &+ \chi_5\phi_i\phi_i^*SS^* + \chi_6\phi_i\phi_iS^* + \chi_6\phi_i^*\phi_i^*S \end{aligned}$$

Scalar Mass Spectra

From this we can find out the relevant scalar masses as,

$$
\begin{aligned}
M^2[\Phi_2(1,3,0)] &= \frac{8}{5} b\omega_s^2 + c\omega_s \\
M^2[\Phi_{10}(8,1,0)] &= \frac{2}{5} b\omega_s^2 - c\omega_s \\
M^2[\Sigma_{22}(3,3,-\frac{1}{3})] &= 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2 \\
M^2[\Sigma_{23}(6,3,+\frac{1}{3})] &= 8\left(\lambda_2 + \lambda_4 + 4\lambda_4'\right)\sigma^2 \\
M^2[\Sigma_{33}(1,1,+2)] &= 8\left(\lambda_2 + \lambda_4 + 4\lambda_4'\right)\sigma^2 \\
M^2[\Sigma_{34}(\overline{3},1,+\frac{4}{3})] &= 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2 \\
M^2[\Sigma_{37}(\overline{6},1,-\frac{4}{3})] &= 8\left(\lambda_2 + \lambda_4 + 4\lambda_4'\right)\sigma^2 \\
M^2[\Sigma_{38}(\overline{6},1,-\frac{1}{3})] &= 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2
\end{aligned}
$$

Contd...

$$M^2[(1,3,+1)] = \begin{pmatrix} \frac{8}{5}b\omega_s + c\omega_s^2 + \frac{1}{2}\beta\sigma^2 & -2i\chi_4\sigma v_s \\ 2i\chi_4\sigma v_s & 8\left(2\lambda_2 + 3\lambda_4 + 2\lambda_4'\right)\sigma^2 \end{pmatrix};$$

$$M^2[(\overline{6},1,+\frac{2}{3})] = \begin{pmatrix} \frac{2}{5}b\omega_s - c\omega_s^2 + \frac{1}{2}\beta\sigma^2 & 2\chi_4\sigma v_s \\ 2\chi_4\sigma v_s & 8\left(2\lambda_2 + 3\lambda_4 + 2\lambda_4'\right)\sigma^2 \end{pmatrix};$$

$$M^2[(3,2,+\frac{7}{6})] = \begin{pmatrix} 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2 + \beta\omega_s^2 & -2\sqrt{2}\chi_4\omega_s v_s \\ -2\sqrt{2}\chi_4\omega_s v_s & 8\left(\lambda_2 + \lambda_4 + 2\lambda_4'\right)\sigma^2 + \beta\omega_s^2 \end{pmatrix};$$

$$M^2[(8,2,+\frac{1}{2})] = \begin{pmatrix} 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2 + \beta\omega_s^2 & -2\sqrt{2}\chi_4\omega_s v_s \\ -2\sqrt{2}\chi_4\omega_s v_s & 8\left(\lambda_2 + \lambda_4 + 2\lambda_4'\right)\sigma^2 + \beta\omega_s^2 \end{pmatrix};$$

$$M^2[(3,2,+\frac{1}{6})] = \begin{pmatrix} 8\left(2\lambda_2 + 3\lambda_4 + 2\lambda_4'\right)\sigma^2 + \beta\omega_s^2 & 2\sqrt{2}\chi_4\omega_s v_s & -2\chi_4\sigma v_s \\ 2\sqrt{2}\chi_4\omega_s v_s & \beta\omega_s^2 & \frac{1}{\sqrt{2}}\beta\sigma\omega_s \\ -2\chi_4\sigma v_s & \frac{1}{\sqrt{2}}\beta\sigma\omega_s & \frac{1}{2}\beta\sigma^2 \end{pmatrix};$$

The Mass Matrix of $M^2[(3,2,+\frac{1}{6})]$ has a zero eigenvalue which corresponds to the goldstone boson.

Contd...

$$M^2[(3,1,-\frac{1}{3})] = \begin{pmatrix} A1 & 4\sqrt{2}\chi_4\omega_s v_s & 0 & 0 & 0 \\ 4\sqrt{2}\chi_4\omega_s v_s & B1 & 16\sqrt{2}\lambda_4'\sigma^2 & 0 & 4\eta_1\sigma^2 \\ 0 & 16\sqrt{2}\lambda_4'\sigma^2 & 8\left(\lambda_2+\lambda_4\right)\sigma^2 & 0 & 4i\sqrt{2}\eta_1\sigma^2 \\ 0 & 0 & 0 & C1 & \sqrt{2}\chi_6 v_s \\ 0 & 4\eta_1\sigma^2 & -4i\sqrt{2}\eta_1\sigma^2 & \sqrt{2}\chi_6 v_s & C2 \end{pmatrix};$$

$$M^2[(1,2,+\frac{1}{2})] = \begin{pmatrix} 8\left(\lambda_2+\lambda_4-2\lambda_4'\right)\sigma^2+\beta\omega_s^2 & 2\sqrt{2}\chi_4\omega_s v_s & 0 & 4\sqrt{3}\eta_1\sigma^2 \\ 2\sqrt{2}\chi_4\omega_s v_s & 4\left(3\lambda_2+3\lambda_4+4\lambda_4'\right)\sigma^2+\beta\omega_s^2 & 0 & 0 \\ 0 & 0 & A2 & \sqrt{2}\chi_6 v_s \\ 4\sqrt{3}\eta_1\sigma^2 & 0 & \sqrt{2}\chi_6 v_s & B2 \end{pmatrix};$$

$$M^2[(1,1,0)] = \begin{pmatrix} \frac{1}{10}c\omega_s+\frac{12}{5}a\omega_s^2+\frac{14}{25}b\omega_s^2 & -\sqrt{\frac{3}{5}}(\alpha-\beta)\sigma\omega_s & -\sqrt{\frac{3}{5}}\chi_3\omega_s v_s \\ -\sqrt{\frac{3}{5}}(\alpha-\beta)\sigma\omega_s & \frac{1}{4}\lambda_0\sigma^2 & \frac{1}{2}\chi_2\sigma v_s \\ -\sqrt{\frac{3}{5}}\chi_3\omega_s v_s & \frac{1}{2}\chi_2\sigma v_s & \chi_1 v_s^2 \end{pmatrix};$$

where

$$\begin{aligned}
A1 &= 4\left(3\lambda_2 + 3\lambda_4 + 4\lambda_4'\right)\sigma^2 + 4\beta\omega_s^2 \\
B1 &= 8\left(\lambda_2 + \lambda_4 + 2\lambda_4'\right)\sigma^2 + 4\beta\omega_s^2 \\
A2 &= \frac{3}{5}\xi_3\omega_s + \frac{6}{5}\eta_0\omega_s^2 + \frac{9}{25}\eta_2\omega_s^2 + \gamma_1\sigma^2 + \frac{1}{2}\chi_5 v_s^2 + m^2 \\
B2 &= \frac{3}{5}\xi_3\omega_s + \frac{6}{5}\eta_0\omega_s^2 + \frac{9}{25}\eta_2\omega_s^2 + \gamma_2\sigma^2 + \frac{1}{2}\chi_5 v_s^2 + m^2 \\
C1 &= -\frac{2}{5}\xi_3\omega_s + \frac{6}{5}\eta_0\omega_s^2 + \frac{4}{25}\eta_2\omega_s^2 + \gamma_1\sigma^2 + \frac{1}{2}\chi_5 v_s^2 + m^2 \\
C2 &= -\frac{2}{5}\xi_3\omega_s + \frac{6}{5}\eta_0\omega_s^2 + \frac{4}{25}\eta_2\omega_s^2 + \gamma_2\sigma^2 + \frac{1}{2}\chi_5 v_s^2 + m^2
\end{aligned}$$

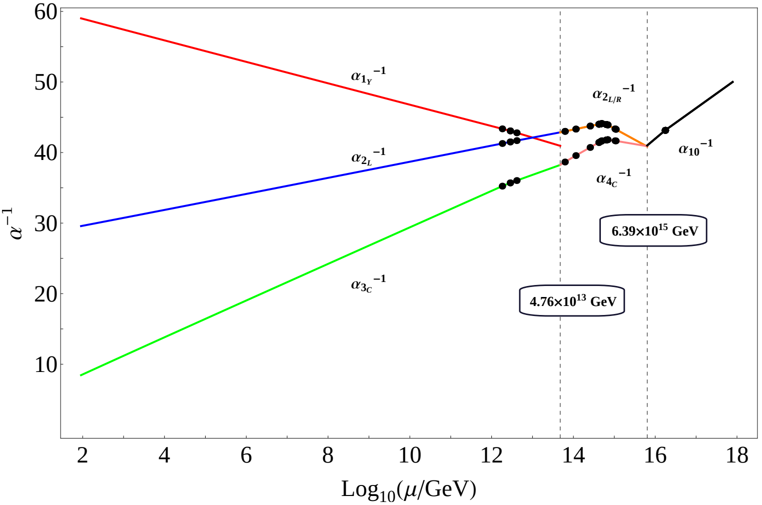
Sample Parameter

Parameter	Value	Parameter	Value
b	1.27	a	0.31
λ_2	0.71	λ_0	0.45
λ_4	0.87	α	0.23
λ_4'	.98	χ_1	0.38
β	1.9×10^{-3}	χ_2	0.12
η_1	0.083	χ_3	-0.71
η_2	-0.83	c	5.57×10^{15} GeV
χ_4	0.89	ξ_3	1.83×10^{15} GeV
χ_5	0.91	χ_6	-3.41×10^{12} GeV
γ_1	-0.70	v_s	5.25×10^{11} GeV
γ_2	-0.65	σ	7.1×10^{13} GeV
η_0	0.25	ω_s	1.1×10^{16} GeV

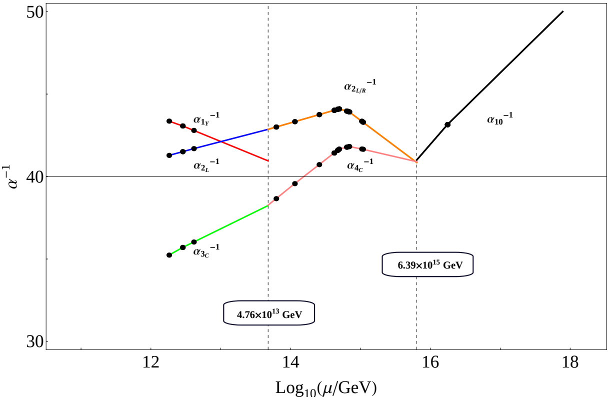
Higgs Spectra (Sample)

Multiplet	Mass [GeV]	Multiplet	Mass [GeV]
$(1,3,0)$	1.75×10^{16}	$(8,1,0)$	1.82×10^{12}
$(3,3,-\frac{1}{3})$	4.18×10^{14}	$(6,3,+\frac{1}{3})$	4.72×10^{14}
$(1,1,+2)$	4.72×10^{14}	$(\overline{3},1,+\frac{4}{3})$	4.18×10^{14}
$(\overline{6},1,-\frac{4}{3})$	4.72×10^{14}	$(\overline{6},1,-\frac{1}{3})$	4.18×10^{14}
$(1,3,+1)$	1.75×10^{16}	$(\overline{6},1,+\frac{2}{3})$	2.84×10^{12}
	4.92×10^{14}		4.92×10^{14}
$(3,2,+\frac{7}{6})$	4.79×10^{14}	$(8,2,+\frac{1}{2})$	6.32×10^{12}
	6.89×10^{14}		6.78×10^{14}
$(3,2,+\frac{1}{6})$	6.78×10^{14}	$(1,2,+\frac{1}{2})$	6.39×10^{14}
	6.32×10^{14}		4.66×10^{14}
$(3,1,-\frac{1}{3})$	1.04×10^{15}		4.10×10^{12}
	1.08×10^{15}		6.78×10^{14}
	1.14×10^{14}	$(1,1,0)$	1.35×10^{16}
	6.19×10^{13}		2.15×10^{13}
	2.55×10^{14}		6.15×10^{10}

Implementing the Mass relations



Zoom in to see the Threshold Effects



- Proton Life-time, $\tau = 3.4 \times 10^{34}$ yrs, beyond the current upper-limit (1.29×10^{34} yrs)

Fermion Masses, Mixings and Leptogenesis

The Yukawa sector of the Model looks like

$$\mathcal{L}_y = 16_F(h_{i,j}10_H + f_{i,j}\overline{126}_H)16_F \quad (1)$$

Fermion masses and mixings comes from the relations like:

$$M_u = hv_u + fk_u; \quad M_d = hv_d + fk_d; \quad M_\nu^D = hv_u - 3fk_u; \quad M_l = hv_d - 3fk_d; \quad M_\nu^M = f\sigma$$

obs.	*fit*	*pull*	*obs.*	*fit*	*pull*
m_u(MeV)	0.49	0.03	$\lvert V_{us}\rvert$	0.225	0.038
m_d(MeV)	0.78	0.75	$\lvert V_{cb}\rvert$	0.042	−0.208
m_s(MeV)	32.5	−1.50	$\lvert V_{ub}\rvert$	0.0038	−0.659
m_c(GeV)	0.287	−1.49	J	3.1×10^{-5}	0.589
m_b(GeV)	1.11	−2.77	$\sin^2\theta^l_{12}$	0.318	0.611
m_t(GeV)	71.4	0.70	$\sin^2\theta^l_{23}$	0.353	−1.548
r	0.031	0.10	$\sin^2\theta^l_{13}$	0.0222	−0.758
η_B	5.699×10^{-10}	−0.001			

Table 5: *Best fit solutions for the fermion observables at the scale* $M_{GUT} = 2 \cdot 10^{16}$ *Ge*

A Best fit parameter values

Here we list the best fit values of the 15 parameters used in our fit procedure. The 12 elements in M_d are as follows:

$$M_d\,(\text{GeV}) = \begin{pmatrix} (-.0034, .0004) & (-7.7\times10^{-6}, -.0098) & (-.0112, -.0712) \\ (-7.7\times10^{-6}, -.0098) & (.0108, .0010) & (.2162, .0060) \\ (-.0112, -.0712) & (.2162, .0060) & (1.062, -.0584) \end{pmatrix},$$

The complex parameter s and the real parameter r_v are:

$$s = (.37, -.079) \qquad r_v = 60.03\,. \quad (30)$$

- The model is completely consistent with the Fermion mass fitting generated for Non-SUSY SO(10) models. For example the sample point has $r_v = 60.9$ and $s = (0.36, 0)$

Babu, Mohapatra (1993) , Bertolini, Frigerio, Malinsky (2004), Fukuyama, Okada (2002)
Babu, Macesanu (2005), Bajc, Melfo, Senjanovic, Vissani (2004), Bertolini, Malinsky, Schwetz (2006)
Fukuyama, Ilakovac, Kikuchi, Meljanac, Okada (2004), Dutta, Mimura, Mohapatra (2007), Aulakh et al (2004)
Bajc, Dorsner, Nemevsek (2009), A. S. Joshipura et al (2011), Dueck, Rodejohann (2013)
Altarelli and Meloni., arXiv:1305.1001v2 [hep-ph] Joshipura and Patel., arXiv:1102.5148 [hep-ph]

Axion in Minimal $SO(10)$ GUT

- One complex scalar with vev v_s
- One uptype Higgs doublet ϕ_1^u from 10_H with vev v_u
- One downtype Higgs doublet ϕ_1^d from 10_H with vev v_d
- One uptype Higgs doublet ϕ_2^u from 126_H with induced vev k_u
- One downtype Higgs doublet ϕ_2^d from 126_H with induced vev k_d

The axion is primarily the Imaginary part of the complex scalar and the Axion decay constant is naturally around the Intermediate Scale

$$m_A = \frac{z^{1/2}}{1+z}\frac{f_\pi m_\pi}{f_A} \approx \frac{0.60meV}{f_A/10^{10}GeV}$$

Summary

- Here, we have constructed a Minimal Non-SUSY $SO(10)$ GUT model which is capable of explaining all the unanswered questions of standard model yet non of the experimental data can exclude the model.
- Besides the fact that the model has to rely on Fine-tuning for problems like hierarchy, the model is quite a natural one. We did not have to abandon ESH (Extended Survival Hypothesis) and no new fermions were needed.
- The Higgs sector was bare minimum to generate realistic fermion masses and that was good enough for solve other issues.
- The axion found in the model can explain Dark Matter.

Thank You