Masses of third family vectorlike quarks and leptons in Yukawa-unified E_{6}

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Masses of Third Family Vector-like Quarks and Leptons in Yukawa-Unified E_6

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Abstract

In supersymmetric E_6 the masses of the third family quarks and charged lepton, $t - b - \tau$, as well as the masses of the vector-like quarks and leptons, $D - \bar{D}$ and $L - \bar{L}$, may arise from the coupling $27_3 \times 27_3 \times 27_H$, where 27_3 and 27_H denote the third family matter and Higgs multiplets respectively. We assume that the SO(10) singlet component in 27_H acquires a TeV scale VEV which spontaneously breaks $U(1)_\psi$ and provides masses to the vector-like particles in 27_3, while the MSSM doublets in 27_H provide masses to t, b and τ. Imposing Yukawa coupling unification $h_t = h_b = h_\tau = h_D = h_L$ at M_{GUT} and employing the ATLAS and CMS constraints on the Z'_ψ boson mass, we estimate the lower bounds on the third family vector-like particles $D - \bar{D}$ and $L - \bar{L}$ masses to be around 5.85 TeV and 2.9 TeV respectively. These bounds apply in the supersymmetric limit.

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Introduction

Yukawa coupling unification (YU) $h_t = h_b = h_\tau$ of third family charged fermions [1] has received a great deal of attention [2] [3]. While originally implemented in SO(10) grand unification [4], YU has also been studied [5] in the framework of $SU(4)_c \times SU(2)_L \times SU(2)_R$ (4-2-2) gauge group [6] with some interesting results. For instance, in 4-2-2 models assuming plausible supersymmetry (SUSY) breaking scenarios such as non universal Higgs and scalar masses (NUHM2), one finds that a scenario consistent with the observed (LSP) dark matter abundance and various other experiments requires a NLSP gluino. This is certainly being tested at the LHC. In a different scenario also with $t-b-\tau$ YU but non-universal gaugino masses [7], the colored sparticles lie in the multi-TeV range, while the scalar partners of the leptons are significantly lighter with some also contributing in an essential way to the muon anomalous magnetic moment [8].

In this letter we propose a new extended version of $t-b-\tau$ Yukawa unification inspired by supersymmetric E_6 grand unification [9] [10] [11] [12]. Assuming that the gauge symmetry $\mathrm{U}(1)_\psi$ in E_6 is spontaneously broken in the TeV region, we will exploit the extended YU boundary conditions to infer the lower bounds on the masses of the third family vector-like quarks and lepton doublets predicted in E_6.

The discussion in the paper proceeds as follows. After a brief overview of $t-b-\tau$ YU, we present some figures based on one-loop RGEs that implement this scenario in the framework of MSSM, as well as MSSM plus three $(5+\bar{5})$ multiplets which are present in E_6 models. The one-loop threshold corrections [2] [13] play an important role here. We estimate the unified Yukawa coupling at M_{GUT} to be approximately 0.6 in MSSM (Figure 1), in agreement with previous work [14]. We then consider MSSM plus three $(5+\bar{5})$ multiplets and show a plot displaying gauge coupling unification (Figure 2). We estimate the unified Yukawa coupling at M_{GUT} in the presence of three $(5+\bar{5})$ fields to be 0.35 (Figure 3). To our knowledge, $t-b-\tau$ YU with three additional vector-like families has not been previously discussed. Finally, we discuss extended Yukawa coupling unification motivated by the E_6 invariant Yukawa coupling $27_3 \times 27_3 \times 27_H$, where the subscripts denote third family matter fields and the Higgs 27-plet. With the assumption that the MSSM Higgs doublets H_u, H_d and the SO(10) singlet field N that breaks $\mathrm{U}(1)_\psi$ arise from this 27_H, we are led to extended YU. Namely, at M_{GUT}, $h_t = h_b = h_\tau = h_D = h_L$, where h_D and h_L respectively refer to the Yukawa couplings to N of the vector-like color triplets and SU(2) doublets. Employing the lower bound on Z'_ψ boson mass provided by ATLAS/CMS [15], we estimate the lower bound on third family D and L masses to be 5.85 TeV and 2.9 TeV respectively. In the E_6 case the Yukawa coupling at M_{GUT} is estimated to be around 0.3-0.35. In the summary section we note that this value is intriguingly close to the estimates of 0.3-0.5 for the unified third family Yukawa coupling obtained in certain F-theory models based on the E_8 gauge symmetry.

$t - b - \tau$ Yukawa Unification

In SUSY SO(10) it is plausible that the third family charged fermions in the 16-plet primarily acquire masses from the invariant coupling $16_3 \times 16_3 \times 10_H$, with the MSSM doublets contained in 10_H. This yields $h_t = h_b = h_\tau$ at M$_{GUT}$ [1]. Note that SUSY plays an essential role here and without it, $t - b - \tau$ YU would not be possible in SO(10) barring additional assumptions.
The one loop renormalization group equations for the Yukawa couplings are [16–19]:

$$\begin{aligned} \frac{dh_t}{dt} &= \frac{h_t}{16\pi^2}\left(6h_t^2 + h_b^2 - \left(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2\right)\right), \\ \frac{dh_b}{dt} &= \frac{h_b}{16\pi^2}\left(6h_b^2 + h_t^2 + h_\tau^2 - \left(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{7}{15}g_1^2\right)\right), \\ \frac{dh_\tau}{dt} &= \frac{h_\tau}{16\pi^2}\left(3h_b^2 + 4h_\tau^2 - \left(3g_2^2 + \frac{9}{5}g_1^2\right)\right), \end{aligned} \qquad (1)$$

with t = log(Q), where Q is the renormalization scale.

Using plausible values for the masses of SUSY particles ($m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$, $m_{\tilde{b}_1}$, $m_{\tilde{b}_2}$ and $m_{\tilde{g}}$ in the range 2-3 TeV), μ parameter ($\approx$ 0.5-0.7 TeV) and $A_t \approx 2.5$ TeV, we present two plots (Figure 1) showing how $t-b-\tau$ YU can be realized. Note that in this paper we do not specify any particular SUSY breaking scenario, and these parameters will be employed throughout the paper. The MSSM parameter tan β is around 50, and we confirm previous results that the unified Yukawa coupling at M$_{GUT}$ is approximately 0.6 [14].

In the evolution of RGEs we take into account one loop threshold corrections due to sparticle loops [2] [13]. In practice, the largest correction is often to the bottom Yukawa coupling. An approximate expression for the bottom correction (in the limit of the masses of gluino and the top and bottom squarks being approximately equal) is given by:

$$\delta h_b^{\rm finite} \approx \frac{g_3^2}{12\pi^2}\frac{\mu m_{\tilde{g}} \tan\beta}{m_{\tilde{b}}^2} + \frac{h_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde{t}}^2}, \tag{2}$$

where $\mathrm{m}_{\tilde{b}} \approx \frac{m_{\tilde{b}_1}+m_{\tilde{b}_2}}{2}$ and $\mathrm{m}_{\tilde{t}} \approx \frac{m_{\tilde{t}_1}+m_{\tilde{t}_2}}{2}$ denote the average bottom and top squark masses respectively.

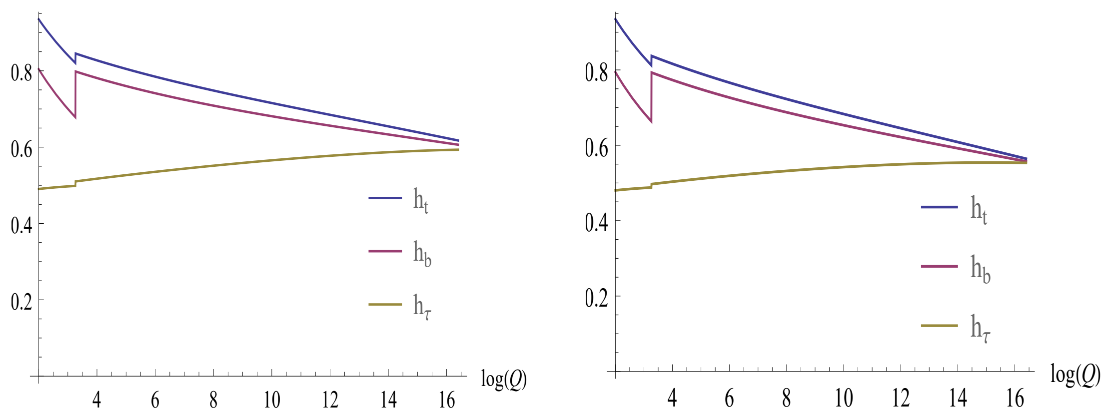

Figure 1: Yukawa coupling unification in MSSM with $\tan\beta = 50$ (left) and $\tan\beta = 51$ (right).

Gauge and $t - b - \tau$ Yukawa unification in MSSM and three $(5 + \bar{5})$ multiplets

We now consider MSSM plus three $(5 + \bar{5})$ multiplets. The one loop RGEs for the gauge couplings are given by:

$$\alpha_i^{-1}(Q) = \alpha_i^{-1}(Q_0) - \frac{b_i}{2\pi}\log\left(\frac{Q}{Q_0}\right). \tag{3}$$

The coefficients b_i depend on the matter content of the theory. For a SUSY theory with n_g families, n_H Higgs doublets and n_v vector-like families, the coefficients b_i are given as follows [16–21]:

$$b_1 = 0 + 2n_g + \frac{3}{10}n_H + n_v, \quad (4)$$
$$b_2 = -6 + 2n_g + \frac{1}{2}n_H + n_v, \quad (5)$$
$$b_3 = -9 + 2n_g + n_v. \quad (6)$$

For MSSM and three vector-like $(5 + \bar{5})$ multiplets, we get the coefficients:

$$\left(\frac{48}{5}, 4, 0\right) \quad (7)$$

The presence of these new particles increases the value of the unified gauge coupling strength at M_{GUT} as shown in Figure 2.

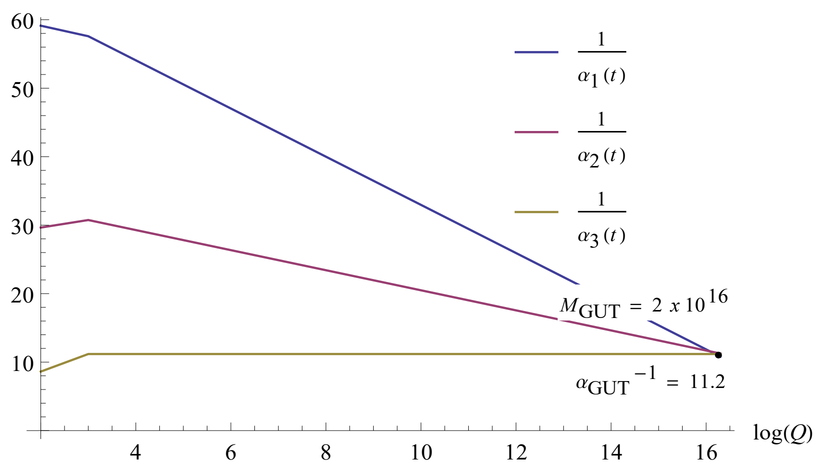

Figure 2: Gauge coupling unification in MSSM and three TeV scale $(5 + \bar{5})$ multiplets.
For the E_6 model, the gauge coupling g_ψ associated with the extra $U(1)_\psi$ symmetry is approximately equal to g_1 of the MSSM in between TeV scale and the M_{GUT} scale.

Next we implement $t - b - \tau$ YU in MSSM plus three families of TeV scale $(5 + \bar{5})$ particles. The RGEs for the Yukawa couplings remain the same as that for MSSM (1). The evolution of the Yukawa couplings in this case is displayed in Figure 3. As one might expect, the larger gauge couplings have a somewhat greater impact on the Yukawa couplings, and the Yukawa coupling at M_{GUT} is estimated to be around 0.35.

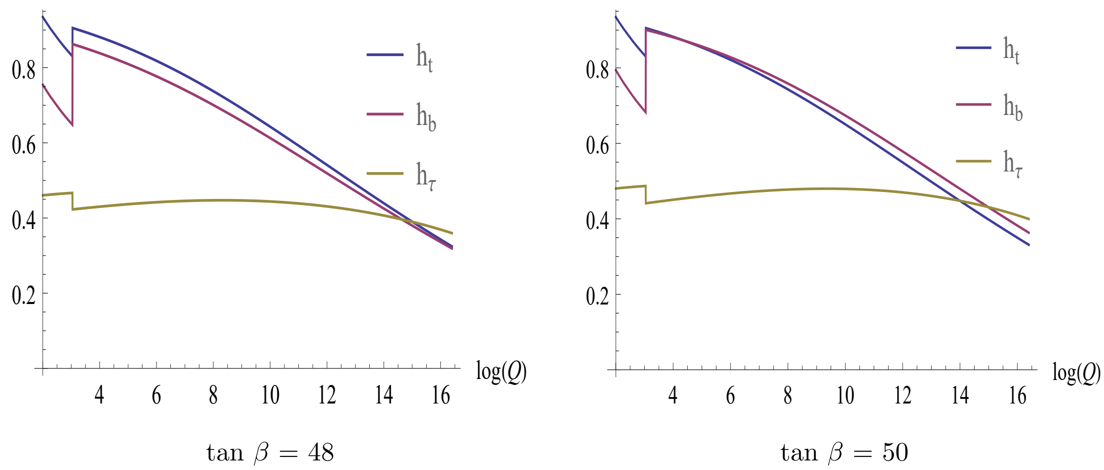

Figure 3: Yukawa coupling unification in MSSM and three TeV scale $(5 + \bar{5})$ multiplets.

E_6 Yukawa unification

We next proceed to E_6 grand unification and make the simplifying assumption that the Higgs scalars that spontaneously break the MSSM gauge symmetry and $U(1)_\psi$ arise from the same Higgs 27-plet (27_H). Under the decomposition $E_6 \to$ SO(10) x $U(1)_\psi$, the 27-plet contains the following fields:

$$27 \to 16_1 + 10_{-2} + 1_4, \tag{8}$$

where the subscripts denote $2\sqrt{6}\ Q_\psi$, with Q_ψ being the normalized $U(1)_\psi$ charge [22] [23]. Note that, gauge coupling unification is based on a low energy spectrum consisting of the MSSM fields and three TeV scale $5 + \bar{5}\quad SU(5)$ multiplets.

The Yukawa couplings $D\bar{D}N$ and $L\bar{L}N$ provide masses to these particles, while the coupling $H_u H_d N$ can yield the MSSM μ term. Indeed, this latter feature provides a good motivation for breaking $U(1)_\psi$ at the TeV scale [22]. From the third family Yukawa coupling $27_3 \times 27_3 \times 27_H$, we obtain the asymptotic YU relation $h_t = h_b = h_\tau = h_D = h_L$. The one loop RGEs for Yukawa coupings are given by [16] [22]:

$$
\begin{aligned}
\frac{dh_t}{dt} &= \frac{h_t}{16\pi^2}\left(6h_t^2 + h_b^2 - \left(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{13}{15}g_1^2 + \frac{1}{2}g_\psi^2\right)\right), \\
\frac{dh_b}{dt} &= \frac{h_b}{16\pi^2}\left(6h_b^2 + h_t^2 + h_\tau^2 - \left(\frac{16}{3}g_3^2 + 3g_2^2 + \frac{7}{15}g_1^2 + \frac{1}{2}g_\psi^2\right)\right), \\
\frac{dh_\tau.}{dt} &= \frac{h_\tau}{16\pi^2}\left(3h_b^2 + 4h_\tau^2 - \left(3g_2^2 + \frac{9}{5}g_1^2 + \frac{1}{2}g_\psi^2\right)\right), \\
\frac{dh_L}{dt} &= \frac{h_L}{16\pi^2}\left(4h_L^2 + 3h_D^2 - \left(3g_2^2 + \frac{3}{5}g_1^2 + 2g_\psi^2\right)\right), \\
\frac{dh_D}{dt} &= \frac{h_D}{16\pi^2}\left(5h_D^2 + 2h_L^2 - \left(\frac{16}{3}g_3^2 + \frac{4}{15}g_1^2 + 2g_\psi^2\right)\right),
\end{aligned}
\tag{9}
$$

with t = log(Q), where Q is the renormalization scale.

In the evolution of MSSM gauge couplings we assume that all three vector-like families have masses in the TeV range. However, Yukawa unification as presented above only applies to 27_3, the third family. We assume that there is negligible mixing between the $\bar{5}$ multiplets contained in the 16-plet and 10-plet of SO(10). We also assume that the 16_H component in the 27_H is decoupled from low energy physics, through appropriate fine-tuning. This decoupling of 16_H is somewhat analogous to the well-known doublet-triplet splitting problem encountered in GUTs such as SU(5) and SO(10). Implementation of this decoupling requires a non-minimal Higgs system. In a string-theoretic setting the decoupling presumably can be accomplished by suitable projections, although we will not attempt to do this here. Also note that decoupling of 16_H from the low energy sector helps preserve unification of the MSSM gauge couplings.
We explore a few scenarios with varying sparticles masses and A terms to convince ourselves that the third family unified Yukawa coupling at M_{GUT} is around 0.35.

Assuming gauge unification, we set the U(1)$_\psi$ gauge coupling g_ψ equal to MSSM U(1) gauge coupling g_1 at M_{GUT}. With b_ψ = Tr Q_ψ^2 = 9.66 [22] being approximately the same as b_1 = 9.6 for g_1, the two couplings stay close to each other between M_{GUT} and the TeV scale.

From gauge coupling unification (Figure 2) we estimate that the U(1)$_\psi$ gauge coupling $g_\psi \approx g_1 = 0.47$ at LHC energies. Together with the lower bound on the Z'_ψ boson mass of 2.79 TeV [15], the VEV of the SO(10) singlet scalar field N is estimated as

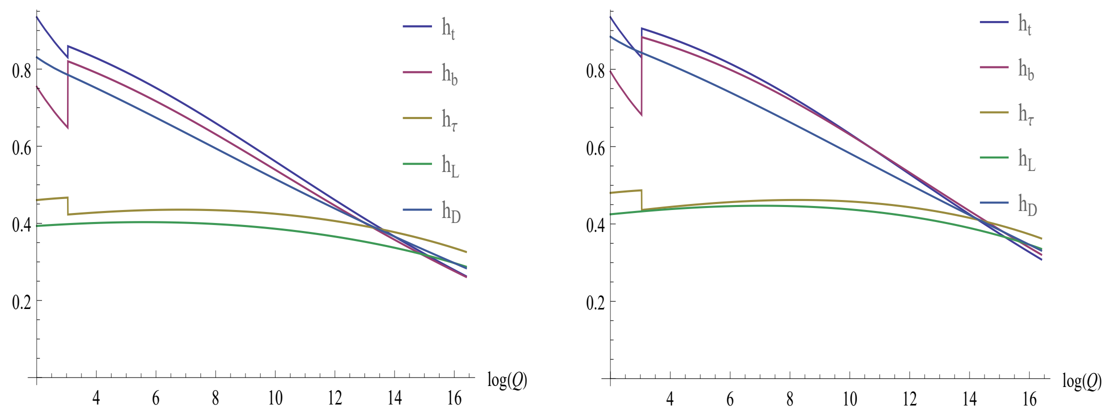

Figure 4: Yukawa coupling unification in E_6 with $\tan\beta = 48$ (left) and $\tan\beta = 50$ (right).

follows:

$$\begin{aligned} m_{Z'_\psi} &= \frac{4}{2\sqrt{6}} g_\psi \langle N \rangle , \\ \Longrightarrow \langle N \rangle &> 7.3 \text{ TeV}. \end{aligned} \tag{10}$$

Combining this with h_D and h_L evaluated in the TeV range (Figure 4), we estimate that the lower bounds on the masses of the third family vector-like D and L fields are

$$M_D \gtrsim 5.85\,\text{TeV} \tag{11}$$

$$M_L \gtrsim 2.90\,\text{TeV}. \tag{12}$$

Clearly these bounds do not take into account supersymmetry breaking. Concerning the first two vector-like families, the masses of the colored components are constrained to be $\gtrsim$ 700 GeV or so by the ATLAS and LHC experiments. The vector-like lepton doublets can, in principle, be much lighter, $\gtrsim$ 200 GeV. Given that $\langle N \rangle \geq 7.3$ TeV, this is readily achieved with a suitable choice of the appropriate dimensionless couplings.

Before closing this section, a few comments are in order here. Firstly, the scale of the μ parameter is determined by the scale of $U(1)_\psi$ gauge symmetry breaking. In a more involved model, embedded in a string framework for example, where the various fields are characterized by additional discrete or continues symmetries the relevant term $\lambda N H_u H_d$ might appear with a suitable suppression factor $\lambda \sim O(10^{-1})$ so that $\mu \lesssim 1$ TeV. A detailed consideration of this string embedding, however, lies beyond the scope of this note.

Secondly, an important issue concerns flavour violating processes. There are constraints on the couplings and masses of the vector-like fields from the electroweak

(EW) sector which depend on how they participate in these interactions. In particular, the S and T parameters limit the number of extra chiral generations. For simplicity, we assume here that the chiral couplings of the vector-like families to the MSSM Higgs doublets are sufficiently small so that the FCNC and precision EW constraints are satisfied. Note that with vector-like masses $\gtrsim 1$ TeV, the corresponding chiral couplings can be of order unity without violating the constraint from T or S.

Summary

We have extended the idea of $t-b-\tau$ Yukawa unification in supersymmetric SO(10) by including the Yukawa couplings of vector-like fields that appear in the matter 27-plet of E_6. Requiring unification of these Yukawa couplings at M_{GUT}, and taking into account both gauge coupling unification and the ATLAS/CMS lower bound on the appropriate Z' boson mass enables us to estimate lower bounds on the third family color triplet and SU(2) doublet vector-like fields. We should remark here that the first two families of vector-like quarks and leptons may well be considerably lighter than the third family, in which case some of them may be accessible at the LHC. It is interesting to note that certain F-theory constructions utilizing E_8 and E_6 gauge symmetries predict unified Yukawa coupling $\sim$ 0.3-0.5 for the third family fields including the vector-like ones contained in E_6 [24]. This is intriguingly close to the value of 0.3-0.35 that we estimate for extended YU in the E_6 model and deserves further exploration.

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