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$SO(10)$ Yukawa Unification : SUSY on the Edge

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In this talk we discuss SO(10) Yukawa unification and its ramifications for phenomenology. The initial constraints come from fitting the top, bottom and tau masses, requiring large $\tan\beta \sim 50$ and particular values for soft SUSY breaking parameters. We perform a global χ^2 analysis, fitting the recently observed 'Higgs' with mass of order 125 GeV in addition to fermion masses and mixing angles and several flavor violating observables. We discuss two distinct GUT scale boundary conditions for soft SUSY breaking masses. In both cases we have a universal cubic scalar parameter, A_0, non-universal Higgs masses and universal squark and slepton masses, m_{16}. In the first case we consider universal gaugino masses, while in the latter case we have non-universal gaugino masses. We discuss the spectrum of SUSY particle masses, consequences for the LHC and the issue of fine-tuning.

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1. Introduction

$SO(10)$ grand unification is clearly suggested by low energy data. Considering that one family of quarks and leptons naturally fit into one spinor representation of $SO(10)$, Fig. 1.

Grand Unification − SO(10)			
State	Y $= -\frac{2}{3}\Sigma(C) + \Sigma(W)$	Color C spins	Weak W spins
$\bar{\nu}$	0	− − −	− −
$\bar{e}$	2	− − −	+ +
u_r	1/3	+ − −	− +
d_r	1/3	+ − −	+ −
u_b	1/3	− + −	− +
d_b	1/3	− + −	+ −
u_y	1/3	− − +	− +
d_y	1/3	− − +	+ −
$\bar{u}_r$	−4/3	− + +	− −
$\bar{u}_b$	−4/3	+ − +	− −
$\bar{u}_y$	−4/3	+ + −	− −
$\bar{d}_r$	2/3	− + +	+ +
$\bar{d}_b$	2/3	+ − +	+ +
$\bar{d}_y$	2/3	+ + −	+ +
ν	−1	+ + +	− +
e	−1	+ + +	+ −

Figure 1: One family of quarks and leptons naturally fit into one spinor representation of $SO(10)$.

We use the following soft SUSY breaking parameters at the GUT scale.

1. m_{16}^2 - Universal scalar masses;
2. $m_{10}^2 \pm \Delta m_H^2$ or NUHM2;
3. A_0 - Universal A parameter; μ, $\tan\beta$;
4. $M_i, \quad i = 1,2,3$ with $M_i = \left(1 + \frac{g_G^2\ b_i\ \alpha}{16\pi^2}\log(\frac{M_{Pl}}{m_16})\right)\ M_{1/2}$, where $\alpha = 0$- Universal or $\alpha \neq 0$- "Mirage"

Thus we assume the following soft SUSY breaking parameters

$$m_{16},\ m_{10}^2 \pm \Delta m_H^2,\ A_0,\ M_{1/2},\ (\alpha),\ \mu,\ \tan\beta. \tag{1.1}$$

Note, also we will only consider one particular value of α which has been shown to be consistent with a well-tempered dark matter candidate [1].

We assume that the only renormalizable term in the superpotential, W, is $\lambda\ 16_3\ 10\ 16_3$ which gives Yukawa coupling unification

$$\lambda = \lambda_t = \lambda_b = \lambda_\tau = \lambda_{\nu_\tau} \tag{1.2}$$

at M_{GUT}. Note, one CANNOT predict the top mass due to large SUSY threshold corrections to the bottom and tau masses, as shown in [2, 3, 4]. These corrections are of the form

$$\delta m_b/m_b \propto \frac{\alpha_3\ \mu\ M_{\tilde{g}}\ \tan\beta}{m_{\tilde{b}}^2} + \frac{\lambda_t^2\ \mu\ A_t\ \tan\beta}{m_{\tilde{t}}^2} + \log \text{ corrections}. \tag{1.3}$$

So instead we use Yukawa unification to predict the soft SUSY breaking masses!! In order to fit the data, we need

$$\delta m_b/m_b \sim -2\%. \tag{1.4}$$

For a short list of references on this subject, see [5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21].

2. Gauge and Yukawa Unification with Universal Gaugino Masses

We take $\mu\ M_{\tilde{g}} > 0$, thus we need $\mu\ A_t < 0$ [17, 19]. We have performed a global χ^2 analysis fitting the 11 observables as a function of the 11 (12 with α) arbitrary parameters, Fig. 2. For a good fit we require $\chi^2 \ll 1$. We find that fitting the top, bottom and tau mass forces us into the

Observable	Exp. Value	Program	Th. Error
$\alpha_3(M_Z)$	0.1184 ± 0.0007	maton	0.5%
$\alpha_{\rm em}$	$1/137.035999074(44)$	maton	0.5%
G_μ	$1.16637876(7) \times 10^{-5}$ GeV^{-2}	maton	1%
M_W	80.385 ± 0.015 GeV	maton	0.5%
M_Z	91.1876 ± 0.0021	Input	0.0%
M_t	173.5 ± 1.0 GeV	maton	0.5%
$m_b(m_b)$	4.18 ± 0.03 GeV	maton	0.5%
M_τ	1776.82 ± 0.16 MeV	maton	0.5%
M_h	$125.3 \pm 0.4 \pm 0.5$ GeV		3 GeV
BR$(b \to s\gamma)$	$(343 \pm 21 \pm 7) \times 10^{-6}$	SuperIso	$(181 - 505) \times 10^{-6}$
BR$(B_s \to \mu^+\mu^-)$	3.2×10^{-9}	susy_flavor	1.5×10^{-9}

Figure 2: (Left) The 11 low energy observables which enter the χ^2 function are fit with either 11 or 12 (with α) parameters at the GUT scale. We require $\chi_2 \ll 1$.

region of SUSY breaking parameter space with

$$A_0 \approx -2m_{16},\ \ m_{10} \approx \sqrt{2}\, m_{16},\ \ m_{16} > \text{ few TeV},\ \ \mu, M_{1/2} \ll m_{16}; \tag{2.1}$$

and, finally,

$$\tan\beta \approx 50. \tag{2.2}$$

In addition, radiative electroweak symmetry breaking requires $\Delta^2_{m_H} \approx 13\%$, with roughly half of this coming naturally from the renormalization group running of neutrino Yukawa couplings from M_G to $M_{N_\tau} \sim 10^{13}$ GeV [5, 6].

It is very interesting that the above region in SUSY parameter space results in an inverted scalar mass hierarchy at the weak scale with the third family scalars significantly lighter than the first two families [22]. This has the nice property of suppressing flavor changing neutral current and CP violating processes.

2.1 Heavy squarks and sleptons

Considering the theoretical and experimental results for the branching ratio $BR(B \to X_s\gamma)$, we argue that $m_{16} \geq 8$ TeV. The experimental value $BR(B \to X_s\gamma)_{\rm exp} = (3.55 \pm 0.26) \times 10^{-4}$, while the NNLO Standard Model theoretical value is $BR(B \to X_s\gamma)_{\rm th} = (3.15 \pm 0.23) \times 10^{-4}$. The amplitude for the process $B \to X_s\gamma$ is proportional to the Wilson coefficient, C_7. $C_7 = C_7^{SM} + C_7^{SUSY}$ and, in order to fit the data, we see that $C_7 \approx \pm C_7^{SM}$. Thus $C_7^{SUSY} \approx -2C_7^{SM}$ or $C_7^{SUSY} \approx 0$. The dominant SUSY contribution to the branching ratio comes from a stop - chargino loop with $C_7^{SUSY} \sim C_7^{\chi^+} \sim \frac{\mu A_t}{\tilde{m}^2} \tan\beta \times sign(C_7^{SM})$ (see Fig. 3). Hence, in the former case (which allows for light scalars) $C_7 \approx -C_7^{SM}$, while in the latter case (with heavy scalars) $C_7 \approx C_7^{SM}$.

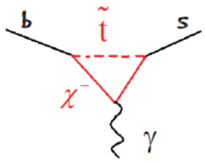

Figure 3: Dominant contribution to the process $b \to s\,\gamma$ in the MSSM.

Recent LHCb data on the $BR(B \to K^*\,\mu^+\,\mu^-)$ now favors $C_7 \approx +C_7^{SM}$ [23] (see Fig. 4). This

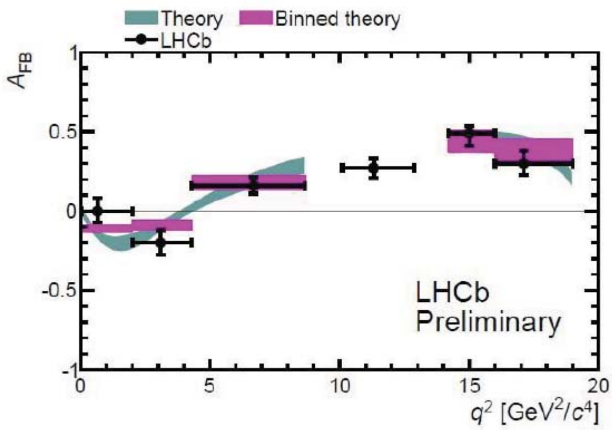

Figure 4: The forward-backward asymmetry for the process $B \to K^*\,\mu^+\,\mu^-$ measured by LHCb.

tension between the processes $b \to s\gamma$ and $b \to s\,\ell^+\,\ell^-$ was already discussed by Albrecht et al. [24]. In order to be consistent with this data one requires $C_7^{\chi^+} \approx 0$ or $C_7 \approx C_7^{SM} + C_7^{SUSY} \approx +C_7^{SM}$ and therefore $m_{16} \geq 8$ TeV.

In 2007, Albrecht et al. [24] performed a global χ^2 analysis of this theory (including the Yukawa structure for all three families). Two of the tables from their paper are exhibited in Fig. 5. This analysis included 27 low energy observables and a reasonable fit to the data was only found for $m_{16} = 10$ TeV. Note, the Higgs mass was predicted to be 129 GeV.

2.2 Light Higgs mass

An approximate formula for the light Higgs mass is given by [25]

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{SUSY}^2}{m_t^2}\right) + \frac{X_t^2}{M_{SUSY}^2}\left(1 - \frac{X_t^2}{12M_{SUSY}^2}\right)\right] \tag{2.3}$$

where $X_t = A_t - \mu/\tan\beta$. The light Higgs mass is maximized as a function of X_t for $X_t/M_{SUSY} = \pm\sqrt{6}$, referred to as maximal mixing. Hence we see that for large values of A_t and M_{SUSY} it is quite easy to obtain a light Higgs mass of order 125 GeV.

Observable	Exp. value	Fit value	Pull (σ)
M_W	80.403	80.6	0.5
M_Z	91.1876	90.7	1.1
$G_F \times 10^5$	1.16637	1.16	0.3
$1/\alpha_{em}$	137.036	136.8	0.4
$\alpha_s(M_Z)$	0.1176	0.117	0.2
M_t	170.9	170.6	0.2
$m_b(m_b)$	4.2	4.22	0.3
$m_c(m_b)$	1.25	1.14	1.2
$m_s(2\,\mathrm{GeV})$	0.095	0.107	0.5
$m_d(2\,\mathrm{GeV})$	0.005	0.00741	1.2
$m_u(2\,\mathrm{GeV})$	0.00225	0.00461	**3.1**
M_τ	1.777	1.78	0.1
M_μ	0.10566	0.106	0.1
M_e	0.000511	0.000511	0.0
$\lvert V_{us}\rvert$	0.2258	0.225	0.6
$\lvert V_{ub}\rvert \times 10^3$	4.1	3.26	**2.1**
$\lvert V_{cb}\rvert$	0.0416	0.0416	0.1
$\sin 2\beta$	0.675	0.639	1.4
$\Delta m^2_{31} \times 10^{21}$	2.6	2.6	0.0
$\Delta m^2_{21} \times 10^{23}$	7.9	7.9	0.0
$\sin^2 2\theta_{12}$	0.852	0.852	0.0
$\sin^2 2\theta_{23}$	0.996	1.0	0.2
$\epsilon_K \times 10^3$	2.229	2.33	0.4
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.55	2.86	1.3
$\mathrm{BR}(B \to X_s\ell^+\ell^-) \times 10^6$	1.6	1.62	0.0
$\Delta M_s/\Delta M_d$	35.05	31.1	1.1
$\mathrm{BR}(B^+ \to \tau^+\nu) \times 10^4$	1.31	0.517	1.7
		total χ^2:	**27.4**

m_{16}	10000
μ	1200
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^8$	2.1
$\hat{s}_0$	0.14
$\mathrm{BR}(\mu \to e\gamma) \times 10^{13}$	0.0026
$\delta a_\mu^{\mathrm{SUSY}} \times 10^{10}$	+0.52
M_{h_0}	129
M_A	842
$m_{\tilde{t}_1}$	1903
$m_{\tilde{b}_1}$	2366
$m_{\tilde{\tau}_1}$	3933
$m_{\tilde{\chi}^0_1}$	60
$m_{\tilde{\chi}^+_1}$	120
$m_{\tilde{g}}$	506

Required $C_7 = +C_7^{SM}$

Figure 5: The results obtained by Albrecht et al. for $m_{16} = 10$ TeV.

2.3 $B_s \to \mu^+ \mu^-$

In this section we argue that the light Higgs boson must be Standard Model-like. To do this we show that the CP odd Higgs boson, A, must have mass greater than ~ 1 TeV and as a consequence this is also true for the CP even Higgs boson, H, and the charged Higgs bosons, $H^\pm$, as well. This is the well-known decoupling limit in which the light Higgs boson couples to matter just like the Standard Model Higgs.

Consider the branching ratio $BR(B_s \to \mu^+ \mu^-)$ which in the Standard Model is $\sim 3 \times 10^{-9}$. In the MSSM this receives a contribution proportional to $\sim \frac{\tan\beta^6}{m_A^4}$. Recent experimental results give [26]

$$LHCb\ :=(3.2\ {}^{+1.5}_{-1.2} \pm 0.2) \times 10^{-9} \ \ \text{with } 1\ \text{fb}^{-1}(7\ \text{TeV}) \text{ and } 1.1\ \text{fb}^{-1}(8\ \text{TeV}). \tag{2.4}$$

Since we have $\tan\beta \sim 50$, our only choice is to take the CP odd Higgs mass to be large with $m_A \geq 1$ TeV. This is the decoupling limit; *hence the light Higgs is SM-like.*

2.4 Gluino Mass

We find an upper bound on the gluino mass (constrained by fitting both the bottom quark and light Higgs masses). For $m_{16} = 20$ TeV the upper bound at 90% CL is $m_{\tilde{g}} \lesssim 2$ TeV (see Fig. 6). For $m_{16} = 30$ TeV the upper bound at 90% CL increases to $m_{\tilde{g}} \lesssim 2.8$ TeV. Note, a gluino with mass $m_{\tilde{g}} \lesssim 1.9$ TeV should be discovered at LHC 14 with 300 fb^{-1} of data at 5 σ [27]!

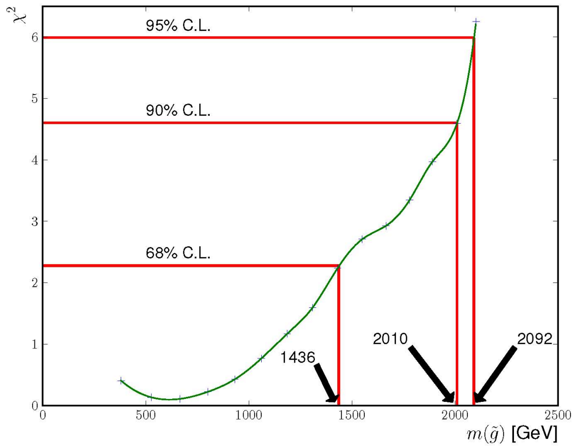

Figure 6: χ^2 as a function of the gluino mass obtained by varying $M_{1/2}$ for fixed $m_{16} = 20$ TeV or 2 degrees of freedom.

3. 3 Family Model

The previous results depended solely on SO(10) Yukawa unification for the third family. We now consider a complete three family SO(10) model for fermion masses and mixing, including neutrinos [28, 29, 24, 17, 21]. The model also includes a $D_3 \times [U(1) \times \mathbb{Z}_2 \times \mathbb{Z}_3]$ family symmetry which is necessary to obtain a predictive theory of fermion masses by reducing the number of arbitrary parameters in the Yukawa matrices. In the rest of this talk we will consider the new results due to the three family analysis. We shall consider the superpotential generating the effective fermion Yukawa couplings. We then perform a global χ^2 analysis, including precision electroweak data which now includes both neutral and charged fermion masses and mixing angles. Note, we are not concerned with physics at the GUT scale, in particular, proton decay or GUT symmetry breaking. We know that this analysis can be performed in either a 4 or 5 dimensional GUT (or orbifold GUT) field theory with completely different mechanism for GUT symmetry breaking and completely different results for proton decay. Nevertheless, one can retain gauge coupling unification and the theory of fermion masses outlined here (see for example, [30].)

The superspace potential for the charged fermion sector of this model is given by:

$$W_{ch.fermions} = 16_3\ 10\ 16_3 + 16_a\ 10\ \chi_a + \bar{\chi}_a\ (M_\chi\ \chi_a + 45\ \frac{\phi_a}{\hat{M}}\ 16_3\ +\ 45\ \frac{\tilde{\phi}_a}{\hat{M}}\ 16_a + \mathbf{A}\ 16_a) \tag{3.1}$$

where 45 is an $SO(10)$ adjoint field which is assumed to obtain a VEV in the B – L direction; and M is a linear combination of an $SO(10)$ singlet and adjoint. Its VEV $M_0(1 + \alpha X + \beta Y)$ gives mass to Froggatt-Nielsen states. Here X and Y are elements of the Lie algebra of $SO(10)$ with X in the direction of the $U(1)$ which commutes with $SU(5)$ and Y the standard weak hypercharge; and α , β are arbitrary constants which are fit to the data.

$$\phi_a, \quad \tilde{\phi}_a, \quad A, \tag{3.2}$$

are $SO(10)$ singlet 'flavon' fields, and

$$\bar{\chi}_a, \quad \chi_a \tag{3.3}$$

are a pair of Froggatt-Nielsen states transforming as a $\overline{16}$ and 16 under $SO(10)$. The 'flavon' fields are *assumed* to obtain VEVs of the form

$$\langle \phi_a \rangle = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}, \ \langle \tilde{\phi}_a \rangle = \begin{pmatrix} 0 \\ \tilde{\phi}_2 \end{pmatrix}. \tag{3.4}$$

After integrating out the Froggatt-Nielsen states one obtains the effective fermion mass operators in Fig. 7. We then obtain the Yukawa matrices for up and down quarks, charged leptons and neu-

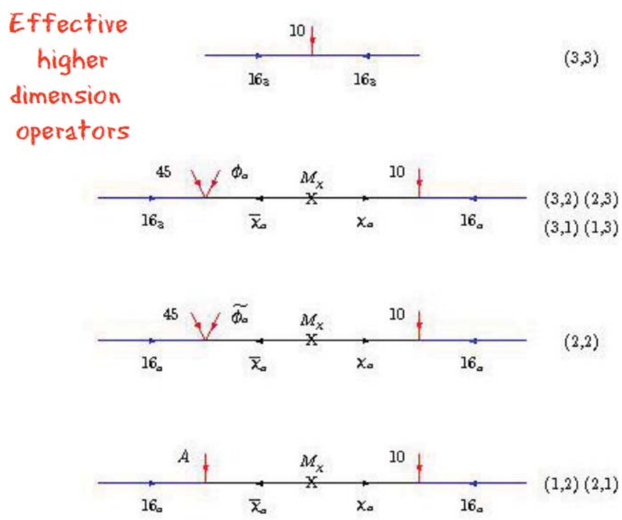

Figure 7: The effective fermion mass operators obtained after integrating out the Froggatt-Nielsen massive states.

trinos given in Fig. 8. These matrices contain 7 real parameters and 4 arbitrary phases. Note, the

$$Y_u = \begin{pmatrix} 0 & \epsilon' \rho & -\epsilon \xi \\ -\epsilon' \rho & \tilde{\epsilon} \rho & -\epsilon \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda$$

$$Y_d = \begin{pmatrix} 0 & \epsilon' & -\epsilon \xi \sigma \\ -\epsilon' & \tilde{\epsilon} & -\epsilon \sigma \\ \epsilon \xi & \epsilon & 1 \end{pmatrix} \lambda$$

$$Y_e = \begin{pmatrix} 0 & -\epsilon' & 3 \epsilon \xi \\ \epsilon' & 3 \tilde{\epsilon} & 3 \epsilon \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

$$Y_\nu = \begin{pmatrix} 0 & -\epsilon' \omega & \frac{3}{2} \epsilon \xi \omega \\ \epsilon' \omega & 3 \tilde{\epsilon} \omega & \frac{3}{2} \epsilon \omega \\ -3 \epsilon \xi \sigma & -3 \epsilon \sigma & 1 \end{pmatrix} \lambda$$

Figure 8: The Yukawa matrices obtained from the effective fermion mass operators after taking into account the flavon VEVs.

superpotential (Eqn. 3.1) has many arbitrary parameters. However, at the end of the day the effective Yukawa matrices have many fewer parameters. This is good, because we then obtain a very predictive theory. Also, the quark mass matrices accommodate the Georgi-Jarlskog mechanism, such that $m_\mu/m_e \approx 9m_s/m_d$. And the small $SU(5)$ breaking parameter $\rho \propto \beta\ Y$ accommodates $m_u/m_d < 1$ when $m_t/m_b \gg 1$.

We then add 3 real Majorana mass parameters for the neutrino see-saw mechanism. The anti-neutrinos get GUT scale masses by mixing with three $SO(10)$ singlets $\{N_a,\ a = 1,2;\ N_3\}$ transforming as a D_3 doublet and singlet respectively. The full superpotential is given by $W = W_{ch.fermions} + W_{neutrino}$ with

$$\begin{aligned} W_{neutrino} = &\ \overline{16}\,(\lambda_2\, N_a\, 16_a\ +\ \lambda_3\, N_3\, 16_3) \\ &+\ \tfrac{1}{2}\,(S_a\, N_a\, N_a\ +\ S_3\, N_3\, N_3)\,. \end{aligned} \tag{3.5}$$

We assume $\overline{16}$ obtains a VEV, v_{16}, in the right-handed neutrino direction, and $\langle S_a\rangle = M_a$ for $a = 1,2$ and $\langle S_3\rangle = M_3$. The effective neutrino mass terms are given by

$$W = \nu\ m_\nu\ \bar\nu + \bar\nu\ V\ N + \frac{1}{2}\ N\ M_N\ N \tag{3.6}$$

with

$$V = v_{16}\begin{pmatrix} 0 & \lambda_2 & 0 \\ \lambda_2 & 0 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix},\ M_N = diag(M_1,\ M_2,\ M_3) \tag{3.7}$$

all assumed to be real. Finally, upon integrating out the heavy Majorana neutrinos we obtain the 3×3 Majorana mass matrix for the light neutrinos in the lepton flavor basis given by

$$\mathscr{M} = U_e^T\ m_\nu\ M_R^{-1}\ m_\nu^T\ U_e, \tag{3.8}$$

where the effective right-handed neutrino Majorana mass matrix is given by:

$$M_R = V\ M_N^{-1}\ V^T\ \equiv\ \mathrm{diag}(M_{R_1}, M_{R_2}, M_{R_3}), \tag{3.9}$$

with

$$M_{R_1} = (\lambda_2\ v_{16})^2/M_2, \quad M_{R_2} = (\lambda_2\ v_{16})^2/M_1, \quad M_{R_3} = (\lambda_3\ v_{16})^2/M_3. \tag{3.10}$$

4. Global χ^2 analysis

Just in the fermion mass sector we can see that the theory is very predictive. We have 15 charged fermion and 5 neutrino low energy observables given in terms of 11 arbitrary Yukawa parameters, $\tan\beta$ and 3 Majorana mass parameters. Hence there are 5 degrees of freedom in this sector of the theory. However in order to include the complete MSSM sector we perform the global χ^2 analysis with 24 arbitrary parameters at the GUT scale given in Table 1 plus α for "Mirage" mediation (which gives a well-tempered dark matter candidate [1]).

In this work [21], we have decided to extend the analysis of Albrecht et al. to values of m_{16} up to 30 TeV, including more low energy observables such as the light Higgs mass, the neutrino mixing angle θ_{13}, lower bounds on the gluino and squark masses coming from recent data and additional B physics observables. We perform a three family global χ^2 analysis. We are using the code, `maton`, developed by Radovan Dermisek (and modified for heavy first and second family scalars

Table 1: Parameters entering the global χ^2 analysis.

Sector	#	*Parameters*
gauge	3	$\alpha_G,\ M_G,\ \varepsilon_3$
SUSY (GUTscale)	5	$m_{16},\ M_{1/2},\ A_0,\ m_{H_u},\ m_{H_d}$
textures	11	$\lambda,\ \varepsilon,\ \varepsilon',\ \rho,\ \sigma,\ \tilde{\varepsilon},\ \xi$
neutrino	3	$M_{R_1},\ M_{R_2},\ M_{R_3}$
SUSY (EWscale)	2	$\mu,\ \tan\beta$

by Archana Anandakrishnan and Akin Wingerter) to renormalize the parameters in the theory from the GUT scale to the weak scale, perform electroweak symmetry breaking and calculate squark, slepton, gaugino masses, as well as quark and lepton masses and mixing angles. We also use the Higgs code of Pietro Slavich (suitably revised for our particular scalar spectrum) to calculate the light Higgs mass and SUSY_Flavor_v2.0 [31] to evaluate flavor violating B decays.

There are 24 arbitrary parameters (Tab. 1) defined mostly at the GUT scale and run down to the weak scale where the χ^2 function is evaluated. However the value of m_{16} has been kept fixed in our analysis, so that we can see the dependence of χ^2 on this input parameter. Thus with 23 arbitrary parameters we fit 45 observables, giving 22 degrees of freedom. The χ^2 function has been minimized using the CERN package, MINUIT.

5. Results

In Fig. 9 we either use the inclusive or exclusive measurements of V_{ub}, V_{cb}. It is clear from the figure that we prefer the exclusive values. In Fig. 10 we show six low energy observables and their

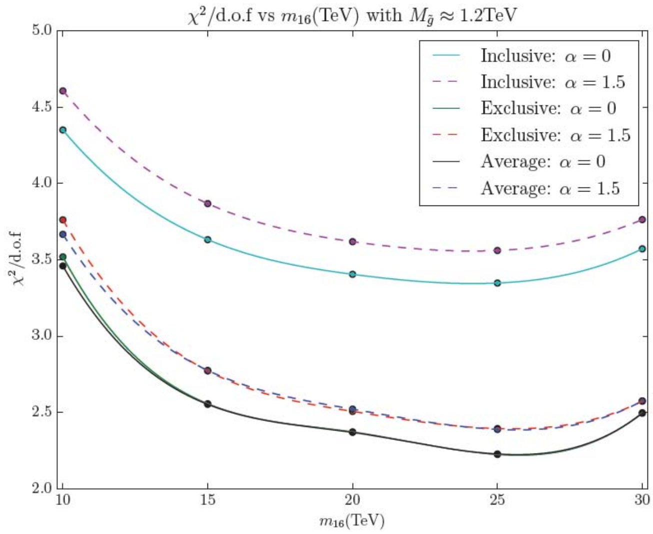

Figure 9: χ^2 as a function of m_{16} where either V_{ub}, V_{cb} (exclusive or inclusive) is fit. Clearly the fit with exclusive data is preferred.

contribution to χ^2. As one can see SUSY contributions to these observables do not decouple.

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- In particular, M_W receives contributions to ρ from stop and sbottom loops, since $m_{\tilde{t}_1}$ $(m_{\tilde{b}_1}) \approx$ 5 (6) TeV for $m_{16} = 25$ TeV.
- The Higgs mass contribution increases, since $\frac{A_t}{\mathrm{M_{SUSY}}}$ increases as m_{16} increases.
- Finally for the process $B \to K^* \mu^+ \mu^-$, the observables F_L and P_5' receive small corrections in the right direction. The term proportional to $C_7^{H^\pm}$ adds constructively, which is good; while the term proportional to $C_7^{\tilde{\chi}^\pm}$ adds destructively, which is bad, but decreases as m_{16} increases.

In Fig. 11 we plot the contribution of these six observables to χ^2. Note the result looks very much like the total χ^2 plot, Fig. 9.

	Pull				
m_{16}	10	15	20	25	30
M_W	0.2110	0.1878	0.1851	0.2320	0.3981
M_h	2.5474	1.1795	0.3454	0.1882	0.6582
$BR(B \to \tau\nu)$	1.1978	1.3952	1.3557	1.3588	1.3771
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2 \leq 6\mathrm{GeV}^2}$	0.2696	0.2488	0.2219	0.2101	0.2057
$P_4'(B \to K^*\mu^+\mu^-)_{1\leq q^2 \leq 6\mathrm{GeV}^2}$	1.7066	1.7066	1.7066	1.7066	1.7066
$P_5'(B \to K^*\mu^+\mu^-)_{1\leq q^2 \leq 6\mathrm{GeV}^2}$	2.4110	2.3432	2.2746	2.2451	2.2339
χ^2	14.1511	8.9744	7.2154	7.0206	7.5220

	Fit Value					Exp.
m_{16}	10	15	20	25	30	Value
M_W	80.4699	80.4606	80.4595	80.4784	80.5454	80.3850
M_h	117.9901	122.1303	124.6547	126.2697	127.6920	125.7000
$BR(B \to \tau\nu) \times 10^5$	6.6329	6.1340	6.2299	6.2223	6.1778	11.4000
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2 \leq 6\mathrm{GeV}^2}$	0.7434	0.7353	0.7251	0.7207	0.7191	0.6500
$P_4'(B \to K^*\mu^+\mu^-)_{1\leq q^2 \leq 6\mathrm{GeV}^2}$	0.8174	0.6711	0.5921	0.5717	0.5657	0.5800
$P_4'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2 \leq 16\mathrm{GeV}^2}$	1.2190	1.2190	1.2190	1.2190	1.2190	-0.1800
$P_5'(B \to K^*\mu^+\mu^-)_{1< q^2 < 6\mathrm{GeV}^2}$	-0.7301	-0.5529	-0.4625	-0.4335	-0.4235	0.2100

Figure 10: Six observables which demonstrate that SUSY does not decouple from the low energy theory, due to relatively light third generation squarks.

In Figs. 12 and 13 we give the fit for our best fit point. The χ^2/dof is not that great. We find $\theta_{13} \approx 7°$. Finally, we obtain some additional predictions (see Fig. 14).

5.1 Gluino mass

Using the three family analysis, we see again that gluinos want to be light. In Figs. 15 we show the χ^2 contours in the $M_{\tilde{g}}$, m_{16} plane. Note the gluino prefers to be lighter than about 2 TeV for values of $\alpha = 0$, or 1.5. Note, in a previous paper [20] we analyze LHC data and show that gluinos in our $SO(10)$ model must have mass $m_{\tilde{g}} > 1.2$ TeV.

5.2 Fine-tuning

We have also analyzed our model with respect to the Barbieri-Giudice fine-tuning parameter, $\frac{\partial \log M_Z}{\partial \log \xi}$ with $\xi = \{\mu,\, M_{1/2},\, m_{16},\, m_{H_u},\, m_{H_d},\, A_0\}$ [21]. In general, we find fine-tuning of order one part in 10^5 (see Fig. 16). However if we keep the ratios, A_0/m_{16} and $(m_{H_u} + m_{H_d})/m_{16}$ fixed, the amount of fine-tuning is reduced to less than one part in 1000. This is possibly an indication of the

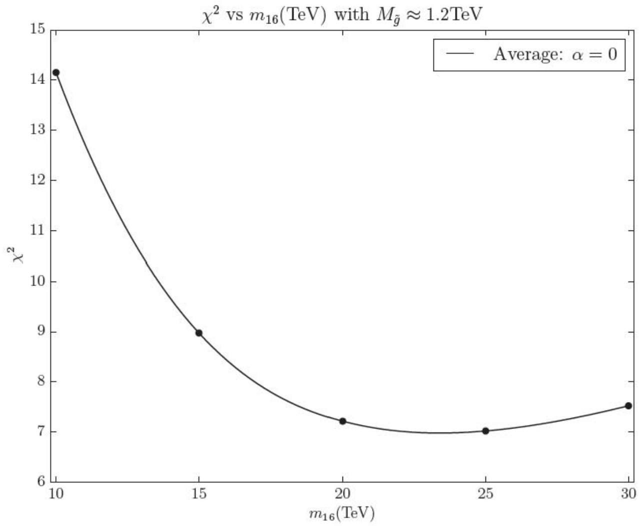

Figure 11: The plot of χ^2 just due to the six observables in Fig. 10.

Observable	Fit	Exp.	Pull	σ
M_Z	91.1876	91.1876	0.0000	0.4535
M_W	80.4507	80.3850	0.1633	0.4025
$1/\alpha_{\text{em}}$	137.7125	0.0073	0.9825	0.6886
$G_\mu \times 10^5$	1.1732	1.1664	0.5798	0.0117
$\alpha_3(M_Z)$	0.1188	0.1185	0.4140	0.0008
M_t	174.1882	173.2100	0.7927	1.2340
$m_b(m_b)$	4.1954	4.1800	0.4220	0.0366
m_τ	1.7781	1.7768	0.1417	0.0089
$M_b - M_c$	3.1568	3.4500	0.9175	0.3196
$m_c(m_c)$	1.2595	1.2750	0.5993	0.0258
m_s(2GeV)	0.0939	0.0950	0.2147	0.0050
m_s/m_d(2GeV)	0.0701	0.0513	2.8052	0.0067
$1/Q^2$	0.0018	0.0019	0.5139	0.0001
M_μ	0.1056	0.1057	0.1818	0.0005
$M_e \times 10^4$	5.1145	5.1100	0.1749	0.0256
$\lvert V_{us}\rvert$	0.2244	0.2253	0.6763	0.0014
$\lvert V_{cb}\rvert$	0.0404	0.0408	0.1729	0.0021
$\lvert V_{ub}\rvert \times 10^3$	3.1033	3.8500	0.8681	0.8601
$\lvert V_{td}\rvert \times 10^3$	8.8101	8.4000	0.6817	0.6016
$\lvert V_{ts}\rvert$	0.0396	0.0400	0.1531	0.0027
$\sin 2\beta$	0.6270	0.6820	2.8562	0.0193
ϵ_K	0.0022	0.0022	0.2052	0.0002
$\Delta M_{B_s}/\Delta M_{B_d}$	35.3739	35.0345	0.0479	7.0854
$\Delta M_{B_d} \times 10^{13}$	3.9433	3.3370	0.7681	0.7894

Figure 12: The fit for the best fit point.

properties of some GUT scale physics. For example, in the appendix of our paper we discussed a heterotic orbifold model which comes close to having the correct boundary conditions at the GUT scale.

6. Conclusion

In this talk we have presented an analysis of $SO(10)$ Yukawa unification with boundary con-

Observable	Fit	Exp.	Pull	σ
$m_{21}^2 \times 10^5$	7.6562	7.5550	0.1886	0.5364
$m_{31}^2 \times 10^3$	2.4631	2.4620	0.0077	0.1455
$\sin^2\theta_{12}$	0.3170	0.3070	0.2689	0.0370
$\sin^2\theta_{23}$	0.6264	0.5125	0.8722	0.1305
$\sin^2\theta_{13}$	0.0149	0.0218	2.1658	0.0032
M_h	124.5054	125.7000	0.3947	3.0265
$BR(B \to s\gamma) \times 10^4$	2.6840	3.4300	0.5789	1.2887
$BR(B_s \to \mu^+\mu^-) \times 10^9$	3.0247	2.8000	0.2429	0.9252
$BR(B_d \to \mu^+\mu^-) \times 10^{10}$	1.1022	3.9000	1.7323	1.6151
$BR(B \to \tau\nu) \times 10^5$	6.1884	11.4000	1.3727	3.7966
$BR(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2} \times 10^8$	4.7640	3.4000	0.2707	5.0381
$BR(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2} \times 10^8$	7.5110	5.6000	0.1336	14.3059
$q_0^2(A_{\mathrm{FB}}(B \to K^*\mu^+\mu^-))$	3.6690	4.9000	0.9579	1.2850
$F_L(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.7225	0.6500	0.2149	0.3374
$F_L(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	0.3108	0.3300	0.0726	0.2644
$P_2(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.0228	0.3300	2.5196	0.1219
$P_2(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.4336	-0.5000	0.3364	0.1974
$P_4'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	0.5820	0.5800	0.0050	0.4001
$P_4'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	1.2190	-0.1800	1.7066	0.8198
$P_5'(B \to K^*\mu^+\mu^-)_{1\leq q^2\leq 6\mathrm{GeV}^2}$	-0.4455	0.2100	2.2578	0.2903
$P_5'(B \to K^*\mu^+\mu^-)_{14.18\leq q^2\leq 16\mathrm{GeV}^2}$	-0.7116	-0.7900	0.1552	0.5052
Total χ^2			48.8413	

Figure 13: The fit for the best fit point cont'd.

m_{16}	25	25	25	25
α	0	1.5	0	1.5
χ^2/d.o.f	2.158	2.275	2.220	2.505
$m_{\tilde{t}_1}$	4.903	5.011	4.909	5.249
$m_{\tilde{t}_2}$	6.021	6.120	6.033	6.301
$m_{\tilde{b}_1}$	5.989	6.088	6.455	6.606
$m_{\tilde{b}_2}$	6.454	6.541	6.445	6.267
$m_{\tilde{\tau}_1}$	9.880	9.931	9.912	10.040
$m_{\tilde{\tau}_2}$	15.369	15.365	15.393	15.516
$M_{\tilde{g}}$	1.202	1.187	1.613	1.690
$m_{\tilde{\chi}_1^0}$	0.203	0.551	0.279	0.900
$m_{\tilde{\chi}_2^0}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_1^+}$	0.404	0.665	0.538	1.018
$m_{\tilde{\chi}_2^+}$	1.128	1.243	1.232	1.537
M_A	2.194	2.082	2.477	3.352
$\sin\delta$	-0.289	-0.482	-0.520	-0.576
$BR(\mu \to e\gamma) \times 10^{-13}$	1.108	1.430	1.239	1.340
$\mathrm{edm}_e \times 10^{-30}$(e cm)	-1.403	-3.305	-1.763	-5.886

Figure 14: In this table we present some benchmark point with additional predictions of the theory.

ditions at the GUT scale having either universal or "mirage" gaugino masses. We find that the light Higgs boson is Standard Model-like. The gluino mass is most likely in the range 1.2 TeV $\leq m_{\tilde{g}} \leq 2$ TeV. In addition, the three family model fits low energy data reasonably well. Hence we expect to observe SUSY at Run II of the LHC.

As a final note, the model we discussed is not "Natural" SUSY, since the fine-tuning is significant. But SUSY still does not decouple from low energy observables due to the inverted scalar mass hierarchy. It is also not "Split" SUSY, since the heaviest scalars have mass of order 25 TeV. Nevertheless the gravitino (and possibly the moduli) are sufficiently heavy, so that there is no cosmological gravitino or moduli problems. We call this "SUSY on the Edge."

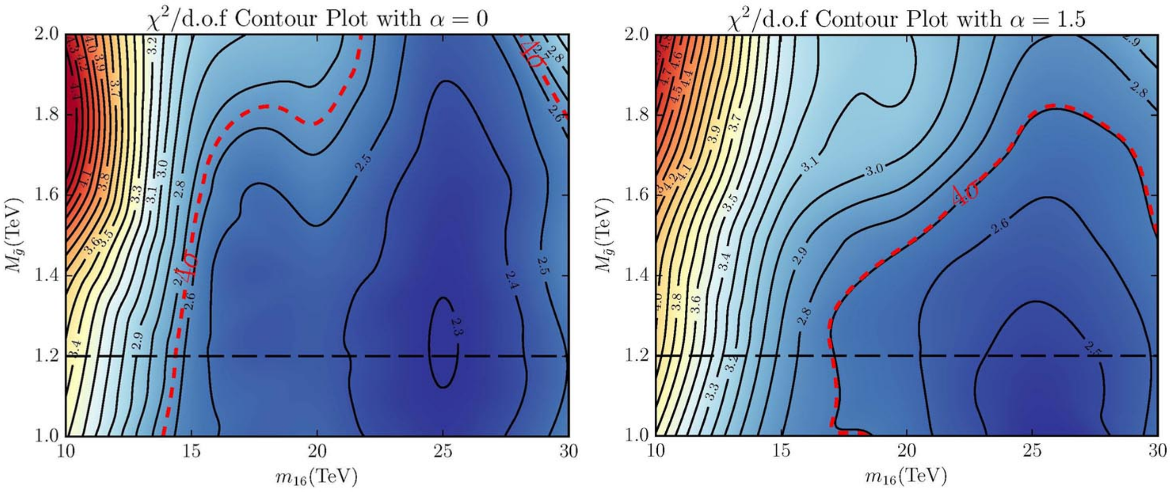

Figure 15: χ^2 contours in the $M_{\tilde{g}}$, m_{16} plane. Note the gluino prefers to be lighter than about 2 TeV for values of $\alpha = 0$, or 1.5. The 4σ bound is the dashed (red) line.

Fine-Tuning of Benchmark Points with $\alpha = 0$ and $M_{\tilde{g}} \approx 1.2$TeV

Varying Parameters	m_{16}				
	10TeV	15TeV	20TeV	25TeV	30TeV
μ	140	190	210	360	490
$M_{1/2}$	260	340	400	430	450
m_{16}	12000	27000	47000	74000	110000
m_{H_d}	760	1500	3900	6100	8700
m_{H_u}	10000	23000	40000	62000	89000
A_0	9300	21000	39000	61000	85000
m_{16} with A_0/m_{16} fixed	22000	49000	87000	130000	190000
m_{16} with $m_{H_{u,d}}/m_{16}$ fixed	9500	22000	40000	62000	86000
m_{16} with $m_{H_{u,d}}/m_{16}$, A_0/m_{16} fixed	240	400	630	740	850

Figure 16: In this table we present an analysis of BG fine-tuning for our model. Note if we keep the ratios, A_0/m_{16} and $(m_{H_u} + m_{H_d})/m_{16}$ fixed, the amount of fine-tuning is reduced to less than one part in 1000.

References

[1] A. Anandakrishnan and K. Sinha, "Viability of thermal well-tempered dark matter in SUSY GUTs," *Phys. Rev.* **D89** (2014), no. 5, 055015, 1310.7579.

[2] L. J. Hall, R. Rattazzi, and U. Sarid, "The Top quark mass in supersymmetric SO(10) unification," *Phys.Rev.* **D50** (1994) 7048–7065, hep-ph/9306309.

[3] M. S. Carena, M. Olechowski, S. Pokorski, and C. Wagner, "Electroweak symmetry breaking and bottom - top Yukawa unification," *Nucl.Phys.* **B426** (1994) 269–300, hep-ph/9402253.

[4] T. Blazek, S. Raby, and S. Pokorski, "Finite supersymmetric threshold corrections to CKM matrix elements in the large $\tan\beta$ regime," *Phys.Rev.* **D52** (1995) 4151–4158, hep-ph/9504364.

[5] T. Blazek, R. Dermisek, and S. Raby, "Predictions for Higgs and supersymmetry spectra from SO(10) Yukawa unification with $\mu > 0$," *Phys.Rev.Lett.* **88** (2002) 111804, hep-ph/0107097.

[6] T. Blazek, R. Dermisek, and S. Raby, "Yukawa unification in SO(10)," *Phys.Rev.* **D65** (2002) 115004, hep-ph/0201081.

[7] H. Baer and J. Ferrandis, "Supersymmetric SO(10) GUT models with Yukawa unification and a positive μ term," *Phys.Rev.Lett.* **87** (2001) 211803, hep-ph/0106352.

[8] D. Auto, H. Baer, C. Balazs, A. Belyaev, J. Ferrandis, *et al.*, "Yukawa coupling unification in supersymmetric models," *JHEP* **0306** (2003) 023, hep-ph/0302155.

[9] K. Tobe and J. D. Wells, "Revisiting top bottom tau Yukawa unification in supersymmetric grand unified theories," *Nucl.Phys.* **B663** (2003) 123–140, hep-ph/0301015.

[10] R. Dermisek, S. Raby, L. Roszkowski, and R. Ruiz De Austri, "Dark matter and $B_s \to \mu^+\mu^-$ with minimal SO(10) soft SUSY breaking," *JHEP* **0304** (2003) 037, hep-ph/0304101.

[11] R. Dermisek, S. Raby, L. Roszkowski, and R. Ruiz de Austri, "Dark matter and $B_s \to \mu^+\mu^-$ with minimal SO(10) soft SUSY breaking II," *JHEP* **0509** (2005) 029, hep-ph/0507233.

[12] H. Baer, S. Kraml, S. Sekmen, and H. Summy, "Dark matter allowed scenarios for Yukawa-unified SO(10) SUSY GUTs," *JHEP* **0803** (2008) 056, 0801.1831.

[13] H. Baer, S. Kraml, S. Sekmen, and H. Summy, "Prospects for Yukawa Unified SO(10) SUSY GUTs at the CERN LHC," *JHEP* **0810** (2008) 079, 0809.0710.

[14] H. Baer, S. Kraml, and S. Sekmen, "Is 'just-so' Higgs splitting needed for $t-b-\tau$ Yukawa unified SUSY GUTs?," *JHEP* **0909** (2009) 005, 0908.0134.

[15] M. Badziak, M. Olechowski, and S. Pokorski, "Yukawa unification in SO(10) with light sparticle spectrum," *JHEP* **1108** (2011) 147, 1107.2764.

[16] I. Gogoladze, Q. Shafi, and C. S. Un, "Higgs Boson Mass from t-b-τ Yukawa Unification," *JHEP* **1208** (2012) 028, 1112.2206.

[17] A. Anandakrishnan, S. Raby, and A. Wingerter, "Yukawa Unification Predictions for the LHC," 1212.0542.

[18] A. Anandakrishnan and S. Raby, "Yukawa Unification Predictions with effective "Mirage" Mediation," *Phys. Rev. Lett.* **111** (2013), no. 21, 211801, 1303.5125.

[19] A. Anandakrishnan, B. C. Bryant, S. Raby, and A. Wingerter, "LHC Phenomenology of SO(10) Models with Yukawa Unification," 1307.7723.

[20] A. Anandakrishnan, B. C. Bryant, and S. Raby, "LHC Phenomenology of SO(10) Models with Yukawa Unification II," *Phys. Rev.* **D90** (2014), no. 1, 015030, 1404.5628.

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[21] Z. Poh and S. Raby, "Yukawa Unification in an SO(10) SUSY GUT: SUSY on the Edge," *Phys. Rev.* **D92** (2015), no. 1, 015017, 1505.00264.

[22] J. A. Bagger, J. L. Feng, N. Polonsky, and R.-J. Zhang, "Superheavy supersymmetry from scalar mass: A parameter fixed points," *Phys.Lett.* **B473** (2000) 264–271, hep-ph/9911255.

[23] **LHCb** Collaboration, R. Aaij *et al.*, "Implications of LHCb measurements and future prospects," *Eur.Phys.J.* **C73** (2013) 2373, 1208.3355.

[24] M. Albrecht, W. Altmannshofer, A. J. Buras, D. Guadagnoli, and D. M. Straub, "Challenging SO(10) SUSY GUTs with family symmetries through FCNC processes," *JHEP* **0710** (2007) 055, 0707.3954.

[25] M. S. Carena, M. Quiros, and C. Wagner, "Effective potential methods and the Higgs mass spectrum in the MSSM," *Nucl.Phys.* **B461** (1996) 407–436, hep-ph/9508343.

[26] **LHCb** Collaboration, R. Aaij *et al.*, "First Evidence for the Decay $B_s^0 \to \mu^+\mu^-$," *Phys. Rev. Lett.* **110** (2013), no. 2, 021801, 1211.2674.

[27] **CMS** Collaboration, "Projected Performance of an Upgraded CMS Detector at the LHC and HL-LHC: Contribution to the Snowmass Process," 1307.7135.

[28] R. Dermisek and S. Raby, "Bi-large neutrino mixing and CP violation in an SO(10) SUSY GUT for fermion masses," *Phys.Lett.* **B622** (2005) 327–338, hep-ph/0507045.

[29] R. Dermisek, M. Harada, and S. Raby, "SO(10) SUSY GUT for Fermion Masses: Lepton Flavor and CP Violation," *Phys.Rev.* **D74** (2006) 035011, hep-ph/0606055.

[30] H. D. Kim, S. Raby, and L. Schradin, "Quark and lepton masses in 5-D SO(10)," *JHEP* **05** (2005) 036, hep-ph/0411328.

[31] A. Crivellin, J. Rosiek, P. Chankowski, A. Dedes, S. Jaeger, *et al.*, "SUSY_FLAVOR v2: A Computational tool for FCNC and CP-violating processes in the MSSM," 1203.5023.