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Flavour Physics in an SO(10) Grand Unified Model

Jennifer Girrbach*
Technische Universität München (TUM)
Institute of Advanced Study (IAS)
Excellence Cluster Universe
E-mail: jennifer.girrbach@ph.tum.de

Grand unified theories open the possibility to transfer the neutrino mixing matrix U_{PMNS} to the quark sector. This is accomplished in a controlled way in a supersymmetric grand-unified model proposed by Chang, Masiero and Murayama (CMM model) where the atmospheric neutrino mixing angle induces large new $b \to s$ and $\tau \to \mu$ transitions. Relating the supersymmetric low-energy parameters to seven new parameters a_0, m_0^2, $m_{\tilde{g}}$, D, ξ, $\tan\beta$ and $\arg(\mu)$ of this SO(10) model, we perform a correlated study of several flavour-changing neutral current (FCNC) processes. The CMM model can serve as an alternative benchmark scenario to the popular constraint MSSM.

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*Speaker.

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1. Introduction

Supersymmetric grand unified theories (SUSY GUTs) are popular extensions of the Standard Model (SM). The generic Minimal Supersymmetric Standard Model (MSSM) has (too) many sources of flavour and CP violation which reside in the soft breaking terms. Contrarily, in the minimal flavour violating (MFV) version of the MSSM large effects in the flavour sector can only appear in very few processes, such as $b \to s\gamma$. SUSY GUTs can lie somewhere in between. The unification of quarks and leptons into symmetry multiplets implies additional relations between SM parameters and correlation between the flavour mixing. Let's consider SU(5) multiplets:

$$\overline{\mathbf{5}}_1 = \begin{pmatrix} d_R^c \\ d_R^c \\ d_R^c \\ e_L \\ -\nu_e \end{pmatrix}, \qquad \overline{\mathbf{5}}_2 = \begin{pmatrix} s_R^c \\ s_R^c \\ s_R^c \\ \mu_L \\ -\nu_\mu \end{pmatrix}, \qquad \overline{\mathbf{5}}_3 = \begin{pmatrix} b_R^c \\ b_R^c \\ b_R^c \\ \tau_L \\ -\nu_\tau \end{pmatrix}. \tag{1.1}$$

If the PMNS matrix U_{PMNS} stems from a mixing of these **5**-plets, then the corresponding mixing angles should also occur in the charged-lepton sector and right-handed down-quark sector. Especially the large atmospheric neutrino mixing angle $\theta_{23} \approx 45^\circ$ induces $b_R \to s_R$ and $\tau_L \to \mu_L$ transitions. Whereas mixing of right-handed quark fields in flavour space is unphysical it is not for the corresponding superfields due to the soft breaking terms. Consequently squark-gluino loops can induce $b_R \to s_R$ transitions. Further slepton-neutralino/sneutrino-chargino loops can induce $\tau \to \mu$ transitions at an observable level. This was the main idea of Moroi and Chang, Masiero and Murayama in [1, 2]. Similar and related works can be found e.g. in [3, 4]. In [5] we have performed a global analysis in the CMM model including an extensive renormalization group (RG) analysis to connect Planck-scale and low-energy parameters. In the next section we sketch the theoretical framework focusing on the flavour structure.

2. The CMM model – a new benchmark scenario

2.1 Theory

The idea of PMNS-like mixing of down-quark singlets and lepton doublets as discussed above is encoded in the following SO(10) superpotential:

$$W_Y^{\text{SO(10)}} = \frac{1}{2}\mathbf{16}_i \, \mathsf{Y}_1^{ij} \, \mathbf{16}_j \, \mathbf{10}_H + \mathbf{16}_i \, \mathsf{Y}_2^{ij} \, \mathbf{16}_j \, \frac{\mathbf{45}_H \, \mathbf{10}'_H}{2M_{\text{Pl}}} + \mathbf{16}_i \, \mathsf{Y}_N^{ij} \, \mathbf{16}_j \, \frac{\overline{\mathbf{16}}_H \overline{\mathbf{16}}_H}{2M_{\text{Pl}}}, \tag{2.1}$$

where M_{Pl} is the Planck mass, $\mathbf{16}_i$ ($i = 1,2,3$) is the SO(10) spinor representation (one matter field per generation) and $\mathbf{10}_H$, $\mathbf{10}'_H$, $\mathbf{45}_H$ and $\overline{\mathbf{16}}_H$ are four Higgs superfields, where $\mathbf{10}_H$ contains the MSSM H_u and $\mathbf{10}'_H$ the MSSM H_d. One assumption of the CMM model is that Y_1 and Y_N are simultaneously diagonalisable which can be achieved through a suitable flavour symmetry at M_{Pl}. This flavour symmetry is broken by the second term in (2.1) with the consequence that the rotation matrix of the right-handed down-squarks is exactly U_{PMNS}. SUSY is broken flavour blind at M_{Pl} implying universal soft- and trilinear terms. That is, the nonrenormalisable term $\propto \mathsf{Y}_2$ in the superpotential contains the whole flavour structure, its diagonalisation involves the PMNS and CKM matrices (up to rephasings). The symmetry breaking chain reads

$$\mathrm{SO}(10) \xrightarrow[\langle 45_H \rangle]{\langle 16_H \rangle, \langle \overline{16}_H \rangle} \mathrm{SU}(5) \xrightarrow{\langle 45_H \rangle} \mathrm{G_{SM}} \xrightarrow{\langle 10_H \rangle, \langle 10'_H \rangle} \mathrm{SU}(3)_C \times \mathrm{U}(1)_{\mathrm{em}}\,, \tag{2.2}$$

which gives naturally small $\tan\beta$. Then Y_1 gives masses to up-type fermions, Y_2 to down-type fermions and Y_N to right-handed Majorana neutrinos. We want to stress that flavour physics observables depend very weakly on the details of the Higgs potential which was not specified in the original paper [2]. But our results motivate further work on the Higgs potential.

The key ingredient for the flavour structure is the following: In a weak basis with diagonal up-type Yukawa matrix we have

$$\mathsf{Y}_d = \mathsf{Y}_\ell^\top = V_{\mathrm{CKM}}^\star \begin{pmatrix} y_d & 0 & 0 \\ 0 & y_s & 0 \\ 0 & 0 & y_b \end{pmatrix} U_D\,, \qquad U_D = U_{\mathrm{PMNS}}^* \,\mathrm{diag}(1, e^{i\xi}, 1) \tag{2.3}$$

and the right-handed down squark mass matrix at the low scale reads

$$m_{\tilde{d}}^2(M_Z) = \mathrm{diag}\left(m_{\tilde{d}_1}^2, m_{\tilde{d}_1}^2, m_{\tilde{d}_1}^2\,(1-\Delta_{\tilde{d}}) \right)\,, \tag{2.4}$$

where $\Delta_{\tilde{d}} \in [0,\,1]$ defines the relative mass splitting between the $1^{st}/2^{nd}$ and 3^{rd} down-squark generation. It is generated by RG effects of the top Yukawa coupling and can easily reach 0.4. If we rotate to mass eigenstate basis and diagonalise Y_d the neutrino mixing enters $m_{\tilde{D}}^2$:

$$m_{\tilde{D}}^2 = U_D m_{\tilde{d}}^2 U_D^\dagger = m_{\tilde{d}_1}^2 \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1-\frac{1}{2}\Delta_{\tilde{d}} & -\frac{1}{2}\Delta_{\tilde{d}} e^{i\xi} \\ 0 & -\frac{1}{2}\Delta_{\tilde{d}} e^{-i\xi} & 1-\frac{1}{2}\Delta_{\tilde{d}} \end{pmatrix}\,. \tag{2.5}$$

Consequently, the 23-entry $\propto \Delta_{\tilde{d}}$ is responsible for $\tilde{b}_R - \tilde{s}_R$-mixing and exactly here a new CP phase ξ enters that affects B_s–$\bar{B}_s$ mixing. Note that there are zeros in the 12- and 13-entries, thus no effects in K–$\bar{K}$ and B_d–$\bar{B}_d$ mixing appear. This is due to the degeneracy of the first two squark generation and the assumed tribimaximal structure of U_{PMNS}.

2.2 Comparison with CMSSM/mSUGRA

Only seven parameters of the CMM model are relevant for our analysis: the universal scalar soft mass m_0 and trilinear coupling a_0 at the Planck scale, the gluino mass $m_{\tilde{g}}$, the D-term mass splitting D, the phase of μ, the phase ξ and $\tan\beta$ (but $2.7 \lesssim \tan\beta \lesssim 10$). We did a comprehensive RG evolution to relate Planck-scale inputs to a set of low-energy inputs: the masses of $\tilde{u}_R$ and $\tilde{d}_R$ of the first generations $m_{\tilde{u}_1}, m_{\tilde{d}_1}$, the 11-element of the trilinear coupling of the down squarks a_1^d, $m_{\tilde{g}}$, $\arg\mu$, ξ and $\tan\beta$. We evolve these parameters twice from M_{ew} to M_{Planck} and back to M_{ew} to find all particle masses and MSSM couplings.

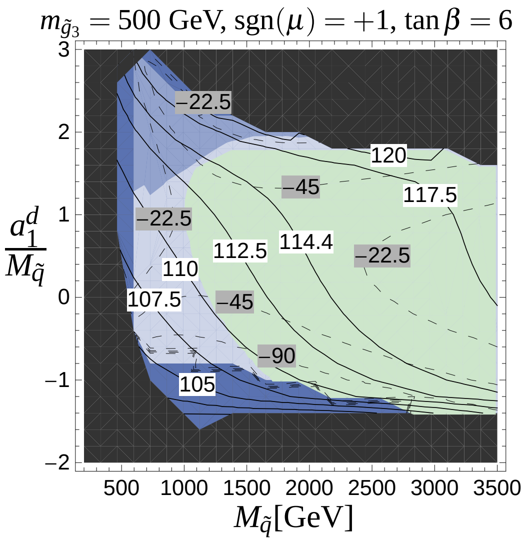
The minimal supergravity (mSUGRA) scenario or its popular variant, the constraint MSSM (CMSSM), has – similar to the CMM model – only a few input parameters. But the philosophy is somewhat different: the CMSSM minimises flavour violation in an ad-hoc way and assumes flavour

generic MSSM	mSUGRA/CMSSM	CMM model
$\approx$ 120 parameters	4 parameters & 1 sign	7 input parameters
SUSY flavour & CP problem	minimize flavour violation ad-hoc	clear flavour structure
no universality	universality at $M_{\rm GUT}$	universality at $M_{\rm Pl}$ but broken at $M_{\rm GUT}$
quarks & leptons unrelated		quark-lepton-interplay
Problem: suppress large effects elsewhere	cannot explain current flavour data (e.g. ϕ_s)	can fit ϕ_s and small effects in 1st/2nd gen.

Table 1: Comparison between the generic MSSM, mSUGRA/CMSSM and the CMM model

universality at the GUT scale with quark and lepton flavour structures being unrelated. However the CMM model has a clear flavour structure different from MFV and universality is already broken at $M_{\rm GUT}$. Furthermore due to this free phase ξ, one can fit the B_s–$\bar{B}_s$ mixing phase ϕ_s to the data. Also the particle spectrum is quite different between the CMSSM and the CMM model (mainly due to the large mass splitting $\Delta_{\tilde{d}}$). This comparison is summarized in tab. 1. Hence the CMM model could serve as a new benchmark model: it is well-motivated, has only seven input parameters and it is a very predictive alternative to the well-studied CMSSM.

2.3 Phenomenology



- black: $m_{\tilde{f}}^2 < 0$, unstable vacuum
- dark blue: excluded by B_s–$\bar{B}_s$
- medium blue: excluded by $b \to s\gamma$
- light blue: excluded by $\tau \to \mu\gamma$
- green: compatible with B_s–$\bar{B}_s$, $b \to s\gamma$, $\tau \to \mu\gamma$
- Higgs mass in GeV: solid line with white labels
- ϕ_s with maximal possible $|\phi_s|$ in degrees: dashed line with gray labels

Figure 1: Correlation of FCNC processes as a function of $M_{\tilde{q}}(M_Z)$ (degenerate squark mass of first two generations) and $a_1^d(M_Z)/M_{\tilde{q}}(M_Z)$ for $m_{\tilde{g}}(M_Z) = 500$ GeV and sgn$(\mu) = +1$ with $\tan\beta = 6$.

We did a global analysis of flavour observables where we expected large CMM effects, namely B_s–$\bar{B}_s$ mixing, $b \to s\gamma$ and $\tau \to \mu\gamma$. Moreover we included vacuum stability bounds, lower bounds on sparticle masses and the mass of the lightest Higgs boson. The result is shown in fig. 1. The flavour effects are proportional to $\Delta_{\tilde{d}}$ and maximized for small $\tan\beta$. However, the Higgs mass constraint excludes too small values for $\tan\beta$. With ξ we can accommodate a large ϕ_s while simultaneously fulfilling all other experimental constraints. The branching ratio $BR(B_s \to \mu^+\mu^-)$ does not get large CMM effects because $\tan\beta$ is small. Realistic GUTs involve dimension-5 Yukawa terms to fix the relation $\mathsf{Y}_d = \mathsf{Y}_\ell^\top$ for the 1^{st} and 2^{nd} generation. Consequently we do not only get $b_R \to s_R$ but also $b_R \to d_R$ and $d_R \to s_R$ transition. This has been worked out in [6] and is strongly constraint by K–$\bar{K}$ mixing. Similar constraints can be found from $\mu \to e\gamma$ [7].

3. Conclusion

SUSY GUTs are theoretical well-motivated scenarios with correlations between hadronic and leptonic observables. If large CP violation in B_s–$\bar{B}_s$ mixing is confirmed we need physics beyond the CMSSM and mSUGRA. We advertise the CMM model where the large atmospheric neutrino mixing angle $\theta_{23} \approx 45^\circ$ induces $b-s$- and $\tau-\mu$-transitions as an alternative benchmark scenario. We did an extensive RG analysis of the CMM model relating several observables (B_s–$\bar{B}_s$ mixing, $b \to s\gamma$, $\tau \to \mu\gamma$, m_h, vacuum stability bounds and lower bounds on sparticle masses) to seven new input parameters beyond those of the SM. Due to a free phase ξ we can adjust CP violation in B_s–$\bar{B}_s$ mixing while at the same time getting only minor effects in $2 \to 1$ and $3 \to 1$ transitions.

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References

[1] T. Moroi, JHEP **0003** (2000) 019. [hep-ph/0002208];
Phys. Lett. B **493** (2000) 366. [hep-ph/0007328].

[2] D. Chang, A. Masiero and H. Murayama, Phys. Rev. D **67** (2003) 075013, [hep-ph/0205111].

[3] R. Barbieri, L. J. Hall and A. Strumia, Nucl. Phys. B **449** (1995) 437. [hep-ph/9504373];
Nucl. Phys. B **445** (1995) 219. [hep-ph/9501334].

[4] R. Harnik, D. T. Larson, H. Murayama and A. Pierce, Phys. Rev. D **69** (2004) 094024. [hep-ph/9501334].

[5] J. Girrbach, S. Jager, M. Knopf, W. Martens, U. Nierste, C. Scherrer and S. Wiesenfeldt, JHEP **1106** (2011) 044 [Erratum-ibid. **1107** (2011) 001] [arXiv:1101.6047 [hep-ph]].

[6] S. Trine, S. Westhoff, S. Wiesenfeldt, JHEP **0908** (2009) 002. [arXiv:0904.0378 [hep-ph]].

[7] J. Girrbach, S. Mertens, U. Nierste, S. Wiesenfeldt, JHEP **1005** (2010) 026. [arXiv:0910.2663 [hep-ph]].
P. Ko, J. -h. Park, M. Yamaguchi, JHEP **0811** (2008) 051. [arXiv:0809.2784 [hep-ph]].