Hadronic vs leptonic flavor and CP violation in SUSY SO(10)*

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ABSTRACT

We study hadronic and leptonic flavor physics in a SUSY SO(10) model proposed by Chang, Masiero, and Murayama, which links \( b \to s \) transitions to the observed large atmospheric neutrino mixing angle. We find large effects in \( B_s - \bar{B}_s \) mixing and \( BR(\tau \to \mu \gamma) \) and comment on \( B_d \to \phi K_S \).

1. Introduction

Within SUSY GUTs, quarks and leptons are unified into irreducible symmetry multiplets, opening the possibility of links between hadronic and leptonic flavor structures. This raises the question if there exist scenarios where the large atmospheric and solar mixing angles can manifest themselves in the hadronic sector. On the other hand, due to the presence of scalar quarks and leptons, there are many new parameters that can violate flavor in supersymmetric theories. Radiative corrections to these above the GUT scale imply mass differences and flavor violation even for universal soft terms at the Planck scale, and certain mixing angles that would otherwise be unphysical can be rendered observable [1]. Chang, Masiero, and Murayama (CMM) have proposed an SO(10) model in which the large \( \nu_\mu-\nu_\tau \) mixing angle can affect transitions between right-handed \( b \) and \( s \) quarks [2]. The SO(10)-symmetric superpotential has the form

\[
W_{10} = \frac{1}{2} 16^T Y^U 16 10_H + \frac{1}{M_{Pl}} 16^T \tilde{Y}^D 16 10_H' 45_H + \frac{1}{M_{Pl}} 16^T Y^M 16 \overline{16}_H \overline{16}_H. \tag{1}
\]

Here \( 16 \) is the usual spinor comprising the matter superfields and the other fields are Higgs superfields in the indicated representations. \( Y^U \) is a symmetric \( 3 \times 3 \) matrix in generation space containing the large top Yukawa coupling. The two dimension-5 terms involve the Planck mass \( M_{Pl} \) and further Higgs fields in the indicated representations. At some scale \( M_{10} \) between the Planck and GUT scales the \( 45_H \) and \( \overline{16}_H \) acquire VEVs \( v_{45} \) and \( \nu_{16} \), and SO(10) is broken to SU(5), which is broken to the MSSM at the GUT scale. The SU(5) superpotential reads

\[
W_5 = \frac{1}{2} \Psi^T Y^U \Phi_5^H + \Psi^T Y^D \Phi \overline{5}_H + \Phi^T Y^{\nu} N_5^H + \frac{1}{2} \nu_{16}^2 \overline{N}^T Y^M N, \tag{2}
\]
with \( Y^D \propto \hat{Y}^D v_{45}/M_{Pl} \). The last term in (2) generates small neutrino masses via the standard seesaw mechanism. From \( m_t \gg m_c \) we observe a large hierarchy in \( Y^U \approx Y^\nu \), which must be largely compensated in \( Y^M \) in order to explain the observed pattern of neutrino masses. This is achieved in a natural way by invoking flavor symmetries, the simplest of which render \( Y^U \) and \( Y^M \) simultaneously diagonal. This is achieved in a natural way by invoking flavor symmetries, the simplest of which render \( Y^U \) and \( Y^M \) simultaneously diagonal. This defines the \((U)\)-basis. In this basis the remaining Yukawa matrix \( Y^D \approx Y^{ET} \), responsible for the masses of down-type quarks and charged leptons, has the form \( Y^D = V^*_{\text{CKM}} \text{diag}(y_d, y_s, y_b) U_{\text{PMNS}} \). Here \( V_{\text{CKM}} \) and \( U_{\text{PMNS}} \) encode flavor mixing in the quark and lepton sectors, and certain diagonal phase matrices have been omitted. The nonsymmetric structure of \( Y^D \) is possible because the corresponding dimension-5 term in (1) transforms reducibly under SO(10).

Note also that generically \( \tan \beta = O(M_{10}/M_{Pl}) \). The matter supermultiplets \( \Psi, \Phi \) and \( N \) are the usual \( 10, \overline{5}, \) and \( 1 \) from the decomposition of the \( 16 \). We also have \( \Psi \supset (Q, U, E), \Phi \supset (D, L), 10_\text{H} \supset 5_\text{H} \supset H_u, \) and \( 10'_\text{H} \supset 5'_\text{H} \supset H_d. \)

The soft SUSY-breaking terms are assumed universal near the Planck scale. The large Yukawa coupling in \( Y^U \) now renormalizes the sfermion mass matrix, keeping it diagonal in the \((U)\)-basis but splitting the mass of the third from those of the first two generations for each MSSM sfermion multiplet. The diagonalization of \( Y^D \) involves the rotation of \( \Phi \) in (2) with \( U_{\text{PMNS}} \). Since \( \Phi \) unifies left-handed (s)leptons with right-handed down-type (s)quarks, the large atmospheric mixing angle will appear in the mixing of \( \bar{b}_R \) and \( \bar{s}_R \).

2. RG analysis of the CMM model

The large Yukawa coupling \( y_t \) driving all nonuniversal renormalization-group effects, its own behavior under RG evolution is crucial. In the MSSM and the considered GUTs, \( y_t \) possesses an IR quasi-fixed point, and for sufficiently small values of \( \tan \beta \) the low-energy value of \( y_t \) will reside above the fixed-point trajectory. For the situation in the CMM model, see Fig. 1. The two vertical lines indicate the GUT and SO(10)-breaking scales.

![Figure 1: RG evolution of \( y_t \). See text for explanation.](image)

The dashed line is the “critical” trajectory, corresponding to the SO(10) fixed point of \( y_t/g \). The dotted and solid lines are examples corresponding to \( y_t(\mu) \) for \( m_t = 174 \text{ GeV} \) and the stated values of \( \tan \beta \), with mild dependence on other supersymmetric parameters (a shift in \( m_t \) can be compensated by a shift in \( \tan \beta \)). In general, \( y_t \) becomes nonperturbative
at high energies if it resides above the fixed point (dotted line). Perturbativity being essential for the model to be predictive, we restrict ourselves to $y_B$ below the critical line.

As anticipated in the introduction, in the $(U)$-basis the mass matrices of the right-handed down-type squarks and of the left-handed sleptons, renormalized at the weak scale, have the form $m^2_{U\bar{d}} (U) = \text{diag} \left(m_{dR}^2, m_{dR}^2, m_{dR}^2 - \Delta_{\bar{d}} \right)$, $m^2_{U\bar{d}} (U) = \text{diag} \left(m_{tL}^2, m_{tL}^2, m_{tL}^2 - \Delta_t \right)$, with $\Delta_{\bar{d}} \approx \Delta_t$ due to SU(5) and SO(10) GUT relations. This nonuniversal structure then induces flavor-changing couplings of gluinos and neutralinos once the charged-lepton and down-type-quark Yukawa matrices are diagonalized, both of which originate from $\tilde{Y}$ in (2) and are the transpose of each other: $Y^E = U^T_{\text{PMNS}} \tilde{Y} E U_E$, $Y^D = V^*_{\text{CKM}} \tilde{Y} D U_D$. $Y^D \approx Y^{ET}$ . Specifically, the couplings of right-handed down-type squarks to gluinos and squarks now contain an element of $U_D \approx U_{\text{PMNS}} \equiv U$, as do the couplings of left-handed sleptons to neutralinos. Imposing (approximate) Yukawa unification only for the bottom and tau, one is left with the weaker statement $|U_{D23}| \approx |U_{D33}| \approx |U_{\mu 3}| \approx |U_{\tau 3}|$, suggesting large FCNC involving second-to-third-generation transitions.

Besides $\tan \beta$, we choose as low-energy input parameters the approximately universal first-generation squark mass $m_{\tilde{q}}$, the gluino mass $m_{\tilde{g}}$, and the down-squark $A$-parameter $a_d$, all of which are constrained by phenomenology. We use the MSSM and GUT RGEs to relate them to Planck-scale parameters and compute the low-energy quantities $\Delta_{\bar{d}}$ and $\Delta_t$ from the RGE solutions, with the dominant contributions coming from above $M_{10}$.

3. $B_s - \bar{B}_s$ mixing, $\tau \to \mu \gamma$, and $B_d \to \phi K_S$

The dominant new contributions to $B_s - \bar{B}_s$ mixing in the CMM model are $\mathcal{O}(\alpha^2)$ corrections from one-loop box diagrams with gluinos and squarks. One obtains the mixing amplitude

$$M_{12} = \frac{G^2_F M_W^2}{32 \pi^2 M_{\text{Ms}}} \lambda_t^2 (C_L + C_R) \langle B_s | O_L | \bar{B}_s \rangle.$$  \hspace{1cm} (3)

Here $\langle B_s | O_L | \bar{B}_s \rangle$ (with $\langle B_s | B_s \rangle = 2E V$) is the matrix element of the usual Standard Model four-quark effective operator $O_L = \bar{s}_{L} \gamma_{\mu} b_{L} \bar{s}_{L} \gamma^{\mu} b_{L}$ and $C_L$ is due to Standard Model $W - t$ exchange. Note that in a general model several operators with independent hadronic matrix elements arise, while we encounter only gluino-squark boxes generating the parity reflection of $O_L$, with the Wilson coefficient

$$C_R = \frac{\lambda_t^2 \alpha^2 \alpha^2 (m_{\tilde{g}}) \left[ \alpha_s (m_{\tilde{g}}) \right]^{6/23}}{G^2_F M_W^2 m_{\tilde{g}}^2 \left[ \alpha_s (m_{\tilde{b}}) \right]^{6/23}} S^{(\tilde{g})}.$$  \hspace{1cm} (4)

Furthermore, $\lambda_t = V_{ts}^* V_{tb}$ is the applicable Standard Model flavor-mixing parameter and $|A_3| = |U_{\nu 3}| |U_{\tau 3}| \approx \frac{1}{2}$ is the relevant combination of mixing-matrix elements in the right-handed down sector, and $S^{(\tilde{g})}$ is a dimensionless function of the squark and gluino masses. Note the twofold enhancement of $C_R$ due to the large atmospheric mixing and the large strong coupling constant. This is, however, partially offset by a smaller loop function $S^{(\tilde{g})}$. The neutral $B_s$-meson mass difference is given by $\Delta M_{B_s} = 2 |M_{12}|$, while the phase of $M_{12}$ is responsible for mixing-induced CP violation. Fig. 2 (left) shows a contour plot of the modulus of the CMM contribution normalized to the Standard Model prediction.
in the \((m_{\tilde{g}}, a_d)\) plane for \(m_{\tilde{g}} = 195 \text{ GeV}\). The shaded area in the plot is excluded by experimental constraints on the sparticle spectrum. We observe that the Standard Model prediction of about \(17.2 \text{ ps}^{-1}\) can be exceeded by a factor of 16. The effect decreases rapidly with increasing gluino mass. Note that the phase of \(\Lambda_3\) is undetermined, so that there is potentially large CP violation in decays such as \(B_s \to \psi \phi\) and \(B_S \to \psi \eta^\prime\).

We have also computed the amplitudes for \(\tau \to \mu \gamma\) and \(B_d \to \phi K_S\). The former now also depends on the \(\mu\)-parameter, but it is clear that rates are in general large compared to the GIM-suppressed Standard Model case. The right plot in Fig. 2 shows contours of constant \(BR(\tau \to \mu \gamma)\), with the shaded area excluded by the (old) Belle upper bound, demonstrating that this mode constrains the CMM model. \(B_d \to \phi K_S\) is more involved because several operators contribute. Using QCD factorization, we find the chromomagnetic penguin operator to be associated with the dominant SUSY contribution, which could give a \(\mathcal{O}(1)\) correction to the Standard Model amplitude, again with an unconstrained phase. Whether this can explain a large deviation of the time-dependent CP asymmetry from \(\sin(2\beta)\) when reconciled with the experimental constraints on \(BR(\tau \to \mu \gamma)\) remains to be assessed.

In conclusion, we find that there are GUT models connecting the atmospheric mixing angle with hadronic observables and being predictive for flavor physics. We find large effects in several observables. Our analysis is complementary to other works studying more general setups [3], whereas we examine a more predictive scenario quantitatively.

4. References

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[3] See e.g.: M. Ciuchini, A. Masiero, L. Silvestrini, S. K. Vempati and O. Vives, Phys. Rev. Lett. 92 071801 (2004); [hep-ph/0307191]. R. Harnik, D. T. Larson, H. Murayama and A. Pierce, Phys. Rev. D69 094024 (2004); [hep-ph/0212180].