Low $\tan\beta$ in the Extended Minimal Gauge Mediated Model

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Abstract

We consider the Minimal Gauge Mediated Model (MGMM) with either fundamental or antisymmetric messenger multiplets and study consequences of messenger-matter mixing. It is shown that constraints on relevant coupling constants and mixing parameters coming from the existing experimental limits on lepton flavor violation and FCNC processes allow a wide range of $\tan\beta$ in MGMM with mixing.

1 Introduction

In this paper we discuss a class of SUSY models with gauge mediated supersymmetry breaking [1]. In these models supersymmetry is broken in a special secluded sector due to nonperturbative dynamics of the corresponding gauge group. The soft terms in the visible sector appear through usual gauge interactions between ordinary fields and some new set of fields (*messengers*) charged under MSSM gauge group. Messengers obtain supersymmetry breaking masses through gauge or Yukawa interactions with the secluded sector. In these models gauge interactions transmitting supersymmetry breaking to the visible sector do not lead to flavor violation because these interactions are

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flavor blind. Nevertheless, flavor changing interactions can appear in gauge mediated models due to possible messenger-matter Yukawa interactions.

The purpose of this talk is to show that in a reasonable range of parameters, messenger-matter mixing in Minimal Gauge Mediated Model (MGMM)[2] can give rise to the observable rates of rare lepton flavor violating processes like $\mu \rightarrow e\gamma$ and $\mu - e$ conversion, can play a significant role in quark flavor physics and at the same time can affect radiative electroweak symmetry breaking crucially.

We find out that, unlike MGMM without mixing, at messenger masses of order 10^5 GeV and messenger-matter Yukawa couplings of order 10^{-2} (such Yukawas are acceptable from the points of view of both theory and experiment), there is a wide region of allowed $\tan\beta$ in the model with mixing. The value of $\tan\beta$ is determined by the magnitude of the mixing terms. This observation leads to an interesting possibility to relate the rates of flavor violating processes to the Higgs sector parameters.

2 The model

The MGMM contains, in addition to MSSM particles, two messenger multiplets Q_M and $\bar{Q}_M$ which belong to $\mathbf{5}$ and $\bar{\mathbf{5}}$ representations of $SU(5)$. We will consider also the antisymmetric messengers ($\mathbf{10}$ and $\bar{\mathbf{10}}$). All other representations are ruled out by the requirement of asymptotic freedom of the theory. Messengers couple to a MSSM singlet Z through the superpotential term

$$\mathcal{L}_{ms} = \lambda Z Q_M \bar{Q}_M.$$

Z obtains non-vanishing vacuum expectation values F and S via hidden-sector interactions,

$$Z = S + F\theta\theta.$$

Messenger masses and soft breaking terms are expressed most conveniently via parameters

$$\Lambda = \frac{F}{S} \quad \text{and} \quad x = \frac{\lambda F}{\lambda^2 S^2}$$

Then masses of fermionic components of messenger superfields are all equal to $M = \frac{\Lambda}{x}$. The vacuum expectation value of Z mixes scalar components of

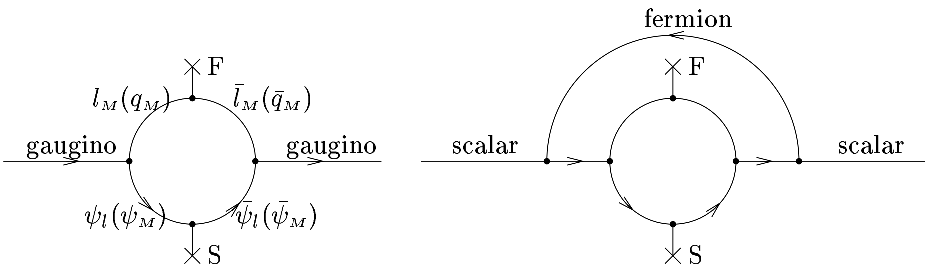

Figure 1: Typical diagrams inducing masses for the MSSM gauginos and scalars. Messenger fields run in loops.

messenger fields and gives them masses

$$M_{\pm}^2 = \frac{\Lambda^2}{x^2}(1 \pm x)$$

It is clear that x must be smaller than 1.

Gauginos and scalar particles of MSSM obtain masses at messenger scale in one and two loops respectively (see Fig. 1). Their values are [3]

$$M_{\lambda_i}(M) = c_i \frac{\alpha_i(M)}{4\pi} \Lambda f_1(x) \tag{1}$$

for gauginos and

$$\tilde{m}^2(M) = 2\Lambda^2 \sum_{i=1}^{3} c_i C_i \left(\frac{\alpha_i(M)}{4\pi} \right)^2 f_2(x) \tag{2}$$

for scalars. Here α_i are gauge coupling constants of $SU(3) \times SU(2) \times U(1)$, C_i are values of the quadratic Casimir operator for the pertinent matter fields: $C_3 = 4/3$ for color triplets (zero for singlets), $C_2 = 3/4$ for weak doublets (zero for singlets), $C_1 = \left(\frac{Y}{2}\right)^2$, where Y is the weak hypercharge. For messengers belonging to the fundamental and antisymmetric representations one has $c_1 = 5/3$, $c_2 = c_3 = 1$ and $c_1 = 5$, $c_2 = c_3 = 3$, respectively. The dependence of the soft masses on x is very mild, as the functions $f_1(x)$ and $f_2(x)$ do not deviate much from 1 [4, 5]. The MSSM spectrum at electroweak scale is obtained from Eqs. (1), (2) by making use of renormalizaton group equations.

The trilinear soft terms appear in two loops, therefore they are suppressed by additional gauge coupling constant as compared to soft masses. MGMM contains in addition to Λ and x one more parameter μ determining supersymmetric Higgs masses, $\mu H_U H_D$. Soft mixing $B_\mu h_U h_D$ appears in two loops like other scalar masses, but it is suppressed due to accidental cancellations.

It has been argued in ref.[6] that Λ must be larger than 70 TeV, otherwise the theory would be inconsistent with mass limits from LEP. The characteristic features of the model without messenger-matter mixing are large $\tan\beta$ [2] (an estimate of refs.[7, 6] is $\tan\beta \gtrsim 50$) and large squark masses. The parameter μ is predicted to be about 500 GeV. There is large mixing between $\tilde{\tau}_R$ and $\tilde{\tau}_L$, proportional to $\tan\beta$ and μ. It results in mass splitting of τ-sleptons so that the Next Lightest Supersymmetric Particle (NLSP) is a combination of $\tilde{\tau}_R$ and $\tilde{\tau}_L$ [2, 6], the LSP being gravitino.

3 Messenger-matter mixing

Messenger fields may be odd or even under R-parity. Fundamental messengers, depending on their R-parity, have the same quantum numbers as either fundamental matter or fundamental Higgs fields, so messenger-matter mixing arises naturally. In the latter case triplet messenger fields will give rise to fast proton decay due to possible Higgs-like mixing with ordinary fields, unless the corresponding Yukawa couplings are smaller than 10^{-21} [8].

We will consider messengers which are odd under R-parity. Then the components of the fundamental messengers $Q_M^{(5)} = (l_M, q_M)$ have the same quantum numbers as left leptons and right down-quarks, while components of antisymmetric messengers $Q_M^{(10)}$ have quantum numbers of the right leptons, left quarks and right up-quarks. We assume that there is one generation of messengers, fundamental or antisymmetric, and consider their mixing with ordinary matter separately.

One can introduce messenger-matter mixing [9]

$$\mathcal{W}_{mm}^{(5)} = H_D L_{\hat{i}} Y_{\hat{i}j}^{(5)} E_j + H_D D_{\hat{i}} X_{\hat{i}j}^{(5)} Q_j \tag{3}$$

in the case of fundamental representation and

$$\mathcal{W}_{mm}^{(10)} = H_D E_{\hat{i}} Y_{\hat{i}j}^{(10)} L_j + H_D Q_{\hat{i}} W_{\hat{i}j}^{(10)} D_j + H_U U_{\hat{i}} X_{\hat{i}\hat{j}}^{(10)} Q_{\hat{j}} \tag{4}$$

in the case of antisymmetric messenger fields, where we use the notation

$$L_{\hat{i}} = \left(\begin{pmatrix} e_L \\ \nu_e \end{pmatrix}, \begin{pmatrix} \mu_L \\ \nu_\mu \end{pmatrix}, \begin{pmatrix} \tau_L \\ \nu_\tau \end{pmatrix}, \begin{pmatrix} l_{m_L} \\ \nu_{m_L} \end{pmatrix} \right)$$

for the left doublet superfields in the lepton sector and similarly for the quark sector.

Hereafter $\hat{i}, \hat{j} = 1, .., 4$ label the three matter generations and the messenger field, $i, j = 1, .., 3$ correspond to the three matter generations. $Y^{(5)}_{\hat{i}j}, X^{(5)}_{\hat{i}j}$, $Y^{(10)}_{\hat{i}j}, W^{(10)}_{\hat{i}j}$ are the 4×3 matrices of Yukawa couplings and $X^{(10)}_{\hat{i}\hat{j}}$ is 4×4 matrix. Explicitly

$$Y^{(5)}_{\hat{i}j} = \begin{pmatrix} Y_e & 0 & 0 \\ 0 & Y_\mu & 0 \\ 0 & 0 & Y_\tau \\ Y^{(5)}_{41} & Y^{(5)}_{42} & Y^{(5)}_{43} \end{pmatrix}$$

and the other matrices have similar form.

There is no CP-violation in this theory in the lepton sector. Arbitrary phases may be rotated away by redefinition of the lepton fields. On the other hand, there appears CP-violation in the quark sector, in addition to the CKM mechanism.

To summarize, messenger-matter mixing in the leptonic sector occurs through the Yukawa couplings $Y^{(5)}_{4i}$ or $Y^{(10)}_{4i}$ ($i = 1, 2, 3$), depending on the representation of the messenger fields. Likewise, mixing in the quark sector appears through $X^{(5)}_{4i}$ or $X^{(10)}_{i4}$, $X^{(10)}_{4i}$, $W^{(10)}_{4i}$. In the following sections we sometimes use the collective notation Y_i for the couplings Y_{4i}, X_{4i}, X_{i4} and W_{4i} in statements applicable to all of them.

One of the most important effects of this mixing is the absence of heavy stable charged (and colored) particles (messengers) in the theory [9]. Other known possibilities to solve this problem [4] faced the necessity of fine-tuning of the messenger mass parameters.

The insertion of the messenger-matter mixing terms has interesting experimental consequences. Supersymmetry breaking in MGMM does not lead to flavor violation because the gauge interactions creating soft terms in the visible sector are flavor blind. In the messenger-matter mixing extension of MGMM we obtain a rich pattern of flavor physics. It is *a priori* clear that the mixing terms induce lepton flavor violation as well as FCNC processes.

Moreover, these terms contain new sources of CP-violation in the quark sector.

4 Induced mixing of matter fields

Let us consider mixing between the fields of MSSM that appears after messengers are integrated out. It is straightforward to check that the fermion mixing terms are small at the tree level. In principle, this mixing may lead to lepton and quark flavor violation due to one loop diagrams involving scalars and gauginos [10]. However, this effect is negligible due to see-saw type mechanism.

The main contribution to the processes in the visible sector comes from slepton and squark mixing. Tree level mixing in the scalar sector is again small. The dominant contributions to mixing in the slepton and the squark sectors appear through one loop diagrams originating from trilinear terms in the superpotential that involve messengers, H_D for fundamental messengers, and also H_U for antisymmetric ones. [1]

After diagonalizing the messenger mass matrix we obtain the diagrams contributing to scalar mixing to the order $(\lambda S)^2$, which are shown in Fig. 2. If supersymmetry were unbroken, the sum of these diagrams would be equal

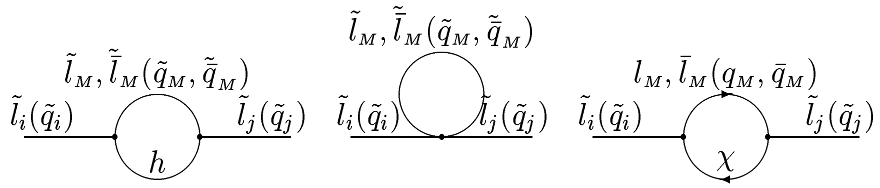

Figure 2: The diagrams dominating the scalar mixing matrix.

to zero. In our case of broken supersymmetry the resulting contributions to

[1] In the case of very small values of x the dominant contributions to δm_{ij}^2 come from two loops rather than one loop, but we will not consider this special case (see discussion in ref. [11]).

the mass matrices of MSSM scalars (for x not very close to 1) are

$$\delta m_{ij}^2 = -a\frac{\Lambda^2}{96\pi^2}Y_i^* Y_j x^2 \tag{5}$$

where $a = 1(2)$ for scalars transforming as weak doublets (singlets).

5 Constraints on Yukawa matrices

There are two types of constraints on Yukawa couplings inherent in this theory.

- Since scalars get negative shifts in squared masses, the expression (5) for the soft terms immediately implies theoretical bounds on Yukawa couplings Y_i which come from the requirement [9] that none of the scalar squared masses becomes negative.
- Mixing (3), (4) leads to the FCNC processes as well as to lepton flavor and CP violation. The existing experimental bounds on these processes provide constraints on the products of Yukawa couplings.

5.1 Theoretical bounds

Let us first obtain theoretical constraints on Yukawa couplings present in this model. With loop corrections (5) to the scalar mass matrix included, its eigenvalues $\tilde{m}_i^2$ are all positive only if

$$\tilde{m}^2 + \sum_{j=1}^{3} \delta m_{jj}^2 > 0 \tag{6}$$

where $\tilde{m}^2$ is given by eq. (2). Making use of inequality $|Y_i Y_j| < \frac{1}{2}\sum |Y_i|^2$ one obtains from eq. (6) the theoretical constraint on mixing

$$-\delta\tilde{m}_{ij}^2 < \frac{1}{2}\tilde{m}^2 \tag{7}$$

As an example, the self-consistency condition of the theory can be written in case of small x as follows,

$$Y_i Y_j x^2 < \frac{96\pi^2}{a}\sum_{i=1}^{3} c_i C_i \left(\frac{\alpha_i}{4\pi}\right)^2 \tag{8}$$

5.2 The experimental limits

Let us now consider the effects of scalar mixing on the usual leptons and quarks. It is clear that different experiments are sensitive, generally speaking, to different combinations of Yukawa couplings and CP-violating phases.

The bounds on various products of Yukawa couplings between messengers and quarks (and leptons) coming from the requirement that corresponding mixing is consistent with the present experimental limits on the rare processes were found in refs. [12, 11]. Some of the theoretical bounds coming from eq. (8) are stronger than corresponding experimental ones.

The typical constraint on Yukawa couplings in the quark sector is $Yx \lesssim 0.1$ and comes from mixing of neutral mesons, while $b \to s\gamma$ decay does not give any bounds and the corresponding Yukawa terms are limited by the self-consistency condition (8). There are also limits on CP-violating terms coming from the analysis of $K^0 - \bar{K}^0$ system and $K \to \pi\pi$ decays.

In the slepton sector there is a single experimental constraint coming from the $\mu \to e\gamma$ decay: $|Y_{41}^{(5,10)} Y_{42}^{(5,10)}|^{1/2} x \lesssim 3 \times 10^{-2}$. Slepton mixing in the gauge-mediated models leads also to $\mu \to e$ conversion, but the existing limit on this process gives weaker bound on the product of Yukawa couplings than one coming from the $\mu \to e\gamma$ decay. Concerning the other processes, the self-consistence of the model requires that the rates $\Gamma(\tau \to e\gamma)$ and $\Gamma(\tau \to \mu\gamma)$ are lower than the present experimental limits at least by factor of 10^{-2}. The same conclusion holds in the case of antisymmetric messengers as well.

Therefore we may conclude that sizeable messenger-matter mixing is consistent both with experimental limits and with electroweak symmetry breaking pattern.

6 Electroweak breaking and squark masses

It was already mentioned that radiative electroweak breaking in MGMM without messenger-matter mixing leads to large values of $\tan\beta \gtrsim 50$. A usual way to avoid this limit is to assume some extra soft contribution to the Higgs sector of the theory. In this section we consider electroweak breaking in the model with messenger-matter mixing. In particular, we show that wide range of values of $\tan\beta$ is now allowed without any introducing additional parameters in the Higgs sector of the model.

Minimization of the Higgs potential

$$V = (\mu^2 + m_{h_U}^2)h_U^2 + (\mu^2 + m_{h_D}^2)h_D^2 + B_\mu(h_U h_D + h.c.) + \frac{g'^2 + g^2}{8}(|h_U|^2 - |h_D|^2)^2 + \frac{g^2}{2}|h_U^+ h_D|^2$$

results in the following two equations,

$$\sin 2\beta = \frac{-2B_\mu}{m_{h_U}^2 + m_{h_D}^2 + 2\mu^2} \;, \quad \mu^2 = \frac{m_{h_D}^2 - m_{h_U}^2 \tan^2\beta}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2 \tag{9}$$

At the two loop level, the parameter B_μ characterizing the magnitude of the soft mixing term $B_\mu h_U h_D$ in the Higgs sector is equal to [2]

$$B_\mu = M_{\lambda_2}\mu(-0.12 + 0.17Y_t^2) \;, \tag{10}$$

where M_{λ_2} is given by eq. (1).

In MGMM without messenger-matter mixing, the value of the soft mass $m_{h_D}^2$ is given by eq. (2) while $m_{h_U}^2$ receives additional large negative one-loop correction due to large Yukawa coupling between H_U and top-quark,

$$\delta m_{h_U}^2 = -\frac{3Y_t^2}{4\pi^2} m_{\tilde{t}}^2 \ln\left(\frac{\Lambda}{x m_{\tilde{t}}}\right) \tag{11}$$

It follows from eqs. (2) and (11) that $\delta m_{h_U}^2 \gtrsim m_{h_U}^2, m_{h_D}^2$, hence eq. (9) takes the following simple form

$$\mu^2 \simeq -\delta m_{h_U}^2 \;, \qquad \sin 2\beta \simeq -\frac{2B_\mu}{\mu^2} \tag{12}$$

It is clear from eqs. (10) and (12) that $\sin 2\beta \ll 1$, and, therefore, $\tan\beta \gg 1$. This simple estimate gives $\tan\beta \geq 50$. Detailed calculations [7, 6] confirm this estimate in MGMM without mixing.

In the presence of messenger-matter mixing squared Higgs masses receive negative contribution from the diagrams analogous to those shown in Fig. 2:

$$\delta m_{h_D}^2 = -d_D \frac{\Lambda^2}{96\pi^2}x^2 \;, \quad \delta m_{h_U}^2 = -d_U \frac{\Lambda^2}{96\pi^2}x^2 \tag{13}$$

where

$$d_D = \sum_{i=1}^{3}\left(|Y_{4i}^{(5)}|^2 + |Y_{4i}^{(10)}|^2 + 3|W_{4i}^{(10)}|^2 + 3|X_{4i}^{(5)}|^2\right) ,$$

$$d_U = \sum_{i=1}^{3} \left(3|X_{4i}^{(10)}|^2 + 3|X_{i4}^{(10)}|^2 \right)$$

and we consider "small" x ($x \lesssim 0.8$).

Depending on the Yukawa coupling constants, the mass splitting $\delta m^2_{h_D}$ may be of the same order as $\delta m^2_{h_U}$. In that case the value of $\sin 2\beta$ gets modified as compared to eq. (12). One has an estimate

$$\mu^2 \simeq \delta m^2_{h_U}, \qquad \sin 2\beta \simeq \frac{-2B_\mu}{\mu^2 - \delta m^2_{h_D}} \tag{14}$$

Therefore messenger-matter mixing reduces $\tan\beta$.

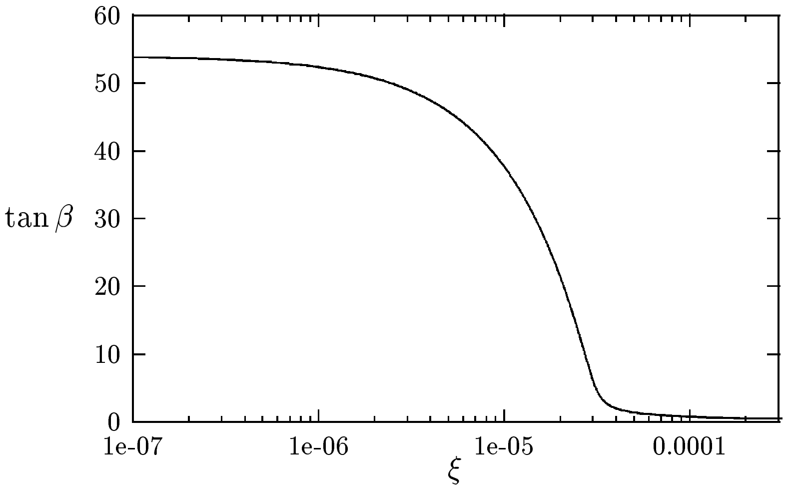

Figure 3: $\tan\beta$ as function of $\xi = \delta m^2_{h_D}/\Lambda^2 = -d_D \frac{f_3(x)}{96\pi^2}$.

As an example, in the case of fundamental messengers, $d_U = 0$ and

$$d_D = \sum_{i=1}^{3} \left(|Y_{4i}^{(5)}|^2 + 3|X_{4i}^{(5)}|^2 \right) \tag{15}$$

The result of numerical solution of eq. (9) in this theory is shown in Fig. 3, where we set $x = 1$ in the argument of the logarithm in eq. (11)

The only bound on $\delta m^2_{h_D}$ is related to the theoretical limit on the value of d_D, coming from eq. (6), which gives $\delta m^2_{h_D}/\Lambda^2 < 3 \times 10^{-4}$. The value of

$\tan\beta$ strongly depends on the mixing parameter d and may actually be rather small. One can show that this conclusion survives if higher order corrections are taken into account.

On the other hand, the parameter μ weakly depends on mixing and grows only slightly at large values of $\xi = \delta m^2_{h_D}/\Lambda^2$.

7 Concluding remarks

We have considered mixing between the usual matter and messengers belonging to either the fundamental or antisymmetric complete $SU(5)$ multiplets in the Minimal Gauge Mediated Model. Limits on the corresponding coupling constants coming from various flavor violating processes in the lepton and the quark sectors and CP violating processes in the quark sector have been found in refs. [12, 11]: at $x \gtrsim 0.1$, experimentally accessible values of most of the messenger-matter Yukawa couplings are in the range $10^{-3} \div 1$, which does not seem unrealistic.

In fact, there are two types of constraints on the allowed region in the space of messenger-matter Yukawa couplings. All experimental bounds coming from the flavor physics limit only the products of different Yukawa couplings $|Y_i Y_j|^{1/2}$ but not Y_i separately. On the other hand, theoretical bounds, coming from the requirement of positivity of the scalar masses, correspond to spherical regions $\sum |Y_i|^2 <$ const in the space of Yukawa couplings.

There are basically no experimental constraints coming from the $\tau \to e\gamma$, $\tau \to \mu\gamma$ and $b \to s\gamma$ decays and the corresponding mixing terms are limited by the self-consistency conditions inherent in the theory. Branching ratios of these decays must be about $10^2 \div 10^3$ $(10^4 \div 10^5)$ times smaller than existing experimental bounds in the case of the fundamental (antisymmetric) messengers. Hence this model forbids flavor violating τ decays and the contribution to the $b \to s\gamma$ decay at the level of the next generation experiments.

We have seen that small value of $\tan\beta$ can naturally appear in MGMM with messenger-matter mixing. It would lead to important changes in the low energy sparticle spectrum [11]. For example, in MGMM without mixing, NLSP is a combination of $\tilde{\tau}_R$ and $\tilde{\tau}_L$ appearing due to large mixing $\Delta m^2_{\tilde{\tau}_R - \tilde{\tau}_L} = 2 m_\tau \mu \tan\beta$ (we remind that in this theory $\mu \gtrsim 500$ GeV and $\tan\beta \gtrsim 50$). In the presence of mixing the possible small value of $\tan\beta$ reduces slepton mixing and NLSP becomes bino. This changes significantly the predictions of this model for collider experiments. This type of NLSP is suitable for explaining the CDF event [13] with $e^+e^-\gamma\gamma E_T$ final state.

One can obtain predictions for parameters d_U and d_D assuming that this model is embedded into a certain Grand Unified Theory. For instance, in the case of $SU(5)$ Grand Unification with fundamental messengers one can predict $\tan\beta$ and consequently the parameter d_D from $b-\tau$ unification condition, $y_b(M_{GUT}) = y_\tau(M_{GUT})$. Given the current uncertainties in the determination of α_3, two narrow regions of $\tan\beta$ are allowed [14] (see Fig. 4). If physics

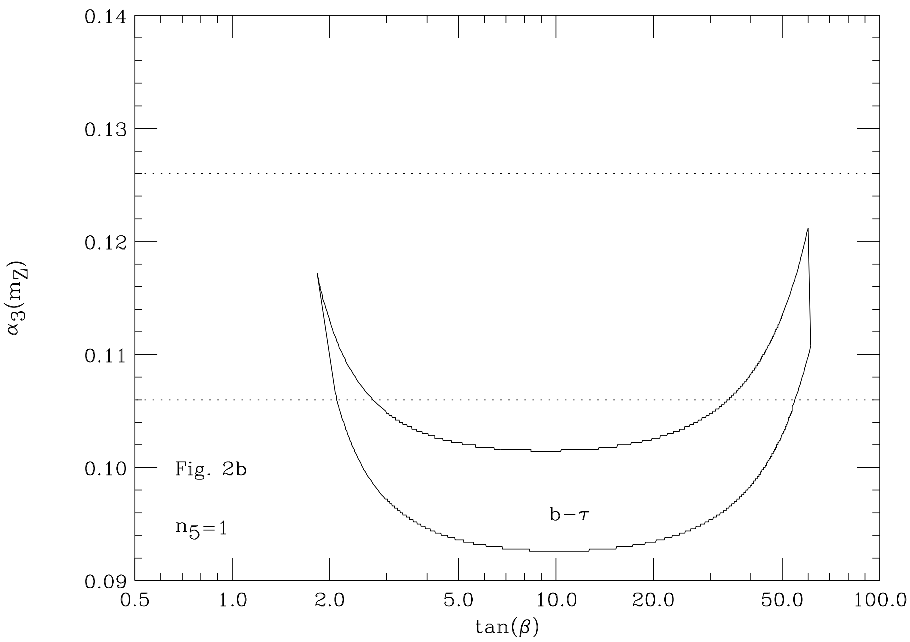

Figure 4: Constraints on $\tan\beta$ in supersymmetric $SU(5)$ model with $n_5 = 1$ fundamental messenger generation that come from the requirement of $b - \tau$ unification [14].

below the GUT scale is indeed described by MGMM with mixing, the predicted range of $\tan\beta$ narrows the parameter space of Yukawa terms and may prove useful for estimating the rates of flavor violation processes.

Messenger-matter mixing can resolve the problem of fast nucleon decay in the $SU(5)$ GUT extension of MGMM [14]. The nucleon life-time depends strongly on β (since $\tau(n \to K^0\tilde{\nu})$ is proportional to $\sin^2 2\beta$) and even in the presence of incomplete messenger multiplets it is necessary to reduce the value of $\tan\beta$ in MGMM in order to suppress proton decay [15]. Messenger-matter mixing is one of the mechanisms which can be responsible for this reduction.

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