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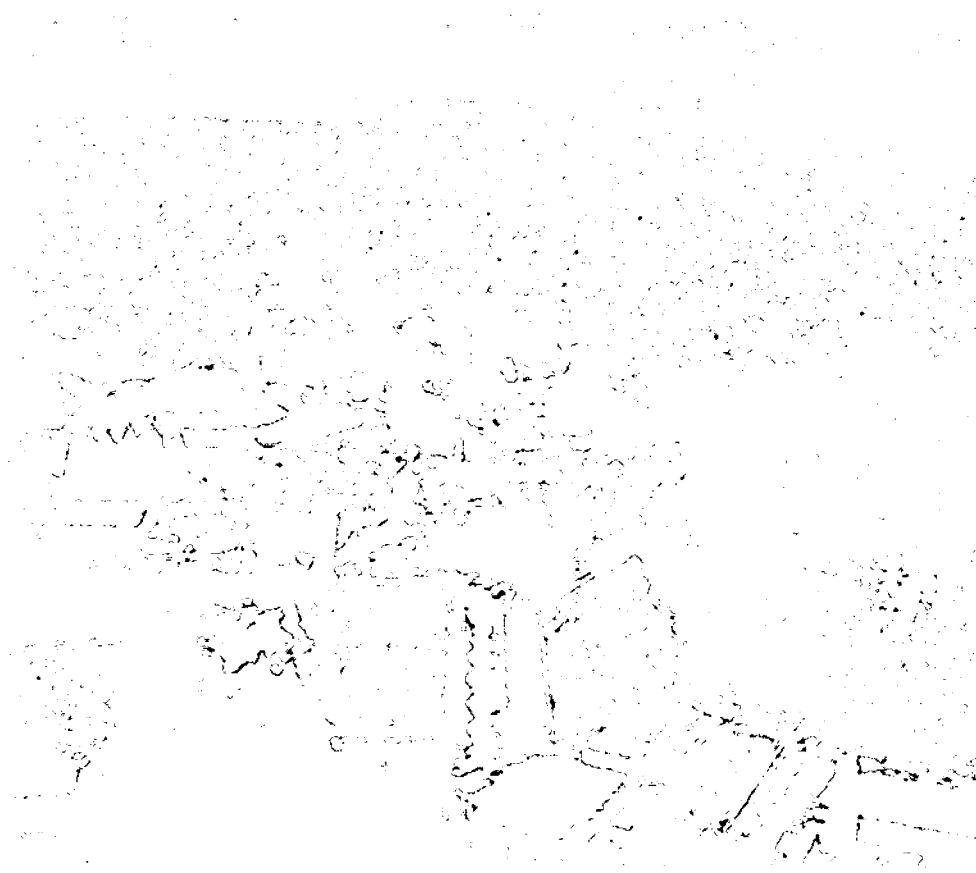
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Higgs-Mediated $B^0 \rightarrow \mu^+ \mu^-$ in Minimal Supersymmetry

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Abstract

In this letter we demonstrate a new source for large flavor-changing neutral currents within the minimal supersymmetric standard model. At moderate to large $\tan\beta$, it is no longer possible to diagonalize the masses of the quarks in the same basis as their Yukawa couplings. This generates large flavor-violating couplings of the form $\bar{b}_R d_L \phi$ and $\bar{b}_R s_L \phi$ where ϕ is any of the three neutral, physical Higgs bosons. These new couplings lead to rare processes in the B system such as $B^0 \rightarrow \mu^+ \mu^-$ decay and $B^0 - \bar{B}^0$ mixing. We show that the latter is anomalously suppressed, while the former is in the experimentally interesting range. Current limits on $B^0 \rightarrow \mu^+ \mu^-$ already provide nontrivial constraints on models of moderate to large $\tan\beta$, with an observable signal possible at Run II of the Tevatron if $m_A \lesssim 400 - 700$ GeV, extending to the TeV range if a proposed Run III of 30 fb^{-1} were to occur.

much of it off, depending on their relative (model-dependent) signs. Perhaps more importantly, this contribution can still lead to large ϵ_u even if the A -terms at the weak scale are small compared to the squark masses.

Now we return to Eq. (1). We can simplify it considerably by working in a basis in which $\mathbf{Y}_U = \mathbf{U}$ and $\mathbf{Y}_D = \mathbf{D}\mathbf{V}^{0\dagger}$ where \mathbf{V}^0 is the CKM matrix at lowest-order (the meaning of this will be clear shortly) and \mathbf{U} and \mathbf{D} are both diagonal. Then

$$-\mathcal{L}_{eff} = \overline{D}_R \mathbf{D}\mathbf{V}^{0\dagger} Q_L H_d + \overline{D}_R \mathbf{D}\mathbf{V}^{0\dagger} [\epsilon_g + \epsilon_u \mathbf{U}^\dagger \mathbf{U}] Q_L H_u^* + h.c. \quad (9)$$

It is clear that in the absence of the ϵ_u term, all pieces of the effective Lagrangian can be diagonalized in the same basis, preventing the appearance of flavor-changing neutral currents (FCNCs). It is the presence of the $\epsilon_u \mathbf{U}^\dagger \mathbf{U}$ piece, however, that will prevent simultaneous diagonalization and generate some flavor-changing.

To see how this works, it is sufficient to keep only the Yukawa couplings of the third generation so that $(\mathbf{U})_{ij} = y_t \delta_{i3} \delta_{j3}$ and $(\mathbf{D})_{ij} = y_b \delta_{i3} \delta_{j3}$. The flavor-conserving pieces of \mathcal{L}_{eff} then have the form

$$(1 + \epsilon_g) \mathbf{D}\mathbf{V}^{0\dagger} = (1 + \epsilon_g) y_b \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ V_{ub}^0 & V_{cb}^0 & V_{tb}^0 \end{pmatrix} \quad (10)$$

while the flavor-changing piece has the form

$$\epsilon_u \mathbf{D}\mathbf{V}^{0\dagger} \mathbf{U}^\dagger \mathbf{U} = \epsilon_u y_t^2 y_b \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & V_{tb}^0 \end{pmatrix}. \quad (11)$$

We can define a physical eigenbasis by rotating the d -component of Q_L by a new matrix \mathbf{V} defined by diagonalizing the mass matrix:

$$(\mathbf{V}^\dagger \mathcal{Y}^\dagger \mathcal{Y} \mathbf{V})_{ij} = \text{diag}(\overline{y}_d^2, \overline{y}_s^2, \overline{y}_b^2) \quad (12)$$

where the \overline{y}_i are defined to be the ‘‘physical’’ Yukawa couplings, *e.g.*, $m_b = \overline{y}_b v_d$; and

$$\mathcal{Y} = \mathbf{D}\mathbf{V}^{0\dagger} [1 + \tan \beta (\epsilon_g + \epsilon_u \mathbf{U}^\dagger \mathbf{U})], \quad (13)$$

the $\tan \beta$ coming from the vev of H_u which multiplies the loop-induced terms. \mathbf{V} can now be interpreted as the physical CKM matrix.

In the physical basis, the (3,3) element of the mass matrix gives us the corrected b -quark mass:

$$\overline{y}_b \simeq y_b [1 + (\epsilon_g + \epsilon_u y_t^2) \tan \beta]. \quad (14)$$

To get to this equation we used the fact that one finds no large (*i.e.*, $\tan \beta$ -enhanced) corrections to V_{tb} [4], so that we can replace $V_{tb}^0 \simeq V_{tb} \simeq 1$.

$m_{A^0} \rightarrow \infty$, driving $\alpha \rightarrow \beta - \frac{\pi}{2}$. There the $h^0 \bar{b}_R d_L$ coupling goes to zero as it should in any single Higgs doublet model.

We will now consider two processes which constrain and/or provide a signal for the Higgs-mediated FCNCs: $B^0 - \bar{B}^0$ mixing and the decay $B^0 \rightarrow \mu^+ \mu^-$. The case of $B^0 - \bar{B}^0$ mixing is actually quite amusing. Δm_{B_d} is very well known and usually provides one of the tightest constraints on new sources of flavor-violation in the d -quark sector. And, in principle, mixing can be generated by single Higgs exchange. The leading order contribution of the 3 physical Higgs bosons to an effective operator $\bar{b}_R^i d_L^i \bar{b}_R^j d_L^j$ (i, j are SU(3) indices) is proportional to the product of vertex factors and propagators given by:

$$\mathcal{F} \equiv \left[\frac{\cos^2(\beta - \alpha)}{m_h^2} + \frac{\sin^2(\beta - \alpha)}{m_H^2} - \frac{1}{m_{A^0}^2} \right]. \quad (21)$$

However, $\mathcal{F} = 0$ at lowest order. The existence of this zero is essentially an accidental cancellation coming from the special form of Eq. (17) and not an indication that the flavor-changing is illusory.

It is natural to ask whether this zero survives loop corrections, and one finds that it does not. However, the cost of adding another loop to the diagram is high and tends to suppress this new contribution too much to dominate the Standard Model contribution. We have considered in detail the largest non-zero contribution, which arises from top-stop induced vacuum polarization on the internal Higgs line. While these propagator corrections to the Higgs are known to be large [10], we find that the leading term (which is a correction to the H_u line) is suppressed by $1/\tan^2 \beta$. The next-leading term (a correction on the H_d line due to left-right stop mixing) is present but is not very large. All other radiative corrections we expect to be even smaller.

One can still derive a bound on m_A by demanding that the MSSM contribution to Δm_{B_d} is less than its observed value. Such a bound will depend sensitively on whether or not the two contributions to ϵ_u from Eqs. (4) and (8) interfere constructively or destructively. Assuming all MSSM masses to be near 500 GeV and constructive interference, we find $m_A \lesssim 100$ to 125 GeV for $\tan \beta = 40$ to 60. Direct search constraints aside, it is known that models with such a light second Higgs doublet generally contribute far too much to $b \rightarrow s \gamma$ and are therefore already ruled out [11]. Thus this new source of flavor-changing rules out a part of parameter space which is already known to be disfavored.

We now consider the rare decay $B^0 \rightarrow \mu^+ \mu^-$. This occurs via emission off the quark current of a single virtual Higgs boson which then decays leptonically. The largest leptonic flavor-changing branching fraction would clearly be to $\tau^+ \tau^-$. However, the branching fraction to μ 's is only suppressed by $(m_\mu/m_\tau)^2$ times a phase space factor, which is only about 1 part in 100. The current experimental limits on $Br(B^0 \rightarrow \mu^+ \mu^-)$ are at the 10^{-6} level, which means that the largest the branching ratio into τ 's could be is about 10^{-4} . Given the extreme difficulties encountered in trying to measure this decay experimentally, it is doubtful that the τ -mode will ever

here we are still far above the Standard Model which predicts $Br(B_{(d,s)}^0 \rightarrow \mu^+\mu^-) \simeq (1.5, 35) \times 10^{-10}$ [13]. Thus further experimental data can significantly improve the bounds on m_A or find a non-zero signal induced by supersymmetry.

So what is implied for Run II at the Tevatron? Assuming no change in their efficiencies and acceptances, CDF can in principle place a bound $Br(B_s^0 \rightarrow \mu^+\mu^-) < 1 \times 10^{-7}$ given 1 fb^{-1} of data, a factor of 20 stronger than present. Thus the region probed in m_A will increase by $20^{1/4} \simeq 2$:

$$m_A > (475, 365, 490, 450) \text{ GeV} \quad (26)$$

for the same sets of inputs as previously. After collecting 5 fb^{-1} these masses increase by another 50%, up to 725 GeV. Finally, if the proposed ‘‘Run III’’ of the Tevatron with 30 fb^{-1} were to occur, masses of A^0 all the way to 1 TeV could be studied. This could be a very important signal for supersymmetry since *this source of flavor-changing does not decouple as $M_{\text{SUSY}} \rightarrow \infty$* so long as m_A does not also get very heavy. That is to say, the bound on m_A is roughly independent of M_{SUSY} . Therefore supersymmetric spectra in the multi-hundred GeV to TeV range may be probed at the Tevatron through rare B -decays even when direct production of supersymmetry (including the second Higgs doublet) cannot be observed. Since the precise predictions for $Br(B_s^0 \rightarrow \mu^+\mu^-)$ are highly dependent on the individual model, these estimates should only be taken as indicative. Further work will be forthcoming [8].

It is also possible to look for new sources of flavor-changing in inclusive semileptonic decays $B \rightarrow X_s \mu^+ \mu^-$. The width for this process can be extracted from Eq. (24) by replacement of f_B with m_B and dividing by $192\pi^2$ for the 3-body phase space. The rate is thus a factor of 10 smaller than for $B_s \rightarrow \mu^+ \mu^-$. Comparing to current bounds [14] yields constraints on m_A that are weaker by a factor of 1.8 than the bounds from the purely leptonic mode. The ability of future experiments to extract information from this mode will be discussed in [8].

Finally, we find it noteworthy that the largest signals tend to occur for $\epsilon_g < 0$ and intermediate values of $\tan \beta$. In minimal GUT models, one expects unification of the b - and τ -Yukawa couplings. But it is well-known that this unification fails over most of the parameter space of the MSSM and generally necessitates the use of the HRS corrections to bring the Yukawas back into agreement. Typically one requires $(\epsilon_g + y_t^2 \epsilon_u) \tan \beta \approx -0.2$ [3, 15] which in turn means that $\epsilon_g < 0$. This provides an argument for believing that the signal might lie in the observable range, as well as providing another test of Yukawa unification (beyond those discussed in [6] for flavor-conserving processes).

In summary, we have found that neutral Higgs bosons are capable of mediating flavor-changing interactions within the MSSM. This result is generic and does not rely on assumptions about sparticle mass non-universality which are usually required in order to get FCNCs. These interactions are enhanced at large $\tan \beta$ and are in the range that will be experimentally probed in the near future.

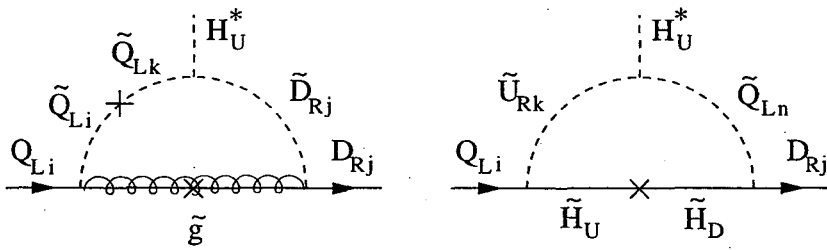


Figure 1: Leading contributions to ϵ_g and ϵ_u . Indices i, j, k, n label flavors.

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