NEUTRALINO CONTRIBUTION TO THE MASS DIFFERENCE OF
$B^0_d - \bar{B}^0_d$

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ABSTRACT

We present a detailed and complete calculation of the neutralino contribution to the mass difference $\Delta m_{B^0_d}/m_{B^0_d}$ within the MSSM. We include the complete mixing matrices of the neutralinos and of the scalar partners of the left and right handed bottom quark. We find that the neutralino contribution is generally small but can be of the same order of the chargino contribution and much larger than that of the gluino over a small range of $m_S$, given $m_{g_2}$ and $\mu$ and for $\tan \beta \sim 50$.

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I. INTRODUCTION

In a recent paper [1] we presented a detailed analysis of the charginos and the scalar partners of the up quarks as well as of the gluino and scalar partners of the down quarks contribution to the mass difference $\Delta m_{B_d}/m_{B_d}$. We included the mixing of the charginos and of the third generation of the scalar partners of the up and down quarks. It was shown that for large values of the gluino mass ($m_{\tilde{g}} > 100$ GeV) and of the soft supersymmetric breaking scalar mass ($m_S > 300$ GeV) the charginos give the most important contribution to the mass difference in the $B$ system, although they couple only weakly to quarks and scalar quarks, whereas the gluino couples strongly. Therefore we concluded that it was not legitimate to neglect the contribution of the neutralinos and the scalar partners of the down quarks in front of the gluino and the scalar partners of the down quarks, as is usually done in the literature, since the neutralinos and charginos couple with same strength.

In this paper we present a detailed analysis of contribution of the neutralinos to the mass difference $\Delta m_{B_d}/m_{B_d}$. In our calculation we include the mixing of the neutralinos and of the scalar partners of left and right handed bottom quark including one loop corrections. Although the bottom quark mass is relatively small the mixing might become important if $\tan \beta = \frac{v_2}{v_1} \gg 1$ where $v_{1,2}$ are the vacuum expectation values (vev's) of the Higgs particles in the MSSM.

In the next section we present the calculation and discuss the results in the third section. We end with the conclusions.

II. NEUTRALINO CONTRIBUTION TO THE $B_d^0$ SYSTEM

For the complete analysis of the contribution of the charginos and scalar up quarks and of the gluino and scalar down quarks we refer the reader to [1]. Here we repeat only shortly the results of the standard model (SM) contribution to $\Delta m_{B_d}/m_{B_d}$, which is obtained by calculating the box diagrams, where $W$ bosons and up quarks are taken within the loop. After summation over all quarks it turns out that the top quark gives the main contribution to $\Delta m_{B_d}$. The result is well known and given by [2]:

$$\frac{\Delta m_{B_d}}{m_{B_d}} = \frac{G_F^2}{6\pi^2} f_B^2 B \eta_t m_W^2 (K_{31}^* K_{33})^2 S(x_t)$$

$$S(x_t) = x_t \left\{ \frac{1}{4} + \frac{9}{4} (1 - x_t)^{-1} - \frac{3}{2} (1 - x_t)^{-2} \right\} - \frac{3}{2} \frac{x_t^3}{(1 - x_t)^3} \ln x_t$$

where $f_B$, $B$ are the structure constant and the Bag factor obtained by QCD sum rules and $\eta_t$ a QCD correction factor [2]. For a large top quark mass their values are given by $f_B = 0.180$ GeV, $B = 1.17$ and $\eta_t = 0.55$ [3]. The experimental value is given by $\Delta m_{B_d}/m_{B_d} \approx 6.4 \times 10^{-14}$ [4].

To obtain $\Delta m_{B_d}$ with neutralinos and scalar down quarks within the loop we have to calculate all those diagrams as shown in Fig.1, where we also include the so

1
called "mass insertion" diagram denoted with \( \otimes \) [5]. This notation means that in this diagram \( P_R(k + m)P_R = mP_R \) remains whereas the other one gives \( P_R(k + m)P_L = kP_L \) (\( P_{L,R} \) are the projection operators). In our calculation we take the full set of couplings as given in Fig.24 of [6]. Furthermore as mentioned above we include the mixing of the neutralinos and the scalar partners of the left and right handed down quarks. For a more detailed description of the mixing of the charginos and of the neutralinos and the scalar partners of the left and right handed down quarks we refer to [1,7]. Here we only repeat the mixing of the scalar partner of the left and right handed bottom quark, that is instead of the current eigenstates \( \bar{q}_{L,R} \) we work with the mass eigenstates

\[
\bar{q}_1 = \cos \Theta_q \bar{q}_L + \sin \Theta_q \bar{q}_R \quad \bar{q}_2 = -\sin \Theta_q \bar{q}_L + \cos \Theta_q \bar{q}_R
\]

A while ago it was shown in [8–9], that when including loop effects flavour changing couplings of the scalar partner of the left handed down quarks with the gluinos are created, whereas the couplings of the gluinos with the scalar partner of the right handed down quarks remain flavour diagonal, that is only the scalar partners of the left handed down quarks have to be considered in the relevant loop diagrams to \( B_d - \bar{B}_d \) mixing. When neutralinos are taken in the loop we have to consider both couplings of the neutralinos to the scalar partners of the left and right handed down quarks. For the mass matrix of the scalar bottom quark we have to take at 1 loop level\(^1\):

\[
M_b^2 = \begin{pmatrix}
  m_{b_L}^2 + m_{b_R}^2 - 0.42D_Z - |c|m_t^2 & -m_b(A_b + \mu \tan \beta) \\
  -m_b(A_b + \mu \tan \beta) & m_{b_R}^2 + m_b^2 - 0.08D_Z
\end{pmatrix}
\]

with \( T_3^b - e_b \sin \Theta_W = -0.42 \) and \( e_b \sin \Theta_W = -0.08 \). \( b \) is understood as subscript for all three generations down, strange and bottom. \( m_{b_{L,R}} \) are soft SUSY breaking mass terms, \( A_b \) the parameter from the trilinear scalar interaction and \( \mu \) the mixing mass term of the Higgs bosons (in the analysis here we take \( m_{b_L} = m_S = m_{b_R} = A_b \)). The model dependent parameter \( c \) plays a crucial role in the calculation of the gluino and scalar down quark contribution to the mass difference in the \( B_d \) system. The value of \( c \) is negative and of order 1 (\( |c| \) increases with the soft SUSY breaking mass term \( m_S \) and decreases with the top quark mass [10]). In the following we take \( c = -1 \), although we keep in mind that it is more likely smaller in magnitude. The mixing term might only get important in the case \( \tan \beta \gg 1 \).

For the mass matrix of the neutralinos we take eq.(A.19) in [6]:

\[
M_{\tilde{N}} = \begin{pmatrix}
  m_{\tilde{g}_1} & 0 & -m_Z \sin \theta_W \cos \beta & m_Z \sin \theta_W \sin \beta \\
  0 & m_{\tilde{g}_2} & m_Z \cos \theta_W \cos \beta & -m_Z \cos \theta_W \sin \beta \\
  -m_Z \sin \theta_W \cos \beta & m_Z \cos \theta_W \cos \beta & 0 & -\mu \\
  m_Z \sin \theta_W \sin \beta & -m_Z \cos \theta_W \sin \beta & -\mu & 0
\end{pmatrix}
\]

\(^1\) To be more exact the term \( |c|m_t^2 \) should be read as \( |c|K^4 m_u m_b K \) where \( m_u \) is the diagonalized up quark matrix and \( K \) the KM-matrix. But since \( m_{u,d}^2 \ll m_t^2 \) only the top quark is of importance.
In order to have fewer free parameters we also use the well known GUT relation between the $U(1)$ and $SU(2)$ gaugino masses $m_{g_1} = \frac{5}{3} m_{g_2} \tan^2 \Theta_W$ \footnote{There is also a similar relation between the gluino and $SU(2)$ gaugino mass $m_{\tilde{g}} = (g_s/g_2)^2 m_{\tilde{g}_2}$} We calculate the mass eigenvalues and mixing angles numerically and take the smallest eigenvalue to be higher than about 30 GeV \cite{11}

After a lengthy but straightforward calculation we obtain the following result when neutralinos and scalar down-type quarks are running on the loop:

\[
\frac{\Delta m_{B_d}^2}{m_{B_d}^0} = \frac{G_F^2}{(4\pi)^2} f_B^2 B_B m_Z^4 (K_{31}^* K_{33})^2 [Z_{11}^N - 2 Z_{31}^N + \tilde{Z}_{33}^N]
\]

\[
Z_{11}^N = \sum_{i,j=1,4} \left( T_i^L T_j^L - T_i^R T_j^R \right)^2 G_{ij}^{gij} + 2 T_i^{mb} T_j^L (T_i^{mb} T_j^R - T_j^{mb} T_i^R) \tilde{F}_{ij}^{dd} + \{ T_i^{mb} T_j^L (T_j^{mb} T_i^L - T_i^{mb} T_j^L) + T_i^{mb} T_j^R (T_j^{mb} T_i^R - T_i^{mb} T_j^R) \} 2 M \tilde{F}_{ij}^{dd}
\]

\[
Z_{31}^N = \sum_{i,j=1,4} \left\{ T_i^L T_j^L \left( T_i^R T_j^R - T_i^L T_j^L \right) [c_{\Theta_b} G_{b1b1}^{gij} + s_{\Theta_b} G_{b2b2}^{gij}] + s_{\Theta_b} \tilde{G}_{b1b2}^{gij} + c_{\Theta_b} \tilde{G}_{b2b1}^{gij} \right\}
\]

\[
\tilde{Z}_{33}^N = \sum_{i,j=1,4} \left\{ T_i^L 2 T_j^L \left[ c_{\Theta_b} G_{b1b1}^{gij} + 2 c_{\Theta_b} s_{\Theta_b} G_{b1b2}^{gij} + s_{\Theta_b} G_{b2b2}^{gij} \right]
\right\}
\]

\[
G_{ab}^{ij} := \tilde{F}_{ab}^{ij} + 2 M \tilde{F}_{ab}^{ij}
\]

\[
T_i^{mb} = \frac{m_b}{m_Z \cos \beta} N_i^3
\]

\[
T_i^L = e_d \sin 2 \Theta_W N_i^1 + (1 + 2 e_d \sin^2 \Theta_W) N_i^2
\]

\[
T_i^R = - \{ e_d \sin 2 \Theta_W N_i^1 - 2 e_d \sin^2 \Theta_W N_i^2 \}
\]

\[
c_{\Theta_b} = \cos^2 \Theta_b, \ s_{\Theta_b} = \sin^2 \Theta_b \] and $\cos \beta$ can be extracted from $\tan \beta$. $N_{ij}$ and $N'_{ij}$ are the diagonalizing angles as defined in eq.(A.20) and eq.(A.23) in \cite{6} and taken
to be real. We calculate them numerically. \( \tilde{F}_{ij} \) and \( M \tilde{F}_{ij} \) are given in the appendix A. \( m_{i,j} = m_{\tilde{N}_{i,j}} \) are the mass eigenvalues of the neutralinos and \( m_{d,b1,2} \) the masses of the scalar down quark and the eigenstates of the scalar bottom quark including the mixing and 1 loop corrections. \( \tilde{F}_{i}^{ii} \) and \( M \tilde{F}_{i}^{ii} \) are the same functions as given in eq.C.2 in [12].

Since we neglected all quark masses except that of the bottom quark, we made use of \( Z_{11} = Z_{12} = Z_{21} = Z_{22} \) and \( Z_{13} = Z_{31} = Z_{32} = Z_{23} \). As was shown in [13] the mixing angles of the scalar down quarks might also become important in the second generation but it is safe to neglect them here since \( m_{\tilde{s}_1} \approx m_{\tilde{s}_2} \) and since the mixing of the scalar quark is proportional to the quark masses \( c^2_{\Theta_b} = \cos^2 \Theta_b \approx 1 \), only for large values of \( \tan \beta \) the mixing angle of the scalar bottom quark mass becomes more important.

III. DISCUSSIONS

We now present those contributions for different values of gaugino and scalar down quark masses. We also vary \( \tan \beta \) and the symmetry-breaking scales. As input parameter we take \( m_{\text{top}} = 174 \text{ GeV}, \ m_b = 4.5 \text{ GeV}, \ \alpha = 1/137 \) and for the strong coupling constant \( \alpha_s = 0.1134 \). For a top quark mass of 174 GeV the SM result eq.1 gives a value of \( 4.67 \times 10^{-16} \).

In Figs. 2, we show the neutralino contribution and compare them with the chargino contribution.

The global behaviour is clear: for small values of \( \tan \beta \) (\( \sim 20 \) or less) the neutralino contribution is small compared to that of the chargino. On the other hand, when \( \tan \beta \sim 50 \), \(^3\) the neutralino contribution can be much larger than that of the chargino for the smallest possible values of \( m_S \). Unfortunately, as we can see on the figure, this contribution falls very quickly as \( m_S \) increases and becomes negligible as soon as \( m_S \) is a few tens of GeV’s above its minimal value (for smaller values of \( m_S \) the square of one of the mass eigenvalues of the scalar bottom quark becomes negative).

A few comments are in order concerning the chargino contribution. First, we note that with the relation \( m_{\tilde{g}} = (g_s/g_2)^2 m_{g_2} \) the gluino mass is in the order of TeV and therefore negligible compared to the chargino contribution as we have shown in [1]. Second, if we allow this mass to be arbitrary, the gluino contribution can be dominant for small gluino mass (\( \sim 200 \text{ GeV} \)) and small values of \( m_S \) (\( \sim 300 \text{ GeV} \) or less). Even in the best cases, this contribution becomes negligible for values of \( m_S \) of 500 GeV or less; even for \( \tan \beta \sim 50 \).

We note that values of \( \mu \) like 100 GeV or 400 GeV for a value of \( m_{g_2} \) of 200 GeV will increase (in magnitude) the contributions from the charginos while negative values of \( \mu \) will decrease them in magnitude. Furthermore, the effects of the mixing of the scalar partners of the top and bottom quarks are more important for large values of \( m_S \): the contributions from the charginos and neutralinos do not decrease

\(^3\) Such high values for \( \tan \beta \) are preferred in models, which require the Yukawa couplings \( h_t, h_b \) and \( h_\tau \) to meet at one point at the unification scale [14].
as quickly with the mixing. For small values of $m_S$, there is also an enhancement.

In Fig.2 in [1] we also have presented the contribution of the charged Higgs and shown that it is quite large for small Higgs masses, but decreases rapidly for values of tan $\beta$ larger than 1. In [1] we also discussed the importance of the factor $c$ that enters the b-quark mixing matrix and shown that reducing it from 1 to 1/2 reduces the gluino contributions by a factor of $\sim 8$ for small values of $m_S$ ($\sim 200$ GeV) while it reduces them by a factor of $\sim 4$ for very large values of $m_S$ ($\sim 1$ TeV). The first factor will vary with $m_{g_2}$, $\mu$ and tan $\beta$ but the reduction of 4 for large $m_S$ is rather stable. Typically it will vary between 3.5 and 4.1. It can be understood by the fact that for those large scales, the mass eigenvalues are almost insensitive to $c$ but the mixing angles are almost linearly dependant on $c$. The same happens for the neutralino contribution.

Finally, one must not forget that in eq.(4) $K_{31}^* K_{33}$ have not necessarily the same values as in the SM. This was shown in [8]: the Kobayashi–Maskawa matrix in the couplings of the neutralinos to quarks and scalar quarks is multiplied by another matrix $V_d$, which can be parametrized as follows:

$$V_d = \begin{pmatrix} 1 & \varepsilon_d & \varepsilon_d^2 \\ -\varepsilon_d & 1 & \varepsilon_d \\ -\varepsilon_d^2 & -\varepsilon_d & 1 \end{pmatrix}$$

so that $K = V_d^4$. For $\varepsilon_d = 0.1$ $K_{31}^* K_{33}$ is identical to the SM values, whereas $\varepsilon_d = 0.5$ enhances it by a factor of 25 and $\varepsilon = 0.3$ by 9. Considering that these values are to be squared in the mass difference of the $B_D^0$ system we can use that enhancement to put limits on $\varepsilon_d$.

In the case at hand $\varepsilon_d$ has to be smaller than 0.1 to keep the results lower than the measured value of $\Delta m_{B_D^0}$. This is not very constraining yet but it is already better than the limit one can get from current data on rare Kaon decays [7].

IV. CONCLUSIONS

In this paper we presented the contributions from neutralinos and scalar down quarks to the mass difference in the $B_d^0$ system via box diagrams. We gave exact results and included the mixing of the neutralinos and the mixing of the scalar bottom quark. We find that this contribution is in general small but can be important for large values of tan $\beta$ ($\sim 50$) and the smallest possible values of $m_S$, given $m_{g_2}$ and $\mu$. As soon as $m_S$ is a few tens of GeV’s above its minimum values, this contribution is very small.

With this paper we complete our analysis within the MSSM where all its particles are taken within the relevant box diagram without neglecting any mixing angles and mass eigenvalues. We conclude that, generally the most important contribution

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4 For simplicity we have taken the flavour non diagonal couplings of the neutralinos to the scalar partners of the left and right handed down quarks to be of the same order
is that of the chargino. Over a narrow range of \( m_S \), for given values of \( m_{q_2} \) and \( \mu \) and for \( \tan \beta \sim 50 \), the neutralino contribution can be quite large and dominant. The gluino contribution is negligible for gluino masses larger than \( \sim 300 \text{ GeV} \). All these are small compared to the charged Higgs contribution for small values of \( \tan \beta \), but this one is negligible \((\Delta Higgs/\Delta SM \sim 1.2 \times 10^{-4})\) for \( \tan \beta = 50 \) and a charged Higgs mass of 100 GeV. We hope that these results will find some application with the upcoming \( B \)-factories.

V. ACKNOWLEDGMENTS

We want to thank our colleague Cherif Hamzaoui for fruitful discussions. One of us (H.K.) would like to thank the physics department of Carleton university for the use of their computer facilities. The figures were done with the program PLOTDATA from TRIUMF and we used the CERN-Library to diagonalize the neutralino mass matrix.

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VI. APPENDIX A

For the box diagram we have to calculate the following integrals:

\[
F_{\mu \nu}^{\alpha \beta ij} := \int \frac{d^4k}{(2\pi)^4} \frac{k^\mu k^{\nu}}{(k^2 - m_a^2)(k^2 - m_b^2)(k^2 - m_i^2)(k^2 - m_j^2)}
\]

\[
F_{\mu \nu}^{\alpha \beta ij} = \frac{1}{4(4\pi)^2} \tilde{F}_{ij}^{ab}
\]

\[
m_i^2 \neq m_j^2 \neq m_a^2 \neq m_b^2
\]

\[
\tilde{F}_{ab}^{ij} = -\frac{1}{(m_j^2 - m_i^2)(m_b^2 - m_a^2)} \left[ \frac{1}{(m_i^2 - m_a^2)(m_i^2 - m_b^2)} \{ m_i^4 \ln \frac{m_b^2}{m_i^2} - m_a^2 \ln \frac{m_b^2}{m_a^2} \right]
\]

\[
- m_i^2 m_a^2 m_b^2 \ln \frac{m_b^2}{m_a^2} \} - (m_i^2 \leftrightarrow m_j^2) \}
\]

\[
m_j^2 \neq m_i^2 \neq m_a^2 \neq m_b^2
\]

\[
\tilde{F}_{aa}^{ij} = -\frac{1}{(m_j^2 - m_i^2)(m_a^2 - m_b^2)} \left[ m_a^2 - \frac{m_i^4}{(m_i^2 - m_a^2)} \ln \frac{m_i^2}{m_a^2} \right] - (m_i^2 \leftrightarrow m_j^2) \}
\]

\[
m_i^2 = m_j^2 \neq m_a^2 \neq m_b^2
\]

\[
\tilde{F}_{ab} = \tilde{F}_{aa}^{ij} (m_a^2 \leftrightarrow m_i^2, m_b^2 \leftrightarrow m_j^2)
\]

\[
m_j^2 = m_i^2 \neq m_a^2 = m_b^2
\]

\[
\tilde{F}_{aa}^{ii} = -\frac{(m_i^2 + m_b^2)}{(m_i^2 - m_a^2)^2} \left[ 1 - \frac{2m_i^2 m_a^2}{(m_i^4 - m_a^4)} \ln \frac{m_i^2}{m_a^2} \right]
\]
The second integral is given by:

\[ M^{F_{ij}}_{ab} := \int \frac{d^4 k}{(2\pi)^4} \frac{m_i m_j}{(k^2 - m_a^2)(k^2 - m_b^2)(k^2 - m_i^2)(k^2 - m_j^2)} \]  

\[ M^{F_{ij}}_{ab} = -ig^{\mu \nu} \frac{(4\pi)^2}{M} \tilde{F}^{ij}_{ab} \]

\[ m_i^2 \neq m_j^2 \neq m_a^2 \neq m_b^2 \]

\[ M\tilde{F}^{ij}_{ab} = -\frac{m_i m_j}{(m_j^2 - m_i^2)(m_b^2 - m_a^2)} \left\{ \frac{1}{(m_i^2 - m_a^2)} \left[ (m_i^2 \ln \frac{m_b^2}{m_i^2} - m_a^2 \ln \frac{m_a^2}{m_i^2}) \right. \right. \]

\[ \left. \left. - m_a^2 m_b^2 \ln \frac{m_b^2}{m_a^2} \right] - (m_i^2 \leftrightarrow m_j^2) \right\} \]

\[ (A5) \]

\[ m_j^2 \neq m_i^2 \neq m_a^2 = m_b^2 \]

\[ M\tilde{F}^{ij}_{aa} = -\frac{m_i m_j}{(m_j^2 - m_i^2)(m_a^2 - m_i^2)} \left\{ \frac{1}{(m_i^2 - m_a^2)} \left[ (m_i^2 \ln \frac{m_i^2}{m_a^2} - m_a^2 \ln \frac{m_i^2}{m_a^2}) \right. \right. \]

\[ \left. \left. - m_a^2 m_i^2 \ln \frac{m_i^2}{m_a^2} \right] - (m_i^2 \leftrightarrow m_j^2) \right\} \]

\[ (A6) \]

\[ m_i^2 = m_j^2 \neq m_a^2 \neq m_b^2 \]

\[ M\tilde{F}^{ii}_{ab} = M\tilde{F}^{ij}_{aa}(m_a^2 \leftrightarrow m_i^2, m_b^2 \leftrightarrow m_j^2, m_i m_j \rightarrow m_i^2) \]

\[ m_i^2 \neq m_a^2 = m_b^2 \]

\[ M\tilde{F}^{ii}_{aa} = -\frac{m_i^2}{(m_i^2 - m_a^2)^2} \left\{ 2 + \frac{(m_i^2 + m_a^2)}{(m_i^2 - m_a^2)} \ln \frac{m_a^2}{m_i^2} \right\} \]

\[ (A7) \]

\[ (A8) \]

\[ (A9) \]

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FIGURE CAPTIONS

Fig.1 The box diagrams with scalar down quarks and neutralinos within the loop including the mass insertion diagram.

Fig.2 The ratios $\Delta m_{B_d}^{\text{Neutralino}} / \Delta m_{B_d}^{\text{SM}}$ for $\tan\beta = 2$, 5 (dotted line, the two lines are on top of each other) and $\tan\beta = 50$ (dash) and $\Delta m_{B_d}^{\text{Chargino}} / \Delta m_{B_d}^{\text{SM}}$ for $\tan\beta = 2$ (very long dash-dot), $\tan\beta = 5$ (long dash-dot), and $\tan\beta = 50$ (dash-dot) as a function of $m_S$ with $m_{g_2} = \mu = 200 \, \text{GeV}$. 
This figure "fig1-1.png" is available in "png" format from:

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