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Constraint on Right-Handed Squark Mixings from $B_s - \bar{B}_s$ Mass Difference

Motoi Endo[1,2] and Satoshi Mishima[3]

[1] *Deutsches Elektronen Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany*

[2] *Institute for Cosmic Ray Research, University of Tokyo, Chiba 277-8582, Japan*

[3] *School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, U.S.A.*

Abstract

We point out that the right-handed squark mixings can sizably enhance SUSY contributions to ΔM_s by taking into account renormalization group effects via the CKM matrix. The recent result of ΔM_s from the DØ experiment at the Tevatron thus implies a strong constraint on the right-handed mixings.

Effects of the underlying physics at high energy scale are imprinted not only in flavor structures of the matters in the standard model (SM), but also in those of their superpartners by extending the SM to include supersymmetry (SUSY). They evolve from the cutoff scale to a low energy via the renormalization running, and are recognized through signals of the flavor-changing neutral currents (FCNCs).

The $\tilde{b}-\tilde{s}$ mixings of the right-handed squarks have attracted a lot of interests [1] in the light of the discovery of the neutrino oscillations with large mixing angles [2], and the success of the supersymmetric grand unification. The mixings are parameterized by the flavor-changing components between $\tilde{b}_R-\tilde{s}_R$ and $\tilde{b}_L-\tilde{s}_R$ in the mass matrices, which are called the RR and RL mixings, respectively. At the weak scale, they contribute to $b \to s$ transition processes. Some golden modes have been already measured precisely in experiments, and their results are compared to the SM predictions. Particularly, the measured branching ratio of the inclusive $B_d \to X_s \gamma$ decay is known to agree well with the SM value [3, 4]. Thus it provides one of the severest constraints on the down-type squark mixings, including the RR and RL mixings. Even with the constraint from $\mathrm{Br}(b \to s\gamma)$, there is still left large possibility to detect sizable effects on some $b \to s$ processes, especially, from the right-handed squark mixings.

Recently, the DØ collaboration have reported the updated result of the mass difference of the B_s mesons [5]:

$$17\,\mathrm{ps}^{-1} \ < \ \Delta M_s \ < \ 21\,\mathrm{ps}^{-1} \quad 90\%\ \mathrm{C.L.}\ , \tag{1}$$

which is the first result with a direct two-side bound. Although the data includes large uncertainties, this result is in agreement with the SM predictions, which are estimated as 21.3 ± 2.6 ps^{-1} by the UTfit group [6] and $20.9^{+4.5}_{-4.2}$ ps^{-1} by the CKMfitter group [7]. In the supersymmetric SM, it is known that a combination of the LL and RR mixings, $(m^2_{\tilde{d}_{LL}})_{23}(m^2_{\tilde{d}_{RR}})_{23}$, can enhance the SUSY contributions to ΔM_s sizably [8]. If the LL mixing is suppressed sufficiently, the current data of ΔM_s remains insensitive to the right-handed mixings [9].

Among the squark mixings, the LL mixing at the weak scale generally receives a correction of at least $O(0.01)$. This is because the SUSY breaking effects are usually mediated to the visible sector at the high energy scale. Actually in general supersymmetric SM at the weak scale, we might choose the down-type LL squark mixing to vanish. However, in realistic models, the mixing will be induced because the CKM matrix affects the left-handed mass matrix of the down-type squarks during the renormalization group evolutions. In a class of supergravity mediations, the LL mixing generally gets a correction of $(\delta^d_{LL})_{23} \sim \lambda^2$, where $\lambda \sim 0.2$ is the Wolfenstein parameter. In this letter, we want to emphasize that this tiny mixing is significant for ΔM_s when we discuss the mixings in the right-handed sector. We will show that even without any imprinted LL mixing, the RR squark mixing can affect ΔM_s to the level of the SM value satisfying with the bound from $\mathrm{Br}(b \to s\gamma)$.

Let us first review the SUSY contributions to ΔM_s. The $B_s - \bar{B}_s$ transition is represented by the transition matrix element,

$$M_{12} \ = \ M_{12}^{\mathrm{SM}} + M_{12}^{\mathrm{SUSY}} \ \equiv \ M_{12}^{\mathrm{SM}}(1+R). \tag{2}$$

In terms of R, which corresponds to the SUSY contributions, the mass difference between B_s and $\bar{B}_s$ becomes $\Delta M_s = \Delta M_s^{\mathrm{SM}}|1+R|$. Although the estimation of the SM value contains large hadronic uncertainties, the ratio $\Delta M_s/\Delta M_d$ can be predicted more cleanly. Then R is given by

$$|1+R| \ = \ \frac{\Delta M_d^{\mathrm{SM}}}{\Delta M_s^{\mathrm{SM}}}\frac{\Delta M_s^{\mathrm{EXP}}}{\Delta M_d^{\mathrm{EXP}}} \ = \ \frac{M_{B_d}}{M_{B_s}}\frac{1}{\xi^2}\left|\frac{V_{td}}{V_{ts}}\right|^2 \frac{\Delta M_s^{\mathrm{EXP}}}{\Delta M_d^{\mathrm{EXP}}}, \tag{3}$$

where $M_{B_{d,s}}$ are masses of the mesons, $M_{B_d} = 5.279$ GeV and $M_{B_s} = 5.375$ GeV, and $\xi \equiv f_{B_s}/f_{B_d}\sqrt{B_{B_s}/B_{B_d}} = 1.24 \pm 0.04 \pm 0.06$ is defined by ratios of the decay constants and of the bag parameters [10]. In above expression, we assume $\Delta M_d^{\mathrm{EXP}} = \Delta M_d^{\mathrm{SM}}$ because the SUSY contributions to $b \to d$ transitions is tightly limited by the experimental results [7] [1]. From the experimental result in Eq. (1) and $\Delta M_d^{\mathrm{EXP}} = 0.507 \pm 0.004\ \mathrm{ps}^{-1}$ [3], the SUSY contributions are favored to be in the region,

$$0.55 \ < \ |1+R| \ < \ 1.37\ , \tag{4}$$

[1]Although the ratio $\Delta M_d^{\mathrm{SM}}/\Delta M_d^{\mathrm{EXP}}$ may include SUSY contributions at $\sim 10\%$ [7], the following discussions remain valid. Similarly, even when we use ΔM_s itself instead of $\Delta M_s/\Delta M_d$, the results are almost same.

with including a 40 % uncertainty from the SM estimations, which is mainly due to the ratio of the CKM matrix elements V_{td}/V_{ts} [6, 7].

The SM contribution, $M_{12}^{\rm SM}$, is obtained by exchanging the W boson and top quark. On the other hand, the SUSY contribution $M_{12}^{\rm SUSY}$ is by exchanging the gluino and down-type squarks. In the following analysis, we evaluate the SUSY contributions by the full expressions, namely, without the mass-insertion approximation [11, 12] (see Ref. [13] for the explicit forms which are relevant for the right-handed mixings). In contrast, it is known that the chargino contributions are much suppressed compared to the gluino ones [8]. Thus we neglect them in the following.

The flavor violations are caused by the intermediating squarks in the diagrams. The mass matrix of the down-type squarks contains the flavor-changing components with/without chirality flipping, and the terms relevant for the $b \to s$ transitions are $(m^2_{\tilde{d}_{RR(LL)}})_{23}$ at the mixing between $\tilde{s}^*_{R(L)}$ and $\tilde{b}_{R(L)}$, and $(m^2_{\tilde{d}_{RL(LR)}})_{23}$ between $\tilde{s}^*_{R(L)}$ and $\tilde{b}_{L(R)}$, where L, R correspond to the chirality of the squarks, and the numbers outside the parenthesis means the mixing components between the second and third generations. The $B_s - \bar{B}_s$ transition is then induced by pairs of the mixings: the $RR(LL)$ and $RL(LR)$ mixings, respectively. It is important to mention that the ratio R is enhanced especially by a pair of the LL and RR mixings, $(m^2_{\tilde{d}_{LL}})_{23} \times (m^2_{\tilde{d}_{RR}})_{23}$ [8].

The LL squark mixing receives the radiative corrections via the CKM matrix during the renormalization group evolution. The running from the cutoff scale M_X to the weak scale M_W gives a mixing such as

$$(\delta^d_{LL})_{23} \equiv \frac{(m^2_{\tilde{d}_{LL}})_{23}}{m^2_{\tilde{q}}} \simeq -\frac{1}{8\pi^2} Y_t^2 V_{ts} \frac{3m_0^2 + a_0^2}{m_0^2} \ln \frac{M_X}{M_W}, \tag{5}$$

where Y_t is the top Yukawa coupling, $m_0 \sim m_{\tilde{q}}$ are typical values of diagonal components of the scalar and squark mass matrices, and a_0 is a trilinear coupling, $A_t \equiv a_0 Y_t$. We stress that the mixing arises even when the mass matrix is diagonal at the cutoff scale. Actually, in supergravity mediations with M_X at the Planck scale or the GUT scale $M_G \simeq 2 \times 10^{16}$ GeV, the renormalization group evolution induces $(\delta^d_{LL})_{23} \simeq 0.04$. With this LL mixing, the RR squark mixing can contribute effectively to the ratio R. It should be stressed that the LL mixing of $O(0.01)$ is rather general independent of the details of the squark mass matrices at the cutoff scale, and it is hard to suppress the LL mixing at the weak scale unless the mixing is tuned at the cutoff scale. In the following analysis, we will use $(\delta^d_{LL})_{23} \simeq 0.04$ as a representative value [2].

Let us consider the bound of the squark mixings from $\mathrm{Br}(b \to s\gamma)$. The SUSY contributions to this mode are induced through the gluino, chargino and charged-Higgs loops [3]. They significantly depend on $\tan\beta$ and a sign of the higgsino mass parameter, μ_H. In fact, the SUSY contributions are enhanced by large $\tan\beta$, and $\mathrm{sign}(\mu_H)$ determines signs of the chargino and gluino contributions compared to the SM and charged-Higgs ones. As well as the evaluations of ΔM_s, we evaluate the SUSY contributions including the gluino ones by the full expressions [16, 17, 18] [4]. In the following analysis, we take the bound,

$$2.0 \times 10^{-4} \ < \ \mathrm{Br}(b \to s\gamma) \ < \ 4.5 \times 10^{-4}, \tag{6}$$

which is rather conservative after taking into account both the experimental and theoretical uncertainties.

We calculated the SUSY contributions to ΔM_s as well as $\mathrm{Br}(b \to s\gamma)$. In Fig. 1, we displayed the regions which is favored by the current result of ΔM_s, and that is excluded by $\mathrm{Br}(b \to s\gamma)$ for a range of the real and imaginary parts of the RR mixing, $(\delta^d_{RR})_{23} \equiv (m^2_{\tilde{d}_{RR}})_{23}/m^2_{\tilde{q}}$, where $m^2_{\tilde{q}}$ is a typical mass of the squarks. Here we assume all relevant soft parameters including μ_H are $m_{\mathrm{soft}} = 500$ GeV, and $\tan\beta = 10$. In order to clarify the effects of the renormalization group evolutions, we show the result of $(\delta^d_{LL})_{23} = 0$ in Fig. 1(a), and that of $(\delta^d_{LL})_{23} = 0.04$ in Fig. 1(b). Consequently, we find that the radiative corrections in

[2]If the LL mixing of $\gtrsim O(0.01)$ is imprinted at the cutoff scale, M_{12}^{SUSY} will be enhanced too much due to the interference with the RR mixing. The analysis, however, depends on the structure of the mass matrices especially of the left-handed sector. In contrast, the LL mixing of $O(0.01)$ at the weak scale is independent of the details of the models, and the following constraint on the right-handed squark mixing is rather generic.

[3]Those diagrams also contribute to the decay amplitude of $b \to sll$, which is sensitive to the sign of $C_{7\gamma}$, and has been already limited by the experiment [14]. The bound is always satisfied here because the LL mixing is small enough, $(\delta^d_{LL})_{23} = 0.04$ [15].

[4]The single mass-insertion approximation of the gluino-mediated diagrams is not consistent with the full estimations for the dipole operators, $C_{7\gamma}$ and C_{8G}, when we study the LL and/or RR squark mixings. Rather the dominant contributions are provided by so-called the double mass-insertion diagrams even for small $\tan\beta$, like $\tan\beta = 5$. See Ref. [19] for the explicit forms of the double-mass insertions.

the LL mixing can enhance the SUSY contributions for ΔM_s extremely to the extent of the magnitude which is implied by the current data (Fig. 1(b)), compared to the result without the effects (Fig. 1(a)).

We also considered other two sets of the mass spectrum of the gluino and squarks. The first pattern is $m_{\tilde{g}} \ll m_{\tilde{q}}$. This type is interesting for the FCNCs whose amplitude is dominated by the Wilson coefficient of the gluon-dipole operator, O_{8G}. Since the relevant contribution to $\mathrm{Br}(b \to s\gamma)$ comes from the photo-dipole operator, $O_{7\gamma}$, the mass pattern is favored to enhance the SUSY contributions for such FCNCs with satisfying the bound from $\mathrm{Br}(b \to s\gamma)$, namely, enhance C_{8G} compared to $C_{7\gamma}$ [13]. We estimated numerically ΔM_s and $\mathrm{Br}(b \to s\gamma)$ in this case: $m_{\tilde{g}} \ll m_{\tilde{q}}$. In Fig. 2, the parameters are set as the same as Fig. 1(b), but the gluino and squark masses are $m_{\tilde{g}} = 300$ GeV and $m_{\tilde{q}} = 1$ TeV, respectively. We find that although both the contributions are suppressed by the heavy squarks, the ΔM_s region remains inside that excluded by $\mathrm{Br}(b \to s\gamma)$.

The second mass spectrum is $m_{\tilde{q}_L} \gg m_{\tilde{q}_R}$. Such a pattern can suppress the SUSY contributions to the electric dipole moments (EDMs). It has been pointed out that the strong bounds are imposed on the CP-violating $\tilde{b} - \tilde{s}$ mixings from the hadronic EDMs [20, 21]. Especially it is very strong for the right-handed sector even when we allow large hadronic uncertainties. In the above discussions, we implicitly assumed accidental cancellations among the additional SUSY contributions for the EDMs. Another way out of the EDMs is to suppress them by large squark masses. When the left-handed squarks decouple, the EDM bound can be relaxed to the negligible level. The numerical result is in Fig. 3, where the parameters are the same as Fig. 1(b) but $m_{\tilde{q}_L} \gg m_{\mathrm{soft}}$. We find the favored regions by ΔM_s in the graph, though all the constraints are satisfied because the SUSY contributions to $\mathrm{Br}(b \to s\gamma)$ as well as the EDMs can be neglected by large $m_{\tilde{q}_L}$.

Even when we take other sets of parameters, the results remain similar. Let us first flip the sign of μ_H parameter. Then the cancellation becomes worse among the SUSY contributions to $\mathrm{Br}(b \to s\gamma)$. In contrast, ΔM_s is insensitive to the $\mathrm{sign}(\mu_H)$. Then the favored region from ΔM_s starts to be restricted by $\mathrm{Br}(b \to s\gamma)$. Instead, when we take $\tan\beta = 40$, the remaining contributions after the cancellation become enhanced for $\mathrm{Br}(b \to s\gamma)$, while ΔM_s

is insensitive to $\tan\beta$. We checked that the favored regions by the observables become narrower for the RR mixing in both cases.

There might be a large mixing in the RL component at the cutoff scale. As already known, the flavor mixings with chirality flipping cannot induce large ΔM_s at the weak scale [8]. This is because the mixings are constrained by $\mathrm{Br}(b \to s\gamma)$ to the extent of the negligible level for ΔM_s. On the contrary, the RL mixing at the high energy scale can contribute sizably to the RR mixing at the weak scale through the renormalization group running [22]. Thus the similar arguments may be applicable for the RL mixing at the cutoff scale as those of the RR case, though the detailed discussion depends on the parameters. Consequently, we conclude that the SUSY contributions to ΔM_s is sensitive to the right-handed squark mixings at the cutoff scale in the light of the current result of ΔM_s by considering the radiative correction for the LL squark mixing.

Let us comment on implications to other $b \to s$ transition processes. The mixing-induced CP asymmetry of $b \to q\bar{q}s$ decays has been measured by BaBar and Belle [3]. Although the results still contain large theoretical/experimental uncertainties, we obtain an important implication from the measurements that all the values tend to shift to the same side from the SM values, which is determined by $b \to c\bar{c}s$ modes. This feature is observed independently of the parity of the final states. If the displacements are due to SUSY effects, the results naturally imply additional CP-violating mixings in the left-handed squark sector [19]. On the contrary, in order to realize the same feature by the right-handed squark mixings, rather large SUSY contributions are required [23]. We checked that such mixings induce too large ΔM_s to stay within the current data as long as we consider the renormalization group effects. This means that although the SUSY $SU(5)$ GUT + ν_R model is one of the best candidates which naturally induce large SUSY contributions to $b \to q\bar{q}s$ decays [1], the model is disfavored in order to explain the current experimental result of ΔM_s as well as those modes. Other interesting $b \to s$ observables are mixing-induced CP asymmetry of the $b \to s\gamma$ decay and $B_s \to J/\psi\phi$. Since they are sensitive to the right-handed squark mixings, we can still expect to detect signals of new physics at LHC/super B-factory. We thus stress that measurements of ΔM_s have impacts on the squark-flavor mixings.

Note Added: shortly after this letter, the CDF collaboration reported the new result of ΔM_s. The experimental error was reduced very well, and the result is found to be consistent with the DØ value, thus the SM estimation. Even taking into account the CDF result, the analysis in this letter does not change because the uncertainties in the analysis dominantly come from the SM estimation. Although the uncertainty may be reduced by combining the other measurements of the flavor changing processes, such an analysis is beyond the scope of this letter and should be studied elsewhere.

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References

[1] T. Moroi, Phys. Lett. B **493**, 366 (2000).

[2] Y. Fukuda *et al.* [Super-Kamiokande Collaboration], Phys. Rev. Lett. **81**, 1562 (1998); Q. R. Ahmad *et al.* [SNO Collaboration], Phys. Rev. Lett. **89**, 011301 (2002); K. Eguchi *et al.* [KamLAND Collaboration], Phys. Rev. Lett. **90**, 021802 (2003).

[3] E. Barberio *et al.* [HFAG], arXiv:hep-ex/0603003; updated results available at http://www.slac.stanford.edu/xorg/hfag/.

[4] H. M. Asatrian, A. Hovhannisyan, V. Poghosyan, C. Greub and T. Hurth, arXiv:hep-ph/0512097.

[5] V. Abazov [D0 Collaboration], arXiv:hep-ex/0603029.

[6] M. Bona *et al.* [UTfit Collaboration], JHEP **0507**, 028 (2005); updated results available at http://utfit.roma1.infn.it/.

[7] J. Charles *et al.* [CKMfitter Group], Eur. Phys. J. C **41**, 1 (2005); updated results available at http://ckmfitter.in2p3.fr/.

[8] P. Ball, S. Khalil and E. Kou, Phys. Rev. D **69**, 115011 (2004).

[9] M. Ciuchini and L. Silvestrini, arXiv:hep-ph/0603114.

[10] M. Battaglia *et al.*, arXiv:hep-ph/0304132.

[11] L. J. Hall, V. A. Kostelecky and S. Raby, Nucl. Phys. B **267**, 415 (1986).

[12] F. Gabbiani, E. Gabrielli, A. Masiero and L. Silvestrini, Nucl. Phys. B **477**, 321 (1996).

[13] R. Harnik, D. T. Larson, H. Murayama and A. Pierce, Phys. Rev. D **69**, 094024 (2004).

[14] A. Ishikawa, arXiv:hep-ex/0603018.

[15] E. Lunghi, A. Masiero, I. Scimemi and L. Silvestrini, Nucl. Phys. B **568**, 120 (2000).

[16] M. Ciuchini, G. Degrassi, P. Gambino and G. F. Giudice, Nucl. Phys. B **527** 21 (1998); F. M. Borzumati and C. Greub, Phys. Rev. D **58** 074004 (1998).

[17] G. Degrassi, P. Gambino and G. F. Giudice, JHEP **0012** 009 (2000); M. Carena, D. Garcia, U. Nierste and C. E. M. Wagner, Phys. Lett. B **499** 141 (2001).

[18] F. Borzumati, C. Greub and Y. Yamada, Phys. Rev. D **69** 055005 (2004).

[19] M. Endo, S. Mishima and M. Yamaguchi, Phys. Lett. B **609**, 95 (2005).

[20] J. Hisano and Y. Shimizu, Phys. Lett. B **581**, 224 (2004); Phys. Rev. D **70**, 093001 (2004).

[21] M. Endo, M. Kakizaki and M. Yamaguchi, Phys. Lett. B **583**, 186 (2004).

[22] G. L. Kane, H. b. Wang, L. T. Wang and T. T. Wang, arXiv:hep-ph/0407351.

[23] D. T. Larson, H. Murayama and G. Perez, JHEP **0507**, 057 (2005).

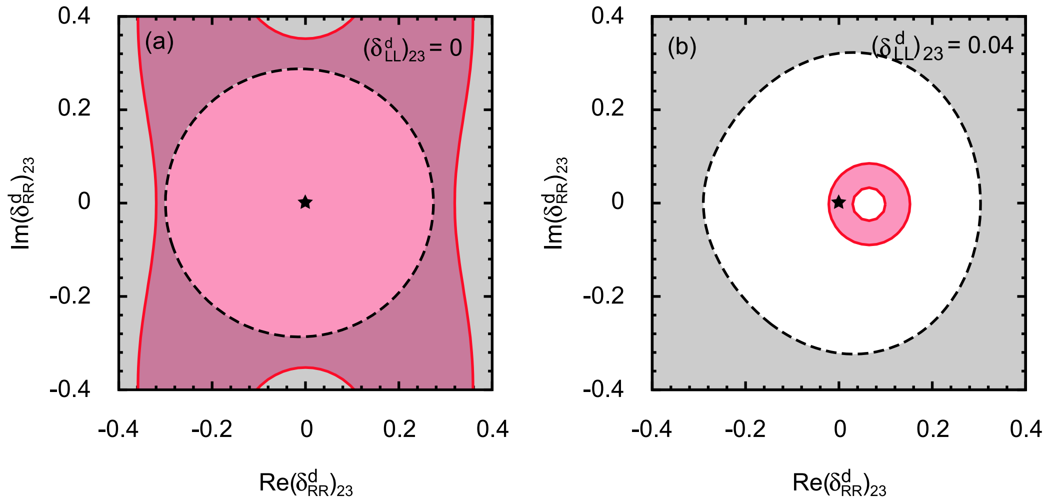

Figure 1: Regions which reproduce the current experimental value of ΔM_s for $(\delta^d_{LL})_{23} = 0$ (a) and $(\delta^d_{LL})_{23} = 0.04$ (b), with the uncertainties of 20% due to the SM estimations (Red, enclosed by solid lines). The star point corresponds to $(\delta^d_{RR})_{23} = 0$. The shadowed region outside the dashed line is excluded by $\text{Br}(b \to s\gamma)$. We take $m_{\tilde{g}} = m_{\tilde{q}} = 500$ GeV, $\mu_H = 500$ GeV, and $\tan\beta = 10$.

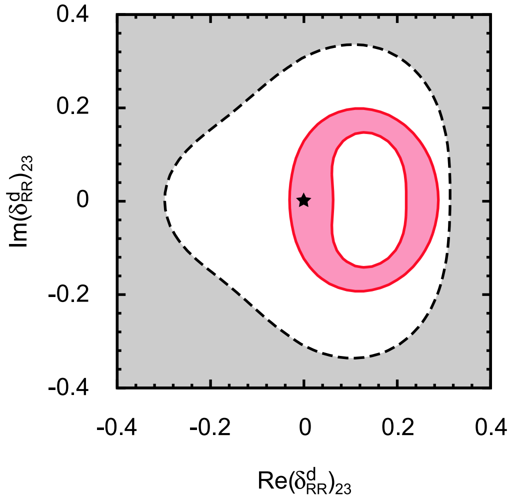

Figure 2: Same as Fig. 1(b), but $m_{\tilde{g}} = 300$ GeV and $m_{\tilde{q}} = 1$ TeV.

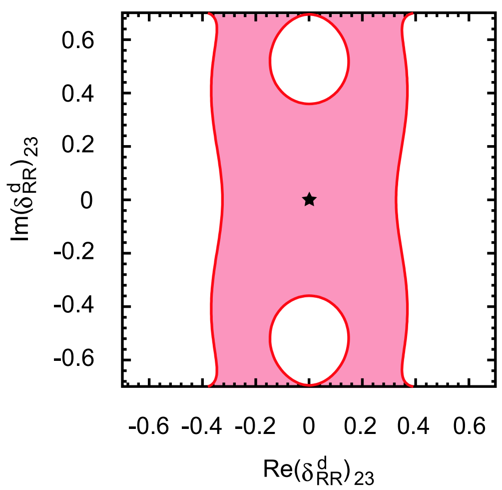

Figure 3: Same as Fig. 1(b), but $m_{\tilde{q}_L}$ decoupled.