The Higgs sector of the NMFV MSSM at the ILC

M. Arana-Catania[1], S. Heinemeyer[2], M.J. Herrero[1] and S. Peñaranda[3,4] [*†]

1- Departamento de Física Teórica and Instituto de Física Teórica, IFT-UAM/CSIC
Universidad Autónoma de Madrid, Cantoblanco, Madrid - Spain

2- Instituto de Física de Cantabria (CSIC-UC), Santander - Spain

3- Departamento de Física Teórica, Universidad de Zaragoza, Spain

4- Departament de Física Fonamental, Universitat de Barcelona, Spain

We calculate the one-loop corrections to the Higgs boson masses within the context of the MSSM with Non-Minimal Flavor Violation in the squark sector. We take into account all the relevant restrictions from $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s}. We find sizable corrections to the lightest Higgs boson mass that are considerably larger than the expected ILC precision for acceptable values of the mixing parameters δ_{ij}^{XY}. We find δ_{ct}^{LR} and δ_{ct}^{RL} specially relevant, mainly at low $\tan\beta$.

1 Introduction

We review the one-loop corrections to the Higgs boson masses in the MSSM with Non-Minimal Flavor Violation (NMFV) [1]. The flavor violation is generated from the hypothesis of general flavor mixing in the squark mass matrices, parameterized by a complete set of δ_{ij}^{XY} ($X, Y = L, R$; $i, j = t, c, u$ or b, s, d). The corrections to the Higgs masses are calculated in terms of these δ_{ij}^{XY} taking into account all relevant restrictions from B-physics data. In particular the present constraints from $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s} are demanded to be fulfilled and our predictions are also compared within NMFV scenarios with the SM predictions. For completeness, we include below the present experimental data [2], and the predictions within the SM [3]:

$$\mathrm{BR}(B \to X_s\gamma)_{\exp} = (3.55 \pm 0.26) \times 10^{-4} \quad ; \quad \mathrm{BR}(B \to X_s\gamma)_{\mathrm{SM}} = (3.15 \pm 0.23) \times 10^{-4} \quad (1)$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\exp} < 1.1 \times 10^{-8} \quad (95\% \ \mathrm{CL}); \mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.6 \pm 0.4) \times 10^{-9} \quad (2)$$

$$\Delta M_{B_s \exp} = (117.0 \pm 0.8) \times 10^{-10} \ \mathrm{MeV} \quad ; \quad \Delta M_{B_s \mathrm{SM}} = (117.1^{+17.2}_{-16.4}) \times 10^{-10} \ \mathrm{MeV} \ . \quad (3)$$

Here we focus on the analysis of the Higgs mass corrections that are originated from the flavor mixing between the second and third generations which is the relevant one in B physics and devote special attention to the LR/RL sector. These kind of mixing effects are expected to be sizable, since they enter the off-diagonal A parameters, which appear directly in the coupling of the Higgs bosons to scalar quarks.

In the following we briefly review the main relevant aspects of the calculation and present the numerical results focusing on the light Higgs boson. For further details we address the reader to the full version of our work [1], where also an extensive list with references to related works can be found.

---

2 SUSY scenarios with Non-Minimal Flavor Violation

The usual procedure to introduce general flavor mixing in the squark sector is to include the non-diagonality in flavor space in the Super-CKM basis. These squark flavor mixings are usually described in terms of a set of dimensionless parameters δ_{ij}^{XY} ($X, Y = L, R$; $i, j = t, c, u$ or b, s, d), introduced in the SUSY-breaking matrices (after RGE running) at low energy as follows,

$$m_{\tilde{U}_L}^2 = \begin{pmatrix} m_{\tilde{U}_{L11}}^2 & 0 & 0 \\ 0 & m_{\tilde{U}_{L22}}^2 & \delta_{23}^{LL} m_{\tilde{U}_{L22}} m_{\tilde{U}_{L33}} \\ 0 & \delta_{23}^{LL} m_{\tilde{U}_{L22}} m_{\tilde{U}_{L33}} & m_{\tilde{U}_{L33}}^2 \end{pmatrix}; m_{\tilde{D}_L}^2 = V_{\text{CKM}}^\dagger m_{\tilde{U}_L}^2 V_{\text{CKM}} \quad (4)$$

$$v_2 \mathcal{A}^u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & \delta_{ct}^{LR} m_{\tilde{U}_{L22}} m_{\tilde{U}_{R33}} \\ 0 & \delta_{ct}^{RL} m_{\tilde{U}_{R22}} m_{\tilde{U}_{L33}} & m_t A_t \end{pmatrix} \quad (5)$$

$$m_{\tilde{U}_R}^2 = \begin{pmatrix} m_{\tilde{U}_{R11}}^2 & 0 & 0 \\ 0 & m_{\tilde{U}_{R22}}^2 & \delta_{ct}^{RR} m_{\tilde{U}_{R22}} m_{\tilde{U}_{R33}} \\ 0 & \delta_{ct}^{RR} m_{\tilde{U}_{R22}} m_{\tilde{U}_{R33}} & m_{\tilde{U}_{R33}}^2 \end{pmatrix} \quad (6)$$

and analogously for $v_1 \mathcal{A}^d$ and $m_{\tilde{D}_R}^2$, changing the up-type indexes to the down-type ones in $v_2 \mathcal{A}^u$ and $m_{\tilde{U}_R}^2$, correspondingly. The flavor diagonal entries in these matrices at low energy are found here as usual, namely after RGE running and assuming universality conditions for the soft parameters at the GUT scale (i.e. within constrained models).

In the present study we will restrict ourselves to the case where there is flavor mixing exclusively between the second and third squark generation. These mixings are known to produce the largest flavor violation effects in B meson physics since their size are usually governed by the third generation quark masses. On the other hand, and in order to reduce further the number of independent parameters, we will focus in the following analysis on constrained SUSY scenarios, where the soft mass parameters fulfill universality hypothesis at the gauge unification (GUT) scale. Concretely, we will restrict ourselves here to the so-called Constrained MSSM (CMSSM) which is defined by $m_0, m_{1/2}, A_0, \text{sign}(\mu), \tan\beta$, where A_0 is the universal trilinear coupling, m_0 and $m_{1/2}$ are the universal scalar mass and gaugino mass, respectively, at the GUT scale, $\text{sign}(\mu)$ is the sign of the μ parameter and $\tan\beta = v_2/v_1$.

For the following numerical estimates we will chose two particular points in the CMSSM that are examples of scenarios with moderate and very heavy sparticles masses, respectively. Firstly, we set the well-known benchmark point SPS2, with $m_0 = 1450$ GeV, $m_{1/2} = 300$ GeV, $A_0 = 0$, $\text{sign}(\mu) > 0$, $\tan\beta = 10$. Secondly, we study a peculiar scenario, nowadays favored by LHC recent data, where the SUSY particles are rather heavy, at the TeV scale, but still the Higgs particle is light. We name this scenario as VHeavyS, defined by $m_0 = m_{1/2} = -A_0 = 800$ GeV, $\text{sign}(\mu) > 0$, $\tan\beta = 5$ and where $m_h^{\text{MSSM}} = 120$GeV. The corresponding analysis for other points in the CMSSM and other scenarios as the Non Universal Higgs Mass case can be found in [1].

3 Results

In this section we review our numerical results for the radiative corrections to the Higgs boson mass m_h from flavor mixing within NMFV-SUSY scenarios. Since all one-loop corrections

in the present NMFV scenario are common to the MSSM except for the corrections from squarks, which depend on the δ_{ij}^{XY} values, we will focus just on the results of these corrections as a function of the flavor mixing parameters, and present the differences with respect to the predictions within the MSSM. Correspondingly, we define:

$$\Delta m_h(\delta_{ij}^{XY}) \equiv m_h^{\text{NMFV}}(\delta_{ij}^{XY}) - m_h^{\text{MSSM}} \tag{7}$$

where $m_h^{\text{NMFV}}(\delta_{ij}^{XY})$ and m_h^{MSSM} have been calculated at the one-loop level. It should be noted that $m_h^{\text{NMFV}}(\delta_{ij}^{XY} = 0) = m_h^{\text{MSSM}}$ and, therefore, by construction, $\Delta m_h(\delta_{ij}^{XY} = 0) = 0$, and Δm_h gives the size of the one-loop NMFV contributions to m_h. The numerical calculation of $m_h^{\text{NMFV}}(\delta_{ij}^{XY})$ and m_h^{MSSM} has been done with `FeynHiggs` [4]. The numerical calculations of the rates for the B observables have been done with the FORTRAN subroutine BPHYSICS included in the SuFla code [5], which we have conveniently modified as to include all the relevant contributions within NMFV scenarios (for more details see [1]).

In Fig.1 we show the numerical results for Δm_h as a function of the various δ_{ij}^{XY}. We have also included our predictions for $\text{BR}(B \to X_s\gamma)$, $\text{BR}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s} and their corresponding experimental allowed areas.

In order to conclude on the allowed delta intervals by B physics data, we have assumed that our predictions of the B observables within SUSY-NMFV scenarios have a somewhat larger theoretical error than the SM prediction. Then, by adding linearly the experimental uncertainty (that we take as $3\sigma_{\text{exp}}$) and the theoretical uncertainty, a given δ_{ij}^{XY} value is considered by us to be allowed by data if the total predicted ratios lie in the following intervals:

$$2.08 \times 10^{-4} < \text{BR}(B \to X_s\gamma) < 5.02 \times 10^{-4}, \tag{8}$$

$$\text{BR}(B_s \to \mu^+\mu^-) < 1.22 \times 10^{-8}, \tag{9}$$

$$63 \times 10^{-10} < \Delta M_{B_s}(\text{MeV}) < 168.6 \times 10^{-10}. \tag{10}$$

In table 1 we summarize the total allowed delta intervals by $\text{BR}(B \to X_s\gamma)$, $\text{BR}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s} for SPS2. Notice that for δ_{sb}^{RR} there are two very narrow allowed region close to ± 1, which indeed for SPS2 reduce just to the two single allowed values ± 0.99.

SPS2	Total allowed intervals
δ_{23}^{LL}	(-0.37:0.34)
δ_{ct}^{LR}	(-0.46:0.46)
δ_{sb}^{LR}	(-0.0069:0) (0.048:0.055)
δ_{ct}^{RL}	(-0.39:0.39)
δ_{sb}^{RL}	(-0.014:0.014)
δ_{ct}^{RR}	(-1.0:0.99)
δ_{sb}^{RR}	(-0.99) (-0.39:0.39) (0.99)

Table 1: Allowed delta intervals by $\text{BR}(B \to X_s\gamma)$, $\text{BR}(B_s \to \mu^+\mu^-)$ and ΔM_{B_s} for SPS2.

As we can see in Fig.1, the most restrictive observables are $\text{BR}(B \to X_s\gamma)$ and ΔM_{B_s}, leading to the total allowed delta intervals summarized in table 1. The main conclusion from this table is that the NMFV deltas in the top-sector can be sizeable $|\delta_{ct}^{XY}|$, larger than $\mathcal{O}(0.1)$ and still compatible with B physics data. In particular δ_{ct}^{RR} is the less constrained parameter. The parameters on the bottom-sector are, in contrast, quite constrained. The most tightly constrained are clearly δ_{sb}^{LR} and δ_{sb}^{RL}. Similar conclusions are found for other CMSSM points studied in [1].

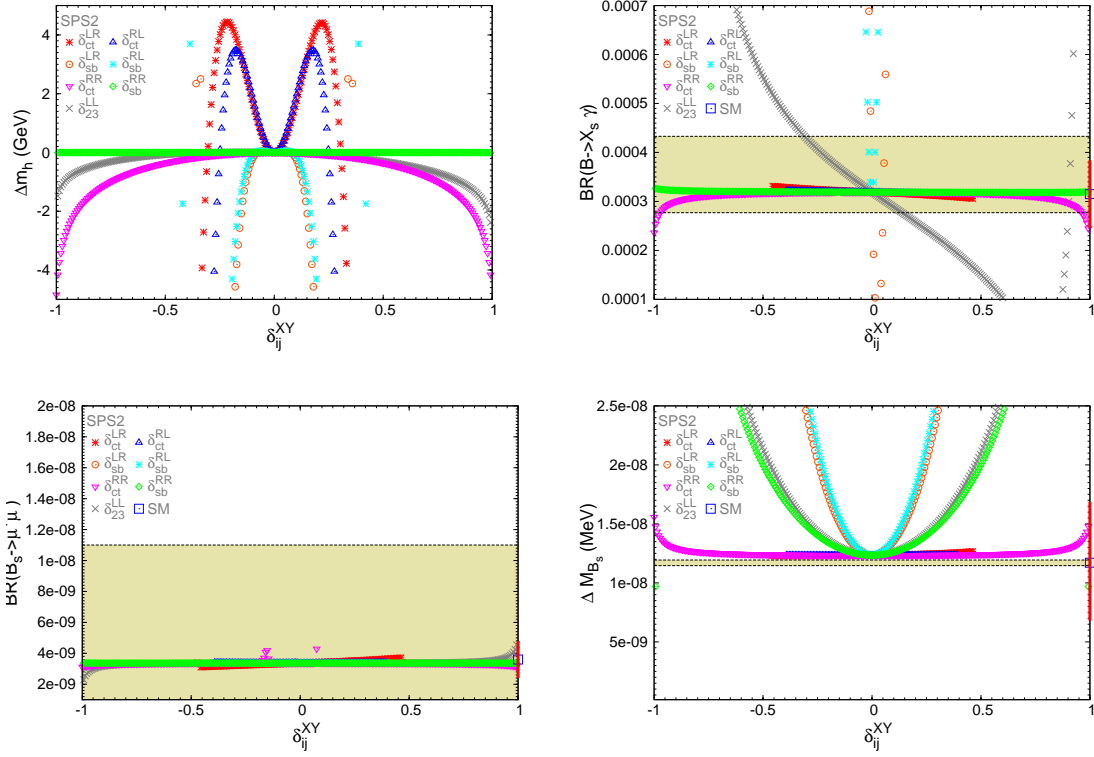Regarding the size of the mass corrections, Δm_h, we clearly see in this figure that

Figure 1: Sensitivity to the NMFV deltas for the SPS2 point for different observables: Δm_h (left upper panel), $\mathrm{BR}(B \to X_s\gamma)$ (right upper panel), $\mathrm{BR}(B_s \to \mu^+\mu^-)$ (left bottom panel), ΔM_{B_s} (right bottom panel). The experimental allowed areas in the plot for B physics observables ($3\sigma_{\mathrm{exp}}$ for $\mathrm{BR}(B \to X_s\gamma)$ and ΔM_{B_s}, 95% CL bound for $\mathrm{BR}(B_s \to \mu^+\mu^-)$) are the horizontal colored bands. The SM prediction for the B physics observables and the theory uncertainty (red bar) is displayed on the right axis, correspondingly.

they can be sizable for non-vanishing deltas in the allowed intervals by B physics data. In particular for δ_{ct}^{LR} and δ_{ct}^{RL} they can be positive and up to about 4 GeV or negative and up to tens of GeV. δ_{ct}^{RR} yields negative corrections and up to about 4 GeV.

In order to explore further the size of the Higgs mass corrections, we have computed numerically the size of Δm_h as a function of two non-vanishing deltas and have looked for areas in these two dimensional plots that are allowed by B physics data (see Fig.3 for the color code of the allowed/disallowed areas). The results for VHeavyS are displayed in Fig.2. Contour lines corresponding to mass corrections Δm_h above 60 GeV or below -60 GeV have not been represented.
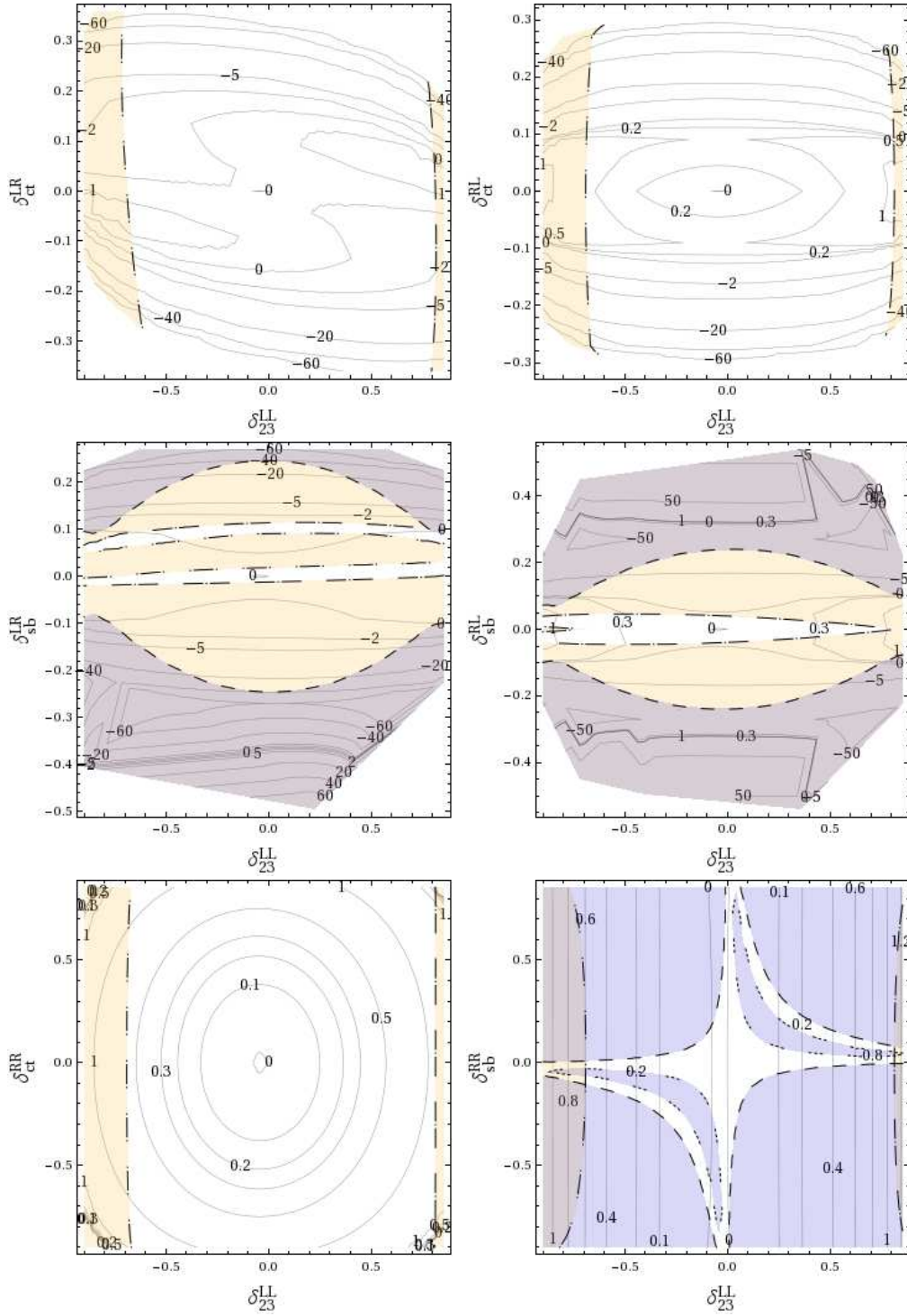
Figure 2: Δm_h (GeV) contour lines from our two deltas analysis for VHeavyS. The color code for the allowed/disallowed areas by B physics data is given in fig.3
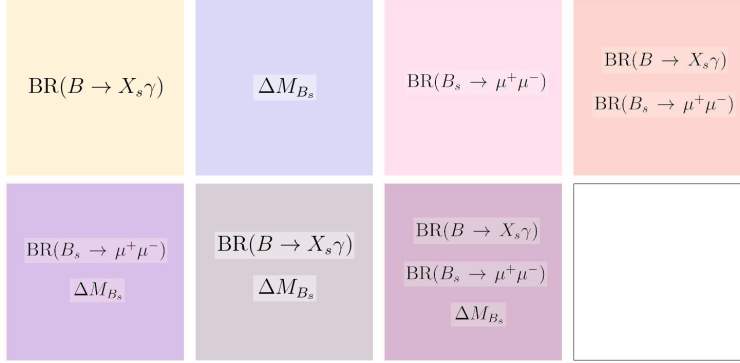
Figure 3: Legend of plots for Fig. 2. Each colored area represents the disallowed region by the specified observable/s inside each box. A white central area represents a region that is allowed by all B physics data

As we can see, the largest mass corrections Δm_h found, being allowed by B physics data occur in the $(\delta_{23}^{LL}, \delta_{ct}^{LR})$ and $(\delta_{23}^{LL}, \delta_{ct}^{RL})$ planes. This applies also to the other points studied in [1]. They can be as large as -60 GeV for δ_{ct}^{LR} or δ_{ct}^{RL} close to ± 0.3. Again these large corrections from the LR and RL parameters are due to the A-terms. Generically, the plots with largest allowed regions and with largest Higgs mass corrections correspond to scenarios with low $\tan \beta = 5$ and heavy spectra like the VHeavyS point considered here.

There are also important corrections in the allowed areas of the two dimensional plots of $(\delta_{23}^{LL}, \delta_{ct}^{RR})$ for some of the studied points, particularly for SPS5 (and to a lesser extent for SPS2). For the first the corrections can be as large as -50 GeV for δ_{ct}^{RR} close to ± 0.5. In the case of SPS2 they can be up to -2 GeV for this same region.

Regarding the plots involving the down-type squark sector deltas it is clear that the constraints from B physics data are so tighted that the Higgs mass corrections found are very tiny.

4 Conclusions

We have reviewed the analysis of the one-loop corrections to the Higgs boson masses in the MSSM with Non-Minimal Flavor Violation, assuming that the flavor violation is being generated from the hypothesis of general flavor mixing in the squark mass matrices. Here we have focused on the analysis of the light Higgs mass corrections that are originated from the flavor mixing between the second and third generations, and that are compatible with the constraints from $\mathrm{BR}(B \to X_s \gamma)$, $\mathrm{BR}(B_s \to \mu^+ \mu^-)$ and ΔM_{B_s} data.

We found large corrections, mainly for the low $\tan \beta$ case, up to several tens of GeV for m_h. These corrections are specially relevant in the case of the light MSSM Higgs boson since they can be negative and up to three orders of magnitude larger than the anticipated ILC precision of 50 MeV [6]. Consequently, these corrections should be taken into account in any Higgs boson analysis in the NMFV MSSM framework. Conversely, in the case of a Higgs boson mass measurement these corrections might be used to set further constraints on δ_{ij}^{XY}. The present work clearly indicates that the flavor mixing parameters δ_{ct}^{LR} and δ_{ct}^{RL} are severely constrained by the present bounds on the lightest Higgs boson mass within the

NMFV-MSSM scenarios.

5   Acknowledgments

References

[1] M. Arana-Catania, S. Heinemeyer, M. J. Herrero and S. Penaranda, "Higgs Boson masses and B-Physics Constraints in Non-Minimal Flavor Violating SUSY scenarios", arXiv:1109.6232 [hep-ph].

[2] D. Asner *et al.* [Heavy Flavor Averaging Group],
`http://www.slac.stanford.edu/xorg/hfag/`, arXiv:1010.1589 [hep-ex].
CMS and LHCb Collaborations,
`http://cdsweb.cern.ch/record/1374913/files/BPH-11-019-pas.pdf`.
K. Nakamura *et al.* [Particle Data Group], J. Phys. G **37**, 075021 (2010).

[3] M. Misiak, Acta Phys. Polon. B **40**, 2987 (2009) [arXiv:0911.1651 [hep-ph]].
A. J. Buras, PoS E PS-HEP2009, 024 (2009) [arXiv:0910.1032 [hep-ph]].
A. J. Buras, M. Jamin and P. H. Weisz, Nucl. Phys. B **347**, 491 (1990).
E. Golowich, J. Hewett, S. Pakvasa, A. A. Petrov and G. K. Yeghiyan, Phys. Rev. D **83**, 114017 (2011) [arXiv:1102.0009 [hep-ph]].

[4] S. Heinemeyer, W. Hollik and G. Weiglein, *Comput. Phys. Commun.* **124** (2000) 76 [arXiv:hep-ph/9812320]; see `www.feynhiggs.de` .
S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J.* **C 9** (1999) 343 [arXiv:hep-ph/9812472].
G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Eur. Phys. J.* **C 28** (2003) 133 [arXiv:hep-ph/0212020].
M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *JHEP* **0702** (2007) 047 [arXiv:hep-ph/0611326].

[5] G. Isidori and P. Paradisi, Phys. Lett. B **639** (2006) 499 [arXiv:hep-ph/0605012]; G. Isidori, F. Mescia, P. Paradisi and D. Temes, Phys. Rev. D **75** (2007) 115019 [arXiv:hep-ph/0703035], and references therein.

[6] J. Aguilar-Saavedra et al., TESLA TDR Part 3: "Physics at an e^+e^- Linear Collider", arXiv:hep-ph/0106315, see: `tesla.desy.de/tdr/`;
K. Ackermann et al., DESY-PROC-2004-01, *prepared for 4th ECFA / DESY Workshop on Physics and Detectors for a 90-GeV to 800-GeV Linear e+ e- Collider, Amsterdam, The Netherlands, 1-4 Apr 2003.*