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Oral contribution

Discarding a 125 GeV heavy Higgs in an MSSM model with explicit CP-violation

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Abstract

Current experimental constraints prove being enough to rule out the possibility of the $m_h \sim 125$ GeV Higgs found at LHC being a heavy Higgs in a general MSSM context, even with explicit CP violation in the Higgs potential. Differently than what has been done in prior studies, we perform this job analitically, with expressions related to a few observables. Te relevance of $\tau\tau$ production through Higgs and BR$(B \to X_s\gamma)$ processes is emphasized, since they are enough to erase the possibility of finding an MSSM neutral Higgs lighter than the scalar discovered at LHC.

Keywords: MSSM, tau-tau, light Higgs, CP-violation

1. Theoretical considerations

In our publication about this topic [1], we study those models characterized by fitting the Minimal Supersymmetric (MSSM) description [2]. For the sake of generalization, we consider a CP-violating Higgs sector formed by two-Higgs doublets including all the possible mixings between the three scalars that are contained in it, besides a charged Higgs, with fields

$$\Phi_1 = \begin{pmatrix} \frac{1}{\sqrt{2}}(\upsilon_1 + \phi_1 + ia_1) \\ \phi_1^- \end{pmatrix}; \quad \Phi_2 = e^{i\xi}\begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(\upsilon_2 + \phi_2 + ia_2) \end{pmatrix} \tag{1}$$

We place the possible light Higgs in the mass range between 90 GeV $< m_h <$ 110 GeV, identifying the scalar found at the LHC as the next one according to mass, being m_H =125.5 GeV the value we used for our analysis. The heaviest neutral scalar mass will be restricted to an upper limit of 200 GeV due to the fact of having small CP violation, and thus avoiding a big splitting of the Higgs mass spectrum.

The mixing between up, down and pseudoscalar nature in the Higgs sector will find its origin in the one-loop corrections of the scalar potential, which leaves the pseudscalar state as $a = a_1 \sin\beta + a_2 \cos\beta$ and a neutral Higgs mass matrix defined according to

$$M_H^2 = \begin{pmatrix} M_S^2 & M_{SP}^2 \\ M_{PS}^2 & M_P^2 \end{pmatrix}, \tag{2}$$

Our analysis will be developed using a small number of parameters, being them $\tan\beta \equiv {}^{\upsilon_2}/_{\upsilon_1}$, the Higgsino mass μ, the stop trilinear coupling A_t, its phase $\alpha(A_t)$, the sparticle mass scale M_{SUSY}, the gaugino mass M_2, and $m_{H^\pm}$ (since the pseudoscalar mass cannot be fixed, and they are related by $m_{H^\pm}^2 = M_P^2 + \frac{1}{2}\lambda_4\upsilon^2 - Re(\lambda_5 e^2 i\xi)\upsilon^2$).

2. Experimental status

2.1. Bounds on SUSY particles

The LHC determination [3, 8] of allowed regions in which we can run the neutralino, stop and gluino masses is shown by the experimental plots of figure 1. In there, we can see that the neutrino mass is mostly forbidden to be below 500 GeV and, according to figure 2, the gluino mass below 1.3 TeV.

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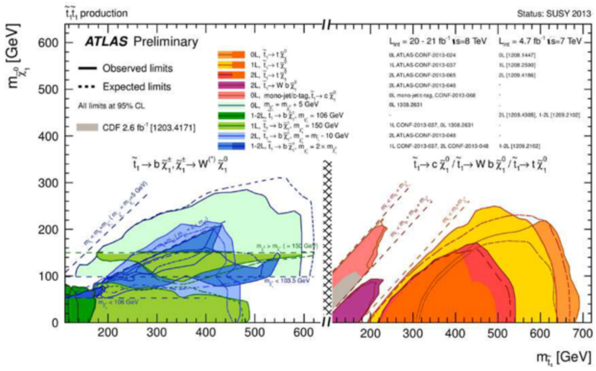

Figure 1: SUSY particle searches at (a) ATLAS (neutralino and stop).

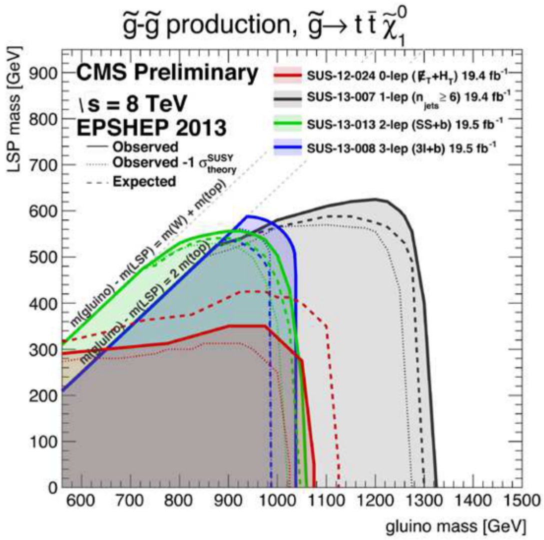

Figure 2: SUSY particle searches at CMS (LSP and gluino).

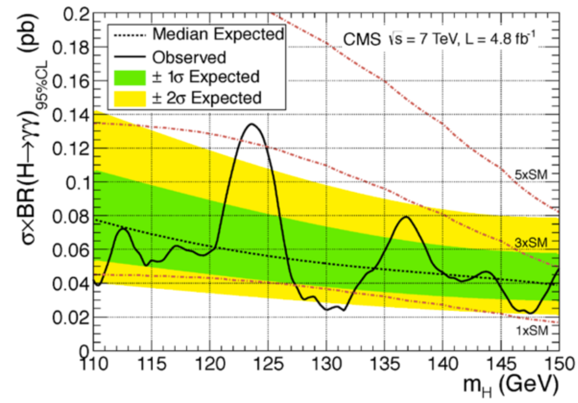

Figure 3: CMS plot indicating the discovery of a neutral scalar in the diphoton channel at the LHC.

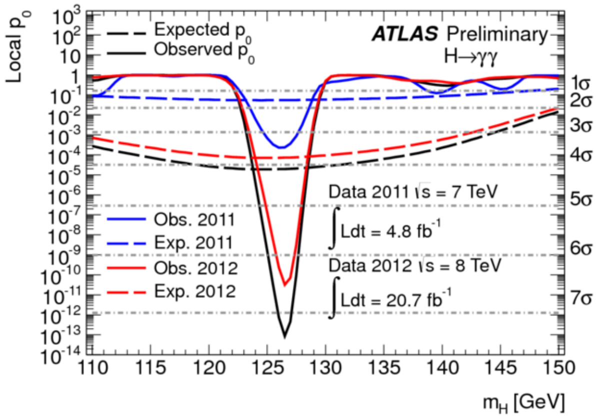

Figure 4: ATLAS plot proving the existence of the scalar in $\gamma\gamma$-channel.

It is important that we consider the stop mass in a more sublte way, though the most visual lower bond is of $m_{\tilde{t}}$ =650 GeV. In case there is stop-neutralino degeneracy, the lower bound for the mass can go down to 250 GeV, and taking into account every possibility for the stop mass is crucial for one of the observables we are going to use for the parameter space analysis.

2.2. LHC Higgs Data: diphoton channel

LHC anounced the discovery [9, 10] of the m_H =125.5 GeV scalar based on the data found at the diphoton channel, which is a loop mediated decay.

In figures 3 and 4 we can see how the peak of this plot fits in an excess corresponding to a signal of 0.90≤ $\mu^{LCH}_{\gamma\gamma}$ ≤1.58, taking the data in a conservative way, and according to the statistics availabe by the time our analysis was done.

3. Theoretical estimation of the diphoton channel events

For MSSM models with the number of parameters we are considering, the diphoton channel decay appears as [11]:

$$\Gamma(H_i \to \gamma\gamma) = \frac{M^3_{H_i}\alpha^2}{256\pi^3 v^2}\left[|S^\gamma_i(M^3_{H_i})|^2 + |P^\gamma_i(M^3_{H_i})|^2\right] \quad (3)$$

which includes contributions coming from both scalar and pseudoscalar nature. The scalar contributions come from quarks, W bosons, squarks, charginos and the charged Higgs; whilst the pseudoscalar contributions only come from quarks, squarks and charginos.

Regarding the scalar Standard Model contributions to the Higgs decay (the pseudoscalar have an equivalent development), their values are:

$$W \to S^{\gamma}_{H_i,W} = -(\mathcal{U}_{i1}\cos\beta + \mathcal{U}_{i2}\sin\beta)F_1(\tau_{iW});$$
$$\tau_{ij} = \frac{M^2_{H_i}}{4m_j^2};\; F_1(\tau_{iW}) \simeq 8$$

$$t \longrightarrow S^{\gamma}_{H_i,t} = \frac{8}{3}\mathcal{U}_{i2}F^S_t(\tau_{it})$$

$$b \to S^{\gamma}_{H_i,b} = \frac{2}{3}\left(Re\left\{\frac{\mathcal{U}_{i1}+\mathcal{U}_{i2}\kappa_d}{1+\kappa_d\tan\beta}\right\}\tan\beta + Im\left\{\frac{\kappa_d(1+\tan^2\beta)}{1+\kappa_d\tan\beta}\right\}\right)\cdot \cdot\mathcal{U}_{i3}F_b(\tau_{ib})$$

$$Both\ quarks \longrightarrow S^{\gamma}_{H_i,t+b} \simeq 1.8\mathcal{U}_{i2} = (-0.025 + i0.034)\cdot \cdot\left(Re\left\{\frac{\tan\beta}{1+\kappa_d\tan\beta}\right\}\mathcal{U}_{i1} + Im\left\{\frac{\kappa_d\tan^2\beta}{1+\kappa_d\tan\beta}\right\}\right)\mathcal{U}_{i3}$$

The SUSY contributions prove to be negligible compared to those previously exposed, since they are approximately:

$$S^{\gamma}_{H_i,\tilde{t}} \lesssim 0.26[-\mathcal{U}_{i1} + 1.7\mathcal{U}_{i2} + \mathcal{U}_{i3}]$$

$$S^{\gamma}_{H_i,\tilde{b}} \propto 1.2\times 10^{-5}\tan^2\beta$$

$$S^{\gamma}_{H_i,\tilde{\chi}^{\pm}} \lesssim 0.15(\mathcal{U}_{i2} + \frac{M_2^2}{\mu^2})$$

$$S^{\gamma}_{H_i,H^{\pm}} \lesssim -0.456\left[\left(\frac{O(\lesssim 1)}{\tan\beta} + O(\lesssim 1)\right) + [\pm\mathcal{U}_{i1} \pm \mathcal{U}_{i2} \pm \mathcal{U}_{i3}]\right]$$

In addition, the calculation of the number of the events needs the computation of the Higgs production, according to:

$$\sigma(pp \to H_i) = K\hat{\sigma}^{LO}_{gg\to H_i}\tau_{H_i}\frac{d\mathcal{L}^{gg}_{LO}}{d\tau_{H_i}} + \hat{\sigma}^{QCD}_{bb\to H_i}\tau_{H_i}\frac{d\mathcal{L}^{bb}_{LO}}{d\tau_{H_i}} \quad (4)$$

Its contributions are defined as:

$$\sigma(pp \to H_i)_{bb} = 0.16\frac{\tan\beta^2}{(1+\kappa_d\tan\beta)^2}\left[|\mathcal{U}_{i1}|^2 + |\mathcal{U}_{i3}|^2\right]\ pb \quad (5)$$

for bb-fusion. Besides, the contribution coming from gluon fusion is:

$$\sigma(pp \to H_i)_{gg} = 13\mathcal{U}^2_{i2} - \frac{1.5\tan\beta}{1+\kappa_d\tan\beta}\mathcal{U}_{i1}\mathcal{U}_{i2} + \frac{0.1\tan^2\beta}{(1+\kappa_d\tan\beta)^2}\mathcal{U}^2_{i1} + + \left(\frac{2}{1+\kappa_d\tan\beta} + \frac{0.1\tan^2\beta}{(1+\kappa_d\tan\beta)^2} + \frac{27}{\tan^2\beta}\right)\mathcal{U}^2_{i3}\ pb$$

The last piece we need to start our study is an estimation of the Higgs total width, which is approximately given by:

$$\Gamma_{H_i} \simeq \frac{g^2}{32\pi M_W^2}\left[\tan^2\beta\left(|\mathcal{U}^2_{i1}| + |\mathcal{U}^2_{i3}|\right)\left(3m_b^2 + m_t^2\right) + 6.7\times 10^{-4}\left(\mathcal{U}^2_{i2} + \frac{\mathcal{U}^2_{i1}}{\tan\beta}\right)^2 m^2_{H_i}\right]$$

4. Analysis of diphoton channel data

Given the expressions of the previous section, we can infer that, if H_2 corresponds to the Higgs found at the LHC, $\tan\beta \to 1$ and the CP-mixing matrix takes the limits $\mathcal{U}_{21} = \mathcal{U}_{22} = 1$ and $\mathcal{U}_{23} = 0$, we will have a gluon fusion cross section and a total width equal to that predicted by the Standard Model (SM).

However, we have seen as well that the diphoton decay practically has no supersymmetrical contribution despite not taking any SM limit, thus forcing us to find a different explanation for the excess present in figure 3, the loop-induced decay channel that drove to claiming the discovery of the Higgs boson.

First of all, we observe that the contributions to the $\gamma\gamma$-channel coming from both the W boson and the top quark (the two most important of them) have a strong dependence on the up-type mixing element $\mathcal{U}_{22}$. The gluon fusion cross section is also enhanced by this matrix element. Therefore, if we plot how the number of events in the diphoton channel changes according to the up-type component, we obtain the growing behavior appearing at figure 5.

Consequently, we choose our mixing matrix to possess this feature, imposing $\mathcal{U}_{22} \simeq 1$ and taking the other components as decreasing according to $\tan\beta$, since we have to keep unitarity and we observe that there is a dependence in $\tan\beta$ for our result (figure 5).

This is the first milestone of our work. In this situation, we need the neutral Higgs identified as that discovered at the LHC being an up-type Higgs for any MSSM model. The lightest and heaviest neutral Higgs bosons will have a mixture of down-type and pseudoscalar nature.

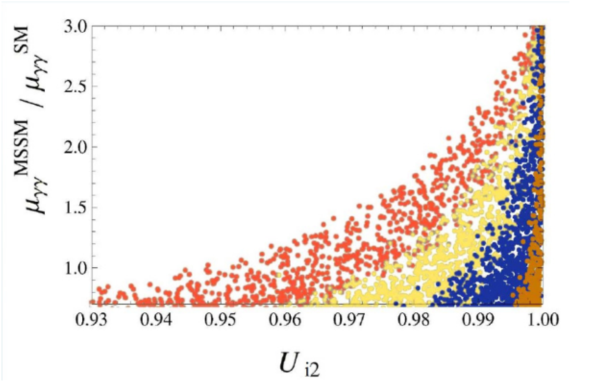

Figure 5: Number of events in the $\gamma\gamma$-channel according to the up mixing mmatrix element. Colors imply different values of $\tan\beta$, being orange the highest and brown the lowest.

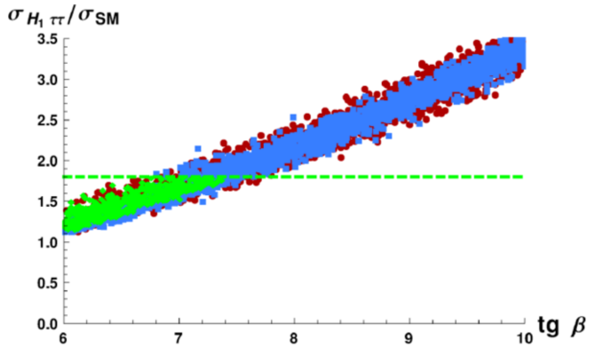

Figure 6: Scan results for the lightest Higgs decay into τ leptons, showing the allowed region in green. In red, points that do not accomplish this bound and neither the diphoton decay. In blue, points that fulfil the diphoton decay value for the second Higgs.

5. Other experimental constraints

Along this section we focus in determining if the scalar mass spectrum assuming the second Higgs to be the currently accepted as the SM Higgs is plausible. For that matter, we will begin with another LHC experimental result, the $H_i \to \tau\tau$ decay [12, 15].

The $\tau\tau$-channel relevance comes from the origin of this decay in the MSSM. Its enhancement will be associated with the particular CP character of the scalar decaying, which must be down-type or pseudoscalar. Taking this into account, the decay rate is, approximatel:

$$\Gamma_{j,\tau\bar{\tau}} \simeq \frac{g^2 m_{H_j} m_\tau^2}{32\pi M_W^2} \tan^2\beta \tag{6}$$

And its production will be mostly originated now by the bb-fusion:

$$\sigma\left(H_j \to pp\right) \simeq 0.16 \frac{\tan^2\beta}{(1+\kappa_d \tan\beta)^2}\, pb \tag{7}$$

in which we have considered the $\mathcal{U}_{j2}$ negligible and the sum of the square of the other components equal to one, thus preserving unitarity in the mixing matrix.

Performing now a scan with $m_{H_1} = 110$ GeV and $m_{H_3} = 160$ GeV, both masses being valid guesses that do not affect generality, is found that only those models with low $\tan\beta$ are good candidates for being in agreement with LHC data, as it is presented in figure 6.

This allowed region needs to be put to test. For this purpose, we make use of a flavour indirect bound, the $B \to X_S\gamma$ decay. This process is supposed to be quite constraining for low values of $\tan\beta$, and it includes the contribution of sparticles. This decay and $B_S^0 \to \mu^+\mu^-$ are the references for low and high values of $\tan\beta$ respectively, though the analysis for its high values is already covered.

Experimentally, the branching ratio of the process (HFAG) [16, 17] is $\mathrm{BR}(B \to X_S\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4}$. Theoretically, I will offer a qualitative approach to the sparticles contributions, though we used exact expressions for our scans [19, 22].

The term coming from the charged Higgs is always additive, defining the Wilson coefficient:

$$C_7^{H^\pm} \simeq \frac{-0.2}{\tan\beta} \tag{8}$$

which shows to be indirectly proportional to $\tan\beta$. In addition, there is a contribution coming from the stop-chargino loop that can compensate it, depending on the sign of our parameters $\mathrm{Re}(\mu A_t)$, defined as:

$$C_{7,8}^{\chi^\pm} \simeq 0.02 \frac{M_2}{\mu} \tag{9}$$

which is only valid for values of the stop mass with an inferior limit $m_{\tilde{t}_1} \geq 650$ GeV. Given this, we can find no compensation whatsoever, as presented in figure 7. Therefore, every MSSM model that includes a Higgs boson lighter than 125.5 GeV would be vanished.

Nevertheless, we stated in Section 2 that there is an experimental region with a light stop that is mostly degenerate with the neutralino, avoiding detection. If this is the case, the Wilson coefficient correspondent to this contribution will not only change its sign, but gain strength with increasing values of $\tan\beta$ too, as shown in:

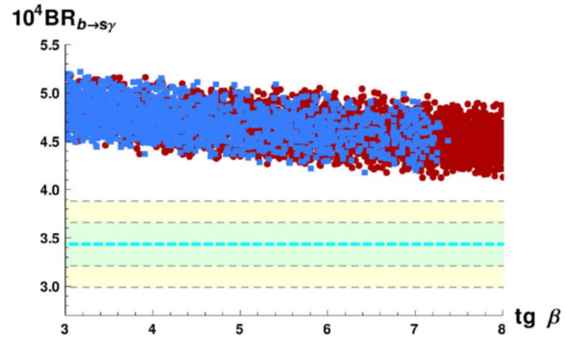

Figure 7: Scan results for $B \to X_S\gamma$. Blue squares survive any previous constraint, red squares have fallen before this. There is no allowed region within 2σ.

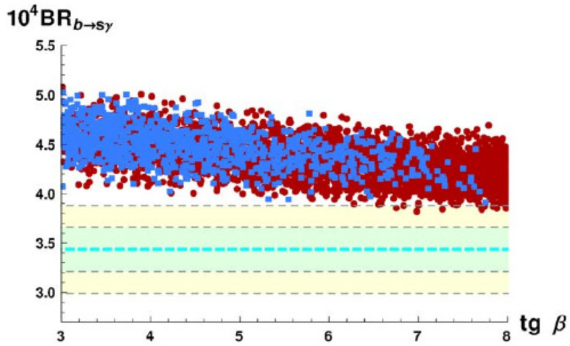

Figure 8: Scan results for $B \to X_S\gamma$ in the light stop regime. Color code is the same as in figure 7.

$$C_{7,8}^{\chi^\pm} \propto -\tan\beta \frac{m_t^2}{m_{\tilde{t}_1}^2 - m_{\tilde{t}_1}^2} \tag{10}$$

Having considered this, we can see in figure 8 that, though data are closer to the 2σ threshold of this decay value, it is impossible to find any plausible MSSM with a light Higgs at all.

6. Conclusions

Our results give some relevant implications both for the purpose of disproving the existence of a MSSM neutral scalar lighter than 125.5 GeV and for searching these neutral bosons independently of their masses.

First of all, the study of the Higgs decaying into two photons gives us enough information for the determination of the CP mixing matrix. Concretely, for any MSSM model, the neutral scalar representing the Higgs boson found at LHC should have an up-type matrix element. The other two neutral scalars are mixed states of down-type and pseudoscalar.

A fundamental decay channel for analysing the validity of the MSSM Higgs sector at high $\tan\beta$ is the Higgs decaying to two tau leptons. As it has been shown, this decay is enhanced when the decaying scalar has an associated CP matrix element with strong down and pseudoscalar components. Therefore, this decay channel deserves being a focus of experimental interest.

In the case of proposing MSSM models with a neutral Higgs lighter than the one found at 125.5 GeV, the $\tau\tau$ decay channel forbids any of them having a value of $\tan\beta \gtrsim 7.5$. If this channel was not enough to cover this range of $\tan\beta$, we should add $B_S^0 \to \mu^+\mu^-$ as a constraint four our scan.

In order to swipe the $\tan\beta$ parameter space completely, a powerful constraint for its low values is given by $B \to X_S\gamma$ and its contributions coming from sparticles.

Including these decay in the analysis, which is very strict, we have been able to discard completely the existence of a Higgs boson lighter than that found in the LHC if it comes from any MSSM model, since there is no $\tan\beta$ value that allows this to happen.

These tools can be used for the analysis of different scalar mass spectra, and we have subsequently done it to study MSSM with a lightest neutral Higgs of m_h =125.5 GeV, since it is the only possibility left by experimental data after our thorough study of it.

References

[1] G. Barenboim, C. Bosch, M.L. Lopez-Ibanez, O. Vives, JHEP **1311**, 051 (2013) [arXiv:1307.5973 [hep-ph]]
[2] A. Djouadi, Phys. Rept. **459**, 1 (2008) [hep-ph/0503173].
[3] S. Chatrchyan *et al.* [CMS Collaboration], JHEP **1303**, 037 (2013) [arXiv:1212.6194 [hep-ex]].
[4] S. Chatrchyan *et al.* [CMS Collaboration], arXiv:1305.2390 [hep-ex].
[5] [CMS Collaboration], PAS-SUS-13-007
[6] [CMS Collaboration], PAS-SUS-13-008
[7] [ATLAS Collaboration], ATLAS-CONF-2012-145.
[8] [ATLAS Collaboration], ATLAS-CONF-2013-007.
[9] G. Aad *et al.* [ATLAS Collaboration], Phys. Lett. B **716**, 1 (2012) [arXiv:1207.7214 [hep-ex]].
[10] S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **716**, 30 (2012) [arXiv:1207.7235 [hep-ex]].
[11] J. S. Lee, A. Pilaftsis, M. S. Carena, S. Y. Choi, M. Drees, J. R. Ellis and C. E. M. Wagner, Comput. Phys. Commun. **156**, 283 (2004) [hep-ph/0307377].
[12] G. Aad *et al.* [ATLAS Collaboration], arXiv:1307.1427 [hep-ex].
[13] G. Aad *et al.* [ATLAS Collaboration], JHEP **1209**, 070 (2012) [arXiv:1206.5971 [hep-ex]].
[14] [CMS Collaboration], CMS-PAS-HIG-13-004.
[15] G. Aad *et al.* [ATLAS Collaboration], JHEP **1302**, 095 (2013) [arXiv:1211.6956 [hep-ex]].
[16] Y. Amhis *et al.* [Heavy Flavor Averaging Group Collaboration], arXiv:1207.1158 [hep-ex].

[17] HFAG: Rare B decay parameterss, http://www.slac.stanford.edu/xorg/hfag/rare/
[18] K. Funakubo, S. Tao and F. Toyoda, Prog. Theor. Phys. **109**, 415 (2003) [hep-ph/0211238].
[19] G. Degrassi, P. Gambino and G. F. Giudice, JHEP **0012**, 009 (2000) [hep-ph/0009337].
[20] M. Misiak, H. M. Asatrian, K. Bieri, M. Czakon, A. Czarnecki, T. Ewerth, A. Ferroglia and P. Gambino *et al.*, Phys. Rev. Lett. **98**, 022002 (2007) [hep-ph/0609232].
[21] E. Lunghi and J. Matias, JHEP **0704**, 058 (2007) [hep-ph/0612166].
[22] M. E. Gomez, T. Ibrahim, P. Nath and S. Skadhauge, Phys. Rev. D **74**, 015015 (2006) [hep-ph/0601163].