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Improving bounds on flavor changing vertices in the two Higgs doublet model from $B^0 - \bar{B}^0$ mixing

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Abstract. We find some constraints on the flavor changing vertices of the two Higgs doublet model, from the ΔM_{B_d} measurement. Although bounds from this observable have already been considered, this paper takes into account the role of a new operator not included previously, as well as the vertices ξ_{bb}, ξ_{tc} and ξ_{sb}. Using the Cheng–Sher parametrization, we find that for a relatively light charged Higgs boson (200–300 GeV), we obtain $|\lambda_{tt}| \lesssim 1$, while the parameter λ_{bb} could have values up to about 50. In addition, we use bounds for λ_{tt} and λ_{bb} obtained from $B^0 \to X_s\gamma$ at next to leading order, and study the case where the only vanishing vertex factors are the ones involving quarks from the first family. We obtain that ΔM_{B_d} is not sensitive to the change of the parameter λ_{sb}, while $|\lambda_{tc}| \lesssim 1$.

1 Introduction

The simplest extension of the standard model (SM) compatible with gauge invariance is the so-called two Higgs doublet model (2HDM), in which the second Higgs doublet is identical to the SM one [1]. In this model, the particle spectrum is enlarged by the appearance of five Higgs bosons, two of them neutral CP-even, a neutral CP-odd and two charged ones. A new feature of the 2HDM consists of the appearance of processes with flavor changing neutral currents (FCNC). One of the main motivations to study scenarios with FCNC is the increasing evidence on neutrino oscillations that lead to lepton flavor violation (LFV) [2].

In this paper we are concerned with FCNC in the quark sector in the framework of the 2HDM type III, in which such processes are allowed at tree level. Recently, constraints on the lepton and quark sectors have been found from leptonic decays, B meson decays and the $B^0 - \bar{B}^0$ mixing [3, 4]. In [3] the box diagrams are assumed negligible while [4] assumes the box diagrams to be dominant. Notwithstanding, the latter reference does not include some operators and vertices that could contribute to the box diagrams significantly. We intend to study the effect of an operator and some vertices not considered in [4].

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2 ΔM calculation

The relevant Feynman diagrams for this process are shown in Fig. 1. The calculation for the SM was first performed in [5], where the diagrams involving gauge bosons are changed by diagrams with Goldstone bosons $\phi^\pm$ considering them as having the same mass as the W. The expression for ΔM in the framework of the SM reads [6]

$$\Delta M_{B_\mathrm{d}} = \frac{G_F^2}{6\pi^2} m_B |V_{td}V_{tb}|^2 B_B f_B^2 m_W^2 \eta_B S_0(x_t)\,,$$

where

$$S_0(x_{wf}) = \frac{4x_{wf} - 11x_{wf}^2 + x_{wf}^3}{4(1-x_{wf})^2} - \frac{3x_{wf}^3}{2(1-x_{wf})^3}\log(x_{wf})\,, \quad (1)$$

$$x_{ij} \equiv \left(\frac{m_j}{m_i}\right)^2 . \quad (2)$$

The functions B_B and η_B are the non-perturbative and perturbative QCD corrections, respectively. Finally, f_B refers to the decay constant of the B meson. On the other hand, regarding the extended Higgs sector, the calculation for the 2HDM of types I and II and a study of ΔM including QCD corrections were made in [7], and for the model of type III ΔM was studied in [4].

In order to make this calculation in the framework of the 2HDM type III, we shall make the following approximations: (1) for two identical quarks in the loop, we shall only take into account the contribution due to the top quark. (2) We shall consider that FC vertices ξ_{ij} involving

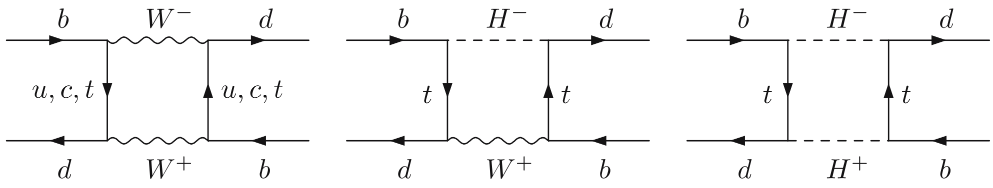

Fig. 1. Box diagrams for B^0–$\bar{B}^0$ in the 2HDM

the first generation are negligible. Combining both approximations, we find that the coefficients $R_{tq}^{U,D}$ in the Yukawa Lagrangian should be taken as

$$R_{td}^D = 0\,; \quad R_{tb}^D = V_{ts}\xi_{sb} + V_{tb}\xi_{bb}\,;$$
$$R_{td}^U = \xi_{tc}V_{cd} + \xi_{tt}V_{td}\,; \quad R_{tb}^U = \xi_{tc}V_{cb} + \xi_{tt}V_{tb}\,. \tag{3}$$

We shall also use the Cheng–Sher parametrization for the FC vertices

$$\xi_{qq'} = \left(\sqrt{2}G_F m_q m_{q'}\right)^{1/2} \lambda_{qq'}\,, \tag{4}$$

and the contributions for ΔM_{B_d} read

$$\Delta M_{B_d} = \frac{G_F^2}{6\pi^2}(V_{td}^\dagger V_{tb})^2 B_B f_B^2 \eta_B m_B^2 m_W^2 S_{2HDM}\,,$$

where

$$\begin{aligned} S_{2HDM} = {} & S_0(x_{wt}) + S_{HH}(x_H(m_t))\left(\sqrt{\frac{m_c}{m_t}}\frac{V_{cd}}{V_{td}}\frac{\lambda_{tc}}{\lambda_{tt}}+1\right)^2 \\ & \times\left(\sqrt{\frac{m_c}{m_t}}\frac{V_{cb}}{V_{tb}}\frac{\lambda_{tc}}{\lambda_{tt}}+1\right)^2 - 5\frac{m_B^2}{(m_b+m_d)^2} \\ & \times S'_{HH}(x_H(m_t))\left(\sqrt{\frac{m_c}{m_t}}\frac{V_{cd}}{V_{td}}\frac{\lambda_{tc}}{\lambda_{tt}}+1\right)^2 \\ & \times\left(\sqrt{\frac{m_s}{m_b}}\frac{V_{ts}}{V_{tb}}\frac{\lambda_{sb}}{\lambda_{bb}}+1\right)^2 \\ & + S_{WH}(x_H(m_t), x_W(m_t)) \\ & \times\left(\sqrt{\frac{m_c}{m_t}}\frac{V_{cd}}{V_{td}}\frac{\lambda_{tc}}{\lambda_{tt}}+1\right)\left(\sqrt{\frac{m_c}{m_t}}\frac{V_{cb}}{V_{tb}}\frac{\lambda_{tc}}{\lambda_{tt}}+1\right) \end{aligned} \tag{5}$$

and

$$\begin{aligned} S_{HH}(x_{Ht}) = {} & \lambda_{tt}^4\frac{x_{Ht}x_{Wt}}{4} \\ & \times\left(\frac{1+x_{Ht}}{(1-x_{Ht})^2}+\frac{2x_{Ht}\log(x_{Ht})}{(1-x_{Ht})^3}\right)\,, \end{aligned} \tag{6}$$

$$\begin{aligned} S_{WH}(x_{Ht}, x_{Wt}) = {} & \lambda_{tt}^2\frac{x_{Ht}x_{Wt}}{4} \\ & \times\left[\frac{(2x_{Wt}-8x_{Ht})\log(x_{Ht})}{(1-x_{Ht})^2(x_{Ht}-x_{Wt})}\right. \\ & +\frac{6x_{Wt}\log(x_{Wt})}{(1-x_{Ht})^2(x_{Ht}-x_{Wt})} \\ & \left.-\frac{8-2x_{Wt}}{(1-x_{Ht})(1-x_{Wt})}\right]\,, \end{aligned} \tag{7}$$

$$\begin{aligned} S'_{HH}(x_{Ht}) = {} & \lambda_{tt}^2\lambda_{bb}^2\frac{x_{Ht}x_{Hb}x_{Wt}}{4} \\ & \times\left(\frac{2(1-x_{Ht})+\log(x_{Ht})(1+x_{Ht})}{(1-x_{Ht})^3}\right)\,. \end{aligned}$$

The function S'_{HH} comes from the vertex ξ_{bb} and it was not considered in [4]. We have also taken into account the perturbative QCD correction η_B taken from [4]. The factor $f_B\sqrt{B_B}$ introduces a lot of uncertainty in most of the calculations. In [4], one can find an estimate of this uncertainty, obtained by plotting $V_{td} - f_B\sqrt{B_B}$, based on the experimental value of ΔM, obtaining allowed values between 0.19 GeV and 0.27 GeV. A more stringent range between 0.219 GeV and 0.273 GeV is obtained from [9], which will be the values we use in our analyses.

Taking $\lambda_{bb} = 0$, the results are the same as in [4], i.e. it is concluded that λ_{tt} should be less than one. On the other hand, values greater than 0.7 would not be favored if one expects the charged Higgs boson to be relatively light, i.e. in the region of 200–300 GeV (we shall assume the charged Higgs boson to be relatively light throughout the paper). Adding the contribution of the λ_{bb} factor, we find that for values between 30 and 50 of this vertex (which are allowed by the $B \to X_s\gamma$ process [4]), the maximum values of λ_{tt} could be lower than in the latter case. Finally, it is worth saying that these bounds are compatible with the ones imposed on λ_{bb}, λ_{tt} from perturbativity grounds [8].

Up to now we have considered that only the vertices λ_{tt} and λ_{bb} contribute to the process. Now, we shall study the possibility of including the contributions of λ_{tc} and λ_{bs} (not considered in [4]). In that case, the coefficients $R_{tq}^{U,D}$ described in (3) and (4) should be taken in complete form (but maintaining the approximations that led to (3)). We will use some of the restrictions found in [4] for λ_{tt} and λ_{bb} from the $B \to X_s\gamma$ process, to reduce the number of free parameters and try to obtain new bounds on the new parameters introduced. Taking $\lambda_{tt} = 0.5$ and $\lambda_{bb} = 22$, we obtain that the behavior of ΔM as a function of λ_{tc} is basically independent of the value taken for λ_{sb}, at least by assuming $|\lambda_{sb}| \leq 100$. The same occurs when we take $\lambda_{tt} = 0.5$, $\lambda_{bb} = 1$. Since λ_{sb} could take large values without affecting the behavior of ΔM, it would be useless to make a graph of ΔM as a function of this factor.

On the other hand, by taking into account the big uncertainty in the $f_B\sqrt{B_B}$ factor, it could be interesting to see what region is permitted by the experimental data for different values of λ_{tc}. The results are shown in Fig. 2 for $\lambda_{tt} = 0.5$ and $\lambda_{bb} = 1$. The trend found in this part is fairly clear regarding λ_{tc} and λ_{sb}. The vertex λ_{tc} is the most constrained; together with λ_{tt} they are both less than one, while λ_{bb} and λ_{sb} could have some higher values. λ_{bb} could be even 50, according to our results and the results in [4], while the values of λ_{sb} do not affect the function ΔM even for very large values.

Finally, there is a naive way to analyze why ΔM is not sensitive to the λ_{sb} factor while it is for the λ_{tc} vertex. By

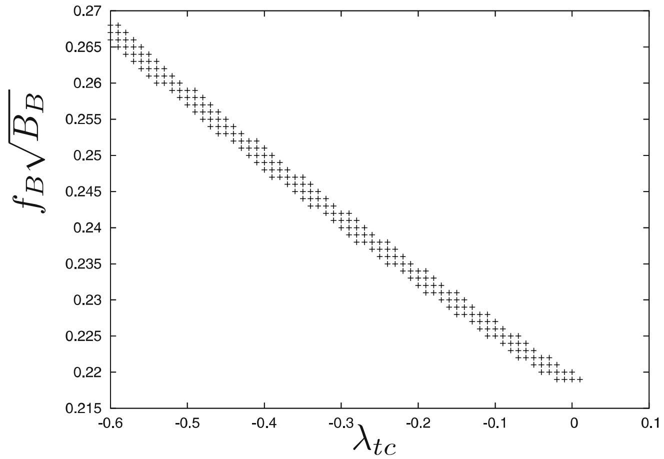

Fig. 2. Contour plot on the $f_B\sqrt{B}_B - \lambda_{tc}$ plane with $\lambda_{sb} = 0$, $m_H = 250\,\text{GeV}$, taking $\lambda_{tt} = 0.5, \lambda_{bb} = 22$

taking the coefficients that accompany the operators S_{HH} and S_{WH}, we can check that for values of $|\lambda_{tc}/\lambda_{tt}|$ between -1 and 1 we find regions in which the contribution of λ_{tc} is of the same order as the contribution of λ_{tt} (in some cases constructive and in some cases destructive). These contributions could also be significant for the new operator S'_{HH}. By contrast, the quotient $|\lambda_{sb}/\lambda_{bb}|$ should be at least of the order of 150 to obtain a significant contribution from λ_{sb} to the operator S'_{HH}.

In conclusion, the combined data from ΔM_{B_d} and $B \to X_s\gamma$ could provide some information about the FC vertices $\lambda_{bb},\ \lambda_{tt},\ \lambda_{tc}, \lambda_{bs}$. A phenomenological analysis shows that λ_{bb} could still have large values up to about 50; the λ_{sb} vertex remains basically unconstrained while the vertices λ_{tt} and λ_{tc} are more restricted and appear to be less than one in magnitude.

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