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 $\Delta M_{B_d}$ 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 $\xi_{ib}$, $\xi_{ic}$ and $\xi_{ab}$. Using the Cheng-Sher parametrization, we found that for a relatively light charged Higgs boson (200-300 GeV), we get that $|\lambda_{tt}| \lesssim 1$, while the parameter $\lambda_{bb}$ could have values up to about 50. In addition, we use bounds for $\lambda_{tt}$ and $\lambda_{bb}$ obtained from $B^0 \rightarrow X_s \gamma$ at next to leading order, and studied the case where the only vanishing vertex factors are the ones involving quarks from the first family. We obtained that $\Delta M_{B_d}$ is not sensitive to the change of the parameter $\lambda_{sb}$, while $|\lambda_{tc}| \lesssim 1$.

The simplest extension of the 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 leads 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 Ref. [3] the box diagrams are assumed negligible while Ref. [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].

$\Delta M$ calculation

The relevant Feynman diagrams for this process are shown in figure [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 with the same mass of the $W$. The expression for $\Delta M$ in the framework of the SM reads [6]:

$$\Delta M_{B_d} = \frac{G_F^2}{6\pi^2} m_B |V_{td} V_{tb}|^2 B B^2 m_W^2 \eta_B S_0(x_t),$$

where

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

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

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The $B_B$ and $\eta_B$ functions 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 on 2HDM of type I and II and a study of $\Delta M$ including QCD corrections was made in [7], and for the model type III $\Delta M$ 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 $\xi_{ij}$ involving the first generation are negligible. Combining both approximations, we find that the coefficients $R^{DU}_{ti}$ in the Yukawa Lagrangian should be taken as

$$
R^{D}_{ti} = 0 ; \quad R^{D}_{tb} = V_{ts} \xi_{sb} + V_{tb} \xi_{bb}
$$

$$
R^{L}_{ti} = \xi_{tc} V_{cd} + \xi_{tt} V_{td} ; \quad R^{L}_{tb} = \xi_{tc} V_{cb} + \xi_{tt} V_{tb}
$$

we shall also use the Cheng-Sher parametrization for the FC vertices

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

and the contributions for $\Delta M_{B_d}$ read

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

where

$$
S_{2HDM} = S_0(x_{wt}) + S_{HH}(x_H(m_t)) \left( \frac{m_c V_{cd} \lambda_{tc}}{m_t V_{td} \lambda_{tt}} + 1 \right) \left( \frac{m_c V_{cb} \lambda_{tc}}{m_t V_{tb} \lambda_{tt}} + 1 \right) + 5 \frac{m_B^2}{(m_b + m_d)^2} S'_{HH}(x_H(m_t)) \left( \frac{m_c V_{cd} \lambda_{tc}}{m_t V_{td} \lambda_{tt}} + 1 \right) \left( \frac{m_s V_{ts} \lambda_{sb}}{m_b V_{tb} \lambda_{bb}} + 1 \right)
$$

$$
+ S_{WH}(x_H(m_t), x_W(m_t)) \left( \frac{m_c V_{cd} \lambda_{tc}}{m_t V_{td} \lambda_{tt}} + 1 \right) \left( \frac{m_c V_{cb} \lambda_{tc}}{m_t V_{tb} \lambda_{tt}} + 1 \right),
$$

and

$$
S_{HH}(x_{Ht}) = \lambda_{tt}^4 \frac{x_{Ht} x_{Wt}}{4} \left( \frac{1 + x_{Ht}}{(1 - x_{Ht})^2} + \frac{2 x_{Ht} \log(x_{Ht})}{(1 - x_{Ht})^3} \right),
$$

$$
S_{WH}(x_{Ht}, x_{Wt}) = \lambda_{tt}^2 \frac{x_{Ht} x_{Wt}}{4} \left( \frac{(2 x_{w} - 8 x_{Ht}) \log(x_{Ht})}{(1 - x_{Ht})^2 (x_{Ht} - x_{Wt})} + \frac{6 x_{w} \log(x_{Wt})}{(1 - x_{Ht})^2 (x_{Ht} - x_{Wt})} - \frac{8 - 2 x_{Wt}}{(1 - x_{Ht})(1 - x_{Wt})} \right),
$$

Figure 1: Box diagrams for $B^0 - \bar{B}^0$ in the 2HDM.
The function $S'_{HH}$ comes from the vertex $\xi_{bb}$ and it was not considered in Ref. [4]. We have also taken into account the perturbative QCD correction $\eta_p$ taken from [4]. The factor $f_{BB}$, introduces a lot of uncertainty in most of the calculations. In [4], one can find an estimate of this uncertainty, obtained by plotting $V_{td} - f_{BB}/\sqrt{B}$, based on the experimental value of $\Delta M$, 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 $\lambda_{tt}$ 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 document). Adding the contribution of the $\lambda_{bb}$ 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 $\lambda_{tt}$ could be lower than in the latter case. Finally, it is worth saying that these bounds are compatible with the ones imposed to $\lambda_{bb}$, $\lambda_{tt}$ from perturbativity grounds [8].

Up to now we have considered that only the vertices $\lambda_{tt}$ and $\lambda_{bb}$ contributes to the process. Now, we shall study the possibility of including the contributions of $\lambda_{tc}$ and $\lambda_{ts}$ (not considered in Ref. [4]). In that case, the coefficients $R^{U,D}_{ij}$ described in Eqs. [8, 11] should be taken in complete form (but maintaining the approximations that led to Eq. [9]). We will use some of the restrictions found in [4] for $\lambda_{tt}$ and $\lambda_{bb}$ from the $B \to X_s \gamma$ process, to reduce the number of free parameters and try to get new bounds on the new parameters introduced. Taking $\lambda_{tt} = 0.5$ and $\lambda_{bb} = 22$, we obtained that the behavior of $\Delta M$ as a function of $\lambda_{tc}$ is basically independent of the value taken for $\lambda_{tt}$, at least by assuming $|\lambda_{ab}| \leq 100$. The same occurs when we took $\lambda_{tt} = 0.5, \lambda_{bb} = 1$. Since $\lambda_{ab}$ could take large values without affecting the behavior of $\Delta M$, it would be useless to make a graph of $\Delta M$ as a function of this factor.

On the other hand, by taking into account the big uncertainty in the $f_{BB}/\sqrt{B}$ factor, it could be interesting to see what options are permitted by the experimental data for different values of $\lambda_{tc}$. The results are shown in figure 2 for $\lambda_{tt} = 0.5$ and $\lambda_{bb} = 1$. The trend found in this part is somehow clear in what has to do with $\lambda_{tc}$ and $\lambda_{ts}$. The vertex $\lambda_{tc}$ is the most constrained; together with $\lambda_{tt}$ both are less than one, while $\lambda_{bb}$ and $\lambda_{ts}$ could have some higher values. $\lambda_{bb}$ could be even 50, according to our results and to the results in [4], while the values of $\lambda_{ab}$ do not affect the function $\Delta M$ even for very large values.

Finally, there is a naive way to analyze why $\Delta M$ is not sensitive to the $\lambda_{ts}$ factor while it is for the $\lambda_{tc}$ vertex. By taking the coefficients that accompany the operators $S_{HH}$ and $S_{WY}$ we can check that for values of $|\lambda_{tc}/\lambda_{tt}|$ between $-1$ and $1$ we get regions in which the contribution of $\lambda_{tc}$ is of the same order of the contribution of $\lambda_{tt}$ (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 $|\lambda_{ab}/\lambda_{bb}|$ should be at least of the order of 150 to get a significant contribution from $\lambda_{ab}$ to the operator $S'_{HH}$.

In conclusion, the combined data from $\Delta M_{B_s}$ and $B \to X_s \gamma$ could provide some information over the FC vertices $\lambda_{bb}$, $\lambda_{tt}$, $\lambda_{tc}, \lambda_{ts}$. A phenomenological analysis shows that $\lambda_{bb}$ could still have large values up to about 50, the $\lambda_{ab}$ vertex keeps basically unconstrained while the vertices $\lambda_{tt}$ and $\lambda_{tc}$ are more restricted and appears to be less than one in magnitude.

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

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