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Flavour changing neutral currents in two Higgs doublet models with Yukawa alignment

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Abstract. In a general two Higgs doublet model where both Higgses couple to all fermions flavour changing neutral currents (FCNCs) can get arbitrarily large. Such models are thus in conflict with experiment unless there is some mechanism suppressing the FCNCs. A possibility to do so recently brought up is the assumption that the Yukawa couplings are aligned, i.e. proportional to each other. This condition presumably holds at a high-energy scale and is spoiled by radiative corrections. In the work presented in this talk, we computed the size of the radiatively induced flavour violating Higgs couplings at the electroweak scale. We showed that these contributions are well below the experimental bounds in large regions of the parameter space.

Two Higgs doublet models (2HDMs) are amongst the easiest extensions of the Standard Model (SM), consisting in simply adding a second Higgs doublet to the SM particle content. Two complex doublets means eight real degrees of freedom. Three degrees of freedom are the massless Goldstone bosons that are eaten by the W and B bosons, leaving us with five physical mass eigenstates: two CP even neutral scalars h and H, one CP odd neutral scalar A and two charged scalars $H^{\pm}$. In this work we considered a general 2HDM where both Higgses can couple to all fermions so that the Yukawa Lagrangian looks like[1]:

$$\begin{aligned}\mathcal{L}_{\text{Yukawa}} = (Y_u^{(1)})_{ij}\bar{q}'_{Li}u'_{Rj}\tilde{\phi}_1 + (Y_d^{(1)})_{ij}\bar{q}'_{Li}d'_{Rj}\phi_1 + (Y_e^{(1)})_{ij}\bar{l}'_{Li}e'_{Rj}\phi_1 \\ +(Y_u^{(2)})_{ij}\bar{q}'_{Li}u'_{Rj}\tilde{\phi}_2 + (Y_d^{(2)})_{ij}\bar{q}'_{Li}d'_{Rj}\phi_2 + (Y_e^{(2)})_{ij}\bar{l}'_{Li}e'_{Rj}\phi_2 + \text{h.c.}\end{aligned} \tag{1}$$

This is problematic since it leads to flavour changing neutral currents (FCNCs) in the Higgs sector. To see this and to be specific, let us consider the down-type quark sector, but the following is equally true for the up-type quarks, of course. The Yukawa Lagrangian expanded in SU(2) components reads:

$$\mathcal{L}_{\text{Yukawa}} \supseteq \bar{u}'_L Y_d^{(1)} d'_R \phi_1^+ + \bar{d}'_L Y_d^{(1)} d'_R \phi_1^0 + \bar{u}'_L Y_d^{(2)} d'_R \phi_2^+ + \bar{d}'_L Y_d^{(2)} d'_R \phi_2^0 + \text{h.c.} \tag{2}$$

In the SM, only the first two terms are present. The coupling to the neutral component of the Higgs gives rise to the mass term for the down-type quarks after electroweak symmetry breaking

[1] This is also sometimes called a type III 2HDM.

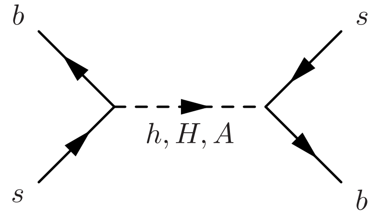


Figure 1: *Tree level mediation of $B_s - \bar{B}_s$-mixing in a 2HDM with flavour violating couplings.*

(EWSB). We can diagonalize its Yukawa matrix by performing bi-unitary transformations on the quark fields:

$$d'_L = V_d^L d_L, \quad d'_R = V_d^R d_R, \quad V_d^{L\dagger} Y_d^{(1)} V_d^R = \text{diag.}(y_d, y_s, y_b) \tag{3}$$

In a type III 2HDM there are also the couplings to the second Higgs and in general these Yukawa matrices are not diagonal in the same basis. The off-diagonal elements will then induce FCNCs. In the SM this cannot happen since there is only one Yukawa coupling per fermion type.

Since FCNCs are known from experiment to be highly suppressed, we must find a way to "tame" these. The standard approach is to impose a discrete symmetry such that all fermions of a given electric charge couple to no more than one Higgs doublet. FCNCs are completely absent at tree level then. This is what is usually called a type I or II 2HDM. Another possibility recently put forward by A. Pich and P. Tuzón [1] is the assumption that the two Yukawa couplings of each fermion type are aligned, i.e. proportional to each other. In the work reported on here [2] we chose to parameterize this condition as:

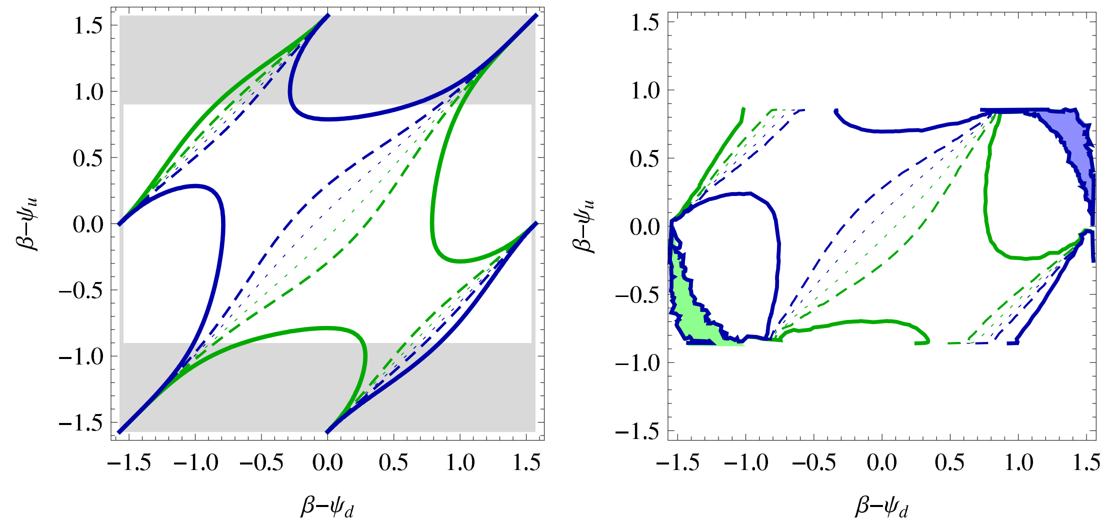
$$Y_u^{(1)}(\Lambda) = \cos\psi_u Y_u, \qquad Y_u^{(2)}(\Lambda) = \sin\psi_u Y_u, \tag{4}$$
$$Y_d^{(1)}(\Lambda) = \cos\psi_d Y_d, \qquad Y_d^{(2)}(\Lambda) = \sin\psi_d Y_d, \tag{5}$$
$$Y_e^{(1)}(\Lambda) = \cos\psi_e Y_e, \qquad Y_e^{(2)}(\Lambda) = \sin\psi_e Y_e; \tag{6}$$

The assumption of Yukawa alignment can be justified if one assumes that there is an underlying flavour symmetry and that this symmetry is broken only by the Yukawa couplings of the SM (so-called Minimal Flavour Violation) [3].
This ansatz is more general than models with a discrete symmetry in two ways:

- It contains type I and type II models as special cases (type I: $\psi_u = \psi_d = \psi_e = 0$, type II: $\psi_u = 0$, $\psi_d = \psi_e = \pi/2$).
- It allows for new sources of CP violation in the Higgs sector (The Higgs vacuum expectation values (vevs) can be complex and in general only one of these vevs can be made real by an appropriate U(1) phase transition.)

Radiative corrections however introduce a misalignment of the Yukawa couplings at the electroweak scale if the alignment condition is implemented at a high energy scale. In [2] we solved the renormalization group equations (RGEs) [4] describing the running of the Yukawa couplings from the high scale to the electroweak scale numerically and analytically in the so-called leading log approximation. In the analytical approximation it turns out that the off-diagonal parts of the couplings of the neutral Higgs bosons can be parameterized as a parameter E_d which depends on the parameters ψ_u and ψ_d describing the alignment condition times a matrix Q_d which is a product of the (known) quark mass matrices and the CKM matrix:

$$\Delta_u^{\text{off-diag.}} = E_u Q_u, \tag{7}$$
$$\Delta_d^{\text{off-diag.}} = E_d Q_d, \tag{8}$$



(a) Analytical approximation of E_d (b) Numerical result for $2.5E_d$

Figure 2: *Contour plots of* E_d *for* $\Lambda = 10^{19}$ GeV*. The left figure corresponds to the analytic formula, eq. (12). Solid/dashed/dotted lines correspond to the absolute values of 1/0.3/0.1, blue lines correspond to negative values, green lines to positive ones. The right figure shows* $2.5\Delta_{d,23}/Q_{d,23}$ *where* $\Delta_{d,23}$ *has been obtained by numerically solving the RGEs. The rescaling was done in order to make the comparison to the analytical result easier.*

where, assuming real ψ_u, ψ_d:

$$Q_u \equiv \frac{1}{v^3}\left(V_{CKM}\left(M_d^{diag.}\right)^2 V_{CKM}^\dagger M_u^{diag.}\right)^{\mathrm{off-diag.}}, \tag{9}$$

$$E_u \equiv \frac{1}{8\pi^2}\frac{\sin(2(\psi_u-\psi_d))}{\cos^2(\beta-\psi_u)\cos^2(\beta-\psi_d)}\log\left(\frac{m_Z}{\Lambda}\right), \tag{10}$$

$$Q_d \equiv \frac{1}{v^3}\left(V_{CKM}^\dagger\left(M_u^{diag.}\right)^2 V_{CKM} M_d^{diag.}\right)^{\mathrm{off-diag.}}, \tag{11}$$

$$E_d \equiv -E_u. \tag{12}$$

The most stringent experimental bounds on E_d come from $B_s - \bar{B}_s$-mixing[2]. This is a process that in the SM can occur only at loop level while in a general 2HDM there is also a tree level mediation, see fig. 1. The mixing leads to a mass difference of the mesons and antimesons since the flavour eigenstates are no longer mass eigenstates. This mass difference can be calculated using the effective Hamiltonian [5, 6]:

$$H_{\mathrm{eff.}}^{\Delta B=2} = \sum_{i,a} C_i^a(m_Z)Q_i^a(m_Z), \tag{13}$$

where the relevant operators for a 2HDM with flavour changing neutral couplings are:

$$Q_1^{SLL} = (\bar{b}_R s_L)(\bar{b}_R s_L), \quad Q_1^{SRR} = (\bar{b}_L s_R)(\bar{b}_L s_R), \quad Q_2^{LR} = (\bar{b}_R s_L)(\bar{b}_L s_R). \tag{14}$$

and the Wilson coefficients C_i^a can be deduced from the full Hamiltonian by integrating out the Higgs bosons. By demanding that the new contribution to the mass difference be smaller than

[2] Bounds on E_u are in general less stringent than those on E_d.

the theoretical uncertainities on the SM value, we get the following upper limit on the parameters of the 2HDM:

$$\left| \frac{s^2_{\alpha-\beta}}{m_H^2} + \frac{c^2_{\alpha-\beta}}{m_h^2} - \frac{1}{m_A^2} \right| |E_d|^2 \lesssim \frac{1}{(80 \text{ Gev})^2}. \tag{15}$$

The parameter E_d characterizing the size of the flavour changing couplings can thus easily be of the order of one or more, depending on the Higgs masses.

These experimental bounds are satisfied for large portions of the parameter space as can be seen in fig. 2(a) where countour plots of $E_d = 1, 0.3, 0.1$ in the parameter space $\beta - \psi_u$, $\beta - \psi_d$ are shown. For $\psi_u = \psi_d$ and $\psi_u = \psi_d \pm \pi/2$, E_d vanishes completely. This comprises the type I ($\psi_u = \psi_d = 0$) and type II ($\psi_u = 0$, $\psi_d = \pi/2$) 2HDM. In fig. 2(b) a plot of E_d obtained by numerically solving the RGEs is shown. It is rescaled by a factor of 2.5 for better comparison with the analytical result. This factor is due to large, flavour-independent effects in the running of the strong coupling constant and the top Yukawa coupling which are not taken into account by the leading log approximation. The white/gray areas in both plots are not accesible as some Yukawa couplings become non-perturbative below the cut-off scale, which is taken to be the Planck scale in these plots.

Conclusions

With the LHC finally running and searching for the Higgs(es) it is important to investigate different scenarios for the Higgs sector. As said at the beginning, 2HDMs are amongst the easiest extensions of the SM Higgs sector. Without any further protection they however lead to unacceptably large FCNCs. The assumption that the Yukawa couplings are aligned at the high energy scale can provide such a protection and there are then no new sources of flavour violation at tree level. Quantum corrections however introduce a misalignment of the Yukawa couplings at low energies. In the work presented here, we calculated the size of the flavour violating Higgs couplings at the electroweak scale. This also determines the minimal size of the exotic contributions to FCNCs in any 2HDM in the absence of tuning and discrete symmetries. We could show that the exotic contributions are well below experimental bounds for a wide parameter range. The authors of the related recent works [7], [8] came to the same conclusions in the aspects where the analyses overlap.

Acknowledgments

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