Two-Higgs-Doublet Models with Minimal Flavour Violation

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Introduction

Several extensions of the Standard Model contain more than one Higgs doublet; the Two-Higgs-Doublet Models (2HDMs) bring many interesting phenomenological features (new sources of CP violation, dark matter candidates, axion phenomenology, etc.), but can contain dangerous Higgs-mediated Flavour Changing Neutral Current (FCNC) interactions. In order to suppress them, two mechanisms can be applied: the Natural Flavour Conservation (NFC), introduced by Glashow and Weinberg in [2], and the Minimal Flavour Violation (MFV) [3]; beyond the tree level some FCNCs are naturally generated in both cases, but we will show that while the NFC loses its effectiveness, the MFV structure is stable. Moreover, we will demonstrate that a 2HDM with MFV enriched with flavour-blind phases can describe the recent experimental anomalies found in the $\Delta F = 2$ transitions.

Protection mechanisms for FCNCs

Let us consider a model with two Higgs doublets H_1 and H_2 with nontrivial vacuum expectation values $v\cos\beta/\sqrt{2}$ and $v\sin\beta/\sqrt{2}$, respectively. The most general renormalizable and gauge-invariant interaction of these fields with the SM quarks is

$$-\mathcal{L}_Y = \bar{Q}_L X_{d1} D_R H_1 + \bar{Q}_L X_{u1} U_R H_1^c + \bar{Q}_L X_{d2} D_R H_2^c + \bar{Q}_L X_{u2} U_R H_2 + \text{h.c.}\ ;$$

X_i : 3×3 matrices with a generic flavour structure

For generic X_i it contains FCNCs, as can be seen by rotating the Higgs fields:

$$-\mathcal{L}_Y = \bar{Q}_L\left(\frac{\sqrt{2}}{v}M_d H_1' + Z_d H_2'\right)D_R + \bar{Q}_L\left(\frac{\sqrt{2}}{v}M_u H_1'^c + Z_u H_2'^c\right)U_R + \text{h.c.}\ .$$

mass terms: $M_{u,d} = \frac{v}{\sqrt{2}}(\cos\beta\, X_{u,d\,1} + \sin\beta\, X_{u,d\,2})$ interaction terms: $Z_{u,d} = \cos\beta\, X_{u,d\,2} - \sin\beta\, X_{u,d\,1}$

The largest group of unitary quark field transformations that commutes with the SM gauge Lagrangian can be decomposed as

$$\mathcal{G}_q = (SU(3)\otimes U(1))^3$$

flavour symmetry: $SU(3)^3 = SU(3)_{Q_L}\otimes SU(3)_{U_R}\otimes SU(3)_{D_R}$

flavour-blind symmetry: $U(1)^3 = U(1)_B \otimes U(1)_Y \otimes U(1)_{PQ}$

One can obtain the suppression of FCNCs by protecting the breaking of one of these two types of symmetry.

- **Natural Flavour Conservation**
  It assumes that only one Higgs field can couple to a given quark species. This structure can be obtained by imposing appropriate continuous or discrete flavour-blind symmetries.
  - Peccei-Quinn symmetry $U(1)_{PQ}$
    In this context it can be defined as the symmetry under which D_R and H_1 have opposite charges, while all the other fields are neutral. Its application implies
    $$X_{u1} = X_{d2} = 0\ .$$
    This symmetry cannot be exact, since it would cause the presence of a massless pseudoscalar Higgs field, and hence it must be broken beyond the tree level; for the down-type Yukawa coupling:
    $$X_{d2} = \epsilon_d \Delta_d$$
    $\epsilon_d = \mathcal{O}(10^{-2})$, typical loop suppression
    Δ_d : 3×3 flavour-breaking matrix with $\mathcal{O}(1)$ entries
    However, the consistency with the experimental value of the observable ϵ_K requires
    $$|\epsilon_d| \times |\text{Im}[(\Delta_d)_{21}^*(\Delta_d)_{12}]|^{1/2} \lesssim 3\times10^{-7}\times\frac{\cos\beta\, M_H}{100\ \text{GeV}}$$
    i. e. a large amount of fine-tuning would be needed to provide an efficient protection from FCNCs.
  - Discrete symmetries $\mathcal{Z}_2$
    They are the two discrete subgroups of $U(1)_{PQ}$ under which $H_1 \to -H_1$ and $D_R \to \pm D_R$; they imply that two of the X_i must vanish. In principle these symmetries could be exact, but they do not exclude the presence of higher-dimensional operators of the type
    $$\Delta\mathcal{L}_Y = \frac{c_1}{\Lambda^2}\bar{Q}_L X_{d1}^{(6)} D_R H_1 |H_1|^2 + \frac{c_2}{\Lambda^2}\bar{Q}_L X_{d2}^{(6)} D_R H_1 |H_2|^2 + \ldots$$
    that, for $c_i = \mathcal{O}(1)$ and $\Lambda = \mathcal{O}(1\text{TeV})$, generate too large FCNCs anyhow.
- **Minimal Flavour Violation**
  It consists in the assumption that the $SU(3)$ quark flavour symmetry is broken only by two independent terms, Y_d and Y_u, transforming as
  $$Y_u \sim (3,\bar{3},1)_{SU(3)^3} \qquad Y_d \sim (3,1,\bar{3})_{SU(3)^3}\ .$$
  It implies for the X_i the structure [3]
  $$\begin{aligned} X_{d1} &= Y_d \\ X_{d2} &= P_{d2}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_d = \epsilon_0 Y_d + \epsilon_1 Y_dY_d^\dagger Y_d + \epsilon_2 Y_uY_u^\dagger Y_d + \ldots \\ X_{u1} &= P_{u1}(Y_uY_u^\dagger, Y_dY_d^\dagger)\times Y_u = \epsilon_0' Y_u + \epsilon_1' Y_uY_u^\dagger Y_u + \epsilon_2' Y_dY_d^\dagger Y_u + \ldots \\ X_{u2} &= Y_u \end{aligned}$$
  that is renormalization group invariant. In this frame the effective down-type FCNC interaction can be written as
  $$\mathcal{L}_{\text{MFV}}^{\text{FCNC}} \propto \bar{d}_L^i\left[\left(a_0 V^\dagger\lambda_u{}^2 V + a_1 V^\dagger\lambda_u{}^2 V\Delta + a_2 \Delta V^\dagger\lambda_u{}^2 V\right)\lambda_d\right]_{ij} d_R^j\, \frac{S_2 + iS_3}{\sqrt{2}} + \text{h.c.}\ .$$
  $a_i = \mathcal{O}(1)$ $\qquad \lambda_{u,d} \propto \text{diag}\left(\frac{m_{u,d}}{v}, \frac{m_{c,s}}{v}, \frac{m_{t,b}}{v}\right)$
  $\Delta = \text{diag}(0,0,1)$ $\qquad S_2, S_3$: heavy neutral Higgses
  double CKM suppression + down-type Yukawa suppression
  The consistency with experimental data requires
  $$|a_0|\tan\beta\frac{v}{M_H} < 18 \qquad \text{from } \epsilon_K$$
  $$\sqrt{|(a_0^* + a_1^*)(a_0 + a_2)|}\tan\beta\frac{v}{M_H} = 10 \qquad \text{from } \Delta M_s$$
  $$\sqrt{|a_0 + a_1|}\tan\beta\frac{v}{M_H} < 8.5 \qquad \text{from Br}(B_s\to\mu^+\mu^-)$$
  that are perfectly acceptable values.

MFV with flavour-blind phases

Three interesting problems have recently emerged in the $\Delta F = 2$ down-type transitions:

- first results from CDF and D0 indicate a value for the weak phase in the $B_s - \bar{B}_s$ mixing that is roughly larger than the SM prediction by a factor 20 [4];
- the value of $\sin 2\beta$ resulting from the UT fits tends to be significantly larger than the measured value of $S_{\psi K_S}$ [5];
- the values of $S_{\psi K_S}$ and ϵ_K cannot be simultaneously described within the SM [5].

We have found that all these issues can be explained in the context of a general 2HDM with MFV enriched by flavour-blind phases.

The mechanisms of flavour and CP violation do not necessary need to be related: in MFV the Yukawa matrices are the only sources of flavour breaking, but other sources of CP violation could be present. Allowing the FCNC parameters a_i to be complex, we investigate the possibility of generic CP-violating flavour-blind phases in the Higgs sector.

Considering the $\Delta F = 2$ FCNC transitions mediated by the neutral Higgs bosons, the leading MFV effective Hamiltonians are:

$$\mathcal{H}^{|\Delta S|=2} \propto -\frac{|a_0|^2}{M_H^2}\frac{m_s}{v}\frac{m_d}{v}\left[\left(\frac{m_b}{v}\right)^2 V_{ts}^* V_{td}\right]^2 (\bar{s}_R d_L)(\bar{s}_L d_R) + \text{h.c.}$$

$$\mathcal{H}^{|\Delta B|=2} \propto -\frac{(a_0^* + a_1^*)(a_0 + a_2)}{M_H^2}\frac{m_b}{v}\frac{m_q}{v}\left[\left(\frac{m_b}{v}\right)^2 V_{tb}^* V_{tq}\right]^2 (\bar{b}_R q_L)(\bar{b}_L q_R) + \text{h.c.}\ ,$$

that show two key properties:

- the impact in K^0, B_d and B_s mixing amplitudes scales with $m_s m_d$, $m_b m_d$ and $m_b m_s$ respectively, opening the possibility of sizable non-standard contributions to the B_s system without serious constraints from K^0 and B_d mixing;
- while the possible flavour-blind phases do not contribute to the $\Delta S = 2$ effective Hamiltonian, they could have an impact in the $\Delta B = 2$ case, offering the possibility to solve the anomaly in the B_s mixing phase.

Using the presence of a new phase in $\mathcal{H}^{|\Delta B|=2}$, we can easily accommodate the anomalous large mixing phase of the B_s system. Moreover, this choice determines a shift in the relation between $S_{\psi K_S}$ and the CKM phase β (Fig. 1, left), that is completely determined and goes in the right direction to improve the existing tension between the experimental value of $S_{\psi K_S}$ and its SM prediction (Fig. 1, right).

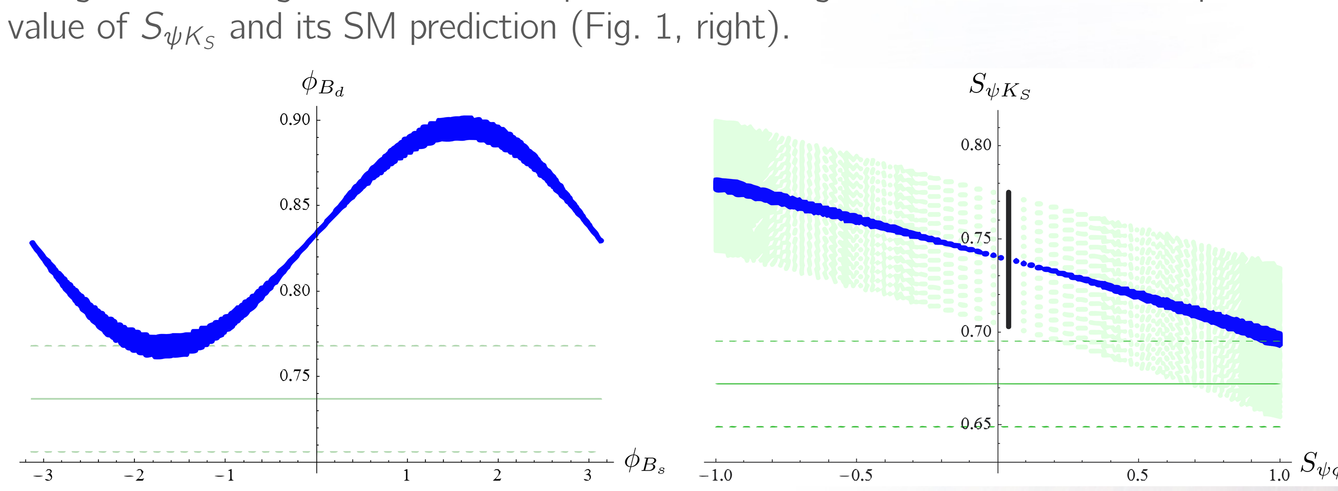

Figure 1: (Left) Correlation between the phases of B_d and B_s mixing. The blue points have been obtained with the CKM phase β fixed to its central value ($\sin(2\beta) = 0.739$): the spread is determined only by the requirement of a deviation of ΔM_s within 10% of its SM value. The horizontal lines indicate the $\pm1\sigma$ range of $\phi_{B_s}^{\text{exp}}$. (Right) Correlation between $S_{\psi K_S}$ and $S_{\psi\phi}$. The meaning of the blue points and the horizontal lines is the same as before; the $\pm1\sigma$ error due to the uncertainty in the extraction of β (light points) and the SM prediction (black vertical line) are also shown.

Due to the $m_s m_d$ factor in $\mathcal{H}^{|\Delta S|=2}$, the new physics contribution to ϵ_K is tiny and does not improve alone the agreement between data and prediction for ϵ_K. However, given the modified relation between $S_{\psi K_S}$ and the CKM phase β, the true value of β extracted in this scenario increases with respect to SM fits. As a result of this modified value of β, also the predicted value for ϵ_K increases with respect to the SM case, resulting in a better agreement with data (Fig. 2, left).

Finally, we present a prediction in the rare decays $B_{d,s}\to\mu^+\mu^-$ that could provide the ultimate and decisive test about magnitude and flavour structure of Higgs-mediated FCNC amplitudes. In fact, due to the structure of $\mathcal{H}^{|\Delta B|=2}$ in the frame of the 2HDM with MFV, the branching ratio of the transitions $B_d\to\mu^+\mu^-$ and $B_s\to\mu^+\mu^-$ are strongly correlated (Fig. 2, right).

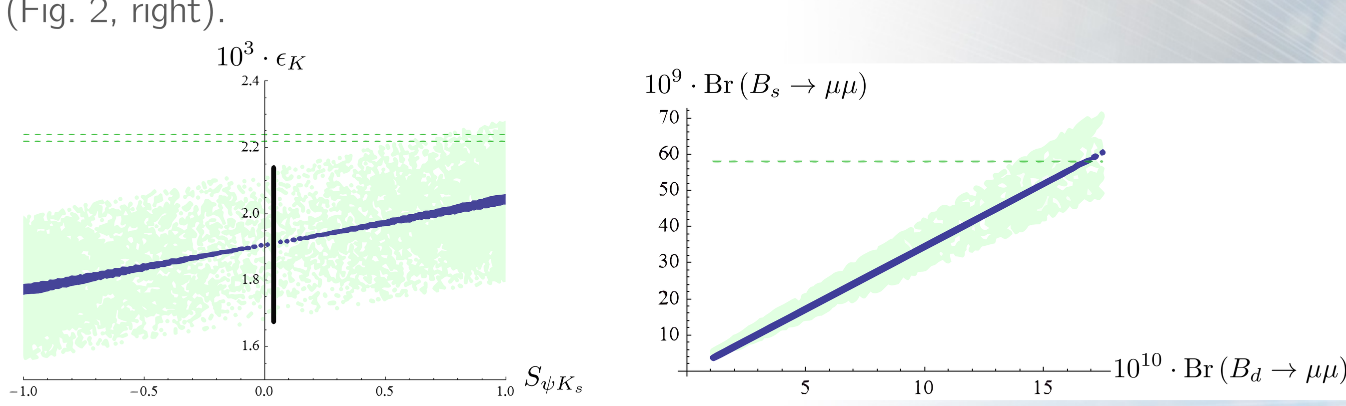

Figure 2: (Left) Correlation between ϵ_K and $S_{\psi K_S}$. Notations as before. (Right) Correlation between $\text{Br}(B_s\to\mu^+\mu^-)$ and $\text{Br}(B_d\to\mu^+\mu^-)$ in presence of scalar amplitudes respecting the MFV hypothesis. The horizontal dotted line represent the present experimental limit on $\text{Br}(B_s\to\mu^+\mu^-)$.

Conclusions

In this work we have compared the effectiveness of two different mechanisms in suppressing the FCNCs in the models with two Higgs doublet. We have demonstrated that the suppression obtained by NFC principle, based on the protection of flavour-blind symmetries, is not stable under quantum corrections, while the protection of the flavour symmetry breaking guaranteed by the MFV hypothesis provides a renormalization group invariant efficient structure. Moreover, we have shown that allowing the presence of flavour-blind CP-violating phases in the Higgs sector of a 2HDM with MFV we can solve the problems recently found in the $\Delta F = 2$ down-type transition, namely the large phase in the B_s mixing and the $\epsilon_K - S_{\psi K_S}$ tension in the CKM fit.

References

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