Flavour Violation in a Class of two Higgs-Doublet Models

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We examine flavour violation in a class of two Higgs-Doublet models where there are FCNC at tree level, but naturally suppressed by a symmetry introduced at tree level. We examine how these class of models can satisfy the stringent constraints from experiment and discuss the prospects for discovering some of the flavour changing Higgs decays in the second run of the LHC at 13TeV.

1 Introduction

Higgs Flavour Violating Neutral Couplings (HFVNC) arise in Two Higgs Doublet Models (2HDM) [1] as well as in other extensions of the SM. There are very stringent experimental constraints on Flavour-Changing-Neutral-Currents (FCNC), so in order to be plausible, models with FCNC have to contain a mechanism to naturally suppress these couplings. In this talk, we analysed BGL models [2] which were suggested for the quark sector but then generalised [3] and extended to the lepton sector [4]. In the 2HDM there are in general three neutral scalars, in the Higgs basis they are denoted H^0, R and I, with H^0 having flavour diagonal couplings in the fermion eigenstate basis. On the contrary, R and I have HFVNC with a flavour structure which in general is arbitrary. The key feature of BGL models is the fact that the HFVNC of R and I are completely fixed in terms of V_{CKM} and U_{PMNS} matrix elements. Apart from the ratio $v2/v1 = \tan(\beta)$, no other free parameters are introduced. This is achieved in a natural way through the introduction of a discrete symmetry at the Lagrangian level. Therefore, BGL models and their flavour structure are stable under renormalisation. Apart from restricting the flavour structure of the Yukawa couplings, the symmetry also restricts the scalar potential in such a way that CP is not violated in the scalar sector, either explicitly or spontaneously. As a result, the pseudo-scalar field I and the charged scalars are physical fields, while the two other two neutral physical fields can be expressed in terms of H^0 and R through a single rotation.

Under the assumption that the Higgs particle discovered at LHC can be identified with H^0, we have studied in detail the experimental restrictions on BGL models, determining the mass ranges allowed for the new scalars [5]. In particular, we have shown that in some of the BGL models the masses of the scalar masses can be in the range of a few hundred GeV, therefore within the reach of LHC-13TeV.

2 Yukawa Interactions in BGL Models

The Yukawa interactions in two Higgs doublet models can be written :

$$\begin{aligned}\mathcal{L}_Y &= -\overline{Q_L^0}\,\Gamma_1\Phi_1 d_R^0 - \overline{Q_L^0}\,\Gamma_2\Phi_2 d_R^0 - \overline{Q_L^0}\,\Delta_1\tilde{\Phi}_1 u_R^0 - \overline{Q_L^0}\,\Delta_2\tilde{\Phi}_2 u_R^0 \\ &\quad -\overline{L_L^0}\,\Pi_1\Phi_1 l_R^0 - \overline{L_L^0}\,\Pi_2\Phi_2 l_R^0 - \overline{L_L^0}\,\Sigma_1\tilde{\Phi}_1\nu_R^0 - \overline{L_L^0}\,\Sigma_2\tilde{\Phi}_2\nu_R^0 + \text{h.c.},\end{aligned} \tag{1}$$

where Γ_i, Δ_i Π_i and Σ_i are matrices in flavour space. In order for the tree level FCNC to depend only on V_{CKM} , a flavour symmetry has to be introduced. Such a symmetry was introduced by Branco, Grimus and Lavoura [2], under which the fields transform in the following way:

$$Q_{Lj}^0 \to \exp(i\tau)\, Q_{Lj}^0\,, \qquad u_{Rj}^0 \to \exp(i2\tau) u_{Rj}^0\,, \qquad \Phi_2 \to \exp(i\tau)\Phi_2\,, \tag{2}$$

where $\tau \neq 0, \pi$ while all other quark field transform trivially under the symmetry. The family index j can be chosen to be 1, 2, 3. One could also choose the d_R to transform non-trivially under the symmetry:

$$Q_{Lj}^0 \to \exp(i\tau)\, Q_{Lj}^0\,, \qquad d_{Rj}^0 \to \exp(i2\tau) d_{Rj}^0\,, \quad \Phi_2 \to \exp(-i\tau)\Phi_2\,. \tag{3}$$

The symmetry of Eq. 2 leads to FCNC in the down sector, while the symmetry of Eq.3 leads to FCNC in the up sector. Taking into account the three possible choices for the index j, one has six different BGL type models in the quark sector. One encounters an entirely analogous situation in the lepton sector if one also includes Dirac mass terms for the neutrinos, so one has altogether thirty six different BGL models. Of course, in the leptonic sector FCNC are controlled by the U_{PMNS} matrix elements.

In order to analyse the physical implications of the three neutral scalars, it is useful to expand the neutral scalar field around their vevs $\phi_j^0 = \frac{1}{\sqrt{2}}(v_j + \rho_j + i\eta_j)$ and define the two following rotations:

$$\begin{pmatrix} H^0 \\ R \end{pmatrix} \equiv \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}; \qquad \begin{pmatrix} H \\ h \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} \tag{4}$$

where $\tan(\beta) = v2/v1$. It is useful to write the Yukawa couplings in terms of the quark mass-eigenstates and the scalar fields in the Higgs basis :

$$\begin{aligned}\mathcal{L}_Y(\text{quark, Higgs}) &= -\frac{\sqrt{2}H^+}{v}\bar{u}\left(VN_d\gamma_R - N_u^\dagger\, V\gamma_L\right)d + \text{h.c.} - \\ -\frac{H^0}{v}\left(\bar{u}D_u u + \bar{d}D_d\, d\right) &- \frac{R}{v}\left[\bar{u}(N_u\gamma_R + N_u^\dagger\gamma_L)u + \bar{d}(N_d\gamma_R + N_d^\dagger\gamma_L)\, d\right] + \\ &+ i\frac{I}{v}\left[\bar{u}(N_u\gamma_R - N_u^\dagger\gamma_L)u - \bar{d}(N_d\gamma_R - N_d^\dagger\gamma_L)\, d\right]\end{aligned} \tag{5}$$

The matrices N_d, N_u, fix the flavour structure of the the scalar couplings to fermions. In the BGL models with HFCNC in the down sector, N_d, N_u are given by:

$$(N_d)_{rs}(\text{up-type}) = \frac{v_2}{v_1}(D_d)_{rs} - \left(\frac{v_2}{v_1} + \frac{v_1}{v_2}\right)(V_{CKM}^\dagger)_{rj}(V_{CKM})_{js}(D_d)_{ss} \tag{6}$$

Note that no sum in j is implied. Particularising for the case $j = 3$, one has:

$$N_u(\text{up-type}) = -\frac{v_1}{v_2}\text{diag}\,(0, 0, m_t) + \frac{v_2}{v_1}\text{diag}\,(m_u, m_c, 0) \tag{7}$$

Entirely analogous equations hold for the case of BGL models with FCNC in the up sector.

3 Brief Discussion of Phenomenological Implications

Like any multi-Higgs extension of the SM, BGL models have to satisfy the stringent constraints of low energy phenomenology. A thorough analysis of the thirty six BGL models was done in [5] in the limit where the discovered scalar particle is identified with H^0. We imposed the present experimental constraints arising from various relevant flavour observables such as neutral meson mixings, $B \to X_s\gamma$, $l_j \to l_i\gamma$, as well as electroweak precision data. It was verified that in some of BGL models all phenomenological constraints are satisfied even for scalar masses of order a few hundred GeV, at the reach of the next round of LHC at 13TeV. Some of the BGL models allow for charged Higgs masses lower than 480 GeV which is the constraint derived from $b \to s\gamma$ on type II 2HDM [6] This results from the different dependence that these models have on $\tan(\beta)$

The fact that in some of the BGL models the masses of the neutral scalars may be relatively light in spite of the presence of FCNC, is due to the automatic suppression by small V_{CKM} elements. For example, in the case of up-type models, with $j = 3$, one can see from Eq. (6) that the tree-level neutral Higgs contribution to $K^0 - \overline{K^0}$ transition has an automatic suppression of $|V_{td}V_{ts}|^2$, which is a suppression of order λ^{10} in the amplitude where lambda stands for the Cabibbo parameter.

In the context of BGL models, there is the possibility that the Higgs particle h discovered at LHC is a mixture of H^0 and R parametrised by the angle $(\beta - \alpha)$. There are then HFVNC of h which depend on $\tan(\beta)$ and $\sin(\beta - \alpha)$. An important task is to find a region in the $\sin(\beta - \alpha)$ versus $\tan(\beta)$ plane where rare processes like $t \to ch$ and $h \to \mu\tau$ can occur at a rate sufficient to discover at LHC-13 TeV [7].

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