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Phenomenological prospects for two Higgs doublet models with controlled FCNC

Miguel Nebot¹

¹ Centro de Física Teórica de Partículas (CFTP),
Instituto Superior Técnico (IST), U. de Lisboa (UL),
Av. Rovisco Pais, P-1049-001 Lisboa, Portugal.

E-mail: miguel.r.nebot.gomez@tecnico.ulisboa.pt

Abstract. Flavour changing processes like $t \rightarrow hu, hc$, $h \rightarrow \tau e, \tau \mu$ as well as hadronic decays $h \rightarrow bs, bd$, are analysed within a class of two Higgs doublet models where flavour changing neutral scalar currents at tree level are present. The most remarkable characteristic of this class of models is that the flavour-violating couplings are entirely determined by the fermion masses, the ratio of vacuum expectation values $\tan \beta$ and the CKM and PMNS matrices. The flavour structure of the scalar currents results from a symmetry of the Lagrangian and consequently it is natural and stable under the renormalization group evolution. We show that, in some of the models, the rates of the mentioned flavour changing processes can reach values at the discovery level for the LHC operating at 13 TeV, even taking into account stringent bounds on low energy processes.

1. Introduction

The second run of the Large Hadron Collider (LHC), with a center of mass energy $\sqrt{s} = 13$ TeV, is starting to probe the flavour changing couplings of the 125 GeV scalar boson h [1, 2]. These couplings can contribute to rare top decays like $t \rightarrow hq$ ($q = u, c$) and may lead as well to (a) flavour changing leptonic decays such as $h \rightarrow \tau^\pm \ell^\mp$, ($\ell = \mu, e$), and (b) flavour changing hadronic decays like $h \rightarrow bs$ and $h \rightarrow bd$. In the Standard Model (SM) these decays are highly suppressed since the required couplings vanish at tree level. However, Higgs Flavour Violating Neutral Couplings (HFVNC) can arise in many extensions of the SM, including in particular the Two Higgs Doublet Models (2HDM) [3–5]. Any extension of the SM featuring HFVNC has to comply with strict experimental limits on processes mediated by flavour changing neutral currents (FCNC) as well as with the constraints on CP violating transitions producing, for example, electric dipole moments of quarks and leptons [6].

We analyse the allowed size of HFVNC in a class of 2HDM, denoted BGL models, which was first proposed for the quark sector [7], and then generalised [8] and extended to the leptonic sector [9]. BGL models have the remarkable property of having HFVNC with a flavour structure entirely determined by the Cabibbo-Kobayashi-Maskawa (CKM) and the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrices, denoted V and U respectively, in addition to fermion masses and the ratio of vacuum expectation values $\tan \beta$ of the two scalar doublets. HFVNC have been widely addressed in the literature [10–28]. The distinctive feature in BGL models is the natural suppression of many of the most dangerous HFVNC through combinations of small mixing matrix elements and/or light fermion masses. This is a consequence of the introduction of



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a symmetry in the Lagrangian and hence the suppression is entirely natural. Another important characteristic of BGL models is that, depending on the specific type model model within this class, HFVNC exist either in the up or in the down sector, but not in both sectors simultaneously; analogous considerations apply to the leptons. A generalisation of BGL models which includes FCNC in both the up and the down sectors at the cost of few extra parameters has been recently proposed in [29]. In the general 2HDM there are three neutral scalars in the so-called Higgs basis [30–32], H^0 , R^0 and A . The couplings of H^0 to fermions in the fermion mass eigenstate basis are flavour diagonal. On the other hand R^0 and A have HFVNC with an arbitrary structure. BGL models are remarkable because the flavour structure of HFVNC is limited to depend on V and U . The neutral scalar mass eigenstates are then linear combinations of H^0 and R^0 together with the pseudoscalar neutral field A . In these models, the symmetry constrains the scalar potential not to violate CP either explicitly or spontaneously, therefore rotating (with angle β) the fields from the symmetry basis to the Higgs basis, makes the charged fields and the pseudoscalar field A already physical fields. It also results in the two other neutral physical fields being related to H^0 and R^0 through a single angle rotation.

Previous work [33] gave a detailed analysis of the allowed mass ranges for the new scalars under the assumption that the discovered Higgs h could be identified with H^0 . In some of the BGL models these masses can be in the range of a few hundred GeV and thus within reach of searches at the LHC running at 13 TeV. The present analysis [34] addresses the general case where h is a mixture of H^0 and R^0 , which is determined by an angle denoted $\beta - \alpha$. The intensity of the HFVNC of h depends crucially on $\tan \beta \equiv v_2/v_1$, with v_i the vacuum expectation values of the scalar doublets, and $\cos(\beta - \alpha)$. BGL models share some features with implementations of the minimal flavour violation hypothesis (MFV) [16, 35–37]. Nevertheless it is important to stress that BGL models have the unique property of coming from a symmetry, which produces a reduced number of free parameters, allowing for definite predictions once constraints on these parameters given by present experimental bounds are considered.

One can summarise the challenge with the following question: can one have regions in the $\tan \beta$ versus $\alpha - \beta$ plane, where, in some of the BGL models, the HFVNC of h can give rates for the rare processes $t \rightarrow hq$, $h \rightarrow \mu\tau$ consistent with discovery at LHC-13 TeV? Of course, these scenarios have to be consistent with the stringent constraints on all Standard Model (SM) processes associated to the Higgs production through different mechanisms (e.g. gluon-gluon fusion, vector boson fusion, Higgs-strahlung) and its subsequent decays into ZZ , WW , $\gamma\gamma$, $b\bar{b}$ and $\tau\bar{\tau}$. In addition, constraints from low energy phenomenology have to be considered: those obtained in [33] and also the new ones due to the presence of a mixing H^0 - R^0 . Although processes such as $h \rightarrow bs$ and $h \rightarrow bd$ are probably out of reach of the LHC, they may become important for the physics of the future Linear Collider, and thus they are also included in the analysis.

The discussion is organised in the following manner. In the next section we review BGL models and set the notation. In Section 3 we analyse top flavour changing decays $t \rightarrow hq$ ($q = u, c$) in BGL models with HFVNC in the up quark sector. Flavour changing decays of the Higgs are addressed in Section 4. We consider in particular neutrino models with HFVNC in the charged lepton sector giving rise to $h \rightarrow \ell\tau$ decays. Up type BGL models, with HFVNC in the down quark sector, are also considered since they give rise to $h \rightarrow bs$, $h \rightarrow bd$ decays. In Section 5 we discuss some aspects of the analysis and investigate the discovery regions and the existing correlations among the decays of interest.

2. BGL Models

The quark Yukawa interactions in the context of 2HDM can be written as:

$$\begin{aligned} \mathcal{L}_Y = & -\bar{Q}_L^0 [\Gamma_1 \Phi_1 + \Gamma_2 \Phi_2] d_R^0 - \bar{Q}_L^0 [\Delta_1 \tilde{\Phi}_1 + \Delta_2 \tilde{\Phi}_2] u_R^0 \\ & - \bar{L}_L^0 [\Pi_1 \Phi_1 + \Pi_2 \Phi_2] l_R^0 - \bar{L}_L^0 [\Sigma_1 \tilde{\Phi}_1 + \Sigma_2 \tilde{\Phi}_2] \nu_R^0 + \text{h.c.}, \end{aligned} \quad (1)$$

where Γ_i , Δ_i , Π_i and Σ_i are matrices in flavour space. The requirement that Γ_i , Δ_i lead to tree level FCNC with strength completely controlled by the Cabibbo-Kobayashi-Maskawa matrix V , was achieved by Branco, Grimus and Lavoura (BGL) [7] through a symmetry of the Lagrangian of the form:

$$Q_{Lj}^0 \mapsto \exp(i\tau) Q_{Lj}^0, \quad u_{Rj}^0 \mapsto \exp(i2\tau) u_{Rj}^0, \quad \Phi_2 \mapsto \exp(i\tau) \Phi_2, \quad (2)$$

where $\tau \neq 0, \pi$, with all other quark fields transforming trivially. The index j can be fixed as either 1, 2 or 3. Alternatively, the symmetry can be chosen as:

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

Equation (2) leads to Higgs FCNC in the down sector, whereas the symmetry of eq. (3) leads to Higgs FCNC in the up sector. These two alternative choices combined with the three possible elections of the index j give rise to six different realizations of 2HDM with the flavour structure, in the quark sector, controlled by the V matrix. Up-type BGL models are those with HFVNC in the down sector, defined by the symmetry imposed through eq. (2); each one of the three implementations is labelled u-type, c-type or t-type depending on the value of the index j , respectively 1, 2 or 3. Likewise for the down-type models. In the leptonic sector, with Dirac neutrinos, there is perfect analogy with the quark sector, and the corresponding symmetry applied to the leptonic fields leads to six different realizations with the strength of Higgs mediated flavour changing neutral currents now controlled by the Pontecorvo-Maki-Nakagawa-Sakata matrix, U . This results in thirty six different implementations of BGL models. However, as shown in [9], in the case of Majorana neutrinos, there are only 18 models corresponding to the neutrino types, and therefore with HFVNC in the charged lepton sector.

The discrete symmetry of Eqs. (2) or (3) constrains the Higgs potential to be of the form:

$$V = \mu_1 \Phi_1^\dagger \Phi_1 + \mu_2 \Phi_2^\dagger \Phi_2 - m_{12} (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1) + 2\lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + 2\lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \lambda_1 (\Phi_1^\dagger \Phi_1)^2 + \lambda_2 (\Phi_2^\dagger \Phi_2)^2. \quad (4)$$

The term in m_{12} is a soft symmetry breaking term; its introduction prevents the appearance of an would-be Goldstone boson due to the continuous global symmetry of the potential which arises when the BGL symmetry is exact. Since such a potential cannot violate CP either explicitly or spontaneously, the scalar and pseudoscalar neutral fields do not mix among themselves and there are only two important rotation angles, β and α . The angle β parametrises the rotation to the Higgs basis, singling out the three neutral fields: H^0 , with couplings to the quarks proportional to mass matrices, R^0 which is a neutral scalar and A which is a neutral pseudoscalar (in addition the physical charged Higgs fields H^\pm and the pseudo-Goldstone bosons). In BGL models, A and H^\pm are already physical fields, while H^0 and R^0 may still mix. In the limit in which H^0 does not mix with R^0 , H^0 is identified with the Higgs field h discovered by ATLAS [1] and CMS [2]. In this limit, H^0 does not mediate tree level flavour changes; α is defined in such a way that the mixing angle between these fields, $(\beta - \alpha)$, acquires the value $\pi/2$ in that case. Expanding around the vacuum expectation values of the neutral fields [38], $\phi_j^0 = \frac{1}{\sqrt{2}}(v_j + \rho_j + i\eta_j)$, we can write:

$$\begin{pmatrix} H^0 \\ R^0 \end{pmatrix} \equiv \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}, \quad \begin{pmatrix} H \\ h \end{pmatrix} \equiv \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}. \quad (5)$$

The angle β is given by $\tan \beta \equiv v_2/v_1$; we use in the following the shorthand notation $\tan \beta \equiv t_\beta$, $\cos(\beta - \alpha) \equiv c_{\beta\alpha}$ and $\sin(\beta - \alpha) \equiv s_{\beta\alpha}$.

In terms of quark mass eigenstates and the scalar fields in the Higgs basis, the Yukawa couplings are:

$$\begin{aligned} \mathcal{L}_{\text{Yuk}} = & -\frac{\sqrt{2} H^+}{v} \bar{u} \left[V N_d \gamma_R - N_u^\dagger V \gamma_L \right] d + \text{h.c.} \\ & - \frac{H^0}{v} \left[\bar{u} D_u u + \bar{d} D_d d \right] \\ & - \frac{R^0}{v} \left[\bar{u} (N_u \gamma_R + N_u^\dagger \gamma_L) u + \bar{d} (N_d \gamma_R + N_d^\dagger \gamma_L) d \right] \\ & + i \frac{A}{v} \left[\bar{u} (N_u \gamma_R - N_u^\dagger \gamma_L) u - \bar{d} (N_d \gamma_R - N_d^\dagger \gamma_L) d \right] \end{aligned} \quad (6)$$

with γ_L and γ_R the left-handed and right-handed chirality projectors, and D_d and D_u are the diagonal mass matrices for down and up quarks, respectively. Equation (6) defines N_d and N_u , the matrices which give the flavour structure and strength of FCNC. In general 2HDM, N_d and N_u are entirely arbitrary. On the contrary, BGL models have the remarkable feature of having N_d and N_u entirely determined by fermion masses, V and the angle β , with no other free parameters. In BGL up-type models the matrices N_d has the simple form:

$$(N_d^{(u_j)})_{rs} = \left[t_\beta \delta_{rs} - (t_\beta + t_\beta^{-1}) V_{jr}^* V_{js} \right] (D_d)_{ss}, \quad (7)$$

with no sum in j implied. The upper index (u_j) indicates that labels a symmetry of the form in eq. (2), i.e. an up-type model with index j leading to FCNC in the down-sector. All FCNC are proportional to the factor $(t_\beta + t_\beta^{-1})$, multiplying products of entries involving one single row of V . The corresponding N_u matrix is:

$$(N_u^{(u_j)})_{rs} = \left[t_\beta - (t_\beta + t_\beta^{-1}) \delta_{rj} \right] (D_u)_{ss} \delta_{rs}. \quad (8)$$

N_u is a diagonal matrix and the t_β dependence is not the same for each diagonal entry: it is proportional to $-t_\beta^{-1}$ for the (jj) element and to t_β for all other elements. The index j fixes the row of the V matrix which suppresses the flavour changing neutral currents in eq. (7). For down-type models, which correspond to the symmetry in eq. (3), the rôles of N_d and N_u are exchanged:

$$(N_u^{(d_j)})_{rs} = \left[t_\beta \delta_{rs} - (t_\beta + t_\beta^{-1}) V_{rj} V_{sj}^* \right] (D_u)_{ss}, \quad (9)$$

$$(N_d^{(d_j)})_{rs} = \left[t_\beta - (t_\beta + t_\beta^{-1}) \delta_{rj} \right] (D_d)_{ss} \delta_{rs}. \quad (10)$$

The flavour changing neutral currents are suppressed, in down-type models, by the columns of the V matrix.

The next ingredient is to allow for the possibility of h being a linear combination of H^0 and R^0 ; this is parametrised by the angle $(\beta - \alpha)$:

$$h = s_{\beta\alpha} H^0 + c_{\beta\alpha} R^0, \quad H = c_{\beta\alpha} H^0 - s_{\beta\alpha} R^0. \quad (11)$$

This mixing will be constrained by data from the LHC observables concerning “the Higgs” (see section 5). The quark Yukawa couplings of h can be written as

$$\mathcal{L}_{hq\bar{q}} = -Y_{ij}^D \bar{d}_{Li} d_{Rj} h - Y_{ij}^U \bar{u}_{Li} u_{Rj} h + \text{h.c.}, \quad (12)$$

and similarly for the leptonic sector with the coefficients denoted by Y_{ij}^ℓ and Y_{ij}^ν . From Eqs. (6) and (11), one can read:

$$\begin{aligned} Y_{ij}^D &= \frac{1}{v} \left[s_{\beta\alpha} (D_d)_{ij} + c_{\beta\alpha} (N_d)_{ij} \right] \\ Y_{ij}^U &= \frac{1}{v} \left[s_{\beta\alpha} (D_u)_{ij} + c_{\beta\alpha} (N_u)_{ij} \right] \end{aligned} \quad (13)$$

Explicitely, for $i \neq j$, we have the following flavour violating Yukawa couplings in the different types of BGL models¹:

(i) up-type u_k model, k fixed as 1 (u) or 2 (c) or 3 (t), with HFVNC in the down quark sector:

$$Y_{ij}^D(u_k) = -V_{ki}^* V_{kj} \frac{m_{d_j}}{v} c_{\beta\alpha}(t_\beta + t_\beta^{-1}), \quad i \neq j, \text{ no sum in } k, \quad (14)$$

(ii) down-type d_k model, k fixed as 1 (d) or 2 (s) or 3 (b), with HFVNC in the up quark sector:

$$Y_{ij}^U(d_k) = -V_{ik} V_{jk}^* \frac{m_{u_j}}{v} c_{\beta\alpha}(t_\beta + t_\beta^{-1}), \quad i \neq j, \text{ no sum in } k, \quad (15)$$

(iii) leptonic sector, neutrino-type, ν_k model, k fixed as 1 (ν_1) or 2 (ν_2) or 3 (ν_3), with HFVNC in the charged lepton sector:

$$Y_{ij}^\ell(\nu_k) = -U_{ik} U_{jk}^* \frac{m_{l_j}}{v} c_{\beta\alpha}(t_\beta + t_\beta^{-1}), \quad i \neq j, \text{ no sum in } k. \quad (16)$$

For Dirac neutrinos one can write similar expressions for charged lepton type models, but in this case FCNC appear in the neutrino sector and are suppressed by the extremely small neutrino masses.

3. Flavour changing decays of top quarks

We analyse now flavour changing decays of top quarks $t \rightarrow hq$. According to eqs. (13) and (15), the couplings of h with a top t and a u or c quark, in a model of type d_ρ , are

$$Y_{qt}^U(d_\rho) = -V_{q\rho} V_{t\rho}^* \frac{m_t}{v} c_{\beta\alpha}(t_\beta + t_\beta^{-1}), \quad q = u, c. \quad (17)$$

The corresponding $t \rightarrow hq$ decay rate is

$$\Gamma_{(d_\rho)}(t \rightarrow hq) = \frac{m_t^3}{32\pi v^2} \left(1 - \frac{m_h^2}{m_t^2} \right)^2 |V_{q\rho}|^2 |V_{t\rho}|^2 c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2. \quad (18)$$

Apart from the global factor $c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$, every other factor in eq. (18) is fixed once the specific down-type model d_ρ and the decay channel $t \rightarrow hc$ or $t \rightarrow hu$ are chosen. Consequently, for a given model, $t \rightarrow hq$ processes constrain the factor $c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$. The branching ratio for $t \rightarrow hq$ in the d_ρ type model is

$$\text{Br}_{(d_\rho)}(t \rightarrow hq) = \frac{\Gamma_{(d_\rho)}(t \rightarrow hq)}{\Gamma(t \rightarrow Wb)} = f(x_h, y_W) \frac{|V_{q\rho} V_{t\rho}|^2}{|V_{tb}|^2} c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2, \quad (19)$$

where

$$f(x_h, y_W) = \frac{1}{2} (1 - x_h)^2 (1 - 3y_W^2 + 2y_W^3)^{-1}, \quad \text{with } x_h = \frac{m_h^2}{m_t^2}, \quad y_W = \frac{M_W^2}{m_t^2}. \quad (20)$$

Table 1. V factors in eq. (18), $\lambda \simeq 0.22$ [39, 40].

Model	$t \rightarrow hu$	$t \rightarrow hc$
d	$ V_{ud}V_{td} ^2 (\sim \lambda^6) = 7.51 \cdot 10^{-5}$	$ V_{cd}V_{td} ^2 (\sim \lambda^8) = 4.01 \cdot 10^{-6}$
s	$ V_{us}V_{ts} ^2 (\sim \lambda^6) = 8.20 \cdot 10^{-5}$	$ V_{cs}V_{ts} ^2 (\sim \lambda^4) = 1.53 \cdot 10^{-3}$
b	$ V_{ub}V_{tb} ^2 (\sim \lambda^6) = 1.40 \cdot 10^{-5}$	$ V_{cb}V_{tb} ^2 (\sim \lambda^4) = 1.68 \cdot 10^{-3}$

Using the top quark pole mass $m_t = 173.3$ GeV [39], $m_h = 125.0$ GeV and $M_W = 80.385$ GeV, one obtains $f(x_h, y_W) = 0.1306$. Table 1 shows the V factors involved in different decay channels and models. The most interesting models for $t \rightarrow hc$ are the s and b models, where the suppression is only at the λ^4 level, compared to the d model which has a strong suppression, at the λ^8 level, for the same decay. The d model has the curiosity that the suppression is higher for $t \rightarrow hc$ than for $t \rightarrow hu$, unlike in the s and b models. Now, considering the upper bounds 0.79% from the ATLAS [41] and 0.56% from the CMS [42, 43] collaborations, we have, for b and s -type models,

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| \lesssim 4.9. \quad (21)$$

Notice that, for this value, perturbative unitarity constraints from the scalar sector have to be considered (see [34]).

4. Flavour changing Higgs decays

4.1. The decays $h \rightarrow \ell\tau$ ($\ell = \mu, e$)

For leptonic HFVNC, the most interesting BGL models are the ν models. As with quarks, there are three neutrino-type BGL models, depending on the column of the U matrix involved in leptonic FCNC. With notation analogous to the one of the quark sector and considering eq. (16) for the coupling of h to μ and τ ,

$$Y_{\mu\tau}^\ell(\nu_\rho) = \frac{1}{v} c_{\beta\alpha} (N_\ell^{(\nu_\sigma)})_{\mu\tau} = -c_{\beta\alpha}(t_\beta + t_\beta^{-1}) U_{\mu\sigma} U_{\tau\sigma}^* \frac{m_\tau}{v}, \quad (22)$$

and the decay rate is

$$\Gamma_{(\nu_\sigma)}(h \rightarrow \mu\bar{\tau}) + \Gamma_{(\nu_\sigma)}(h \rightarrow \bar{\mu}\tau) = c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 |U_{\mu\sigma} U_{\tau\sigma}|^2 \Gamma_{\text{SM}}(h \rightarrow \tau\bar{\tau}), \quad (23)$$

with $\Gamma_{\text{SM}}(h \rightarrow \tau\bar{\tau}) = \frac{m_h}{8\pi} \frac{m_\tau^2}{v^2}$. Notice, again, the appearance of the same factor $c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$. Table 2 lists the PMNS mixing matrix factors for the different ν - type models. The first direct search for lepton-flavour-violating decays of the observed Higgs boson performed by the CMS collaboration [44], led to the observation of a slight excess of signal events, with a significance of 2.4 standard deviations. The best fit value is:

$$\text{Br}(h \rightarrow \mu\bar{\tau} + \tau\bar{\mu}) = (0.84^{+0.39}_{-0.37}) \%, \quad (24)$$

which sets a constraint on the branching fraction $\text{Br}(h \rightarrow \mu\bar{\tau} + \tau\bar{\mu}) < 1.51\%$ at the 95% confidence level. The ATLAS collaboration presented a result based on hadronic τ decays [45], giving $\text{Br}(h \rightarrow \mu\bar{\tau} + \tau\bar{\mu}) = (0.77 \pm 0.62)\%$. While analyses at 8 TeV have been extended to

¹ These couplings, as well as the diagonal ones, can be extracted from equations (7) – (10) making, where necessary, the corresponding changes of quarks by leptons.

Table 2. U factors in eq. (23); estimates, e.g. $1/9$, $1/36$, correspond to a tri-bimaximal U (except for $|U_{e3}|$, of course); analogous information for $h \rightarrow e\mu$ and $h \rightarrow e\tau$ decays is included.

Model	$h \rightarrow e\mu$	$h \rightarrow e\tau$	$h \rightarrow \mu\tau$
ν_1	$ U_{e1}U_{\mu 1} ^2 (\sim \frac{1}{9}) = 0.105$	$ U_{e1}U_{\tau 1} ^2 (\sim \frac{1}{9}) = 0.118$	$ U_{\mu 1}U_{\tau 1} ^2 (\sim \frac{1}{36}) = 0.028$
ν_2	$ U_{e2}U_{\mu 2} ^2 (\sim \frac{1}{9}) = 0.089$	$ U_{e2}U_{\tau 2} ^2 (\sim \frac{1}{9}) = 0.126$	$ U_{\mu 2}U_{\tau 2} ^2 (\sim \frac{1}{9}) = 0.115$
ν_3	$ U_{e3}U_{\mu 3} ^2 = 0.0128$	$ U_{e3}U_{\tau 3} ^2 = 0.0097$	$ U_{\mu 3}U_{\tau 3} ^2 (\sim \frac{1}{4}) = 0.234$

additional channels [46, 47], results at 13 TeV are yet unclear [48]. Assuming the h width to be $\Gamma_h \simeq \Gamma_h^{[\text{SM}]} (= 4.03 \text{ MeV})$, one can use the SM branching ratio $\text{Br}_{\text{SM}}(h \rightarrow \tau\bar{\tau}) = 0.0637$ in eq. (23), and obtain the estimate

$$|c_{\beta\alpha}(t_\beta + t_\beta^{-1})| \sim 1, \quad (25)$$

necessary to produce $\text{Br}(h \rightarrow \mu\bar{\tau} + \tau\bar{\mu})$ of order 10^{-2} .

4.2. The flavour changing decays $h \rightarrow bq$ ($q = s, d$)

We now address FCNC in the down sector. The most promising experimental signatures correspond to $h \rightarrow bq$ decays, with $q = s, d$. The relevant h couplings to down quarks in eq. (12) are, according to eq. (14):

$$Y_{qb}^D(u_k) = -c_{\beta\alpha}(t_\beta + t_\beta^{-1}) V_{kq}^* V_{kb} \frac{m_b}{v}, \quad q \neq b, \text{ no sum in } k. \quad (26)$$

Once again, it should be emphasised that once the up-type model u_k is chosen, the strength of the flavour changing couplings only depends on the combination $c_{\beta\alpha}(t_\beta + t_\beta^{-1})$ together with the down quark masses and V factors which are already known. The decay rate of h to pairs of quarks $q_i q_j$ ($i \neq j$) is

$$\Gamma_{(u_k)}(h \rightarrow \bar{q}_i q_j + q_i \bar{q}_j) = \frac{3 m_h}{8\pi} \left[\frac{1}{2} |Y_{ij}|^2 + \frac{1}{2} |Y_{ji}|^2 \right], \quad (27)$$

and thus

$$\Gamma_{(u_k)}(h \rightarrow \bar{b}q + b\bar{q}) = c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 |V_{kq}|^2 |V_{kb}|^2 \Gamma_{\text{SM}}(h \rightarrow b\bar{b}). \quad (28)$$

With $\Gamma_h \simeq \Gamma_h^{[\text{SM}]}$, one can make the following estimate

$$\text{Br}_{(u_k)}(h \rightarrow \bar{b}q + b\bar{q}) = c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 |V_{kq}|^2 |V_{kb}|^2 \text{Br}_{\text{SM}}(h \rightarrow b\bar{b}), \quad (29)$$

where $\text{Br}_{\text{SM}}(h \rightarrow b\bar{b}) = 0.578$. The relevant CKM factors for $h \rightarrow bs$ and $h \rightarrow bd$ in u_k BGL models are given in Table 3.

To a good approximation we have

- in models c and t , $\text{Br}(h \rightarrow \bar{b}s + b\bar{s}) \sim c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 \lambda^4 \sim 10^{-3} c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$,
- in model u , $\text{Br}(h \rightarrow \bar{b}s + b\bar{s}) \sim c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 \lambda^8 \sim 10^{-7} c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$,
- in all u , c and t models, $\text{Br}(h \rightarrow \bar{b}d + b\bar{d}) \sim c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2 \lambda^6 \sim 10^{-5} c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$.

We stress that, a priori, in models without the $h \rightarrow \mu\tau$ constraint, one can reach values for $\text{Br}(h \rightarrow b\bar{s} + s\bar{b})$ not far from 10^{-1} . This can happen in charged lepton models of the charm and top types with $c_{\beta\alpha}(t_\beta + t_\beta^{-1})$ ranging from 5 to 10 (again, perturbative unitarity constraints from the scalar sector can be relevant for these values of $c_{\beta\alpha}(t_\beta + t_\beta^{-1})$).

Table 3. V factors entering eq. (28).

Model	$h \rightarrow bd$	$h \rightarrow bs$
u	$ V_{ud}V_{ub} ^2 (\sim \lambda^6) = 1.33 \cdot 10^{-5}$	$ V_{us}V_{ub} ^2 (\sim \lambda^8) = 7.14 \cdot 10^{-7}$
c	$ V_{cd}V_{cb} ^2 (\sim \lambda^6) = 8.52 \cdot 10^{-5}$	$ V_{cs}V_{cb} ^2 (\sim \lambda^4) = 1.59 \cdot 10^{-3}$
t	$ V_{td}V_{tb} ^2 (\sim \lambda^6) = 7.90 \cdot 10^{-5}$	$ V_{ts}V_{tb} ^2 (\sim \lambda^4) = 1.61 \cdot 10^{-3}$

5. Analysis and results

An interesting aspect of flavour violation in BGL models is the possibility to establish clear correlations between various flavour violating processes owing to the reduced number of parameters which are involved: apart from the CKM and/or PMNS mixing matrices and fermion masses, FCNC only depend on the values of $\tan \beta$ and $\cos(\beta - \alpha)$. Moreover, the suppression depends on the specific BGL model, and thus the correlations differ from model to model. Although the focus of this presentation is in tree level flavour violating processes involving the Higgs boson already discovered at the LHC, the analysis has to take into consideration the flavour conserving Higgs constraints already obtained from Run 1 of the LHC. In particular one has to comply with the measured signal strengths for the different combinations of production mechanism and decay channel. For a detailed account and the latest combined results of the ATLAS and CMS collaborations, see [49]. They involve the flavour conserving couplings of the Higgs and put constraints in the t_β vs. $\alpha - \beta$ available space (we refer the reader to [34] for details). Figure 1 illustrates the effect of these constraints alone in a few models.

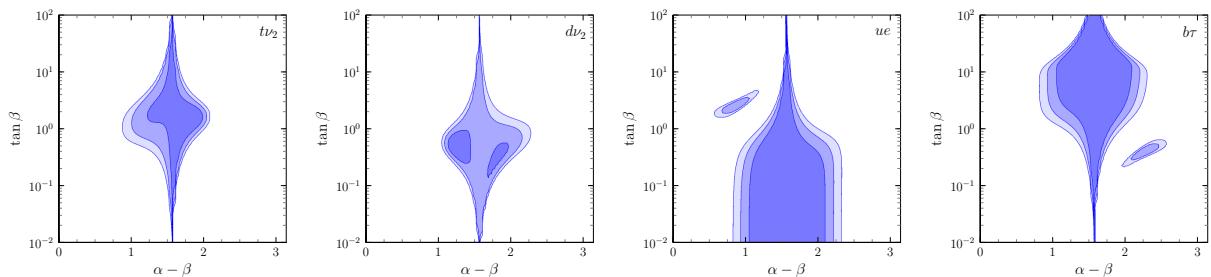


Figure 1. Effect of flavour conserving Higgs constraints alone on t_β vs. $\alpha - \beta$ in a sample of models; darker to lighter colouring represents 68%, 95% and 99% CL regions.

Furthermore, although an extended analysis of the phenomenology of the models under consideration, of the type presented in [33], is beyond the present scope, some attention has been devoted to potential bounds on the combination $c_{\beta\alpha}^2(t_\beta + t_\beta^{-1})^2$ from low energy processes like $B_d - \bar{B}_d$, $B_s - \bar{B}_s$, $K^0 - \bar{K}^0$ and $D^0 - \bar{D}^0$ mixings (see, appendix B.2 of [34] in particular and also [50]).

As pointed out before, given the nature of BGL models, we can analyse different kinds of correlations among the different HFVNC observables considered in the previous sections:

- within the same quark sector:
 - $t \rightarrow hc$ vs. $t \rightarrow hu$, in down-type models, where there are tree level FCNC in the up quark sector,
 - $h \rightarrow bs$ vs. $h \rightarrow bd$, in up-type models, where there are tree level FCNC in the down quark sector,

- within the quark and the lepton sector in neutrino-type models (where there are tree level FCNC in the charged lepton sector),
 - $t \rightarrow hq$ vs. $h \rightarrow \mu\tau$, in down-neutrino-type models,
 - $h \rightarrow bq$ vs. $h \rightarrow \mu\tau$, in up-neutrino-type models.

For an exhaustive analysis of the different correlations of interest, on the constraints operating in each case and additional relevant aspects for the interpretation of them, we refer again to reference [34], and content ourselves with an illustrative sample in terms of the plots presented in figure 2.

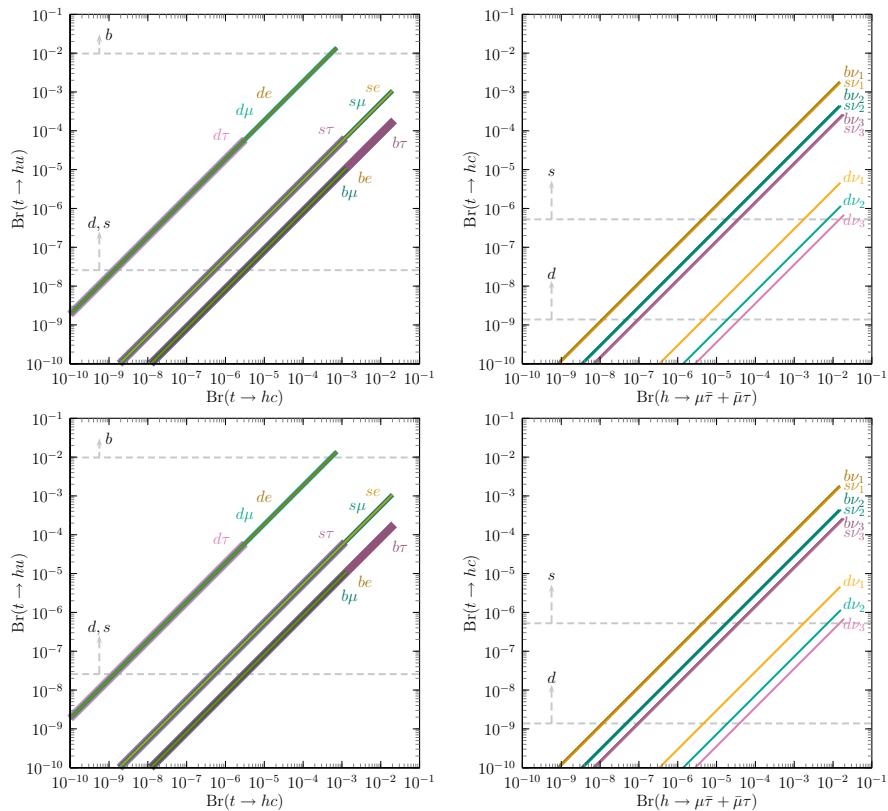


Figure 2. Correlations of different observables in BGL models.

Conclusions

We have discussed prospects for the observability of several flavour changing rare processes involving the Higgs in the context of a class of two Higgs doublet models which feature flavour changing neutral currents which have a controlled intensity and which are shaped by a symmetry to depend on the CKM and PMNS mixing matrices.

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