Flavour-Changing Decays of a 125 GeV Higgs-like Particle

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Abstract

The ATLAS and CMS experiments at the LHC have reported the observation of a possible excess of events corresponding to a new particle $h$ with mass $\sim 125$ GeV that might be the long-sought Higgs boson, or something else. Deciphering the nature of this possible signal will require constraining the couplings of the $h$ and measuring them as accurately as possible. Here we analyze the indirect constraints on flavour-changing $h$ decays that are provided by limits on low-energy flavour-changing interactions. We find that indirect limits in the quark sector impose such strong constraints that flavour-changing $h$ decays to quark-antiquark pairs are unlikely to be observable at the LHC. On the other hand, the upper limits on lepton-flavour-changing decays are weaker, and the experimental signatures less challenging. In particular, we find that either $\mathcal{B}(h \rightarrow \tau \bar{\mu} + \bar{\mu} \tau)$ or $\mathcal{B}(h \rightarrow \tau \bar{\mu} + \bar{\mu} \tau)$ could be $O(10\%)$, i.e., comparable to $\mathcal{B}(h \rightarrow \tau^+ \tau^-)$ and potentially observable at the LHC.

1 Introduction

The LHC experiments ATLAS and CMS have excluded the existence of the Higgs boson of the Standard Model (SM) below 115.5 GeV and between 127 and 600 GeV, and have reported indications of an apparent excess of events with a mass around 125 GeV \cite{1,2}. It is not yet established whether this excess is due to a new particle nor, if so, whether this new particle resembles closely the SM Higgs boson. However, we consider this hint to be sufficiently plausible that it is important to consider all the available constraints on the possible couplings of a new neutral spin-zero particle $h$ with a mass around 125 GeV, with a view to understanding better its nature.

The LHC phenomenology of a SM-like Higgs boson, with mass around 125 GeV, is characterized in the first place by six effective couplings: the couplings of $h$ to $\bar{b}b$, $\tau^+ \tau^-$, $\gamma \gamma$, $W^+ W^-$, $ZZ$ and $gg$. ATLAS and CMS are indeed searching for possible decays of any new neutral particle in these flavour-conserving final states (except for $gg$, whose coupling to $h$ is accessible only through the production mechanism). Within the SM, flavour-changing decays of $h$ are expected to strongly suppressed and well beyond the LHC reach. However, there are alternatives
to the SM Higgs interpretation of the 125 GeV hint, and in some of these cases relatively large flavour-changing couplings become a significant possibility. This is the case, for example, of the pseudo-dilaton Higgs boson look-alike discussed in \[3\], which is quite compatible with the hint observed by ATLAS and CMS. Flavour-changing decays of $h$ are expected also in the case of a composite Higgs \[4\] in models where the Yukawa couplings are functions of the Higgs field \[5\] and in several other extensions of the SM with more than one Higgs field (see, e.g., Ref. \[6\] and references therein). It is therefore important to explore the possible existence and the allowed magnitudes of flavour-changing couplings of a neutral 125 GeV scalar particle $h$, looking for possible deviations from SM predictions.

In this paper we adopt a phenomenological bottom-up approach, analyzing the flavour-changing couplings of the hypothetical $h$ particle allowed by low-energy data. Several previous studies of this type have been presented in the recent literature, see, e.g., \[6,11\]. However, a systematic analysis of both the quark and lepton sectors and their implications for the $h$ decays was still missing. As we will show, the available experimental constraints on flavour-changing neutral-current (FCNC) interactions provide strong bounds on many possible quark- and lepton-flavor-changing couplings. However, there are instances where relatively large flavour-changing $h$ couplings are still allowed by present data, cases in point being the $h\bar{\tau}\mu$ and $h\bar{\tau}e$ couplings (as already noticed in \[10,11\]). Specifically, we find that current experimental upper limits on lepton-flavour-violating processes allow the branching ratio $B(h \to \tau\bar{\mu} + \bar{\mu}\tau) = O(10\%)$, and that this can be obtained without particular tuning of the effective couplings. It is also possible that $B(h \to \tau\bar{e} + \bar{e}\tau) = O(10\%)$, though this possibility could be realized only at the expense of some fine-tuning of the corresponding couplings and, if realized, would forbid a large $B(h \to \tau\bar{\mu} + \bar{\mu}\tau)$. The bound on the $\mu e$ modes are substantially stronger, implying $B(h \to \bar{\mu}e + \bar{e}\mu) = O(10^{-9})$ in the absence of fine-tuned cancellations.

We note that CMS currently reports a 68% CL range of $0.8^{+1.2}_{-1.3}$ for a possible $h \to \tau^+\tau^-$ signal relative to its SM value \[2\], and that in the SM $B(h \to \tau^+\tau^-) \sim 6.5\%$ for a SM Higgs boson weighing 125 GeV. It therefore seems that dedicated searches in the LHC experiments might already be able to explore flavour-changing leptonic beyond the limits imposed by searches for lepton-flavour-violating processes.

On the other hand, the indirect upper bounds on possible quark-flavour-violating couplings of a scalar with mass 125 GeV are much stronger, and the detection of hadronic flavour-changing decays are much more challenging, so these offer poorer prospects for direct detection at the LHC.

### 2 Effective Lagrangian

We employ here a strictly phenomenological approach, considering the following effective Lagrangian to describe the possible flavour-changing couplings of a possible neutral scalar boson $h$ to SM quarks and leptons:

$$L_{\text{eff}} = \sum_{i,j=d,s,b \ (i \neq j)} c_{ij} \bar{d}_L^i d_R^j h + \sum_{i,j=u,c,t \ (i \neq j)} c_{ij} \bar{u}_L^i u_R^j h + \sum_{i,j=e,\mu,\tau \ (i \neq j)} c_{ij} \bar{\ell}_L^i \ell_R^j h + \text{H.c.} \quad (1)$$

The field $h$ can be identified with the physical Higgs boson of the SM or, more generally, with a mass eigenstate resulting from the mixing of other scalar fields present in the underlying theory with the SM Higgs (if it exists). Therefore, the operators in (1) are not necessarily...
Figure 1: Left: Tree-level diagram contributing to $\Delta F = 2$ amplitudes. Right: One-loop diagram contributing to anomalous magnetic moments and electric dipole moments of charged leptons ($i = j$), or radiative LFV decay modes ($i \neq j$).

| Operator | Eff. couplings | 95% C.L. Bound $|c_{\text{eff}}|$ | 95% C.L. Bound $|\text{Im}(c_{\text{eff}})|$ | Observables |
|---------|----------------|---------------------|---------------------|-------------|
| $(\bar{s}_R d_L)(\bar{s}_L d_R)$ | $c_{sd}$, $c_{ds}^*$ | $1.1 \times 10^{-10}$ | $4.1 \times 10^{-13}$ | $\Delta m_K$; $\epsilon_K$ |
| $(\bar{s}_R d_L)^2$, $(\bar{s}_L d_R)^2$ | $c_{ds}^2$, $c_{sd}^2$ | $2.2 \times 10^{-10}$ | $0.8 \times 10^{-12}$ | $\Delta m_K$; $|q/p|$, $\phi_D$ |
| $(\bar{c}_R u_L)(\bar{c}_L u_R)$ | $c_{cu}$, $c_{uc}^*$ | $0.9 \times 10^{-9}$ | $1.7 \times 10^{-10}$ | $\Delta m_D$; $\Delta m_{B_s}$; $S_{B_d \rightarrow \psi K}$ |
| $(\bar{c}_R u_L)^2$, $(\bar{c}_L u_R)^2$ | $c_{uc}^2$, $c_{cu}^2$ | $1.4 \times 10^{-9}$ | $2.5 \times 10^{-10}$ | $\Delta m_{B_d}$; $S_{B_d \rightarrow \psi K}$ |
| $(\bar{b}_R d_L)(\bar{b}_L d_R)$ | $c_{bd}$, $c_{db}^*$ | $0.9 \times 10^{-8}$ | $2.7 \times 10^{-9}$ | $\Delta m_{B_d}$; $S_{B_d \rightarrow \psi K}$ |
| $(\bar{b}_R d_L)^2$, $(\bar{b}_L d_R)^2$ | $c_{db}^2$, $c_{bd}^2$ | $1.0 \times 10^{-8}$ | $3.0 \times 10^{-9}$ | $\Delta m_{B_d}$; $S_{B_d \rightarrow \psi K}$ |
| $(\bar{b}_R s_L)(\bar{b}_L s_R)$ | $c_{bs}$, $c_{sb}^*$ | $2.0 \times 10^{-7}$ | $2.0 \times 10^{-7}$ | $\Delta m_{B_s}$ |
| $(\bar{b}_R s_L)^2$, $(\bar{b}_L s_R)^2$ | $c_{sb}^2$, $c_{bs}^2$ | $2.2 \times 10^{-7}$ | $2.2 \times 10^{-7}$ | $\Delta m_{B_s}$ |

Table 1: Bounds on combinations of the flavour-changing $h$ couplings defined in (1) obtained from $\Delta F = 2$ processes [12], assuming that $m_h = 125$ GeV.

$SU(2)_L \times U(1)_Y$ invariant. However, they may be regarded as resulting from higher-order $SU(2)_L \times U(1)_Y$-invariant operators after the spontaneous breaking of $SU(2)_L \times U(1)_Y$.

By construction, the effective couplings described by (1) are momentum-independent. In principle, higher-order operators with derivative couplings could also appear, leading to momentum-dependent terms, or effective form factors for the flavour-changing vertices. We assume here that any such effects are subleading, though it is clear that direct observation of $h$ decays would, in general, provide much more stringent constraints on such momentum dependence than could be provided by the indirect low-energy constraints considered below.

3 Bounds in the Quark Sector

In the quark sector, strong bounds on all the effective couplings in (1) involving light quarks (i.e., excluding the top) can be derived from the tree-level contributions to meson-antimeson mixing induced by diagrams of the type shown in the left panel of Fig. 1. Using the bounds on dimension-six $\Delta F = 2$ operators reported in [12], we derive the indirect limits on different
Table 2: Bounds on combinations of the flavour-changing $h$ couplings defined in (1) obtained from experimental constraints on rare $B$ decays \(^{[13]}\), assuming that $m_h = 125$ GeV. (Here and in subsequent Tables, the [*] denotes bounds obtained under the assumption that the flavour-diagonal couplings of $h$ are the same as the corresponding SM Yukawa couplings.)

| Operator | Eff. couplings | Bound | Constraint |
|----------|----------------|-------|------------|
| $(\bar{\mu}_R \epsilon_L)(\bar{q}Lq_R)$, $(\bar{\mu}_L \epsilon_R)(\bar{q}Lq_R)$ | $|c_{\mu e}|^2$, $|c_{\epsilon \mu}|^2$ | $3.0 \times 10^{-8}$ [*] | $\mathcal{B}(B_s \to \mu^+ \mu^-) < 1.4 \times 10^{-8}$ |
| $(\bar{\tau}_R \mu_L)(\bar{\mu}_L \mu_R)$, $(\bar{\tau}_L \mu_R)(\bar{\mu}_R \mu_L)$ | $|c_{\tau \mu}|^2$, $|c_{\mu \tau}|^2$ | $2.0 \times 10^{-1}$ [*] | $\Gamma(\tau \to \mu \mu \mu) < 2.1 \times 10^{-8}$ |
| $(\bar{\tau}_R \epsilon_R)(\bar{\mu}_L \mu_R)$, $(\bar{\tau}_L \epsilon_L)(\bar{\mu}_R \mu_L)$ | $|c_{\epsilon \tau}|^2$, $|c_{\tau \epsilon}|^2$ | $4.8 \times 10^{-1}$ [*] | $\Gamma(\tau \to e \mu \mu) < 2.7 \times 10^{-8}$ |
| $(\bar{\tau}_R \tilde{\epsilon}_L)(\bar{\mu}_L \mu_R)$, $(\bar{\tau}_L \tilde{\epsilon}_R)(\bar{\mu}_R \mu_L)$ | $|c_{\epsilon \tau}|^2$, $|c_{\tau \epsilon}|^2$ | $0.9 \times 10^{-4}$ | $\Gamma(\tau \to \mu ee) < 1.5 \times 10^{-8}$ |
| $(\bar{\tau}_R \epsilon_L)(\bar{\mu}_R \mu_L)$, $(\bar{\tau}_L \epsilon_R)(\bar{\mu}_L \mu_R)$ | $|c_{\epsilon \tau}|^2$, $|c_{\tau \epsilon}|^2$ | $1.0 \times 10^{-4}$ | $\Gamma(\tau \to e \mu \mu) < 1.7 \times 10^{-8}$ |

Table 3: Bounds on combinations of the flavour-changing $h$ couplings defined in (1) obtained from charged-lepton-flavour-violating decays, assuming that $m_h = 125$ GeV.

combinations of $c_{ij}$ couplings reported in Table 1. As we discuss in Section 5, these bounds forbid any flavour-changing decay of the $h$ into a pair of quarks with a branching ratio exceeding $10^{-3}$.

The $\Delta F = 1$ bounds on the $c_{ij}$ also prevent sizable Higgs-mediated contributions in $\Delta F = 1$ amplitudes, if the flavour-diagonal couplings of the $h$ are the same as the SM Yukawa couplings. In Table 2 we report the bounds on the $c_{ij}$ couplings obtained from $B_{s,d} \to \mu^+ \mu^-$ under this assumption, namely setting $c_{\mu \mu} = \sqrt{2}m_{\mu}/v$ with $v \approx 246$ GeV \(^{[1]}\). As can be seen, these $\Delta F = 1$ bounds are weaker than those in Table 1. This would not be true if the flavour-diagonal couplings of $h$ were enhanced with respect to the SM Yukawa couplings, or if there were some extra contribution cancelling $h$-exchange in the $\Delta F = 2$ amplitudes. The latter happens, for instance, in some two-Higgs doublet models, because of the destructive interference of scalar and pseudo-scalar exchange amplitudes: see, e.g., \(^{[6],[14]}\).

4 Bounds in the Lepton Sector

In the lepton sector we do not have an analogous of the $\Delta F = 2$ constraints, leaving more room for sizeable non-standard contributions.

\(^{1}\) This assumption is not true in general. For example, in the pseudo-dilaton scenario of \(^{[3]}\) the flavour-diagonal $h$ couplings are in general suppressed by a universal factor $c < 1$, in which case the bounds in Table 2 would be weakened by a factor $1/c > 1$. 

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Table 4: Bounds on combinations of the flavour-changing $h$ couplings defined in (1) obtained from the naturalness requirement $|\delta m_{\ell}| < m_{\ell}$ (assuming $\Lambda = 1$ TeV), from the contributions to $a_{\ell}$ and $d_{\ell}$ ($\ell = e, \mu$), and from radiative LFV decays (in all cases we set $m_h = 125$ GeV.

We start by analyzing the tree-level contributions of $h$ to the lepton-flavour violating (LFV) decays of charged leptons and $\mu \rightarrow e$ conversion in nuclei. In most cases bounds on the effective couplings in (1) can be derived only with an Ansatz about the flavour-diagonal couplings. Here we assume again that the flavour-diagonal couplings are the SM Yukawas,

$$c_{\ell\ell} = y_{\ell\ell} \equiv \frac{\sqrt{2} m_{\ell}}{v}.$$  

(2)

This leads to the bounds reported in Table 3 where we have used the limits of the corresponding dimension-six operators reported in [15], updating the results on various $\tau$ decay modes from Ref. [16]. As can be seen, all the bounds except that derived from $\mu \rightarrow e$ conversion are quite weak. Note in particular that if we impose $c_{\mu e}, c_{e\mu} < y_{\mu} \approx 6 \times 10^{-4}$ we have essentially no bounds on the flavour-violating couplings involving the $\tau$ lepton. Note also that we cannot profit from the strong experimental bound on $\Gamma(\tau \rightarrow e\gamma)$, since the corresponding amplitude is strongly suppressed by the electron Yukawa coupling.

Next we proceed to analyze one-loop-induced amplitudes. At the one-loop level the flavour-violating couplings in (1) induce: (i) logarithmically-divergent corrections to the lepton masses; (ii) finite contributions to the anomalous magnetic moments and the electric-dipole moments (edms) of charged leptons; and (iii) finite contributions to radiative LFV decays of the type $l_{\ell} \rightarrow l_j \gamma$ (see the right panel of Fig. 1).

As far as the mass corrections are concerned, in the leading-logarithmic approximation we

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2 The bound from $\mu \rightarrow e$ conversion has been derived following the recent analysis of Ref. [17]: the dominant constraint follows from $B_{\mu \rightarrow e}(\text{Ti})$ and, in order to derive a conservative bound, we have set $y = 2\langle N | \bar{s}s | N \rangle / \langle N | \bar{d}d + \bar{u}u | N \rangle = 0.03$.

3 As commented previously, in the scenario of Ref. [3] the flavour-diagonal $h$ couplings are in general suppressed by a universal factor $c < 1$, in which case the first three bounds in Table 3 would be weakened by a factor $1/c > 1$. 

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\[ \delta m_\ell = \frac{1}{(4\pi)^2} \sum_{j\neq \ell} c_{\ell j} c_{j\ell} m_j \log \left( \frac{m_h^2}{\Lambda^2} \right) . \] (3)

In absence of fine-tuning we expect \(|\delta m_\ell| < m_\ell\) for each of the two possible contributions in the sum. The most significant bounds thus derived, setting \(\Lambda = 1\) TeV, are reported in Table 4. Note that in this case no assumption on the flavour-diagonal couplings is needed.

More stringent (and more physical) bounds on the same combinations of couplings are derived from the contributions to the anomalous magnetic moments, \(a_\ell = (g_\ell - 2)/2\) and the edms of the electron and the muon. The corresponding one-loop amplitudes are

\[ |\delta a_\ell| = \frac{4m_\ell^2}{m_h^2} \frac{1}{(4\pi)^2} \sum_{j \neq \ell} \text{Re}(c_{\ell j} c_{j\ell}) \frac{m_j}{m_\ell} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{3}{2} \right) , \] (4)

\[ |d_\ell| = \frac{2m_\ell}{m_h^2} \frac{e}{(4\pi)^2} \sum_{j \neq \ell} \text{Im}(c_{\ell j} c_{j\ell}) \frac{m_j}{m_\ell} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{3}{2} \right) , \] (5)

from which we derive the bounds reported in Table 4. We do not report the corresponding bounds from \(a_\tau\) and \(d_\tau\) since they are much weaker. As can be seen, with the exception of the bound from the electron edm, which can easily be evaded assuming real couplings, the bounds are still rather weak.

The radiative LFV decay rates generated at one loop level can be written as

\[ \Gamma(l_i \rightarrow l_j \gamma) = m^3_i \frac{e^2}{16\pi} (|A_{ij}^L|^2 + |A_{ij}^R|^2) \] (6)

with coefficients

\[ |A_{\mu e}^R| = \frac{1}{(4\pi)^2} |c_{e\tau} c_{\tau\mu}| \frac{m_\tau}{m_h^2} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{3}{2} \right) , \quad |A_{\mu e}^L| = \frac{1}{(4\pi)^2} |c_{e\tau} c_{\mu\tau}| \frac{m_\tau}{m_h^2} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{3}{2} \right) , \] (7)

\[ |A_{\tau e}^R| = \frac{1}{(4\pi)^2} |c_{\tau\ell} y_{\tau\ell}| \frac{m_\tau}{m_h^2} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{4}{3} \right) , \quad |A_{\tau e}^L| = \frac{1}{(4\pi)^2} |c_{\tau\ell} y_{\tau e}| \frac{m_\tau}{m_h^2} \left( \log \frac{m_h^2}{m_\tau^2} - \frac{4}{3} \right) , \] (8)

and corresponding bounds reported in Table 4. Here it should be noted the strong and model-independent bound from \(\mu \rightarrow e\gamma\) \(^4\) which prevents the \(h\tau\mu\) (\(h\bar{\mu}\tau\)) and \(h\bar{\tau}e\) (\(h\tau e\)) couplings to be both large at the same time.

Finally we consider the bounds coming from two-loop diagrams of Barr-Zee type \(^5\), with a top-quark loop, whose relevance in constraining Higgs LFV couplings has been stressed recently in \(^{10,11}\). Despite being suppressed by an extra \(1/(16\pi^2)\) factor, these amplitudes are proportional to a single lepton Yukawa coupling and cannot be neglected. The resulting bounds, shown in Table 5, are obtained under the assumption that the coupling of \(h\) to the top quark is the same as in the SM (\(c_{yy} = y_t \equiv \sqrt{2}m_t/v\)). These bounds are consistent with those reported in Ref. \(^{11}\).

\(^4\) The complex mass correction \(\delta m_\ell\) is defined by \(m_\ell \rightarrow m_\ell + \text{Re}(\delta m_\ell) + i\text{Im}(\delta m_\ell)\) \(\ell\).

\(^5\) As usual, we define \(a_\ell\) and \(d_\ell\) in terms of the couplings of the corresponding dipole operators as follows: \((c_{a\ell}/4m_\ell)\sigma_{\mu\nu}\ell F^{\mu\nu}, i(d_\ell/2)\bar{\sigma}_{\mu\nu}\gamma_\ell F^{\mu\nu}\). The error on \(\delta a_\ell\) reported in Table 4 is the theoretical error in predicting \((g - 2)_e\) using independent determinations of \(\alpha_{\text{em}}\) \(^{18}\).
The possible observation of a new particle with mass around 125 GeV raises the important question of its possible nature: is it a SM-like Higgs boson, or not? Key answers to this ques-
tion will be provided by measurements of the $h$ couplings, and ATLAS and CMS have already provided valuable information \cite{1,2} on its flavour-diagonal couplings (if the $h$ exists). Further information could be provided by searches for (and measurements of) its flavour-changing couplings. In this paper we have analyzed the indirect upper bounds on these couplings that are provided by constraints on flavour-changing and other interactions in both the quark and lepton sectors.

We have found that in the quark sector the indirect constraints are so strong, and the experimental possibilities at the LHC so challenging, that quark flavour-changing decays of the $h$ are unlikely to be observable.

However, the situation is very different in the lepton sector. Here the indirect constraints are typically much weaker, and the experimental possibilities much less challenging. Specifically, we find that either $\mathcal{B}(h \rightarrow \tau \bar{\mu} + \mu \tau)$ or $\mathcal{B}(h \rightarrow \tau \bar{e} + \bar{e} \tau)$ of order 10% is a possibility allowed by the available LFV constraints. These large partial decay rates are the combined result not only of relatively weak bounds on Higgs-mediated LFV amplitudes involving the $\tau$ lepton, but also of the smallness of the total $h$ decay width for $m_h \approx 125$ GeV. Interestingly, these potentially large LFV rates are comparable to the expected branching ratio for $h \rightarrow \tau^+ \tau^-$ in the SM, which is already close to the sensitivity of the CMS experiment \cite{2}. Therefore the LHC experiments may soon be able to provide complementary information on the LFV couplings of the (hypothetical) $h$ particle with mass 125 GeV. The decays $h \rightarrow \mu e, \bar{e} \mu$ are constrained to have very small branching ratios, but their experimental signatures are so clean that here also the LHC may soon be able to provide interesting information.

We therefore urge our experimental colleagues to make dedicated searches for these interesting flavour-violating decays of the possible $h$ particle with mass 125 GeV.

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