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Flavor and CP violation in Higgs decays

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Abstract: Flavor violating interactions of the Higgs boson are a generic feature of models with extended electroweak symmetry breaking sectors. Here, we investigate CP violation in these interactions, which can arise from interference of tree-level and 1-loop diagrams. We compute the CP asymmetry in flavor violating Higgs decays in an effective field theory with only one Higgs boson and in a general Type-III Two Higgs Doublet Model (2HDM). We find that large ($\sim \mathcal{O}(10\%)$) asymmetries are possible in the 2HDM if one of the extra Higgs bosons has a mass similar to the Standard Model Higgs. For the poorly constrained decay modes $h \to \tau\mu$ and $h \to \tau e$, this implies that large lepton charge asymmetries could be detectable at the LHC. We quantify this by comparing the sensitivity of the LHC to existing direct and indirect constraints. Interestingly, detection prospects are best if Higgs mixing is relatively small — a situation that is preferred by the current data. Nevertheless, CP violation in $h \to \tau\mu$ or $h \to \tau e$ will only be observable if nonzero rates for these decay modes are measured very soon.

Keywords: Higgs Physics, Beyond Standard Model, CP violation

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Contents

1 Introduction

Precision measurements of the Higgs sector of elementary particles are becoming one of the major topics in the physics program at the Large Hadron Collider (LHC). The main goal of these measurements is to search for deviations from Standard Model (SM) expectations that would herald the existence of new physics at the TeV scale, such as additional Higgs bosons, as predicted for example in supersymmetry, secondary sources of electroweak symmetry breaking, for instance due to strong dynamics, or non-standard couplings of the Higgs boson due to higher-dimensional operators.

Many of these extensions of the SM predict the recenly discovered particle [1, 2] (hereafter refered to as the Higgs boson) to possess flavor non-diagonal couplings (see for example [3–26] and references therein). Existing constraints on some of these couplings are surprisingly weak, especially when couplings to third generation fermions are involved as in the processes $h \to \mu\tau$, $h \to e\tau$, $t \to hc$ and $t \to hu$. A number of search strategies for flavor violating Higgs couplings has been proposed [14–16, 27, 28] and first experimental searches for top-charm-Higgs couplings have been carried out by ATLAS [29] and CMS [30].

Also CP violation in Higgs decays is an active topic of research, with the main focus being on its effects on the polarization of the final state particles in $h \to t\bar{t}$, $h \to ZZ^*$, $h \to \gamma\gamma$ and $h \to \tau\tau$ [31–40].

Here we bring the two topics together by investigating Higgs decays that violate flavor and CP. In particular, we consider possible asymmetries between the processes $h \to \ell^{i-}\ell^{j+}$ and $h \to \ell^{i+}\ell^{j-}$, as parameterized by the observable

$$A_{\rm CP}^{\ell^i\ell^j} \equiv \frac{\Gamma(h \to \ell^{i-}\ell^{j+}) - \Gamma(h \to \ell^{i+}\ell^{j-})}{\Gamma(h \to \ell^{i-}\ell^{j+}) + \Gamma(h \to \ell^{i+}\ell^{j-})}\,, \tag{1.1}$$

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where $\ell^i, \ell^j = \{e,\ \mu,\ \tau\}$ and $i \neq j$. This observable offers perhaps the most direct way of searching for CP violation in Higgs decays and does not require considering any differential cross sections. On the downside, a measurement of $A_{\rm CP}^{\ell^i\ell^j}$ requires large integrated luminosity due to the smallness of (usually loop-induced) CP violating effects in general, and due to the possible smallness of the decay rates $\Gamma(h \to \ell^{i\pm}\ell^{j\mp})$ themselves. The current 95% CL upper limit on the branching ratios $\mathrm{BR}(h \to \tau\mu)$ and $\mathrm{BR}(h \to \tau e)$ is 13% from LHC searches [15, 41], while the indirect limit on $\mathrm{BR}(h \to \mu e)$ is 2×10^{-8} [15].[1] We will therefore not consider the decay $h \to \mu e$ in our phenomenological analysis.

In section 2, we derive analytic expressions for $A_{\rm CP}^{\ell^i\ell^j}$ in an effective theory of CP violation in the Higgs sector induced by new particles above the electroweak scale and in the type III Two Higgs Doublet Model (2HDM). We then constrain combined flavor and CP violation in Higgs decays from low-energy observables in section 3, and we estimate the sensitivity of the LHC in section 4. We summarize and conclude in section 5.

2 Flavor and CP violation in the Higgs sector

2.1 Low energy effective field theory with only one Higgs boson

We begin by considering a simple low energy effective field theory (EFT) of the Higgs sector, assuming that new physics which leads to flavor and CP violation can be integrated out (see also II of [15]).

If the energy scale associated with the new physics is sufficiently high, it can be encoded in a series of higher dimensional operators suppressed by a cut-off scale Λ. Among all the operators that can modify the strenght of the lepton-lepton-Higgs couplings, the lowest order one is[2]

$$\Delta\mathcal{L} = -\frac{\lambda'_{ij}}{\Lambda^2}\overline{L}^i_L \ell^j_R H \left(H^\dagger H\right) + h.c.\,. \tag{2.1}$$

The simultaneous presence of this term and of the SM Higgs Yukawa coupling $-\lambda_{ij}\overline{L}^i_L\ell^j_R H +$ $h.c.$ can induce lepton flavor and CP violation.

After electroweak symmetry breaking and diagonalization of the resulting lepton mass matrices, the relevant terms in the EFT Lagrangian become

$$\mathcal{L}_{\rm EFT} \supset -m_i \bar{\ell}^i_L \ell^i_R - Y^h_{ij}(\bar{\ell}^i_L \ell^j_R)h + h.c.\,, \tag{2.2}$$

where ℓ^i are charged lepton fields in the mass basis, h is the Higgs boson, and Y^h_{ij} is, in general, a complex 3×3 Yukawa matrix. Specifically, from eq. (2.1) we obtain $Y^h_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$, where $\hat{\lambda} \equiv V_L \lambda' V_R$, and V_L, V_R are the unitary matrices diagonalizing the mass matrix $m \equiv \frac{v}{\sqrt{2}}\left(\lambda + \frac{v^2}{2\Lambda}\lambda'\right)$ according to $\mathrm{diag}(m_1, m_2, m_3) = V_L m V_R$.

[1] Here and in the following, we denote by $\mathrm{BR}(h \to \ell^i\ell^j)$ the combined branching ratio for the processes $h \to \ell^{i+}\ell^{j-}$ and $h \to \ell^{i-}\ell^{j+}$. When referring to the branching ratio into only one of these CP-conjugate final states, we use the notation $\mathrm{BR}(h \to \ell^{i+}\ell^{j-})$.

[2] Operators of the form $\overline{f}\not{D}f\left(H^\dagger H\right)$ have the same mass dimension as eq. (2.1), but are redundant once the equations of motion are taken into account.

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Naturalness arguments suggest that the maximal size of the off diagonal elements of Y^h_{ij} should be related to the observed hierarchy of fermion masses. For example in [42] in order to avoid tunings, relations like the following have to hold

$$\left|Y^h_{\mu\tau} Y^h_{\tau\mu}\right| \lesssim \frac{m_\tau m_\mu}{v^2} \,. \tag{2.3}$$

Despite this general expectation one has to remark that the size of the flavor violating couplings is encoded in the details of the ultraviolet theory and in several explicit models larger flavor violating effects will be possible. For this reason, in our approach we are not going to rely on any specific extension and we consider the couplings as free parameters.

It is also important to keep in mind that, besides the operator from (2.1), additional dimension 6 operators not involving the Higgs boson could exist (see for example [24, 43]). In specific UV-complete models, these may lead to stronger constraints than observation of Higgs properties. Here, however, our goal is to focus on Higgs physics and we will therefore assume that new physics affects predominantly the Higgs sector.

The branching ratio for $h \to \ell^{i+}\ell^{j-}$ is given by

$$\mathrm{BR}(h \to \ell^{i+}\ell^{j-}) = \frac{\Gamma(h \to \ell^{i+}\ell^{j-})}{\Gamma(h \to \ell^{i+}\ell^{j-}) + \Gamma_{\mathrm{SM}}} \,, \tag{2.4}$$

with

$$\Gamma(h \to \ell^{i+}\ell^{j-}) = \frac{m_h}{16\pi}\left(|Y^h_{ji}|^2 + |Y^h_{ij}|^2\right) \tag{2.5}$$

and with the SM Higgs width $\Gamma_{\mathrm{SM}} = 4.1\,\mathrm{MeV}$ for a $125\,\mathrm{GeV}$ Higgs boson [44].

The Lagrangian (2.2) leads to non-zero $A^{\ell^i\ell^j}_{\mathrm{CP}}$ through interference of the first two diagrams shown in figure 1. The bubble diagram (2.2) (c) exists, but does not contribute to $A^{\ell^i\ell^j}_{\mathrm{CP}}$. The tree level diagram is given by

$$i\mathcal{A}_{\mathrm{tree}} = \bar{\ell}^i(p_i)\, i\big(Y^h_{ij} P_R + Y^{h*}_{ji} P_L\big)\, \ell^j(p_j) \,, \tag{2.6}$$

while the expression for the triangle diagram is

$$\begin{aligned} i\mathcal{A}_{\mathrm{triangle}} = \int \frac{d^4 q}{(2\pi)^4} \bar{\ell}^i(p_i)\, i(Y^h_{im} P_R + Y^{h*}_{mi} P_L)\, \frac{i(\not{q} + \not{p}_i + m_m)}{(q+p_i)^2 - m_m^2}\, i(Y^h_{mn} P_R + Y^{h*}_{nm} P_L) \\ \frac{i(\not{q} - \not{p}_j + m_n)}{(q-p_j)^2 - m_n^2}\, i(Y^h_{nj} P_R + Y^{h*}_{jn} P_L)\, \ell^j(p_j) \,. \end{aligned} \tag{2.7}$$

Here, p_i, p_j are the 4-momenta of the final state leptons, m_i is the mass of ℓ^i, and $P_L = (1-\gamma^5)/2$, $P_R = (1+\gamma^5)/2$ are the chirality projection operators.

From eqs. (2.6) and (2.7), we can compute $A^{\ell^i\ell^j}_{\mathrm{CP}}$ and find for the phenomenologically most interesting case where $\ell^i = \mu$ and $\ell^j = \tau$

$$\begin{aligned} A^{\mu\tau}_{\mathrm{CP}} = \frac{1-\log 2}{8\pi} \frac{\mathrm{Im}\left[Y^h_{\tau\tau}\left(Y^h_{e\mu} Y^{h*}_{e\tau} Y^{h*}_{\mu\tau} - Y^h_{\mu e} Y^{h*}_{\tau e} Y^{h*}_{\tau\mu}\right)\right]}{\left|Y^h_{\mu\tau}\right|^2 + \left|Y^h_{\tau\mu}\right|^2} \\ + \frac{1}{8\pi} \frac{m_\tau^2}{m_h^2} \frac{\left|Y^h_{\mu\tau}\right|^2 - \left|Y^h_{\tau\mu}\right|^2}{\left|Y^h_{\mu\tau}\right|^2 + \left|Y^h_{\tau\mu}\right|^2} \mathrm{Im}\left[(Y^h_{\tau\tau})^2\right] \,. \end{aligned} \tag{2.8}$$

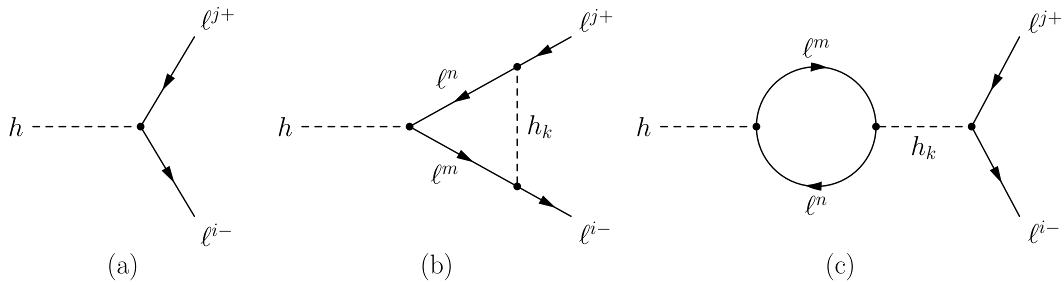

Figure 1. Feynman diagrams contributing to flavor and CP violating Higgs boson decays $h \to \ell^{i-}\ell^{j+}$. In the effective theory model (section 2.1), only one Higgs boson $h \equiv h_1$ exists and the bubble diagram (c) does not contribute to the CP asymmetry $A_{\rm CP}^{\ell^i\ell^j}$. In the two Higgs doublet model (section 2.2, there are three physical neutral Higgs mass eigenstates h_1, h_2, h_3, and all three diagrams contribute to $A_{\rm CP}^{\ell^i\ell^j}$.

Here, we have neglected terms proportional to m_μ, m_e, $|Y^h_{\mu\mu}|$, $|Y^h_{ee}|$ as well as terms suppressed by more than one of the small quantities m_τ^2/m_h^2, $|Y^h_{e\mu}|$ and $|Y^h_{\mu e}|$. An analogous expression for $A_{\rm CP}^{e\tau}$ is obtained by replacing $\mu \leftrightarrow e$ in eq. (2.8).

We see that, if only two lepton families (here τ and μ) participate in flavor changing Higgs couplings, $A_{\rm CP}^{\mu\tau}$ is suppressed by the loop factor $1/(8\pi)$ and by a factor m_τ^2/m_h^2. When all three lepton generations experience flavor changing Higgs couplings, $A_{\rm CP}^{\mu\tau}$ receives additional contributions that do not depend on lepton masses, but are proportional to a product of three flavor violating Yukawa couplings involving all three flavor combinations $e\mu$, $e\tau$ and $\mu\tau$. Since $(|Y_{\mu e}|^2 + |Y_{e\mu}|^2)^{1/2}$ is constrained to be smaller than 3.6×10^{-6} by searches for $\mu \to e\gamma$, $\mu \to e$ conversion in nuclei, and $\mu \to 3e$ [13, 15, 45], these products are far too small for this source of CP violation to be observable at the LHC.

We conclude that CP violation in flavor changing Higgs couplings is not accessible at the LHC when the additional degrees of freedom responsible for its generation are so heavy that they can be integrated out. We will therefore now consider scenarios in which additional Higgs bosons appear as dynamical degrees of freedom at the LHC. We will show that, in this case, large CP asymmetries are possible.

2.2 A Type-III Higgs doublet model

If not one but two Higgs doublets exist in nature [46] (for a recent review see [47]) and have masses of order 100 GeV, the phenomenology of the Higgs sector becomes considerably richer than in the SM. We will here consider a general "type-III" Two Higgs Doublet Model (2HDM), in which both Higgs doublets Φ_1 and Φ_2 have Yukawa couplings to charged leptons. We work in the Georgi basis [48], in which only Φ_1 acquires a vev so that Φ_1 and Φ_2 can be decomposed according to

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \eta_1 + iG^0) \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\eta_2 + iA) \end{pmatrix}. \tag{2.9}$$

Here η_1 and η_2 are real scalar fields, A is a real pseudoscalar, $H^\pm$ are the charged Higgs bosons and $G^\pm$, G^0 are Goldstone bosons. The charged lepton Yukawa couplings are given by

$$\mathcal{L} \supset -\frac{\sqrt{2}m_i}{v}\delta_{ij}\,\bar{L}_L^i \ell_R^j \Phi_1 - \sqrt{2}Y_{ij}\,\bar{L}_L^i \ell_R^j \Phi_2 + h.c.\,, \tag{2.10}$$

where L_L^i denotes the lepton doublets and (δ_{ij}), (Y_{ij}) are Yukawa matrices. After electroweak symmetry breaking, the Yukawa couplings become

$$\mathcal{L} \supset -\left(\frac{m_i}{v}\delta_{ij}\,\eta_1 + Y_{ij}\,\eta_2 + iY_{ij}\,A\right)\bar{\ell}_L^i \ell_R^j\,. \tag{2.11}$$

In the most general Two Higgs Doublet Model, η_1, η_2 and A are not identical to the physical mass eigenstates, which we denote by h_1, h_2 and h_3. The two sets of fields are related by an orthogonal transformation

$$(\eta_1, \eta_2, A)^T = O \cdot (h_1, h_2, h_3)^T\,, \tag{2.12}$$

with $O \in \mathrm{SO}(3)$. We denote by h_1 the lightest mass eigenstate, which is usally assumed to approximately resemble the SM Higgs boson. (Occasionally, we will use the notation h and h_1 interchangeably for this physical Higgs state.) In the physical basis, the Lagrangian becomes

$$\mathcal{L} = -m_i\bar{\ell}_L^i \ell_R^i - \sum_{r=1,2,3} Y_{ij}^{h_r}\,\bar{\ell}_L^i \ell_R^j\,h_r + h.c. \tag{2.13}$$

with

$$Y_{ij}^{h_r} = \frac{m_i\delta_{ij}}{v}O_{1r} + Y_{ij}O_{2r} + iY_{ij}O_{3r}\,. \tag{2.14}$$

One might worry that a Type-III 2HDM consistent with constraints from quark and lepton flavor observables has to be extremely fine-tuned since there is no symmetry that forbids large off-diagonal Yukawa couplings Y_{ij}. We will here accept this potential fine-tuning, assuming that at a high scale the 2HDM itself is embedded into a more complete theory which enforces the desired flavor structure, for instance through a flavor symmetry. Note that it has been shown that smallness of the off-diagonal Yukawa couplings is stable under renormalization group evolution [49, 50].

For an arbitrary scalar mixing matrix O, the CP asymmetry in $h_1 \to \mu\tau$ decays is given by

$$A_{\mathrm{CP}}^{\mu\tau} = A_{\mathrm{CP}}^{\mu\tau,(0)} + A_{\mathrm{CP}}^{\mu\tau,(1)}\frac{m_\tau}{v} + \ldots\,, \tag{2.15}$$

where "…" stands for terms that are second order in m_τ/v or first order in m_μ/v, m_e/v, $|Y_{\mu\mu}|$, $|Y_{ee}|$, $|Y_{e\mu}|$ or $|Y_{\mu e}|$. Setting $Y_{\mu\mu}$ and Y_{ee} to zero is motivated by the observed SM-like nature of the 125 GeV Higgs boson, which suggests that $|Y_{\mu\mu}\,(O_{21} + iO_{31})\,|$ and $|Y_{ee}\,(O_{21} + iO_{31})\,|$ cannot be larger than few $\times\, 10^{-2}$. $Y_{e\mu}$ and $Y_{\mu e}$ in turn are tightly constrained by searches for lepton flavor violation in $\mu \to e\gamma$, $\mu \to e$ conversion in nuclei and $\mu \to 3e$ [13, 15, 45] (see also section 2.1). The zeroth and first order terms $A_{\mathrm{CP}}^{\mu\tau,(0)}$ and

$A_{\rm CP}^{\mu\tau,(1)}$ in eq. (2.15) are given by

$$A_{\rm CP}^{\mu\tau,(0)} = \sum_{\alpha=2,3} \frac{1}{4\pi} \frac{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2}{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} \left(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2 + |Y_{\tau\tau}|^2\right) R_\alpha \left[g\left(\frac{m_{h_1}^2}{m_{h_\alpha}^2}\right) + \frac{m_{h_1}^2}{m_{h_1}^2 - m_{h_\alpha}^2} \right], \tag{2.16}$$

$$A_{\rm CP}^{\mu\tau,(1)} = \sum_{\alpha=2,3} \frac{1}{8\pi} \frac{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2}{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2} |Y_{\tau\tau}| \left[R_\alpha^V\, g\left(\frac{m_{h_1}^2}{m_{h_\alpha}^2}\right) + R_\alpha^L\, g\left(\frac{m_{h_1}^2}{m_{h_\alpha}^2}\right) + R_\alpha^L \frac{2m_{h_1}^2}{m_{h_1}^2 - m_{h_\alpha}^2} \right], \tag{2.17}$$

with the loop function

$$g(x) = \frac{x - \log(1+x)}{x} \tag{2.18}$$

and the vectors

$$R_\alpha = \frac{(O_{3\alpha}O_{21} - O_{2\alpha}O_{31})(O_{2\alpha}O_{21} + O_{3\alpha}O_{31})}{O_{21}^2 + O_{31}^2}, \tag{2.19}$$

$$R_\alpha^V = \frac{O_{2\alpha}O_{21} + O_{3\alpha}O_{31}}{O_{21}^2 + O_{31}^2} \left[\sin\theta_\tau\,(O_{11}O_{2\alpha} - O_{1\alpha}O_{21}) + \cos\theta_\tau\,(O_{11}O_{3\alpha} - O_{1\alpha}O_{31})\right], \tag{2.20}$$

$$R_\alpha^L = \frac{O_{3\alpha}O_{21} - O_{2\alpha}O_{31}}{O_{21}^2 + O_{31}^2} \left[\cos\theta_\tau\,(O_{11}O_{2\alpha} + O_{1\alpha}O_{21}) - \sin\theta_\tau\,(O_{11}O_{3\alpha} + O_{1\alpha}O_{31})\right]. \tag{2.21}$$

The angle θ_τ is defined according to $Y_{\tau\tau} \equiv |Y_{\tau\tau}|\, e^{i\theta_\tau}$. The analogous expressions for $h_1 \to e\tau$ are again obtained by simply replacing $\mu \leftrightarrow e$ in the above expressions. We see that in the general 2HDM, $A_{\rm CP}^{\mu\tau}$ and $A_{\rm CP}^{e\tau}$ are unsuppressed except by the loop factor $1/(4\pi)$. Therefore the CP asymmetries can easily be of order 10%. If $m_{h_2} \simeq m_{h_1}$ or $m_{h_3} \simeq m_{h_1}$, even larger asymmetries are possible as the last term in square brackets in eqs. (2.16) and (2.17) becomes large. Note, however, that in this case, the expansion in m_τ/v from eq. (2.15) breaks down, so our analytic expressions are no longer directly applicable.

Eqs. (2.19), (2.20) and (2.21) can be simplified if we parameterize the scalar mixing matrix O in terms of two mixing angles θ_{12} and θ_{13},

$$O = \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{21} & 0 \\ -s_{21} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \tag{2.22}$$

with the definitions $c_{ij} \equiv \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$. A third mixing angle θ_{23}, corresponding to rotations about the 1-axis, is unphysical because it can always be absorbed into a redefinition of the of second Higgs doublet $\Phi_2 \to e^{i\theta_{23}}\Phi_2$. With the explicit parameterization (2.22), eq. (2.19) becomes

$$R = (0,\, -r,\, r)^T \qquad \text{with} \qquad r \equiv \frac{s_{12}c_{12}s_{13}c_{13}^2}{c_{12}^2 s_{13}^2 + s_{12}^2}. \tag{2.23}$$

We see that $R_2 = -R_3$, i.e. that the contributions from h_2 and h_3 to the CP violating loop diagrams tend to cancel each other in the limit $m_{h_2} \approx m_{h_3}$. The explicit expressions for R^V and R^L are more lengthy.

We now consider several special cases of the general 2HDM.

Case 1: heavy h_3. Let us first consider a scenario where one of the neutral Higgs mass eigenstates, say h_3, is much heavier than the other two. The low energy effective Lagrangian for this scenario is (see also eqs. (2.13) and (2.14))

$$\mathcal{L}_{h_1 h_2} = -m_i \bar{f}_L^i f_R^i - Y_{ij}^{h_1} (\bar{f}_L^i f_R^j) h_1 - Y_{ij}^{h_2} (\bar{f}_L^i f_R^j) h_2 + h.c.\,. \tag{2.24}$$

The CP asymmetry is given by

$$A_{\rm CP}^{\mu\tau,\text{case 1}} = \frac{1}{8\pi}\left[g\!\left(\frac{m_{h_1}^2}{m_{h_2}^2}\right) \frac{\mathrm{Im}\left[\left(Y_{\tau\mu}^{h_2} Y_{\tau\mu}^{h_1 *} - Y_{\mu\tau}^{h_2} Y_{\mu\tau}^{h_1 *}\right)\left(\sum_{ij} Y_{ij}^{h_2} Y_{ij}^{h_1 *}\right)\right]}{\left|Y_{\mu\tau}^{h_1}\right|^2 + \left|Y_{\tau\mu}^{h_1}\right|^2} \right.$$
$$\left. +2\frac{m_{h_1}^2}{m_{h_1}^2 - m_{h_2}^2} \frac{\mathrm{Im}\left[Y_{\tau\mu}^{h_2} Y_{\tau\mu}^{h_1 *} - Y_{\mu\tau}^{h_2} Y_{\mu\tau}^{h_1 *}\right] \mathrm{Re}\left[\sum Y_{ij}^{h_2} Y_{ij}^{h_1 *}\right]}{\left|Y_{\mu\tau}^{h_1}\right|^2 + \left|Y_{\tau\mu}^{h_1}\right|^2} \right], \tag{2.25}$$

with the loop function $g(x)$ from eq. (2.18). We have again neglected diagrams involving electrons. We see that even in this considerably simplified version of the 2HDM, unsuppressed CP violation can occur.

Case 2: small mixing angles in the scalar sector. The observed Standard Model-like nature of the 125 GeV Higgs boson suggests that its mixing with the components of a heavy Higgs doublet should be small. This leads us to consider the limit $\theta_{12}, \theta_{13} \ll 1$. The scalar mixing matrix thus becomes

$$O \approx \begin{pmatrix} 1 & \theta_{12} & \theta_{13} \\ -\theta_{12} & 1 & 0 \\ -\theta_{13} & 0 & 1 \end{pmatrix} \tag{2.26}$$

and the Yukawa couplings in the physical basis are

$$\begin{aligned} \mathcal{L} \supset & -Y_{\tau\mu} \bar{\tau}_L \mu_R \left[(\theta_{12} + i\theta_{13}) h_1 + h_2 + i h_3\right] - Y_{\tau\mu} \bar{\nu}_{\tau L} \mu_R H^+ + (\mu \leftrightarrow \tau) + h.c. \quad &\text{(flavor violating)} \\ & - \sum_i \frac{m_i}{v} \bar{\ell}_L^i \ell_R^i \left(h_1 + \theta_{12} h_2 + i\theta_{13} h_3\right) + h.c.\,. \quad &\text{(flavor conserving)} \end{aligned} \tag{2.27}$$

This leads to the rate for $h_1 \to \tau^\pm \mu^\mp$,

$$\Gamma(h_1 \to \tau^+ \mu^-) = \frac{m_{h_1}}{16\pi} \left(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2\right) \left(\theta_{12}^2 + \theta_{13}^2\right). \tag{2.28}$$

The CP asymmetry is again given by eqs. (2.15)–(2.17), but with eqs. (2.19)–(2.21) simplified to

$$R = \frac{1}{\theta_{12}^2 + \theta_{13}^2} \left(0,\, -\theta_{12}\theta_{13},\, \theta_{12}\theta_{13}\right)^T, \tag{2.29}$$

$$R^V = \frac{1}{\theta_{12}^2 + \theta_{13}^2} \left(0,\, -\theta_{12}\sin\theta_\tau,\, -\theta_{13}\cos\theta_\tau\right)^T, \tag{2.30}$$

$$R^L = \frac{1}{\theta_{12}^2 + \theta_{13}^2} \left(0,\, \theta_{13}\cos\theta_\tau,\, \theta_{12}\sin\theta_\tau\right)^T. \tag{2.31}$$

Case 3: no CP violation in the scalar sector. We now analyze the case where the scalar sector is CP conserving. In the Georgi basis this means that $A = h_3$ is a mass eigenstate while η_1 and η_2 can have a mixing. This mixing should not be too large so that the lightest mass eigenstate h_1 is mostly η_1-like and behaves like the SM Higgs boson, in agreement with LHC measurements of Higgs couplings. Nevertheless, h_1 is still allowed to have an η_2 admixture of order 20% as this is the accuracy to which the couplings of the 125 GeV Higgs boson have been measured (see for instance [51]). Thus, sizeable flavor changing Yukawa couplings are still allowed. We are thus led to consider a scalar mixing matrix of the form given by eq. (2.22), with $\theta_{13} = 0$ and $\theta_{12} \ll 1$. With these approximations, $A_{\rm CP}^{\mu\tau,(0)}$ in eq. (2.15) vanishes, and the leading term in the CP asymmetry, generated by loops involving $h_2 \approx \eta_2$ and $h_3 = A$ is given by $A_{\rm CP}^{\mu\tau,(1)}$:

$$A_{\rm CP}^{\mu\tau,\text{case 3}} = -\frac{1}{8\pi}\frac{|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2}{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2}\frac{1}{\theta_{12}}\frac{m_\tau}{v}\,{\rm Im}(Y_{\tau\tau})\left[g\left(\frac{m_{h_1}^2}{m_{h_2}^2}\right) - g\left(\frac{m_{h_1}^2}{m_{h_3}^2}\right) - \frac{2m_{h_1}^2}{m_{h_1}^2 - m_{h_3}^2}\right]. \tag{2.32}$$

The loop function $g(x)$ is again given by eq. (2.18). Note that eq. (2.32) is again based on the approximation $m_\mu = m_e = Y_{\mu\mu} = Y_{ee} = 0$. Eq. (2.32) shows that in the 2HDM without CP violation in the scalar sector the CP asymmetry is always suppressed by m_τ/v and by $|Y_{\tau\tau}|$.

3 Direct and indirect constraints

Direct and indirect searches constrain the maximal allowed amount of CP and flavor violation in the Higgs decays accessible at the LHC. In this section we summarize how existing bounds on various low energy and high energy observables constrain ${\rm BR}(h \to \ell^i\ell^j) \times A_{\rm CP}^{\ell^i\ell^j}$.

3.1 Constraints on flavour violating couplings of the SM-like Higgs boson

Even though we saw in the previous section that large CP violating effects in flavor changing Higgs decays can be observable only if new particles exist very close to the electroweak scale, it is instructive to first derive constraints on the parameters of the phenomenological Lagrangian eq. (2.2). In doing assume that the flavor conserving couplings of the Higgs to quarks and gauge bosons are at their SM values.

Let us start by considering constraints coming from direct searches. Since we assume for simplicity that flavor violating new physics affects predominantly the lepton sector, the production cross section σ for the Higgs boson is the same as in the SM. It is therefore straightforward to use existing searches for $h \to \tau^+\tau^-$ and $h \to \mu^+\mu^-$ to set bounds on the flavor diagonal couplings $Y_{\tau\tau}^h$ and $Y_{\mu\mu}^h$. The recent CMS analysis [52] finds a signal cross section for $h \to \tau^+\tau^-$ equal to 0.78 ± 0.27 times the standard model prediction. This means equivalently that $\left|Y_{\tau\tau}^h\right|^2 / \left|(Y_{\tau\tau}^h)_{\rm SM}\right|^2$ has to lie within this range. (Here and in the following, the index SM denotes the SM values of the model parameters and observables.) In a similar way the value of $Y_{\mu\mu}^h$ is bounded from the results in [53], where $\Gamma(h \to \mu^+\mu^-)$ has been constrained to be smaller than 7.4 times its SM value.

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The most recent constraints on flavor *violating* couplings to the Higgs boson to leptons have been derived in [15] by recasting an ATLAS search for $h \to \tau^+\tau^-$ [41] in 4.7 fb^{-1} of 7 TeV LHC data. They require $\text{BR}(h \to \tau\ell) < 0.13$, or equivalently $\sqrt{|Y^h_{\tau\ell}|^2 + |Y^h_{\ell\tau}|^2} < 0.011$, where $\ell = e, \mu$. We expect that a similar analysis including data on $h \to \tau^+\tau^-$ from the 8 TeV run of the LHC could increase the sensitivity to the Yukawa couplings by about a factor 1.5. A dedicated analysis could do significantly better still (see [16, 28] and section 4). Note that a simple recasting of the existing $h \to \tau\tau$ searches at $\sqrt{s} = 8$ TeV is not as promising as it was for the 7 TeV data used in [15]. In the case of the latest ATLAS search [54], the reason is the usage of a boosted decision tree which has been trained on SM $h \to \tau\tau$ decays and is therefore expected to be less sensitive to other decay modes, in particular $h \to \tau\mu$ and $h \to \tau e$. The latest CMS search for $h \to \tau\tau$ is cut-based, but employs a maximum likelihood method to determine the most likely value of the Higgs mass on an event-by-event basis in spite of the incomplete kinematic information. This method is based on the assumption that any muon or electron in the event originates from a τ decay and is thus accompanied by two neutrinos. Since this is not the case for $h \to \tau\mu$ and $h \to \tau e$ events, we expect the Higgs mass reconstruction to be very poor for the flavor violating decay channels, leading to significant smearing of our signal and a corresponding loss of sensitivity.

The direct bounds on the flavor-diagonal and flavor-off-diagonal Yukawa couplings are summarized in the upper part of table 1. In the lower part, we also show indirect constraints from the radiative decays $\ell_i \to \ell_j + \gamma$, derived in the context of the phenomenological Lagrangian eq. (2.2) [13, 15]. Other indirect observables like the electric and magnetic moments of the electron and the muon give weaker bounds. (The electric dipole moment of the electron leads, however, to a strong constraint on $\text{Im}(Y_{e\tau}Y_{\tau e}.)$ A more detailed discussion can be found, for example, in [13, 15, 19, 45].

3.2 Type-III two Higgs doublet model

Constraining the high dimensional parameter space of the general type-III Two Higgs Doublet Model discussed in section 2.2 is a formidable task (see for instance ref. [55] for a discussion of flavor observables in Two Higgs Doublet Models). Here, our goal is only to explore the region of parameter space where large CP violating effects in flavor violating Higgs decays are possible and detectable at the LHC. We therefore simplify our analysis by assuming the mixing angles θ_{12} and θ_{13} in the scalar sector to be small, and we set θ_{23} to zero (cf. section 2.2, case 2). We will also assume that $Y_{\tau\mu}$ and $Y_{\mu\tau}$ are the only nonzero element of the Yukawa matrix Y. This means that the second Higgs doublet couples to SM fermions only through $Y_{\tau\mu}$ and $Y_{\mu\tau}$, and that the dominant decay modes of the heavy Higgs mass eigenstates will be $h_2, h_3 \to \tau^\pm\mu^\mp$, $H^\pm \to \mu^\pm \overset{(-)}{\nu}_\tau$, $H^\pm \to \tau^\pm \overset{(-)}{\nu}_\mu$

Decays to other combinations of SM fermions are possible due to Higgs mixing, but since their rate is suppressed by the square of a small mixing angle, we will neglect them. The heavy scalars can also decay through gauge interactions as in the decay $H^\pm \to W^\pm h_i$. However, in the region of parameter space where large $A^{\mu\tau}_{\text{CP}}$ can be observed at the LHC, these decay channels are always subdominant.

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Channel	Coupling	Bound on coupling	Bound on BR	C.L.
$h \to \tau^+\tau^-$	$\lvert Y^h_{\tau\tau}\rvert$	8.3×10^{-3}	0.083	95%
$h \to \mu^+\mu^-$	$\lvert Y^h_{\mu\mu}\rvert$	1.1×10^{-3}	1.6×10^{-3}	95%
$h \to \tau\mu$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	0.011	0.13	95%
$h \to \tau e$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	0.011	0.13	95%
$\mu \to e\gamma$	$\sqrt{\lvert Y^h_{\mu e}\rvert^2 + \lvert Y^h_{e\mu}\rvert^2}$	3.6×10^{-6}	2.4×10^{-12}	90%
$\mu \to e\gamma$	$\left(\lvert Y^h_{\tau\mu} Y^h_{\tau e}\rvert^2 + \lvert Y^h_{\mu\tau} Y^h_{e\tau}\rvert^2\right)^{1/4}$	3.4×10^{-4}	2.4×10^{-12}	90%
$\tau \to e\gamma$	$\sqrt{\lvert Y^h_{\tau e}\rvert^2 + \lvert Y^h_{e\tau}\rvert^2}$	0.014	3.3×10^{-8}	90%
$\tau \to \mu\gamma$	$\sqrt{\lvert Y^h_{\tau\mu}\rvert^2 + \lvert Y^h_{\mu\tau}\rvert^2}$	0.016	4.4×10^{-8}	90%

Table 1. Direct and indirect constraints on flavor conserving and flavor violating Yukawa couplings of the SM-like Higgs boson based on the phenomenological Lagrangian eq. (2.2). In the 2HDM, the constraints apply equivalently to Y^{h_1} (see eq. (2.14)). We have assumed that Higgs couplings to quarks and gauge bosons are unmodified compared to the SM.

The couplings of the SM-like Higgs mass eigenstate h_1 are constrained in the same way as in section 3.1. The bounds from table 1 translate into the limit

$$\sqrt{|Y_{\tau\mu}|^2 + |Y_{\mu\tau}|^2}\sqrt{\theta_{12}^2 + \theta_{13}^2} < 0.011\,. \tag{3.1}$$

We see from eqs. (2.15), (2.16), (2.28) and (2.31) that the largest observable CP violating effects, as measured by

$$\begin{aligned}\Gamma(h_1 \to \tau^+\mu^-) \times A_{\rm CP}^{\mu\tau} \simeq &-\frac{m_{h_1}}{64\pi^2}\theta_{12}\theta_{13}\left(|Y_{\tau\mu}|^2 - |Y_{\mu\tau}|^2\right)\left(|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2 + |Y_{\tau\tau}|^2\right)\\ &\times \sum_{\alpha=2,3}(-1)^\alpha\left[g\left(\frac{m_{h_1}^2}{m_{h_\alpha}^2}\right) + \frac{m_{h_1}^2}{m_{h_1}^2 - m_{h_\alpha}^2}\right],\end{aligned} \tag{3.2}$$

are obtained if either $Y_{\mu\tau} = 0$, $Y_{\tau\mu} \neq 0$ or $Y_{\mu\tau} \neq 0$, $Y_{\tau\mu} = 0$. Moreover, to obtain large CP violation, the limit from eq. (3.1) should be saturated, $|Y_{\tau\tau}|$ should be of order $0.1/\sqrt{\theta_{12}^2 + \theta_{13}^2}$ (larger values are excluded by measurements of $\mathrm{BR}(h_1 \to \tau\tau)$) and $\theta_{12} = \theta_{13}$. Finally, h_2 and h_3 should be very different in mass since there is no CP violation if $m_{h_2} = m_{h_3}$. Most interesting to us is therefore the limit $m_{h_3} \gg m_{h_2} \approx m_{h_1}$.

Constraints on h_2 and h_3 from direct production are not important in the small mixing angle limit since the production of the heavy Higgs mass eigenstates is suppressed by θ_{12}^2 or θ_{13}^2. Since the second Higgs doublet Φ_2 does not acquire a vev, and since we assume that it does not have large Yukawa couplings to quarks, h_2 and h_3 can experience production through gluon fusion, vector boson fusion or associate production only through their mixing with the components of Φ_1. If the dominant decay mode of h_2 and h_3 is to $\tau + \mu$ as assumed here, conventional searches for flavor conserving final states are suffering from an additional mixing angle suppression in the flavor conserving branching ratios. The strongest limits

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on h_2 and h_3 are therefore coming from indirect searches, in particular $\tau \to \mu\gamma$. We obtain these limits following the procedure outlined in ref. [15]. We match the full 2HDM onto the effective Lagrangian

$$\mathcal{L} = c_L Q_{L\gamma} + c_R Q_{R\gamma} + h.c. \,, \tag{3.3}$$

with the operators

$$Q_{L\gamma,R\gamma} = \frac{e}{8\pi^2} m_\tau \big(\bar{\mu}\,\sigma^{\alpha\beta} P_{L,R}\tau\big) F_{\alpha\beta} \,. \tag{3.4}$$

Here, $F_{\alpha\beta}$ is the electromagnetic field strength tensor. The Wilson coefficients c_L, c_R receive contributions from one-loop diagrams involving neutral Higgs boson-charged lepton bubbles and from two-loop diagrams containing top or W loops. For simplicity, we neglect diagrams involving the charged Higgs bosons $H^\pm$, assuming they are sufficiently heavy. The contributions of h_1 to c_L and c_R are given by the expressions summarized in the appendix of [15], with the modification that, following eq. (2.27), $Y_{\tau\mu}$ and $Y_{\mu\tau}$ are replaced by $Y_{\tau\mu}(\theta_{12} + i\theta_{13})$ and $Y_{\mu\tau}(\theta_{12} + i\theta_{13})$, respectively. Similarly, for the contribution of diagrams containing h_2 (h_3), the flavor-diagonal Yukawa couplings as well as the Higgs couplings to gauge bosons have to be multiplied by $-\theta_{12}$ ($-\theta_{13}$). For the h_3 contributions, moreover, $Y_{\tau\mu}$ is replaced by $iY_{\tau\mu}$ and $Y_{\mu\tau}$ by $iY_{\mu\tau}$.

A second set of indirect limits on 2HDMs arises from measurements of the electric and magnetic dipole moments of the electron and muon. If the only non-negligible Yukawa couplings of the second Higgs doublet are $Y_{\tau\mu}$ and $Y_{\mu\tau}$, the one-loop contributions of the heavy Higgs bosons to the electric (magnetic) dipole moment d_μ (a_μ) of the muon are proportional to $\Re(Y_{\tau\mu}Y_{\mu\tau})$ ($\Im(Y_{\tau\mu}Y_{\mu\tau})$). They are, however *not* suppressed by the mixing angles θ_{12} and θ_{13}. However, as we have seen above, large CP violation in $h_1 \to \tau\mu$ is only possible if $Y_{\tau\mu}$ and $Y_{\mu\tau}$ are very different in magnitude. In this case, dipole moment constraints deteriorate rapidly and we will therefore not consider them further here.

In figures 2 and 3, we compare the indirect $\tau \to \mu\gamma$ constraints on the Yukawa couplings (black dashed curves) and the direct constraint $\mathrm{BR}(h_1 \to \tau\mu) < 0.13$ [15] (orange shaded region) to the expected $\mathrm{BR}(h_1 \to \tau\mu)\, A_{\mathrm{CP}}^{\mu\tau}$ (blue dotted contours). The latter quantity is a measure for the observability of CP violation in $h_1 \to \tau\mu$ decays. We also show the expected sensitivity of the LHC to CP violation in $h_1 \to \tau\mu$ decays (see section 4 for details). For illustration, we have here assumed that $Y_{\tau\mu}$ is the only nonzero element of the Yukawa matrix Y since we see from eqs. (2.16) and (2.17) that a large asymmetry between $|Y_{\tau\mu}|$ and $|Y_{\mu\tau}|$ maximizes the CP asymmetry. Note that in the left panel of figure 2, no CP violation is expected because we have assumed $m_{h3} = m_{h2}$ there. We see from figures 2 and 3 that the largest observable CP violation is expected when $m_{h2} \sim m_{h1}$ and m_{h3} much heavier. Moreover, the Higgs mixing angles θ_{12} and θ_{13} should be small — a situation that is actually preferred by the current LHC data, which is very SM-like.

Finally, we comment on constraints on the charged Higgs bosons $H^\pm$ whose quantum numbers are the same as those of a left-handed slepton in supersymmetry. Therefore, limits on slepton masses from direct production at the LHC can in principle be recast into limits on the charged Higgs boson mass $m_{H^\pm}$. The ATLAS slepton search in $20.3\,\mathrm{fb}^{-1}$ of

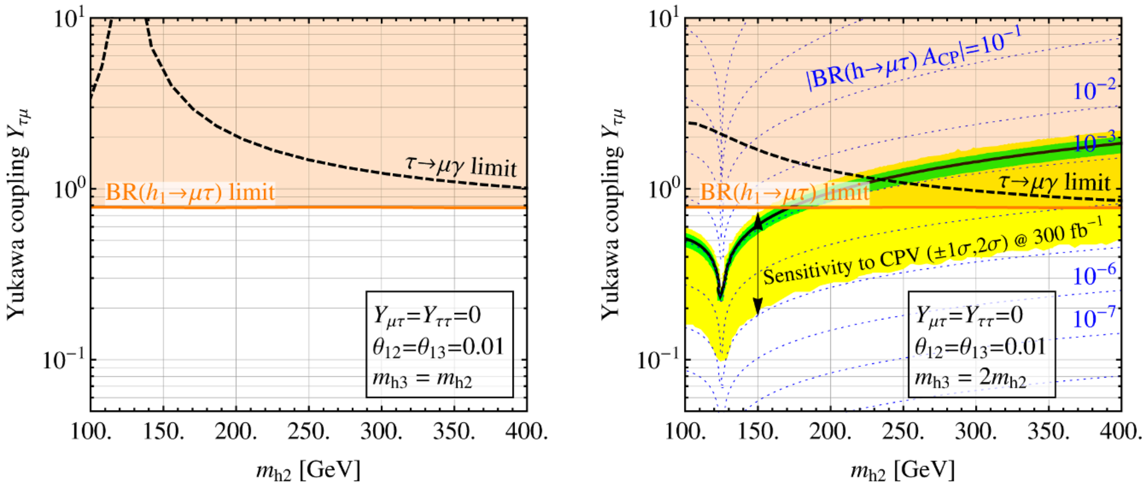

Figure 2. Direct and indirect constraints on the flavor violating Yukawa couplings $Y_{\tau\mu}$ in the general type-III 2HDM. We have assumed all other entries of the Yukawa matrix Y (including in particular $Y_{\mu\tau}$) to vanish. In the left panel, we have assumed $m_{h_2} = m_{h_3}$, a situation in which no CP violation is expected, while in the right panel, we consider a benchmark scenario with $m_{h_3} > m_{h_2}$. We show the region excluded by the direct limit on BR($h_1 \to \tau\mu$) from LHC data [15] (orange) together with indirect limits from $\tau \to \mu\gamma$ (black dashed). In the right panel, the "Brazilian band" (black curve with green and yellow $\pm 1\sigma$ and $\pm 2\sigma$ bands) indicates the expected 95% C.L. limit from a search for CP violation at the 13 TeV LHC with an integrated luminosity of 300 fb^{-1} (see section 4 for details). The regions above the band is approximately equal to the region in which evidence for CP violation can be found. The blue dotted contours indicate constant values of the quantity $|\text{BR}(h_1 \to \tau\mu) \times A_{\text{CP}}^{\mu\tau}|$, which is a measure for the observability of CP violation. The largest CP violating effects are expected for m_{h_2} similar to the mass of the SM-like Higgs boson. (Note that our plots are only approximate very close to the resonance at $|m_{h_1} - m_{h_2}| \lesssim \mathcal{O}(1\,\text{GeV})$ where the 1-loop approximation used in eq. (2.15) breaks down.)

8 TeV data [56] constrains the mass of left-handed sleptons to be $m_{\tilde{\ell}} \gtrsim 300$ GeV, assuming a simplified scenarios with mass-degenerate left-handed selectrons and smuons, massless neutralinos, and all other SUSY particles very heavy. Comparing slepton pair production in this simplified SUSY model to the production of $H^\pm$ of the same mass in our 2HDM, we note that $H^\pm$ production leads to about a factor of 8 fewer events. The reason is that there are two new particles (selectron and smuon) in the SUSY scenario, but only one new particle in the 2HDM. Moreover, $pp \to H^+H^-$ has a branching ratio to the dimuon + MET final state of only 25% — the remainder of the events contains one or two tau leptons. Therefore, the bound on $m_{H^\pm}$ is significantly weaker than the one on $m_{\tilde{\ell}}$, so requiring the charged Higgs bosons to be heavier than 300 GeV is a very conservative assumption.

4 Flavor and CP violating Higgs decays at the LHC

To investigate the sensitivity of future LHC searches to the CP asymmetry $A_{\text{CP}}^{\mu\tau}$ in the decay $h \to \tau\mu$, we follow the strategy proposed in [16]. (Results for $h \to \tau e$ will be very similar.) The search proposed there is sensitive to Higgs boson production through

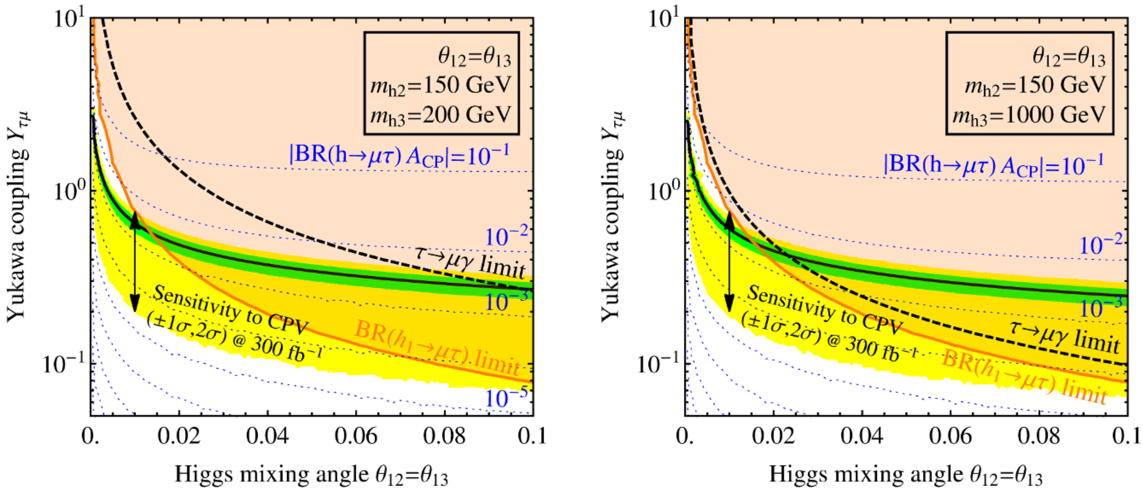

Figure 3. Direct and indirect constraints on the flavor violating Yukawa couplings $Y_{\tau\mu}$ in the general type-III 2HDM for fixed Higgs boson masses m_{h_2} and m_{h_3}, but varying Higgs mixing angles. We have assumed all entries of the Yukawa matrix Y other than $Y_{\tau\mu}$ to vanish. We show the region excluded by the direct limit on $\mathrm{BR}(h_1 \to \tau\mu)$ from LHC data [15] (orange) together with indirect limits from $\tau \to \mu\gamma$ (black dashed). The "Brazilian bands" (black curves with green and yellow $\pm 1\sigma$ and $\pm 2\sigma$ bands) indicate the expected 95% C.L. limits from a search for CP violation at the 13 TeV LHC with an integrated luminosity of 300 fb^{-1} (see section 4 for details). The regions above the bands are approximately equal to the regions in which evidence for CP violation can be found. The blue dotted contours indicate constant values of the quantity $|\mathrm{BR}(h_1 \to \tau\mu) \times A^{\mu\tau}_{\mathrm{CP}}|$, which is a measure for the observability of CP violation. A search for CP violating effects is most promising if the mixing angles are small.

gluon fusion, and is therefore expected to be more sensitive than the alternative strategy proposed in [15], which is optimized for Higgs production through vector boson fusion. We adapt the method outlined in [16] to a hadronic center of mass energy $\sqrt{s} = 13\,\mathrm{TeV}$ and an integrated luminosity of $300\,\mathrm{fb}^{-1}$. We normalize the Higgs production cross section to the gluon fusion cross section from [44].

Following [16], we require exactly one electron (assumed to come from a leptonic τ decay) and one muon with $p_T > 30\,\mathrm{GeV}$ and $|\eta| < 2.5$, and with azimuthal separation $\Delta\phi(e,\mu) > 2.7$. The azimuthal separation between the muon and the missing transverse momentum, $\Delta\phi(\mu, \not{p}_T)$ must be less than 0.3. The leptons are required to have opposite charge, and events with central high-p_T jets ($p_T > 30\,\mathrm{GeV}$, $|\eta| < 2.5$) are vetoed. After this preselection, we classify events as signal-like or background-like based on the p_T of the muon and the value of the variable

$$r_{\not{E}_T} \equiv \frac{\not{E}_T^{\mathrm{calc}} - \not{E}_T^{\mathrm{obs}}}{\not{E}_T^{\mathrm{obs}}}\,. \tag{4.1}$$

Here, $\not{E}_T^{\mathrm{obs}}$ is the measured missing energy and $\not{E}_T^{\mathrm{calc}}$ is the transverse energy of the neutrinos calculated from the momenta of the two charged leptons under the hypothesis of a true $h \to \tau\mu$ decay. In the approximation that all decay products of the τ are collinear, $\not{E}_T^{\mathrm{calc}}$ is

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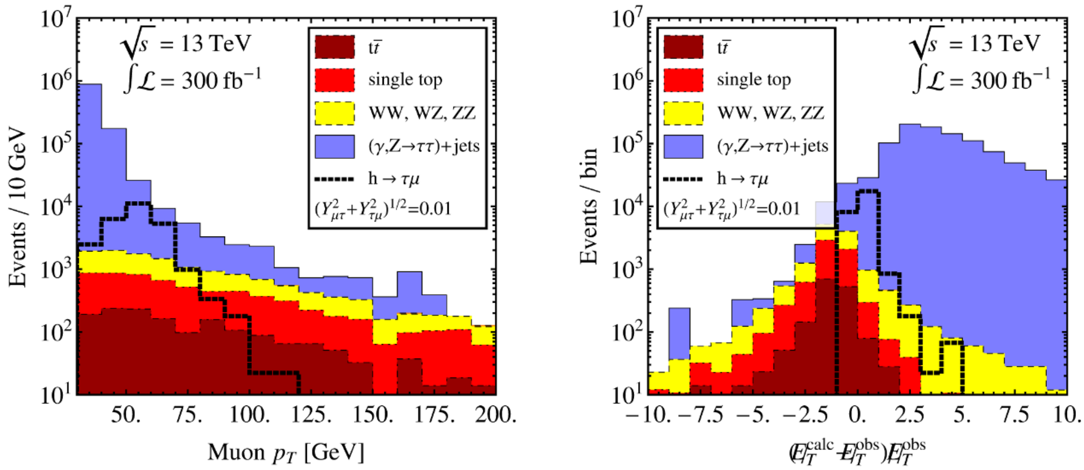

(a) (b)

Figure 4. Distributions of (a) the p_T of the muon and (b) the relative difference between the measured $\not{E}_T$ and the $\not{E}_T$ calculated from the kinematics of the charged leptons.

given by

$$\not{E}_T^{\text{calc}} = p_{T,e}\left(\frac{m_h^2}{2E_e E_\mu(1-\cos\theta_{e\mu})} - 1\right), \tag{4.2}$$

where E_e and E_μ are the energies of the electron and the muon, respectively, $p_{T,e}$ is the transverse momentum of the electron, and $\theta_{e\mu}$ is the angle between the electron and muon momenta.

The dominant backgrounds to the search for $h \to \tau\mu$ are $Z+$jets production with leptonic decay of the Z, Standard Model diboson (WW, WZ and ZZ) production, single top production and $t\bar{t}$ production. We simulate the signal and background rates in MadGraph 5 v2.0.0.beta3 [57], followed by parton showering an hadronization in Pythia 6.426 [58]. We use the MLM scheme [59] for matching between the matrix element and the parton shower. For detector simulation we use PGS [60] with the default implementation of the CMS detector.

The predicted distributions of $r_{\not{E}_T}$ and $p_{T,\mu}$ are shown in figure 4. Our plots confirm that the findings from [16] still hold at $\sqrt{s} = 13$ TeV: the p_T of the muon tends to be larger for the signal than for the dominant $Z+$jets background, and the difference between the measured and calculated $\not{E}_T$ is typically much smaller for signal events than for background events.

For the final selection, we require

$$\left(\frac{p_{T,\mu} - 60\text{ GeV}}{25\text{ GeV}}\right)^2 + \left(\frac{r_{\not{E}_T}}{0.5}\right)^2 < 1\,, \tag{4.3}$$

thus restricting the analysis to an ellipse in the $p_{T,\mu}$–$r_{\not{E}_T}$ plane (see figure 5). After this final cut, the total predicted background cross section is

$$\sigma_{\text{BG}} \simeq 64\text{ fb}\,, \tag{4.4}$$

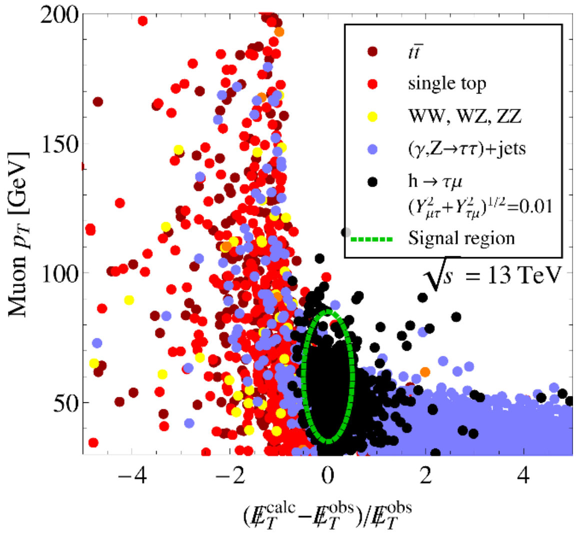

Figure 5. Two-dimensional distribution of signal events (black) and background events (colored). The horizontal axis shows the relative difference between the measured $\not{E}_T$ and the $\not{E}_T$ calculated from the kinematics of the charged leptons. The vertical axis shows the transverse momentum of the muon. The blue ellipse is the signal region defined in eq. (4.3).

while for the signal we obtain in the 2HDM

$$\sigma_{\text{sig}} \simeq 634 \text{ fb} \times \text{BR}(h_1 \to \tau\mu) = 69 \text{ fb} \times \left(\frac{\sqrt{(Y_{\tau\mu}^2 + Y_{\mu\tau}^2)(\theta_{12}^2 + \theta_{13}^2)}}{0.01} \right)^2 . \tag{4.5}$$

As a crude estimate for the relative accuracy of a measurement of the rate for $h \to \tau\mu$, we use $\sqrt{S+B}/S$, where S and B are the number of signal and background events, respectively, satisfying all preselection cuts as well as the condition (4.3). For the LHC (300 fb^{-1} integrated luminosity) and $[(Y_{\tau\mu}^2 + Y_{\mu\tau}^2)(\theta_{12}^2 + \theta_{13}^2)]^{1/2} = 0.01$, we find $\sqrt{S+B}/S \simeq 0.0053$.

This implies that, in the 2HDM and taking into account only statistical uncertainties, the LHC would be able to set a 95% confidence level upper limit $\text{BR}(h_1 \to \tau\mu) \lesssim 7.7 \times 10^{-4}$ or $[(\theta_{12}^2 + \theta_{13}^2)(Y_{\mu\tau}^2 + Y_{\tau\mu}^2)]^{1/2} \lesssim 4.0 \times 10^{-4}$. Evidence for flavor violating Higgs decays at the 3σ level would be achievable for $\text{BR}(h_1 \to \tau\mu) \gtrsim 0.0013$ or $[(\theta_{12}^2 + \theta_{13}^2)(Y_{\mu\tau}^2 + Y_{\tau\mu}^2)]^{1/2} \gtrsim 5.2 \times 10^{-4}$. Similarly 3σ evidence for CP violation from the difference between $\text{BR}(h_1 \to \tau^+\mu^-)$ and $\text{BR}(h_1 \to \tau^-\mu^+)$ requires $\text{BR}(h_1 \to \tau\mu) \times A_{\text{CP}} \gtrsim 0.0013$.

The equivalent numbers for the effective theory from section 2.1 are obtained by simply setting $\theta_{12}^2 + \theta_{13}^2 = 1$ in these expressions and replacing Y by Y^h.

We emphasize again that the above estimates do not account for systematic uncertainties, which would slightly decrease the sensitivity of a realistic experimental analysis. However, the inclusion of other decay channels — in particular those involving hadronic tau decays and those involving same flavor leptons — can be expected to significantly enhance the sensitivity, so that our limits can still be considered conservative.

For the 2HDM, we show the expected 95% C.L. sensitivity to CP violating signals in $h_1 \to \tau\mu$ decays as “Brazilian bands” in figures 2 and 3. To compute these bands, we have assumed that the observed rate for $h_1 \to \tau\mu$ decays is at the predicted level at each parameter point, but CP is not violated in the data. In computing the central black curve, we have therefore assumed the observed rates for $h_1 \to \tau^+\mu^-$ and $h_1 \to \tau^-\mu^+$ to be identical. For parameter points below the curve, the LHC is then able to disfavor CP violation at the actually predicted level for these parameter points at the 95% C.L. The green (yellow) bands are obtained in a similar way, but allowing for 1σ (2σ) statistical fluctuations of the observed asymmetry away from zero.

5 Conclusions

To summarize, we investigated the prospects for discovering a CP asymmetry in the flavor-violating Higgs decays $h \to \tau\mu$ and $h \to \tau e$ at the LHC.

Flavor violating Yukawa couplings of the SM-like 125 GeV Higgs boson appear quite generally in models with extended electroweak symmetry breaking sectors unless they are forbidden by the introduction of extra symmetries. Low energy constraints are weak for couplings involving τ leptons, so that branching ratios $\mathrm{BR}(h \to \tau\mu)$ and $\mathrm{BR}(h \to \tau e)$ of order 10% — comparable to $\mathrm{BR}(h \to \tau\tau)$ in the SM — are possible. (Constraints can be stronger in UV-complete models that lead to flavor violation also outside the Higgs sector, for instance in the form of flavor changing 4-fermion couplings.) If the flavor violating Yukawa couplings are complex, CP violation is possible in these decays and would manifest itself as an asymmetry between $\mathrm{BR}(h \to \tau^+\mu^-)$ and $\mathrm{BR}(h \to \tau^-\mu^+)$ or between $\mathrm{BR}(h \to \tau^+e^-)$ and $\mathrm{BR}(h \to \tau^-e^+)$.

We have computed the CP asymmetries for an effective field theory with only one Higgs boson and for a Type-III Two Higgs Doublet Model (2HDM). In the effective theory, the asymmetries are typically suppressed by m_τ^2/m_h^2 and/or by the Yukawa couplings $Y_{e\mu}$ and $Y_{\mu e}$, which are required to be small due to strong constraints from $\mu \to e\gamma$. To come to this conclusion, we have only considered modifications of the Higgs sector due to new physics. If the UV completion of the theory also leads to sizeable dimension-6 contributions elsewhere, for instance to flavor changing 4-lepton couplings, constraints from rare lepton decays would become even stronger, reinforcing our conclusion that CP violation in flavor changing Higgs decays can be observable only if new particles exist close to the electroweak scale.

Indeed, in the 2HDM we have found that even asymmetries of order few $\times$ 10% are possible if one of the new Higgs bosons is similar in mass to the SM Higgs. We have summarized current direct and indirect constraints on flavor and CP violating Higgs decays involving τ leptons as a function of the parameters of the 2HDM, and we have highlighted the regions of parameter space where a discovery of CP violation could be possible at the LHC (see figures 2 and 3). Interestingly, we have found that this is the case if Higgs mixing is small — a situation that is preferred due to the so-far SM-like nature of the 125 GeV Higgs boson. On the other hand, CP violation at an observable level would require that the decay $h \to \tau\mu$ or $h \to \tau e$ would have to be observed very soon.

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