LHC sensitivity to $h \to \tau^\pm \mu^\mp$

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We study the sensitivity of the LHC, with 20 fb$^{-1}$ of data, to lepton flavour violating Higgs boson decays $h \to \tau^\pm \mu^\mp$ (and $h \to \tau^\pm e^\mp$). We consider the large population of Higgses produced in gluon fusion, combined with leptonic decays of the $\tau$, and estimate that the LHC could set a 95% confidence level bound $BR(h \to \tau^\pm \mu^\mp) < 4.5 \times 10^{-3}$. This corresponds to a coupling of order the Cheng-Sher ansatz $y_{\tau\mu} = \sqrt{m_{\tau} m_{\mu}/v^2}$.

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A new resonance, hereafter referred to as the Higgs boson ($h$), was recently discovered around 126 GeV. Its couplings and branching ratios will be determined with additional data; meanwhile, one can speculate on possible departures from Standard Model (SM) expectations. It is known that Beyond-the-Standard-Model (BSM) physics is present in the lepton sector to generate neutrino masses, and should induce Lepton Flavour Violating (LFV) Higgs decays at some rate. We suppose that this rate could be detectable.

The prospects of observing LFV Higgs couplings have been studied in the past, both at colliders, and in low energy experiments (see also for supersymmetric models, and for a recent discussion with R-parity violation). The low energy bounds, and their implications for collider searches, were studied in detail for the Two Higgs Doublet Model [6, 8, 9, 19], and for a single Higgs doublet with effective operators [8, 11, 29]. They do not exclude observable $h \to \tau^\pm \mu^\mp$ or $h \to \tau^\pm e^\mp$ at the LHC. The bounds that can be set from current $h \to \tau^\pm \tau^\mp$ data, and prospects of a dedicated $h \to \tau^\pm \mu^\mp$ search (in the vector boson fusion channel) are discussed in [6, 8].

This brief note advocates searching for $h \to \tau^\pm \mu^\mp$ with Higgses produced in gluon fusion, followed by $\tau \to e\nu\bar{\nu}$. This channel was discussed for heavy Higgs bosons in [13]. Due to the large SM gluon fusion cross section, which we denote as $\sigma_{SM}(pp(gg) \to h) = 19.2 \pm 2.8$ pb, this channel produces more signal events than producing a Higgs in vector boson fusion (VBF), $\sigma_{SM}(VBF) = 1.68 \pm 0.05$ pb. The VBF channel is used for $h \to \tau^+\tau^-$ because the two jets distinguish the signal in the large $(\gamma/Z)^* \to \tau^+\tau^-$ background. However, in the case of $h \to \tau^\pm \mu^\mp$, the hard $\mu$ momentum and specific missing energy allow the signal to be sufficiently distinguished from the background that one obtains an interesting sensitivity with current data. Our sensitivity compares favourably with the results of [9], who studied $h \to \tau^\pm \mu^\mp$ following Higgs production in VBF.

We are interested in the lepton flavour violating Higgs decays $h \to \mu^\pm \tau^\mp$, and $h \to e^\pm \tau^\mp$, because we expect the “SM-like” Higgs to couple most strongly to the third generation. We only study $h \to \mu^\pm \tau^\mp \to \mu^\pm e^\mp \nu\bar{\nu}$, because we anticipate that the sensitivity to $h \to e^\pm \tau^\mp \to e^\pm \mu^\mp \nu\bar{\nu}$ should be equivalent, or better. The final state particles $e^\pm \mu^\mp + E_T$ are the same, so the SM backgrounds should be similar, and the detection prospects for a low $p_T$ muon from tau decay are better than those of a low $p_T$ electron.

The couplings of the SM Higgs are flavour diagonal, so New Physics is required to allow $h \to \tau^\pm \mu^\mp$. For a single doublet Higgs field $H$, the presence of non-renormalisable operators, for instance of the form $[H^*H]_R [\tau_R H]_R$, allows flavour-changing couplings for the physical Higgs field $h$ [14]. In the presence of additional scalar fields, such as a 2 Higgs Doublet Model [15], or the NMSSM [16, 17], renormalisable flavour-changing interactions can arise, provided the mass spectrum is away from the decoupling limit [30]. The production rate via gluon fusion could also be modified by New Physics. For instance, in the 2HDM, neglecting the heavy charged Higgses in the loop, it is multiplied by $\sin^22(\beta - \alpha)$, where $(\beta - \alpha)$ is the angle between the CP-even mass eigenstate basis and the basis where only one doublet has a vev [31].

There are weak constraints on LFV Higgs decays from low energy data. The limits from processes which the Higgs could mediate at tree level, such as $\tau \to \mu\mu\mu$, $\tau \to e\mu\mu$ and $\tau \to \eta\mu$, allow $O(1)$ LFV couplings to the Higgs [8, 15, 19]. More restrictive model-dependent bounds arise from $\tau \to \mu\gamma$ (see e.g. 8, 9 for a single Higgs, and 8, 7, 19 for the 2HDM): a LFV Higgs coupling of order the tau yukawa is allowed.

We assume a single “SM-like” Higgs at 126 GeV. In particular, we assume the change in the total decay rate due to New Physics is sufficiently small that the narrow width approximation for production and decay can be used. Most

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of the backgrounds arise from non-Higgs mediated processes, so we study the observable

$$\frac{\sigma(pp(gg) \rightarrow h)}{\sigma_{SM}(pp(gg) \rightarrow h)} BR(h \rightarrow \tau^+\tau^-)$$

(1)

This circumvents the issue of parametrising New Physics couplings. However, in simulating the backgrounds from Higgs decays, we use the SM production rate $\sigma_{SM}(pp(gg) \rightarrow h)$. This is innocuous because the Higgs background is negligible compared to the dibosons and $Z^*$s.

Our signal process is $pp(gg) \rightarrow h \rightarrow \tau^+\tau^- \rightarrow e^+e^-\nu\bar{\nu}h$, where the Higgs boson is produced by gluon fusion, and was simulated with the Monte Carlo event generator PYTHIA version 8.162. Other production mechanisms for the Higgs boson were not taken into account, since their rates are at least one order of magnitude lower. The Higgs boson mass was set to 126 GeV.

The background simulations from our previous study of lepton flavour violating $Z$ decays was used to estimate SM backgrounds leading to $e^\pm\mu^\mp$ dilepton final states. These includes the following processes: $pp \rightarrow Z/\gamma^* \rightarrow \tau^+\tau^-$, $t\bar{t}$ and $tW$, and gauge boson ($W$ and $Z$) pair production. In the background simulations of this new analysis, we also included Higgs boson production via gluon fusion, followed by lepton flavour conserving decays. The SM decays of the Higgs boson leading to $e^\pm\mu^\mp$ final state are: $pp \rightarrow h \rightarrow \tau^+\tau^-$ where both tau lepton decay leptonically, and $pp \rightarrow h \rightarrow ZZ^*$. Those processes were also simulated using PYTHIA version 8.162 with a Higgs boson mass of 126 GeV.

The simulated signal and SM Higgs boson backgrounds are summarized in Table I (see [23] for similar information on other background processes). The SM cross section of Higgs production by gluon fusion is 19.2 pb for a Higgs boson mass of 126 GeV, with a total uncertainty of $\pm$7% [24]. Branching ratios from SM were used for $h \rightarrow \tau^+\tau^-$, $h \rightarrow W^+W^-$, and $h \rightarrow ZZ^*$ decays; these are 6.73%, 23.3%, and 2.85%, respectively.

Those Monte Carlo events were passed through the DELPHES program [25], with the anti-kt jet reconstruction of FASTJET [26], to simulate the CMS detector response as described in [23].

| Processes | $\sigma \times BR$ (pb) | Number of simulated events |
|-----------|-------------------------|---------------------------|
| SM Higgs back. $pp(gg) \rightarrow h \rightarrow \tau^+\tau^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ with $\ell, \ell' = e, \mu$ | 0.160 | 30,000 |
| SM Higgs back. $pp(gg) \rightarrow h \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ with $\ell, \ell' = e, \mu, \tau$ | 0.469 | 100,000 |
| SM Higgs back. $pp(gg) \rightarrow h \rightarrow ZZ^* \rightarrow f\bar{f}f'\bar{f}'$ with $f = q, \nu, e, \mu, \tau$ | 0.548 | 100,000 |
| Signal $pp(gg) \rightarrow h \rightarrow \tau^+\tau^- \rightarrow e^+e^-\nu\bar{\nu}$ | | 100,000 |

TABLE I: Standard Model Higgs boson backgrounds in the search for lepton flavour violating $h$ decay at the LHC (see [23] for similar information about non-Higgs processes); the second column contains $\sigma \times BR$ (in pb) for p-p collisions at $\sqrt{s} = 8$ TeV for Higgs boson production via gluon fusion, and the third column shows the number of simulated events in this analysis, which is in all cases greater than 10 times $\mathcal{L} \sigma BR$, with $\mathcal{L} = 20$ fb$^{-1}$.

The $h \rightarrow \tau^+\tau^-$ event selection follows closely what was done in [23] to select $Z \rightarrow \tau^+\tau^-$ events with an electron and a muon back-to-back in the transverse plane. Events are required to contain at least one muon with $p_T$ greater than 30 GeV and $|\eta| < 2.1$, and at least one electron with $p_T$ greater than 15 GeV and $|\eta| < 2.5$. Events must contain exactly 2 opposite-sign (OS) leptons. Events having one or more reconstructed jets with $p_T > 30$ GeV and $|\eta| < 2.5$ are rejected. The azimuthal angle between the electron and the muon, $\Delta\phi(e, \mu)$, has to be higher than 2.7 radians. And the azimuthal angle between the electron and the direction of the missing transverse energy, $\Delta\phi(e, \vec{E}_T)$, has to be lower than 0.3.

The final selection criterium has been chosen to exploit the kinematic properties of $h \rightarrow \tau^+\tau^-$ compared to the remaining SM backgrounds. The $\tau$ lepton produced in this Higgs boson decay is highly boosted. Assuming massless particles in the $\tau$-lepton decay $\tau \rightarrow e\nu\bar{\nu}$ and using the collinear approximation for these decay products, the $\tau$ momentum $p_\tau$ can be expressed from the measured electron momentum $p_e$ as

$$p_\tau = \alpha p_e$$

(2)

The momentum of the two-neutrinos system is then simply $(\alpha - 1)p_e$; and its transverse component should correspond to the missing transverse energy measured in the detector. This $\alpha$ factor can then be related to the Higgs boson mass with the following formula:

$$\alpha = \frac{M_h^2}{4E_eE_\mu \sin^2(\theta_{ee}/2)}$$

(3)
using the electron and muon energies $E_e$ and $E_\mu$, and the $\theta_{e\mu}$ angle between the electron and the muon directions. For $M_h = 126$ GeV, $\alpha$ can be used to compare the transverse momentum of the two-neutrinos system, computed under the above hypotheses, to the measured value of transverse missing energy of the event ($E_T^{\text{reco}}$):

$$\delta E_T = \frac{(\alpha - 1)p_\mu^T - E_T^{\text{reco}}}{E_T^{\text{reco}}}$$

The distribution of the $\delta E_T$ variable from Eqn. 4 is shown in Fig. 1a after applying all selection criteria described so far. As expected, the distribution for the signal is peaked at 0 while the backgrounds have lower or higher values, which means that the measured value $E_T^{\text{reco}}$ is not compatible with the value of $(\alpha - 1)p_\mu^T$ expected for a Higgs boson of mass of 126 GeV decaying to $\tau^\pm \mu^\mp \to e^\pm \nu e\bar{\nu}$. There are however important overlaps between signal and background for this distribution. Therefore, we also exploit that the transverse momentum of the muon, $p_\mu^T$, is higher in $h \to \tau^+ \mu^-$ events than in SM background events (see Fig. 1b). The 2-dimensional distribution ($\delta E_T, p_\mu^T$) is shown in Fig. 2. Events are then required to be in an ellipse centered around the signal distribution and defined as:

$$\left(\frac{p_\mu^T - 60}{25}\right)^2 + \left(\frac{\delta E_T}{0.25}\right)^2 < 1$$

FIG. 1: Distributions of $\delta E_T$ (a), and of the muon $p_T$ (b), before applying the final selection criterium in the ($\delta E_T, p_\mu^T$) plane.

The number of background and signal events at each step of the selection are reported in Tab. III for an integrated luminosity of 20 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. A good signal to background ratio is achieved, allowing sensitivity to the $h \to \tau^\pm \mu^\mp$ signal with a branching ratio below 1%. In this Table III contributions from SM Higgs decays, which are included in the total background evaluation, are solely indicated to show how the angular criteria reduce their contribution. At the final stage, LFV Higgs decays largely dominates over SM Higgs decays, whose contribution is almost negligible compared to other SM backgrounds. The number of events selected after applying all selection criteria are reported in Tab. III. The dominant backgrounds are $pp \to Z \to \tau^\pm \tau^\mp$ and diboson pair production (mainly $W^+W^-$).

The number of events obtained in Tab. III were used to extract a limit on $BR(h \to \tau^\pm \mu^\mp)$. For that purpose, the modified frequentist CL$_s$ [27] method was used. As in our previous study [23], a 3% systematic uncertainty was set on the signal and background yields due to experimental uncertainties on lepton identifications. In addition, we also took into account the 15% systematic uncertainty on Higgs boson production via gluon fusion for the signal and for the backgrounds from SM Higgs decays. The expected 95% C.L. limit calculated with this procedure is:

$$\frac{\sigma(pp(gg) \to h)}{\sigma_{SM}(pp(gg) \to h)} BR(h \to \tau^\pm \mu^\mp) < 4.5 \times 10^{-3}$$

The reach indicated by eqn (6) is phenomenologically interesting. The Cheng-Sher ansatz [28], which can parametrise extra-dimensional models of flavour, gives flavour-changing couplings of order $y_{\tau\mu} \sim \sqrt{m_\tau m_\mu/v^2}$, where
v = 174 GeV is the Higgs vev. For the h boson, this gives

$$BR(h \to \tau^+ \tau^-) \simeq \frac{m_{\mu}}{m_{\tau}} BR(h \to \tau^+ \tau^-) \simeq 4.1 \times 10^{-3}$$ (7)

where the last number applies when h has the Standard Model branching ratio to taus.

The sensitivity of eqn (6) can be compared to the prospects of $h \to \tau^+ \tau^-$ with Higgs production via VBF (where hadronic and leptonic tau decays could be used), as was studied by Harinik, Kopp, and Zupan [9]. Current data indicate that the production cross sections via gluon fusion and VBF have approximately their SM values, implying more signal events in the channel pp($gg \to h \to \tau^+ \tau^- \rightarrow e^+ \mu^- + E_T$). We find a signal efficiency of 5.34%. Although the results of [9] are presented differently from ours, the gluon fusion channel with leptonic taus, appears to have better sensitivity than VBF with hadronic taus.

| Selection criteria | $N_{background}$ | $N_{h \rightarrow \tau^+ \tau^-}$ | $N_{h \rightarrow WW}$ | $N_{h \rightarrow ZZ}$ | Signal efficiency (%) | $N_{sig}$ |
|-------------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| $\geq 1$ muon with $p_T > 30$ GeV and $|\eta| < 2.1$ and $\geq 1$ electron with $p_T > 15$ GeV and $|\eta| < 2.5$ | 59271 ± 76 | 89. ± 3. | 235. ± 5. | 4.2 ± 0.7 | 21.2 ± 0.1 | 145.4 ± 0.9 |
| jet veto: no jet with $p_T > 30$ GeV and $|\eta| < 2.5$ | 58447 ± 79 | 89. ± 3. | 235. ± 5. | 2.2 ± 0.5 | 21.2 ± 0.1 | 145.4 ± 0.9 |
| $\Delta \phi(e, \mu) > 2.7$ | 19477 ± 44 | 51. ± 2. | 123. ± 3. | 1.0 ± 0.3 | 13.1 ± 0.1 | 89.7 ± 0.7 |
| $\Delta \phi(e, E_T) < 0.3$ | 13261 ± 36 | 40. ± 2. | 8.7 ± 0.9 | 0.1 ± 0.1 | 10.7 ± 0.1 | 72.9 ± 0.7 |
| 2D cut in $(\delta E_T, p_T^\mu)$ plane | 3885 ± 20 | 15. ± 1. | 2.4 ± 0.5 | 0.1 ± 0.1 | 7.85 ± 0.09 | 53.7 ± 0.6 |

The results of Table III for the $h \to \tau^+ \tau^-$ search at the $\sqrt{s} = 8$ TeV LHC with $\mathcal{L} = 20$ fb$^{-1}$, number of events expected for each SM background and for the signal normalized to $\sigma_{SM}(pp(gg) \to h) \times BR(h \to \tau^+ \tau^-)$ is $10^{-2}$.
This analysis used missing transverse energy reconstructed from the whole event. However, the $E_T$ modeling in a fast detector simulation is too optimistic; a full detector simulation including pile-up effects will enlarge $E_T$ resolution and the overlap between signal and backgrounds, thus reducing slightly the sensitivity. These effects have to be studied by the LHC collaborations in order to perform this analysis. We estimate that the sensitivity is worsened by a factor $\lesssim 2$, if the missing transverse energy is reconstructed solely from the lepton momenta.

The SM Higgs boson is very narrow, mostly decaying to $b\bar{b}$ via a coupling $g_0 \approx 1/35$. Its branching ratios are therefore a sensitive probe of small non-standard Higgs couplings since, away from the peak of the Breit-Wigner, observables lose the $1/g_0^2$ amplification and are suppressed by another small Higgs coupling squared. This is different from the $Z$ boson, many of whose non-standard couplings are better constrained by low energy observables. In this paper we explored the sensitivity of the LHC with $20 \, fb^{-1}$ of data to a SM-like Higgs boson decaying to $\tau^\pm \mu^\mp$ or $\tau^\pm e^\mp$. We considered Higgs boson production via the largest cross section, which is gluon fusion, and leptonic tau decays, because this gives a clean signature. Assuming experimental systematic uncertainties of 3%, and accurate missing transverse energy reconstruction, we find that the LHC could exclude at 95% C.L. $BR(h \to \tau^\pm \mu^\mp), BR(h \to \tau^\pm e^\mp) < 4.5 \times 10^{-5}$.

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[1] S. Chatrchyan et al. [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” Phys. Lett. B 716 (2012) 30 [arXiv:1207.7235 [hep-ex]]. G. Aad et al. [ATLAS Collaboration], “Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC,” Phys. Lett. B 716 (2012) 1 [arXiv:1207.7214 [hep-ex]].

[2] T. Han and D. Marfatia, “$h \to \mu\tau$ at hadron colliders,” Phys. Rev. Lett. 86 (2001) 1442 [hep-ph/0008141]. K. A. Assamagan, A. Deandrea and P. A. Delsart, “Search for the lepton flavor violating decay $A_0/H_0 \to \tau^\pm \mu^\mp$ at hadron colliders,” Phys. Rev. D 67 (2003) 035001 [arXiv:hep-ph/0207302]. S. Arcelli, “Search for $H/A \to \mu\tau$ and $H \to \tau\tau$ at the LHC,” Eur. Phys. J. C 33 (2004) S726.

[3] R. Diaz, R. Martinez and J. A. Rodriguez, “Lepton flavor violation in the two Higgs doublet model type III,” Phys. Rev. D 63 (2001) 095007 [arXiv:hep-ph/0010140]. E. O. Iltan, “Electric dipole moments of charged leptons and lepton flavor violating interactions in the general two Higgs doublet model,” Phys. Rev. D 64 (2001) 013013 [hep-ph/0101017].

[4] A. Brignole and A. Rossi, “Anatomy and phenomenology of mu-tau lepton flavor violation in the MSSM,” Nucl. Phys. B 701 (2004) 3 [hep-ph/0404211].

[5] Abdessalem Arhrib, Yifan Cheng, Otto C. W. Kong, “A Comprehensive Analysis on Lepton Flavor Violating Higgs to $\mu + \tau$ Decay in Supersymmetry without R Parity”, arXiv:1210.8241.

[6] S. Kanemura, T. Ota and K. Tsumura, “Lepton flavor violation in Higgs boson decays under the rare tau decay results,” Phys. Rev. D 73 (2006) 016006 [hep-ph/0506519].

[7] S. Davidson and G. J. Grenier, “Lepton flavour violating Higgs and tau to mu gamma,” Phys. Rev. D 81 (2010) 095016 [arXiv:1001.0434 [hep-ph]].

[8] A. Goudelis, O. Lebedev and J. -h. Park, “Higgs-induced lepton flavor violation,” Phys. Lett. B 707 (2012) 369 [arXiv:1111.1715 [hep-ph]].

[9] R. Harnik, J. Kopp and J. Zupan, “Flavor Violating Higgs Decays,” arXiv:1209.1397 [hep-ph].

[10] C. -H. Chen and C. -Q. Geng, “Lepton flavor violation in tau decays,” Phys. Rev. D 74 (2006) 035010 [hep-ph/0605299].

[11] D. McKeen, M. Pospelov and A. Ritz, “Modified Higgs branching ratios versus CP and lepton flavor violation,” arXiv:1208.4597 [hep-ph].

[12] G. Blankenburg, J. Ellis and G. Isidori, “Flavour-Changing Decays of a 125 GeV Higgs-like Particle,” Phys. Lett. B 712 (2012) 386 [arXiv:1202.5704 [hep-ph]].

[13] J. L. Diaz-Cruz, D. K. Ghosh and S. Moretti, “Lepton Flavour Violating Heavy Higgs Decays Within the nuMSSM and Their Detection at the LHC,” Phys. Lett. B 679 (2009) 376 [arXiv:0809.5158 [hep-ph]].

[14] K. S. Babu and S. Nandi, “Natural fermion mass hierarchy and new signals for the Higgs bosons,” Phys. Rev. D 62 (2000) 033002 [hep-ph/9907213]. G. F. Giudice and O. Lebedev, “Higgs-dependent Yukawa couplings,” Phys. Lett. B 665 (2008) 79 [arXiv:0804.1753 [hep-ph]].

[15] J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, *The Higgs Hunter’s Guide* (Perseus Publishing, Cambridge, MA, 1990).

[16] U. Ellwanger, C. Hugonie and A. M. Teixeira, “The Next-to-Minimal Supersymmetric Standard Model,” Phys. Rept. 496 (2010) 1 [arXiv:0910.1785 [hep-ph]].

[17] G. Belanger, U. Ellwanger, J. F. Gunion, Y. Jiang, S. Kraml and J. H. Schwarz, “Higgs Bosons at 98 and 125 GeV at LEP and the LHC,” arXiv:1210.1976 [hep-ph].
[18] S. Davidson and H. E. Haber, “Basis-independent methods for the two-Higgs-doublet model,” Phys. Rev. D 72 (2005) 035004 [Erratum-ibid. D 72 (2005) 099902] [hep-ph/0504050].

[19] P. Paradisi, “Higgs-mediated $\tau \to \mu$ and $\tau \to e$ transitions in II Higgs doublet model and supersymmetry,” JHEP 0602 (2006) 050 [hep-ph/0508054].

[20] LHC Higgs Cross Section Working Group, A. David, A. Denner, M. Duehrssen, M. Grazzini, C. Grojean, G. Passarino and M. Schumacher et al., “LHC HXSWG interim recommendations to explore the coupling structure of a Higgs-like particle,” arXiv:1209.0040 [hep-ph].

[21] G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J. -B. Flament, “Higgs couplings beyond the Standard Model,” arXiv:1210.8120 [hep-ph].

[22] T. Sjostrand, S. Mrenna and P. Z. Skands, “A Brief Introduction to PYTHIA 8.1,” Comput. Phys. Commun. 178 (2008) 852 [arXiv:0710.3820 [hep-ph]].

[23] S. Davidson, S. Lacroix and P. Verdier, “LHC sensitivity to lepton flavour violating $Z$ boson decays,” JHEP 1209 (2012) 092 [arXiv:1207.4894 [hep-ph]].

[24] S. Dittmaier et al. [LHC Higgs Cross Section Working Group Collaboration], “Handbook of LHC Higgs Cross Sections: 1. Inclusive Observables,” arXiv:1101.0593 [hep-ph].

[25] S. Ovyn, X. Rouby and V. Lemaitre, “DELPHES, a framework for fast simulation of a generic collider experiment,” arXiv:0903.2225 [hep-ph].

[26] M. Cacciari, G. P. Salam and G. Soyez, “FastJet user manual,” Eur. Phys. J. C 72 (2012) 1896 [arXiv:1111.6097 [hep-ph]].

[27] T. Junk, “Confidence level computation for combining searches with small statistics,” Nucl. Instrum. Meth. A 434 (1999) 435 [hep-ex/9902006];
A. Read, “Modified Frequentist Analysis of Search Results (The CLs Method),” CERN-2000-005 (2000).

[28] T. P. Cheng and M. Sher, “Mass Matrix Ansatz and Flavor Nonconservation in Models with Multiple Higgs Doublets,” Phys. Rev. D 35 (1987) 3484.

[29] For a detailed discussion, see [12].

[30] For instance, in the 2HDM, two neutral scalars with masses below the decoupling scale, is consistent with low energy constraints including $b \to s\gamma$.

[31] A 2HDM with LFV is of “Type III”, so $\tan \beta$ is not uniquely defined [18]. However, if the $\tau$ is the heaviest charged lepton, and $\tan \beta$ in the ratio $y_\tau/m_\tau$, where $y_\tau$ is the $\tau$ Yukawa coupling, then the flavour-changing vertices have a factor $\tan \beta$.

[32] see, e.g. [20], or [21] for a recent discussion and references.