The $h \to \mu\tau$ Decay in the Two Higgs Doublets Model with a fourth generation of fermions

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1. Introduction and Motivations

- CMS and ATLAS experiments reported an excess at a center of mass energy of 8 TeV and an integrated luminosity of $19.7\ fb^{-1}$,

$$BR(h \to \mu\tau) = (0.84^{+0.39}_{-0.37})\% \quad \textbf{[CMS]}$$

$$BR(h \to \mu\tau) = (0.53 \pm 0.51)\% \quad \textbf{[ATLAS]}$$

[CMS Collaboration, Phys. Lett. 749, 337 (2015)].

[ATLAS Collaboration], arXiv:1508.03372 (2015)]

- Now at 13 TeV , CMS reported that " THERE IS NOT OBSERVED EXCESS"

$$BR(h \to \mu\tau) = (0.76^{+0.81}_{-0.84})\%$$

[CMS-PAS-HIG-16-005].

More data are needed to make definitive conclusions on the origin of that excess.

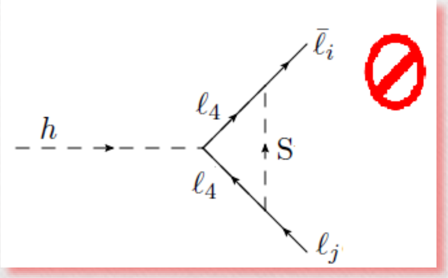
2. Two Higgs Doublets Model for the Fourth Generation (4G2HDM)

We can differentiate three types of 2HDM in which the heavy fourth family can be incorporated, we analyzed the scenario in which ϕ_1 gives masses only to fermions of the fourth family while ϕ_2 generates masses for all other fermions, in this case $\tan\beta = \frac{m_4}{m_t} \sim \mathcal{O}(1)$.

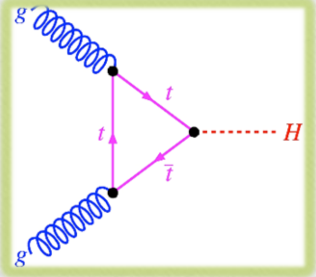
$$L_{\phi^0} = \frac{g}{4m_W} g_\phi \bar{l}_i \left[\left(g_s^\phi\right)_{ij} + \left(g_p^\phi\right)_{ij} \gamma_5 \right] l_j \phi^0, \qquad L_\phi = \frac{g}{2\sqrt{2}m_W} g_\phi \bar{\nu}_i \left[\left(g_s^\phi\right)_{ij} + \left(g_p^\phi\right)_{ij} \gamma_5 \right] l_j H^+$$

S. Bar-Shalom, et al. Phys Lett B, Volume 709, 3. (2012).

- If $\phi = h^0$, then $i, j \neq 4$.



Higgs boson production by fusion of Gluons is not altered .



3. The $h \to \mu\tau$ Decay at tree level in 4G2HDM

- The amplitude of decay is

$$i\mathfrak{M} = i\overline{u_2}(p_2, m_\tau)(A + iB\gamma_5)u_1(p_1, m_\mu)$$

where, for 125 GeV Higgs boson, we have at tree level

$$A = \frac{g}{4m_W} g_{h^0} \left(g_s^{h^0}\right)_{ij} \quad \text{where} \quad g_{h^0} = {}^{c_\alpha}/_{s_\beta} + {}^{s_\alpha}/_{c_\beta}$$

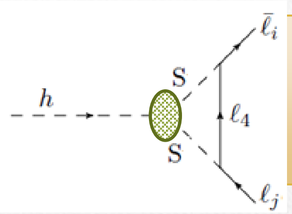
B is obtained by changing the factors $g_s^{h^0} \longrightarrow -i g_p^{h^0}$

- $x \equiv \frac{\pi}{2} - (\beta - \alpha)$
- We have chosen:

$$\Sigma_{4\mu}^{l} \Sigma_{4\tau}^{l*} = 10^{-3}$$

$\tan\beta$	$Br(x \to 0.1)[\%]$	$Br(x \to 0.01)[\%]$
1	1.17×10^{-4}	1.17×10^{-6}
2	1.83×10^{-4}	1.83×10^{-6}
3	3.25×10^{-4}	3.26×10^{-6}
4	5.29×10^{-4}	5.31×10^{-6}
5	7.92×10^{-4}	7.95×10^{-6}

Triple Scalar Couplings



- The scalar trilinear couplings have the form

$$
\begin{aligned}
\lambda_{H^+H^-h} &= \frac{1}{v}\left[\left(2M^2 - 2m_{H^\pm}^2 - m_h^2\right) s_{\beta-\alpha} + 2\left(M^2 - m_h^2\right) \cot 2\beta\, c_{\beta-\alpha}\right], \\
\lambda_{AAh} &= \frac{1}{2v}\left[\left(2M^2 - 2m_A^2 - m_h^2\right) s_{\beta-\alpha} + 2\left(M^2 - m_h^2\right) \cot 2\beta\, c_{\beta-\alpha}\right], \\
\lambda_{HHh} &= \frac{s_{\beta-\alpha}}{2v}\left[\left(2M^2 - 2m_H^2 - m_h^2\right) s_{\beta-\alpha}^2 + 2\left(3M^2 - 2m_H^2 - m_h^2\right) \cot 2\beta\, s_{\beta-\alpha} c_{\beta-\alpha}\right. \\
&\quad \left. - \left(4M^2 - 2m_H^2 - m_h^2\right) c_{\beta-\alpha}^2\right]
\end{aligned}
$$

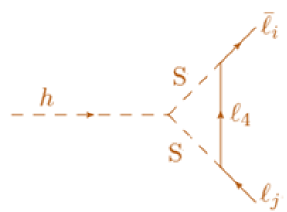
S. Kanemura, Y. Okada, and E Senaha. Phys. Lett. B606, 361 (2005).

M describes the soft breaking scale of the Z_2 symmetry, we have fixed this scale through

$$\sqrt{\lambda v^2} = \sqrt{m_\phi^2 - M^2}$$

4. The $h \to \mu\tau$ Decay at one loop in 4G2HDM

- $S = \phi = H^0, A^0, H^+$, then $i, j = 1,2,3,4$



in this case

$$A = \frac{g^2 g_\phi^2}{16 m_h m_W^2} \int_{x=0}^{1} \int_{y=0}^{1-x} \Xi(x,y)\, dx dy$$

where the function $\Xi(x,y)$ is given by

$$\Xi(x,y) = \frac{(g_p^\phi)_{i4}(g_p^\phi)_{j4}\left(-r_{\ell_4} + r_i x + r_j y\right) + (g_s^\phi)_{i4}(g_s^\phi)_{j4}\left(r_{\ell_4} + r_i x + r_j y\right)}{r_j^2 y^2 + r_\phi^2 x - (x+y-1)\, r_{\ell_4}^2 + \left(r_\phi^2 - x^2 + r_j^2(x-1)\right) y + r_i^2 x\,(x+y-1)}$$

- The form factor B is obtained by changing the factors

$$\left(g_p^\phi\right)_{i4}\left(g_p^\phi\right)_{j4} \longrightarrow \left(g_p^\phi\right)_{j4}\left(g_s^\phi\right)_{i4}$$

$$\left(g_s^\phi\right)_{i4}\left(g_s^\phi\right)_{j4} \longrightarrow \left(g_p^\phi\right)_{4}\left(g_s^\phi\right)_{i4}$$

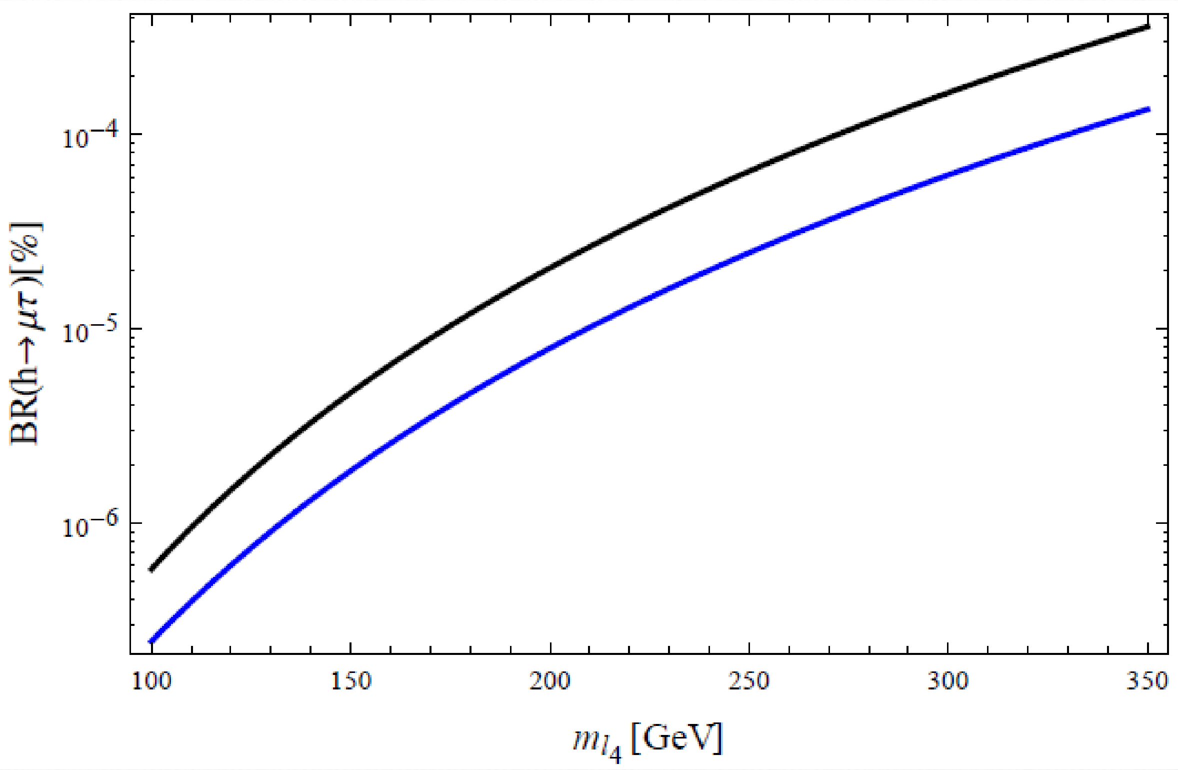


Figure 1. Branching fraction as a function of the leptons mass of the fourth family for $m_{H^\pm} = 1000\ GeV$. $\tan\beta = 1$ (blue line), $\tan\beta = 3$ (black line). In this plots we have fixed $x = 0.1$, $\sqrt{\lambda v^2} = 400\ GeV$.

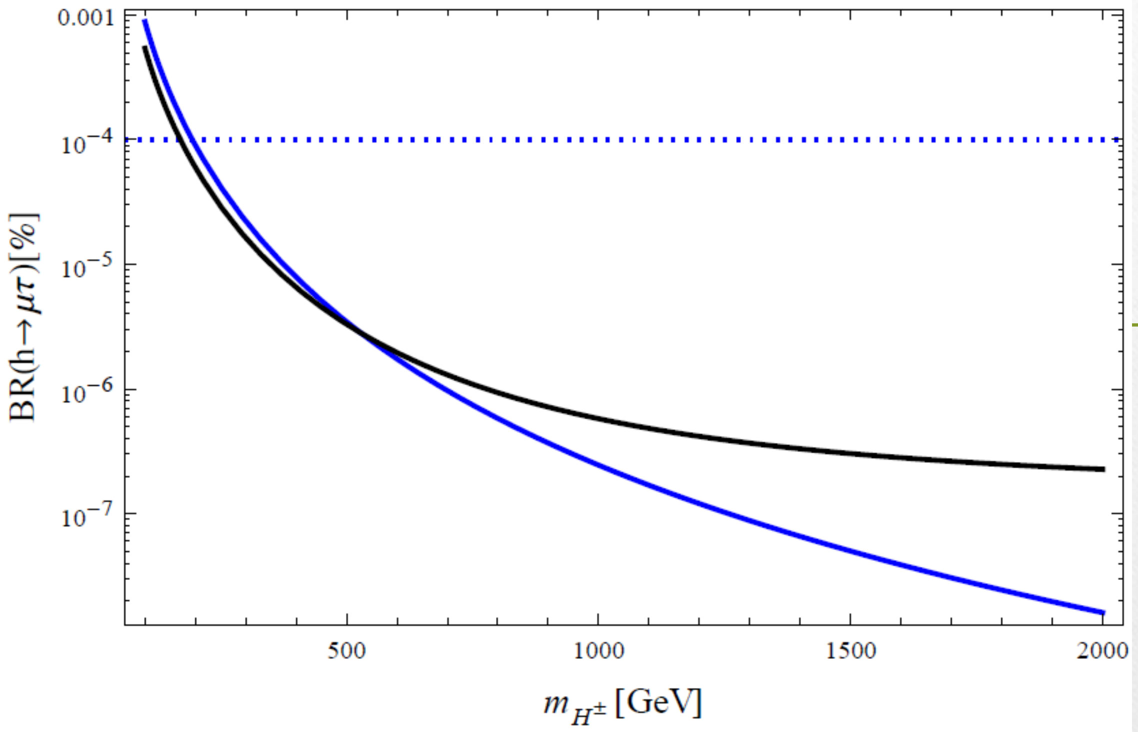


Figure 2. Branching fraction as a function of the charged scalar's mass for $m_{l_4} = 100\ GeV$. The horizontal line shows the branching of decay at tree level. $\tan\beta = 1$ (blue line), $\tan\beta = 3$ (black line). In this plots we have fixed $x = 0.1$, $\sqrt{\lambda v^2} = 400\ GeV$.

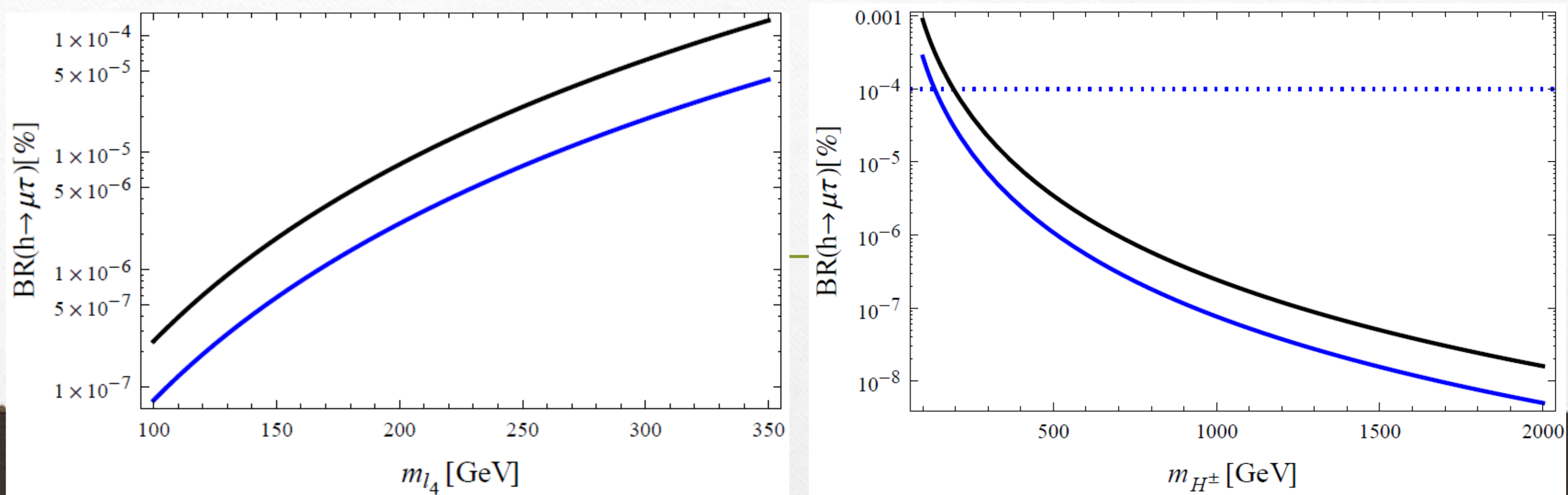


Figure 3. Branching fraction as a function of the **Left.** leptons mass of the fourth family for $m_{H^\pm} = 1000$ GeV. **Right.** charged scalar's mass for $m_{l_4} = 100$ GeV $\Gamma = 4.07$ MeV (black line), $\Gamma = 13$ MeV (blue line). In this plots we have fixed $\tan\beta = 1\,,\; x = 0.1, \sqrt{\lambda v^2} = 400\ GeV$.

$\Gamma \sim 4.07$ MeV. SM prediction.

$\Gamma < 13$ MeV [CMS-HIG-14-032 (2016)].

5. Conclusions

1. The fourth family of fermions has not been completely ruled out and may well be accommodated in a two Higgs doublets model.
2. Although $h \to \mu\tau$ decay could take place at tree level, the contributions of the fourth family can improve the respective branching ratio.
3. Our best results for the branching fraction can be for heavy charged leptons of the fourth family and the limit for the product of mixing matrices, which is very small.