PROCEEDINGS OF SCIENCE

Seeking a light CP-odd Higgs state

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Exclusive decays of the Higgs boson to a pseudoscalar quarkonium and a pair of leptons, $h \to \eta_{c,b}\ell^+\ell^-$ are rare and can be substantially enhanced in a scenario which includes a light CP-odd Higgs A ($m_A \lesssim m_h$) which makes them experimentally appealing. We illustrate that feature in two Higgs doublet models (2HDM) and show that $\mathscr{B}(h \to \eta_{c,b}\tau^+\tau^-)$ can be an order of magnitude larger than in the Standard Model, i.e. $\mathscr{O}(10^{-6} \div 10^{-5})$.

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1. Introduction

Studies of the Higgs boson decaying to a quarkonium were so far limited to the extraction of the Yukawa coupling from the radiative decay $h \to J/\psi\gamma$, or from $h \to \eta_c Z, J/\psi Z$, as well as to the search of lepton flavour violation via $h \to J/\psi \ell_1 \ell_2$ [1]. In various forms of two-Higgs doublet models (2HDM) the CP-odd Higgs state is often assumed to be heavier than the CP-even one, $m_A > m_h$, i.e. the one observed at LHC. That assumption, however, needs to be tested experimentally. Here we propose a study of the rare decay $\mathcal{B}(h \to \eta_{c,b}\ell^+\ell^-)$, where $\eta_{c,b}$ stands for the pseudoscalar $c\bar{c}$ or $b\bar{b}$ quarkonium, as a promising mode to probe the light pseudoscalar Higgs state because the branching fraction of this decay mode can be enhanced by an order of magnitude if $m_A < m_h$ [2].

2. Decay rate in the Standard Model and in 2HDM

In the Standard Model the dominant contribution to $h \to P\ell^+\ell^-$ ($P = \eta_c$ or η_b) comes from the diagram shown in Fig. 1c and reads,

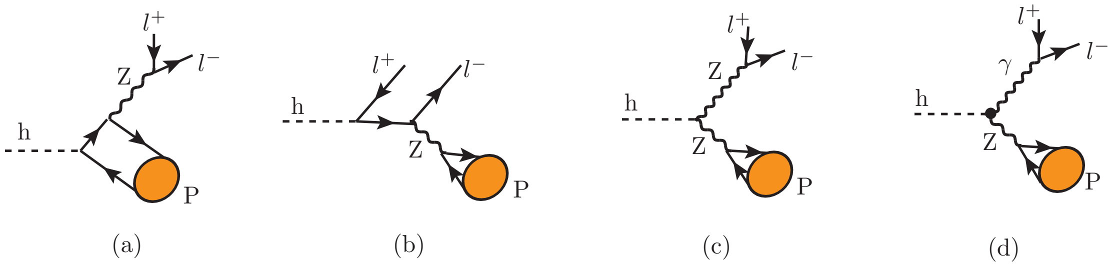

Figure 1: *Diagrams relevant to $h \to P\ell^+\ell^-$ decay in the Standard Model. The full dot in the diagram (d) indicates that the vertex is loop-induced. Its contribution to the decay rate is nevertheless zero.*

$$\mathcal{M}(h \to P\ell^+\ell^-)^{1c} = -\frac{1}{4}\left(\frac{g}{\cos\theta_W}\right)^3 m_Z \frac{g_A^q f_P}{(q^2-m_Z^2)\,(k^2-m_Z^2)}\left(-g^\alpha_\mu + \frac{q^\mu q_\alpha}{m_Z^2}\right) \left(-g^{\nu\alpha} + \frac{k^\nu k^\alpha}{m_Z^2}\right) k_\nu\, \bar{u}_\ell \gamma^\mu (g_V^\ell - g_A^\ell \gamma_5) v_\ell \,, \tag{2.1}$$

where we used the standard notation with $g_A^f = T_q^3$ and with

$$\langle P(k)|\bar{q}\gamma^\mu\gamma_5 q|0\rangle = -i f_P k_\mu, \qquad \langle P(k)|\bar{q}\gamma^5 q|0\rangle = -i f_P \frac{m_P^2}{2m_q}. \tag{2.2}$$

The values of the decay constants are known from lattice QCD, namely $f_{\eta_c} = 391 \pm 4$ MeV and $f_{\eta_b} = 667 \pm 7$ MeV [3]. The full expression, which includes all contributions depicted in Fig. 1 can be found in Ref. [2] which contains a full list of references.

In the 2HDM, besides the diagrams shown in Fig. 1, one also has to deal with the ones depicted in Fig. 2, of which the first two are numerically much less significant than the remaining three:

$$\mathcal{M}^{(2c)} = -\left(\frac{g}{2\cos\theta_W}\right)^2 \frac{m_q \xi_A^q}{v} \frac{m_P^2 f_P}{2m_q} \frac{\cos(\beta-\alpha)}{(q^2-m_Z^2)\,(k^2-m_A^2)}\left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{m_Z^2}\right)(k+p)^\mu\, \bar{u}_\ell \gamma^\nu (g_V^\ell - g_A^\ell\gamma_5) v_\ell \,,$$

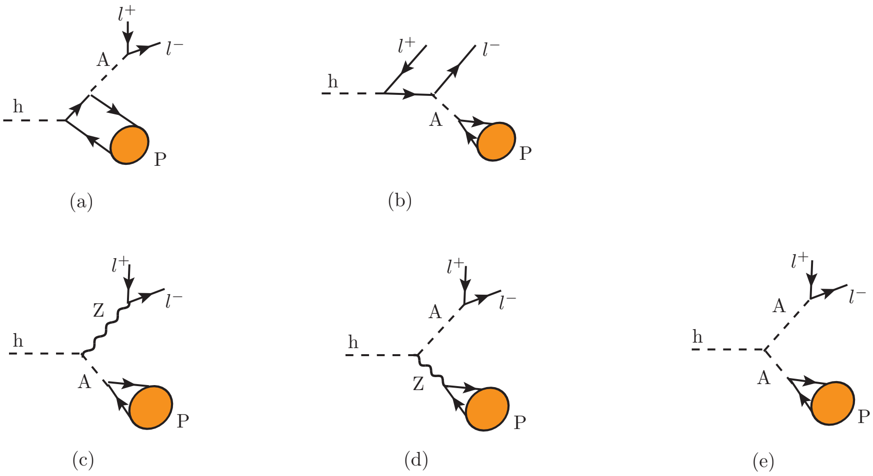

Figure 2: *Contributions to the $h \to P\ell^+\ell^-$ decay amplitude in a 2HDM scenario.*

$$\mathscr{M}^{(2d)} = \left(\frac{g}{2\cos\theta_W}\right)^2 \frac{m_\ell \xi_A^\ell}{v} \frac{g_A^q f_P \cos(\beta-\alpha)}{(q^2-m_A^2)\,(k^2-m_Z^2)} \left(-g_{\mu\nu} + \frac{k_\mu k_\nu}{m_Z^2}\right) (q+p)^\mu k^\nu \,\bar{u}_\ell \gamma_5 v_\ell\,,$$

$$\mathscr{M}^{(2e)} = -\,\lambda_{hAA} v \,\frac{m_q \xi_A^q}{v} \frac{m_\ell \xi_A^\ell}{v} \frac{m_P^2 f_P}{2m_q} \frac{1}{(q^2-m_A^2)\,(k^2-m_A^2)} \bar{u}_\ell \gamma_5 v_\ell\,,$$

where v is the Standard Model vev, λ_{hAA} is the trilinear coupling defined in [2], while ξ_A^q is a coupling of the $q\bar{q}$-pair to the CP-odd Higgs state, $\xi_A^u = -i\zeta^u$, $\xi_A^{d,\ell} = i\zeta^{d,\ell}$, the values of which depend on the type of 2HDM and are given in Tab. 1. We checked that, to a very good approximation,

$$\Gamma(h \to P\ell^+\ell^-) \simeq \Gamma(h \to PZ^* \to P\ell^+\ell^-) + \Gamma(h \to PA^* \to P\ell^+\ell^-). \tag{2.3}$$

where for the two pieces we obtained [with $\lambda_{Z,A} \equiv \lambda(m_h, m_P, m_{Z,A})$],

$$\Gamma(h \to P\ell^+\ell^-) \overset{Z^*}{=} \frac{f_P^2 m_Z^3}{384\pi^2 \Gamma_Z m_h^3 v^6} \left[\cos^2(2\theta_W) + 4\sin^4\theta_W\right] \left(g_A^q - \frac{\xi_A^q m_P^2 \cos(\beta-\alpha)}{2(m_A^2-m_P^2)}\right)^2 \lambda_Z^{3/2},$$

$$\Gamma(h \to PA^* \to P\ell^+\ell^-) = \frac{f_P^2 m_A}{512\pi^2 \Gamma_A m_h^3 v^2} \left(\frac{m_\ell \xi_A^\ell}{v}\right)^2 \left[\lambda_{hAA} \frac{m_P^2}{m_A^2 - m_P^2} \frac{\xi_A^q}{v} v^2 + 2\cos(\beta-\alpha) \frac{g_A^q}{v} (m_h^2 - m_A^2)\right]^2 \lambda_A^{1/2},$$

with $g_V^f = T_f^3 - 2Q_f \sin^2\theta_W$, and we neglected terms $\propto m_\ell^2/m_Z^2$.

Model	ζ^d	ζ^u	ζ^ℓ
Type I	$\cot\beta$	$\cot\beta$	$\cot\beta$
Type II	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
Type X (lepton specific)	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Type Z (flipped)	$-\tan\beta$	$\cot\beta$	$\cot\beta$

Table 1: *Couplings ζ^f in various types of 2HDM.*

3. Results and Conclusion

After making a full scan of the 2HDM as explained in Ref. [2], with an emphasis on $m_A < m_h$, we studied

$$R^{\tau\tau}_{\eta_{cb}} = \frac{\mathscr{B}(h\to\eta_{cb}\tau^+\tau^-)^{\rm 2HDM}}{\mathscr{B}(h\to\eta_{cb}\tau^+\tau^-)^{\rm SM}}, \qquad R^{\mu\mu}_{\eta_{cb}} = \frac{\mathscr{B}(h\to\eta_{cb}\mu^+\mu^-)^{\rm 2HDM}}{\mathscr{B}(h\to\eta_{cb}\mu^+\mu^-)^{\rm SM}}, \tag{3.1}$$

and found that for the muons in the final state that ratio is always $R^{\mu\mu}_{\eta_{cb}} \in (0.7, 1.1)$, the only exception being the Type-2 2HDM in which this enhancement can go up to 30%. Instead, in the case of τ-leptons in the final state the enhancement can go up to an order of magnitude. More specifically, we obtain

$$\begin{aligned} R^{\tau\tau}_{\eta_c} &\in \{(0.7,3.3)_{\rm Type\ I}, (0.8,3.2)_{\rm Type\ II}, (0.7,21)_{\rm Type\ X}, (0.7,1.1)_{\rm Type\ Z}\}, \\ R^{\tau\tau}_{\eta_b} &\in \{(0.7,3.6)_{\rm Type\ I}, (0.9,58)_{\rm Type\ II}, (0.7,23)_{\rm Type\ X}, (0.8,1.2)_{\rm Type\ Z}\}. \end{aligned} \tag{3.2}$$

Pronounced sensitivity on the CP-odd Higgs is due to the second piece in Eq. (2.3) because $\Gamma(h \xrightarrow{A} P\ell^+\ell^-) \propto m_\ell^2$, which can also be seen by using an approximate relation, $\Gamma(h\to\eta_{cb}\tau\tau) \approx \Gamma(h\to\eta_{cb}A)\ \mathscr{B}(A\to\tau\tau)$. Notice that for larger values of m_A, $\mathscr{B}(h\to\eta_{cb}\tau^+\tau^-)$ rapidly approaches its Standard Model result ($\mathscr{O}(10^{-7})$, which is why this decay mode is indeed a good probe of the light *CP*-odd Higgs.

Furthermore there is a good correlation between $R^{\tau\tau}_{\eta_c}$ and $R^{\tau\tau}_{\eta_b}$, especially in the case of Type I and Type X models as shown in Fig. 3

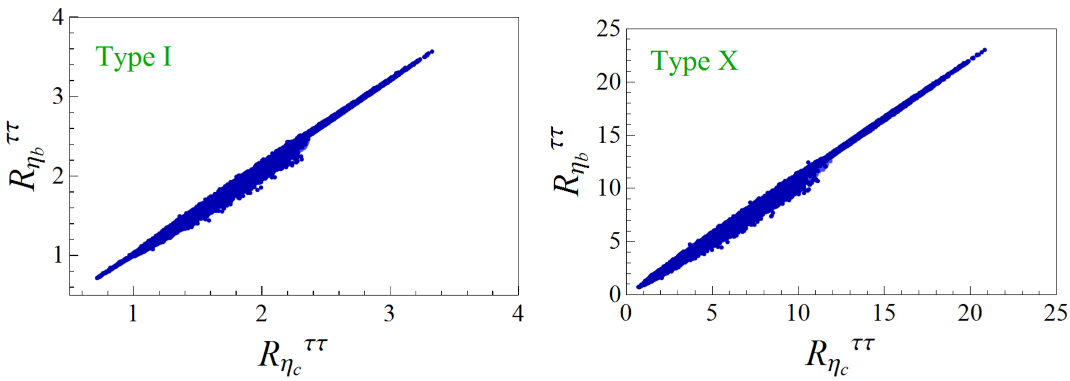

Figure 3: *Correlation of the ratios $R^{\tau\tau}_{\eta_c}$ and $R^{\tau\tau}_{\eta_b}$ in Type I and Type X models arises from the fact that the Yukawa couplings of the charm and bottom quarks to the CP-odd Higgs are equal in these two models.*

References

[1] G. T. Bodwin et al, Phys. Rev. D **88**, no. 5, 053003 (2013); M. Konig and M. Neubert, JHEP **1508**, 012 (2015), ibid **1612**, 037 (2016); S. Alte et al, JHEP **1612**, 037 (2016); D. N. Gao, Phys. Lett. B **737**, 366 (2014); P. Colangelo et al, Phys. Lett. B **760**, 335 (2016).

[2] D. Becirevic, B. Melic, M. Patra and O. Sumensari, arXiv:1705.01112 [hep-ph].

[3] D. Becirevic et al, Nucl. Phys. B **883** (2014) 306; C. McNeile et al, Phys. Rev. D **86** (2012) 074503.