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Nuclear Physics B Proceedings Supplement 00 (2014) 1–3
Nuclear Physics B Proceedings Supplement

125 GeV Higgs decays into $\gamma\gamma$, γZ and rare top quark decay in generic 2HDM

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Abstract

Models of electroweak symmetry breaking with extended Higgs sectors are theoretically well motivated. In this study, we investigate the phenomenology of the new Yukawa couplings in generic two-Higgs-doublet models. We find that a heavy charged Higgs together with $\alpha, \tan\beta \sim O(1)$, type-II and III could enhance the two-photon production cross section; however, with large $\tan\beta$ scenario, only type-III could match the LHC data. Additionally, we study the implications of LHC data on the production cross sections for the channel $h \to Z\gamma$ and branching ratio for $t \to ch$ decay.

Keywords: SM, 2HDM, type-II, type-III, LHC, Yukawa couplings

1. Introduction

It has been two years since a new particle has been discovered at the Large Hadron Collider (LHC) by ATLAS and CMS with more than 5σ significance. Although the observation showed that it is more and more likely to be the SM Higgs boson, however some of the measured couplings of the Higgs boson may not be consistent with the SM predictions, especially the overall signal strength for diphoton at ATLAS is about 1.29 ± 0.30[1] and at CMS is about $1.12^{+0.37}_{-0.32}$[2]. Nevertheless those data are now brought closer to the SM value.
In addition to the diphoton signal, the $h \to \gamma Z$ is also a clean final state that can provide some complementary information on the Higgs properties. So, to understand the diphoton excesses in ATLAS experiments, one should consider what sorts of models might naturally lead to these deviations. It is interesting to study the simplest extension from one Higgs doublet to two-Higgs-doublet models (2HDMs)[3, 4, 5]. The direct consequences of this extension are: an increase in the scalar spectrum, a more generic pattern of Flavor Changing Neutral Currents (FCNC), including FCNC at tree level, which are highly excluded in low energy experiments.
In this study, we not only explore the influence of the new diagonal and off-diagonal couplings between Higgs and fermions on $pp \to h \to \gamma\gamma$, but also study the measurable FCNC process $t \to ch$ in the type-III model.

2. Review of 2HDM

We start with the most general form for the Yukawa interactions for quarks, which is no longer flavor sepa-

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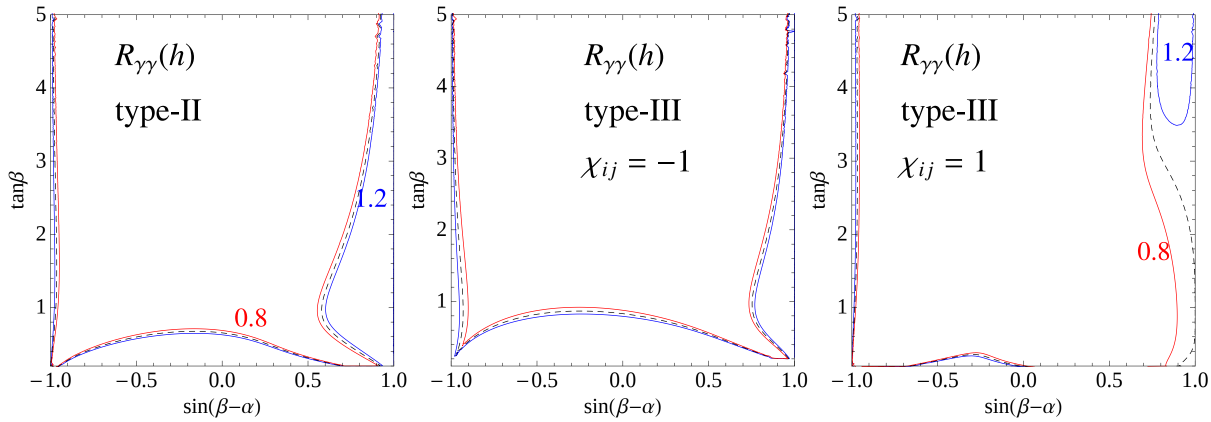

Figure 1: The $R_{\gamma\gamma}(h)$ contours for $m_h = 125$ GeV in the type-II (left panel), type-III with $\chi_{ij} = -1$ (middel panel) and type-III with $\chi_{ij} = 1$ (right panel). The contour lines are $\sigma/\sigma_{SM} = 0.8$ (red), 1 (dashed) and 1.2 (blue).

rable and is written as :

$$-\mathcal{L}_Y = \overline{Q}^0_L \tilde{\Phi}_1 \eta_1^{u,0} u_R^0 + \overline{Q}^0_L \Phi_1 \eta_1^{d,0} d_R^0 + \overline{Q}^0_L \tilde{\Phi}_2 \eta_2^{u,0} u_R^0 + \overline{Q}^0_L \Phi_2 \eta_2^{d,0} d_R^0 + h.c \quad (1)$$

where i, j are flavor indices, $Q_L^T = (u_L, d_L)$ is the doublet of $SU(2)_L$, Y^k and $\tilde{Y}^k$ denote the 3×3 Yukawa matrices, $\tilde{\phi}_k = i\sigma_2 \phi_k^*$ and k is the doublet number.
Therefore, After spontaneous symmetry breaking the lightest higgs coupling to fermions are written as [6] :

$$-\mathcal{L}_Y^{III} = \overline{u}_i \left(\frac{\cos\alpha}{\sin\beta}\frac{m_{u_i}}{v}\delta_{ij} - \frac{\cos(\alpha-\beta)}{\sqrt{2}\sin\beta}X_{ij}\right) u_j h + \overline{d}_i \left(\frac{-\sin\alpha}{\cos\beta}\frac{m_{d_i}}{v}\delta_{ij} + \frac{\cos(\alpha-\beta)}{\sqrt{2}\cos\beta}X_{ij}\right) d_j h \quad (2)$$

where $v = \sqrt{v_1^2 + v_2^2}$ with v_i being the VEV of neutral component of Higgs doublet H_i, α is the mixing angle of the two CP-even scalar bosons, $X_{ij}^q = \sqrt{m_{q_i} m_{q_j}}/v \chi_{ij}^q$ ($q = u, d$) and χ_{ij}^q are free parameters.
In order to study the new physics effects on the LHC measurements for some specific XY finale state, we define the quantities R_{XY} as the ratio of the number of events predicted in the model, 2HDM, to that obtained in the SM for a given final state XY.

$$R_{XY} = \frac{\sigma(pp \to h)\mathcal{B}(h \to XY)}{\sigma(pp \to h)_{SM}\mathcal{B}(h \to XY)_{SM}} \quad (3)$$

We have taken into account some theoretical and experimental constraints. Since χ_{ij}^q are free parameters, in order to get the maximum contributions, we adopt $\chi_{ij}^{u,d} = \chi_{ij} = \pm 1$ in our numerical analysis.

3. Results and discussion

To understand the influence of 2HDM on $h \to \gamma\gamma$ we study the measured $R_{\gamma\gamma}$ defined in Eq(3), we plot it in fig.1 as a function of $\sin(\alpha-\beta)$ with $\tan\beta = 5(30)$ for 3 types 2HDM.

It is clear that the new fermion couplings, the quark contribution, in type-II and III could enhance $R_{\gamma\gamma}$. In type-III, both $\chi_{ij} = \pm1$ could fit the data at different region of $\cos(\alpha-\beta)$. It is worthy to mention that in large $\tan\beta$ scenario and $\alpha \sim O(0.1)$, only type-III with $\chi_{ij} = 1$ could explain the data of $R_{\gamma\gamma}$.
Apparently, type-III 2HDM provides a wider allowed parameter space.

For further understanding the new effects in type-III 2HDM, we calculate the unmeasured $R_{Z\gamma}$, fig.2, and the BR for $t \to ch$. Except the different gauge couplings to W-boson and fermions, $pp \to h \to Z\gamma$ is similar to two-photon production. If the data for $R_{\gamma\gamma} > 1$ is confirmed with more data in the future, $R_{Z\gamma} \neq 1$ should be expected. Since $t \to ch$ is induced at tree level in type-III model, if a large BR for $t \to ch$ is measured, this will be a strong evidence to distinguish the type-III from other models.
If $R_{Z\gamma}(h)$ requires to be between 1 and 2, then type-II is almost excluded. However both type-III with $\chi_{ij} = \pm1$ provides a wider allowed parameter space especially type-III with $\chi_{ij} = -1$ in the region where $\sin(\beta-\alpha)$ is negative.
Therefore, the type-III model could be the preferable extension of the SM if a large BR for $t \to ch$ is measured.

$$\Gamma(t \to ch) = \frac{G_F m_t^2 m_c}{8\sqrt{2}\pi} \frac{\cos^2(\alpha-\beta)}{\sin^2\beta} \left(1 - \frac{m_h^2}{m_t^2}\right)^2$$

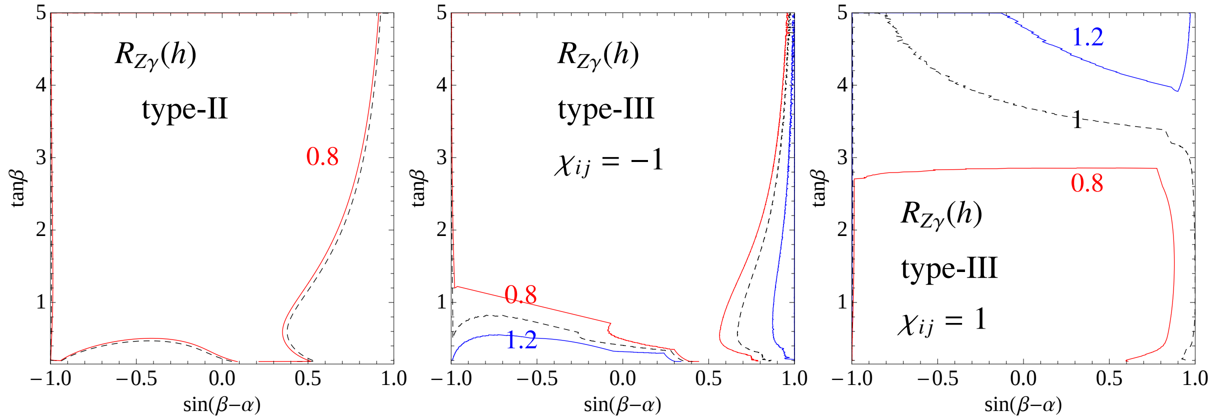

Figure 2: The $R_{Z\gamma}(h)$ for $m_h = 125$ GeV in the type-II (left panel), type-III with $\chi_{ij} = -1$ (middel panel) and type-III with $\chi_{ij} = 1$ (right panel). The contour lines are $\sigma/\sigma_{SM} = 0.8$ (red), 1 (dashed) and 1.2 (blue).

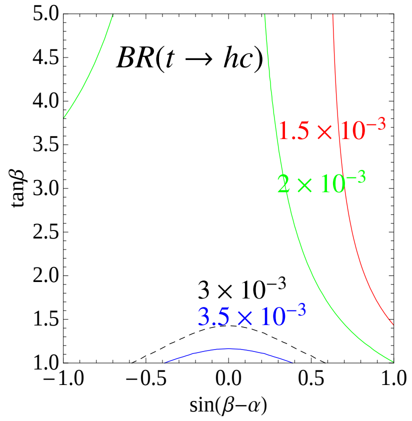

Figure 3: The contour plot of $BR(t \to hc)$ in Type-III with $m_h = 125.5$ GeV.

With 300 fb^{-1} of data and an energy of the center of mass of 14 TeV, it may be expected to find evidence of new physics beyond SM at Run 3 in LHC such that $t \to ch$. Despite the absence of flavor-changing neutral Higgs interactions in SM, $t \to ch_{SM}$ decay can occur at one-loop level. The reported result for the branching ratio is of the order of $10^{-14} - 10^{-13}$ [7]. In the framework of 2HDM type 2, we diplay in Figure. 3 the $Br(t \to ch)$ in $(\sin(\beta - \alpha), \tan\beta)$ plane for $m_h = 125.5$ GeV, it is clear that the $Br(t \to ch)$ is in order of 10^{-3}.

4. Conclusion

In summary, we have discussed the phenomenology of the three possibles types of Yukawa interactions in the general two Higgs doublet model. Although the particle contents are the same in these models, their phenomenologies are completely different from each other. The differences between the types of the Yukawa interactions largely affect the production and the decay of the Higgs boson. We have evaluated the production and decay branching ratios in each type of 2HDM when the charged Higgs boson mass is taken to be heavy.

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