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Interpreting the 750 GeV diphoton excess in minimal extensions of Two-Higgs-Doublet models

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ABSTRACT

It is shown that the 750 GeV diphoton excess can be explained in extensions of Two-Higgs-Doublet Models that do not involve large multiplicities of new electromagnetically charged states. The key observation is that at moderate and large $\tan\beta$ the total decay width of the 750 GeV Higgs is strongly reduced as compared to the Standard Model. This allows for much more economical choices of new states that enhance the diphoton signal to fit the data. In particular, it is shown that one family of vector-like quarks and leptons with SM charges is enough to explain the 750 GeV diphoton excess. Moreover, such charge assignment can keep the 125 GeV Higgs signal rates exactly at the SM values. The scenario can interpret the diphoton excess provided that the total decay width of a hypothetical resonance that would be measured at the LHC turns out to not exceed few GeV.

1. Introduction

The ATLAS and CMS collaborations reported recently an excess in the diphoton mass distribution around 750 GeV [1,2]. Local significances of these excesses are somewhat above 3σ at ATLAS and slightly less than 3σ at CMS. While global significance of this excess is not yet large enough to celebrate discovery of New Physics, it is the most significant excess observed simultaneously at ATLAS and CMS in searches for New Physics at the LHC so far. Thus, it is tempting to interpret this signal in extensions of the Standard Model (SM).

There are many ways how to explain the 750 GeV excess by New Physics [3]. Among candidates for a new resonance there are singlets coupled to vector-like fermions [4–20], composite states [21–30], states originating from reduction of extra dimensions [31, 32], axions [33,34] or sgoldstinos [35–37].[1] Some authors speculate also on a possible link of this new resonance to a dark matter particle [39–45]. Here, we assume that the 750 GeV diphoton excess is due to new Higgs boson(s) in Two-Higgs-Doublet Model (2HDM) [46]. Such interpretations of the diphoton signal were already presented in Refs. [47–49]. In those articles the main focus was on small values of $\tan\beta$ with dominant contribution to production of a 750 GeV states in gluon fusion coming from a top quark loop. It has been shown, however, that in order to fit the diphoton signal 2HDM must be extended by additional new states with large multiplicities and/or large exotic electromagnetic charges.

In the present paper we investigate a possibility to fit the 750 GeV diphoton excess in extensions of 2HDMs with moderate and large $\tan\beta$. At first sight, it might seem to be not a good choice of parameter space because at large $\tan\beta$ top quark contribution to gluon fusion is strongly suppressed. However, since new states have to be added anyway to 2HDMs to enhance 750 GeV Higgs decays to diphotons it is reasonable to assume that these new states also carry colour charge and contribute to the 750 GeV Higgs production via gluon fusion. In such a case top quark contribution to gluon fusion is no longer necessary and $\tan\beta$ can be large. The main advantage of large $\tan\beta$ is that the total decay width of the 750 GeV Higgs is suppressed in this regime. This allows for much smaller diphoton decay width of the 750 GeV Higgs to explain the excess. Moreover, if the excess is due to narrow resonance produced in gluon fusion, preferred signal rate of this resonance is about 6 fb, as compared to 11 fb for a resonance with total decay width of 45 GeV [9]. Due to larger diphoton signal rate the wide resonance hypothesis is in bigger tension with LHC run-1 data [9] (see also Ref. [50]). On the other hand, in the narrow resonance hypothesis, the best-fit point from 13 TeV data is consistent with constraints from the run-1 data. Nevertheless, the best-fit point in a global fit to all diphoton data shifts downwards to about 3 fb.

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[1] It has also been suggested that the excess may not originate from a 750 GeV resonance [38].

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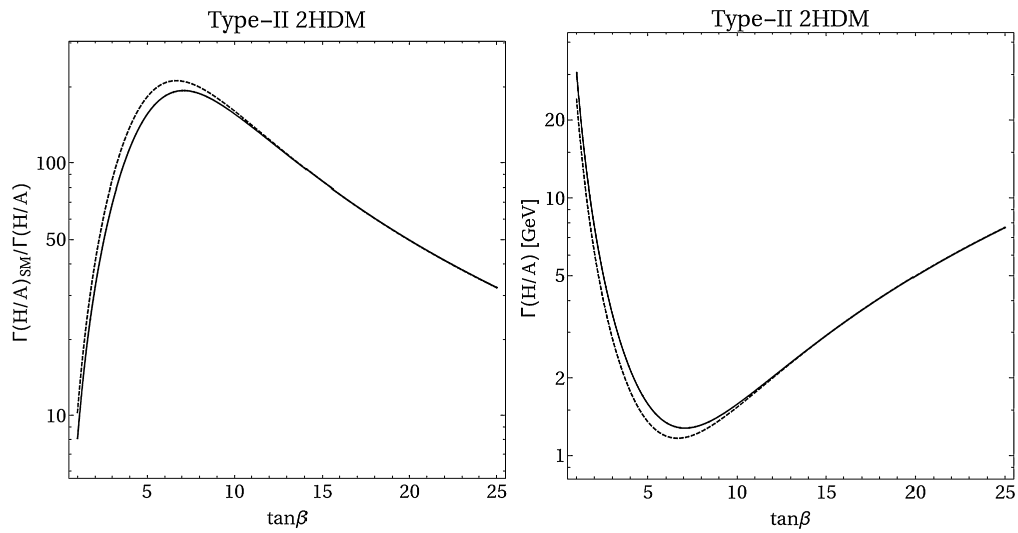

Fig. 1. Left panel: enhancement of the total decay width of the 750 GeV CP-even (solid lines) and CP-odd (dashed lines) Higgs in Type-II 2HDM in the alignment limit $\alpha = \beta - \pi/2$, with respect to the 750 GeV SM Higgs. Right panel: the total decay width in GeV in the same case as in the left panel. Difference between the CP-even and CP-odd Higgs comes from a different phase space suppression in $H/A \to t\bar{t}$.

We investigate possible size of the suppression of the total decay width of the 750 GeV Higgses in Type-I and Type-II 2HDM and show that it is large enough to fit the diphoton excess with rather small multiplicities of new particles. In particular, we demonstrate that one family of vector-like quarks and leptons with SM charges is enough to explain the 750 GeV diphoton excess. By construction, this scenario can interpret the diphoton excess provided that the total decay width of a hypothetical resonance that would be measured at the LHC turns out to not exceed few GeV.

2. Suppression of a Higgs total decay width in 2HDMs and enhanced 750 GeV diphoton signal

The total decay width of a 750 GeV Higgs in the SM is about 247 GeV [51]. The main decay channels are into WW, ZZ and $t\bar{t}$ with the corresponding branching ratios of about 59%, 29% and 12%, respectively. As a consequence of large total decay width, BR($H \to \gamma\gamma$) is only 2×10^{-7}. Since the SM production cross-section for the 750 GeV Higgs, dominated by gluon fusion rate, is about 0.74 pb [51], it is clear that if the 750 GeV resonance is a Higgs it must have totally different properties than in the SM.

In 2HDMs there are three physical neutral Higgs bosons, two CP-even and one CP-odd, that originate from two Higgs doublets, H_u and H_d. Two important parameters of this class of models are $\tan\beta = v_u/v_d$, the ratio of vacuum expectation values of the doublet neutral components, H_u^0 and H_d^0, and angle α which parametrizes the mixing between the two CP-even states:

$$H_u^0 = \cos\alpha h + \sin\alpha H \,, \qquad H_d^0 = -\sin\alpha h + \cos\alpha H \,. \qquad (1)$$

In the present work, we identify h with the 125 GeV Higgs, while H is a candidate for the 750 GeV resonance. We focus on the so-called alignment limit $\alpha = \beta - \pi/2$ [52]. In such a case h has exactly the same couplings as the SM Higgs while H couples to the SM fermions but not to the gauge bosons. This is motivated, in part, by the fact that the LHC 125 GeV Higgs data agree quite well with the SM prediction [53]. More importantly, in the alignment limit the total decay width of H is generically much smaller than in the SM. In particular, for $\tan\beta = 1$, when the H couplings to the SM fermions are the same as in the SM, the total decay width is about 30 GeV. Similar decay width has CP-odd scalar, which has the same couplings to SM particles as H in the alignment limit. In spite of vanishing couplings to gauge bosons, the branching ratios of H and A to diphoton are of order 10^{-5}, much too small to explain the 750 GeV excess.

In the most widely studied Type-I and Type-II 2HDMs, the correct magnitude of the 750 GeV diphoton signal could be, in principle, adjusted by choosing appropriately small value of $\tan\beta$. This is because the effective gluon coupling of H/A is proportional to the coupling to top quark which is rescaled by a factor $1/\tan\beta$, as compared to the SM. However, such possibility is experimentally excluded since $t\bar{t}$ production from H/A decays would be too large.

The remaining possibility is to assume that there exist new electromagnetically charged particles that modify $\Gamma(H/A \to \gamma\gamma)$. In Ref. [47] it was shown that it is indeed possible to fit the 750 GeV excess using decays of degenerate H and A to $\gamma\gamma$ enhanced by vector-like leptons. However, in such a case the price to pay is very high multiplicity of vector-like leptons. Moreover, in order not to spoil the 125 GeV Higgs decays into photons fine cancellation in the amplitude between the contributions from different vector-like leptons is required. In an explicit example presented in Ref. [47] $\tan\beta = 1$ was used, for which the model is at the verge of exclusion by the LHC searches for $H \to t\bar{t}$.

We focus instead on larger values of $\tan\beta$ since they allow to reduce $\Gamma(H/A \to t\bar{t})$, hence also the total decay width. The reduction of the H/A couplings to top quarks results also in decrease of the gluon fusion production cross-section. Therefore, in this case new particles should exist that carry colour charge that are responsible for large enough production cross-section of H/A, however, as we will see with much smaller multiplicity than for $\tan\beta = 1$. Since couplings of H and A to bottom quarks are different in type-I and type-II 2HDMs we discuss these models separately in the following subsections.

2.1. Type-II 2HDM

In type-II 2HDM, in which the Higgs sector is that of MSSM, the couplings of H and A to bottom quarks are proportional to $\tan\beta$. For the SM Higgs with mass of 750 GeV the decay width into top quarks is about 2900 times larger than that into bottom quarks [51]. This implies in Type-II 2HDM that those decay widths equalize at $\tan\beta \approx 7.3$. At this value of $\tan\beta$ the total decay width of H is minimized and equals around 1 GeV, as can be seen in the left panel of Fig. 1. Hence, it is smaller by more than two