The LHC Phenomenology of the CP-odd Scalar in Two-Doublet Models

Dimitris Kominis

Dept. of Physics, Boston University, 590 Commonwealth Avenue, Boston, MA 02215

Abstract

We discuss possible signatures of the CP-odd scalar of two-doublet models at the LHC. We find that the inclusive two-photon decay mode and the decay sequence $A^0 \rightarrow Z h, h \rightarrow \gamma \gamma$, where $h$ is a CP-even neutral scalar, can give viable signals in fairly large and complementary regions of parameter space.

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†e-mail address: kominis@budoe.bu.edu
The prospects of detecting the Higgs bosons of non-minimal models at future high-energy colliders have been the focus of many studies. In the Two-Higgs-Doublet Model (THDM), the simplest extension of the scalar sector of the Standard Model, the masses and self-couplings of the Higgs bosons are unknown parameters. Nonetheless, restrictions on their range of values can be imposed from existing experimental data, as well as from considerations of triviality and stability of the effective potential \[ \text{(1,2)} \]. The purpose of the study reported here is to determine the potential of the Large Hadron Collider to probe the \( CP \)-odd scalar particle of the THDM in the region of parameter space defined by the triviality (and stability) bounds.

We shall consider a THDM with an exact discrete symmetry meant to ensure natural flavor conservation \[ \text{(3)} \]. This symmetry is commonly implemented in one of two ways, which differ in the manner the fermions couple to the scalar doublets, and are referred to as Model I and Model II in the literature \[ \text{(4)} \]. After the two doublets acquire vacuum expectation values \( v_1, v_2 \), the scalar spectrum contains five physical states: two \( CP \)-even particles \( h, H \), the \( CP \)-odd scalar \( A^0 \) and two charged states \( H^\pm \). The scalar sector can be described in terms of six independent parameters, which can be taken to be the four masses and two mixing angles \( \alpha \) and \( \beta \), with \( \tan \beta = v_2/v_1 \).

Let us now consider the signatures of the \( CP \)-odd scalar at the LHC. If the \( A^0 \) is light, it will mostly decay into the heaviest fermion pair available. At a hadron collider, this implies that one has to rely on rare decay modes, such as the two-photon mode with a typical branching ratio of \( 10^{-3} \). As the \( A^0 \) gets progressively heavier, other channels open up, notably \( t\bar{t} \) and channels that contain other scalars: \( A^0 \rightarrow Zh, ZH, W^\pm H^\mp \). These decays have branching ratios which are typically of the order of 10% or larger; this means that, if the \( A^0 \) is heavy, these channels are likely to represent the best way for us to search for it. We will thus consider signatures which involve the two-photon decay of the \( A^0 \) or the decay into a \( Z \) boson and another neutral scalar, which in turn will be detected through its decay to two photons.

We illustrate our results for the inclusive two-photon signal in Fig. 1, where, for integrated luminosities of 10 fb\(^{-1}\) and 100 fb\(^{-1}\), we show the regions of the \( (M_{A^0}, \beta) \) plane where the statistical significance of the signal (defined by \( S/\sqrt{B} \)) is greater than 5. The sections of the parameter space depicted in this figure correspond to the following choice of parameters: \( M_H = 400 \text{ GeV}, M_h = 260 \text{ GeV}, M_{H^\pm} = 350 \text{ GeV}, M_t = 180 \text{ GeV}, \alpha = 30^\circ \) for Fig. 1a, and \( M_H = 400 \text{ GeV}, M_h = 100 \text{ GeV}, M_{H^\pm} = 350 \text{ GeV}, M_t = 180 \text{ GeV}, \alpha = -75^\circ \) for Fig. 1b. We shall refer to these two choices as Set A and Set B respectively. The irreducible background was calculated in a mass bin \( \Delta M_{\gamma\gamma} = 3\%M_{\gamma\gamma} \), while the reducible jet background was assumed to amount to 25% of the direct di-photon level. The following rapidity and transverse momentum cuts were employed: \( |\eta\gamma| < 2.5 \) and \( p_T^\gamma > 20 \text{ GeV} \). Further details of the calculation can be found in Ref. 5. Fig. 1 also
Figure 1: Significance contours for the two-photon signal, for (a) Set A and (b) Set B of parameters, as explained in the text. The outer curve represents the triviality bound. The statistical significance is at least $5\sigma$ in the interior of the contours. Results are shown for integrated luminosities of $10\text{ fb}^{-1}$ (solid) and $100\text{ fb}^{-1}$ (dashed line). Model I is assumed; the contours for Model II are similar.

Illustrates the effect of the various parameters on the triviality bounds. Note that the region of large $\beta$ is not efficiently explored in this channel. In general, we find that this mode can only be helpful if $\beta \lesssim 60^\circ$. Because of the uncertainty over the extent to which the jet backgrounds can be contained, we also examined the process where the $CP$-odd Higgs is produced in association with a $t\bar{t}$ pair and decays to two photons, while one of the $t/\bar{t}$ decays leptonically. Despite the fact that the lepton tag eliminates a great deal of the jet backgrounds, it turns out that the signal itself is weak and that this mode cannot be very helpful.

In contrast, the process $A^0 \to Z(\to l^+l^-) h(\to \gamma\gamma)$ (where $l = e, \mu$) can give significant signals, provided $40\text{ GeV} \lesssim M_h \lesssim 160\text{ GeV}$. Tens or even hundreds of $Z\gamma\gamma$ events can be accumulated if $|\alpha|$ is large in Model I or small in Model II. We have assumed the same rapidity and $p_T$ cuts as in the $\gamma\gamma$ case; furthermore, we have imposed an isolation cut of $\Delta R > 0.4$ on all pairs of final state particles. Fig. 2 shows contours of the regions where 10 events or more are expected over a background which turns out to be truly negligible. This plot corresponds to Set B of parameters, as defined above, and illustrates the fact that with this mode one can explore regions of parameter space which are inaccessible to the two-photon mode. These are generally regions of large $M_{A^0}$, as in Fig. 2, but they can also be regions of relatively large $\beta$.

In conclusion, we examined three different signatures of the $CP$-odd scalar $A^0$ of the ($CP$-conserving) Two-Higgs-Doublet Model at the LHC: (i) the two-photon decay appears to be promising if $M_{A^0} < 2M_t$ and $M_{A^0} < M_h + M_Z$ and for not too large values of $\beta$; (ii)
Figure 2: 10-event contours for the $Z\gamma\gamma$ signal, in the region of the $(M_{A^0}, \beta)$ plane allowed by triviality (outer curve) in (a) Model I and (b) Model II. Set B of parameters is used. More than 10 events are expected in the interior of the contours. Results are shown for integrated luminosities of $10\, \text{fb}^{-1}$ (solid) and $100\, \text{fb}^{-1}$ (dashed line).

The associated $t\bar{t}A^0$ production followed by $A^0 \rightarrow \gamma\gamma$ and tagged by the leptonic decay of the $t$ or $\bar{t}$ proved to give a very weak signal throughout the parameter space under investigation; and (iii) the decay $A^0 \rightarrow Zh$ followed by $h \rightarrow \gamma\gamma$, $Z \rightarrow l^+l^-$ gives rise to clear signals in substantial regions of parameter space, in particular regions which are largely complementary to those covered by the other modes examined.

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References

[1] R. Dashen and H. Neuberger, *Phys. Rev. Lett.* **50** (1983) 1897.

[2] D. Kominis and R. S. Chivukula, *Phys. Lett.* **B304** (1993) 152.

[3] S. L. Glashow and S. Weinberg, *Phys. Rev.* **D15** (1977) 1958.

[4] For example, J. F. Gunion, H. E. Haber, G. L. Kane and S. Dawson, *The Higgs hunter’s guide*, (Addison-Wesley, Reading, MA, 1990), p. 201.

[5] D. Kominis, *Nucl. Phys.* **B427** (1994) 575.

[6] W. J. Marciano and F. E. Paige, *Phys. Rev. Lett.* **66** (1991) 2433; J. F. Gunion, *Phys. Lett.* **B261** (1991) 510.