Triple Higgs Coupling as a Probe of the Twin-Peak Scenario

Amine Ahriche,1,2,3 Abdesslam Arhrib,4 and Salah Nasri5,6

1Department of Physics, University of Jijel, PB 98 Ouled Aissa, DZ-18000 Jijel, Algeria
2The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, I-34014, Trieste, Italy
3Fakultät für Physik, Universität Bielefeld, 33501 Bielefeld, Germany
4Université AbdelMalek Essaadi, Faculté des Sciences et Techniques, B.P 416, Tangier, Morocco
5Physics Department, UAE University, POB 17551, Al Ain, United Arab Emirates
6Laboratoire de Physique Theorique d’Oran, Oran University, DZ-31000, Es-Senia, Oran, Algeria

In this letter, we investigate the case of a twin peak around the observed 125 GeV scalar resonance, using di-Higgs production processes at both LHC and $e^+e^-$ Linear Colliders. We show that the triple Higgs couplings play an important role to identify this scenario; and also that this scenario is surely distinguishable from any Standard Model extension by extra massive particles which might modify the triple Higgs coupling.

On July 2012, ATLAS and CMS collaborations have shown the existence of a Higgs-like resonance around 125 GeV confirming the cornerstone of the Higgs mechanism that predicted such particle long times ago. All Higgs couplings measured so far seem to be consistent, to some extent, with the Standard Model (SM) predictions. Moreover, in order to establish the Higgs mechanism as responsible for the phenomena of electroweak symmetry breaking one still needs to measure the self couplings of the Higgs and therefore to reconstruct its scalar potential.

Recent measurements at the LHC show that there is still uncertainty on the Higgs mass; $m_h = 125.3 \pm 0.4\text{(stat.)} \pm 0.5\text{(syst.) GeV}$ for CMS and $m_h = 125.0 \pm 0.5\text{ GeV}$ for ATLAS from the diphoton channel and $m_h = 125.5 \pm 0.37\text{(stat.)} \pm 0.18\text{(syst.) GeV}$ from combined channels. Despite this relatively large uncertainty, a scenario of two degenerate scalars around 125.5 GeV resonance is neither excluded nor confirmed.

In the twin peak scenario (TPS); it is assumed that there are two scalars $h_{1,2}$ with almost degenerate masses around 125 GeV. The couplings of the twin peak Higgs to SM particles $g_{h_{1,2}X}$ are simply scaled with respect to SM rate by $\cos\theta$ (for $h_1$) and $\sin\theta$ (for $h_2$), where $\theta$ is a mixing angle, such that we have the following approximate sum rule:

$$g_{h_1XX}^2 + g_{h_2XX}^2 \simeq g_{h_{SM}XX}^2,$$

(1)

where $X$ can be any of the SM fermions or vector bosons. Consequently, the single Higgs production such as gluon-gluon fusion at LHC, Higgs-strahlung, Vector Boson fusions, and $t\bar{t}H$ at LHC and $e^+e^-$ Linear Colliders (LC) will obey the same sum rule. The summation of event numbers (both for production and decay) of the two possible cases will be identical to SM case since $\cos^2\theta + \sin^2\theta = 1$. However, for processes with di-Higgs final states ($pp(e^-e^+) \rightarrow hh + X$), the triple Higgs couplings may play an important role, and therefore these processes can be useful to distinguish between the cases of one scalar or two degenerate ones around the observed 125 GeV resonance.

It is well known that the triple Higgs couplings can be, in principle, measured directly at the LHC with high luminosity option through double Higgs production $pp \rightarrow gg \rightarrow hh$ [4]. Such measurement is rather challenging at LHC, and for this purpose several parton level analysis have been devoted to this process. It turns out that $hh \rightarrow b\bar{b}\gamma\gamma$
vanishing vacuum expectation value, which breaks scalar fields. The approach is based on the di-Higgs production which is sensitive to the triple Higgs coupling, that is modified in the SM. However, according to the latest experimental results, both for ATLAS and CMS the di-photon channel seems to be rather consistent with the SM. In this work we propose a new approach to distinguish the TPS. This approach is based on the di-Higgs production which is sensitive to the triple Higgs coupling, that is modified in the majority of SM extensions.

Here, as an example, we consider, the Two-Singlets Model proposed in \cite{14}, where the SM is extended with two real scalar fields $S_0$ and $\chi_1$; each one is odd under a discrete symmetry $Z_2^{(0)}$ and $Z_2^{(1)}$ respectively. The field $\chi_1$ has a non vanishing vacuum expectation value, which breaks $Z_2^{(1)}$ spontaneously, whereas, $\langle S_0 \rangle = 0$; and hence, $S_0$ is a dark matter candidate. Both fields are SM gauge singlets and hence can interact with the ‘visible’ particles only via the Higgs doublet $H$. The spontaneous breaking of the electroweak and the $Z_2^{(1)}$ symmetries introduces the two vacuum expectation values $v$ and $v_1$ respectively. The physical Higgs $h_1$ and $h_2$, with masses $m_1$ and $m_2 \geq m_1$, are related to the excitations of the neutral component of the SM Higgs doublet field, $\text{Re}(H^{(0)})$, and the field $\chi_1$ through rotation with a mixing angle $\theta$ and, with a specific choice in the parameter space, could give rise to two degenerate scalars around 125 GeV. In what follows, we denote by $c = \cos \theta$ and $s = \sin \theta$. The quartic and triple couplings of the physical fields $h_i$ are given in the appendices in \cite{15}.

In our analysis we require that: (i) all the dimensionless quartic couplings to be $\ll 4\pi$ for the theory to remain perturbative, (ii) the two scalar eigenmasses should be in agreement with recent measurements \cite{14, 12}: we have checked that for the Two-Singlets model, the splitting between $m_1$ and $m_2$ could be of the order of 40 MeV. (iii) the ground state stability to be ensured; and (iv) we allow the DM mass $m_0$ to be as large as 1 TeV.

In our work, we consider di-Higgs production processes at the LHC and $e^+e^-$ LC, whose values of the cross section could be significant, namely, $\sigma^{LHC}(hh)$ and $\sigma^{LHC}(hh+tt)$ at 14 TeV; $\sigma^{LC}(hh+Z)$ at 500 GeV and $\sigma^{LC}(hh+E_{\text{miss}})$ at 1 TeV. All these processes include, at least, one Feynman diagram with triple Higgs coupling. For the TPS, the total cross section get contributions from the final states $h_1h_1$, $h_1h_2$ and $h_2h_2$. However, each contribution should be weighted by the $h_{1,2}$ modified couplings since the Higgs is detected through its SM final states decay. Therefore the quantity to be compared with the standard scenario can be expressed as:

\[
\sigma^{TPS}(hh+X) = c^4\sigma(h_1h_1+X) + c^2s^2\sigma(h_1h_2+X) + s^4\sigma(h_2h_2+X),
\]

which can be parameterized as:

\[
\sigma^{TPS} = \sigma_{aa}r_1 + \sigma_{ab}r_2 + \sigma_{bb}r_3,
\]

1 Actually, we considered that all quartic couplings to be of order unity; and the singlet vev $v_1 = \langle \chi_1 \rangle = 20 \sim 2000$ GeV.
with \( \sigma_{aa} + \sigma_{ab} + \sigma_{bb} = \sigma^{SM}(hh + X) \) and \( \sigma_{aa}, \sigma_{bb} \) and \( \sigma_{ab} \) correspond to the cross section contributions coming from triple Higgs diagrams (a), non-triple Higgs diagrams (b) and the interference term in the amplitude, respectively. The coefficients \( r_i \) are dimensionless parameters, that receive contributions from the final states \( h_i h_j \), which depend on the mixing angle \( \theta \) and the Higgs triple couplings \( \lambda^{(3)}_{ijk} \). The SM case can be obtained by taking \( s = 0 \) and \( r_i = 1 \). \(^2\)

In the TPS, the amplitudes for di-Higgs production processes have SM Feynman diagrams where the the Higgs field \( h \) is replaced by \( h_i \). To compute the parameters \( r_i \), we first estimate how does each amplitude get modified with respect to the corresponding SM one for each case \( h_i h_j \). For example, in the case of \( h_1 h_1 \) production, there are two types of diagrams: (1) The ones that involve triple scalar interactions \( h_1 h_1 h_1 \) and \( h_2 h_1 h_1 \), with couplings equal to the one of a SM times a factor of \( c\lambda^{(3)}_{111}/\lambda^{SM}_{hhh} \) and \( s\lambda^{(3)}_{112}/\lambda^{SM}_{hhh} \), respectively. We denote the total amplitude of these two contributions by \( M_{(a)} \). (2) The ones with no triple Higgs couplings. Their amplitude, denoted by \( M_{(b)} \), is given by the one of the SM scaled by a factor of \( c^2 \). Therefore, the amplitudes \( M_{(a,b)} \) (where \( a \) (b) stand for triple Higgs (non-triple Higgs) Feynman diagrams) for the di-Higgs production can be written in terms of their corresponding SM values as:

\[
\begin{align*}
\h_1 \h_1 : & \quad M_{(a)} = \left[ (c\lambda^{(3)}_{111} + s\lambda^{(3)}_{112})/\lambda^{SM}_{hhh} \right] M^{SM}_{(a)}, \\
& \quad M_{(b)} = c^2 M^{SM}_{(b)}, \\
\h_2 \h_2 : & \quad M_{(a)} = \left[ (c\lambda^{(3)}_{112} + s\lambda^{(3)}_{122})/\lambda^{SM}_{hhh} \right] M^{SM}_{(a)}, \\
& \quad M_{(b)} = s^2 M^{SM}_{(b)}, \\
\h_1 \h_2 : & \quad M_{(a)} = \left[ (c\lambda^{(3)}_{112} + s\lambda^{(3)}_{122})/\lambda^{SM}_{hhh} \right] M^{SM}_{(a)}, \\
& \quad M_{(b)} = cs M^{SM}_{(b)}. 
\end{align*}
\]

where \( \lambda_{hhh}^{SM} \) is the SM triple Higgs coupling calculated at one-loop. Then the parameters \( r_i \) are given by:

\[
\begin{align*}
& r_1 = (c^4 [\lambda^{(3)}_{111} + s\lambda^{(3)}_{112}]^2 + s^4 [\lambda^{(3)}_{112} + c\lambda^{(3)}_{122}]^2 + c^2 s^2 [\lambda^{(3)}_{112} + s\lambda^{(3)}_{122}]^2)/[\lambda_{hhh}^{SM}]^2, \\
& r_2 = (c^7 \lambda^{(3)}_{111} + c^4 s\lambda^{(3)}_{112} + c^4 \lambda^{(3)}_{122} + s^7 \lambda^{(3)}_{122})/\lambda_{hhh}^{SM}, \\
& r_3 = c^8 + s^8 + c^4 s^4. 
\end{align*}
\] (4)

Thus, the values of \( r_i \) quantify by how much each di-Higgs process deviates from the SM case. In Fig. 1 we show the parameters \( r_i \) as a function of \( \sin \theta \) for about 600 chosen sets of the model parameters. We see that for very small

\(^2\) Indeed, \((s,r_{1,2}) = (0,1)\) is true only if the couplings of the new singlet does not couple to the Higgs doublet, and hence does contribute to the triple Higgs coupling \( \lambda^{(3)}_{111} \).
mixing angle $r_i$'s are approximately equal to unity, where as for $|s| > 0.8$, the parameter $r_1$ ($r_2$) becomes larger than unity (negative). This behavior could lead to an enhancement/reduction to the cross section depending on the sign of the interference contribution, $\sigma_{ab}$, to the total cross section. This means that the measurement of the ratio:

$$\xi (hh + X) = \frac{\sigma^{TPS} (pp(e^-e^+ \rightarrow hh + X)}{\sigma^{SM} (pp(e^-e^+ \rightarrow hh + X)}.$$  

(5)

could be very useful to confirm or exclude this scenario based on the deviation of any of the parameters $r_i$ from unity. For instance, the ratio $\xi (hh + X)$ can deviate from unity if the SM is extended with massive particles (SM+MP) that couple to the Higgs doublet and contribute to the triple Higgs coupling as well the Higgs mass. In this case, $r_1 = (1 + \Delta)^2$, $r_2 = 1 + \Delta$ and $r_3 = 1$, where $\Delta$ represents the relative enhancement of the triple Higgs coupling due to SM+MP. As we will show later, our discussed scenario will be surely distinguished from the case of SM+MP by combining the ratio (5) for different processes.

In Table I we give the values of $\sigma_{aa}$, $\sigma_{ab}$ and $\sigma_{bb}$ for the corresponding di-Higgs production processes. We note that their contributions to the LHC process $pp \rightarrow hh$ and to the LC one $e^+e^- \rightarrow Zhh$ seem to be uncorrelated, which makes the Higgs triple coupling useful to probe this scenario and distinguish it from (SM+MP). For the benchmarks considered previously in Fig. 1 we illustrate in Fig. 2 the production cross section of di-Higgs at $e^+e^-$ LC and LHC and in Fig. 3 the ratio $\xi$. As it can be seen, in the TPS, the cross section of the processes $pp \rightarrow hh + t\bar{t}$ and $e^-e^+ \rightarrow hh + Z$ are always reduced, while for $pp \rightarrow hh$ and $e^-e^+ \rightarrow hh + E_{miss}$ it could be enhanced or reduced depending on the mixing angle. 

Now let us discuss the possibility of disentangling the TPS from the SM+MP. According to the ratios $\xi (hh)$ and $\xi (hh + t\bar{t})$ (Fig. 3 left), the TPS coincides with the SM+MP in two tight regions of the triple Higgs coupling relative enhancement $\Delta \sim -0.5, -0.7$ and $\Delta \sim -1.7$. While for the ratios $\xi (hh + Z)$ and $\xi (hh + E_{miss})$ (Fig. 3 right), the TPS coincides with the SM+MP only for $\Delta \sim -2.2$. Therefore, by measuring these quantities at both the LHC and $e^+e^- \text{ LC}$ it possible to confirm/exclude the TPS since a coincidence between the TPS and the SM+MP can not takes place in both measurements. Moreover, if the observed 125 GeV scalar resonance is a twin-peak, then one needs to measure (5) for three well chosen di-Higgs production processes (either at the LHC, $e^+e^- \text{ LC}$ or both of them) in order to deduce the values of the three parameters $r_i$, while any other remaining di-Higgs production processes (at both LHC & $e^+e^- \text{ LC}$) could be used to confirm/exclude this scenario. In fact, by studying all the di-Higgs production channels at both LHC and $e^+e^- \text{ LC}$ one not only confirm/exclude this scenario, but also distinguished it from models where only one type of processes gets modified by new physics such as: it manifests as new sources of missing energy.
in $e^-e^+ \rightarrow hh + E_{miss}$, new colored scalar singlet contribution to $pp \rightarrow hh$ (or $hh + t\bar{t}$), or the presence of a heavy resonant Higgs.

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|}
\hline
 & $\sigma_{aa} (fb)$ & $\sigma_{ab} (fb)$ & $\sigma_{bb} (fb)$ \\
\hline
$hh$ & 9.66 & -49.9 & 70.1 & 29.86 \\
$hh + t\bar{t}$ & $3.3164 \times 10^{-2}$ & 0.13952 & 0.84731 & 1.02 \\
$hh + Z$ & $9.0206 \times 10^{-3}$ & $4.6999 \times 10^{-2}$ & $0.905 \times 10^{-2}$ & 0.14607 \\
$hh + E_{miss}$ & $5.1631 \times 10^{-2}$ & $-0.20867$ & 0.29708 & 0.14004 \\
\hline
\end{tabular}
\caption{Different contributions to the considered processes cross sections. Numbers for LHC are taken from [16] at NLO.}
\end{table}

\begin{figure}[h]
\centering
\includegraphics[width=0.45\textwidth]{fig1a.png}
\includegraphics[width=0.45\textwidth]{fig1b.png}
\caption{The cross section values for the di-Higgs production processes for the 600 benchmarks used previously. The solid lines correspond to the SM cross sections.}
\end{figure}

In order to show whether this scenario can be tested at colliders, we consider three benchmarks and compare the di-Higgs distribution (of the di-Higgs invariant mass as an example) with the SM one. The corresponding values of ratios $\xi_i$ are given in Table [III] and in Table [III] we present the expected number of events at both the LHC and LC. We see that for benchmark $B_2$, the events number is significantly larger than the SM for the channels $pp \rightarrow 2b2\tau$ at the LHC and $e^-e^+ \rightarrow 4b + E_{miss}$ at LC’s, while it is reduced for the processes $pp \rightarrow 4b + t\bar{t}$ and $e^-e^+ \rightarrow 4b + Z$. For benchmark $B_1$, the events number of the processes $pp \rightarrow 2b2\tau$ and $e^-e^+ \rightarrow 4b + E_{miss}$ is SM-like but it is reduced for the processes $pp \rightarrow 4b + t\bar{t}$ and $e^-e^+ \rightarrow 4b + Z$. For benchmark $B_3$, the events number is reduced for the considered
FIG. 3: The ratios $\xi$ given in (5) for the di-Higgs production processes for the 600 benchmark used previously. The blue point represents the SM; and the solid curve represents the case of a SM extension, where the new physics affects the triple Higgs coupling as $\lambda_{hhh} = \lambda_{hhh}^{SM}(1 + \Delta)$; and the value of the relative enhancement $\Delta$ can be read from the palette.

\begin{table}[h]
\centering
\begin{tabular}{cccc}
\hline
 & $B_1$ & $B_2$ & $B_3$
\hline
$\sin \theta$ & -0.39562 & -0.95234 & 0.74812 \\
r_1 & 0.18747 & 1.76098 & 0.45689 \\
r_2 & 0.18245 & -1.09175 & 0.28869 \\
r_3 & 0.52422 & 0.68382 & 0.19644 \\
$\xi(hh)$ & 0.98642 & 3.99949 & 0.12555 \\
$\xi(hh + t\bar{t})$ & 0.46652 & 0.47597 & 0.21753 \\
$\xi(hh + Z)$ & 0.39345 & 0.17903 & 0.24220 \\
$\xi(hh + E_{\text{miss}})$ & 0.90933 & 3.72668 & 0.15501 \\
\hline
\end{tabular}
\caption{Different values of the ratios (4) and (5) for the three chosen benchmarks.}
\end{table}

TABLE II: Different values of the ratios (4) and (5) for the three chosen benchmarks.

\begin{table}[h]
\centering
\begin{tabular}{cccc}
\hline
Events number & channel & $SM$ & $B_1$ & $B_2$ & $B_3$
\hline
$pp \rightarrow hh$ & $4b$ & 966.75 & 953.62 & 3866.5 & 122.34 \\
 & $2b\tau$ & 106.70 & 105.25 & 426.74 & 13.50 \\
 & $2b\gamma$ & 3.89 & 3.84 & 15.56 & 0.49 \\
$pp \rightarrow hh + t\bar{t}$ & $4b$ & 33.02 & 15.41 & 15.72 & 7.18 \\
$e^-e^+ \rightarrow hh + Z$ & $4b$ & 23.65 & 9.30 & 4.23 & 5.73 \\
$e^-e^+ \rightarrow hh + E_{\text{miss}}$ & $4b$ & 45.34 & 41.23 & 168.97 & 7.03 \\
\hline
\end{tabular}
\caption{The events number for the different processes within the luminosity values mentioned above for the SM and the benchmarks shown in Table II.}
\end{table}

TABLE III: The events number for the different processes within the luminosity values mentioned above for the SM and the benchmarks shown in Table II.

In Fig. 4 we illustrate the di-Higgs invariant mass distribution ($M_{hh}$) for the process $e^-e^+ \rightarrow hh + E_{\text{miss}}$. Clearly, the TPS can be easily distinguished from the SM, especially in the case where $|\sin \theta| > 0.2$, i.e far from the decoupling limit. However, the full confirmation of the TPS requires the enlargement of the investigation by taking into account other di-Higgs production channels such as $hhjj$, $hhW^\pm$, $hhZ$ and $hhtj$ at the LHC [20] and the $e^+e^- LC$ [11].
In conclusion, we have investigated the case of twin-peak at the 125 GeV observed scalar resonance, where we have shown that by considering different di-Higgs production processes at both LHC and $e^+e^-$ LC, this scenario that can be surely distinguished from the SM and SM extended by massive fields. It has been shown also that in the case where the mixing between singlet and doublet is slightly small, the di-Higgs production processes would mimic SM predictions and therefore not distinguishable from SM.

Last but not least, we should note that this scenario could be realized within SM +(real/complex) singlet scalar, or any larger scalar content model where two degenerate scalar eigenstates $h_{1,2}$ at 125 GeV and couple together to the SM gauge fields and fermions by more than $\sim 90\%$, i.e., the sum rule (11) is fulfilled. If the measurement of di-Higgs processes at LHC and/or $e^+e^-$ LC turn out to be consistent with SM predictions, then it will be very challenging to distinguish the TPS scenario.

Acknowledgments

We would like to thank A. Djouadi and R. Santos for the valuable comments; and E. Vryonidou for sharing with us her code and for many useful discussions. A. Ahriche is supported by the Algerian Ministry of Higher Education and Scientific Research under the CNEPRU Project No. D01720130042.

[1] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012).
[2] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012).
[3] S. Chatrchyan et al. [CMS Collaboration], CMS-PAS-HIG-13-001.
[4] G. Aad et al. [ATLAS Collaboration], arXiv:1406.3827 [hep-ex].
[5] For example see: M. Heikinheimo et al., Phys. Lett. B 726, 781 (2013).
[6] A. Djouadi et al., Eur. Phys. J. C 10, 45 (1999); E. W. N. Glover et al., Nucl. Phys. B 309, 282 (1988); T. Plehn et al., Nucl. Phys. B 479, 46 (1996) [Erratum-ibid. B 531, 655 (1998)]. J. Baglio et al., JHEP 1304, 151 (2013).
[7] U. Baur et al., Phys. Rev. D 69, 053004 (2004).
[8] M. J. Dolan et al., JHEP 1210, 112 (2012).
[9] A. Papaefstathiou et al., Phys. Rev. D 87, 011301 (2013).
[10] S. Chatrchyan et al., [CMS Collaboration], CMS-PAS-HIG-13-032.
[11] D. M. Asner et al., arXiv:1310.0763 [hep-ph]; A. Djouadi et al., Eur. Phys. J. C 10, 27 (1999).
[12] G. Weiglein et al. [LHC/LC Study Group Collaboration], Phys. Rept. 426, 47 (2006).
[13] J. F. Gunion et al., Phys. Rev. Lett. 110, 051801 (2013).
[14] A. Abada et al., Phys. Rev. D 83, 095021 (2011); A. Ahriche and S. Nasri, Phys. Rev. D 85, 093007 (2012).
[15] A. Ahriche et al., JHEP 1402, 042 (2014).
[16] M. Spira, hep-ph/9510347.
[17] A. Ahriche et al., Phys. Rev. D 89, 095010 (2014)
[18] G. D. Kribs et al., Phys. Rev. D 86, 095023 (2012); Z. Heng et al., JHEP 1402, 083 (2014); T. Enkhbat, JHEP 1401, 158 (2014).
[19] M. J. Dolan et al., Phys. Rev. D 87, 055002 (2013). J. Cao et al., JHEP 1304, 134 (2013) U. Ellwanger, JHEP 1308, 077 (2013) A. Arhrib et al., JHEP 0908, 035 (2009).
[20] R. Frederix et al., Phys. Lett. B 732, 142 (2014) [arXiv:1401.7340 [hep-ph]].