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Triple Higgs coupling as a probe of the twin-peak scenario

Amine Ahriche [a,b,c,*], Abdesslam Arhrib [d], Salah Nasri [e]

[a] Department of Physics, University of Jijel, PB 98 Ouled Aissa, DZ-18000 Jijel, Algeria
[b] The Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, I-34014, Trieste, Italy
[c] Fakultät für Physik, Universität Bielefeld, 33501 Bielefeld, Germany
[d] Université AbdelMalek Essaadi, Faculté des Sciences et Techniques, B.P 416, Tangier, Morocco
[e] Physics Department, UAE University, POB 17551, Al Ain, United Arab Emirates

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ABSTRACT

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 have shown that both at LHC and Linear Collider the triple Higgs couplings play an important role to identify this scenario; and also that this scenario can be distinguishable from any Standard Model extension by extra massive particles which might modify the triple Higgs coupling. We also introduce a criterion that can be used to rule out the twin peak scenario.

In July 2012, ATLAS and CMS Collaborations [1,2] have shown the existence of a Higgs-like resonance around 125 GeV confirming the cornerstone of the Higgs mechanism that predicted such particle long time 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 [3] and $m_h = 125.0 \pm 0.5$ GeV for ATLAS [4] 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 [5].

In the twin peak scenario (TPS); it is assumed that there are two scalars $h_{1,2}$ with almost degenerate masses around 125 GeV. To our knowledge, there is no indication from experimental data which disfavor this scenario. The couplings of the twin peak Higgs to SM particles $g_{h_i XX}$ are simply scaled with respect to SM rate by $\cos\theta$ (for h_1) and $\sin\theta$ (for h_2), where θ is a mixing angle, such that we have the following approximate sum rule:

$$g^2_{h_1 f\bar{f}} + g^2_{h_2 f\bar{f}} \simeq g^2_{h_{SM} f\bar{f}}, \quad g^2_{h_1 VV} + g^2_{h_2 VV} \simeq g^2_{h_{SM} VV}, \tag{1}$$

where f can be any of the SM fermions and $V = W, Z$ vector boson. In fact, the branching ratios of the Higgs to SM particles are SM-like only if the Higgs invisible is very suppressed or kinematically forbidden as will be considered in our example. 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 ($pp(e^-e^+) \to hh + X$), 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 $pp \to gg \to hh$ [6]. Such measurement is rather challenging at the LHC, and for this purpose several parton level analysis have been devoted to this process. It turns out that $hh \to b\bar{b}\gamma\gamma$ [7], $hh \to b\bar{b}\tau^+\tau^-$ [7,8] and $hh \to b\bar{b}W^+W^-$ [8,9] final states are very promising for High luminosity.

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* Corresponding author.
E-mail addresses: aahriche@ictp.it (A. Ahriche), aarhrib@ictp.it (A. Arhrib), snasri@uaeu.ac.ae (S. Nasri).

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Recently, CMS reported a preliminary result on the search for resonant di-Higgs production in $b\bar{b}\gamma\gamma$ channel [10].

The LC has also the capability of measuring with better precision: the Higgs mass and some of the Higgs couplings together with the self coupling of the Higgs [11]. Using recoil technique for the Higgs-strahlung process, the Higgs mass can be measured with an accuracy of about 40 MeV [11]. We note that at LHC with high luminosity we can measure the Higgs mass with about 100 MeV uncertainty which is quite comparable to e^+e^- colliders. The triple Higgs coupling can be extracted from $e^+e^- \to Zh^* \to Zhh$ at 500 GeV and even better from $e^+e^- \to \nu\bar{\nu}h^* \to \nu\bar{\nu}hh$ at $\sqrt{s} > 800$ GeV. In this regard, the LHC and e^+e^- LC measurements are complementary [12].

In Ref. [13], the authors have provided a tool to distinguish the two-degenerate states scenario from the single Higgs one. The approach of [13] applies only to models which enjoy modifications of $h \to \gamma\gamma$ rate with respect to the SM. However, according to the latest experimental results, both for ATLAS and CMS the di-photon channel seem to be rather consistent with the SM [3,4]. 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 [14], where the SM is extended with two real scalar fields S_0 and χ_1; each one is odd under a discrete symmetry $\mathbb{Z}_2^{(0)}$ and $\mathbb{Z}_2^{(1)}$ respectively. The field χ_1 has a non-vanishing vacuum expectation value, which breaks $\mathbb{Z}_2^{(1)}$ 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 $\mathbb{Z}_2^{(1)}$ symmetries introduces the two vacuum expectation values υ and υ_1 respectively. The physical Higgs h_1 and h_2, with masses m_1 and $m_2 \gtrsim m_1$, are related to the excitations of the neutral component of the SM Higgs doublet field, $\mathrm{Re}(H^{(0)})$, and the field χ_1 through rotation with a mixing angle θ 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 [15].

In our analysis we require that [1]: *(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 [3,4]: 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 $\sigma^{LHC}(hh + t\bar{t})$ at 14 TeV; $\sigma^{LC}(hh + Z)$ at 500 GeV and $\sigma^{LC}(hh + E_{miss})$ at 1 TeV. All these processes include, at least, one Feynman diagram with triple Higgs coupling. For the TPS, the total cross section gets contributions from the final states h_1h_1, h_1h_2 and h_2h_2. Therefore the quantity to be compared with the standard scenario can be expressed as:

$$\sigma^{\mathrm{TPS}}(hh + X) = \sigma(h_1h_1 + X) + 2\sigma(h_1h_2 + X) + \sigma(h_2h_2 + X), \tag{2}$$

which can be parameterized as:

$$\sigma^{\mathrm{TPS}} = \sigma_{aa}r_1 + \sigma_{ab}r_2 + \sigma_{bb}, \tag{3}$$

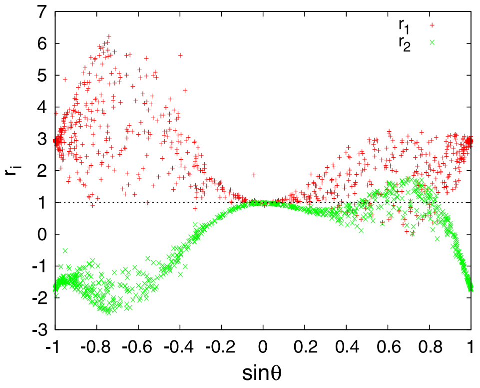

Fig. 1. Numerical values of the parameters r_i in (4) for 600 benchmarks that fulfill the above mentioned requirements.

with $\sigma_{aa} + \sigma_{ab} + \sigma_{bb} = \sigma^{SM}(hh + X)$ and σ_{aa}, σ_{bb} and σ_{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_ih_j, which depend on the mixing angle θ and the Higgs triple couplings $\lambda_{ijk}^{(3)}$.

In the TPS, the amplitudes for di-Higgs production processes have SM Feynman diagrams where theHiggs 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_ih_j. For example, in the case of h_1h_1 production, there are two types of diagrams: (1) The ones that involve triple scalar interactions $h_1h_1h_1$ and $h_2h_1h_1$, with couplings equal to the one of a SM times a factor of $c\lambda_{111}^{(3)}/\lambda_{hhh}^{SM}$ and $s\lambda_{112}^{(3)}/\lambda_{hhh}^{SM}$, respectively. We denote the total amplitude of these two contributions by $\mathcal{M}_{(a)}$. (2) The ones with no triple Higgs couplings. Their amplitude, denoted by $\mathcal{M}_{(b)}$, is given by the one of the SM scaled by a factor of c^2. Therefore, the amplitudes $\mathcal{M}_{(a,b)}$ (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:

$$\begin{array}{ll}
h_1h_1: & \mathcal{M}_{(a)} = [(c\lambda_{111}^{(3)} + s\lambda_{112}^{(3)})/\lambda_{hhh}^{SM}]\mathcal{M}_{(a)}^{SM}, \\
& \mathcal{M}_{(b)} = c^2\mathcal{M}_{(b)}^{SM}, \\
h_2h_2: & \mathcal{M}_{(a)} = [(c\lambda_{122}^{(3)} + s\lambda_{222}^{(3)})/\lambda_{hhh}^{SM}]\mathcal{M}_{(a)}^{SM}, \\
& \mathcal{M}_{(b)} = s^2\mathcal{M}_{(b)}^{SM}, \\
h_1h_2: & \mathcal{M}_{(a)} = [(c\lambda_{112}^{(3)} + s\lambda_{122}^{(3)})/\lambda_{hhh}^{SM}]\mathcal{M}_{(a)}^{SM}, \\
& \mathcal{M}_{(b)} = cs\mathcal{M}_{(b)}^{SM},
\end{array}$$

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

$$\begin{aligned}
r_1 = &\Big\{c^2[\lambda_{111}^{(3)2} + \lambda_{122}^{(3)2} + 2\lambda_{112}^{(3)2}] + s^2[\lambda_{112}^{(3)2} + \lambda_{222}^{(3)2} + 2\lambda_{122}^{(3)2}] \\
&+ 2cs[\lambda_{111}^{(3)}\lambda_{112}^{(3)} + 2\lambda_{112}^{(3)}\lambda_{122}^{(3)} + \lambda_{122}^{(3)}\lambda_{222}^{(3)}]\Big\} \Big/ \left(\lambda_{hhh}^{SM}\right)^2, \\
r_2 = &\{c^3\lambda_{111}^{(3)} + 3c^2s\lambda_{112}^{(3)} + 3cs^2\lambda_{122}^{(3)} + s^3\lambda_{222}^{(3)}\}/\lambda_{hhh}^{SM}.
\end{aligned} \tag{4}$$

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 within the condition (1). We see that for very small mixing angle r_i's are approximately equal to unity, while for $\sin\theta > 0.8$ and $\sin\theta < -0.2$, the parameter r_1 becomes larger than unity and

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[1] Actually, we considered that all quartic couplings to be of order unity; and the singlet vev $\upsilon_1 = \langle\chi_1\rangle = 20 \sim 2000$ GeV.

Table 1
Different contributions to the considered processes cross sections. Numbers for LHC are taken from [16] at NLO.

	σ_{aa} (fb)	σ_{ab} (fb)	σ_{bb} (fb)	σ^{SM} (fb)
hh	9.66	-49.9	70.1	29.86
$hh+t\bar{t}$	3.3164×10^{-2}	0.13952	0.84731	1.02
$hh+Z$	9.0206×10^{-3}	4.6999×10^{-2}	9.005×10^{-2}	0.14607
$hh+E_{miss}$	5.1631×10^{-2}	-0.20867	0.29708	0.14004

r_2 acquires negative values. This behavior could lead to an enhancement/reduction to the cross section depending on the sign of the interference contribution, σ_{ab}, to the total cross section. This means that the measurement of the following ratio:

$$\xi\,(hh+X)=\frac{\sigma^{\mathrm{TPS}}\left(pp(e^-e^+)\to hh+X\right)}{\sigma^{\mathrm{SM}}\left(pp(e^-e^+)\to hh+X\right)},\qquad(5)$$

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, $r_1=(1+\Delta)^2$ and $r_2=1+\Delta$, where Δ represents the relative enhancement of the triple Higgs coupling due to SM + MP. As we will show later, our considered scenario for small or large mixing could be distinguished from the case of SM + MP by combining the ratio (5) for different processes.

In Table 1, we give the values of σ_{aa}, σ_{ab} and σ_{bb} for the corresponding di-Higgs production processes. We note that their contributions to the LHC process $pp\to hh$ and to the LC one $e^+e^-\to Zhh$ 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 ξ. As it can be seen, in the TPS, the cross section of the processes $pp\to hh$, $pp\to hh+t\bar{t}$ and $e^-e^+\to hh+E_{miss}$ are mostly enhanced, while for $e^-e^+\to hh+Z$ it is enhanced just for the mixing values $0.5<\sin\theta<0.8$.

Now let us discuss the possibility of disentangling the TPS from the SM + MP. It is clear from Fig. 3 that for both LHC and LC processes with large mixing, $0.35<\cos^2\theta<0.65$, the TPS may coincide with SM + MP. However, for non-maximal mixing values the TPS is clearly different than SM + MP where all benchmarks have the following feature

$$\xi_1^{TPS}+\xi_2^{TPS}>\xi_1^{SM+MP}(\Delta)+\xi_2^{SM+MP}(\Delta)\,,\qquad(6)$$

where ξ_i^{TPS} the ratio in (5) for any LHC or LC processes and $\xi_i^{SM+MP}(\Delta)$ is the same ratio due the existence of massive particles. Therefore, when measuring the quantities (5) for both the LHC and e^+e^- LC processes, and one finds that the criterion (6) is not fulfilled, then it is a certain exclusion for this scenario. In

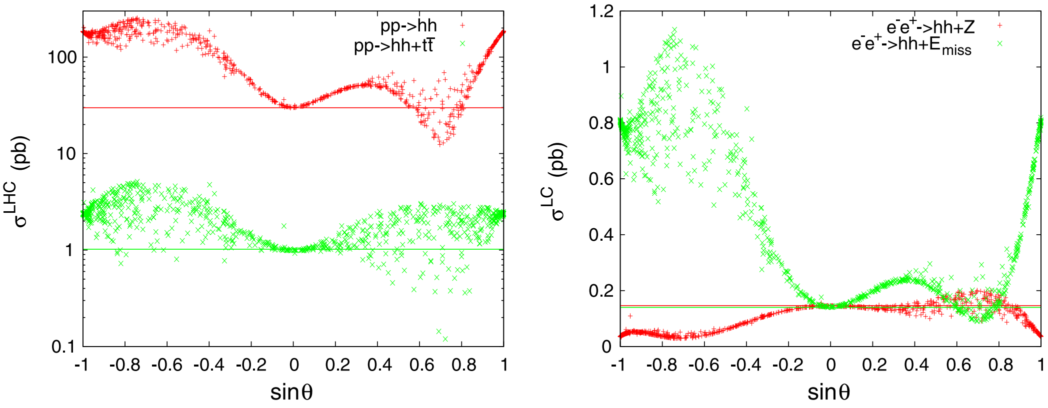

Fig. 2. The cross section values (2) for the di-Higgs production processes for the 600 benchmarks used previously. The solid lines correspond to the SM cross sections.

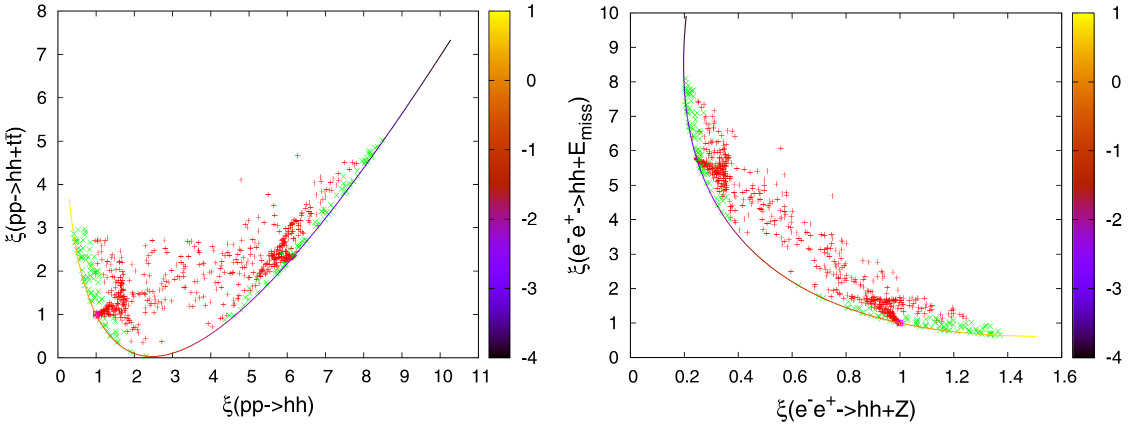

Fig. 3. The ratios ξ given in (5) for the di-Higgs production processes for the 600 benchmark used previously. The green benchmarks correspond to the large mixing case where $0.35<\cos^2\theta<0.65$, and the blue point represents the SM; and the solid curve represents the case of a SM extension, where the new physics affects the triple Higgs coupling as $\lambda_{hhh}=\lambda_{hhh}^{SM}(1+\Delta)$; and the value of the relative enhancement Δ can be read from the palette. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Different values of the ratios (4) and (5) for the three chosen benchmarks.

	B_1	B_2	B_3
$\sin\theta$	0.53555	0.90126	−0.39802
r_1	2.95386	2.88466	5.62286
r_2	1.31634	0.28189	−1.26011
$\xi\,(hh)$	1.10345	2.80975	6.27248
$\xi\,(hh+t\bar{t})$	2.69728	2.51821	4.66603
$\xi\,(hh+Z)$	1.22243	0.88532	0.55827
$\xi\,(hh+E_{miss})$	1.24900	2.76488	6.07213

Table 3
The events number for the different processes within the luminosity values mentioned above for the SM and the benchmarks shown in Table 2.

Events number	Channel	SM	B_1	B_2	B_3
$pp \to hh$	$4b$	966.75	1066.8	2716.3	6063.9
	$2b2\tau$	106.70	117.74	299.8	669.27
	$2b2\gamma$	3.89	4.29	10.93	24.4
$pp \to hh+t\bar{t}$	$4b$	33.02	89.06	83.15	154.07
$e^-e^+ \to hh+Z$	$4b$	23.65	28.91	20.94	13.2
$e^-e^+ \to hh+E_{miss}$	$4b$	45.34	56.63	125.36	275.31

case where the criterion (6) is fulfilled, detailed analysis is required for in order to identify the mixing angle, the parameters $\mathbf{r_i}$ and therefore the Higgs triple couplings. In fact, by studying all the di-Higgs production channels at both LHC and e^+e^- 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 $e^-e^+ \to hh + E_{miss}$ [17], new colored scalar singlets contribution to $pp \to hh$ (or $hh + t\bar{t}$) [18], or the presence of a heavy resonant Higgs [19].

In order to show whether this scenario can be tested at colliders, we consider three benchmarks that may be distinguished from SM + MP (i.e., three red points from Fig. 3), and compare the di-Higgs distribution (of the di-Higgs invariant mass as an example) with the SM one. The corresponding values of ratios r_i and ξ_i are given in Table 2, and in Table 3, 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 $pp \to 2b2\tau$ at the LHC and $e^-e^+ \to 4b + E_{miss}$ at LC's, while it is reduced for the processes $pp \to 4b + t\bar{t}$ and $e^-e^+ \to 4b + Z$. For benchmark B_1, the events number of the processes $pp \to 2b2\tau$ and $e^-e^+ \to 4b + E_{miss}$ is SM-like but it is reduced for the processes $pp \to 4b + t\bar{t}$ and $e^-e^+ \to 4b + Z$. For benchmark B_3, the events number is reduced for the considered processes.

In Fig. 4, we illustrate the di-Higgs invariant mass distribution ($M_{h,h}$) for the process $e^-e^+ \to hh + E_{miss}$. Clearly, the TPS can be easily distinguished from the SM, especially in the case of non-maximal mixing. 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 by considering different di-Higgs production processes at both LHC and e^+e^- LC. We have introduced a criterion whose violation excludes the TPS scenario, otherwise this scenario can be surely distinguished from the SM and SM extended by massive fields in case of non-maximal mixing.

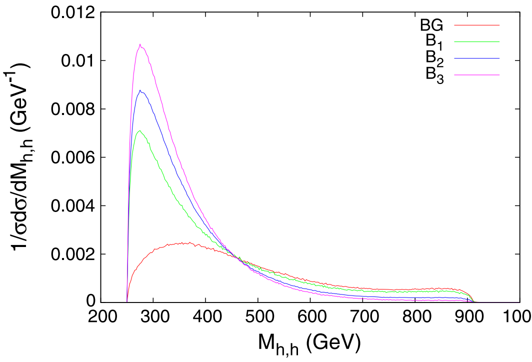

Fig. 4. Normalized di-Higgs invariant mass distribution for the process $e^-e^+ \to hh + E_{miss}$ for the background (BG) and the considered benchmarks in Table 2.

Last but not least, we should note that this scenario could be realized within SM + (real/complex) singlet scalar, or any larger scalar field content. This includes neutral or charged scalars that are members any multiplets, where two degenerate scalar eigenstates $h_{1,2}$ at 125 GeV, do couple to the SM gauge fields and fermions by more than ~90%, i.e., the sum rule (1) is fulfilled.[2] 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.

If the measurement of the couplings $hf\bar{f}$ and hVV become much more precise from the future experiment data, it may be possible that one could be sensitive to the radiative corrections effect to these couplings. Such radiative corrections to $hf\bar{f}$ and hVV couplings in a variety of extended Higgs sector have been evaluated in [22–24]. These one-loop effects are of the order of 2–10% and even more in some special cases. The present LHC measurements are not yet sensitive to such effects.

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