Electroweak production of light scalar–pseudoscalar pairs from extended Higgs sectors

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**A R T I C L E   I N F O**

Article history:
Received 5 August 2016
Received in revised form 2 September 2016
Accepted 6 November 2016
Available online 10 November 2016
Editor: G.F. Giudice

**A B S T R A C T**

In models with extended Higgs sectors, it is possible that the Higgs boson discovered at the LHC is not the lightest one. We show that in a realistic model (the Type I 2-Higgs Doublet Model), when the sum of the masses of a light scalar and a pseudoscalar (h and A) is smaller than the Z boson mass, the Electroweak (EW) production of an hA pair can dominate over QCD production by orders of magnitude, a fact not previously highlighted. This is because in the gg-initiated process, hA production via a resonant Z in the s-channel is prohibited according to the Landau–Yang theorem, which is not the case for the q̅q-initiated process. We explore the parameter space of the model to highlight regions giving such hA solutions while being consistent with all constraints from collider searches, b-physics and EW precision data. We also single out a few benchmark points to discuss their salient features, including the hA search channels that can be exploited at Run II of the LHC.

**1. Introduction**

Most models for physics beyond the Standard Model (SM) predict extended Higgs sectors, with additional Higgs (pseudo)scalars. Two-Higgs Doublet Models (2HDMs), which contain two Higgs doublets \( \phi_1 \) and \( \phi_2 \) (see [1] for a review), are among the simplest non-trivial extensions of the SM. The Higgs sector of a CP-conserving 2HDM contains three neutral Higgs bosons, two scalars and a pseudoscalar (h, H, with \( m_h < m_H \), and A, respectively), and a charged pair \( H^\pm \). One of the two CP-even Higgs bosons must have properties consistent with the observed 125 GeV state [2-4], \( H_{\text{obs}} \). At the Large Hadron Collider (LHC), the neutral Higgs bosons of a 2HDM can be produced both singly, dominantly via gluon fusion, and in identical or mixed pairs. We discuss here a scenario in which the \( h \) and \( A \) states of the Type-I 2HDM (2HDM-I),\textsuperscript{1} with masses satisfying \( m_h + m_A < M_Z \), can pass the present experimental constraints from the Large Electron Positron (LEP) collider, the Tevatron and the LHC, with the heavier \( H \) state being identified with \( H_{\text{obs}} \).

The LHC is a hadron collider that can yield collisions with very small momentum fraction \( x \) of the scattered partons and very large squared momentum transfer \( Q^2 \). Because the proton has a large gluon density at small \( x \), one would hope to initiate \( Z \) production from gluon-gluon (gg) scattering (see the left diagram of Fig. 1a), with the hA final state produced from Z decay. However, owing to the Landau–Yang theorem [5,6], gg can only scatter via a \( Z \) if it is non-resonant (i.e., off-shell, denoted by \( Z^* \)) [7]. This leads to a much depleted cross section for the hA signal and, additionally, to the inability of using \( Z^* \) mass reconstruction from the invariant mass of the hA (visible) decay products for suppressing backgrounds. In the case of the tree-level quark-antiquark (q̅q)-initiated process, however, the \( Z \) boson can be produced on-shell (left diagram of Fig. 1b). The hA final state can also be produced from double Higgs-strahlung off heavy quarks (i.e., b- and t-quarks), at the one-loop level (right diagram of Fig. 1a) and at the tree level (right diagram of Fig. 1b), in the case of gg and q̅q collisions, respectively.

It is the purpose of this Letter to highlight the hitherto neglected predominance of the q̅q-initiated tree-level production of a light hA pair at the LHC with respect to the gg-initiated one-loop production in a Type-I 2HDM. (See Ref. [8] for higher order

\textsuperscript{1} In the Type I model, all fermions get mass from Yukawa couplings to only one of the doublets, see below.

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\url{http://dx.doi.org/10.1016/j.physletb.2016.11.012}

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QCD corrections to the corresponding diagrams. We additionally outline the region of the 2HDM-I parameter space where the former can be accessed above and beyond the yield of the latter and present benchmark points to serve as a guideline for probing this production process at the current LHC run.

2. Model, parameter scan and constraints

In general, in a 2HDM, depending on how the two doublets couple to fermions, Flavor Changing Neutral Currents (FCNCs) can be mediated by (pseudo)scalars at the tree level. The requirement of vanishing FCNCs thus puts very strong restrictions on the coupling matrices. The simplest way to avoid large FCNCs is to impose a $Z_2$ symmetry so that each type of fermion only couples to one of the doublets (“natural flavor conservation”) [9,10]. There are four basic ways of assigning the $Z_2$ charges, and here we consider the case where only the doublet $\phi_2$ couples to all fermions, known as the Type I model. The Higgs potential for the CP-conserving 2HDM-I is written as

$$V = m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 - [m_{12}^2 \phi_1^\dagger \phi_2 + h.c.]$$

$$+ \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2)$$

$$+ \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \left[ \frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)^2 + h.c. \right],$$

which is invariant under the symmetry $\phi_1 \to -\phi_1$ up to the soft breaking term proportional to $m_{12}^2$. Through the Higgs fields, the tree-level mass relations allow the quartic couplings $\lambda_{1-5}$ to be substituted by the four physical Higgs boson masses and the neutral sector term $s_{\beta-\alpha}$ (short for $\sin(\beta - \alpha)$), with the angle $\beta$ defined through $\tan \beta = v_2/v_1$, where $\alpha$ mixes the CP-even Higgs states.

In order to test the consistency of solutions with $m_h + m_A < M_Z^2$ in the 2HDM-I with the most crucial and relevant theoretical and experimental constraints (listed further below), we performed a scan of its parameter space\footnote{Note that a similar region of parameter space was captured by Ref. [11].} using 2HDMC-v1.7.0 [12]. The (randomly) scanned ranges of the free parameters (with $m_{H^\pm} = 125$ GeV) are given in the second column of Table 1. Because only a select region of the parameter space is allowed by current constraints, we used the distributions resulting from this initial scan to determine the most relevant parameter ranges, which we focused on in a second scan, shown in the rightmost column of Table 1.

During the scan, each sampled model point was subjected to the following conditions:

- Unitarity, perturbativity, and vacuum stability enforced through the default 2HDMC method.
- Consistency at 95% Confidence Level (CL) with the experimental measurements of the oblique parameters $S$, $T$ and $U$, again, calculated by 2HDMC. We compare these to the fit values [13], $S = 0.00 \pm 0.08$ and $T = 0.05 \pm 0.07$, in an ellipse with a correlation of 90%. All points further satisfy $U = 0.05 \pm 0.10$.
- Satisfaction of the 95% CL limits on $b$-physics observables calculated with the public code SuperIso-v3.4 [14].
- Consistency with the $Z$ width measurement from LEP, $\Gamma_Z = 2.4952 \pm 0.0023$ GeV [13]. The partial width $\Gamma(Z \to hA)$ was required to fall within the 2σ experimental uncertainty of the measurement.
- Consistency of the mass and signal rates of $Z$ with the LHC data on $H_{bb}$. The combined 68% CL results from ATLAS and CMS for the most sensitive channels are [15]: $\mu_{H^+}\mu^{-}\bar{H} = 1.15^{+0.28}_{-0.25}$, $\mu_{H^+}\mu^{-}\bar{H}$ = $1.17^{+0.58}_{-0.53}$, $\mu_{H^+}\mu^{-}\bar{H}$ = $1.40^{+0.30}_{-0.25}$. We required that the equivalent quantities, calculated with HiggsSignals-v1.3.2 [16], satisfy these measurements at 95% CL, assuming Gaussian uncertainties.
- Consistency of all Higgs states with the direct search constraints from LEP, Tevatron, and LHC at the 95% CL tested using the public tool HiggsBounds-v4.3.1 [17–20].

The points were also required to satisfy some additional constraints from LEP and LHC that have not (yet) been implemented in HiggsBounds. Consistency with the combined LEP $H^\pm$ searches in the 2HDM-I [21] was ensured by requiring that $m_{H^\pm} > 90$ GeV. The LEP-II constraints on $e^+e^- \to \gamma \gamma \bb$ [22] were also taken into account. While these constraints are mass dependent, we conservatively required $\cos^2(\beta - \alpha)BR(h \to \gamma \gamma)BR(A \to \bb) < 0.02$. Moreover, the results of the $\mu \mu \tau \tau$ final state studies performed by ATLAS [23] as well as of the $\tau \tau \tau \tau$ [24], $\mu \mu \tau \tau$ [25] and $\mu \bb \bb$ [26] analyses from CMS were tested against.

3. Scan results

From the output of our initial scan, we noticed that the LHC observation of a very SM-like $H_{bb}$ pushes the model towards the alignment limit, $s_{\beta-\alpha} \to 0$. Additionally, strong constraints from LEP searches lead to suppressed $h/A$ couplings to fermions, producing a strong correlation $s_{\beta-\alpha} \approx -1/\tan \beta$. We also find that a relatively light charged Higgs $(m_{H^\pm} \lesssim 120$ GeV) is necessary, as a charged Higgs mass too far separated from $m_h$ or $m_A$ results

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| Parameter | Initial range | Refined range |
|-----------|---------------|---------------|
| $m_h$ (GeV) | (10, 80) | (10, 2M_{Z/3}) |
| $m_A$ (GeV) | (10, M_2 - m_h) | (m_h/2, M_2 - m_h) |
| $m_{H^\pm}$ (GeV) | (90, 500) | (90, 150) |
| $s_{\beta-\alpha}$ | (-1, 1) | (-0.25, 0) |
| $m_{H^\pm}^2$ (GeV$^2$) | (0, m_h^2 sin(\beta cos(\beta)) | (0, m_h^2 sin(\beta cos(\beta)) |
| $\tan \beta$ | (2, 25) | (-0.95, -1.1)/s_{\beta-\alpha} |
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\footnote{In the 2HDM-I, the couplings of $h$ and $A$ to fermions go as $g_{Hf} = \cos \alpha / \sin \beta$ and $g_{A\ell} = \sin \alpha / \cos \beta$.}
in large contributions to the $T$-parameter. Existing searches for charged Higgs bosons in this mass range typically focus on production from top decays followed by charged Higgs boson decays to either $\tau\nu$ or $c\bar{s}$. For the points selected by the scan, these branching ratios typically fall below the percent level, in many cases by several orders of magnitude, with maximal values of $\text{BR}(t \to H^+ b) \lesssim 0.04$, $\text{BR}(H^+ \to \tau^+ \nu_\tau) \lesssim 0.01$, and $\text{BR}(H^+ \to c\bar{s}) \lesssim 6 \times 10^{-3}$. This places them well below existing constraints, including recent LHC results [27–29] not yet included in HiggsBounds. Instead of the standard decays, the low masses of $h$ and $A$ in the scenario considered here allow the $H^+$ to decay dominantly in the $W^+h$ or $W^+A$ channels (with the respective branching ratios alternatively near unity), which have not yet been examined at the LHC.

Numerous constraints restrict the possible masses of $h$ and $A$. In Fig. 2 we show the points passing all the constraints mentioned above in the $(m_h,m_A)$ plane. Because the $hA\bar{Z}$ coupling is maximized in the favored $s_{P_{13}} \to 0$ limit, the constraint from $\Gamma_Z$ the $1\sigma$ and $2\sigma$ contours for which are also shown, is particularly severe. We note two distinct regions with a large density of points in the figure. The region near the top left corner corresponds to the $m_A > m_h$ (heavier $A$) scenario. This region cuts off sharply at $m_A = m_h/2$ due to the possibility of the $H \to AA$ decay arising, which potentially leads to a suppression of the signal strengths for the SM-like $H$ (for the 2HDM-I scenarios we consider, these signal strengths are always below 1 to begin with). This possibility can be avoided with a sufficiently suppressed $HAA$ coupling, as a result of which additional points satisfying all constraints appear in the region corresponding to the $m_h > m_A$ (heavier $h$) scenario near the lower right corner of the figure. When $m_h > 2m_A$, the $h \to AA$ decay channel opens up, and the model is severely constrained by LEP searches for processes such as $e^+e^- \to H \to (AA)A \to (bb\bar{b}b)\bar{b}b$ [31]. Consequently, we did not find acceptable points with $m_h > 2m_A$.

The color map in Fig. 2 depicts the total cross section for the $q\bar{q} \to hA$ process, which evidently grows larger as one moves away from the diagonal and $m_h + m_A$ gets smaller. For calculating this cross section, we used the 2HDMC model [12] with MadGraph5_aMC@NLO [32], considering both 4- ($q = u, d, c, s$) and 5- ($q = u, d, c, s, b$) flavor schemes. The 5-flavor scheme predictions differ by less than 3% from those of the 4-flavor one due to the small $b$-quark couplings. Also highlighted in the figure are the three Benchmark Points (BPs) selected to demonstrate the typical characteristics of the interesting parameter space regions. These BPs will be discussed in detail later.

4. EW vs. QCD production

In order to be able to compare the relative strengths of the $q\bar{q} \to hA$ production mode and the $gg \to hA$ mode, we also calculated the cross section for the latter for each point using codes developed with MadGraph5_aMC@NLO [32] for Higgs pair production [33]. The comparison is shown in Fig. 3, where one notices that the maximal cross section achievable for QCD production is about three orders of magnitude smaller than that for EW production, which can reach as high as $\sim 90$ pb. Also, for the points shown, while the maximal cross section for EW production is consistent across the two $(m_h,m_A)$ regions, which can be distinguished through the color map in $m_A$, QCD production clearly prefers the heavier $A$ scenario.

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4 This requirement of a light charged Higgs prevents us from finding similar points in Type-II models, where a higher $m_{H^\pm}$ is required by $B$-physics constraints.

5 These decay modes of the $H^\pm$ will be discussed further in [30].

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Fig. 2. Constraints and accepted points in the $(m_h,m_A)$ plane. Shaded areas: Red – $m_h > 2m_A$, allowing $h \to AA$ decays; Blue – theoretical prediction of the $Z \to hA$ partial width exceeds experimental uncertainty at the $1\sigma$ (lighter) and $2\sigma$ (darker) levels, in the limit $\cos(\beta-\alpha) = 1$; Orange – $m_h + m_A$ above the $m_Z$ threshold, not considered in this study. The color map corresponds to the total cross section for the $q\bar{q} \to hA$ process at $\sqrt{s} = 13$ TeV, and the three benchmark points have been highlighted in yellow. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 3. Cross sections for $q\bar{q}$- vs. $gg$-initiated $hA$ production at the LHC with $\sqrt{s} = 13$ TeV, for points satisfying all the constraints described in the text. The color map indicates $m_A$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Benchmarks

The input parameters for the three BPs shown in Fig. 2 are given in Table 2 along with the corresponding cross sections in the two $hA$ production channels analyzed. BP1 corresponds to the heavier $h$ scenario while BP2 and BP3 correspond to the heavier $A$ scenario.

In Table 3 we list the BRs of $h$ and $A$ in the most important decay channels for each BP. The allowed points in the heavier $h$ scenario all have characteristics similar to BP1 – a highly fermiophobic $h$ which consequently decays dominantly to $Z^*A$ and a light $A$ which decays primarily into pairs of third genera-
Table 2

| BP | m_h | m_A | m_{h\rightarrow \gamma \gamma} | \sigma(\gamma\gamma)/\sigma(gg) |
|----|-----|-----|-----------------------------|-----------------------------|
| 1  | 54.2| 33.0| 95.9                        | -0.12                       |
| 2  | 22.2| 64.9| 1015                        | -0.05                       |
| 3  | 14.3| 71.6| 1072                        | -0.06                       |

Table 3

| BP | m_A | BR(h\rightarrow...) [%] | m_{A\rightarrow...} [%] |
|----|-----|-------------------------|-------------------------|
| 1  | 94  | 5                       | 6                       |
| 2  | 60  | 3                       | 12                      |
| 3  | 60  | 24                      | 8                       |

6 The large signatures of interest would then include Z^*b\bar{b}, Z^*b\bar{t}, and Z^*t\bar{t}. A similar situation is also possible in the heavier A scenario, as seen for BP2, where the roles of A and h are now reversed, but the most common final states remain the same. Unlike A, however, the light h can also decay dominantly to two photons (due to contribution from W^\pm loops, which is missing in the A \rightarrow \gamma\gamma decay), thus opening up the possibility of Ah \rightarrow (Z^*h) \rightarrow Z^*\gamma\gamma or Z^*\gamma\gamma\gamma or Z^*\gamma\gamma\gamma\gamma decay chain for points like BP3.

6 The h \rightarrow Z^*A and A \rightarrow Z^*h decays were previously discussed in a fermiophobic model in [34].

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