Constraints on a 2HDM with a singlet scalar and implications in the search for heavy bosons at the LHC

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ABSTRACT: We study a two-Higgs doublet model extended with an additional singlet scalar (2HDM+S), and provide a brief introduction to the model and its parameters. Constraints are applied to the parameter space of this model in order to accommodate a number of discrepancies in the data that have been interpreted in Ref. [1] as the result of the $H \to Sh$ decay produced via gluon-gluon fusion and in association with top quarks. Implications on the phenomenology of the heavy pseudo-scalar ($A$) and charged scalar ($H^+$) are discussed. In particular, the decays $A \to ZH$ and $H^+ \to W^+H$ become prominent. This leads to final states with multiple leptons and $b$-quarks. The decay $A \to ZH \to ZSh$ results in the production of a high transverse momentum $Z$ produced in association with a lepton and two $b$-quarks with little additional jet activity. These predictions are compared to the data.

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1 Introduction

The discovery of a Higgs boson [2–5] at the Large Hadron Collider (LHC) [6, 7] represents a new window of opportunity for the field of particle physics. Following this discovery, the focus has shifted towards the understanding of the couplings of this boson to particles in the Standard Model (SM) and beyond (BSM), and towards the search for new bosons. The Run 2 at the LHC is expected to deliver about 140 fb$^{-1}$ of usable data at a proton-proton centre of mass of 13 TeV. Most of the studies released by the experiments at the LHC have been performed on a quarter of this data set. Furthermore, some important studies have not yet been released with Run 2 data altogether.

In Refs. [8–10] the scalars $H$ and $S$ were introduced via an effective model to explain a number of features in the Run 1 data. These include distortions of the Higgs boson transverse momentum spectrum, accompanied with elevated associated jet activity, elevated rates of leptons in association with $b$-tagged jets used for the search of the associated production of the Higgs boson with top quarks, and results from the search for double Higgs boson and weak boson production. The potential impact on the measurements of some of the signal strengths of the newly discovered Higgs boson has been evaluated in Ref. [11]. The relevance and advantages of electron-proton collisions to search for additional scalar bosons has also been pointed out in Refs. [12–14].

One simple extension of the Standard Model (SM) are the two-Higgs doublet models (2HDMs), which need an additional Higgs-doublet in the model. As a result of this additional doublet, the scalar spectrum is populated (with respect to the SM scalar sector, that is, the Higgs boson $h$) with extra CP-even ($H$), CP-odd ($A$) and charged ($H^\pm$) scalar...
bosons. Note that 2HDMs have been explored in the literature, where various facets related to the theory, phenomenology and constraints on these models using the experimental data from different collider environments have been explored [15]. However, as pointed out in Refs. [9, 10, 16, 17], a 2HDM alone is not able to accommodate the above-mentioned features of the data. As a result, a scalar singlet $S$ is introduced in conjunction with a 2HDM in Ref. [10], referred to here as the 2HDM+S model. In addition, this type of model may also able to explore scenarios with dark matter. In Ref. [10] it was discussed that a 2HDM+S model would result in the anomalous production of multiple leptons. This hypothesis has been compared to data [1, 18], where large discrepancies between the data and SM MCs are observed that cannot be resolved with the current understanding of theoretical systematics.

Here we are expanding on the phenomenology described in Ref. [10]. In this paper we attempt to identify the parameter space of the 2HDM+S model that will accommodate the discrepancies in the data studied in Ref. [1]. Here we focus on understanding the implications of this choice of parameter space for the heavy pseudo-scalar and the charged scalar. We are particularly interested in investigating the CP-odd scalar in the 2HDM+S model. In particular, we study the production of $A$ through the gluon-gluon-fusion (ggF) mode, and its decay into $A \to ZH$ channels, where the decay modes $H \to hh, Sh, SS$ are considered. This setup leads to a number of interesting final states with leptons and $b$-tagged jets.

The resulting kinematics of the decay of $A \to ZH$, where $m_A > m_Z + m_H$ and $H \to SS, Sh$, have been studied in Ref. [10]. Assuming that the width of $A$ is much smaller than the experimental resolution obtained with the $llbb$ decay, it was noted that a relatively narrow structure in the invariant mass spectrum of $Zh$ is expected, such that $m_{Zh} < m_A$.

A structure in the $Zh$ invariant mass spectrum has been reported by the ATLAS collaboration [19] with Run 2 data. The CMS collaboration has reported limits with Run 1 and Run 2 data that do not contradict the aforementioned results [20, 21]. The structure has been interpreted in terms of the decay $A \to Zh$ within a 2HDM, with a cross-section $\sigma(pp \to Zh) \approx 100 - 300 \text{fb}$ in Ref. [22]. Here we interpret the structure in terms of the 2HDM+S model with the spectroscopy discussed in Refs. [8, 10] and Ref. [1], where $m_H \approx 270 \text{GeV}$ and $m_S \approx 150 \text{GeV}$. The structure includes events with more than two $b$-tagged jets, which can be interpreted within a 2HDM as coming from a bottom-quark induced production of the CP-odd boson at intermediate values of $\tan \beta$. Here the production of $Zh$ with additional $b$-tagged jets from $A \to ZH \to ZSh, Zhh$ is discussed.

Note also that the CMS collaboration has reported discrepancies of 2.85$\sigma$ in the production of three leptons, where one pair comes from the decay of a Z boson, in association with $b$-tagged jets but with reduced hadronic jet activity [23, 24]. These events are identified in the context of studying $ttZ$ production where the discrepancy emerges with low jet multiplicity. This excess can be explained by the production $A(600) \to ZH(270) \to ZS(145)h, Zhh$. In this setup we elaborate on the resulting characteristics corresponding to the production of three leptons, including a Z boson in association with $b$-tagged jets. The potential impact of the signal from a heavy CP-odd boson discussed in Ref. [22] is considered here on the measurement of the signal strength of $Vh$, $(V = ZW)$ production.
This paper is organised into the following sections: In section 2 we describe the model, in section 3 we describe the tools used and constraints imposed on the parameter scan, reporting on the allowed region of the parameter space where the implications on the branching ratios of the heavy pseudo-scalar and charged scalar are reported. In section 4 the findings from section 3 are compared to the data, and in section 5 we summarise and conclude.

2 The Model

Following Ref. [10], a 2HDM with an additional real singlet $\Phi_S$ is the baseline for our formalism, where we use the notation used in Ref. [25], and call this model the 2HDM+S. As such, the potential is given by:

$$V(\Phi_1, \Phi_2, \Phi_S) = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2$$
$$+ \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} \left[ (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right]$$
$$+ \frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8} \Phi_4^4 + \frac{\lambda_7}{2} (\Phi_1^\dagger \Phi_1) \Phi_S^2 + \frac{\lambda_8}{2} (\Phi_2^\dagger \Phi_2) \Phi_S^2. \quad (2.1)$$

Here the fields $\Phi_1$ and $\Phi_2$ are the $SU(2)_L$ Higgs doublets. The first two lines are the terms from real 2HDM potential, while the last line contains the contribution of the singlet field $\Phi_S$. Generally, models with more than one Higgs doublet have tree-level Flavour Changing Neutral Currents (FCNC). To prevent tree-level FCNCs, we must couple all quarks of a given charge to a single Higgs doublet. This can be accomplished by imposing a $Z_2$ symmetry, which can be softly broken. We have also extended the $Z_2$ symmetry to the Yukawa sector with softly broken terms involving $m_{12}^2$. A trivial generalisation of the usual 2HDM $Z_2$ symmetry requires:

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow -\Phi_2, \quad \Phi_S \rightarrow \Phi_S. \quad (2.2)$$

One can also consider another $Z'_2$ symmetry:

$$\Phi_1 \rightarrow \Phi_1, \quad \Phi_2 \rightarrow \Phi_2, \quad \Phi_S \rightarrow -\Phi_S, \quad (2.3)$$

which is not broken explicitly. For our study, we consider a scenario where the real singlet field $\Phi_S$ acquires a vacuum expectation value ($vev$) with $Z_2$ symmetry. Note that if $\Phi_S$ doesn’t acquire a $vev$, the $Z'_2$ symmetry then becomes a source of a viable dark matter candidate.

In this work we set the term $m_{12}^2 \neq 0$ in the 2HDM+S potential, which corresponds to a soft breaking of the $Z_2$ symmetry, and consider the $\lambda_i$ to be real, which corresponds to a model without explicit CP violation. More discussions can be found in Refs. [25–27].

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1In principle $\Phi_S$ could be a complex singlet, and, in this case, the discrete $Z_2$ symmetry would be promoted to a global $U(1)$ symmetry, where the spontaneous breaking would lead to a massless pseudo-scalar. This might be important and acceptable for phenomenology if it does not couple to the SM particles [26].
Assuming the vevs for the fields $\Phi_1 \to v_1/\sqrt{2}$, $\Phi_2 \to v_2/\sqrt{2}$ and $\Phi_S \to v_S$ are real after electroweak symmetry breaking (EWSB), the minimisation of the potential of the three Higgs fields leads to the three minimisation conditions:
\[
\frac{\partial V}{\partial v_1} = \frac{\partial V}{\partial v_2} = \frac{\partial V}{\partial v_S} = 0. 
\] (2.4)

The first derivative conditions for $\Phi_i$ $(i = 1, 2, S)$ are:
\[
\frac{\partial V}{\partial \Phi_1} = 0 \Rightarrow m_{11}^2 = -\frac{1}{2}(v_1^2\lambda_1 + v_2^2\lambda_{345} + v_S^2\lambda_7) + \frac{v_2}{v_1}m_{12}^2, 
\] (2.5)
\[
\frac{\partial V}{\partial \Phi_2} = 0 \Rightarrow m_{22}^2 = -\frac{1}{2}(v_1^2\lambda_2 + v_2^2\lambda_{345} + v_S^2\lambda_8) + \frac{v_2}{v_1}m_{12}^2, 
\] (2.6)
\[
\frac{\partial V}{\partial \Phi_S} = 0 \Rightarrow m_S^2 = -\frac{1}{2}(v_1^2\lambda_7 + v_2^2\lambda_8 + v_S^2\lambda_6), 
\] (2.7)

where $\lambda_{345} \equiv \lambda_3 + \lambda_4 + \lambda_5$. Further, the doublet fields $\Phi_1$, $\Phi_2$ and singlet field $\Phi_S$ can be parameterised as:
\[
\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \rho_1 + i\eta_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \rho_2 + i\eta_2) \end{pmatrix}, \quad \Phi_S = v_S + \rho_S, 
\] (2.8)

where $\phi_j^\pm (j = 1, 2)$ are the charged complex fields, $\rho_1$ are real neutral CP-even fields and $\eta_i$ are the real CP-odd fields. By substituting the parametrisation (2.8) into the Higgs potential (2.1), the mass matrices in the gauge basis can be easily obtained from the second derivatives of the fields. Accordingly, the mass-matrix for the charged ($M_{H^\pm}^2$) and CP-odd ($M_A^2$) scalar sector will remain as it is in the 2HDM. Using a $2 \times 2$ rotation matrix, given as:
\[
\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \phi_1^+ \\ \phi_2^+ \end{pmatrix}, 
\] (2.9)

where $G^\pm$ are a pair of charged Goldstone bosons and $H^\pm$ are the physical charged scalars; the mass squared charged scalar matrix is the same as in a 2HDM. It can be represented as:
\[
M_{H^\pm}^2 = \begin{pmatrix} -(2m_{12}^2 + (\lambda_4 + \lambda_5)v_1v_2) \frac{\eta_2}{v_1} & m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5)v_1v_2 \\ m_{12}^2 + \frac{1}{2}(\lambda_4 + \lambda_5)v_1v_2 & -(2m_{12}^2 + (\lambda_4 + \lambda_5)v_1v_2) \frac{\eta_1}{v_1} \end{pmatrix}. 
\] (2.10)

Similarly, the CP-odd scalar sector can be diagonalised using the same $2 \times 2$ rotation matrix:
\[
\begin{pmatrix} G^0 \\ A \end{pmatrix} = \begin{pmatrix} \cos \beta & \sin \beta \\ -\sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix}, 
\] (2.11)

where $G^0$ is a neutral Goldstone boson, $A$ is the physical pseudo-scalar, and $\eta_{1,2}$ are real CP-odd fields. The mass squared CP-odd scalar matrix is exactly the same as in the 2HDM. It can be formulated as:
\[
M_A^2 = \begin{pmatrix} -(m_{12}^2 + \lambda_5v_1v_2) \frac{\eta_2}{v_1} & m_{12}^2 + \lambda_5v_1v_2 \\ m_{12}^2 + \lambda_5v_1v_2 & -(m_{12}^2 + \lambda_5v_1v_2) \frac{\eta_1}{v_1} \end{pmatrix}, 
\] (2.12)
where diagonalising the CP-odd mass squared matrix will result in the pseudo-scalars physical mass eigenstates $A$.

Since the 2HDM+S CP-even Higgs sector consists of additional Higgs bosons with respect to the 2HDM, due to the addition of the real scalar singlet, the CP-even neutral Higgs mass matrix is enlarged to a $3 \times 3$ matrix. In the interaction basis, $(\rho_1, \rho_2, \rho_3)$, it can be written as (using eqs. (2.5)-(2.7)):

$$M_{\text{CP-even}}^2 = \begin{pmatrix}
\lambda_1 c_\beta^2 v^2 + t_\beta m_{12}^2 & -m_{12}^2 + \lambda_{345} c_\beta s_\beta v^2 & \lambda_7 c_\beta v v_S \\
-m_{12}^2 + \lambda_{345} c_\beta s_\beta v^2 & \lambda_8 s_\beta v v_S & \lambda_8 s_\beta v v_S \\
\lambda_7 c_\beta v v_S & \lambda_8 s_\beta v v_S & \lambda_6 v_S^2
\end{pmatrix}, \quad (2.13)$$

and it can be diagonalised by an orthogonal $3 \times 3$ matrix $\mathcal{R}$, in terms of mixing angles $\alpha_k$ ($k = 1, 2, 3$), and given as:

$$\mathcal{R} = \begin{pmatrix}
c_{\alpha_1} c_{\alpha_2} & s_{\alpha_1} c_{\alpha_2} & s_{\alpha_2} \\
-(c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3}) & c_{\alpha_1} c_{\alpha_3} - s_{\alpha_1} s_{\alpha_2} c_{\alpha_3} & c_{\alpha_2} s_{\alpha_3} \\
-c_{\alpha_1} s_{\alpha_2} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_3} & -(c_{\alpha_1} s_{\alpha_3} + s_{\alpha_1} c_{\alpha_2} c_{\alpha_3}) & c_{\alpha_2} c_{\alpha_3}
\end{pmatrix}. \quad (2.14)$$

The three physical mass eigenstates $h, S$ and $H$ in terms of the interaction basis $(\rho_1, \rho_2, \rho_3)$, are given as:

$$\begin{pmatrix} h \\ S \\ H \end{pmatrix} = \mathcal{R} \begin{pmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \end{pmatrix}. \quad (2.15)$$

Here the mixing angles $\alpha_{1,2,3}$ for the CP-even Higgs states can be constrained within

$$-\frac{\pi}{2} < \alpha_{1,2,3} < \frac{\pi}{2},$$

without loss of generality. And thus the CP-even mass squared matrix $M_{\text{CP-even}}^2$ can be diagonalised using the orthogonal matrix $\mathcal{R}$ as:

$$\mathcal{R} M_{\text{CP-even}}^2 \mathcal{R}^T = \text{diag}(m_h^2, m_S^2, m_H^2). \quad (2.16)$$

As such, the physical masses of the CP-even scalars are given by:

$$m_h^2 = v_S \sin \alpha_2 \left[ \lambda_7 v \cos \alpha_1 \cos \alpha_2 \cos \beta + \lambda_8 v \sin \alpha_1 \cos \alpha_2 \sin \beta + \lambda_6 v_S \sin \alpha_2 \right],$$

$$m_S^2 = (\cos \alpha_1 \cos \alpha_3 - \sin \alpha_1 \sin \alpha_2 \sin \alpha_3) \left[ \cos \alpha_1 \cos \alpha_2 \left( \lambda_{345} v^2 \sin \beta \cos \beta - m_{12}^2 \right) + \sin \alpha_1 \cos \alpha_2 \left( m_{12}^2 \cot \beta + \lambda_2 v^2 \sin^2 \beta \right) + \lambda_8 v v_S \sin \alpha_2 \sin \beta \right],$$

$$m_H^2 = (\sin \alpha_1 \sin \alpha_3 - \sin \alpha_2 \cos \alpha_1 \cos \alpha_3) \left[ \cos \alpha_1 \cos \alpha_2 \left( m_{12}^2 \tan \beta + \lambda_4 v^2 \cos^2 \beta \right) + \sin \alpha_1 \cos \alpha_2 \left( \lambda_{345} v^2 \sin \beta \cos \beta - m_{12}^2 \right) + \lambda_7 v v_S \sin \alpha_2 \cos \beta \right], \quad (2.17)$$

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The abbreviations used here are $s_{\alpha_k} \equiv \sin \alpha_k$, $c_{\alpha_k} \equiv \cos \alpha_k$ and $t_{\beta} \equiv \tan \beta$, where $t_{\beta}$ is defined as $t_{\beta} = v_2/v_1$ and $v^2 = v_1^2 + v_2^2$. By letting $\alpha_{2,3} \to 0$ and $\alpha_1 \to \alpha + \pi/2$ the 2HDM+S approaches the limit of a 2HDM with an added decoupled singlet, where $\alpha$ diagonalises the $2 \times 2$ mass matrix of the CP-even sector.
where \( v = \sqrt{v_1^2 + v_2^2} = 246 \text{ GeV} \). It is important to note that this model can connect the anomalies and deviations (or excesses) seen and discussed in section 1, including the few analyses performed in Refs. [8, 10, 11, 16, 17], by considering the couplings of additional bosons among themselves, as well as with gauge bosons and fermions. For example, consider the coupling of \( H_i = (h, S, H) \) with a pseudo-scalar \( A \) and the \( Z \) boson, where the Feynman rule is given by:

\[
\lambda_\mu(H_iZA) = \frac{\sqrt{g'^2 + g^2}}{2} (p_{Hi} - p_A) \mu \tilde{c}(H_iZA),
\]

where \( g' \) is the \( U(1)_Y \) gauge coupling with \( \tilde{c}(hZA) = -c_{\alpha_2}s_{\beta - \alpha_1}, \tilde{c}(SZA) = s_{\beta - \alpha_1}s_{\alpha_2}s_{\alpha_3} + c_{\alpha_3}c_{\beta - \alpha_1}, \) and \( \tilde{c}(HZA) = c_{\alpha_3}s_{\beta - \alpha_1}s_{\alpha_2} - s_{\alpha_3}c_{\beta - \alpha_1} \). The four-momenta \( p_{Hi} \) and \( p_A \) of \( H \) and \( A \) respectively, are taken as incoming. It is to be noted that the tilde over the coupling factor \( \tilde{c} \) denotes that it is not an effective coupling, since due to no SM counterpart it is not normalised to a corresponding SM coupling. Similarly, the trilinear Higgs coupling \( hSH \) is given by:

\[
\lambda_{hSH} = \frac{1}{v} \left[ \mu^2 \left( 2R_{12}R_{13} + R_{32}R_{33} \right)c_\beta + (R_{31}R_{33} - 3R_{12}R_{23}R_{33} - R_{21}R_{23})s_\beta 
+ 3R_{13}R_{22} \left( \frac{R_{31}}{c_\beta} - \frac{R_{32}}{s_\beta} \right) + 3R_{13}R_{23}R_{31} \frac{s_\beta^2}{c_\beta} \right] 
+ \sum_{i=1}^{3} \frac{m_{Hi}^2}{v_S} \left[ R_{13}R_{23}R_{33}v + R_{12}R_{22}R_{32} \frac{v_S}{s_\beta} - R_{11} \left( R_{22}R_{32} + R_{23}R_{33} \right) \frac{v_S}{c_\beta} \right],
\]

(2.19)

where \( \mu^2 = \frac{m_{12}^2}{s_\beta c_\beta} \) and \( R_{ij} \) are the elements of the orthogonal matrix \( R \). For further details we refer the reader to Ref. [25].

3 Tools and phenomenology

For our phenomenological analysis we first fix the masses of CP-even and CP-odd scalars in the theory as a benchmark point. From here we denote the lightest CP-even scalar as around the SM Higgs boson with mass \( m_h = 125 \text{ GeV} \), the second one as \( S \) with mass \( m_S = 140 \text{ GeV} \), and the heaviest one as \( H \) with mass \( m_H = 270 \text{ GeV} \). The CP-odd neutral scalar mass \( m_A = 600 \text{ GeV} \) and the charged scalar is taken with \( m_{H^\pm} = 600 \text{ GeV} \). These mass ranges of scalars are based on the previous studies considered by the authors of Ref. [10]. To start with we first scan the parameter space of the 2HDM+S described in section 2 using the publicly available code N2HDECAY [25]. The N2HDECAY code calculates all 2HDM+S scalar boson decay widths and branching ratios (BRs), which include higher order QCD corrections and off-shell decays, however, in this code electroweak corrections are neglected. Furthermore, theoretical constraints on this model for the above-defined benchmark points, like perturbative unitarity and vacuum stability, are also checked with the package ScannerS [28]. In addition to these, the following constraints are applied to get the allowed parameter space:
Figure 1: Allowed values of $\alpha_1$, $\alpha_2$ and $\alpha_3$ for the benchmark considered here, where the values in red (blue) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

- BRs of the lightest boson should be consistent with the SM within 20% and 10%. This is in order to comply with the wealth of constraints coming from the SM Higgs boson measurements.

- The sum of the BRs of the heavy scalar to lighter scalars should be 80%-90% [8, 29].

- The size of the coupling of $h$ to particles in the SM must be in the range $0.8 \pm 0.12$ of the prediction of the SM [29].

- Based on the estimate of the Yukawa coupling of the heavy scalar to top quarks, $\beta_g^2 = 1.38 \pm 0.22$ [1], where $\beta_g$ is a scaling factor with respect to the SM. From here
Figure 2: Allowed values of $\alpha_1$, $\alpha_2$ and $\alpha_3$ against $\tan \beta$ for the benchmark considered here, where the values in red (blue) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

It follows $\tan^2 \beta = 0.72 \pm 0.12$.

In Figure 1 we show the allowed values of $\alpha_1$, $\alpha_2$ and $\alpha_3$ for the benchmark considered here. One can appreciate that the mixing angle $\alpha_1$ seems more constrained than the other mixing angles. The constraints on $\alpha_2$ and $\alpha_3$ are better appreciated in Figure 1 (c), where one can see that certain areas in the plane are excluded. Results are shown by imposing the condition that the BRs of the lightest scalar be consistent within 20% and 10%. Going from 20% to 10% has a strong impact on how the mixing angles are constrained. Figure 2 displays the correlation between mixing angles and $\tan \beta$, where the results are also shown for the two different constraints on the BRs of the light scalar. The allowed values of $\tan \beta$
become constrained even further. The correlation between $\tan \beta$ and $\alpha_1$ is noticeable, while the correlation with $\alpha_2$ and $\alpha_3$ appears small.

The sensitivity to the Higgs boson BRs at the LHC is not significantly better than 20%. This leaves a significant window of opportunity for new physics. Here we investigate the correlations among the relevant BRs that emerge within this 20% constraint, where ratios of BRs can vary considerably. In Figure 3 we show these correlations which are consistent within the BRs of $m_h = 125$ GeV within 10% and 20%. One can appreciate that the allowed parameter space corresponding to a maximum 10% deviation is considerably more constrained than for 20%. This has to do with the fact that the central values for some of the BRs deviate from the SM, thus strongly restricting the range of deviations from the SM. While the decay $h \to ZZ\gamma$ is not yet observed at the LHC, the correlation between the $h \to WW$, $h \to Z\gamma$ and $h \to b\bar{b}$ rates can now be measured by the experiments. The ratio of the BR of $h \to WW$ to that of $h \to Z\gamma$ can be measured with an accuracy better than 3%, and an integrated luminosity that is expected to be accumulated by the High Luminosity LHC. This can be achieved with the application of a full jet veto, where theoretical uncertainties corresponding to the signal production will cancel.

Figure 4 displays the correlations between the BRs of $S$ to SM particles. As opposed to the SM Higgs boson, $S$ is significantly less constrained. Two distinct regimes can be appreciated in Figure 4 (b). The first regime corresponds to the dominance of the $S \to b\bar{b}$ decay, where the second would correspond to the dominance of the $S \to WW$ decay for $m_S = 140$ GeV. The latter regime would be the preferred one in light of the multi-lepton excesses reported in Ref. [1]. This behaviour is closer to that displayed by SM Higgs-like boson. In section 4 $S$ will be assumed to have the same decays as the SM Higgs boson after taking $m_S$ into account.

The two regimes identified here generate certain correlations in the $\text{BR}(S \to \gamma \gamma)$ vs $\text{BR}(S \to WW)$ plane, shown in Figure 4 (a), and the $\text{BR}(S \to Z\gamma)$ vs $\text{BR}(S \to \gamma \gamma)$ plane, shown in Figure 4 (c). The first regime corresponds to the ridges in Figure 4 (a) and (c) where the $\text{BR}(S \to \gamma \gamma)$ is largest. The second and preferred regime corresponds to a situation where $\text{BR}(S \to Z\gamma) > \text{BR}(S \to \gamma \gamma)$, where $\text{BR}(S \to Z\gamma) \approx 10^{-3}$. The latter is accessible at the LHC.

Furthermore, we investigate the BRs of $S, H, A$ and $H^\pm$ to understand the implications of the constraints detailed above on the decays, and how these can lead to final states that have not been explored before in the context of searches for new bosons. For this purpose a set of allowed parameter values is selected: $\alpha_1 = +0.885$, $\alpha_2 = -0.167$, $\alpha_3 = -1.28$, $m_{12}^2 = 3.5$ (TeV)$^2$ and $v_S = 1.5$ TeV. Figure 5 shows the BRs of $S, H, A$ and $H^\pm$ in the mass ranges of interest.

Figure 5 (a) displays the BRs of the $S$ boson to SM particles, where the mass of $S$ is varied within the range of interest [10]. One can appreciate that the selected set of parameters sit within the regime where the decay to $b\bar{b}$ is dominant for $m_H = 140$ GeV (see the earlier discussions regarding Figure 4). In this setup the BRs of $S$ behave somewhat differently from that of a SM Higgs-like boson. For the case of the SM Higgs-like boson, the BRs to $W^+W^-$ and $b\bar{b}$ cross just above $m_S = 130$ GeV, where here it happens just over 150 GeV. In the case of the SM Higgs-like boson the BRs $Z\gamma$ and $\gamma \gamma$ cross at 130 GeV, where
Figure 3: Correlation plots between the BRs of (a) $h \to WW$ vs $h \to \gamma\gamma$, (b) $h \to b\bar{b}$ vs $h \to WW$ and (c) $h \to \gamma\gamma$ vs $h \to Z\gamma$ where the values in red (blue) are by considering the BRs of the lightest $h$ boson consistent within 10% (20%).

here this happens at 145 GeV. In the case of $\tau^+\tau^-$ and $ZZ^*$ the corresponding masses are 130 GeV and just over 150 GeV. In this setup the decay to $b\bar{b}$ would be sub-dominant up to $m_S = 180$ GeV.

Figure 5 (b) displays the BRs of the $H$ boson. It is shown that the CP-even heavy scalar $H$ decays predominantly to $hh$ and $Sh$ for a mass of $m_S < 145$ GeV and $m_H > 265$ GeV. These limits on the masses depend on the masses of the other scalars and it is due to the fact that the N2HDECAY program does not include Higgs-to-Higgs off-shell decays in computing the BRs. It means also that the range of the masses of $S$ and $H$ is constrained. In this setup, and ignoring off-shell decays involving $S$ and $h$ bosons, the dominant decay
Figure 4: Correlation plots between the BRs of (a) $S \to WW$ vs $S \to \gamma\gamma$, (b) $S \to b\bar{b}$ vs $S \to WW$ and (c) $S \to \gamma\gamma$ vs $S \to Z\gamma$ where the values in red (blue) are by considering the BRs of the lightest $h$ boson consistent within 10% (20%). Here $m_S = 140$ GeV and $m_H = 270$ GeV.

up to $m_H \approx 200$ GeV is $b\bar{b}$, where the decay to $W^+W^-$ overtakes it at $m_H \approx 210$ GeV. Significantly large BRs for rare decays, such as $\gamma\gamma$, $Z\gamma$ and $\mu^+\mu^-$ can be achieved for $m_H < 2m_h$.

The constraints from the data implemented here apply to the masses and production rates of the neutral scalar bosons. It is therefore very interesting to evaluate the impact on the BRs of the pseudo-scalar and the charged scalar with the assumption that $m_A, m_{H\pm} > m_H$. With the parameter choice used here the dominant decay mode in the range $2m_t < m_A < 600$ GeV is $A \to t\bar{t}$. For $m_A > 600$ GeV the dominant decay is $A \to ZH$. The latter
Figure 5: (a) Plot of BR($S \to xy$) against $m_S$, (b) BR($H \to xy$) against $m_H$. (c) BR($A \to xy$) against $m_A$ and (d) BR($H^{\pm} \to xy$) against $m_{H^{\pm}}$ on the right. In the left, it is shown that the CP-odd scalar $A$ decays predominantly to $ZH$ if its mass is above 600 GeV. On the right, the charged scalar $H^{\pm}$ decays predominantly to $HW^{\pm}$ if its mass is greater than 600 GeV.

leads to interesting final states, as discussed in Ref. [10]. In section 4 we further investigate this decay and, most notably, we scrutinize the rate of production of $Zh$ in association with $b$-tagged jets. In addition, the production of $Z$ in association with a lepton and $b$-tagged jets coming from this decay is compared to the data reported by CMS. The production of this final state with a large enough rate to be produced at the LHC is a feature of the $A \to ZH$ decay.

Figure 5 (c) displays the BRs of the pseudo-scalar. The decay $A \to t\bar{t}$ is dominant up
to $m_A \approx 600\text{ GeV}$ where the $A \rightarrow ZH$ decay becomes dominant. The third most important decay is $A \rightarrow ZS$, which also leads to interesting final states \cite{10}. The decay $A \rightarrow Zh$ is suppressed and sits at the level of 1%. The production of $Zh$ would come from the decay chain $A \rightarrow ZH \rightarrow ZSh, Zhh$ (see Figure 5 (b) and section 4). As the pseudo-scalar gets heavier the decay $A \rightarrow W^\pm H^\mp$ opens up. A distinctive feature of this model is that the decay $A \rightarrow \tau^+\tau^-$ would be suppressed, sitting at the level of $10^{-4} - 10^{-5}$, depending on the mass.

Figure 5 (d) shows the BRs of the charged scalar. The decay $H^+ \rightarrow t\bar{b}$ is dominant up to $m_{H^+} \approx 600\text{ GeV}$, where the $H^+ \rightarrow HW^+$ decay becomes dominant. The latter leads to a tri-boson final state, which is produced in association with $t\bar{b}$ due to the production mechanism $gb \rightarrow tbH^\pm$. Multiple leptons in association with $b$-tagged jets are expected \cite{10}. The third dominant decay is $H^+ \rightarrow SW^+$, where as in the case of the $A \rightarrow \tau^+\tau^-$, the $H^+ \rightarrow \tau^+\nu$ decay is suppressed. The decay $H^+ \rightarrow hW^+$ is suppressed relative to the $H^+ \rightarrow HW^+, SW^+$ decays and it stands at about 1%.

Production cross-sections of different bosons have been checked with the set of parameters used here. The production cross-section of the scalar $S$ is about ten times smaller than of the SM Higgs boson. The cross-section for the production of $H$ is compatible with that obtained in Ref. [1]. Therefore, the main production mechanism for $S$ would be that of the decay of $H$.

4 Comparisons to data

The primary aim of this section is to confront the data with the benchmark points in the parameter space described in section 3. One of the relevant implications with regards to heavy pseudo-scalars considered here is the dominance of $A \rightarrow t\bar{t}, ZH$ decays, where the decay $A \rightarrow Zh$ appears suppressed. As seen in Figure 5, the branching ratio of the $A \rightarrow ZH$ decay becomes dominant for $m_A > 600\text{ GeV}$. The decay $A \rightarrow ZH$ leads to interesting final states, as pointed out in Ref. [10]. For the sake of simplicity, here we consider the case where $S$ decays exclusively to SM particles and the decays $H \rightarrow hh, Sh$ are dominant.

It is important to reiterate that the scan performed in this section pertains to a significant number of measurements that do not include the $A \rightarrow Zh$ resonance search, which is interpreted here as emerging from $A \rightarrow ZH \rightarrow hh, Sh$. Therefore, the parameters are greatly constrained by data different from the $Zh$ spectrum. The latter constrains the mass of the pseudo-scalar, whereas the branching ratios are constrained with other data sets.

A distinctive set of final states that emerge from the $A \rightarrow ZH$ decay is the production of relatively high transverse momentum $Z$ bosons in association with a lepton and two $b$-tagged jets. This final state would not appear in $A \rightarrow Zh$ decay in that no additional leptons would be expected in addition to the $Z$ boson and $b$-tagged jets. The $bbA$ production mechanism could produce this final state. However, the yield would be too small, as discussed below. The CMS experiment has recently reported a discrepancy in the production of $Z$ bosons with an additional lepton, $b$-tagged jets and low additional jet multiplicity [23, 24]. The discrepancy, corresponding to a local significance of $2.85\sigma$, appears in the study of the production of $ttZ$ with $Z \rightarrow \ell\ell, \ell = e, \mu$. Here we interpret this discrepancy with the
production of $A \rightarrow ZH$, where the parameters of the model are fixed elsewhere, as discussed above.

Monte Carlo simulation samples are used to model the background and signal processes for this search. Signal samples are simulated using Pythia8 [30] and then passed through Delphes [31] to estimate the detector response. Events were generated for an $A$ boson mass at fixed working points: 500, 550 and 600 GeV. For the interpretation of the $H \rightarrow Sh$, where $h$ is the Higgs boson with $m_h=125$ GeV, the masses of the $H$ and $S$ are assumed to be equal to 270 GeV and 145 GeV, respectively. For simplicity, $S$ branching ratios are taken from that of the SM Higgs boson at the corresponding mass. Jets were clustered using Fast-Jet [32] with the anti-$k_T$ algorithm [33] using the distance parameter, $R = 0.4$.

Section 4.1 covers the interpretation of the $A \rightarrow ZH$ search, whereas section 4.2 interprets the discrepancy observed in the $Z(\rightarrow \ell\ell) + \ell + 2b$-tagged jet final state.

4.1 $A \rightarrow Zh$ search

The ATLAS and CMS collaborations perform searches for a CP-odd heavy scalar within a 2HDM using various decay channels, where the decay $\ell\ell bb$ plays an important role. A structure in the $Zh$ invariant mass spectrum has been recently reported by the ATLAS collaboration [19] with Run 2 data. The CMS collaboration has reported limits with Run 1 data that do not contradict these results [20].

The authors of Ref. [22] have interpreted the structure in terms of a 2HDM where $A \rightarrow Zh$. Here we attempt a different interpretation in light of the spectroscopy discussed in Refs. [8, 10] and Ref. [1] in the context of an extension of the 2HDM, as discussed in section 2. In Ref. [10] it was demonstrated that the decay chain $A \rightarrow ZH$, where $H \rightarrow Sh$ generates a structure in the invariant mass spectrum of the $Zh$ system that resembles that of a resonance with moderate width and a mass in the neighbourhood of $m_A - m_S$. The structure reported in Ref. [19] peaks around 450 GeV. Assuming $m_S = 145$ GeV, the mass of the pseudo-scalar considered here is 600 GeV. The corresponding cross-section of the structure lies in the range of 100 fb to 300 fb.

An important feature of the $Zh$ structure is that it also appears in events with additional $b$-tagged jets. Within the context of a 2HDM the structure has been interpreted in terms of the ggF and $bbA$ production mechanisms. In the scenario considered here, the decay entails a three boson final state that also produces a structure in the $Zh$ invariant mass spectrum in association with additional $b$-tagged jets.

Figure 6 displays the multiplicity of all jets and $b$-tagged jets for the decay $A \rightarrow ZH \rightarrow ZSh$ produced via ggF. Hadronic jets have $p_T > 25$ GeV and $|\eta| < 2.5$. One can appreciate that the average jet multiplicity overshoots that expected from the direct production of $A \rightarrow Zh$. Because of the significant branching ratio of $S \rightarrow b\bar{b}$, the yield of events with more than two $b$-tagged jets becomes significant so as to mimic the production of $bbA$ in a 2HDM.

In order to evaluate the ability of the 2HDM and the 2HDM+S approaches to describe the data the event selection described in Ref. [19] is adopted here as a baseline. This includes the following requirements:
Figure 6: The jet multiplicity for the decay $A \rightarrow ZH \rightarrow ZSh$ produced via gluon-gluon fusion (see text). The plot on the left corresponds to all jets, whereas the plot on the right shows the multiplicity of $b$-tagged jets.

- At least two $b$-tagged jets are required such that $p_T > 20$ GeV and $|\eta| < 2.5$. The invariant mass of the two leading $b$-tagged jet has to lie in the range $100 - 145$ GeV. The transverse momentum of the leading $b$-tagged jet has to be greater than $45$ GeV.

- Transverse momentum of the leading and sub-leading leptons should be greater than $27$ GeV and $7$ GeV, respectively.

- The missing transverse momentum is required to be below a threshold (in GeV):
  \[ E_T^{miss}/\sqrt{H_T} < 1.15 + 8 \times 10^{-3} \cdot m_{Zh}, \]  
  where $H_T$ is defined as the scalar sum of the transverse momenta of all leptons and hadronic jets.

- The transverse momentum of the di-lepton system should conform to the following expression (in GeV):
  \[ p_T^{\ell\ell} > 20 + 9 \cdot \sqrt{m_{Zh} - 320} \]  
  This requirement is applied for $m_{Zh} > 320$ GeV.

- The invariant mass of the di-lepton system should obey the following expression (in GeV):
  \[ \max[40, 87 - 0.030 \cdot m_{Zh}] < m_{\ell\ell} < 97 + 0.013 \cdot m_{Zh} \]  

It is probably relevant to note that this event selection is the result of optimizing for the sensitivity of the search for $A \rightarrow Zh$ in a 2HDM. Here the efficiencies for different production mechanism relative to the ggF production of $A \rightarrow Zh$, in a 2HDM are compared.
Table 1: The efficiency of different production mechanisms of $Zh$ after the application of the event selection described in the text with respect to the ggF production of $A \rightarrow Zh$ in a 2HDM. The second and third rows display the fraction of events with exactly two or more than two $b$-tagged jets after the application of the same event selection. Here $m_H = 270$ GeV and $m_S = 145$ GeV are used, where $S$ is treated as a SM Higgs-like scalar.

| Process            | $A(450) \rightarrow Zh$ | $bbA(450) \rightarrow bbZh$ | $A(600) \rightarrow Zhh$ | $A(600) \rightarrow ZSh$ |
|--------------------|--------------------------|-----------------------------|--------------------------|--------------------------|
| Efficiency         | 1                        | 1.13                        | 1.23                     | 0.81                     |
| $f(N_b = 2)$       | 0.95                     | 0.83                        | 0.73                     | 0.77                     |
| $f(N_b > 2)$       | 0.05                     | 0.17                        | 0.27                     | 0.23                     |

Table 1 shows the efficiency of the different mechanisms for the production of $Zh$ with respect to the ggF production of $A \rightarrow Zh$ in a 2HDM. The efficiency of $A(600) \rightarrow ZH \rightarrow Zhh$ and $A(600) \rightarrow ZH \rightarrow ZSh$ is 13% larger and 19% smaller than that obtained with $A(450) \rightarrow Zh$. The fraction of events with at least one additional $b$-tagged jet varies for different production mechanisms. The fraction is small for $A(450) \rightarrow Zh$, whereas for $bbA(450) \rightarrow bbZh$ the fraction increases to 17%. The fraction of events with additional $b$-tagged jets increases to 27% and 23% for $A(600) \rightarrow ZH \rightarrow Zhh$ and $A(600) \rightarrow ZH \rightarrow ZSh$, respectively. The fraction of events in the $Zh$ mass region between 400 GeV and 500 GeV with an additional $b$-tagged jet is about 25% of the total amount of events in the structure, but the statistical error on this fraction is too large at this moment.

4.2 Three leptons in association with two $b$-tagged jets

The CMS collaboration has reported a discrepancy in a particular corner of the phase space [24]. This includes the presence of two opposite sign and same flavor charged leptons (electrons or muons) with the invariant mass close to that of the Z boson, an additional charged lepton and at least two $b$-tagged jets. The discrepancy appears in events with exactly two and three hadronic jets. This region of the phase space is weakly populated by the $ttZ$ process, where a large number of hadronic jets is expected. The number of events in the data in excess of the SM prediction corresponds to $28.1 \pm 9.5$ events with an integrated luminosity of 35.9 fb$^{-1}$ at 13 TeV center of mass energy.

Following Ref. [24], the event selection includes the following kinematic requirements:

- The events are required to have exactly three leptons ($\mu\mu\mu$, $\mu\mu\mu$, $\mu\mu\mu$ or $\mu\mu\mu$), where the leading, subleading, and trailing lepton are required to have $p_T$ thresholds above 40, 20, and 10 GeV, respectively.
- Leptons are required to have $p_T > 10$ GeV and $|\eta| < 2.5$ (2.4) for electrons (muons).
- It is required to have a pair of leptons with an opposite charge and same flavor (OSSF) which satisfies $|m_{\ell\ell} - m_{\ell\ell}| < 10$ GeV.
Table 2: The fraction of events after the application of the event selections described in the text with respect to three lepton final states for both $A \rightarrow ZH \rightarrow Zhh$ and $A \rightarrow ZH \rightarrow ZSh$ signals. Here $m_H = 270$ GeV and $m_S = 145$ GeV are used.

| Process         | $N_j$ | $A = 500$ GeV | $m_A = 550$ GeV | $m_A = 600$ GeV |
|-----------------|-------|---------------|-----------------|-----------------|
| $A \rightarrow ZH \rightarrow Zhh$ | =2    | 0.26          | 0.27            | 0.25            |
|                 | =3    | 0.39          | 0.38            | 0.36            |
|                 | >3    | 0.35          | 0.35            | 0.39            |
| $A \rightarrow ZH \rightarrow ZSh$ | =2    | 0.32          | 0.27            | 0.23            |
|                 | =3    | 0.33          | 0.36            | 0.30            |
|                 | >3    | 0.35          | 0.37            | 0.46            |

- Events containing more than one jet are selected, and then are further split into three categories according to the hadronic jet multiplicity, $N_j = 2, 3,$ and $> 3$.

Hadronic jets, including $b$-tagged jets, have $p_T > 30$ GeV and $|\eta| < 2.5$. After the application of the event selections described above over the samples we tabulated, the fraction of events for the $A \rightarrow Zhh$ and $A \rightarrow ZSh$ decay channels are as detailed in Table 2. The quantitative analysis reported here indicates that about 60% to 65% of the signal displays low hadronic jet multiplicity with $N_j < 3$.

The efficiency of the event selection with DELPHES is checked against that reported for the production of $ttZ$ in events with at least two $b$-tagged jets and at more than three jets. Taking into account the results from section 4.1, the expected yield of the signal $A(600) \rightarrow ZH(270) \rightarrow ZS(145)h$ with $N_j < 3$ is about 3 events. This estimate appears low despite the relatively large uncertainties that characterise the discrepancy discussed here. That being said, it is very important to note that the simplified ansatz that $S$ behaves as a SM Higgs-like boson plays a very important role in the prediction of the cross-section in the corner of the phase-space described here. The assumption made here impacts directly the branching ratio of $S$ decaying into leptons and the jet multiplicity in the final state. The contribution from the $bbA(450)$ signal in this corner of the phase-space is too little to be considered.

4.3 Measurement of $Vh$ production signal strength

The ATLAS [34, 35] and CMS [36, 37] collaborations have independently reported observation of the decay of the decay $h \rightarrow b\bar{b}$. The evidence reported is based on excesses in the data in the search for the SM Higgs boson in association with a $Z$ or a $W$ boson. In doing so the experiments also report the corresponding signal strength of the $Vh$ production mechanism in the SM.

Different event selections are developed depending on the presence of high transverse momentum charged leptons. Here the impact of the different production mechanisms normalised to the size of the structure observed by ATLAS in the $Zh$ spectrum on the measurement of the $Vh$ signal strength in the different final states is discussed here. The potential
contamination from the different BSM signal production mechanisms in the phase-space of the measurement of \( Vh \) production is evaluated.

Events with two jets tagged as containing \( b \)-tagged jets and with either zero, one or two charged leptons (electrons or muons) are selected. The lepton candidates are required to have \( p_T > 7 \text{ GeV} \) and \( |\eta| < 2.47 \) (2.7) for electrons (muons). All events are required to have at least two jets with \( p_T > 20 \text{ GeV} \) and \( |\eta| < 2.5 \), and exactly two with \( 100 \text{ GeV} \leq m_{bb} \leq 145 \text{ GeV} \) must pass the \( b \)-tagging requirement. The \( p_T \) of the leading \( b \)-tagged jet is required to be above 45 GeV. Events are assigned to zero-, one- and two-lepton channels depending on the number of charged leptons. In the following, the physics objects and the event selection criteria for each channel are described:

- The zero-lepton events are required to have \( E_T^{\text{miss}} > 150 \text{ GeV} \). The scalar sum of the transverse momenta of the jets in the event, \( H_T \), is required to be less than 150 GeV. This is to remove a marginal region of phase space in which the trigger efficiency exhibits a small dependence on the jet multiplicity. Also, the following angular selection is applied:
  - \( \Delta \phi(b_1, b_2) < 140^\circ \),
  - \( \Delta \phi(E_T^{\text{miss}}, bb) > 120^\circ \),
  - \( \min[\Delta \phi(E_T^{\text{miss}}, \text{jets})] > 30^\circ \),

  where \( b_1 \) and \( b_2 \) are the two \( b \)-tagged jets forming the Higgs boson candidates dijet system \( bb \), and \( E_T^{\text{miss}} > 150 \text{GeV} \) is the missing transverse momentum which is defined as the negative vector sum of the transverse momenta of electrons, muons and jets.

- In the one-lepton channel events are required to contain exactly one electron with \( p_T > 27 \text{ GeV} \) or one muon with \( p_T > 25 \text{ GeV} \). With the electron an additional of \( E_T^{\text{miss}} > 30 \text{ GeV} \) is applied.

- In the two-lepton channel events are required to have exactly two leptons of the same flavor with leading lepton \( p_T > 27 \text{ GeV} \). In dimuon events, the two muons are considered to have opposite-sign charges. The invariant mass of the dilepton system must be consistent with the \( Z \) boson mass, such that \( 81 \text{ GeV} < m_{\ell\ell} < 101 \text{ GeV} \).

Events are then categorized into two categories according to jet multiplicity. In the zero- and one-lepton channels events are considered with three or fewer jets. In the two-lepton channel events are considered with higher jet multiplicities which is three or more jets. Furthermore, selections for the reconstructed vector boson’s transverse momentum, \( p_T^V \), are applied. This observable corresponds to \( E_T^{\text{miss}} \) in the zero-lepton channel, to the vectorial sum of \( E_T^{\text{miss}} \) and the charged lepton’s transverse momentum in the one- and two-lepton channels. In the zero- and one-lepton channels a single region is defined, with \( p_T^V > 150 \text{ GeV} \). In the 2-lepton channel two regions are considered, \( 75 \text{ GeV} < p_T^V < 150 \text{ GeV} \) and \( p_T^V > 150 \text{ GeV} \). Here yields of the different signals are integrated for \( p_T^V > 75 \text{ GeV} \).

Table 3 displays the potential contamination of the BSM signals. Results are shown in terms of the BSM signal yield normalized to the yield of the SM \( Vh \) production in the

-- 18 --
\[ \text{Process} | A(450) \rightarrow Zh | bbA(450) \rightarrow bbZh | A(600) \rightarrow Zh \bar{h} | A(600) \rightarrow ZSh \]

\begin{tabular}{|c|c|c|c|c|}
\hline
\( N_\ell = 0 \) & 1.12 & 1.42 & 0.68 & 0.42 \\
\( N_\ell = 1 \) & 0.05 & 0.06 & 0.08 & 0.07 \\
\( N_\ell = 2 \) & 0.71 & 0.70 & 0.67 & 0.48 \\
\hline
\end{tabular}

Table 3: The potential contamination from the BSM production mechanisms discussed here in the measurement of the signal strength of the \( Vh, Z = Z, W \) in the SM. Results are presented in terms of the signal yield with respect to the \( Vh \) production in the SM for zero, one and two charged lepton final states (see text). Here \( m_H = 270 \text{ GeV} \) and \( m_S = 145 \text{ GeV} \) are used.

phase-space described here. A cross-section of 200 fb is assumed for all BSM signals reported in Table 3. It is very important to note that a number of more sophisticated techniques have been used by the experiments to extract the SM signal. As a result, the potential contamination reported in Table 3 is an upper bound of the potential contamination. Making a more accurate estimate of the contamination goes beyond the scope of this paper. The results shown in Table 3 are better suited for a comparative analysis.

One can appreciate that the contamination on the one-lepton final state is quite small, whereas the contamination on the zero-lepton final state is significant, followed by that of the one-lepton final state. The contamination is maximum for the 2HDM signals, where for the \( bbA \) production mechanism the contamination would be largest and comparable to the \( Vh \) signal in the SM. By contrast, the 2HDM+S signals have a moderate impact on the SM \( Vh \) production where the most important decay, \( A \rightarrow ZH \rightarrow ZSh \) would have the smallest effect.

5 Summary and Conclusions

In Refs. [8, 10] scalars \( H \) and \( S \) were introduced via an effective model to explain a number of features in the Run 1 data. These scalars were embedded into a 2HDM+S model in Ref. [10], where it was pointed out that the anomalous production of multiple leptons would be a prominent feature of the model. This hypothesis has been compared to data [1, 18] where large discrepancies between the data and SM MCs are observed that cannot be resolved with available tools. These discrepancies are interpreted using a simplified model where \( m_H = 270 \text{ GeV} \) and \( m_S = 145 \text{ GeV} \).

In this paper we attempt to identify the corners of the parameter space in a 2HDM+S model that satisfy the conclusions arrived at in Ref. [1]. The implications on the decays of the heavy pseudo-scalar and charged scalar are discussed. With the parameter choice used here the dominant decay mode in the range \( 2 m_t < m_A < 600 \text{ GeV} \) is \( A \rightarrow t\bar{t} \). For \( m_A > 600 \text{ GeV} \) the dominant decay is \( A \rightarrow ZH \). The third most important decay is \( A \rightarrow ZS \), which also leads to interesting final states. The decay \( A \rightarrow Zh \) is suppressed and sits at the level of 1%. The production of \( Zh \) would come from the decay chain \( A \rightarrow ZH \rightarrow ZSh, Zhh \). As the pseudo-scalar gets heavier the decay \( A \rightarrow W^\pm H^\mp \) opens up. A distinctive feature of this model is that the decay \( A \rightarrow \tau^+\tau^- \) would be suppressed, sitting
at the level of $10^{-4} - 10^{-5}$ depending on the mass. The decay $H^+ \rightarrow t\bar{b}$ is dominant up to $m_{H^+} \approx 600$ GeV where the $H^+ \rightarrow HW^+$ decay becomes dominant. The third dominant decay is $H^+ \rightarrow SW^+$, the $H^+ \rightarrow \tau^+\nu$ decay is suppressed. The decay $H^+ \rightarrow hW^+$ is suppressed relative to the $H^+ \rightarrow HW^+, SW^+$ decays. The conclusions from these studies further reinforce the relevance of multi-lepton final states in the search for new bosons.

A structure in the $Zh$ invariant mass spectrum has been reported by the ATLAS collaboration [19] with Run 2 data, which appears in association with $b$-tagged jets, in addition to those assigned to the decay of $h$. Here we interpret the structure in terms of the 2HDM+S model. The production of $Zh$ with additional $b$-tagged jets from $A(600) \rightarrow Z(270)H \rightarrow ZS(145)h$, $ZhH$ is discussed. The fiducial efficiency of this production mechanism is similar to other production mechanisms, like $A(450) \rightarrow Zh$ and $bbA(450) \rightarrow bbZh$. However, one of the features of the 2HDM+S signal considered here is the production of $Z(\rightarrow \ell\ell)$ in association with a lepton and two $b$-tagged jets. The jet activity would be significantly different from that displayed by the production of $ttZ$. An excess is seen by CMS in this final state in events with low additional jet multiplicity, a regime where the production of $ttZ$ is suppressed. By contrast, the 2HDM signals considered here do not contribute significantly to this final state. The potential existence of a heavy pseudo-scalar would contribute to the production of $Zh$ and contaminate the phase-space where the signal strength of the $Vh$ production is measured by the experiments. The 2HDM signals considered here would bring considerable contamination, where the largest contamination would come from $bbA(450) \rightarrow bbZh$, the preferred option in a 2HDM to explain the structure in the $Zh$ invariant mass spectrum. The preferred signal in a 2HDM+S would yield a moderate impact on the measurement of the $Vh$ signal strength.

A Additional parameter correlations

This appendix shows additional parameter correlations. Results are shown for the requirement that the BRs of the lightest scalar be within 20% and 10% of the BRs predicted in the SM for the Higgs boson. Figure 7 displays the correlation between $m_{12}^2$ and $\alpha_1$, $\alpha_2$ and $\alpha_3$, the mixing angles. The correlation with $\alpha_1$ is weak, where the correlation with the other two mixing angles is noticeable. Figure 8 shows the correlations between $v_s$ and $\alpha_1$, $\alpha_2$ and $\alpha_3$, where overall the correlations are weak. Figure 9 shows the correlations between $\tan \beta$ and $m_{12}^2$, $v_s$ and $m_{12}^2$ and finally, $v_s$ and $\tan \beta$. Correlations are weak except for Figure 9 (b) where a certain range of values for $v_s$ and $m_{12}^2$ are disallowed.

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Figure 7: Allowed values of $\alpha_1, \alpha_2$ and $\alpha_3$ against $m_{12}^2$ for the benchmark considered here, where the values in red (blue) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

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Figure 8: Allowed values of $\alpha_1, \alpha_2$ and $\alpha_3$ against $v_S$ for the benchmark considered here, where the values in red (blue) are by considering the BRs of the lightest CP-even scalar consistent within 10% (20%) of the prediction for the SM Higgs boson.

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