

Phenomenology of additional scalar bosons at the LHC

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Abstract. The confirmation of the Higgs boson in Run I data at the Large Hadron Collider (LHC) and the deviations from the Standard Model (SM) (which are strictly not statistically significant excesses at this stage) in recent Run II data can be considered suggestive of scenarios beyond the SM. We pursue a study in a minimal model which is an extension of a scalar doublet in the SM known as two-Higgs doublet model (THDM). Following earlier suggestions two real scalars χ and S have been introduced in the THDM where χ is treated as a candidate for dark matter. χ does not receive any vacuum expectation value (vev) in the model whereas the Higgs-like scalar S acquires vev . This allows small mixing between the CP -even scalars of the THDM, h , H and S . In this study the mass spectrum of new scalars is taken to be $2m_h < m_H < 2m_t$, $m_\chi < m_h/2$, $m_h \lesssim m_S \lesssim m_H - m_h$, $m_A > 2m_t$ and $m_H^\pm < m_A$, where m_h and m_t is masses of the SM Higgs and top-quark respectively, m_H , m_A and m_{H^\pm} are the masses of the heavy CP -even scalar H , CP -odd scalar A , and charged Higgs H^\pm , respectively. A partial list of potential search channels at the LHC has been provided with possible phenomenological consequences. The expected phenomenology and constraints on parameters are also discussed in a model-independent approach .

1. Introduction

After the confirmation of the Higgs boson (h) in Run I data at the Large Hadron Collider (LHC) [1, 3, 2, 4, 5, 6], it is pragmatic to move forward in searches of physics beyond the Standard Model (BSM). In this context we already have well-defined models with a rich particle spectrum which shall be supplemented through observed deviations in the experimental data. Some of the deviations in Run I data at the ATLAS and CMS, namely, the deviation in transverse momentum (p_T) spectrum of the Higgs boson in $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ \rightarrow 4l$ [7, 8, 9, 10] channel has been addressed in Ref. [11] by corroborating other source of deviations in heavy scalar

searches through di-Higgs boson production [12, 13, 14, 15] and in associated production of top-quarks [16, 17, 18, 19]. A deviation noted as a non statistically significant excess in the di-photon channel around 750 GeV [20, 21] in early data of Run II at the LHC¹ also provides hints of new physics BSM where it could be assumed to arise through a scalar or pseudo-scalar resonance around this mass.

These deviations can be explained by introducing a particle spectrum BSM in an effective theory as well as in a proper model by considering the appropriate sources of constraints in the theory and known limits on parameter space in that particular model. It is evident that this new particle spectrum comes with new phenomenology and helps in not only explaining the observed data but also in searches beyond a particular model(s). In this proceeding we intend to address the phenomenology of scalars BSM, assuming the particle spectrum of two-Higgs doublet model (THDM) in addition with other real singlets χ and S introduced in Refs. [24, 25].

2. The Model

Before moving towards the phenomenological implications of the additional scalars BSM, we first discuss the particle spectrum and parameters introduced in a model dependent as well as in a model independent approach. A simple extension of the SM is known as the THDM with one more additional scalar doublet, where this additional scalar doublet transform under the SM gauge symmetries similar to the Higgs field in the SM. After spontaneous electroweak symmetry breaking, five physical Higgs particles are left in the spectrum of THDM, two CP -even states, H (heaviest) and h (lightest), one CP -odd scalar, A , and one charged Higgs pair, H^\pm . The ratio of the two vacuums (v_1, v_2) of corresponding doublets is a free parameter of the theory, $\tan\beta = v_2/v_1$ in addition with the masses of the scalars² and the mixing angle α between h and H . Based on different choices of symmetries and couplings to fermions different types of THDM is available, *viz.*, Type-I, Type-II, Lepton-specific or Flipped THDMs. For more details of this model we refer the Refs. [26, 27].

In a model-independent approach i.e. *via* an effective theory the authors of Refs. [11, 24, 25] introduced three real scalars H ,³ χ - introduced as a dark matter (DM) candidate whose signature is a source of missing energy in the colliders, and S - a Higgs-like real singlet scalar. In these studies, it is found necessary to fit all data that the heavier H should have a large branching ratio in the channel $H \rightarrow h\chi\chi$, where h is the Standard Model (SM) Higgs boson. However, this explanations can also be accommodated by introducing the on-shell participation of S in the decay of $H \rightarrow Sh, S \rightarrow \chi\chi$. To achieve the fittings, the free parameters of the theory are fixed by considering various observed limits in VV ($V = W^\pm, Z$) resonance searches [28, 29, 30] and the DM constraints.

As an extension to this model-independent approach, it is interesting to add χ and S in a THDM as a model-dependent scenarios. In that case all new parameters of interactions among these scalars follow the constraints from THDM with few additional parameters in the theory. The details of this model can be found in Ref. [25], where χ does not acquire vacuum expectation value (vev) while S acquires vev in result there is small mixing between h, H and S is considered to obtain hHS coupling which should respect the bounds from the Higgs data.

¹ Note the earlier reference [20, 21] is deprecated and now replaced with [22, 23] where the deviations, though they remain, have nonetheless diminished with more data and a more careful analysis.

² It is to be noted that the two CP -even scalars h and H may have different interpretations in terms of masses in comparison to the SM Higgs boson. In our case we assume the lighter h to aligned with the SM Higgs boson.

³ H may not be same as THDM heavier CP -even scalar. The difference is also noticed since in this approach it is considered to be a real singlet scalar while in THDM it is a part of doublet which appear after spontaneous electroweak symmetry breaking.

3. Phenomenology

In this section we discuss the phenomenology associated with the scalars introduced in previous sections which is useful in explaining the observed data in experiments as well as to provide hints for searches at particular energy and parameter choices in the colliders like the LHC. The observed final states are highly dependent on the choice(s) of masses of these scalars after production rates *via* gluons, quarks or gluons and quarks.

Following the results of Ref. [11], we consider following mass ranges for THDM scalars with additional real scalars χ and S to explain the phenomenology:

- (a) Light Higgs: $m_h = 125$ GeV (assuming as the SM Higgs),
- (b) Heavy Higgs: $2m_h < m_H < 2m_t$,
- (c) CP -odd Higgs: $m_A > (m_H + m_V)$, where $(V = W^\pm, Z)$,
- (d) Charged Higgs: $(m_H + m_V) < m_{H^\pm} < m_A$,
- (e) Additional scalars χ, S : $m_\chi < m_h/2$ and $m_h \lesssim m_S \lesssim (m_H - m_h)$.

Based on these masses we can study the branching fractions of THDM scalars into the SM particles and additional scalars χ and S as listed in Table 1 with following production channels:

- (a) $gg \rightarrow h, H, A, S$,
- (b) $pp \rightarrow tH^-(\bar{t}H^+), tH^-\bar{b} + \bar{t}H^+b, H^+H^-, H^\pm W^\pm$.

A partial list of interesting searches are summarised in Table 2 which leads striking signatures of clean final states involving the scalars introduced in this proceedings. Mostly we discussed leptonic final states with missing energy signatures through the decays of heavy scalars. The same-sign leptonic channels provides prominent signatures for any new physics models beyond the SM. Apart from these search list

- (1) It is interesting to constrain the parameter space of THDM and associated parameters with χ and S by explaining the distortion in the p_T spectrum of the Higgs boson in $h \rightarrow \gamma\gamma$ and $h \rightarrow ZZ \rightarrow 4l$ channels as in Ref. [11]. Also the consequences of introducing S to explain the large branchings in the effective theory due to $H \rightarrow h\chi\chi$ can be understood in both model independent and dependent approaches by allowing $H \rightarrow hS$ and $S \rightarrow \chi\chi$.
- (2) The first LHC data at $\sqrt{s} = 13$ TeV observed a deviation in the $\gamma\gamma$ final state peaked at the invariant mass around 750 GeV [20, 21] (but later moderated by the ATLAS [22] and CMS [23]) with the best fit width of the resonance as 45 GeV. Here according to our parameter choice that resonance could be a CP -odd scalar A . And further based on the choices of mass and width of this possible resonance the model parameters can be constrained.

A few analyses of interesting final states with selected leptonic signatures are discussed in the Ref. [25] by considering $H \rightarrow 4W \rightarrow 4l$ with missing energy and associated H production with top quarks and decays as $t(t)H \rightarrow 6W \rightarrow l^\pm l^\pm l^\pm + X$. With this note we summarise our work in the next section.

4. Summary

In this proceedings we discuss the phenomenology of the scalars beyond the Standard Model. These scalars are introduced in a model independent way as an effective theory and also in a model dependent approach - considering the two-Higgs doublet model. A logical way of introducing χ and S has been discussed. A list of search strategies has been drawn up based on

Table 1: List of possible decay modes of 2HDM scalars to the SM particles and additional scalars based on the mass choices of all scalars as described in the text. Note that we are not interested in $h \rightarrow \chi\chi$ decay, instead we prefer $S \rightarrow \chi\chi$ decay mode. In the final states of all decay we consider W^\pm , $Z \rightarrow$ leptonic decay modes.

S. No.	Scalars	Decay modes
D.1	h	$bb, \tau^+\tau^-, \mu^+\mu^-, s\bar{s}, c\bar{c}, gg, \gamma\gamma, Z\gamma, W^+W^-, ZZ$
D.2	H	D.1, hh, SS, Sh
D.3	A	D.1, $t\bar{t}, Zh, ZH, ZS, W^\pm H^\mp$
D.4	H^\pm	$W^\pm h, W^\pm H, W^\pm S$
D.5	S	D.1, $\chi\chi$

Table 2: A list of potential search channels arising from the addition of the new scalars presented in this proceedings. This list is by no means complete, but contains clean search channels (mostly leptonic) which could make for striking signatures in the LHC physics regime. Note that in the mass ranges we are considering, H almost always decays to SS or Sh , where S and h are likely to decay to W s or b -jets.

Scalar	Production mode	Search channels
H	$gg \rightarrow H, Hjj$ (ggF and VBF)	Direct SM decays as in Table 1 $\rightarrow SS/Sh \rightarrow 4W \rightarrow 4\ell + \text{MET}$ $\rightarrow hh \rightarrow \gamma\gamma b\bar{b}, b\bar{b}\tau\tau, 4b, \gamma\gamma WW$ etc. $\rightarrow Sh$ where $S \rightarrow \chi\chi \implies \gamma\gamma, b\bar{b}, 4\ell + \text{MET}$
	$pp \rightarrow Z(W^\pm)H$ ($H \rightarrow SS/Sh$)	$\rightarrow 6(5)l + \text{MET}$ $\rightarrow 4(3)l + 2j + \text{MET}$ $\rightarrow 2(1)l + 4j + \text{MET}$
	$pp \rightarrow t\bar{t}H, (t + \bar{t})H$ ($H \rightarrow SS/Sh$)	$\rightarrow 2W + 2Z + \text{MET}$ and b -jets $\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET
H^\pm	$pp \rightarrow tH^\pm$ ($H^\pm \rightarrow W^\pm H$)	$\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET
	$pp \rightarrow tbH^\pm$ ($H^\pm \rightarrow W^\pm H$)	Same as above with extra b -jet
	$pp \rightarrow H^\pm H^\mp$ ($H^\pm \rightarrow HW^\pm$)	$\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET
	$pp \rightarrow H^\pm W^\pm$ ($H^\pm \rightarrow HW^\pm$)	$\rightarrow 6W \rightarrow 3$ same sign leptons + jets and MET
A	$gg \rightarrow A$ (ggF)	$\rightarrow t\bar{t}$ $\rightarrow \gamma\gamma$
	$gg \rightarrow A \rightarrow ZH$ ($H \rightarrow SS/Sh$)	Same as $pp \rightarrow ZH$ above, but with resonance structure over final state objects
	$gg \rightarrow A \rightarrow W^\pm H^\mp$ ($H^\mp \rightarrow W^\mp H$)	$6W$ signature with resonance structure over final state objects

recent observed excesses in ATLAS and CMS data, a sketch has been suggested incorporating the mass spectrum of the introduced scalars. In most of the cases we considered the leptons with missing energy final states with a significant number of same-sign leptons make the searches to be clean and striking.

Here it is also important to summarise the present constraints on the two-Higgs doublet model parameters from Run-I data at the LHC. In Ref. [31] a summary of exclusion limits were presented for several searches on additional heavy Higgs bosons in physics BSM. In the case of THDM, two benchmark scenarios Type-I and Type-II were considered. The Type-I (II) THDM is generally constrained to $\cos(\beta - \alpha) \lesssim 0.5(0.2)$, $m_H \lesssim 380(\approx 380)$ and $\tan\beta \lesssim 2$ (all) of the heavy Higgs boson. These constraints have been obtained by considering the decay channels

$A/H/h \rightarrow \tau\tau$, $H \rightarrow WW/ZZ$, $A \rightarrow ZH(l\bar{l}b\bar{b})$ and $A \rightarrow ZH(l\bar{l}\tau\tau)$. We hope that our work towards this direction in Run-II data will show interesting features.

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