Compatibility of the CMS dilepton spectra with the Neutral Scalar with Mass around 151 GeV

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Abstract.

The measurements related to the different properties of the newly discovered Higgs boson (h) at the LHC by ATLAS and CMS indicate that this 125 GeV boson is compatible with the one predicted by the Standard Model (SM). However, this does not exclude the existence of additional scalar bosons as long as their possible mixing with the SM Higgs is sufficiently small, such that the properties of the latter remain to a good approximation unchanged. In a recent phenomenological analysis, a search for narrow resonances with $S \to \gamma\gamma, Z\gamma$ along with leptons, di-jets, bottom quarks and missing energy was reported. The global significance of the excess at $m_S = 151.5$GeV is 4σ, whereas a combination with the multi-lepton anomalies gives a significance larger than 5σ. Moreover, a recent CMS study in the W boson pair in proton-proton collisions presented an excess in dilepton channel associated with the $0, 1$ jet ggH tagged categories . There it shows an excesses around 150 GeV. With this motivation, in this analysis, we consider a new physics model, namely, $2HDM + S$, containing two new hypothetical scalar bosons, H and S and check the compatibility of this CMS di-lepton spectra with the scalar mass around 150 GeV.

1. Introduction

With the discovery of a Higgs-like boson at the Large Hadron Collider (LHC) by ATLAS and CMS collaboration, the Standard Model (SM) of particle physics was complete. However, this compatibility of the measurement with the SM does not exclude the possibility of additional scalar bosons as long as the mixing with the SM higgs is small. In recent times, several investigations of multi-lepton final states from ATLAS and CMS have revealed the so-called "multi-lepton anomalies" as departures from the predictions of the Standard Model [1, 2, 3, 4].

These anomalous features of the LHC data can be explained well with singlet scalar bosons extended to the SM. The full model that describes this signal is known as 2HDM+S, where the 2HDM model is extended by a real singlet scalar. The scalar spectrum in the 2HDM+S model has two CP-even (h, H), one CP-odd (A), and charged scalar bosons $(H^{\pm})$, providing ample area to examine the structure of scalar spectrum. Recently, a potential candidate for S with a mass of 151.5 GeV was published in Ref. [5], where by integrating the side-band data from the CMS and ATLAS searches (several analysis from di-photon, $Z\gamma$ and $b\bar{b}$ resonances [6, 7, 8, 9]) for the SM Higgs, they have gathered evidences for the associated generation of new scalar particle S (perhaps via the decay of a heavier boson H) with a mass $m_S = 151.5$ GeV. The global significance of the excess at $m_S = 151.5$GeV is 4σ, whereas a combination with the multi-lepton anomalies gives a significance larger than 5σ. Furthermore, if a dark matter candidate is included with this 2HDM+S model, it is possible to account for a variety of astrophysical anomalies [10]. It is interesting that it may be simply extended to account for the muon $g-2$ anomaly [11, 12].

Moreover, the Higgs decays into a pair of W bosons is one of the most important channels for measuring the Higgs boson production cross section and couplings to SM particles since it has the second-highest branching fraction (21.5%) of all the Higgs boson decay channels predicted by the SM. The CMS collaboration recently published measurements of the Higgs boson properties in the $H \to W^+W^-$ decay channel considering the Vector Boson Fusion (VBF) and gluon fusion (ggH) production mechanism. They have also considered the associated production with a vector boson with the final states with at least two charged leptons [13]. Here they presented an excess around 150 GeV in dilpeton channel associated with the 0, 1 jet ggh tagged categories.

With this motivation, we have considered these dilepton channels and studied the transverse mass distribution of Higgs in light of the $2HDM + S$ model. We here studied the Observed distributions of the m_{TH} in the 0-jet and 1-jet ggH $p_{T2} > 20$ GeV and $p_{T2} < 20$ GeV different flavor (DF) categories.

2. The Model

Here, we provide a quick overview of the 2HDM+S model. We have expanded a 2HDM with a real singlet scalar, Φ_S; the notation is maintained from the reference, [14]. The model's potential is indicated by:

$$\begin{aligned} V(\Phi_1,\Phi_2,\Phi_S) &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) \\ &+ \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\ &+ \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.] \\ &+ \frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2. \end{aligned} \tag{1}$$

The $SU(2)_L$ Higgs doublets in this case are Φ_1 and Φ_2, while the singlet field is Φ_S. The first three lines of eqn. 1 are the 2HDM potential. The singlet scalar field is represented by the final four terms. By enforcing a Z_2 symmetry, which causes all the quarks of a given charge to couple to a single Higgs doublet, the tree-level FCNCs may be avoided. The m_{12}^2 term softly breaks the Z_2 symmetry. Additionally, the extension of the Z_2 symmetry to the Yukawa sector guarantees the absence of FCNC at tree level. In this work, we suppose that the real singlet scalar obtains a vacuum expectation value (vev) and satisfies the Z_2 symmetry. This makes the singlet scalar a strong candidate for dark matter. We assumed λ_i to be real as the explicit CP violation is not considered. The minimization conditions then obtained by minimizing the potential with the three Higgs fields with $vevs$. $\Phi_1 \to v_1/\sqrt{2}$, $\Phi_2 \to v_2/\sqrt{2}$ and $\Phi_S \to v_S$. The conditions are,

$$\frac{\partial V}{\partial[v_1, v_2, v_S]} = 0. \tag{2}$$

Which then results in the following three relations:

$$m_{11}^2 = -\tfrac{1}{2}(v_1^2\lambda_1 + v_2^2\lambda_{345} + v_S^2\lambda_7) + \tfrac{v_2}{v_1}m_{12}^2, \tag{3}$$

$$m_{22}^2 = -\tfrac{1}{2}(v_2^2\lambda_2 + v_1^2\lambda_{345} + v_S^2\lambda_8) + \tfrac{v_2}{v_1}m_{12}^2, \tag{4}$$

$$m_S^2 = -\tfrac{1}{2}(v_1^2\lambda_7 + v_2^2\lambda_8 + v_S^2\lambda_6), \tag{5}$$

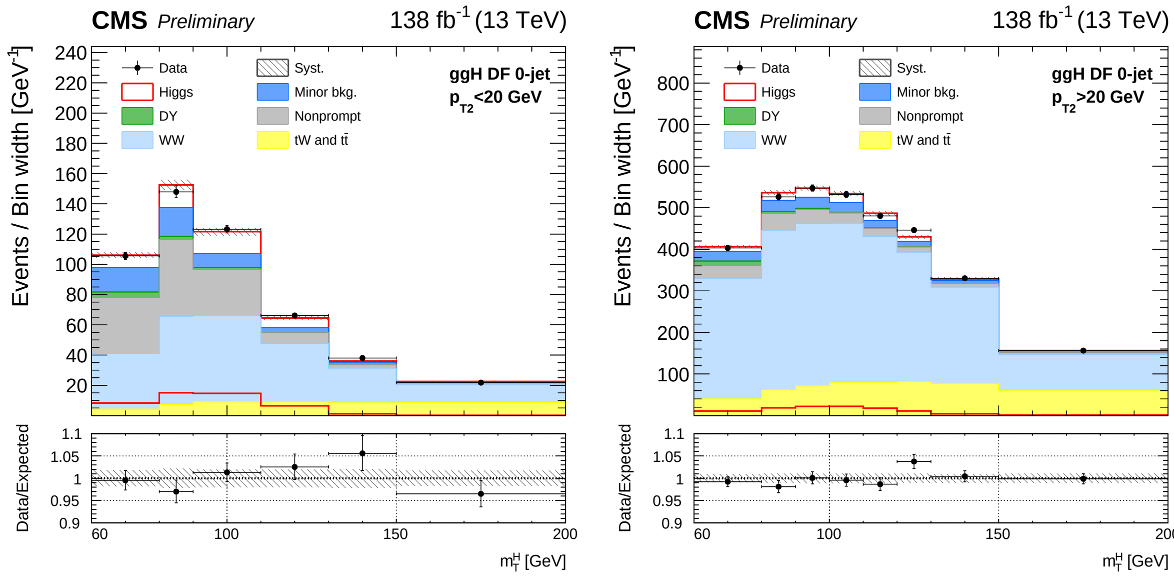

Figure 1. m_T^H distributions for 0-jet ggh $p_{T2} < 20$ GeV (left) and $p_{T2} > 20$ GeV (right) DF Categories [13].

where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$.

Then, in order to determine the relationship between the physical parameters and the masses of the neutral and charged higgses, we solve these conditions in addition to the ones that were obtained after diagonalizing the mass matrices of the CP-even, CP-odd, and charged higgs. For further information, see the Ref. [14] and the references there in.

3. Simulation and Event selection

The Monte Carlo simulation of proton - proton collisions at the LHC is simulated with CM energy of 13 TeV. The model file for the 2HDM+S is implemented with `FeynRules` [15]. Using Madgraph5 [16] and the `NNPDF3.0` parton distribution functions [17], the parton level signal events are produced. After this parton level event simulation, we have used `Pythia8` [18] for the showering and hadronization. The detector level simulation is conducted using `Delphes`(v3) [19].

In this analysis, the events are chosen by necessitating the presence of at least two charged leptons (electron or muon) with high p_T, high p_T^{miss}, and a varying number of hadronic jets. Through out the analysis, only hadronic jets with $p_T > 30$ GeV are considered. The highest p_T (leading) lepton in the event is required to be greater than 25 GeV and for sub-leadng leptons, the minimum p_T requirement is of 10 GeV. On top of these basic selection criteria, the leading leptons must join up to produce an opposite-charged eμ pair. By vetoing events that contain any b-jet with $p_T > 20$ GeV, contributions from top quark production are minimised. To minimize QCD events with multiple misidentified jets, the dilepton invariant mass $m_{\ell\ell}$ must be larger than 12 GeV. The p_T of the dilepton system $p_T^{\ell\ell}$ is considered to exceed 30 GeV. Moreover, the transverse mass built with p_T^{miss} and the momentum of the subleading lepton $m_T(\ell 2, p_T^{miss})$ is needed to be higher than 30 GeV. Here m_T for a group of particles $\{P_i\}$ with transverse momenta $\overrightarrow{p}_{T,i}$ is identified as :

$$m_T(\{P_i\}) = \sqrt{\left(\sum |\overrightarrow{p}_{T,i}|\right)^2 - |\sum \overrightarrow{p}_{T,i}|^2} \quad (6)$$

The events with zero and one hadronic jets are subdivided into two distinct categories. Finally, these sub-categories are further separated based on whether the sub-leading lepton's

Table 1.

	Parameter	Fit Result
$p_{T2} < 20$ GeV	N_{SM}	0.98 ± 0.02
	N_{BSM}	3.86 ± 1.72

p_T is more than or less than 20 GeV.

4. Results

As mentioned in the previous section, in this analysis we have selected events for the dilepton final states, based on the cuts and analysis techniques given in the experimental search results [13].The SM background predictions and their related systematic uncertainties were obtained straight from the experimental papers to ensure agreement with the experimental findings. As the mass of Higgs boson cannot be reconstructed in the W^+W^- channel because of the existence of neutrinos in the final state, the Higg's Boson transverse mass $m_T^H = m_T(\ell\ell, p_T^{miss})$ is chosen as a good observable to discriminate the signal from different background processes, such as $DY \rightarrow \tau^+\tau^-$ and $V\gamma$. The distributions of m_T^H for 0-jet category are given in fig. 1 [13]. Each figure's bottom panel displays the comparison between the total SM prediction and the number of events observed in the data. It is quite apparent from the left panel of fig. 1 that, there exists an excess in the transverse mass distribution of Higgs at around 150 GeV. To address this excess, a fit has performed to the data using the SM+BSM hypothesis. Here, we consider a single degrees of freedom, namely N_{SM} which normalizes the SM components of the fit (SM Higgs + SM background). On the other hand, another degree of freedom N_{BSM} is considered, which maps directly to the normalisation of BSM signal. As a representative case, we here discuss the fit for 0-jet, $p_{T2} < 20$ GeV category. The preliminary result of this fit is given in Table 1 corresponding to a significance of 3.38 σ. The distribution overlaid with the SM+BSM fit is shown in the upper panel of Figure 2. The fit for $p_{T2} > 20$ GeV will be done later. However, $p_{T2} < 20$ GeV fit has the largest sensitivity.

5. Summary and Conclusion

In this analysis, we have studied the dilepton anomalies reported in recent CMS analysis in the W boson pair in proton-proton collisions. We investigated the transverse mass distribution of Higgs, m_T^H as an important kinematic observable in various signal regions. The events with zero and one hadronic jets are subdivided into two distinct categories depending on the value of the p_T of subleading lepton. As a representative case, we here present the preliminary result of the fit for 0-jet with $p_{T2} < 20$ GeV category. The fitted distribution is in good agreement with the data. Therefore, in conclusion we found that the signal from the 2HDM+S model explain the data reasonably well.

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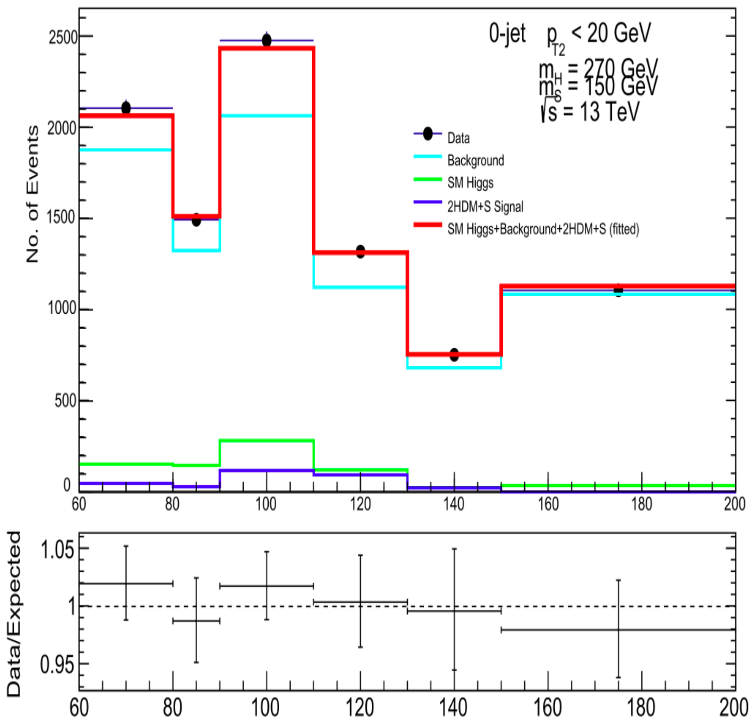

Figure 2. The SM+BSM fit result for the transverse mass spectrum of Higgs .

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