Constraining hypothetical extensions to the Higgs sector at the LHC

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Abstract. With Run 2 of the LHC currently under way at a record-breaking centre of mass energy of 13 TeV, new physics searches are becoming more feasible than ever before. In particular, the ATLAS and CMS collaborations are beginning to focus more on searches which may extend the Higgs sector of the Standard Model. Here it is shown that Run 1 data from both ATLAS and CMS hint at the existence of a new heavy scalar with a mass around 270 GeV. This work will also extend this idea by introducing a full Two-Higgs Doublet Model and outlining the potential Run 2 searches which could constrain the parameters of such a model, should it exist in nature. This will be presented in the context of searches for Higgs production in association with missing energy, leptons and large jet multiplicities. Some preliminary studies related to the rates and kinematic distributions of processes of interest are presented and their implications are discussed in the context of the ATLAS Z+MET search.

1. Introduction

The experimental discovery [1, 2] of the Standard Model (SM) Higgs boson (h) has finalised the minimal particle content which the SM requires. Most of what has been observed about this particle is consistent with what we expect in terms of its spin-parity [3, 4] and coupling strength to the SM particles [5]. There are, however, some measurements on the Higgs boson's properties which show deviations from what is expected in the SM.

The deviations which are considered here involve the following: distortions in the Higgs p_{T} spectra, di-Higgs resonance searches, VV resonance searches (where V is a weak vector boson – either Z or $W^{\pm}$), and enhancements of top associated Higgs production cross section. Due to space constraints, the reader is encouraged to read reference [6] for a review of these references.

This short paper explores the result of combining these deviations under the common hypothesis that a heavy scalar H exists with assumptions on its production mechanism and decay modes. As opposed to previous studies done on this topic (i.e. those in references [6] and [7]), this short paper first summarises the introduction of the model, and then focuses on a particular final state with the data in mind – that is, two same flavour opposite sign (SFOS) leptons plus large missing energy. In section 2, an effective theory approach is taken to determine how well the hypothesis can explain data. The possible consequences of embedding H into a two Higgs doublet model (2HDM) are discussed in section 3, after which an interesting search channel is presented for this approach in section 4. The work is concluded in section 5.

2. The effective model

It can be argued that each of the afore-mentioned deviations can be explained by the existence of a heavy scalar:

- The boosted Higgs p_{T} spectra can be explained if the Higgs is a decay product of some heavy resonance H to give $H \to h + \mathrm{X}$.
- Deviations around 300 GeV in the hh and VV searches could be due to the same resonance.
- Top associated H production is enhanced if the H couples weakly to the vector bosons. This idea has been explored in reference [8].

The most minimalistic way to model this hypothesis is to write down an effective Lagrangian which allows H to decay to the necessary final states which explain the deviations. Under the assumption that H is produced dominantly through gluon fusion (ggF), we can extend the SM by adding the following beyond SM (BSM) sectors to the SM Lagrangian [6]:

$$\mathscr{L}_{Hgg} = -\frac{1}{4}\beta_g\ \kappa_{hgg}^{\mathrm{SM}} G_{\mu\nu}G^{\mu\nu}H, \tag{1}$$

$$\mathscr{L}_{HVV} = \beta_V \kappa_{hVV}^{\mathrm{SM}}\ V_\mu V^\mu H, \tag{2}$$

$$\mathscr{L}_{\mathrm{Y}} = -\frac{1}{\sqrt{2}} y_{ttH}\bar{t}tH - \frac{1}{\sqrt{2}} y_{bbH}\bar{b}bH, \tag{3}$$

$$\mathscr{L}_{\mathrm{T}} = -\frac{1}{2}\lambda_{Hhh}Hhh - \frac{1}{2}\lambda_{h\chi\chi}h\chi\chi - \frac{1}{2}\lambda_{H\chi\chi}H\chi\chi, \tag{4}$$

$$\mathscr{L}_{\mathrm{Q}} = -\frac{1}{4}\lambda_{HHhh}H^2h^2 - \frac{1}{4}\lambda_{hh\chi\chi}h^2\chi^2 - \frac{1}{4}\lambda_{HH\chi\chi}H^2\chi^2 - \frac{1}{2}\lambda_{Hh\chi\chi}Hh\chi^2. \tag{5}$$

Here, Equation 1 describes an effective interaction between H and the gluon field in order to model ggF. It is multiplied by a dimensionless free parameter β_g, which controls the rate of H production. Similarly Equation 2 models the decay of $H \to VV$, controlled by the free parameter β_V. The decay of $H \to hh$ is brought about by the first term in Equation 4.

In order to model the $H \to h+\mathrm{X}$ to explain the distortion in the Higgs p_{T} spectra, a massive scalar dark matter (DM) candidate χ has been introduced. The fourth term of Equation 5 allows for an $H \to h\chi\chi$ decay mode which allows for an $h + E_{\mathrm{T}}^{\mathrm{miss}}$ search channel.

Assuming that H can only decay to hh, VV and $h\chi\chi$, one can fix the former two's branching fractions against the data mentioned in section 1 and, in doing so, fix the latter by allowing it to saturate the remaining width. Then the free parameter $\beta_g$can be fixed by making a fit to the Higgs p_{T} spectra. This was done by generating Monte Carlo (MC) events in `MadGraph` [9] at leading order (LO), showering them in `Pythia 8.2` [10] and passing them through an appropriate analysis using the `Rivet` [11] framework. A χ^2 function was minimised to find the best fit value of β_g. This can be done for any value of m_H (the mass of H), so a scan was performed to find the best fit to all of the public Higgs p_{T} spectra simultaneously. The best fit result of this is shown in Figure 1. Note here that $m_\chi = 60$ GeV $\simeq m_h/2$ in order to suppress the invisible branching fraction of the Higgs boson. The best fit point was at $m_H = 270$ GeV, with $BR(H \to hh) = 0.030 \pm 0.037$, $BR(H \to ZZ) = 0.025 \pm 0.018$ and $BR(H \to WW) = 0.057 \pm 0.041$. The parameter $\beta_g$was best fit at the value of 1.5 ± 0.6.

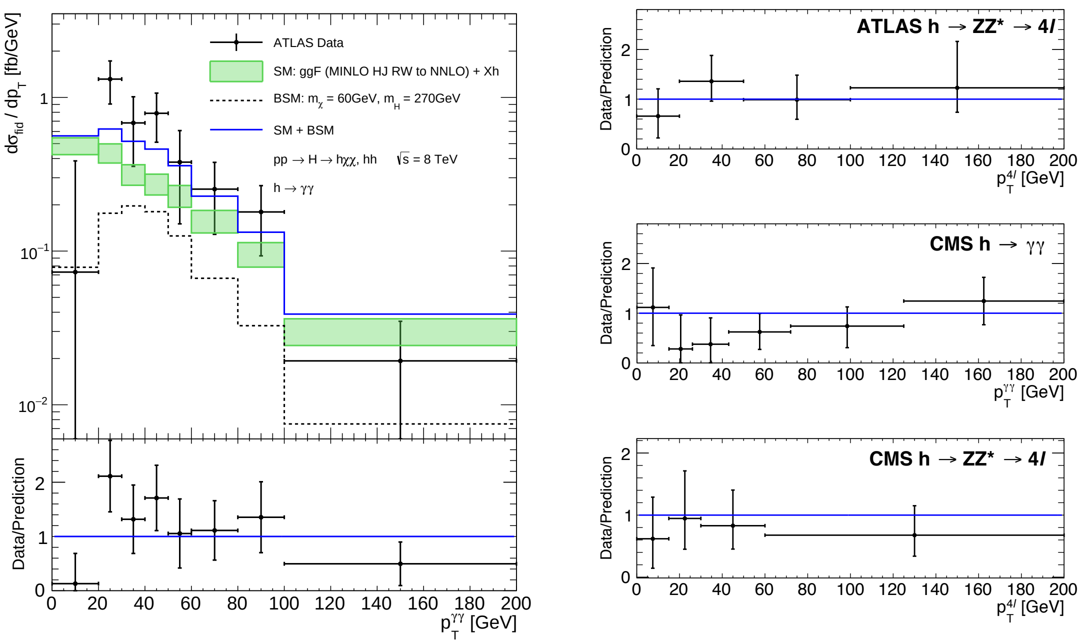


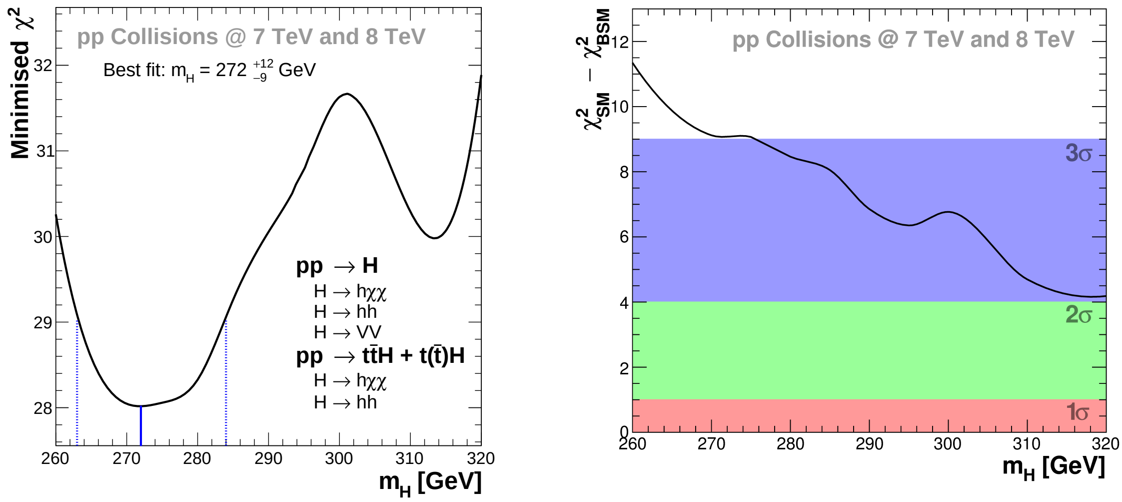
Figure 1. Fits to the $h \to \gamma\gamma$ and $h \to ZZ \to 4\ell$ p_{T} spectra for both ATLAS and CMS. On the left is the ATLAS $h \to \gamma\gamma$ spectrum, where the green blocks represent the NLO SM prediction as calculated using `MINLO` [12] reweighted to NNLO and normalised to the cross section computed in reference [13]. The contribution from other Higgs prodcution modes is included. The black dotted line represents the Higgs p_{T} coming from $gg \to H \to h + \mathrm{X}$, and the blue is a sum of the SM and BSM contributions. Due to space constraints, only the ratio plots are shown for the other channels (on the right).

This fit method can be done for any value of m_H in the range $[2m_h,\ 2m_t]$ – the lower bound is because we require $H \to hh$ to be an on-shell decay and the upper bound is to avoid a large $H \to t\bar{t}$ branching fraction. Doing a scan on mass points, the χ^2 for the hypothesis against the data is shown in Figure 2 (a). Interpolating between these points gives a minimised value at $m_H = 272^{+12}_{-9}$ GeV. This mass point corresponds to the best fit point for H mass hypotheses, with an error having a 1σ coverage. In Figure 2 (b), a test statistic of $\Delta\chi^2$ is used to measure the significance of this result. It can be seen from this plot that at 272 GeV, the local significance of the BSM hypothesis over the SM is around 3σ.

3. Extending the model

A local 3σ hint at a new ~ 270 GeV heavy scalar is a promising thought from an experimental point of view. There are, however, theoretical grievances with the effective model presented in section 2. For one, we have assumed that the three body decay of $H \to h\chi\chi$ dominates the width of H, where it would be far more natural if the two body decays were dominant. In addition to this, gauge invariance stipulates that the Lagrangian is incomplete. There are terms which arise from the gauge structures in the theory that have been omitted, some of which might influence the results presented here.

For this reason, the theory can be made more natural by introducing two theoretical modifications, as suggested in reference [7]. Firstly, we can easily make the assumption that H is the CP-even component of a 2HDM. 2HDMs are well motivated models which have no theoretical issues pertaining to unitarity, gauge invariance, etc. The ramifications of requiring



(a) (b)

Figure 2. The results of a χ^2 calculation (a) and $\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm BSM}$ (b) as a function of the mass of H. These results were obtained by fitting to all $p_{\rm T}$ spectra, hh rates, VV rates and $t\bar{t}h$ rates. The free parameter $\beta_g$was marginalised for each value of m_H so as to minimise the χ^2.

a 2HDM are that four new particles are introduced: the CP-even (scalar) H, the CP-odd (pseudoscalar) A, and two charged scalars $H^{\pm}$.

Secondly, we solve the issue of the dominant three body decay by introducing a singlet scalar S. We then postulate that H can decay to SS or Sh (in addition to hh, VV, etc.) and that S can decay invisibly to $\chi\chi$ as well as to SM particles. Doing this transforms the three body decay into a chain of two body decays – this is shown in Figure 3. S can take on a mass in the range $[m_h,\ m_H - m_h]$ so that decays of $H \to SS, Sh$ can be kept on-shell in most of the parameter space. The admixture of SS and Sh is controlled by the parameter a_1, which is a ratio of the $H \to Sh$ and $H \to SS$ branching fractions.

4. $A \to ZH$: a potential search channel

As mentioned before, using a 2HDM introduces four new bosons to the theory. With some hints that H exists, one should also ask whether the model presented here can be used to make searches for the other new bosons too. Here a search channel for A is presented in the context of an ATLAS supersymmetry search.

(a) (b)

Figure 3. The effective decay of $H \to h\chi\chi$ (a) is replaced by a tree level decay process when the singlet scalar S is introduced (b).

Given that the model is embedding into a 2HDM, we find the following mixing terms in the Lagrangian of the theory:

$$\mathscr{L}_{V\phi\phi} \subset \frac{m_W}{v\,\cos\theta_W}\Big[\sin(\beta-\alpha)Z_\mu\left(A\partial_\mu H - H\partial_\mu A\right) + \cos(\beta-\alpha)Z_\mu(A\partial_\mu h - h\partial_\mu A)\Big], \qquad (6)$$

where α and β are mixing angles, and v is the vacuum expectation value. For an SM-like H, we require that $\cos(\beta-\alpha)\sim 0$. This necessarily sets $\sin(\beta-\alpha)\sim 1$, meaning that the A-Z-H coupling is far stronger than the A-Z-h coupling. Therefore, if A is produced through ggF, we could expect a non negligible rate of $pp\to A\to ZH$ events, where $H\to SS, Sh$.

If S has a large branching fraction to $\chi\chi$, this should be a viable in Z+MET supersymmetry searches. These searches typically search for a $Z\to\ell\ell$ candidate with large missing energy

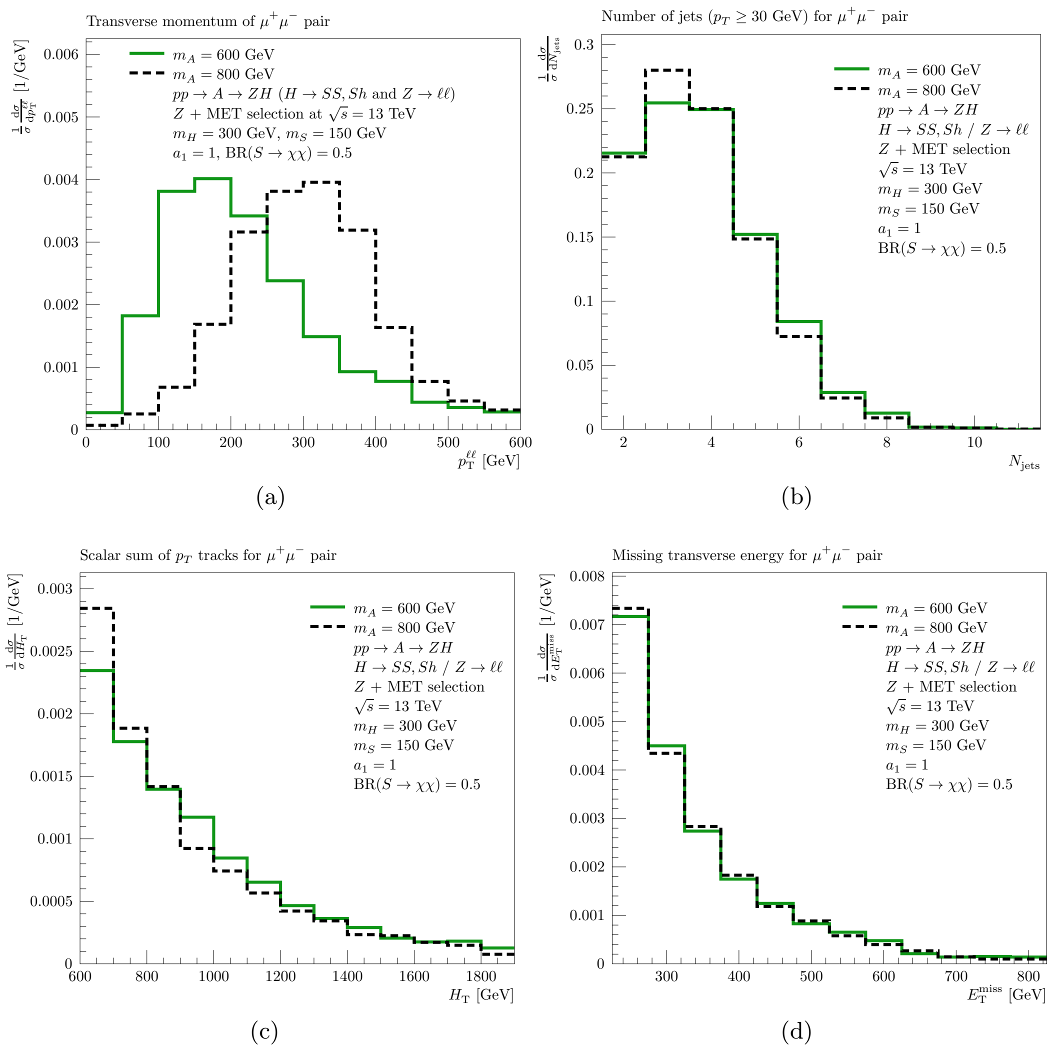


Figure 4. Sample distributions for $A\to ZH$ with the final state $\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}} + \mathrm{X}$. Events were generated in `Pythia 8.2` and analysed according to the Run 2 ATLAS Z+MET cuts [14] using `Rivet`. These show the di-lepton p_{T} (a), the jet multiplicity (b), the H_{T} – a scalar sum of jet and lepton p_{T} (c), the the missing transverse energy (d).

and jets. This final state could be predicted by certain supersymmetry models, but the model presented here could also predict this final state with $S \to \chi\chi$ or jets and $h \to$ jets.

In order to test the validity of this, a sample of $pp \to A \to ZH$ was simulated and decayed with $Z \to \ell\ell$ and $H \to SS, Sh$ in `Pythia 8.2`. S was given Higgs-like branching fractions as well as a 50% branching fraction to $\chi\chi$. m_A was considered at 600 GeV and 800 GeV, while m_H was fixed at 300 GeV, $m_S = 150$ GeV and $m_\chi = 60$ GeV. These events were selected and plotted using the ATLAS Run 2 Z+MET SRZ selection [14], where a 2.2σ excess was observed in data.

Some sample distributions from this procedure are shown in Figure 4 for the $Z \to \mu\mu$ channel. Here we see that the di-lepton p_{T} is a good discriminant in determining the effect of m_A, since a lower mass A predicts a softer spectrum which is arguably observed in the ATLAS data. The jet multiplicity is small compared to the supersymmetry models considered in reference [14], which is closer to what is seen in the data. The H_{T} and $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra shown resemble tails of a distribution rather than peaks, which is also close to what the data shows. The efficiencies for the events passing the cuts are 0.68% and 1.86% for $m_A = 600$ and 800 GeV, respectively (for both the $Z \to ee$ and $\mu\mu$ channels).

5. Concluding remarks

Under the assumption that various deviations observed in Run 1 of the LHC can be explained by the existence of a heavy scalar H, an analysis has been done to show that the data can be explained better by this hypothesis with a significance of 3σ over the SM. This approach has been expanded to fit with a 2HDM in association with a singlet scalar to resolve theoretical issues. Using this theory, a search channel has been presented for the pseudoscalar component of the 2HDM, A. A viable channel has been identified in the generic Z+MET supersymmetry searches.

While some tantalising results have been presented, it is noted here that much work is still needed to explain the theory fully. Since this work is data driven and can only progress when ATLAS and CMS publish more results, further studies will be done when these results are available.

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