A heavy scalar of mass 270 GeV and its possible connection to the 750 GeV excess

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Abstract. Run 1 of the LHC saw many interesting and surprising results, hinting at physics beyond the Standard Model. One of these is the search for lepton pairs in association with high missing energy, which produced a sizeable excess in its rate from both the ATLAS and CMS collaborations. While ATLAS and CMS interpret this using a supersymmetric model, we have shown that the excess can partly be explained by the existence of a new heavy scalar boson, H. This heavy scalar can decay to weak vector bosons and also Standard Model Higgs bosons and missing energy, making it a prime candidate in the search for high p_{T} di-lepton pairs. An analysis is performed to determine the rate of di-lepton production with large missing energy for opposite sign pairs. We show that the heavy scalar produces a non-negligible rate, but cannot fully explain the excesses. For this reason, we look also to incorporating a full two Higgs doublet model to enhance this rate, where the pseudo-scalar A in the spectrum of new particles is considered to be a candidate for the Run 2 di-photon excess at 750 GeV.

1. Key Higgs results from Run 1

By now it is clear that Run 1 of the Large Hadron Collider (LHC) saw the discovery of the Higgs boson, which was measured to have a mass of 125.09 ± 0.24 GeV according to a combination of both ATLAS and CMS results [1]. This particle's couplings have also been shown to behave like a Higgs boson predicted by the Standard Model (SM) [2].

However, studies on the kinematics of this particle have revealed some deviations from SM predictions. In particular, here we can consider the Higgs differential fiducial p_{T} spectra published by both ATLAS [3, 4] and CMS [5, 6]. Looking at the ATLAS results, it is clear that the observed Higgs boson events have significantly more transverse momentum than what is predicted by the SM. Typically, this is indicative of the Higgs boson decaying from some heavy object. The CMS results are not as compelling as the ATLAS results, but the trend is still observable in the $h \to ZZ^* \to 4\ell$ spectrum albeit with a small significance.

Searches for heavy Higgs boson-like particles from Run 1 have also produced some exciting results. For instance, several searches for resonant production of di-Higgs pairs (that is, the decay of some heavy resonance to two Higgs bosons $H \to hh$) from ATLAS [7] and CMS [8, 9, 10] have shown excesses around the ~ 300 GeV region of the resonance mass. A similar effect can be seen in searches for resonant VV production (where V is a vector boson, either Z or $W^{\pm}$). In this channel, CMS [11] sees an excess of events where the resonance mass is about ~ 275 GeV.

This result is compatible with the limits set by ATLAS in the same search channels [12, 13], where a much smaller excess can be seen.

Finally, it is apparent from top associated Higgs production Run 1 results that the SM underestimates the rate of Higgs bosons being produced in association with top quarks. There are many analyses which study this effect, but it can be seen most convincingly when we consider the ATLAS and CMS combination of the μ_{tth} measurement [2]. The parameter μ_{tth} is a signal strength and gives a ratio of the cross section measured for $pp \to t\bar{t}h$ production against what the SM predicts. The measurement lies at

$$\mu_{tth} = \frac{\sigma_{tth}}{\sigma_{tth}^{\text{SM}}} = 2.3^{+0.7}_{-0.6},$$

meaning that ATLAS and CMS measure more than two times as many top associated Higgs events than what the SM predicts. It should be noted that all of the other Higgs production mechanisms all have measured signal strengths which are within 1σ of the SM prediction ($\mu = 1$), yet the tth measurement is more than 2σ away. This excess could also be explained by the existence of a heavy Higgs-like particle of which the main decay product is a SM Higgs boson. It has been shown that top associated Higgs production is enhanced if the Higgs boson in question has a small VV branching ratio [14]. The excess, therefore, could be accounted for if we postulate the existence of a heavy scalar H, with a small $H \to VV$ branching ratio and the ability for it to decay to a SM Higgs boson.

2. A 2HDM interpretation

In the section above, it was stated that the excesses and results mentioned can all be explained by proposing the existence of a new heavy scalar H. This approach was taken in reference [15], advocating the existence of a heavy scalar with a mass around ~ 270 GeV using data only from Run 1 of the LHC. The best fit point for this hypothesis was determined to be

$$m_H = 272^{+12}_{-9} \text{ GeV},$$

and at this mass point the significance of the measurement was of the order of 3σ.

Extending the SM by introducing a single heavy scalar is possible, but a far more natural and theoretically motivated extension is by introducing a second Higgs doublet – often called a two-Higgs doublet model (2HDM) [16]. In this model, the Higgs sector is extended by the addition of all Lorentz invariant terms involving two Higgs doublets, instead of just one as in the SM. The observable consequence of this is the hypothetical existence of four new mass eigenstates in the theory. In addition to the SM Higgs boson h, a 2HDM predicts another CP-even scalar H, a CP-odd scalar A, and two charged scalars $H^{\pm}$.

While the details of 2HDMs are not discussed in this short paper in any detail (a contemporary discussion can be found in reference [17]), it should be noted that the heavy scalar which is the subject of reference [15] could be the extra CP-even scalar found in a 2HDM. If this is the case, then the A and $H^{\pm}$ bosons should also exist in nature. These particles have not been discovered yet, but in this short paper we consider the possibility that the 750 GeV excess in both the ATLAS [18] and CMS [19] di-photon mass spectra from Run 2.

It is important, however, to take note that the heavy scalar scenario presented in reference [15] can not be mapped to a 2HDM alone. In this case, the heavy scalar's production cross section is modified by a factor β_g. Since H is produced dominantly through gluon fusion (ggF), a modification of its production cross section could mean that extra coloured particles run in the ggF loop (in addition to the heavy quarks). If this is the case, then a 2HDM would not completely describe the excesses seen in Run 1. The model also includes a hypothetical dark matter particle, χ, of mass $\sim m_h/2$ which can explain events with large missing transverse energy ($E_{\text{T}}^{\text{miss}}$).

Signal region	Expected	Observed	Significance
Run 1 ATLAS SR-Z [20]	10.6 ± 3.2	29	3.0σ
Run 2 ATLAS SR-Z [21]	10.3 ± 2.3	21	2.2σ
Run 1 CMS low-mass edge-search [22]	730 ± 40	860	2.6σ

Table 1. The event yields for current significant excesses in di-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ searches in the literature to date. The Run 2 result from CMS [23] did see a small excess, but this was not classified as significant.

3. Excesses for di-lepton + large $E_{\mathrm{T}}^{\mathrm{miss}}$ events

Several other excesses were observed in Run 1, and some of the most notable of these are in the di-lepton + large $E_{\mathrm{T}}^{\mathrm{miss}}$ channels. These are typically supersymmetry (SUSY) searches, since it is common in SUSY extensions of the SM to expect leptons in the decays of neutralinos – either via a direct decay or from a $Z \to \ell\ell$ decay, since neutralinos also have decay modes involving Z bosons. These searches most commonly look for same-flavour opposite-sign (SFOS) di-lepton pairs, since this is typically what a Z boson can decay to.

The analyses performed for a selection of di-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ events are, therefore, largely based on the features predicted by SUSY di-lepton production. Some common selection criteria include:

- Two high p_{T} SFOS leptons: typically seen in the leptonic decay of a Z boson.
- Large missing energy: SUSY events often contain invisible final state particles not detected in the calorimeters.
- Many jets: SUSY models characteristically predict large jet multiplicities in events with di-lepton final states.
- Large H_{T} – that is, the scalar sum of jet transverse momenta: this variable is highly correlated to both jet multiplicity and $E_{\mathrm{T}}^{\mathrm{miss}}$, and has therefore been left out of some signal regions in the literature because of this redundancy.

The different signal regions (SRs) used by ATLAS and CMS make use of different combinations of cuts on the variables mentioned above. They can further be classified as either peak (on-Z) or edge (off-Z) searches, where the former restricts the invariant mass of the di-lepton pair to be close to the Z boson mass and the latter excludes this region. The significant excesses as reported by ATLAS and CMS in their respective SRs are shown in Table 1, which compares the expected and observed rates.

The SUSY models considered in these searches can of course be tuned to match the observed rates, but when one considers the differential distributions of a few key variables in the study it becomes clear that the SUSY models do not explain the excesses well. In this short paper, we consider only the peak search SR from ATLAS (SR-Z) since this is where the excess is largest and the differential distributions from this analysis are clear enough to make a comparison between the SUSY models and the data. One can see from the ATLAS SR-Z jet multiplicity distributions that events passing the selection criteria have far fewer jets than what the SUSY models predict. This is confirmed by the H_{T} distributions. The data seem to show that H_{T} decreases like the tail of a distribution, whereas the SUSY models predict a peak at large H_{T}. These two observations are a good argument against a SUSY explanation of the excess, primarily since the models considered in the publications predict far too many jets.

4. Results in ATLAS SR-Z

In light of the discrepancy mentioned above, it must be mentioned that proposing the existence of the heavy scalar mentioned in section 2 can partly explain the excesses measured while

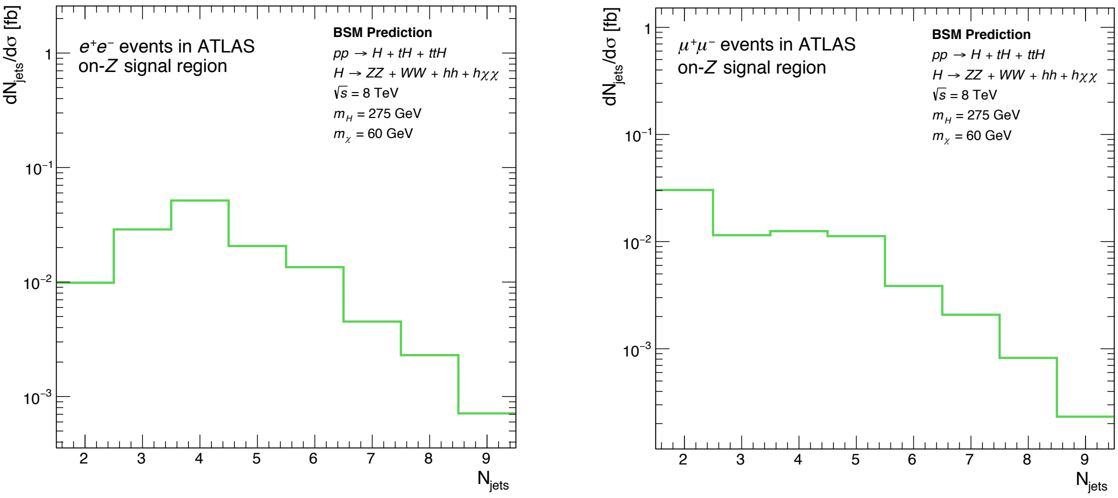

Figure 1. The jet multiplicity differential distributions for the di-lepton signal (e^+e^- on the left and $\mu^+\mu^-$ on the right) generated from heavy scalar production and decays, normalised to a cross section calculable from the parameters in reference [15]. These are intended for comparison against the distributions in reference [20].

predicting differential distributions more closely related to what is seen in the data. For this reason, a simulation was performed to determine whether or not a heavy scalar extension of the SM could match the results given in the ATLAS SR-Z signal region. In detail, the cuts applied for the ATLAS SR-Z signal region are as follows:

- Two SFOS leptons (either e^+e^- or $\mu^+\mu^-$) are selected with a minimum $p_{\rm T}$ of 25(10) GeV for the (sub-)leading lepton.
- The pseudorapidity is bound such that $|\eta| < 2.47(2.4)$ for electrons (muons). For electrons, the crack region is also excluded: $1.37 < |\eta| < 1.52$.
- At least two jets with $p_{\rm T} > 35$ GeV are required.
- This is a peak-search, so the invariant mass of the di-lepton pair is limited to $81 < m_{\ell\ell} < 101$ GeV.
- The $E_{\rm T}^{\rm miss}$ is required to be larger than 225 GeV.
- $H_{\rm T} = p_{\rm T}^{\ell 1} + p_{\rm T}^{\ell 2} + \sum_i p_{\rm T}^{\rm jet-\it i}$ is required to be larger than 600 GeV.
- The azimuthal between the two leading jets four vector and the $E_{\rm T}^{\rm miss}$ four vector is required to be larger than 0.4.

Events were generated using `MadGraph` [24] in order to simulate the production of the heavy scalar in its three dominant production modes: $pp \to H$ (ggF), $pp \to tH + \bar{t}H$ (single top associated production) and $pp \to t\bar{t}H$ (double top associated production). These events were then decayed, showered and hadronised in `Pythia 8.2` [25]. The decay modes of H which could generate a signal for the di-lepton + $E_{\rm T}^{\rm miss}$ SRs are: $H \to ZZ$ (where $Z \to \ell\ell$ or $\nu\nu$), $H \to WW$ (where $W \to \ell\nu$) and $H \to h\chi\chi$. The last decay mode produces a di-lepton signal in the way the SM Higgs boson decays, and generates large $E_{\rm T}^{\rm miss}$ through the existence of the dark matter candidate χ. The mass points considered for this analysis were $m_H = 275$ GeV and $m_\chi = 60$ GeV, which arise from the best fit points in reference [15].

The differential distributions for jet multiplicity from this analysis are shown in Figure 1. It can be seen that the heavy scalar production predicts few jets, especially for the case of a

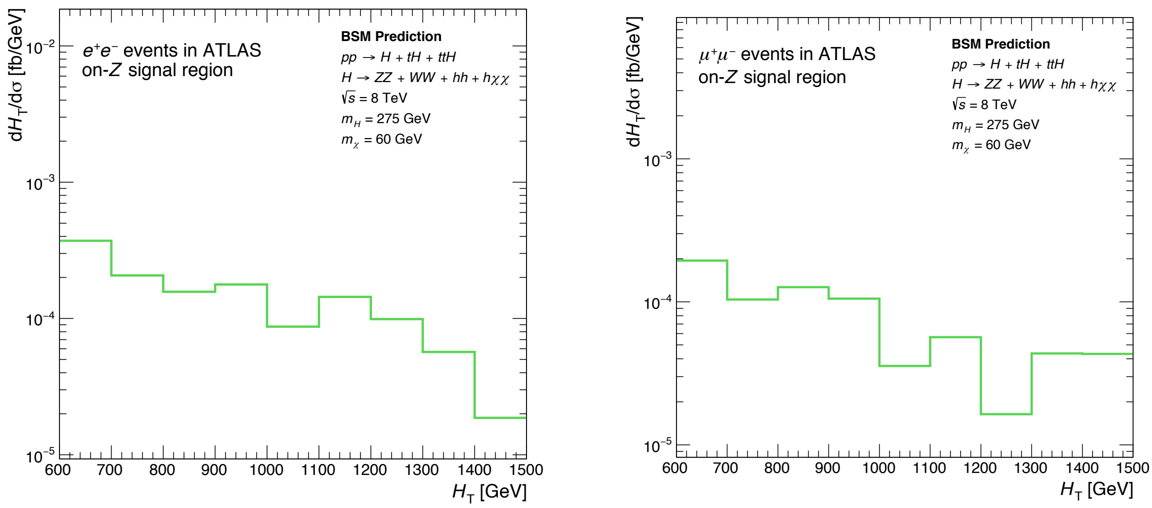

Figure 2. The jet multiplicity differential distributions for the di-lepton signal (e^+e^- on the left and $\mu^+\mu^-$ on the right) generated from heavy scalar production and decays, normalised to a cross section calculable from the parameters in reference [15]. These are intended for comparison against the distributions in reference [20].

$\mu^+\mu^-$ pair. This is confirmed by the H_T differential distributions in Figure 2, which show what appears to be the tail of the distributions. When one compares these two distributions to the ATLAS data, it is apparent that they explain the shapes of what is observed fairly well, and far more convincingly than the SUSY models considered in the published analyses.

The rate, however, does not fully explain the large excesses observed. Using the constrained parameters in reference [15], a total rate was able to be predicted for the production mechanisms and decays mentioned above. The prediction is a total of 4.2 ± 1.8 events. This is a non-negligible rate, but is clearly not enough to saturate the ~ 18 event excess seen in the ATLAS data. This is where the need for the CP-odd Higgs boson A comes about.

Hypothetically, the rate of di-lepton events with large $E_\mathrm{T}^\mathrm{miss}$ will be greatly enhanced by the production of the A pseudo-scalar. While there is not enough information about the model as yet to predict a rate, a study was done to calculate the fiducial efficiency of events which could pass the selection mentioned above, through the production $pp \to A \to ZH$ (where $H \to ZZ, WW, h\chi\chi$). When the mass points $m_A = 750$ GeV, $m_H = 275$ GeV and $m_\chi = 60$ GeV are chosen, the selection efficiency was of the order of 20%, which is large and shows promise for a sizeable rate in the di-lepton + $E_\mathrm{T}^\mathrm{miss}$ search channel as well as an explanation for the 750 GeV di-photon excesses.

5. Conclusions

A number of unexplained excesses were seen in Run 1 of the LHC, both from ATLAS and CMS. The proposition has been made that many of these excesses can be explained by postulating the existence of a heavy scalar with mass around 270 GeV (as shown in reference [15]). When applying this hypothesis to excesses seen in di-lepton + $E_\mathrm{T}^\mathrm{miss}$ search channels, it is observed that the heavy scalar can explain part of the excess as well as the shapes of the differential distributions seen in data. The rate predicted, however, is not comparable with the large excess observed by ATLAS in Run 1. For this reason, a small study has been done to determine how effective a pseudo-scalar at 750 GeV could be at enhancing this rate. This pseudo-scalar was postulated as an explanation for the 750 GeV excess seen in the ATLAS and CMS Run 2

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di-photon mass spectra. The efficiency for di-lepton + $E_{\mathrm{T}}^{\mathrm{miss}}$ events coming from the process $pp \to A \to ZH$ is a promising large number, and requires further study to determine whether its existence could help saturate the large excess seen in Run 1.

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