Compatibility of a simplified BSM model with the observed excesses in multi-lepton production at the LHC

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Abstract. The discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments at the Large Hadron Collider experiments has opened a window to a wide range of physics searches. The study of a number of features in the Run 1 data has lead to unearthing excesses in the production of multiple-leptons with intermediate transverse momentum in proton-proton collisions. The elevated production of leptons has the potential to provide indirect evidence for new physics Beyond the Standard Model. Here we investigate the compatibility of a simplified BSM model with the observed multi-lepton anomalies in the LHC public data. The BSM model predicts the existence of a heavy scalar H with a mass of about 270 GeV that decays to a SM Higgs boson in association with a scalar singlet S with a mass of about 150 GeV. In particular, here we investigate the invariant mass spectrum of four leptons (e, μ) and two muons in the region of interest.

1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) by the ATLAS and CMS Collaborations in 2012 put together the last piece of the puzzle to help understand the mechanism of electroweak (EW) symmetry breaking, and completed the Standard Model of particle physics [1, 2]. The Collaborations have since been making detailed measurements to better understand the couplings of the Higgs boson to other Standard Model (SM) particles. The measurements made by the LHC are compared to SM predictions, and they agree to a great extent. There however exists some discrepancies between the SM predictions and the observed experimental results, especially in events that produce multiple leptons [3, 4].

A number of Beyond the Standard Model (BSM) models interpret the discrepancies between the observed LHC experimental results and SM predictions as signatures of new physics. One of such models, the Madala hypothesis, postulates the existence of a heavy scalar boson H (which may participate in the electroweak symmetry breaking) with a mass of about 270 GeV produced in association with a scalar singlet S which has a mass of about 150 GeV [5, 6].

A study detailed in Reference [7] was performed with the aim of understanding the multi-lepton anomalies in the LHC data and their compatibility with new physics at the EW scale. In the study, the prediction of the Madala hypothesis was compared with public results with

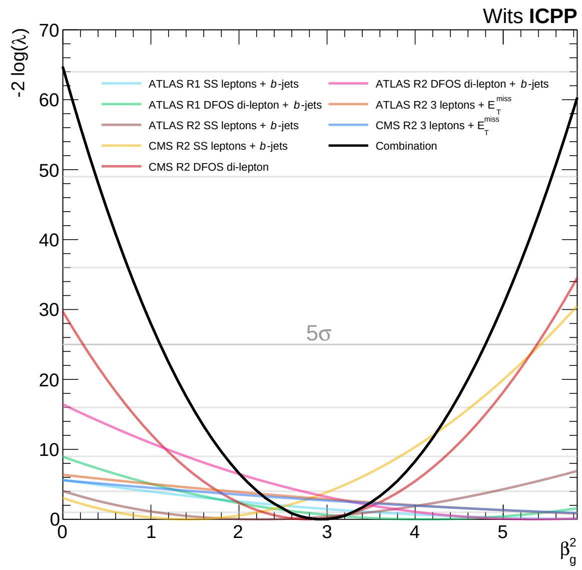

Figure 1. The profile likelihood ratio obtained for each fit result considered in the study in Reference [7]. The black curve is the combination of the results.

multi-lepton final states from ATLAS and CMS Collaborations. The comparison was made by performing a statistical fit with the aim of establishing constraints on the fit parameter β_g^2 (the single degree of freedom of the Madala hypothesis). The parameter β_g^2 controls the Yukawa couplings of H, with $\beta_g^2 = 0$ corresponding to the absence of a BSM signal. The parameter β_g^2 was constrained using the profile likelihood ratio, with the best fit value taken as the β_g^2 value that minimises the negative log likelihood function, $-2\log\lambda\beta_g^2$.

Figure 1 shows the profile likelihood ratios of each fit result considered in the study in Reference [7]. The combined profile likelihood ratio is obtained by multiplying the profile likelihood ratios obtained for each measurement and the combinations yields $\beta_g^2 = 2.92 \pm 0.35$. The Poisson significance of the fit results is calculated as the square root of the point where $\beta_g^2 = 0$ and the combined profile likelihood ratio has a local significance of 8.04σ, revealing large discrepancies between SM predictions and the LHC experimental data. The discrepancies are observed at a corner of the phase space where different SM processes dominate, indicating that the discrepancies are unlikely to be due to mismodelling of the SM processes.

In the wake of these results, this article aims to perform a direct search of H on the invariant mass spectra of public ATLAS and CMS results containing final states with 4ℓ and 2μ in a mass range 230 to 280 GeV with different natural decay widths, Γ, values ranging from 0 to 10% of the resonant mass.

2. Methodology

The study considers published Run 2 results from both ATLAS and CMS Collaborations containing four leptons [9–11] in their final states and one publication with final state containing two muons [12]. The results were recorded from proton-proton (pp) collisions at $\sqrt{s} = 13$ TeV.

Two of the four publications used are searches of a pair of Z bosons decaying to a final state with four leptons ($\ell^+\ell^-\ell^+\ell^-$). The papers used are published by the ATLAS [9] and CMS [11] Collaborations using pp collisions with integrated luminosity of 36.1 fb^{-1} and 35.9 fb^{-1} for ATLAS and CMS experiments, respectively. The searches considered the production of

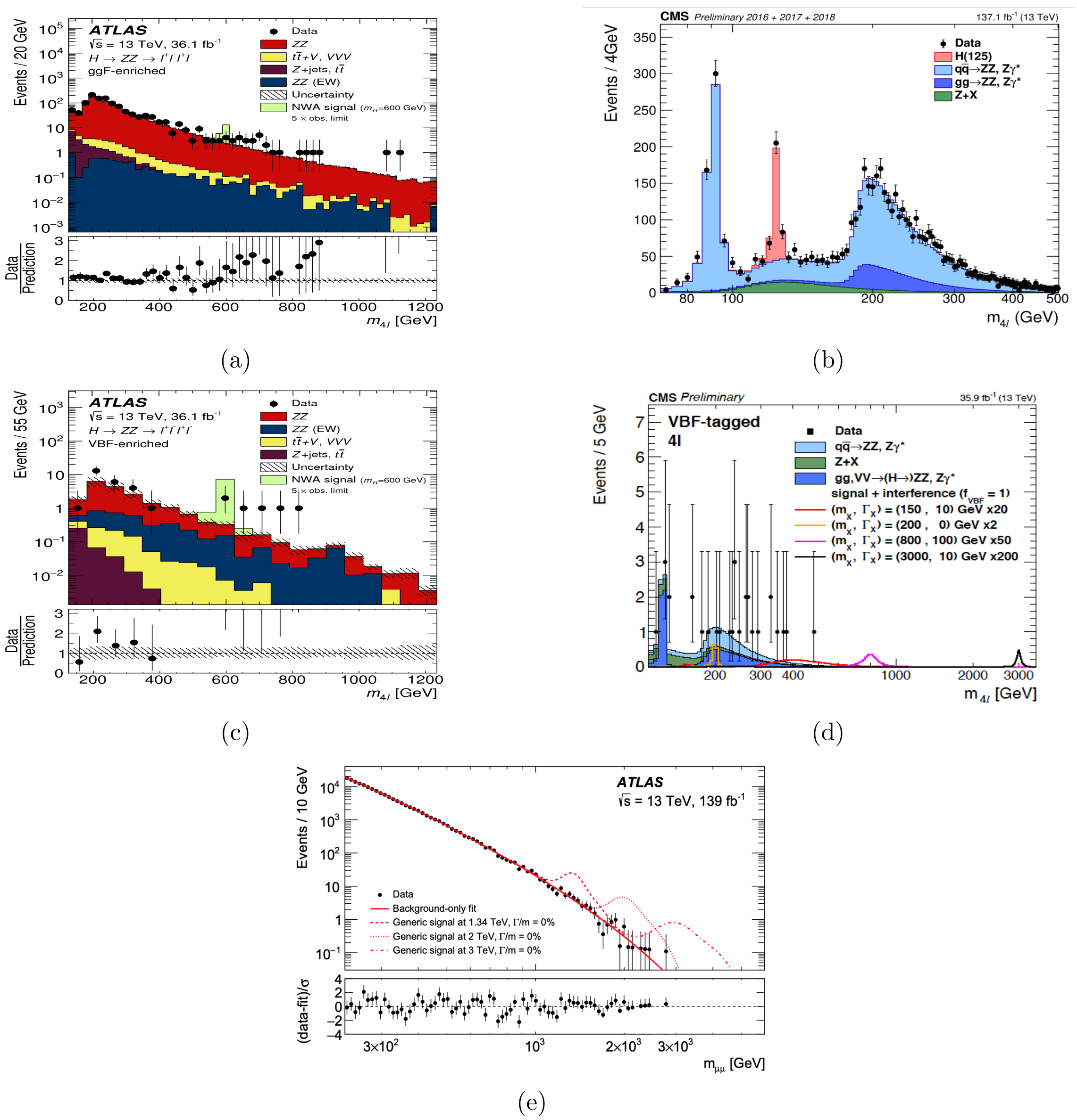

Figure 2. The invariant mass distribution of $ggF \to ZZ \to 4\ell$ published by (a), ATLAS and (b) CMS. (c) ATLAS and (d) CMS invariant mass distribution of the VBF $\to ZZ \to 4\ell$ process. (e) The invariant mass distribution of the 2μ as recorded by ATLAS.

a heavy scalar boson via gluon-gluon fusion (ggF) and an electroweak production dominated by the vector boson fusion (VBF). The heavy scalar then decays to a pair of Z bosons which then decay to a pair of same flavour but oppositely charged lepton ($e^+e^-, \mu^+\mu^-$) pairs. The studies required that the reconstructed Z boson candidates be formed by oppositely charged electron or muon pairs with invariant mass that fall in the mass window $12 < m_{\ell^+\ell^-} < 120$ GeV.

Further selection requirement were applied to categorize the four leptons events produced through the VBF process. The ATLAS search required that selected VBF events should contain at least two jets with transverse momentum $p_T > 30$ GeV, with the leading two jets being well separated in η, $|\Delta\eta_{jj}| > 3.3$, and having an invariant mass $m_{jj} > 400$ GeV [9]. The CMS search required that the four leptons events produced via the VBF process should have two energetic and forward associated jets and to pass a cut on a matrix-element discriminant sensitive to the VBF signal topology [11].

The third publication considered is a study that measures the properties of the Higgs boson in $h \to ZZ \to 4\ell$ using pp collisions recorded by the CMS detector with an integrated luminosity of 137.1 fb^{-1} [10]. The Z boson candidates formed are with pairs of the same flavour and oppositely charged leptons are required to pass the $12 < m_{\ell^+\ell^-} < 120$ GeV requirement. In the 4μ and $4e$ channels where the four leptons invariant mass, $m_{4\ell}$, is reconstructed from same flavour leptons, the reconstructed invariant mass is required to be greater than 70 GeV. Figure 2 (b) shows the reconstructed $m_{4\ell}$ distribution up to 500 GeV.

The fourth publication considered searches for high-mass dielectron or dimuon resonances using 139 fb^{-1} of pp collision data collected by the ATLAS detector [12]. The reconstructed invariant mass of the dimuon system is required to be greater that 225 GeV, reconstructed from oppositely charged muons. The dimuon system was chosen because it is predicted that at high masses the heavy Higgs boson-like scalars would have a higher decay rate into muon pairs over electron pairs [13].

A statistical fit was performed using RooFit and RooStat statistical tools [14] distributed in Root [15], an object-oriented data analysis framework. The combined background and signal statistical model used to describe the observed experimental data is given by the following expression:

$$N_{\text{bkg}} \times f_{\text{bkg}}(m_H) + N_{\text{sig}} \times \mu \cdot f_{\text{sig}}(m_H, \sigma, \Gamma), \tag{1}$$

where N_{bkg} and N_{sig} are the number of fitted background and signal events, respectively. The parametrized background shape ($f_{\text{bkg}}(m_H)$) and the data points are scanned from the published distributions considered in this study, shown on Figure 2. The generic signal shape is taken to be a Voigtian distribution (convolution of the Breit–Wigner and Gaussian distributions), $V(mass, \sigma, \Gamma)$, where the σ of the Gaussian distribution accounts for the detector resolution and Γ of the Breit-Wigner distribution gives the natural decay width of the resonance. The decay width Γ is given by:

$$\Gamma = a \times m_H, \tag{2}$$

where a is expressed as a percentage. The decay width of the heavy scalar in this study is varied from 0% to 10%, the case where $\Gamma = 0\% \times m_H = 0$ is called the narrow width approximation and the width of H is determined by the detector resolution.

The significance of a SM+BSM signal hypothesis of mass m_H and Γ is summarised by a p-value, the probability of observing a background+signal excess in data using the background-only hypothesis. The local p-value (p_0) for the compatibility of a signal hypothesis of mass m_H and decay width Γ with a background-only hypothesis is obtained by scanning the test statistic, $q_0(m_H, \Gamma)$, given by [16]:

$$q_0(m_H, \Gamma) = -2 \log \frac{L\Big(N_{\text{sig}} = 0 | m_H, \Gamma, \hat{\hat{\nu}}\Big)}{L\Big(\hat{N_{\text{sig}}} | m_H, \Gamma, \hat{\nu}\Big)}, \tag{3}$$

where N_{sig} is the parameter of interest and ν is a set of nuisance parameters. The parameter $\hat{\hat{\nu}}$ is chosen to maximise the likelihood L in a background-only fit and $\hat{N_{\text{sig}}}$ and $\hat{\nu}$ are chosen to maximise the likelihood function over the entire parameter space. The local p_0 value of the background only hypothesis is calculated by applying the asymptotic approximation to the test statistic $q_0(m_H, \Gamma)$ distribution. The significance is obtained by taking the square root of the test statistic, $Z = \sqrt{q_0}$.

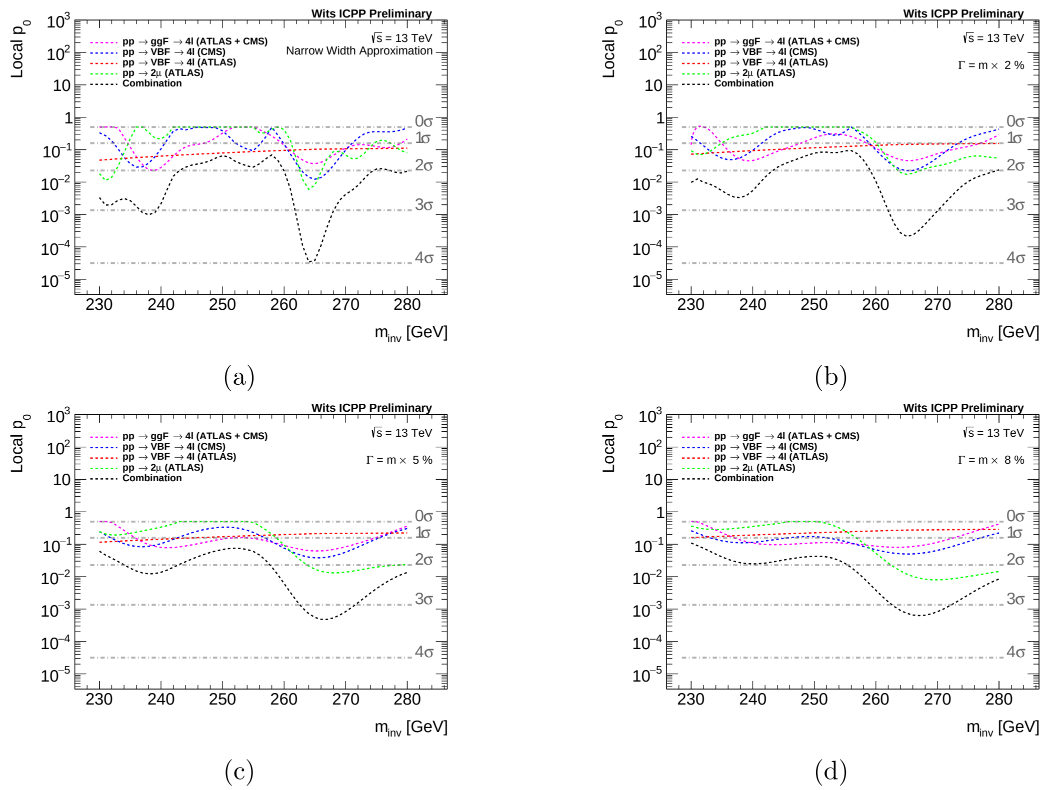

Figure 3. The observed local p_0 values as a function of the hypothesised mass of H with a natural decay width of (a) 0%, (b) 2%, (c) 5% and (d) 8%. The red, blue, green and magenta curves correspond to the observed local p_0 values from fitting the ATLAS $pp \to 4\ell$ VBF produced events, CMS $pp \to 4\ell$ VBF produced events, ATLAS $pp \to 2\mu$ events and ATLAS and CMS $pp \to ggF \to 4\ell$ events, respectively. The black curve corresponds to the quadrature sum of the other curves.

3. Results

For each distribution in Figure 2, a hypothesis test is performed at mass points from 230 GeV to 280 GeV with 1 GeV intervals for decay widths ranging from the narrow width approximation ($0\%\times\Gamma$) to 10% of the resonant mass. The $pp \to ggF \to ZZ \to 4\ell$ results from ATLAS and CMS Collaborations, Figures 2 (a) and (b), were combined into a single dataset and a simultaneous fit was used to do the hypothesis testing. The simultaneous fit took into consideration the different luminosities (36.1 fb^{-1} for ATLAS and 137.1 fb^{-1} for CMS) and the signal model of each dataset. The event selection used in the selection of VBF $\to ZZ \to 4\ell$ events is different for ATLAS and CMS published studies, therefore a simultaneous fit was not performed to combine these measurements.

The final results presented in Figure 3 are a combination of the simultaneous fit results combining the ggF 4ℓ results from ATLAS and CMS, separated ATLAS and CMS VBF fit results and the fit result to the ATLAS dimuon mass distribution used in the high-mass resonance search illustrated in Figure 2 (e). The independent results are combined by adding the significance at each mass point for all the channels in quadrature:

$$Z_{\text{combined}} = \sqrt{(Z_{\text{gg}F})^2 + (Z_{\text{VBF,ATLAS}})^2 + (Z_{\text{VBF,CMS}})^2 + (Z_{2\mu})^2}. \quad (4)$$

The observed local p_0-values as a function of m_H at different Γ are shown in Figures 3. The dashed horizontal lines correspond to the local significance levels. Figure 3 (a) shows the a maximum local 4σ deviation from the SM prediction in favour of SM+BSM hypothesis, with Γ taken as the narrow width approximation ($\Gamma = 0$ GeV). Figures (b), (c) and (d) show the observed local p_0-values as a function of m_H at $\Gamma = 2\% \times m_H$, $5\% \times m_H$ and $8\% \times m_H$ GeV, respectively.

From the results in Figure 3 it can be seen that the heavy scalar resonance seems to be a double humped structure located at around 237 GeV and 265 GeV for small decay widths. The resonance remains above 3σ when the decay width is being increased, hinting that the resonance might also be broad one located between 236 and 280 GeV.

4. Conclusions

From the results shown in the above section it is evident that the published LHC multi-lepton results show discrepancies in the 235 - 280 GeV region. The largest deviation from the SM-only hypothesis is observed at 267 GeV using the narrow width approximation. The observed local 4σ deviation should be treated as a lead to where future searches can optimise their event selection to search for a BSM signal originating from the decay of a heavy scalar boson may participate in the electroweak symmetry breaking mechanism.

The results obtained for small decay widths showed a possibility that the resonance might be a double humped structure located at around 237 GeV and 265 GeV. The signal does not completely disappear when the decay width is increased to larger widths also hinting that it is possible that we are actually looking at a broad excess in the 236-280 region. Further studies will shed light on the nature of these structures.

5. References

[1] Aad G *et al.* (ATLAS) 2012 *Phys. Lett.* **B716** 1–29 (*Preprint* `1207.7214`)

[2] Chatrchyan S *et al.* (CMS) 2012 *Phys. Lett.* **B716** 30–61 (*Preprint* `1207.7235`)

[3] Ahmad M (CMS) 2016 *Acta Phys. Polon.* **B47** 1365–1377

[4] Gemme C (ATLAS Collaboration) 2016 Latest ATLAS results from Run 2 Tech. Rep. arXiv:1612.01987 CERN Geneva URL `http://cds.cern.ch/record/2241217`

[5] von Buddenbrock S, Chakrabarty N, Cornell A S, Kar D, Kumar M, Mandal T, Mellado B, Mukhopadhyaya B and Reed R G 2015 (*Preprint* `1506.00612`)

[6] von Buddenbrock S, Chakrabarty N, Cornell A S, Kar D, Kumar M, Mandal T, Mellado B, Mukhopadhyaya B, Reed R G and Ruan X 2016 *Eur. Phys. J.* **C76** 580 (*Preprint* `1606.01674`)

[7] von Buddenbrock S, Cornell A S, Fang Y, Fadol Mohammed A, Kumar M, Mellado B and Tomiwa K G 2019 (*Preprint* `1901.05300`)

[8] von Buddenbrock S, Cornell A S, Fadol A, Kumar M, Mellado B and Ruan X 2018 *J. Phys.* **G45** 115003 (*Preprint* `1711.07874`)

[9] Aaboud M *et al.* (ATLAS Collaboration) 2018 *Eur. Phys. J.* **C78** 293 (*Preprint* `1712.06386`)

[10] Sirunyan A M *et al.* (CMS Collaboration) 2019 Measurements of properties of the Higgs boson in the four-lepton final state in proton-proton collisions at $\sqrt{s} = 13$ TeV Tech. Rep. CMS-PAS-HIG-19-001 CERN Geneva URL `https://cds.cern.ch/record/2668684`

[11] Sirunyan A M *et al.* (CMS Collaboration) 2017 Search for a new scalar resonance decaying to a pair of Z bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV Tech. Rep. CMS-PAS-HIG-17-012 CERN Geneva URL `https://cds.cern.ch/record/2296714`

[12] Aad G *et al.* (ATLAS Collaboration) 2019 *Phys. Lett.* **B796** 68–87 (*Preprint* `1903.06248`)

[13] Djouadi A 2008 *Phys. Rept.* **459** 1–241 (*Preprint* `hep-ph/0503173`)

[14] Cranmer K, Lewis G, Moneta L, Shibata A and Verkerke W (ROOT Collaboration) 2012 HistFactory: A tool for creating statistical models for use with RooFit and RooStats Tech. Rep. CERN-OPEN-2012-016 New York U. New York URL `https://cds.cern.ch/record/1456844`

[15] Antcheva I *et al.* 2009 *Comput. Phys. Commun.* **180** 2499–2512 (*Preprint* `1508.07749`)

[16] Cowan G, Cranmer K, Gross E and Vitells O 2011 *Eur. Phys. J.* **C71** 1554 [Erratum: Eur. Phys. J.C73,2501(2013)] (*Preprint* `1007.1727`)