Search for a heavy pseudo-scalar decaying into a Z boson and another heavy scalar boson leading to four lepton final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

Onesimo Mtintsilana[1], Abdualazem Fadol[1,2], Humphry Tlou[1], Bruce Mellado[1] and Xifeng Ruan[1]

[1] School of Physics and Institute for Collider Particle Physics, Wits, Johannesburg, Wits 2050, South Africa
[2]Institute of High Energy Physics Chinese Academy of Sciences, 19B Yuquan Road, Shijingshan District, Beijing
[3] iThemba LABS, National Research Foundation, PO Box 722, Somerset West 7129, South Africa

E-mail: onesimo.mtintsilana@cern.ch

Abstract. A current study showed that a simplified model predicting a 270 GeV heavy scalar (H) that decays to a Standard Model (SM) Higgs boson in association with a 150 GeV scalar singlet (S) may accommodate numerous anomalous multi-lepton observations in proton-proton (pp) collisions at the Large Hadron Collider (LHC). With this in mind, the purpose of this article is to provide a search for a heavy resonance pseudo-scalar, A, which decays into a Z boson and another heavy scalar boson, H. The $H \to SS$ decay mode will be investigated with at least four leptons in the final state, using a data sample corresponding to an integrated luminosity of 139 fb^{-1} from pp collisions at $\sqrt{s} = 13$ TeV.

1. Introduction

The discovery of a Higgs-like scalar [1, 2] at the Large Hadron Collider (LHC) has offered up a new window of opportunity for particle physics. Following its discovery, many studies have been done to better understand the boson's couplings to particles in the Standard Model (SM) and beyond Standard Model (BSM), as well as to search for new bosons. So far, conclusive proof for any of these BSM hypotheses has proved elusive. Many dedicated investigations are being undertaken within the LHC experimental collaborations to look for such evidence. Recently, in an effort uncover evidence of BSM physics, the ATLAS experiment conducted a model-independent study [3] in events involving three or four leptons.

Simple extensions of the SM include the two-Higgs doublet models (2HDM) [4, 5], which require the inclusion of an additional Higgs-doublet. Due to this additional doublet, the scalar spectrum contains two CP-even (h, H) scalar bosons, one CP-odd (A), and charged $(H^{\pm})$ scalar bosons. However, as shown in Ref. [6, 7], a 2HDM alone cannot incorporate certain characteristics of the data. An early 2015 research looked at the potential of a heavy scalar, H, being consistent with various LHC Run 1 measurements [8]. Following a discussion of the results in Ref. [8] the next step was to investigate the idea of introducing a scalar mediator S (rather than utilizing effective vertices), so that H might decay to Sh, SS, and hh [6]. The S was supposed to have globally re-scaled Higgs-like couplings, allowing for constant branching ratios (BRs). In this configuration, particularly in light of the observations in Ref. [9], which ruled out a 100% branching ratio of S into Dark Matter, multi-lepton final states became a focus. These couplings are supposed to be suppressed by some undefined BSM physics, resulting in a Higgs-like hierarchy of relative couplings to the SM particles. Although S is not generated directly with a large cross section, its BRs should be identical to those of an SM-like Higgs boson with a larger mass. This significantly decreases the model's number of free parameters. If this is the case, then when the mass of S approaches $\sim 2m_W$, it should decay more strongly to W and Z boson pairs. As a result of the gauge boson decays, S becomes a source of many leptons. The potential of embedding H into a 2HDM was also explored, with the model's permitted parameter space stated in Ref. [6, 10]. Furthermore, a predicted set of possible search channels for the new scalars was demonstrated. Several of these predictions have been tested and elaborated upon in Ref. [11, 12]. As such, the BSM scenario discussed in Ref. [11] is of special importance here.

The parameters of the model were fixed in 2017 in order to further investigate outcomes with more data and new final states while minimizing biases and look-elsewhere effects. This includes assigning the scalar masses to $m_H = 270$ GeV and $m_S = 150$ GeV, treating S as an SM Higgs-like scalar, and assuming that the decays $H \to Sh, SS$ are dominant. Excesses in opposite sign di-leptons, same-sign di-leptons, and three leptons were reported in Ref. [13], with and without the presence of b-tagged hadronic jets. Furthermore, CMS and ATLAS have reported $t\bar{t}$ and $Zb\bar{b}$ final state [14] excesses that may be interpreted with $m_A \approx 600$ GeV using the aforementioned model. As a result, the 2HDM+S model with the parameters derived in Ref [12] may accommodate the LHC excesses reported in Ref. [15]. Additional excesses in the Zh spectrum and the production of three leptons plus two b-tagged jets can be explained without changing these parameters, assuming $m_A \approx 600$ GeV. The conclusions from these studies further reinforce the relevance of multi-lepton final states in the search for new bosons.

Due to the impossibility of analyzing all possible final states that may contain potential for discovery, we shall build on the phenomenology found in Ref. [6, 12]. We present an introduction to a study of the production of A via the gluon-gluon fusion (ggF) mode and its decay into the AZH channel, taking into account the decay mode $H \to SS$. This configuration results in the final state containing four leptons.

2. $A \to ZH \to 4\ell$ search

The model described in Ref. [6] is a 2HDM with an additional real singlet Φ_s, and it serves as the foundation for our formalism. We will build on the phenomenology given in Ref. [11] and focus is on the production of A via the ggF mode and its decay into $A \to ZH \to 4\ell$ channel as shown in Figure 1. In the scenario considered here, Z decays further into two opposite-sign leptons, while the other two leptons are produced by the HSS decay mode, in which one of the S's decays to a positively charged lepton and the other to a negatively charged lepton. The resulting kinematics of the decay of $A \to ZH$, where $m_A > m_Z + m_H$ and $H \to SS$, have been explored in Ref. [11].

For the purpose of interpreting the $H \to SS$, H denotes the heavy Higgs boson with mass m_H= 270 GeV, S and Z are considered to have fixed masses of 150 GeV and 91.190 GeV, respectively. The masses were chosen based on the best-fit values obtained from previous research [11, 8]. Fixing these parameters based on the outcomes of entirely different data-

SAIP2021 Proceedings

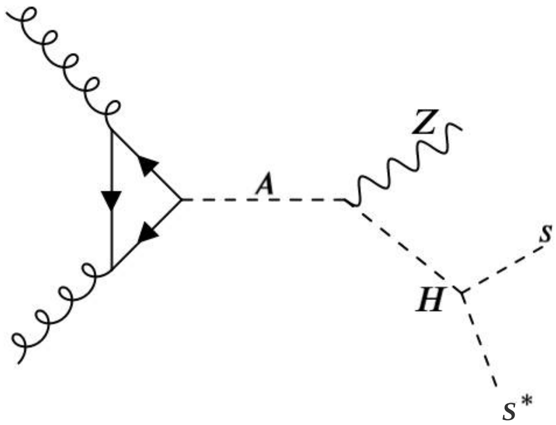


Figure 1. The representative Feynman diagram for the production mode of A and its subsequent decay to SS via gluon fusion (ggF) production mode.

Table 1. This table outlines the preselection cuts applied.

	Trigger
	At least 1-lepton matched to triggering-lepton
	Each lepton must have p_T^l >10 Gev
	Events with SFOS require m_μ >12 GeV
	Require exactly four leptons with total charge equal zero
Preselection	Leptons require loose identification and isolation criteria
	$\|\eta^e\| < 2.47$, excluding $1.37 < \|\eta^e\| < 1.52$
	$\|\eta^\mu\| < 2.5$
Categories	1-SFOS

sets allows us to prevent possible bias in adjusting the masses to reproduce data excesses. As a result, because no additional masses are considered, a "look elsewhere effect" is not required to quantify a global relevance in fits.

The mass of H was calculated using data from the LHC Run 1 experiment, which included distortions in the Higgs boson spectrum [16], searches for di-Higgs and di-boson resonances [16], and measurements on the rate of top associated Higgs production [16]. Likewise, the mass of S is set at 150 GeV based on the best-fit point in the statistical study described in Ref. [11].

3. Monte Carlo samples

The data used in this study corresponds to the entire Run II of the LHC. This was collected by the ATLAS detector between 2015 and 2018 at $\sqrt{s} = 13$ TeV with stable beam conditions and all detector systems running normally. The data sample has an integrated luminosity of 139.0 fb^{-1} after data-quality requirements. Madgraph5_aMC@NLO [17] interfaced with PYTHIA 8 [18] is used for the showering and hadronisation with A14 tune NNPDF23LO PDF set [19] and EvtGen was used to simulate B-hadron decays. Background processes such $q\bar{q} \rightarrow ZZ, q\bar{q} \rightarrow ZZ(EW), VVV$ and Z+jets are simulated with SHERPA 2.2.2 and the NNPDF30NNLO parton distribution function (PDF) set. POWHEG-BOX v2 with NNPDF30NNLO PDF set was used to produce the $t\bar{t}$ events.

Table 2. Summary of the yield calculations for different background categories.

	$qqZZ$	$ggZZ$	$qqZZEW$	$Z + jets$	VVV	ttV	$t\bar{t}$	WZ	Total
4ℓ	4228.96	25.99	107.34	5645.82	31.28	435.29	2651.21	110.18	13236.10
1-SFOS	104.50	0.36	1.32	896.55	13.89	213.31	1312.53	53.14	2595.64
1-SFOS & $\|m_z - m_{34}\|$ <15 GeV	75.34	0.30	0.83	705.45	12.82	170.48	273.84	36.75	1275.81
1-SFOS & $\|m_z - m_{34}\|$ >15 GeV	29.20	0.06	0.49	191.10	1.07	42.83	1038.69	16.39	1319.83

4. Event Selection

The preselection cuts used are shown in Table 1. In general in HZZ, each channel four-lepton candidates are generated by identifying a lepton-quadruplet composed of two same-flavour, opposite-sign lepton pairs (SFOS), as reported in Ref [20]. However, for the purposes of our analysis, we solely examine 1-SFOS events. We eliminate all 2-SFOS events and only examine the following pairings: $e\mu 2e/e\mu 2\mu$ Each electron must have a $p_T > 7$ GeV and be measured in the $|\eta|$ <2.47 pseudorapidity range. The highest-$p_T >$ lepton in the quadruplet must satisfy $p_T > 20$ GeV, and the second lepton in $p_T >$ order must have $p_T > 15$ GeV. If assigning leptons to pairs is ambiguous, only one quadruplet per channel is chosen by keeping the quadruplet with the invariant mass of the lepton pairings closest (leading pair) and second closest (subleading pair) to the Z boson mass, with invariant masses referred to as m_{12} and m_{34}, respectively. m_{12} must satisfy 50 GeV $< m_{12} <$ 106 GeV and m_{34} must satisfy 50 GeV$< m_{34} <$ 115 GeV in the chosen quadruplet.

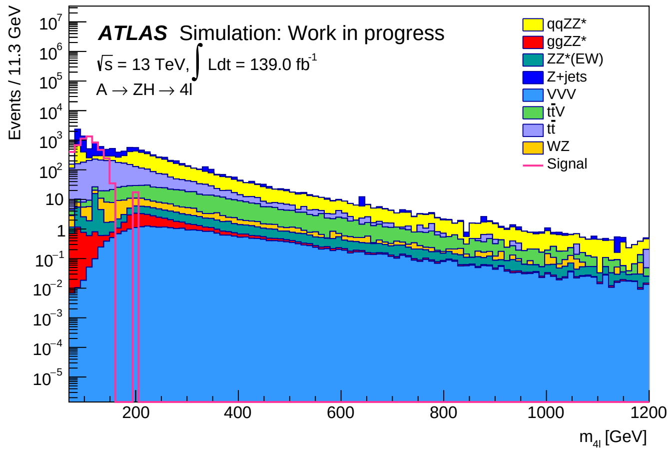
5. Results

Before one begins to construct a model to separate signal and background, it is important to check that the MC simulation with which the model is construsted, actually reflects the true distributions of the data. This section will present the results for both signal and background events. The preceding section's set of event selection cuts are used to assist us identify the signal events and determine how much of the background is needed to be removed while avoiding inadvertently removing signal events. Figure 2 shows the transverse mass ($m_{4\ell}$) and the transverse momentum ($p_T^{4\ell}$) distribution for the four leptons for both the signal and background events.

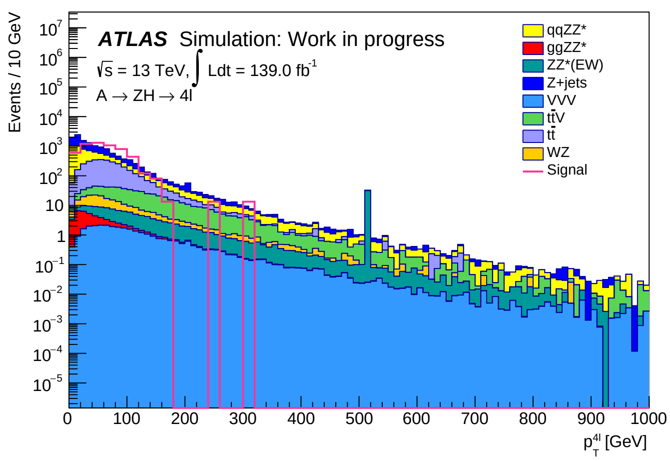
In order to separate the signal from the different background concentrations, more complex techniques will have to be introduced and applied to each category to deal with specific background events that need to be separated. As seen in Table 2, the concentrations for certain processes are different per category, with the Z+jets background being dominant. The events are tested for 1-SFOS ($e\mu 2e/e\mu 2\mu$) and also with a cut in the m_Z ($|m_z - m_{34}|$ <15) GeV and also outside the m_Z ($|m_z - m_{34}|$ >15) GeV mass window. Outside the m_Z mass window we are looking for lepton pairs ($m_{\ell\ell}$) from other processes other than the Z boson. It is worth noting that, owing to the lepton pairing technique used here, m_{34} is the leading lepton pair rather than the well-known m_{12}.

Additionally, the event yields were computed after the aforementioned standard selection criteria are applied. The signal events are generated to provide the event topology with a lepton pair decaying from the associated Z boson and at least another two same sign or different flavor leptons. The background yields were either obtained from MC for the ZZ continuum, or using data driven techniques for the reducible contributions, as described previously.

Table 2 shows that the total number of events generated for the background, after the 4ℓ selection is 13236.10. When the 1-SFOS cut is implemented, the number of events decreases



(a)



(b)

Figure 2. Signal and background events for the transverse momentum ($p_T^{4\ell}$) and transverse mass ($m_{4\ell}$) of the 4ℓ respectively.

by about 80%, as expected. This is because the events with two Z candidates will be removed, while events with a Z boson candidate and a non-Z boson pair will be kept.

6. Conclusion

The BSM scenario presented in this article introduces a search for a heavy pseudo-scalar decaying into a Z boson and another heavy scalar boson leading to four lepton final states in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector. This is an attempt to explain a number of features of the Run 1 data, which persist in the Run 2 data as explained in Ref. [**?**].

MC simulation samples are used to model the background and signal processes for this search. The decay process analysed was the $gg \to A \to ZH$.

The decay $A \to ZH$ leads to interesting final states, as pointed out earlier. For the sake of simplicity, here we considered the case where S decays to 2ℓ and Z to the other 2ℓ pairs.

A comparison of the 4ℓ between the background and signal has been shown. The background study shows after the exact 1-SFOS selection the major background will be significantly suppressed, while the features of part of the signal will be kept. The study is still on going to optimise the parameter spaces for the signal production.

Acknowledgments
Onesimo Mtintsilana acknowledges the funding support by the National Research Fund (NRF).

References

[1] Englert F and Brout R 1964 *Phys. Rev. Lett.* **13** 321–323
[2] Higgs P W 1964 *Phys. Rev. Lett.* **13**(16) 508–509
[3] Aad G *et al.* (ATLAS) 2021 (*Preprint* 2107.00404)
[4] Lee T D 1973 *Phys. Rev. D* **8** 1226–1239
[5] Branco G C, Ferreira P M, Lavoura L, Rebelo M N, Sher M and Silva J P 2012 *Phys. Rept.* **516** 1–102 (*Preprint* 1106.0034)
[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. C* **76** 580 (*Preprint* 1606.01674)
[7] Kumar M, von Buddenbrock S, Chakrabarty N, Cornell A S, Kar D, Mandal T, Mellado B, Mukhopadhyaya B, Reed R G and Ruan X 2016 *61st Annual Conference of the South African Institute of Physics* pp 507–511 (*Preprint* 1608.03466)
[8] 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)
[9] Aaboud M *et al.* (ATLAS) 2017 *Phys. Rev. D* **96** 112004 (*Preprint* 1706.03948)
[10] von Buddenbrock S and Mellado B 2019 *64th Annual Conference of the South African Institute of Physics* (*Preprint* 1909.04370)
[11] von Buddenbrock S, Cornell A S, Fadol A, Kumar M, Mellado B and Ruan X 2018 *J. Phys. G* **45** 115003 (*Preprint* 1711.07874)
[12] von Buddenbrock S, Cornell A S, Iarilala E D R, Kumar M, Mellado B, Ruan X and Shrif E M 2019 *J. Phys. G* **46** 115001 (*Preprint* 1809.06344)
[13] Buddenbrock S, Cornell A S, Fang Y, Fadol Mohammed A, Kumar M, Mellado B and Tomiwa K G 2019 *JHEP* **10** 157 (*Preprint* 1901.05300)
[14] Sirunyan A M *et al.* (CMS) 2020 *JHEP* **04** 171 (*Preprint* 1908.01115)
[15] Aaboud M *et al.* (ATLAS) 2018 *Phys. Lett. B* **783** 392–414 (*Preprint* 1804.01126)
[16] Aad G *et al.* (ATLAS) 2014 *JHEP* **09** 112 (*Preprint* 1407.4222)
[17] Alwall J, Herquet M, Maltoni F, Mattelaer O and Stelzer T 2011 *JHEP* **06** 128 (*Preprint* 1106.0522)
[18] Sjöstrand T *et al.* 2015 *Comput. Phys. Commun.* **191** 159–177 (*Preprint* 1410.3012)
[19] Ball R D *et al.* (NNPDF) 2015 *JHEP* **04** 040 (*Preprint* 1410.8849)
[20] Aad G *et al.* (ATLAS) 2021 *Eur. Phys. J. C* **81** 332 (*Preprint* 2009.14791)