Search for a heavier Higgs like boson and a dark force boson using ATLAS experimental data.

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Abstract. This paper presents the search for the Higgs boson, with mass 125 GeV, decaying to two new intermediate states and then into four lepton final states, $H \to Z_d Z_d \to 4l$. The analysis is conducted using the Run 2 data set from pp collisions collected with the ATLAS detector corresponding to a total integrated luminosity of 140fb^{-1} at a centre of mass energy of $\sqrt{s} = 13TeV$. A study on modifying the signal region has been conducted, assuming a broader width on the Z_d. It was found that the broader signal region has a minimal effect on the local p-value.

1 Introduction

Astronomers have made several observations in the cosmos which point to the existence of dark matter. These include observations of Einstein rings, which form as a result of gravitational lensing [1]. In addition, astronomers have observed discrepancies between the theoretical and observed radial velocities of spiral galaxies [2]. Both of these observations, among others, point to the existence of dark matter in the cosmos. However, the Standard Model (SM) is unable to explain the occurrence of dark matter [3]. The Higgs boson could be a portal into the dark sector that appears in many extensions of SM. The dark sector would provide candidates for the dark matter observed in the universe. The proposed search overlaps with a well studied SM process $H \to ZZ^* \to 4\ell$.

A dark sector would appear by adding a broken $U(1)_d$ gauge symmetry coupled to the SM through mixing with the hypercharge gauge boson via the kinetic mixing parameter. [4, 5]. The SM Higgs boson may mix with the dark sector Higgs boson if the introduction of a dark Higgs breaks the $U(1)_d$ gauge symmetry. The Higgs portal coupling parameter κ controls this mixing in this scenario. The lighter partner of the extended sector, which would also decay via the dark sector would be the observed Higgs, providing candidates for dark matter that account for both direct and indirect astronomical observations [6].

The published Run 2 results of the search for the Higgs boson decaying to four leptons via two Z_d bosons using pp data at $\sqrt{s} = 13$ TeV with an integrated luminosity of 36.1 fb^{-1} collected at the ATLAS experiment [7] are presented in this paper [8]. In this search, we consider the Z_d bosons that decays to muon and electron same flavor pairs,where the final states include $4e$, $2e2\mu$, and 4μ. We emphasise the adjustment made to a previous event selection cut in the signal region which yielded a slight excess of 13 observed events for a background of 7.7 ± 0.1 in the 2015+6+7 iteration of the analysis.

Section 2 gives a brief description of the ATLAS detector together with a description of the triggers, pre-selection, event selection criteria and Monte Carlo simulation of the signal and background used in the analysis. Section 3 describes contributions of various processes to the background together with systematics uncertainties. Section 4 describes the results of the analysis while Section 5 presents the conclusion of the paper.

2 Experimental Setup

The ATLAS detector is a general purpose physics detector that has a cylindrical geometry which is symmetric and covers almost 4π solid angle.

The events must contain one primary vertex [9] where the transverse momentum of two or more track must be $p_T > 400$ MeV. Tracks that have too much noise in the calorimeter are rejected according to a cleaning criteria. In addition, the events have to adhere to the event selection criteria outlined in Table 1 where m_{12} and m_{34} are the leading and sub-leading dilepton pair masses, respectively.

Table 1: Summary of the event selection [8].

Object	$\boldsymbol{H \rightarrow Z_d Z_d \rightarrow 4\ell}$
Quadruplet selection	-Require at least one quadruplet of leptons consisting of two pairs of same-flavor opposite-charge leptons - Three leading-p_{T} leptons satisfy $p_{\mathrm{T}} > 20$ GeV, 15 GeV, 10 GeV. - At least three muons are required to be reconstructed by combining ID and MS tracks in the 4μ channel. - Leptons in the quadruplet responsible for firing at least one trigger - $\Delta R(\ell, \ell') > 0.10$ (0.20) for all same (different) flavor leptons in the quadruplet
Quadruplet ranking	-Select quadruplet with smallest $\Delta m_{\ell\ell} = \lvert m_{12} - m_{34} \rvert$
Event selection	-Reject event if: $(m_{J/\Psi} - 0.25 \text{ GeV}) < m_{12,34,14,23} < (m_{\Psi(2S)} + 0.30 \text{ GeV})$ $(m_{\Upsilon(1S)} - 0.70 \text{ GeV}) < m_{12,34,14,23} < (m_{\Upsilon(3S)} + 0.75 \text{ GeV})$ - $m_{34}/m_{12} > 0.85$ - 115 GeV $< m_{4\ell} <$ 130 GeV - 10 GeV $< m_{12,34} <$ 64 GeV - 5 GeV $< m_{14,32} <$ 75 GeV for $4e$ and 4μ channels

Simulated event samples generated using Monte Carlo are used to estimate the SM background and model the signal process which are then passed through a simulation of the ATLAS detector which uses Geant4 [10, 11]

2.1 Signal

The Hidden Abelian Higgs Model (HAHM) is used to generate the $H \rightarrow Z_d Z_d \rightarrow 4\ell$ signal process [12] in MadGraph5 [13] interfaced with Pythia8 [14] to model the parton shower, hadronisation and underlying event. The mass of the Z_d is varied between 15 GeV and 60 GeV for different signal hypotheses in steps of 5 GeVfor the process $H \rightarrow Z_d Z_d \rightarrow 4\ell$. The production mode under consideration for the Higgs is gluon-gluon-Fusion (ggF) where the mass of the Higgs is set to $m_H = 125$ GeV. The next-to-next-to-next-to-leading-order (N3LO) cross-section of the samples is normalized to $\sigma_{SM}(ggF) = 48.58$ pb as recommended in [15].

2.2 Backgrounds

- $H \to ZZ^* \to 4\ell$**:** Higgs that are produced through ggF [16] are simulated using POWHEG-BOX v2 MC event generator [17] while vector boson fusion (VBF) [18] and vector boson (VH) [19] processes are simulated using the PDF4LHC NLO PDF set [20]. For Higgs production through heavy quark pair annihilation, MADGRAPH5_aMC@NLO [21] is used to simulate the events while CT10nlo PDF set [22] for $t\bar{t}H$ and the NNPDF23 PDF set [23] for $b\bar{b}H$. PYTHIA8 [24] is used to model the ggF, VBF, VH, and $b\bar{b}H$ production mechanisms for the $H \to ZZ^* \to 4\ell$ decay process and the AZNLO parameter set for modelling parton showering, hadronisation and multiple parton interactions. HERWIG++ [25] and the UEEE5 parameter set [26] are used to model $t\bar{t}H$ showering.

- $ZZ^* \to 4\ell$**:** SHERPA 2.2.2 was used to model the non-resonant SM $ZZ^* \to 4\ell$ processes for quark anti-quark annihilation [27–29], using the NNPDF3.0 NNLO PDF set. GG2VV interfaced with PYTHIA8 was used to model the loop induced gg initiated ZZ^* production. Double counting was avoided by omitting the s-channel H diagrams using the CT10 PDFs. The latter process, which received large QCD corrections at NLO, was it was calculated at LO. Therefore, the sample was multiplied by an NLO/LO K-factor of 1.70 ± 0.15 [30]. This background contributes approximately 30% of the total background prediction.

- VVV/VBS are modeled using SHERPA 2.1 with the CT10 PDFs. These processes have cross-sections proportional to α^6 at leading order (LO) which include triboson production and vector boson scattering. This leads to four lepton final states that include two additional particles (electrons and muons or quarks). Some duplicates in this background are avoided by subtracting Higgs production through VBF from the estimates obtained with this generator. This background accounts for approximately 17% of the total prediction for the background of the high and low mass selections respectively.

- $Z{+}(t\bar{t}/J/\psi/\Upsilon) \to 4l$**:** The Z boson produced via a quarkonium state ($b\bar{b}$ or $c\bar{c}$) that decays to four leptons are simulated using PYTHIA8 with the NNPDF 2.3 PDFs while $t\bar{t}H$background was generated with POWEHEG-BOX interfaced to PYTHIA6 [31] for parton shower and hadronisation and underlying event.

- **Other Background** Jets can be misidentified as leptons which are produced by $Z+$jets $t\bar{t}$ and WZ that decay to less than four prompt leptons but include jets. $Z+$jets processes are modeled using SHERPA 2.2, while the production of $t\bar{t}$ is generated with POWHEG-BOX interfaced to PYTHIA6 [31] for parton shower and hadronisation. In addition, POWHEG-BOX interfaced to PYTHIA8 and the CTEQ6L1 is used to model the WZ production.

3 Analysis procedure

3.1 Original signal region cut

The previous MSR cut was defined in [8], used the narrow width mentioned in the HAHM model. This kinetic mixing parameter ϵ and the vector boson width are related with a scaling $\Gamma_{Z_d} \sim \epsilon$, where the point (Γ_{Z_d}, ϵ) corresponds to the mass $m_{Z_d} = 20$ GeV. In order to have maximal kinetic mixing, the kinetic mixing parameter $\epsilon = 0.03$ which corresponds to prompt decay of the dark vector boson having masses in the range 10 GeV $< m_{Z_d} <$ 50 GeV. This then gives the broadest expectation of the vector boson width to be $\Gamma_{Z_d} < 0.025$MeV. Since this width is too narrow for the detector to observe, the observed width would be the detector resolution. Figure

1 shows a scatter plot for the Run 2 [32] data taking where the previous signal region cut was used.

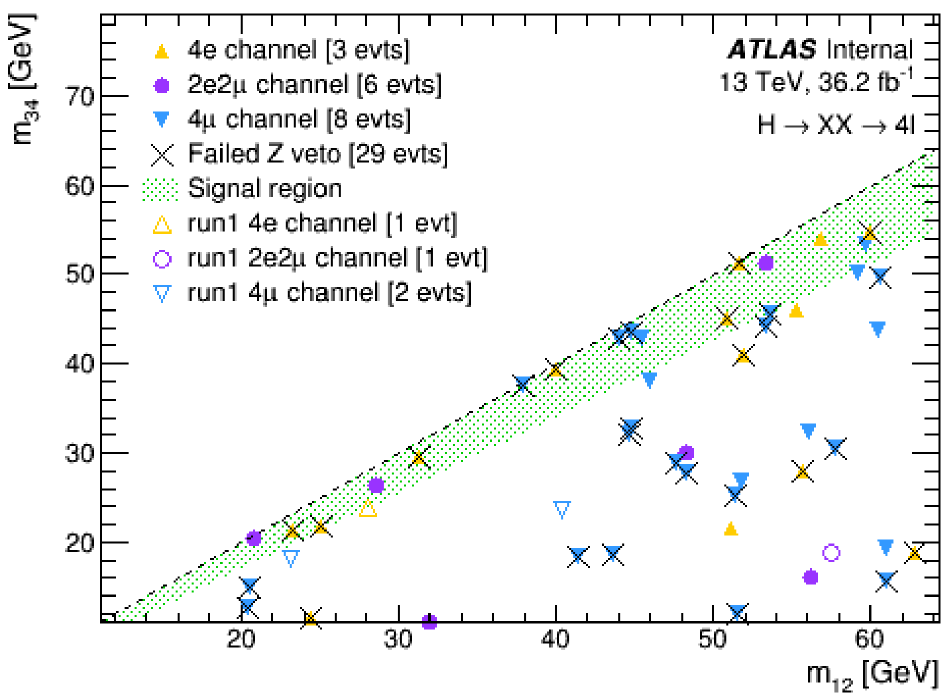

Figure 1: Scatter plot of the m_{12} vs m_{34} plane in the HM search. The shaded region represents events that are admitted in the previous MSR. The crossed out events indicated those that failed the Z boson veto cut. The 2015-6 in the previous MSR ($m_{34}/m_{12} > 0.85$) were internally unblinded [8].

The detector's lepton energy resolutions over the region of interest are given by $\Delta E_e \sim 3.5\%$ and $\Delta E_\mu \sim 3.8\%$. A 2σ window would then correspond to 13 GeV(14%) for electrons and 10 GeV(11.2%) for muons. Therefore, the m_{34}/m_{12} wedge cut listed in Table 1 corresponds to 15% for both electrons and muons when reconstructing dilepton masses. This cut seems to be optimal in the context of broadening the MSR.

3.2 Broadening the signal region cut

We observed in the previous iteration of the analysis [33] that the expected background in the MSR had few events for low Z_d masses. We therefore tested the sensitivity of the signal strength parameter μ_d to different width values of the MSR for various Z_d masses. We found that the local significance has a weak dependence on the MSR width for low masses m_{Z_d}. However, dependence grew stronger for values where $m_{Z_d} > 35$ GeV which indicates that we can modulate the MSR according to the background shape such that the cut could be 3.5σ at 10 GeVand decrease as the background increases so that it reverts to the previous MSR cut of 2.0σ where the background is most prominent, giving rise to a new MSR cut [8] expressed by Equation 1

$$m_{34} > 0.85m_{12} - 0.1125 \times f(m_{12}) \times m_{12} \tag{1}$$

where $f(m_{12})$ is the modulating function constructed using the parametrically fitted background shape. This new cut is represented by the new MSR shape shown in Figure 2

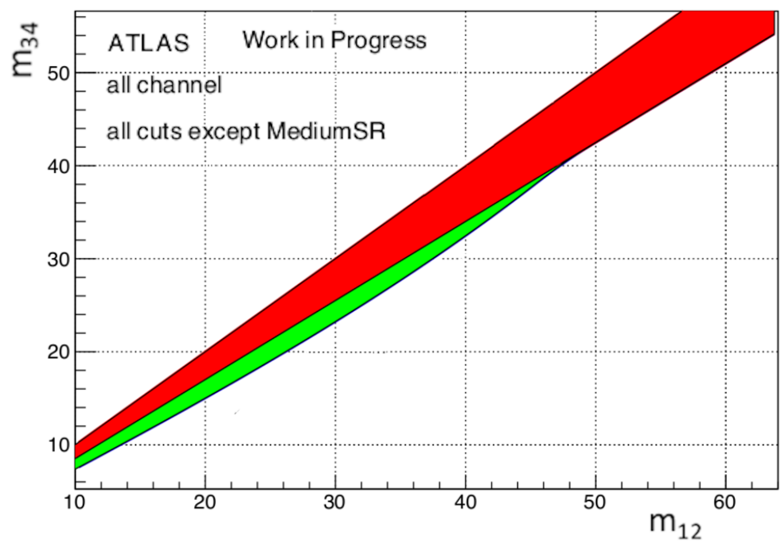

Figure 2: The new signal region is shown by green region while the old signal region is shown by the red region.

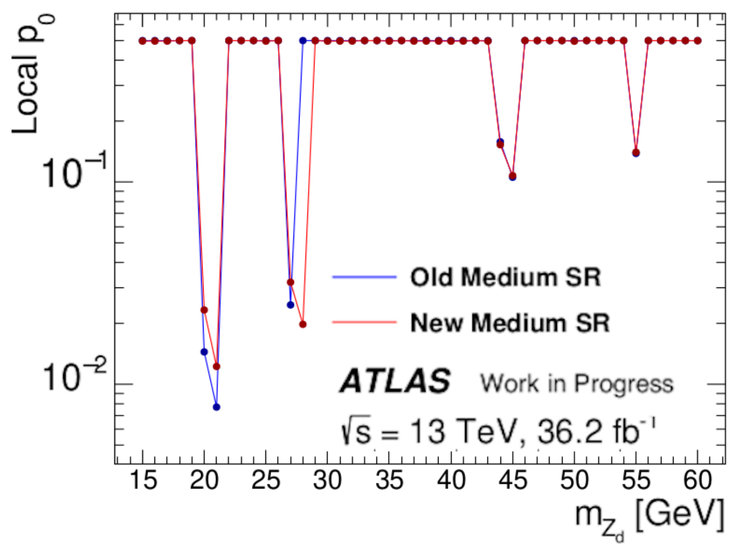

Figure 3: The old (blue) and the new (red) local p_0 value over the high-mass m_{Z_d} range.

4 Results

We tested the new signal region's impact on discovery by calculating the local p_0 value over the high-mass m_{Z_d} range with 2015-6 signal and data distributions in the i) new signal region and ii) old signal region. Figure 3 shows the p-values for the old signal region (blue) and the new signal region (red). The local p-value increases at around 20 GeVdue to an increase in background events. The discrepancy between the new and old p-value at 28 GeVis due to convergence failure in the asymptotic calculator when calculating the p-value for the old signal region. Therefore, it is evident that the impact of the new signal region on the local p-value is minimal. However, for new data in the forthcoming analysis, the new MSR cut should enhance the p0 sensitivity.

5 Conclusion

We presented a dedicated search for the exotic decays of the SM Higgs boson of mass 125 GeVdecaying to two dark vector bosons which decay to two leptons each in this proceedings article. Particular emphasis was placed on re-optimizing the MSR. A modulated MSR shape was constructed with a 3.5σ width at 10 GeV, where the background has vanishingly few events and decreases to the original 2.0σ width at 49.64 GeVwhere there is much background present. It was subsequently found that the new MSR has a minimal effect on the local p-value for the present dataset. This new re-optimized signal region will be unblinded in order to quantify the amount of signal yield that is observed as a result of it and its effect on the statistical limits on various parameters of interest. It is expected that the new MSR will accommodate more signal after unblinding and thus have a more pronounced effect on the local p-value.

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