Z-dark search with the ATLAS detector

Elizabeth Castaneda-Miranda
Department of Physics, University of Johannesburg, South Africa
E-mail: elizabeth.castaneda.miranda@cern.ch

Abstract. The search of the “hidden sector” via new neutral light bosons Z-dark (Zd) could be revealed by the study of the decay of the discovered Higgs-like boson or any other undiscovered Higgs boson. After the LHC concluded a successful first period of running, The ATLAS Collaboration published its latest results on the H → ZdZd → 4l analysis using up to 20 fb⁻¹ of integrated luminosity at √s = 8 TeV. In this proceeding I present a summary of the recent results on the search of the Zd in the signature H → ZdZd → 4l with the ATLAS detector at the LHC.

1. Introduction

The H → ZdZd → 4l is an interesting search compatible with one of the main decay channels used in the discovery of the SM Higgs boson, H → ZZ* → 4l [1]. This search is motivated by many extensions to the Standard Model (SM) which provide a candidate for the dark force mediator to explain the astrophysical observations of the positron excess [2], or a candidate mediator of the “hidden or dark sector” [3, 4, 5].

This document presents the results on the Zd search, for both model independent and dependent cases. The study is based on the SM H → ZZ* → 4l [1, 6], with objective to find a significant excess in the dilepton mass region 15 ≤ mZd → ll ≤ 60 GeV, with a Higgs mass fixed mH = 125 GeV. Otherwise, 95% upper bound are set on the main parameters of interest as a function of the mZd. The information presented here is reported and published by the ATLAS Collaboration [7].

2. The ATLAS detector

It is a multipurpose detector located at point 1 at the LHC. Generally speaking, the ATLAS detector consists of four major subsystems: Inner Detector (ID), Calorimeter, Muon Spectrometer (MS) and Magnet System. These subsystems are integrated with the following components: Trigger and Data Acquisition System and Computing System [8, 9]. The coordinate system used in ATLAS is the right-handed with origin at interaction point in the center of the detector, the z-axis along the beam line and the x-y plane perpendicular to the beam line. Cylindrical coordinates (r, φ) are used in the transverse plane, φ is the azimuthal angle around the beam line. Observables labelled “transverse” are projected into the x-y plane. The pseudorapidity is defined in terms of the polar angle θ as η = − ln tan θ/2.

3. Signal and background simulation samples

The new neutral light boson is produced via the Higgs boson production (H → ZdZd → 4l) in the gluon fusion (ggF). The benchmark model used is the hidden Abelian Higgs model
Table 1. List of the background processes and their corresponding event generators, PDF’s
calculators, and their QCD and EW applied corrections. The references of the generators, used
for this study, are found in [7].

| Process | Generator | PDF   | QCD corr.          | EW corr. |
|---------|-----------|-------|--------------------|----------|
| ggFF, VBF | POWHEG+PYTHIA8 | CT10  | NLO and NNLO      | NLO      |
| WH, ZH  | PYTHIA8   | CT10  | NLO                |          |
| t\bar{t}H | PYTHIA8 | CTEQ6L1 | NLO            |          |
| q\bar{q} \rightarrow ZZ* | POWHEG+PYTHIA8 | CT10  | NLO                |          |
| gg \rightarrow ZZ* | gg2ZZ+JIMMY | CT10  | NLO                |          |
| Z+jets  | ALPGEN    | CTEQ6L1 | NLO and NNLO     |          |
| t\bar{t} | MC@NLO+HERWIG, JIMMY | CT10  | NLO                |          |
| WZ and WW | SHERPA | CT10  | NLO                |          |
| Z/\psi, Z  | PYTHIA8 | CTEQ6L1 | —             |          |

(HAHM) [3, 4, 5]. The samples are generated for $m_H = 125$ GeV and $15 \leq m_{Zd} \leq 60$ GeV, in
steps of 5 GeV, using MadGraph with CTEQ6L1 for the parton distribution functions (PDF). For
taking into account the parton showering, hadronization, and initial- and final-state radiation
PYTHIA8 and PHOTOS are used. In the $H \rightarrow Z_dZ_d \rightarrow 4l$ search, the $h \rightarrow 4l$ is normalized from
data.

The background processes considered for this study are listed in Table 1. For the SM
Higgs boson in ggF production, the QCD soft-gluon resummations, calculated in the next-
to-next-to-leading-logarithmic (NNLL) approximation, are applied. The Z+jets production,
modelled with up to five partons, is divided in two sources: Z+light-jets and Zb\bar{b}. For data and
simulation comparison, the QCD cross-section calculations (see Table 1) are used to normalize
the simulation for inclusive Z boson and Zb\bar{b} production. The Z/\psi and ZY Monte Carlo
(MC) samples are normalized using the ATLAS measurement described in [10]. The SM Higgs
productions, SM ZZ* and diboson processes are normalized with the theoretical cross-sections
and decay branching ratios as well as their uncertainties. For taking into account the different
conditions in the pileup, as a function of the instantaneous luminosity, the simulated minimum-
bias overlaid events, generated with PYTHIA onto the hard-scattering process, were used.
Such events were reweighted according to the distribution of the mean number of interactions
observed in data. All the MC background samples generated are reconstructed using the “full
detector simulation” ATLAS software [11] which is based on GEANT4 [12]. The signal samples are
reconstructed with the “fast detector simulation” ATLAS software [13] which only parametrized
the response of the electromagnetic and hadronic showers in the ATLAS calorimeter, and the
rest of the systems are reconstructed as “full detector simulation”.

4. Event selection

For this search, 20.3 fb$^{-1}$ of integrated luminosity is used which was recorded in the optimal
function of the detector. All the MC processes are normalized with integrated luminosity
mentioned. The event selection applied is the same for both data and MC. There are three
categories that are studied: 4—electrons (4e), 4—muons (4\mu) and 2—electrons 2—muons (2e2\mu).

It is requested that the (data/MC) events pass the combination of single-lepton and dilepton
triggers. Table 2 shows the list of single-lepton and dilepton triggers used, with their respective
thresholds in transverse energy/momentum. All these events must contain a reconstructed
primary vertex, defined as the vertex with highest $\sum p_T^2$ of the associated tracks, with at least
three tracks of $p_T > 0.4$ GeV each one. The muon candidates selected are formed by matching
reconstructed ID tracks with either a complete track or track-segment reconstructed in MS
[14]. The acceptance is extended using tracks reconstructed in the forward region of the MS
Table 2. Triggers used with their respective $E_T$ or $p_T$ thresholds.

| Trigger       | $E_T$ [GeV] | $p_T$ [GeV] |
|---------------|-------------|-------------|
| single-electron | 25          | —           |
| single-muon   | —           | 24          |
| dielectron    | 12          | —           |
| dimuon (symm.) | —           | 13          |
| dimuon (asymm.) | —           | 18 and 8   |
| electron-muon | 12 or 24    | 8           |

(2.5 < |$\eta$| < 2.7), which is outside the ID coverage. If both an ID or a complete MS track are present, the two independent momentum measurements are combined; otherwise the information of the ID or the MS is used alone. In the case of the electrons candidates, they must have well-reconstructed ID track pointing to an electromagnetic calorimeter cluster and the cluster should satisfy a set of identification criteria [15]. Tracks associated with electromagnetic clusters are fitted using a Gaussian-Sum Filter [15], which allows for bremsstrahlung energy losses to be taken into account. Each electron (muon) must satisfy $p_T > 7$ GeV ($p_T > 6$ GeV) and be measured in the range $|\eta| < 2.47$ ($|\eta| < 2.7$). The longitudinal impact parameters of the leptons along the beam axis $z_0$ are required to be within 10 mm of the reconstructed primary vertex (muons without ID track are exempted of this requirement). To reject the cosmic rays, muon tracks are required to have a transverse impact parameter $d_0$ (closest approach to the primary vertex in the x-y plane) of less than 1mm. For avoiding double-counting of leptons, an overlap removal is applied. If two electrons share the same ID track or within in a cone ($\Delta R \equiv \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} < 0.1$), the one with the highest transverse energy deposit in the calorimeter ($E_T$) is kept. An electron within in a muon cone ($\Delta R = 0.2$) is removed, and a calorimeter-based reconstructed muon within an electron cone ($\Delta R = 0.2$) is removed.

After selecting the leptons with proper quality, events with at least four leptons, with all possible combinations of four leptons containing two same-flavor and opposite-sign (SFOS) defined the “quadruplets”, are kept. Each lepton is ordered by $p_T$, the three highest-$p_T$ leptons should have: $p_{T11} > 20$ GeV, $p_{T12} > 15$ GeV and $p_{T13} > 10$ GeV. It is also required that at least one (two) of the lepton(s), from the quadruplet, must satisfy the single-lepton (dilepton) trigger requirements. Each dilepton invariant mass or each SFOS pair, from the quadruplet, are denoted by $m_{12}$ (formed by leptons 1 and 2) and $m_{34}$ (formed by leptons 3 and 4). For the $H \rightarrow ZdZd \rightarrow 4l$ study, both $Z_d$ boson are considered to be on-shell, because of that, there is not any distinction between the SFOS pairs. If in the event there are several “quadruplets”, only the quadruplet that satisfies the minimum value of $\Delta m \equiv |m_{12} - m_{34}|$ is selected. Subsequently, the transverse impact parameter significance (IP) and the isolation requirements are imposed to the leptons of the quadruplet selected, and four final requirements that defined the two signal regions (SR) considered in this study are shown in Table 3. In Figs. 1 and 2 show the dilepton and four-lepton invariant masses after the IP requirements, respectively, in the dilepton mass the $m_{12}$ and $m_{34}$ are combined.

5. Background estimation

For the $H \rightarrow ZdZd \rightarrow 4l$ analysis, the main background contributions are $ZZ^* \rightarrow 4l$ and $H \rightarrow ZZ^* \rightarrow 4l$ which are reduced considerably after applying the tight SR (see Table 3). Also small contribution from $Z+\text{jets}$, $t\bar{t}$, $WW$ and $WZ$ can be seen from Fig. 3. The $H \rightarrow ZZ^* \rightarrow 4l$, $ZZ^* \rightarrow 4l$, $WW$ and $WZ$ background processes are estimated from MC simulation, their normalization is based on theoretical cross-sections calculations, integrated
Table 3. Requirements after selecting the one quadruplet, and the loose and tight SR definitions.

| Requirements       | Track isolation | Calorimeter isolation | IP |
|--------------------|-----------------|-----------------------|----|
|                    | $\sum_{\text{tracks}} E_{\text{track}} (\Delta R = 0.2) < 0.15$ | $\sum_{\text{clusters}} E_{\text{cluster}} (\Delta R = 0.2) < 0.2$ (0.3 for $\mu$'s no ID 0.15) | $\sigma_{\text{IP, uncer.}} < 6.5$ for $e$'s (3.5 for $\mu$'s) |
| Loose SR           | $115 < m_4 < 130$ GeV, $|m_{Z_d} - m_{ll}| < \frac{m_H}{2}$, $m_{ll} = 125$ GeV, and $Z, J/\psi - \Upsilon$ vetoes: $|m_{Z,\Upsilon} - m_{ll}| < 10$ GeV, $m_{ll} < 12$ GeV (ll=12,34, and 23, 14) | |
| Tight SR           | Loose SR and $|m_{Z_d} - m_{ll}| < 6$ GeV (5/3/4.5 GeV for 4e/4$\mu$/2e2$\mu$) | |

Figure 1. Dilepton invariant mass $m_{ll}=12,34$ for $m_H = 125$ GeV at the IP requirements.

Figure 2. Four-lepton invariant mass for $m_H = 125$ GeV at the IP requirements.

luminosity recorded, and acceptance efficiency. In the case of zero MC background expected events, in the tight SR, 68% C.L. upper bound, which corresponds to 1.14 events [16], is estimated as $N_{\text{background}} < L \times \sigma \times \frac{14}{N_{\text{tot}}}$, where $L$ is the integrated luminosity recorded, $\sigma$ the cross-section of the background processes and $N_{\text{tot}}$ is the total number of weighted events simulated for the background processes. This background estimation is validated using a control region defined by reversing, the four-lepton invariant mass requirement ($m_{4l} < 115$ GeV or $m_{4l} > 115$ GeV), good agreement is found between the expectation and observation results [7].

6. Systematic uncertainties

The systematic uncertainties on the theoretical cross-section calculations as well as the detector uncertainties are taken into account. The PDF effects, $\alpha_s$, renormalization and factorization scale uncertainties are applied to the $ZZ^*$ backgrounds, and for all the SM Higgs productions applied on the total inclusive cross-sections, using values obtained from [17]. Uncertainties due to the limited number of MC events in the $tt$, $Z$+jets, $ZJ/\psi$, $Z\Upsilon$ and $WW/WZ$ background processes are estimated (see Sec. 5). The luminosity uncertainty [18] is applied to all signal and background yields. The detector systematic uncertainties on the electron and muons, within the acceptance on SR, are applied (see Table 4): uncertainties on electron/muon identification, reconstruction and trigger efficiency (summarized in Electron/Muon identification), on
the electron/muon energy/momentum scale, and on the electron/muon energy/momentum resolution (summarized in Electron/Muon energy/momentum scale). Also the uncertainties from the isolation and IP requirements are taken into account.

7. Results
Four data events pass after applying the loose SR requirements: one in the 4e, two in the 4µ and one in the 2e2µ channel. Only two of these events pass the tight SR: the event in the 4e and one of the events in the 4µ channel. The events in 4e and 4µ channels are consistent with the Z_d mass range $23.5 \leq m_{Z_d} \leq 26.5$ GeV and $20.5 \leq m_{Z_d} \leq 21.0$ GeV, respectively, as shown in Fig. 3. In the mass range of 15 to 60 GeV the interpolated histograms are used [19], generated, based on the MC signal simulations, in steps of 0.5 GeV to obtain the signal acceptance at the hypothesized $m_{Z_d}$. Table 5 shows the expected and observed number of events after applying the tight SR requirements. In the absence of any significant excess, the 95% C.L. upper bound is computed on the parameter of interest, the signal strength, which is defined as:

$$\mu_d = \frac{\sigma \times BR(H \rightarrow Z_dZ_d \rightarrow 4l)}{[\sigma \times BR(H \rightarrow ZZ^* \rightarrow 4l)]_{SM}}.$$  \hspace{1cm} (1)

The limits are computed for each final state and their combination for the model independent case, following the $CL_s$ modified frequentist formalism with the profile-likelihood test statistic [20]. The nuisance parameters associated with the systematic uncertainties described
Table 5. The expected and observed number of events in the tight signal region for each final state are shown. The results are for the mass regions $m_{Z_d} = 25$ and 20.5 GeV. The statistical and systematic uncertainties are given for the signal and background expected events. The $H \rightarrow ZZ^* \rightarrow 4l$ expected events are the combination of the ggF, VBF, $ZH, WH$ and $ttH$ processes.

| Process       | $4e$            | $4\mu$          | $2e2\mu$        |
|---------------|-----------------|-----------------|-----------------|
| $H \rightarrow ZZ^* \rightarrow 4l$ | $(1.5 \pm 0.3 \pm 0.2) \times 10^{-2}$ | $(1.0 \pm 0.3 \pm 0.3) \times 10^{-2}$ | $(2.9 \pm 1.0 \pm 2.0) \times 10^{-3}$ |
| $ZZ^* \rightarrow 4l$ | $(7.1 \pm 3.6 \pm 0.5) \times 10^{-4}$ | $(8.4 \pm 3.8 \pm 0.5) \times 10^{-3}$ | $(9.1 \pm 3.6 \pm 0.6) \times 10^{-3}$ |
| $WW, WZ$      | $< 0.7 \times 10^{-2}$ | $< 0.7 \times 10^{-2}$ | $< 0.7 \times 10^{-2}$ |
| $t\bar{t}$   | $< 3.0 \times 10^{-2}$ | $< 3.0 \times 10^{-2}$ | $< 3.0 \times 10^{-2}$ |
| $Zb, Z+jets$  | $< 0.2 \times 10^{-2}$ | $< 0.2 \times 10^{-2}$ | $< 0.2 \times 10^{-2}$ |
| $ZJ/\psi, Z\gamma$ | $< 2.3 \times 10^{-3}$ | $< 2.3 \times 10^{-3}$ | $< 2.3 \times 10^{-3}$ |
| Total background | $< 5.6 \times 10^{-2}$ | $< 5.9 \times 10^{-2}$ | $< 5.3 \times 10^{-2}$ |
| Data          | 1               | 0               | 0               |

in Sec 6 are profiled. The systematic uncertainties on Table 4 are 100% correlated between the signal and background. In Figs. 4 and 5 show the 95% C.L. upper bound on the $H_{4\ell}$ and on the branching ratio of $H \rightarrow Z_dZ_d \rightarrow 4l$ as a function of the mass $m_{Z_d}$ for the combination of the three final states: $4e$, $4\mu$ and $2e2\mu$; assuming the SM Higgs boson cross-section and $BR(H \rightarrow ZZ^* \rightarrow 4l)_{SM} = 1.25^{-1}$ [17].

Figure 5. The 95% C.L. upper bound on the $BR(H \rightarrow Z_dZ_d \rightarrow 4l)_{SM}$.

Figure 6. The 95% C.L. upper bound on the Higgs mixing parameter, see Eq. 2.
Higgs mixing parameter $\kappa'$ [4]:

$$\kappa' = \kappa \times \frac{m_H^2}{|m_H^2 - m_s^2|},$$  \hspace{1cm} (2)

where $\kappa$ is the size of the Higgs portal coupling and $m_s$ is the mass of the dark Higgs boson. The partial width of the $H \to Z_dZ_d$ is given in terms of $\kappa$ [4]. In the regime where the Higgs mixing parameter dominates ($\kappa \gg \epsilon$), $m_s > m_H/2$, $m_{Z_d} < m_H/2$ and $H \to Z_dZ^* \to 4l$ are negligible, the only relevant decay is $H \to Z_dZ_d$. The Higgs portal coupling parameter $\kappa$ is [4]:

$$\kappa^2 = \frac{\Gamma_{SM}(H \to Z_dZ_d)}{f(m_{Z_d}) (1 - BR(H \to Z_dZ_d))}. \hspace{1cm} (3)$$

The upper bound on the effective Higgs mixing parameter as a function of $m_{Z_d}$ is shown in Fig. 6 for $m_H/2 < m_s < 2m_H$, this corresponds to an upper bound on the Higgs portal coupling in the range $\kappa \sim (1 - 10) \times 10^{-4}$.

8. Conclusions

The search of the $Z_d$ light boson in a mass range of $15 \leq m_{Z_d} \leq 60$ GeV, via $H \to Z_dZ_d \to 4l$ with $m_H = 125$ GeV, is presented at $\sqrt{s} = 8$ TeV. Two data events in the tight SR are observed in 4e and 4$\mu$ final states: 4e, $m_{Z_{\text{d1,2}}} = 21.8$, 28.1 GeV and 4$\mu$, $m_{Z_{\text{d1,2}}} = 23.2$, 18.0 GeV. Since there is not significant excess observed, the 95% C.L. upper bound on the $\mu_d$, and on the $BR(H \to Z_dZ_d \to 4l)$ are set, combining the three final states. For the mass range $20 \leq m_{Z_d} \leq 28$ GeV, in the model independent case, the upper bounds for $\mu_d$ are $(18 - 27) \times 10^{-2}$; in case of the model depending study, the upper bound for the $BR(H \to Z_dZ_d \to 4l)$ is $(2.1 - 3.2) \times 10^{-5}$, and the upper bound on the Higgs mixing parameter is $(5.0 - 6.5) \times 10^{-4}$ (see Fig. 4, 5 and 6).

8.1 Acknowledgments

It is a pleasure to thank the ATLAS Collaboration, to CONACyT for the support received as a postdoctoral fellow with the University of Johannesburg, to Professor Simon Connell, Ketevi Assamagan and the University of Cape Town for giving me the opportunity to be part of the SouthAfrican group in the ATLAS Collaboration and for working in this project.

References

[1] The ATLAS Collaboration 2012 Phys. Lett. B 716 1
[2] The AMS Collaboration 2013 Phys. Rev. Lett. 110 141102
[3] S. Gopalakrishna, S. Jung, and J. D. Wells 2008 Phys. Rev. D 78 055002; J. D. Wells 2008 arXiv:0803.1243
[4] D. Curtin, R Essig, S. Gori, and J. Shelton 2015 J. High Energy Phys. 02 157
[5] D. Curtin et al. 2014 Phys. Rev. D 90 075004
[6] The ATLAS Collaboration 2015 Phys. Rev. D 91 012006
[7] The ATLAS Collaboration 2015 Phys. Rev. D 92 092001
[8] The ATLAS Collaboration 2008 arXiv:0901.0512;
[9] The ATLAS Collaboration 2012 Eur. Phys. J. C 72 1849
[10] The ATLAS Collaboration 2015 Eur. Phys. J. C 75 229
[11] The ATLAS Collaboration 2010 Eur. Phys. J. C 70 823
[12] S. Agostinelli et al. 2003 Nucl. Instrum. Methods Phys. Res. Sect A 506 250
[13] The ATLAS Collaboration 2010 ATL-PHYS-PUB-2010-013
[14] The ATLAS Collaboration 2011 ATLAS-CONF-2011-063
[15] The ATLAS Collaboration 2012 Eur. Phys. J. C 72 1909; ATLAS-CONF-2012-047
[16] K. Olive et al. 2014 Chin. Phys. C 38 090001
[17] LHC Higgs cross section working group et al. arXiv: 1101.0593 arXiv:1201.3084
[18] The ATLAS Collaboration 2013 Eur. Phys. J. C 73 2518
[19] A. L. Read 1999 Nucl. Instrum. Methods Phys. Res. Sect. A 425 357
[20] A. L. Read 2002 J. Phys. G 28 2693; G. Cowan et al. 2011 Eur. Phys. J. C 71 1554