Exploring the Dark Sector extension to the Standard Model via the Higgs Portal

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Abstract. The Standard Model (SM) is known to be incomplete. The introduction of a Dark Sector via an additional $U(1)_d$ gauge symmetry added to the SM Lagrangian provides a mechanism to introduce much needed new physics without perturbing the already excellent agreement between the SM theoretical description and the Electroweak Precision Observables (EWPO) experimental constraints. The model has a dark vector boson Z_d which can mix with the hypercharge gauge boson with the coupling ϵ. This opens the Hypercharge Portal which can mediate the fluctuation of a Z to a Z_d, or the decay of the Z_d to SM leptons. If a dark Higgs singlet h_d also exists, this then breaks the $U(1)_d$, opening the Higgs portal and also allowing for Higgs mass mixing between the SM and dark sectors, described by the Higgs mass mixing parameter, κ. Including dark fermionic fields in the Lagrangian allows for long-lived cold Dark Matter candidates. The various connections between the Dark and SM sectors allow descriptions of many key astro-physical phenomena. The Model is therefore a fascinating candidate for new physics beyond the SM. It becomes crucial to search for experimental signatures of this model. A promising avenue is to exploit the production of the dark force boson Z_d via the Higgs Portal and the search for its decay back to SM leptons: $H \to h_d \to Z_d Z_d \to 4\ell$. The detailed design and results of this search are presented.

1. Introduction

Introduction of the hidden or dark sector is a method to extend the Standard Model (SM) [1, 2, 3, 4, 5, 6, 7, 8, 9, 10], to provide candidates for dark matter [11] and dark forces which accomodate both the indirect and the (potential) direct evidence based on astronomical observations or space platform experiments [12, 13, 14]. The hidden or dark sector can be introduced with an additional $U(1)_d$ dark gauge symmetry [5, 6, 7, 8, 9, 10].

This analysis focusses on a Higgs Portal model, which has a Higgs level coupling between the dark sector and the SM. Accrdingly, the $U(1)_d$ symmetry is broken by the introduction of a dark Higgs boson, which mixes with the SM Higgs boson [5, 6, 7, 8, 9, 10] with a coupling strength κ. The observed Higgs boson would then be the lighter partner of the new Higgs doublet, which can also decay via the dark sector. We then conceptually allow the decay $H \to h_d \to Z_d Z_d$. The dark sector can additionally couple to the SM through kinetic mixing with the hypercharge gauge via the kinetic mixing parameter ϵ. This allows the decay $Z_d \to \ell\ell$. The current EWPO restrict the hypercharge portal to a greater degree than the Higgs Portal [5, 6, 7, 8, 9, 10, 15, 16]. We can further assume the dark fermions are sufficiently heavy $m_{f_d} < m_{Z_d}/2$, so that the branching ratio for the decay $Z_d \to \ell\ell$ may be taken as 100%, even though the kinetic mixing parameter ϵ can be set small to be consistent with EWPO, $\epsilon \approx 10^{-4}$, and still satisfy the requirement for prompt decays (a displaced vertex is not observed). The Higgs Portal is opened by the observation of the discovered Higgs at 125 GeV [17, 18, 19] during Run 1 of the Large Hadron

Collider (LHC) [20, 21]. This ushers in a new and rich experimental program for physics beyond the SM.

This paper summarises the work of [22] which presents a search for Higgs bosons decaying to four leptons via one or two Z_d bosons using pp collision data at $\sqrt{s} = 8$ TeV collected at the CERN LHC with the ATLAS experiment. The search uses a dataset corresponding to an integrated luminosity of 20.3 fb^{-1} with an uncertainty of 2.8% for $H \to Z_d Z_d \to 4\ell$ [23]. Same-flavor decays of the Z_d bosons to electron and muon pairs are considered, giving the $4e$, $2e2\mu$, and 4μ final states. Final states including τ leptons are not considered. In the absence of a significant signal, upper bounds are set on the relative branching ratio $\mathrm{BR}(H \to Z_d Z_d \to 4\ell)/\mathrm{BR}(H \to ZZ^* \to 4\ell)$ as functions of the mass of the dark vector boson m_{Z_d}. The branching ratio limits are used to set upper bounds on the Higgs boson mixing parameters [5, 6]. The search is restricted to the mass range where the Z_d from the decay of the Higgs boson is on-shell, i.e. $15\,\mathrm{GeV} < m_{Z_d} < m_H/2$, where $m_H = 125$ GeV. Dark vector boson masses below 15 GeV are not considered in the present search. Although the low-mass region is theoretically well motivated [7, 8], the high p_T of the Z_d boson relative to its mass leads to signatures that are better studied in dedicated searches [24].

2. Experimental Setup, Monte Carlo Simulation : Signal and backgrounds

The ATLAS detector covers almost the whole solid angle around the collision point with layers of tracking detectors, calorimeters and muon chambers. Further details can be found in [25] The data are collected using an online three-level trigger system [26] that selects events of interest and reduces the event rate from several MHz to about 400 Hz for recording and offline processing. **Signal** : Samples of Higgs boson production in the gluon fusion (ggF) mode, with $H \to Z_d Z_d \to 4\ell$ and were generated for $m_H = 125$ GeV and $15 < m_{Z_d} < 60$ GeV (in 5 GeV steps) in MadGraph5 [27] with CTEQ6L1 [28] parton distribution functions (PDF) using the Hidden Abelian Higgs Model (HAHM) as a benchmark signal model [5, 9, 10]. Pythia8 [29, 30] and Photos [31, 32, 33] are used to take into account parton showering, hadronization, and initial- and final-state radiation. **Backgrounds** : The background processes follow those used in the $H \to ZZ^* \to 4\ell$ measurements [34], and consist of: Higgs boson production via the SM ggF, VBF (vector boson fusion), also WH, ZH, and $t\bar{t}H$ processes with $H \to ZZ^* \to 4\ell$ final states, $ZZ^* \to 4\ell$ Z+jets and $t\bar{t}$ and SM WZ and WW production. There are also backgrounds containing J/ψ and Υ, namely ZJ/ψ and $Z\Upsilon$. Further details may be found in [22].

3. Analysis procedure

The selection of four leptons (e, μ) proceeds in the same way as in the discovery analyis channel $H \to ZZ^* \to 4\ell$ as described in [34] and is not described further here. The association of these four leptons into two same flavour opposite sign (SFOS) pairs is different. Instead of the requirement that a primary pair reconstructs back to a Z boson, there is the requirement that the mass difference $\Delta m = |m_{12} - m_{34}|$ is minimised. Here m_{12} and m_{34} are the invariant masses of the first and second pairs associations which achieve this requirement. The mass difference Δm is expected to be minimal for the signal since the two dilepton systems should have invariant masses consistent with the same m_{Z_d}. No requirement is made on Δm; it is used only to select a unique quadruplet with the smallest Δm. Subsequently, isolation and impact parameter significance requirements are imposed on the leptons of the selected quadruplet as described in Ref. [34]. The dilepton m_{12} and m_{34} combinedand four-lepton invariant mass distributions are shown in Figs. 1.

For the $H \to Z_d Z_d \to 4\ell$ search with hypothesized m_{Z_d}, after the impact parameter significance requirements on the selected leptons, four final requirements are applied:

(1) $115 < m_{4\ell} < 130$ GeV where $m_{4\ell}$ is the invariant mass of the four leptons in the quadruplet.

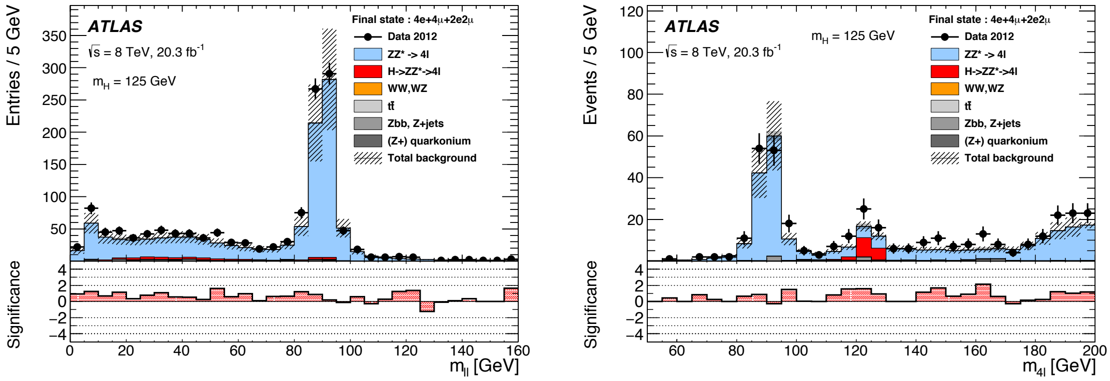

Figure 1. Left : Dilepton invariant mass, $m_{\ell\ell} \equiv m_{12}$ or m_{34}, in the combined $4e$+$2e2\mu$+4μ final state, for $m_H = 125$ GeV. Right : Four-lepton invariant mass, in the combined $4e$+$2e2\mu$+4μ final state, for $m_H = 125$ GeV. The data is represented by the black dots, and the backgrounds are represented by the filled histograms. The shaded area shows both the statistical and systematic uncertainties. The bottom plots show the significance of the observed number of events in the data compared to the expected number of events from the backgrounds. These distributions are obtained after the impact parameter significance requirement.

(2) Z, J/ψ, and Υ vetoes on all SFOS pairs in the selected quadruplet. The Z veto discards the event if either of the dilepton invariant masses is consistent with the Z-boson pole mass: $|m_{12} - m_Z| < 10$ GeV or $|m_{34} - m_Z| < 10$ GeV. For the J/ψ and Υ veto, the dilepton invariant masses are required to be above 12 GeV.

(3) the loose signal region requirement: $m_{12} < m_H/2$ and $m_{34} < m_H/2$, where $m_H = 125$ GeV.

(4) the tight signal region requirement: $|m_{Z_d} - m_{12}| < \delta m$ and $|m_{Z_d} - m_{34}| < \delta m$. The optimized values of the δm requirements are 5/3/4.5 GeV for the $4e/4\mu/2e2\mu$ final states respectively (the δm requirement varies with the hypothesized m_{Z_d} but the impact of the variation is negligible).

These requirements (1)–(4) define the signal region (SR) of $H \to Z_d Z_d \to 4\ell$ that is dependent on the hypothesized m_{Z_d}, and is essentially background-free, but contains small estimated background contributions from $H \to ZZ^* \to 4\ell$ and $ZZ \to 4\ell$ processes.

The analysis exploits the small mass difference between the two SFOS lepton pairs of the selected quadruplet to perform a counting experiment. After the small mass difference requirements between the SFOS lepton pairs, the estimated background contributions, coming from $H \to ZZ^* \to 4\ell$ and $ZZ \to 4\ell$, are small. These backgrounds are normalized with the theoretical calculations of their cross sections. The other backgrounds are found to be negligible. Since there is no significant excess, upper bounds on the signal strength, defined as the ratio of the $H \to Z_d Z_d \to 4\ell$ and $ZZ \to 4\ell$ rate normalized to the SM $H \to ZZ^* \to 4\ell$ expectation are set as a function of the hypothesized m_{Z_d}. In a benchmark model where the SM is extended with a dark vector boson and a dark Higgs boson, the measured upper bounds on the signal strength are used to set limits on the branching ratio of $H \to Z_d Z_d$ and on the Higgs boson mixing parameter as a function of m_{Z_d} [5, 6].

These backgrounds are further suppressed compared to figure 1 by the requirements of the tight signal region. The Z+jets and $t\bar{t}$, WW and WZ backgrounds now yield zero events. In the case where the Monte Carlo calculation yields zero expected background events in the tight signal region, an upper bound at 68% CL on the expected events is estimated using 1.14 events [35], scaled to the data luminosity and normalized to the background cross section:

The systematic uncertainties on the theoretical calculations of the cross sections used and the event selection and identification efficiencies are taken into account. The effects of PDFs, α_S, and renormalization and factorization scale uncertainties on the total inclusive cross sections for the Higgs production by ggF, VBF, VH and $t\bar{t}H$ are obtained from Refs. [36, 37]. The renormalization, factorization scales and PDFs and α_S uncertainties are applied to the ZZ^* background estimates. The uncertainties due to the limited number of MC events in the $t\bar{t}$, Z+jets, ZJ/ψ, $Z\Upsilon$ and WW/WZ background simulations are estimated as described in [22]. The luminosity uncertainty [23] is applied to all signal yields, as well as to the background yields that are normalized with their theory cross sections. The detector systematic uncertainties due to uncertainties in the electron and muon identification efficiencies are estimated within the acceptance of the signal region requirements. There are several components to these uncertainties. For the muons, uncertainties in the reconstruction and identification efficiency, and in the momentum resolution and scale, are included. For the electrons, uncertainties in the reconstruction and identification efficiency, the isolation and impact parameter significance requirements, the energy scale and energy resolution are considered.

4. Results

Four data events pass the loose signal region requirements, one in the $4e$ channel, two in the 4μ channel and one in the $2e2\mu$ channel. Two of these four events pass the tight signal region requirements: the event in the $4e$ channel and one of the events in the 4μ channel. The event in the $4e$ channel has dilepton masses of 21.8 GeV and 28.1 GeV, and is consistent with a Z_d mass in the range $23.5 \leq m_{Z_d} \leq 26.5$ GeV. The local significance of this event is 1.7σ. For the event in the 4μ channel that passes the tight signal region requirements, the dilepton invariant masses are 23.2 GeV and 18.0 GeV, and they are consistent with a Z_d mass in the range $20.5 \leq m_{Z_d} \leq 21.0$ GeV. The local significance of the 4μ event is 1.7σ. In the m_{Z_d} range of 15 to 30 GeV where four data events pass the loose signal region requirements, histogram interpolation [38] is used in steps of 0.5 GeV to obtain the signal acceptances and efficiencies at the hypothesized m_{Z_d}.

For each m_{Z_d}, in the absence of any significant excess of events consistent with the signal hypothesis, the upper limits are computed from a maximum-likelihood fit to the numbers of data and expected signal and background events in the tight signal regions, following the CL_s modified frequentist formalism [39, 40] with the profile-likelihood test statistic [41, 42]. The nuisance parameters associated to the systematic uncertainties are profiled [22]. The parameter of interest in the fit is the signal strength μ_d defined as the ratio of the $H \to Z_d Z_d \to 4\ell$ rate relative to the SM $H \to ZZ^* \to 4\ell$ rate:

$$\mu_d = \frac{\sigma \times \mathrm{BR}(H \to Z_d Z_d \to 4\ell)}{[\sigma \times \mathrm{BR}(H \to ZZ^* \to 4\ell)]_{\mathrm{SM}}}. \tag{1}$$

The systematic uncertainties in the electron and muon identification efficiencies, renormalization and factorization scales and PDF are 100% correlated between the signal and backgrounds. Pseudoexperiments are used to compute the 95% CL upper bound μ_d in each of the final states and their combination, and for each of the hypothesized m_{Z_d}. The 95% confidence-level upper bounds on the $H \to Z_d Z_d \to 4\ell$ rates are shown in the left of Fig. 2 relative to the SM Higgs boson process $H \to ZZ^* \to 4\ell$ as a function of the hypothesized m_{Z_d} for the combination of the three final states $4e$, $2e2\mu$ and 4μ.

The simplest benchmark model is the SM plus a dark vector boson and a dark Higgs boson as discussed in Refs. [6, 10], where the branching ratio of $Z_d \to \ell\ell$ is given as a function of m_{Z_d}. This can be used to convert the measurement of the upper bound on the signal strength μ_d into an upper bound on the branching ratio $\mathrm{BR}(H \to Z_d Z_d)$. (One has also assumed the SM Higgs boson production cross section and used $\mathrm{BR}(H \to ZZ^* \to 4\ell)_{\mathrm{SM}} = 1.25 \times 10^{-4}$ [36, 37]).

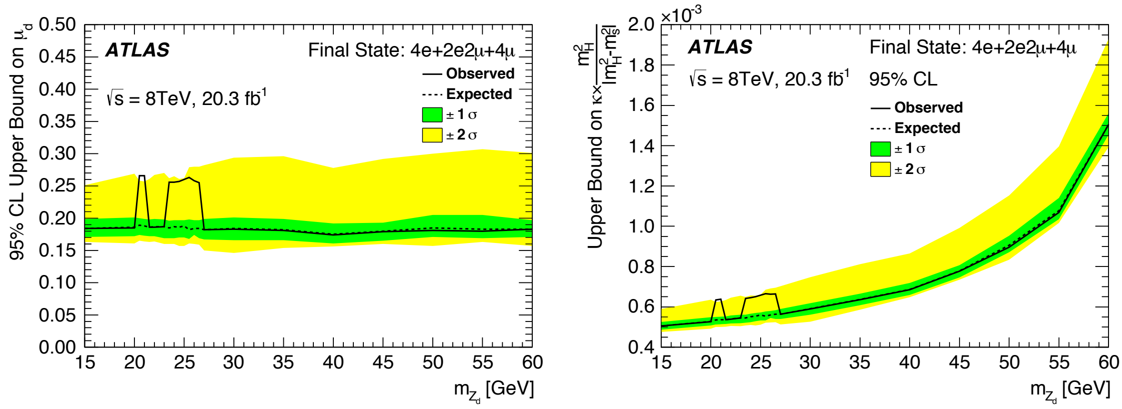

Figure 2. Left : The 95% confidence level upper bound on the signal strength $\mu_d = \frac{\sigma\times\mathrm{BR}(H\to Z_dZ_d\to 4\ell)}{[\sigma\times\mathrm{BR}(H\to ZZ^*\to 4\ell)]_{\mathrm{SM}}}$ of $H \to Z_dZ_d \to 4\ell$ in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm1\sigma$ and $\pm2\sigma$ expected exclusion regions are indicated in green and yellow, respectively. Right : The 95% confidence level upper bound on the Higgs mixing parameter $\kappa \times m_H^2/|m_H^2 - m_S^2|$ as a function of m_{Z_d}, in the combined $4e + 2e2\mu + 4\mu$ final state, for $m_H = 125$ GeV. The $\pm1\sigma$ and $\pm2\sigma$ expected exclusion regions are indicated in green and yellow, respectively.

The $H \to Z_dZ_d$ decay can now be used to obtain a m_{Z_d}-dependent limit on an Higgs mixing parameter κ' [6]. The algebra and rationale are described in reference [22]. Figure 2 shows the upper bound on the effective Higgs mixing parameter as a function of m_{Z_d}: for $m_H/2 < m_S < 2m_H$, this would correspond to an upper bound on the Higgs portal coupling in the range $\kappa \sim (1\text{–}10) \times 10^{-4}$.

5. Conclusion

The $H \to Z_dZ_d \to 4\ell$ search for an exotic gauge boson Z_d that couples to the discovered SM Higgs boson at a mass around 125 GeV in four-lepton events are presented, using the ATLAS detector at the LHC and covers the exotic gauge boson mass range from 15 GeV up to the kinematic limit of $m_H/2$. An integrated luminosity of 20.3 fb^{-1} at 8 TeV is used in this search. One data event is observed to pass all the signal region selections in the $4e$ channel, and has dilepton invariant masses of 21.8 GeV and 28.1 GeV and a local significance of 1.7σ. This $4e$ event is consistent with a Z_d mass in the range $23.5 < m_{Z_d} < 26.5$ GeV. Another data event is observed to pass all the signal region selections in the 4μ channel, and has dilepton invariant masses of 23.2 GeV and 18.0 GeV and a local significance of about 1.7σ. This 4μ event is consistent with a Z_d mass in the range $20.5 < m_{Z_d} < 21.0$ GeV. In the absence of a significant excess, upper bounds on the signal strength (and thus on the cross section times branching ratio) are set for the mass range of $15 < m_{Z_d} < 60$ GeV using the combined $4e$, $2e2\mu$, 4μ final states.

Using a simplified model where the SM is extended with the addition of an exotic gauge boson and a dark Higgs boson, and assuming the SM Higgs production cross section, upper bounds on the branching ratio of $H \to Z_dZ_d$, as well as on the Higgs portal coupling parameter κ are set in the range $(2\text{–}3) \times 10^{-5}$ and $(1\text{–}10) \times 10^{-4}$ respectively at 95% CL, for $15 < m_{Z_d} < 60$ GeV.

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