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Letter

Search for a new scalar decaying into new spin-1 bosons in four-lepton final states with the ATLAS detector

The ATLAS Collaboration ⋆

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ABSTRACT

A search is conducted for a new scalar boson S, with a mass distinct from that of the Higgs boson, decaying promptly into four leptons ($\ell = e$, μ) via an intermediate state containing two on-shell, promptly decaying new spin-1 bosons Z_d: $S \to Z_d Z_d \to 4\ell$, where the Z_d boson has a mass between 15 and 300 GeV, and the S boson has a mass between either 30 and 115 GeV or 130 and 800 GeV. The search uses proton–proton collision data collected with the ATLAS detector at the Large Hadron Collider with an integrated luminosity of 139 fb^{-1} at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. No significant excess above the Standard Model background expectation is observed. Upper limits at 95% confidence level are set on the production cross-section times branching ratio, $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$, as a function of the mass of both particles, m_S and m_{Zd}.

1. Introduction

Notwithstanding its spectacular successes, the Standard Model (SM) is incomplete. In particular, the nature of dark matter is unknown. A potential framework for extending the SM to include dark matter is the Hidden Abelian Higgs Model (HAHM) [1–6], which posits a 'hidden' or 'dark' sector of particles and fields, including a field with a $U(1)_d$ symmetry that mixes kinetically with the SM $U(1)_Y$ hypercharge gauge field with some coupling strength ϵ. This results in an additional scalar S along with a new gauge boson Z_d or 'dark photon'. The scalar S mixes with the SM Higgs boson with coupling κ, so all processes that can produce a SM Higgs boson also produce an S boson. Hence, the dominant production process for S in proton–proton (pp) collisions would be gluon–gluon fusion. The decays of the Z_d boson are determined by the gauge couplings and are independent of the mixings for $\epsilon, \kappa \ll 1$; the branching ratio of the Z_d boson into electron or muon pairs would therefore vary between 10% to 15% over the Z_d boson mass range $1 < m_{Z_d} < 300$ GeV, except in the range $60 < m_{Z_d} < 135$ GeV where it is smaller, falling to about 4% at $m_{Z_d} = m_Z$ [1].

Previous studies [7–12] have searched for a resonantly produced SM Higgs boson mixing with a new scalar decaying into a $Z_d Z_d$ or a ZZ_d pair, with each Z_d or Z boson decaying into a pair of electrons or muons ($\ell \equiv e, \mu$) with opposite electric charge. Other similar searches, including searches for pairs of light bosons decaying into muons, τ-leptons, photons, and/or jets, as well as searches for a single light boson decaying into a pair of muons, using both $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV data, were performed at the Large Hadron Collider (LHC) by the ATLAS [13–17], CMS [18–21], and LHCb [22] experiments. Further searches for a SM Higgs boson decaying into undetected particles are reported in Refs. [23,24]. The present work extends the previous ATLAS $H \to Z_d Z_d \to 4\ell$ search [7], where the additional scalar S decaying into the $Z_d Z_d$ pair, $S \to Z_d Z_d \to 4\ell$, has a mass distinct from that of the SM Higgs boson. The search reported here is restricted to the region $m_S < 800$ GeV and $m_{Z_d} < 300$ GeV. In the HAHM, the S and Z_d boson widths increase rapidly with mass, resulting in a loss of sensitivity above these masses. It is additionally restricted to regions of parameter space where all decays are prompt and further makes no use of information about any possible jets or missing transverse energy, so may also be sensitive to other signal processes that may produce extra particles in addition to four leptons.

2. The ATLAS detector

The ATLAS experiment [25] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner track-

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[1] ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upwards. Polar coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the z-axis. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

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ing detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [26] detector, which is located close to the beampipe. A two-level trigger system is used to select events [27]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate close to 100 kHz. This is followed by a software-based trigger that reduces the accepted rate of complete events to 1.25 kHz on average depending on the data-taking conditions. A software suite [28] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3. Data and simulated event samples

The data used in this search were recorded during the 2015–2018 LHC run with pp collisions at $\sqrt{s} = 13$ TeV. After requiring that all detector systems were operational [29] without excess calorimeter noise [30], this corresponds to an integrated luminosity of 139 fb^{-1} [31]. Events were selected by triggers requiring either one or two electron or muon candidates [32–34]. The trigger thresholds on transverse momentum p_{T} range from $p_{\mathrm{T}} > 7$ GeV to $p_{\mathrm{T}} > 60$ GeV, depending on lepton multiplicity and flavour. In either case, the trigger efficiency is above 95 % relative to the offline signal event selection criteria. Collision events are selected by requiring an identified primary vertex with at least two tracks [35] and at least four lepton candidates satisfying the requirements given in Section 4.

The expected contribution of the $S \to Z_{\mathrm{d}} Z_{\mathrm{d}} \to 4\ell$ ($\ell = e, \mu$) signal is determined from Monte Carlo (MC) simulations. Samples for this process are produced according to the HAHM implementation [36] for the gluon–gluon fusion production process at leading order (LO) using MadGraph5_aMC@NLO 2.2.2 [37] with the mixing parameters ϵ and κ both set to 10^{-4} so that decays of the Z_{d} boson are prompt [1]. Parton showers and decays are simulated using Pythia 8.186 [38], along with EvtGen 1.2.0 [39] to decay heavy-flavour hadrons. The NNPDF2.3lo [40] set of parton distribution functions (PDFs) and the A14 tune [41] are used. The width of the scalar S is taken to vary with mass in the same way as the SM Higgs boson [42]. The signal samples cover different m_S and $m_{Z_{\mathrm{d}}}$ mass hypotheses, in two regions. In the first region, there are 32 samples with $30\,\mathrm{GeV} \le m_S \le 110\,\mathrm{GeV}$ and $15\,\mathrm{GeV} \le m_{Z_{\mathrm{d}}} \le 48\,\mathrm{GeV}$ (the upper $m_{Z_{\mathrm{d}}}$ limit being chosen to avoid overlaps with the analyses of Ref. [7]; see Section 4), and in the second there are 49 samples with $150\,\mathrm{GeV} \le m_S \le 800\,\mathrm{GeV}$ and $15\,\mathrm{GeV} \le m_{Z_{\mathrm{d}}} \le 300\,\mathrm{GeV}$. In both cases, $m_S > 2m_{Z_{\mathrm{d}}}$. Detector effects are included using a Geant4 [43] simulation of the ATLAS detector [44]. The effects of additional pp collisions in the same or a neighbouring bunch crossing (pile-up) are included in the simulation.

Most background processes are estimated by using MC simulations, which consider $\ell = e, \mu, \tau$, and thus include leptonic τ-lepton decays. The samples used are identical to those of Ref. [7] and are briefly summarized here. The non-resonant $q\bar{q} \to ZZ^* \to 4\ell$ and $gg \to ZZ^* \to 4\ell$ background processes are simulated using Sherpa 2.2.2 [45–51] at next-to-leading order (NLO) for up to one additional parton and at LO for up to three additional partons. The $H \to ZZ^* \to 4\ell$ background is simulated with Powheg Box v2 [52–56] for the gluon–gluon fusion, vector–boson fusion, and $t\bar{t}H$ processes, with Pythia 8.186 for the VH process, and with MadGraph5_aMC@NLO for the $b\bar{b}H$ process. Higher-order electroweak processes, including triboson production (VVV) and vector–boson scattering (VBS), are simulated using Sherpa 2.2.2, while the process $t\bar{t} + (Z \to \ell\ell)$ is simulated with Sherpa 2.2.0. Other, reducible, backgrounds have fewer than four prompt leptons in the final state, but can be accepted by the event selection if there are additional leptons from, for example, heavy-flavour decay or jets misidentified as leptons. Backgrounds due to Z + jets and $t\bar{t}$ processes are estimated from data (see Section 5), but the method also requires simulations of these processes; the Z + jets process is simulated with Sherpa 2.2.1, while the $t\bar{t}$ process is simulated with Powheg Box v2. The WZ process was generated with Powheg Box at NLO. For processes simulated with MadGraph5_aMC@NLO and Powheg Box v2, Pythia is used to simulate parton showers and decays along with EvtGen. For the portion of the $gg \to ZZ^* \to 4\ell$ sample with $m_{4\ell} > 130$ GeV (corresponding to a few percent of the total estimated background) and the VVV samples, detector effects are included using a fast simulation [44], of just the calorimeter response [57] component, which relies on a parameterization. All other samples use the full Geant4 simulation.

In addition to the backgrounds mentioned above, numerous other simulated background processes were checked, including $t\bar{t}$ associated with a diboson pair, VH with the Higgs boson decaying into two W bosons, $Z\Upsilon$, tH, tWH, and $q\bar{q} \to ZZ^*$ at low p_{T}. The contributions from these backgrounds were less than 0.1% of the total, so they were not included in the further background calculations.

4. Event selection

After reconstruction, electrons and muons are identified using the standard ATLAS 'Loose' criteria [58,59], defined to maximize the reconstruction and identification efficiencies while still providing good-quality candidates. Electron candidates must satisfy $p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.47$, and must also have an additional associated hit in the innermost layer of the silicon detector. Longitudinal and transverse impact parameters with respect to the primary vertex must satisfy $|z_0 \sin\theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 5$. Muon candidates must satisfy $p_{\mathrm{T}} > 5$ GeV and $|\eta| < 2.5$, except that 'calorimeter-tagged' (CT) muons, identified by matching an inner-detector (ID) track (with no corresponding track in the muon system) with a deposit in the calorimeter consistent with a minimum-ionizing particle, must instead satisfy $p_{\mathrm{T}} > 15$ GeV. Except for 'stand-alone' (SA) muons lacking a matching ID track, muon candidates must also have impact parameters satisfying $|z_0 \sin\theta| < 0.5$ mm, $|d_0| < 1$ mm, and $|d_0|/\sigma_{d_0} < 3$. Leptons must be isolated from other deposits in the calorimeter or ID tracks [58,59]. This rejects backgrounds in which leptons arise from the decay of heavy-flavour hadrons, or in which jets are misidentified as leptons [60]. For each lepton, the sum of the transverse energies of topological clusters [61] within a cone of $\Delta R = 0.2$ around it (excluding energy attributed to the lepton itself) must be less than 20% of its p_{T} for electrons, and less than 30% of its p_{T} for muons. The transverse momenta of tracks in a cone around the lepton are also summed, and must be less than 15% of its p_{T}. The radius of the cone depends on the momentum of the lepton. For electrons, it is $\Delta R = \min(0.2, 10\,\mathrm{GeV}/p_{\mathrm{T}})$, while for muons it is $\Delta R = \min(0.3, 10\,\mathrm{GeV}/p_{\mathrm{T}})$.

Quadruplets are then formed from two same-flavour, opposite-sign lepton pairs: either $4e$, $2e2\mu$, or 4μ. For the computation of isolation of a lepton in a quadruplet, tracks and energy clusters attributed to the other leptons in the same quadruplet are excluded from the sums. A quadruplet may contain no more than one CT or SA muon. In the case of four same-flavour leptons, two quadruplets are formed, one for each possible pairing. If there are more than four leptons then there may be additional quadruplets, depending on the flavours and signs of the leptons.

For each possible quadruplet, the invariant masses of the two pairs are denoted m_{ab} and m_{cd}, where $m_{ab} > m_{cd}$. If all four leptons have the same flavour, then the alternative pairing $m_{ad,bc}$ can be defined taking the positively charged lepton of the m_{ab} pair and the negatively charged lepton of the m_{cd} pair to make m_{ad} and the remaining two leptons to make m_{bc}.[2]

Each quadruplet must contain all the leptons corresponding to at least one of the triggers satisfied by the event. The three highest-p_{T} leptons must satisfy $p_{\mathrm{T}\ell_1} > 20\,\mathrm{GeV}$, $p_{\mathrm{T}\ell_2} > 15\,\mathrm{GeV}$, and $p_{\mathrm{T}\ell_3} > 10\,\mathrm{GeV}$. To remove poorly-measured leptons and electrons from bremsstrahlung, all pairs of same-flavour leptons in the quadruplet must satisfy a separation requirement of $\Delta R(\ell,\ell') > 0.1$, while different-flavour pairs must satisfy $\Delta R(\ell,\ell') > 0.2$. At least one quadruplet per event is required. If more than one quadruplet passes these requirements, the one with the smallest mass difference between the two pairs, $\Delta m_{\ell\ell} = |m_{ab} - m_{cd}|$, is chosen.

All dilepton pair masses m_{ab}, m_{cd}, m_{ad}, and m_{bc} must be larger than $11.105\,\mathrm{GeV}$, corresponding to $m_{\Upsilon(3S)} + 0.75\,\mathrm{GeV}$, where $m_{\Upsilon(3S)}$ is taken to be $10.355\,\mathrm{GeV}$ [62]. This removes events where the alternate pairing may be consistent with ZZ^* decay as well as events with lepton pairs consistent with J/ψ or Υ decay.

Two signal regions are defined, each considering a scalar S with a mass different from that of the SM Higgs boson. The lower mass signal region (SR1) requires $m_{4\ell} < 115\,\mathrm{GeV}$ and, to reject background from Z bosons, either $m_{ab} < 50\,\mathrm{GeV}$ or $m_{ab} > 106\,\mathrm{GeV}$ (this is the complement of one of the signal region requirements from the $H \to ZZ_{\mathrm{d}} \to 4\ell$ search in Ref. [7], and was chosen to avoid overlap with that search). The higher mass signal region (SR2) requires $m_{4\ell} > 130\,\mathrm{GeV}$, and $|m_{ab,cd} - m_Z| > 8\,\mathrm{GeV}$ and $|m_{ad,bc} - m_Z| > 4\,\mathrm{GeV}$, where the latter requirement on the alternative pairing applies only to the $4e$ and 4μ events. These pair mass requirements were set to optimize the expected significance.

Consistency between m_{ab} and m_{cd} is enforced by requiring $m_{cd}/m_{ab} > 0.85 - 0.1125 f(m_{ab})$, where the modulating function f decreases monotonically from $f(m_{ab} \le 10\,\mathrm{GeV}) = 1$ to $f(m_{ab} \ge 50\,\mathrm{GeV}) = 0$. It is the result of re-optimizing the analysis to allow for larger Z_{d} widths at lower lepton-pair invariant masses, where the background is low, and is fully described in Ref. [7].

Finally, if E'_{ab} is defined as the energy of the ab dilepton pair in the rest frame of the four-lepton system, then

$$\frac{E'_{ab}}{m_{4\ell}} = \frac{1}{2}\left(1 + \frac{m_{ab}^2 - m_{cd}^2}{m_{4\ell}^2}\right).$$

The additional requirement $|E'_{ab}/m_{4\ell} - 0.5| < 0.008$ reduces the dominant ZZ^* background by about a factor of 1.5, while reducing the efficiency for the signal by less than five percent over most of the explored $(m_S, m_{Z_{\mathrm{d}}})$ range.

5. Background estimation

Backgrounds with four prompt leptons are estimated directly from simulation (see Section 3). The dominant background, comprising 90%–95% of the total, is the non-resonant process $ZZ^* \to 4\ell$. As described in Ref. [7], the prediction of this background was verified using background-dominated validation regions.[3] The background from SM Higgs boson production is effectively suppressed by the requirement that the overall invariant mass $m_{4\ell}$ not be consistent with that of the SM Higgs boson. Other processes with four prompt leptons include $t\bar{t}Z \to 4\ell + X$ and processes with three gauge bosons and are found to be small in comparison with the dominant ZZ^* background. The reducible background due to WZ production is similarly small.

Contributions from Z + jets and $t\bar{t}$ (including $t\bar{t}Z$ decays with fewer than four leptons) processes to the signal regions are estimated from data. They are estimated separately but with similar techniques. In both cases, the event sample is enlarged by relaxing the requirements on isolation and impact parameters for two of the lepton candidates. For the $t\bar{t}$ background, the two candidates with largest p_{T} must satisfy the nominal requirements. For the Z + jets background, the two candidates in the pair with invariant mass closest to that of the Z boson must satisfy the nominal requirements. In both cases, events are then classified into four regions based on the requirements satisfied by the other two candidates:

- Region A: The remaining two candidates both satisfy isolation and impact parameter requirements.
- Region B: The remaining two candidates both satisfy the isolation requirement, but at least one does not satisfy the impact parameter requirement.
- Region C: The remaining two candidates both satisfy the impact parameter requirement, but at least one does not satisfy the isolation requirement.
- Region D: All other events.

To obtain adequate statistics, event selections are applied only as far as the quarkonia veto, and the electron identification is also relaxed. Backgrounds other than the one being estimated are subtracted from the event counts in regions B, C, and D, using estimates from simulation. The number of background events in the signal region A can then be estimated as $N_{\mathrm{A}} = \epsilon_{\mathrm{sel}} N_{\mathrm{B}} N_{\mathrm{C}} / N_{\mathrm{D}}$, where ϵ_{sel} is the efficiency of the remaining selections as determined from simulation. This assumes that the isolation and impact parameter requirements are uncorrelated. This is nearly the case for the $4e$ and $2e2\mu$ final states (correlation coefficient $r < 0.01$), but they are more correlated for the 4μ final state ($r \approx 0.4$). The effect of the correlation is taken into account as a systematic uncertainty assigned to the yields of the Z + jets and $t\bar{t}$ backgrounds.

6. Systematic uncertainties

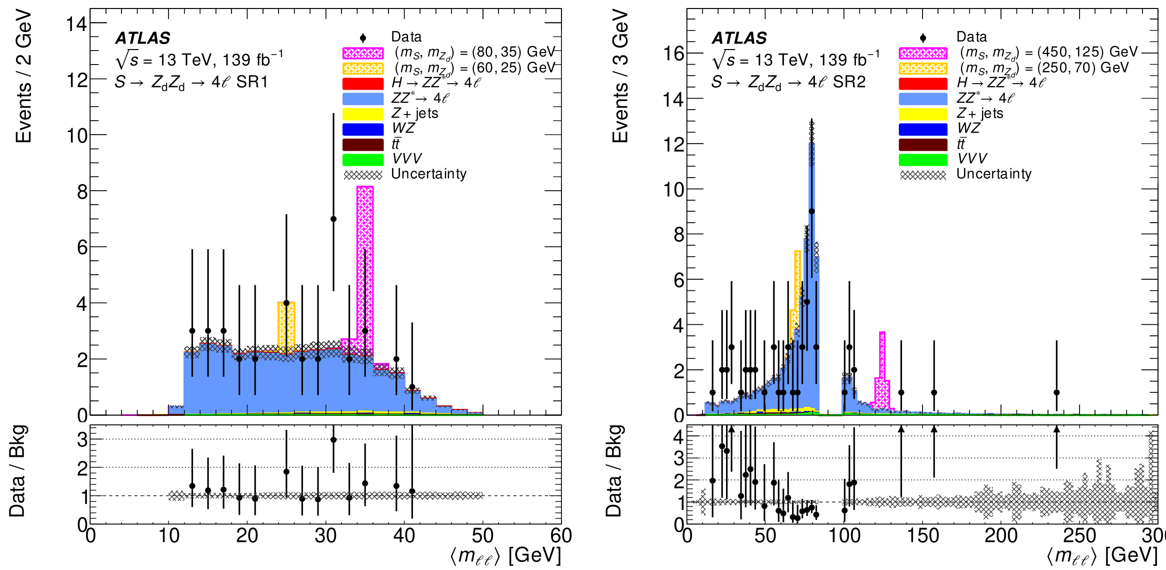
The uncertainty in the integrated luminosity is 1.7% [31], obtained using the LUCID-2 detector [26]. Uncertainties in the yields and efficiencies of simulated samples due to pile-up arise from differences between the predicted and measured inelastic cross-sections and from the reweighting procedure. These uncertainties are approximately 1%.

The efficiency for events to satisfy the selection depends on the triggering, reconstruction, identification, and isolation efficiencies for leptons, as well as the determination of their momentum scale. Tag-and-probe techniques are applied to dilepton resonances, including $Z \to \ell^+\ell^-$, $J/\psi \to \ell^+\ell^-$, and $\Upsilon \to \mu^+\mu^-$, to measure the efficiencies as well as momentum scales and resolutions for electrons and muons. This leads to corrections to account for differences between data and simulation along with an estimate of the residual uncertainty [58,59]. As there are four leptons in the final state, small single-lepton uncertainties can result in larger uncertainties in the final yields and efficiencies for simulated samples, up to 17%, dominated by the uncertainties on the electron reconstruction and identification efficiencies.

Uncertainties in the modelling of the simulated signal and background processes are estimated by varying the PDFs according to the prescription of Ref. [63] and the factorization and renormalization scales up and down by a factor of two. For the signal process, the resulting yield uncertainties are taken from the results for gluon–gluon fusion production of Ref. [64] and vary from 10%–19% depending on m_S, dominated by the uncertainty from factorization and renormalization scale variations. For the dominant $ZZ^* \to 4\ell$ background, these same sources result in an uncertainty in the yield of about 6%. Addition-

[2] These $m_{ab,cd}$ variables are distinct from the $m_{12,34}$ variables used in Ref. [7], which were chosen such that $|m_{12} - m_Z| < |m_{34} - m_Z|$. For $m_{4\ell} < 2m_Z$, $m_{ab,cd} = m_{12,34}$. For larger $m_{4\ell}$, either $m_{ab,cd} = m_{12,34}$ or $m_{ab,cd} = m_{34,12}$.

[3] In particular, Validation Region 3 of Ref. [7] requires $m_{4\ell} < 115\,\mathrm{GeV}$ or $m_{4\ell} > 130\,\mathrm{GeV}$ and thus probes the $ZZ^* \to 4\ell$ background that is dominant for this analysis.



(a) (b)

Fig. 1. Distributions of the average dilepton mass $\langle m_{\ell\ell}\rangle = \frac{1}{2}\left(m_{ab} + m_{cd}\right)$ for the two signal regions (a) SR1 and (b) SR2. The hatched bands show the uncertainty in the background prediction. The uncertainties on the data points are asymmetric Poisson errors (Eqs. (40.82a) and (40.82b) of Ref. [62]). The lower panels show the ratio of the observed data to the background ('Bkg') predictions. The arrows at the upper edge indicate data points that fall outside of the y-axis range, and the plotted uncertainties include both the Poisson errors on the data and the uncertainty on the background prediction. Distributions for two example signal points are also shown. These are normalized to production cross sections of 0.5 fb for SR1 and 0.1 fb for SR2.

Table 1
Expected event yields of the SM background processes and observed data in the two signal regions SR1 and SR2. The first uncertainty is the statistical component of the total uncertainty and the second the systematic component.

Process	Yield (± stat. ± syst.)	
	SR1	SR2
$ZZ^* \to 4\ell$	30.9±0.5±3.2	62.0±0.5±7.9
$H \to ZZ^* \to 4\ell$	0.61±0.01±0.04	0.22±0.01±0.03
WZ	0.06±0.04±0.03	0.42±0.10±0.05
VVV	0.06±0.01±0.01	0.78±0.02±0.14
$t\bar{t}$	0.33±<0.01±0.31	0.78±0.01±0.46
Z + jets	0.70±0.01±0.72	2.53±<0.01±1.08
Total	32.6±0.5 ±3.3	66.8±0.6±8.0
Data	36	55

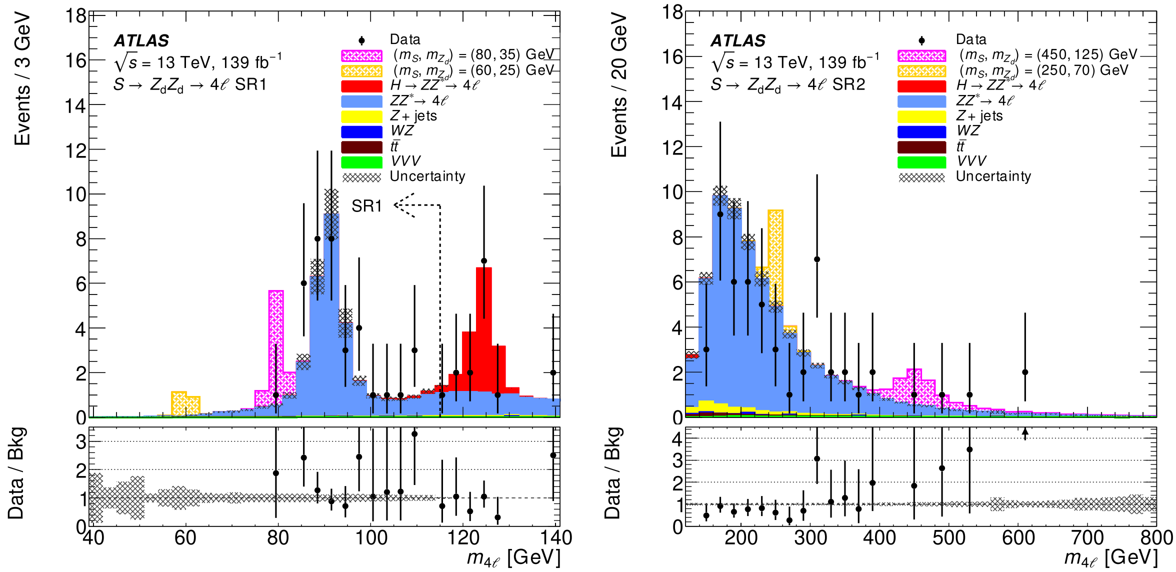
ally, for this sample, the matrix element matching scale is varied from the nominal value of 20 GeV to 15 GeV and 30 GeV; the resummation scale is varied up and down by a factor of four; and the alternate recoil scheme of Ref. [65] (SHERPA parameter `CSS_KIN_SCHEME=1`) is compared. This results in an uncertainty in the yield of 6% in SR1 and 12% in SR2, dominated by the matrix element matching scale. The uncertainty in the yield for the $H \to ZZ^* \to 4\ell$ process is about 9% [66]. The uncertainty in the data-driven Z + jets/$t\bar{t}$ background estimate is 50%–100%.

7. Results

Table 1 reports the observed and expected yields in the signal regions. In SR1 ($m_{4\ell} < 115$ GeV), 36 events are observed with an estimated background of 32.6 ± 3.3, while in SR2 ($m_{4\ell} > 130$ GeV), there are 55 events with an estimated background of 66.8 ± 8.0. The distributions of $\langle m_{\ell\ell}\rangle = \frac{1}{2}\left(m_{ab} + m_{cd}\right)$ for both signal regions are shown in Fig. 1, while Fig. 2 shows the overall invariant mass $m_{4\ell}$, which can also be interpreted as the mass of the scalar candidate. The selected events are represented in the $(m_{4\ell}, \langle m_{\ell\ell}\rangle)$ plane in Fig. 3, while the estimated backgrounds and example signal shapes in SR1 and SR2 are shown in Fig. 4.

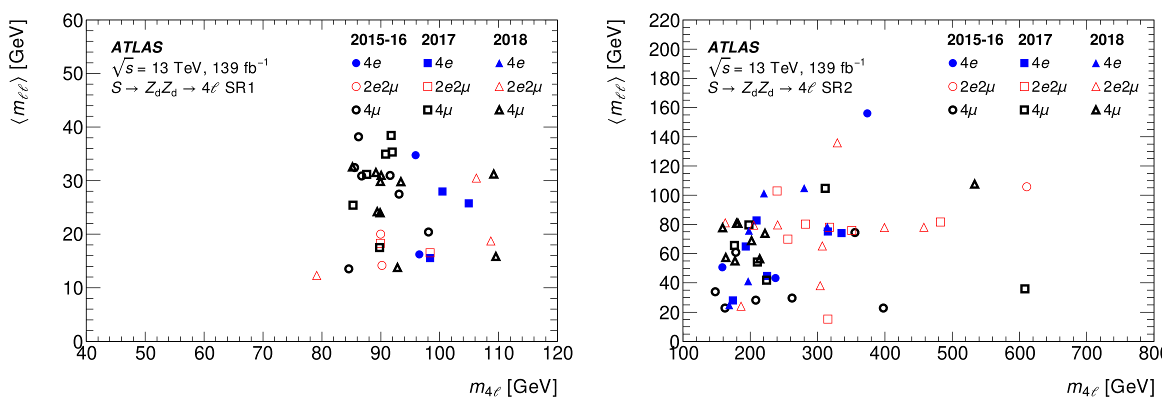
A two-dimensional interpolation procedure is used to obtain the shape of the $\langle m_{\ell\ell}\rangle$ distribution for the predicted signal at any point on the (m_S, m_{Z_d}) plane. For each generated signal MC sample, the $\langle m_{\ell\ell}\rangle$ distribution is fit. In SR1, these distributions are fit well by Gaussians, with three parameters. However, in SR2, the distributions are observed to be asymmetric, and a double-sided Crystal Ball distribution [67] is used instead, with seven parameters. For this interpolation, the S boson production cross-section and decay branching ratios are factored out, with the cross-section taken from Ref. [64] and the branching ratio set to one. Each fit parameter is then interpolated separately using the thin plate spline method [68–70], with the regularization parameter set to zero so that the interpolation passes smoothly through each control point. The interpolation procedure is validated by removing points from the interpolation one by one and then comparing the $\langle m_{\ell\ell}\rangle$ distribution for that point to what would be interpolated.

Exclusion limits on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ are set using frequentist significance testing of a statistic derived from a profile likelihood ratio that considers the data, the background model, and the signal model distributions for various hypothesized (m_S, m_{Z_d}) points [71–73]. To reduce the resources required, events are binned coarsely in $m_{4\ell}$ and limits set independently within each $m_{4\ell}$ bin as a function of $\langle m_{\ell\ell}\rangle$. Bins with a width of 1 GeV are used for $\langle m_{\ell\ell}\rangle$. In SR1 there are eight equal-sized bins in $m_{4\ell}$ in the range of 30 GeV to 110 GeV, and for SR2, there are 14 equal-sized bins in the range of 125 GeV to 825 GeV. These bin widths were chosen to have sufficient statistics while still being commensurate with the widths of the new scalar and the dark vector boson. Only signal MC events with $m_{4\ell}$ within one bin width of the generated m_S value are used to form the signal model distributions for this calculation. Limits are evaluated as described in Refs. [7–9] (using the `HypoTestInverter` component of the ROOSTATS toolkit [74] and evaluating the test statistic distributions with MC pseudoexperiments taking into account both statistical and systematic uncertainties), resulting in $\mathrm{CL_s}$ frequentist upper limits at 95% confidence level (CL) on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ as a function of the m_{Z_d} parameter in each $m_{4\ell}$ bin. Expected and observed limits and their ratios are shown in Figs. 5(a) to 5(c) for SR1 and Figs. 5(d) to 5(f)



(a) (b)

Fig. 2. Distributions of the total invariant mass $m_{4\ell}$ for the two signal regions (a) SR1 and (b) SR2. In (a), the requirement $m_{4\ell} < 115\,\text{GeV}$ is not applied, but is shown by the arrow. The hatched bands show the uncertainty in the background prediction; however, in (a), background uncertainties are not shown for $m_{4\ell} > 115\,\text{GeV}$. The uncertainties on the data points are asymmetric Poisson errors (Eqs. (40.82a) and (40.82b) of Ref. [62]). The lower panels show the ratio of the observed data to the background ('Bkg') predictions. The arrows at the upper edge indicate data points that fall outside of the y-axis range, and the plotted uncertainties include both the Poisson errors on the data and the uncertainty on the background prediction. Distributions for two example signal points are also shown. These are normalized to production cross sections of 0.5 fb for SR1 and 0.1 fb for SR2.



(a) (b)

Fig. 3. Events selected in signal regions (a) SR1 and (b) SR2, represented in the $(m_{4\ell}, \langle m_{\ell\ell}\rangle)$ plane. The points are differentiated by final state ($4e$, $2e2\mu$, and 4μ) and by data-taking period (2015–2016, 2017, and 2018).

for SR2. The corresponding one-dimensional local p_0-values are shown in Figs. 6(a) and 6(b). In SR1, the point with the smallest p_0-value is at $(m_S, m_{Z_d}) = (110\,\text{GeV}, 30\,\text{GeV})$ with a local significance of 2.7σ, while in SR2 the smallest p_0-value is at $(m_S, m_{Z_d}) = (350\,\text{GeV}, 75\,\text{GeV})$ with a local significance of 2.8σ. The local significance can be converted to a global significance by including the look-elsewhere effect using MC pseudo experiments as outlined in Ref. [75]. For SR2, the largest global significance is 0.5σ.

The local significance of the deviation in SR1 is re-evaluated using the same frequentist significance testing as described above but applied in the two-dimensional $(m_{4\ell}, \langle m_{\ell\ell}\rangle)$ plane with a binning of $\Delta m_{4\ell} \times \Delta\langle m_{\ell\ell}\rangle = 3\,\text{GeV} \times 1\,\text{GeV}$. The evaluation is done in a narrow window scanned over the plane with size set to contain at least 99% of the expected signal. The resulting local p_0-value still corresponds to a significance of 2.7σ but for the mass point $(m_S, m_{Z_d}) = (109\,\text{GeV}, 31\,\text{GeV})$. Converting this to a global significance yields 1.6σ.

8. Conclusions

A search is presented for the decay of a new scalar S into two new spin-1 particles $S \to Z_d Z_d$, with each Z_d boson decaying promptly into a pair of electrons or muons, yielding an inclusive four-lepton final state. It is conducted in the plane of the reconstructed four-lepton mass and the average dilepton mass of the $Z_d \to \ell\ell$ candidates, and it uses 139 fb^{-1} of pp collision data at $\sqrt{s} = 13\,\text{TeV}$ recorded by the ATLAS experiment at the LHC during the period 2015–2018. Two different signal regions are studied, corresponding to $30\,\text{GeV} < m_S < 115\,\text{GeV}$ and $130\,\text{GeV} < m_S < 800\,\text{GeV}$. The data are found to be consistent with the Standard Model background expectation, and 95% CL upper limits are set on the total cross-section times branching ratio $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ as a function of m_S and m_{Z_d}. In the first signal region, the limits range from 0.14 fb to 3.1 fb and in the second, from 0.05 fb to 0.60 fb. These constraints apply to the dark sector described by the Hidden Abelian

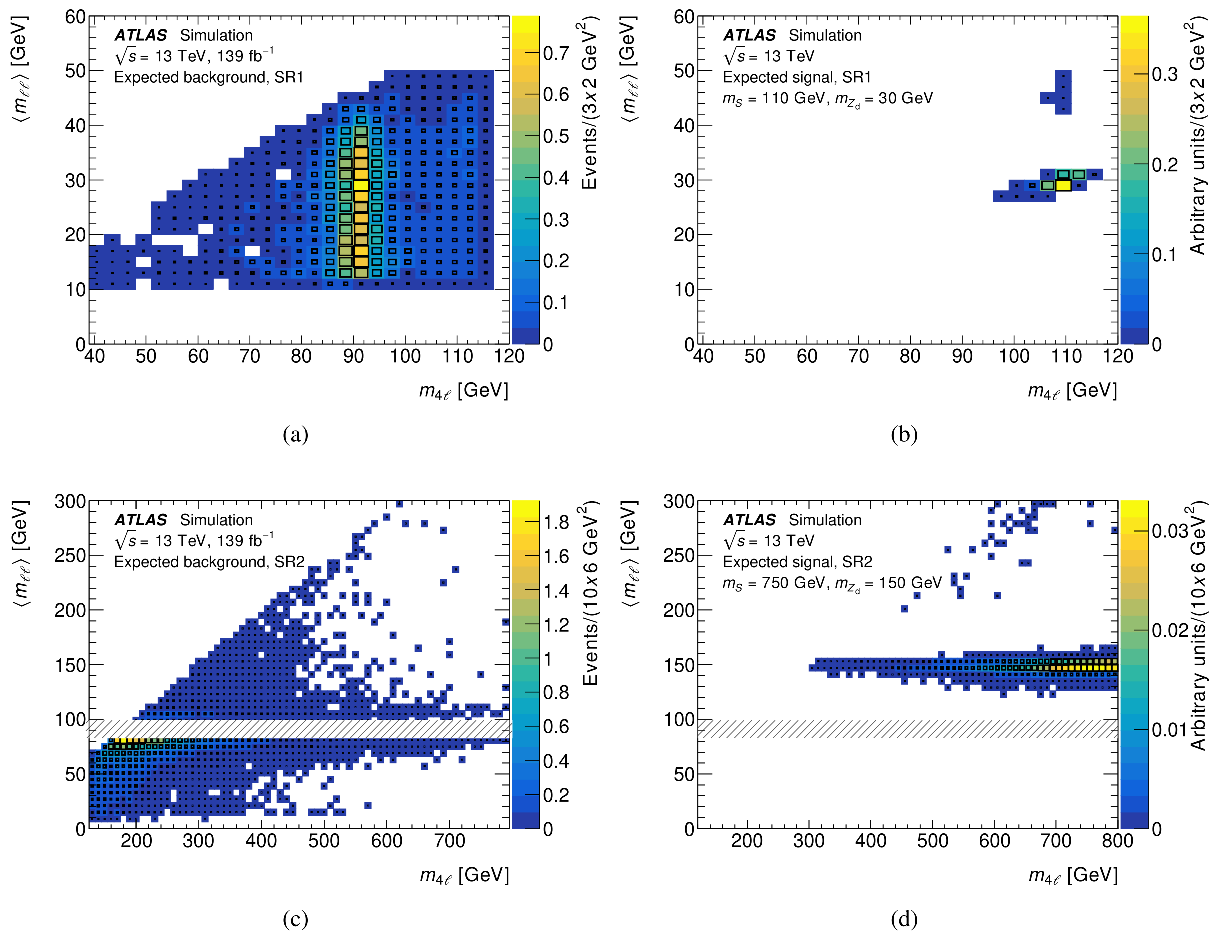


Fig. 4. (a) Estimated background and (b) expected signal shape for $(m_S, m_{Z_d}) = (110\,\text{GeV}, 30\,\text{GeV})$ in SR1 in the $(m_{4\ell}, \langle m_{\ell\ell}\rangle)$ plane, using both histograms and box representations. (c, d) The corresponding plots for SR2 with $(m_S, m_{Z_d}) = (750\,\text{GeV}, 150\,\text{GeV})$. The signal distributions are normalized to unit volume. Bins with less than 0.1% of the content of the largest bin are drawn as white.

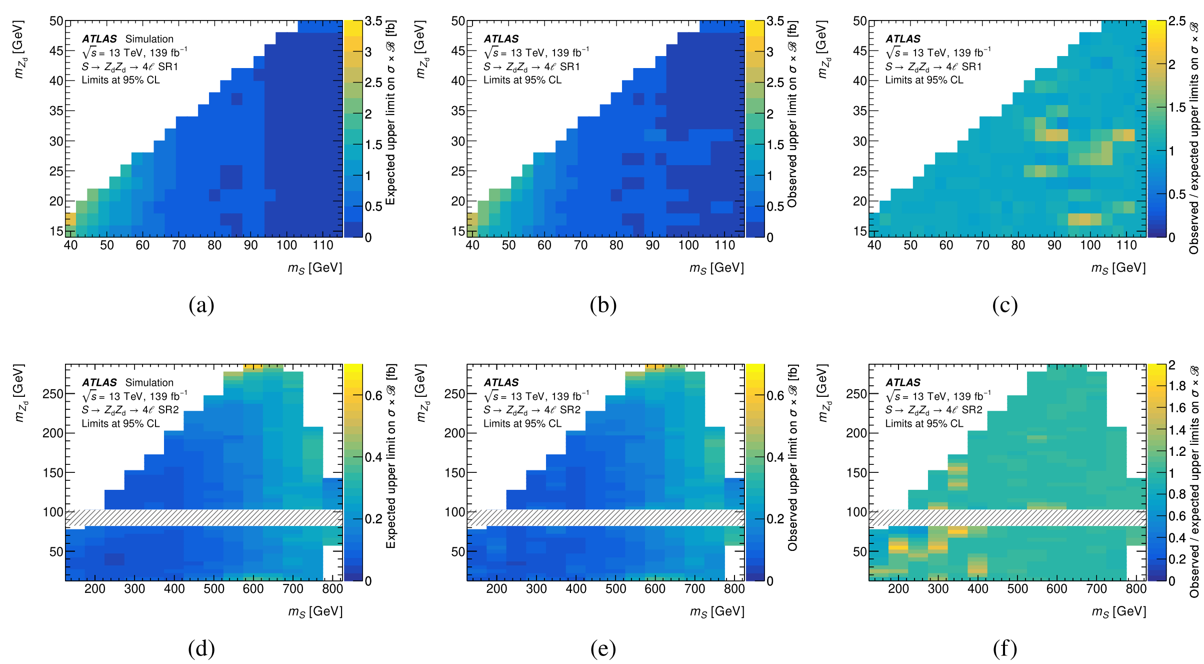
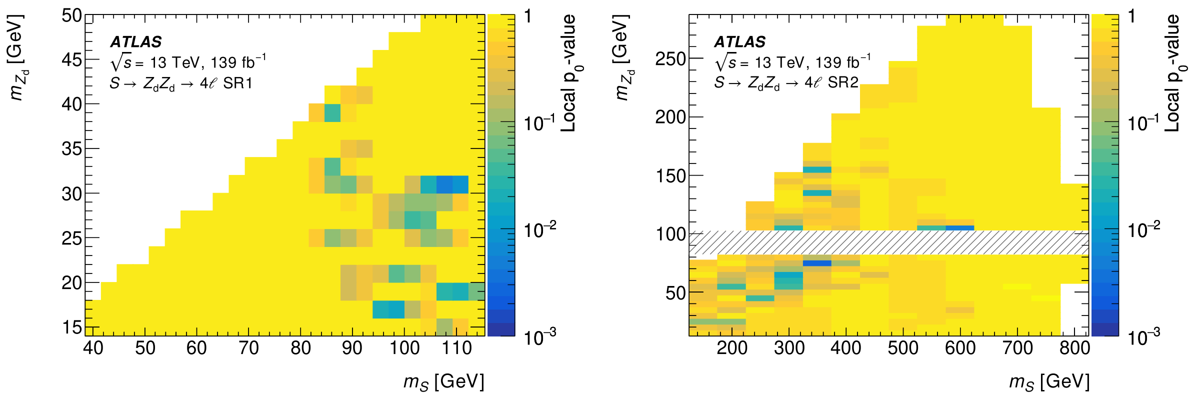


Fig. 5. 95% CL expected and observed limits on the total cross-section times branching ratio $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$. (a) SR1 expected limit; (b) SR1 observed limit; (c) ratio of observed to expected limits in SR1; (d) SR2 expected limit; (e) SR2 observed limit; (f) ratio of observed to expected limits in SR2. The horizontal bands in the SR2 figures show the region excluded by the Z boson veto requirement, $|m_{ab,cd} - m_Z| > 8\,\text{GeV}$.



(a) (b)

Fig. 6. Local p_0-values in the $(m_{4\ell}, \langle m_{\ell\ell} \rangle)$ plane for (a) SR1 and (b) SR2, evaluated in slices in $m_{4\ell}$. The horizontal band in the SR2 figure shows the region excluded by the Z boson veto requirement, $|m_{ab,cd} - m_Z| > 8$ GeV.

Higgs Model, as well as to similar models resulting in a four-lepton final state.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that support the findings of this article are not publicly available. The values in the plots and tables associated with this article are stored in https://www.hepdata.net/record/145171.

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