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Search for Higgs boson decays to a photon and a Z boson in pp collisions at $\sqrt{s} = 7$ and 8 TeV with the ATLAS detector

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ABSTRACT

A search is reported for a neutral Higgs boson in the decay channel $H \to Z\gamma$, $Z \to \ell^+\ell^-$ ($\ell = e, \mu$), using 4.5 fb^{-1} of pp collisions at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} of pp collisions at $\sqrt{s} = 8$ TeV, recorded by the ATLAS detector at the CERN Large Hadron Collider. The observed distribution of the invariant mass of the three final-state particles, $m_{\ell\ell\gamma}$, is consistent with the Standard Model hypothesis in the investigated mass range of 120–150 GeV. For a Higgs boson with a mass of 125.5 GeV, the observed upper limit at the 95% confidence level is 11 times the Standard Model expectation. Upper limits are set on the cross section times branching ratio of a neutral Higgs boson with mass in the range 120–150 GeV between 0.13 and 0.5 pb for $\sqrt{s} = 8$ TeV at 95% confidence level.

1. Introduction

In July 2012 a new particle decaying to dibosons ($\gamma\gamma$, ZZ, WW) was discovered by the ATLAS [1] and CMS [2] experiments at the CERN Large Hadron Collider (LHC). The observed properties of this particle, such as its couplings to fermions and bosons [3,4] and its spin and parity [5,6], are consistent with those of a Standard Model (SM) Higgs boson with a mass near 125.5 GeV [3].

This Letter presents a search for a Higgs boson H decaying to $Z\gamma$, $Z \to \ell^+\ell^-$ ($\ell = e, \mu$),[1] using pp collisions at $\sqrt{s} = 7$ and 8 TeV recorded with the ATLAS detector at the LHC during 2011 and 2012. The Higgs boson is assumed to have SM-like spin and production properties, but in order to retain sensitivity to additional, non-SM Higgs bosons, its mass is allowed to take any value between 120 and 150 GeV. The integrated luminosity presently available enables the exclusion of large anomalous couplings to $Z\gamma$, compared with the SM prediction. The signal is expected to yield a narrow peak in the reconstructed $\ell\ell\gamma$ invariant-mass distribution over a smooth background dominated by continuum $Z+\gamma$ production, $Z \to \ell\ell\gamma$ radiative decays and Z + jets events where a jet is misidentified as a photon. A similar search was recently published by the CMS Collaboration [7], which set an upper limit of 9.5 times the SM expectation, at 95% confidence level (CL), on the $pp \to H \to Z\gamma$ cross section for $m_H = 125$ GeV.

In the SM, the Higgs boson is produced mainly through five production processes: gluon fusion (ggF), vector-boson fusion (VBF), and associated production with either a W boson (WH), a Z boson (ZH) or a $t\bar{t}$ pair ($t\bar{t}H$) [8–10]. For a mass of 125.5 GeV the SM $pp \to H$ cross section is $\sigma = 22$ (17) pb at $\sqrt{s} = 8$ (7) TeV. Higgs boson decays to $Z\gamma$ in the SM proceed through loop diagrams mostly mediated by W bosons, similar to $H \to \gamma\gamma$. The $H \to Z\gamma$ branching ratio of an SM Higgs boson with a mass of 125.5 GeV is $B(H \to Z\gamma) = 1.6 \times 10^{-3}$, to be compared to $B(H \to \gamma\gamma) = 2.3 \times 10^{-3}$. Including the branching fractions of the Z decays to leptons leads to a $pp \to H \to \ell\ell\gamma$ cross section of 2.3 (1.8) fb at 8 (7) TeV, similar to that of $pp \to H \to ZZ^* \to 4\ell$ and only 5% of that of $pp \to H \to \gamma\gamma$.

Modifications of the $H \to Z\gamma$ coupling with respect to the SM prediction are expected if H is a neutral scalar of a different origin [11,12] or a composite state [13], as well as in models with additional colourless charged scalars, leptons or vector bosons coupled to the Higgs boson and exchanged in the $H \to Z\gamma$ loop [14–16]. A determination of both the $H \to \gamma\gamma$ and $H \to Z\gamma$ decay rates can help to determine whether the newly discovered Higgs boson is indeed the one predicted in the SM, or provide information on the quantum numbers of new particles exchanged in the loops or on the compositeness scale. While constraints from the observed rates in the other final states, particularly the diphoton channel, typically limit the expected $H \to Z\gamma$ decay rate in the models mentioned above to be within a factor of two of the SM expectation, larger enhancements can be obtained in some scenarios by careful parameter choices [13,14].

2. Experimental setup and dataset

The ATLAS detector [17] is a multi-purpose particle detector with approximately forward–backward symmetric cylindrical

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[1] In the following ℓ denotes either an electron or a muon, and the charge of the leptons is omitted for simplicity.

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Table 1
Event generators used to model the signal (first two rows) and background (last four rows) processes.

Process	Generator
ggF, VBF	POWHEG [20–22] + PYTHIA8 [23]
WH, ZH, $t\bar{t}H$	PYTHIA8
$Z+\gamma$ and $Z\to\ell\ell\gamma$	SHERPA [24,25]
Z + jets	SHERPA, ALPGEN [26] + HERWIG [27]
$t\bar{t}$	MC@NLO [28,29] + HERWIG
WZ	SHERPA, POWHEG + PYTHIA8

geometry.[2] The inner tracking detector (ID) covers $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field and by a high-granularity lead/liquid–argon (LAr) sampling electromagnetic calorimeter. The electromagnetic calorimeter measures the energy and the position of electromagnetic showers with $|\eta| < 3.2$. It includes a presampler (for $|\eta| < 1.8$) and three sampling layers, longitudinal in shower depth, up to $|\eta| < 2.5$. LAr sampling calorimeters are also used to measure hadronic showers in the end-cap ($1.5 < |\eta| < 3.2$) and forward ($3.1 < |\eta| < 4.9$) regions, while an iron/scintillator tile calorimeter measures hadronic showers in the central region ($|\eta| < 1.7$). The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting air-core toroid magnets, each with eight coils, a system of precision tracking chambers ($|\eta| < 2.7$), and fast tracking chambers ($|\eta| < 2.4$) for triggering. A three-level trigger system selects events to be recorded for offline analysis.

Events are collected using the lowest threshold unprescaled single-lepton or dilepton triggers [18]. For the single-muon trigger the transverse momentum, p_T, threshold is 24 (18) GeV for $\sqrt{s} = 8$ (7) TeV, while for the single-electron trigger the transverse energy, E_T, threshold is 25 (20) GeV. For the dimuon triggers the thresholds are $p_T > 13$ (10) GeV for each muon, while for the dielectron triggers the thresholds are $E_T > 12$ GeV for each electron. At $\sqrt{s} = 8$ TeV a dimuon trigger is also used with asymmetric thresholds $p_{T1} > 18$ GeV and $p_{T2} > 8$ GeV. The trigger efficiency with respect to events satisfying the selection criteria is 99% in the $ee\gamma$ channel and 92% in the $\mu\mu\gamma$ channel due to the reduced geometric acceptance of the muon trigger system in the $|\eta| < 1.05$ and $|\eta| > 2.4$ region. Events with data quality problems are discarded. The integrated luminosity after the trigger and data quality requirements corresponds to 20.3 fb^{-1} (4.5 fb^{-1}) [19] at $\sqrt{s} = 8$ (7) TeV.

3. Simulated samples

The event generators used to model SM signal and background processes in samples of Monte Carlo (MC) simulated events are listed in Table 1.

The $H \to Z\gamma$ signal from the dominant ggF and VBF processes, corresponding to 95% of the SM production cross section, is generated with POWHEG, interfaced to PYTHIA 8.170 for showering and hadronisation, using the CT10 parton distribution functions (PDFs) [30]. Gluon-fusion events are reweighted to match the Higgs boson p_T distribution predicted by HRES2 [31]. The signal from associated production (WH, ZH or $t\bar{t}H$) is generated with PYTHIA 8.170 using the CTEQ6L1 PDFs [32]. Signal events are generated for Higgs boson masses m_H between 120 and 150 GeV, in intervals of 5 GeV, at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. For the same value of the mass, events corresponding to different Higgs boson production modes are combined according to their respective SM cross sections.

The predicted SM cross sections and branching ratios are compiled in Refs. [8–10]. The production cross sections are computed at next-to-next-to-leading order in the strong coupling constant α_s and at next-to-leading order (NLO) in the electroweak coupling constant α, except for the $t\bar{t}H$ cross section, which is calculated at NLO in α_s [33–43]. Theoretical uncertainties on the production cross section arise from the choice of renormalisation and factorisation scales in the fixed-order calculations as well as the uncertainties on the PDFs and the value of α_s used in the perturbative expansion. They depend only mildly on the centre-of-mass energy and on the Higgs boson mass in the range $120 < m_H < 150$ GeV. The scale uncertainties are uncorrelated among the five Higgs boson production modes that are considered; for $m_H = 125.5$ GeV at $\sqrt{s} = 8$ TeV, they amount to $^{+7}_{-8}$% for ggF, ±0.2% for VBF, ±1% for WH, ±3% for ZH and $^{+4}_{-9}$% for $t\bar{t}H$. PDF + α_s uncertainties are correlated among the gluon-fusion and $t\bar{t}H$ processes, which are initiated by gluons, and among the VBF and WH/ZH processes, which are initiated by quarks; for $m_H = 125.5$ GeV at $\sqrt{s} = 8$ TeV, the uncertainties are around ±8% for $gg \to H$ and $t\bar{t}H$ and around ±2.5% for the other three Higgs boson production modes. The Higgs boson branching ratios are computed using the HDECAY and Prophecy4f programs [44–46]. The relative uncertainty on the $H \to Z\gamma$ branching ratio varies between ±9% for $m_H = 120$ GeV and ±6% for $m_H = 150$ GeV. An additional ±5% [47] accounts for the effect, in the selected phase space of the $\ell\ell\gamma$ final state, of the interfering $H \to \ell\ell\gamma$ decay amplitudes that are neglected in the calculation of Refs. [8–10]. They originate from internal photon conversion in Higgs boson decays to diphotons ($H \to \gamma^*\gamma \to \ell\ell\gamma$) or from radiative Higgs boson decays to dileptons ($H \to \ell\ell^* \to \ell\ell\gamma$ in the Z mass window) [48,49].

Various background samples are also generated: they are used to study the background parameterisation and possible systematic biases in the fit described in Section 6 and not to extract the final result. The samples produced with ALPGEN or MC@NLO are interfaced to HERWIG 6.510 [27] for parton showering, fragmentation into particles and to model the underlying event, using JIMMY 4.31 [50] to generate multiple-parton interactions. The SHERPA, MC@NLO and POWHEG samples are generated using the CT10 PDFs, while the ALPGEN samples use the CTEQ6L1 ones.

All Monte Carlo samples are processed through a complete simulation of the ATLAS detector response [51] using Geant4 [52]. Additional pp interactions in the same and nearby bunch crossings (pile-up) are included in the simulation. The MC samples are reweighted to reproduce the distribution of the mean number of interactions per bunch crossing (9 and 21 on average in the data taken at $\sqrt{s} = 7$ and 8 TeV, respectively) and the length of the luminous region observed in data.

4. Event selection and backgrounds

4.1. Event selection

Events are required to contain at least one primary vertex, determined from a fit to the tracks reconstructed in the inner detector and consistent with a common origin. The primary vertex with the largest sum of the squared transverse momenta of the tracks associated with it is considered as the primary vertex of the hard interaction.

[2] 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 upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln\tan(\theta/2)$.

The selection of leptons and photons is similar to that used for the $H \to \gamma\gamma$ and $H \to 4\ell$ measurements [1], the main difference being the minimum transverse momentum threshold. Events are required to contain at least one photon and two opposite-sign same-flavour leptons.

Muon candidates are formed from tracks reconstructed either in the ID or in the MS [53]. They are required to have transverse momentum $p_T > 10$ GeV and $|\eta| < 2.7$. In the central barrel region $|\eta| < 0.1$, which lacks MS coverage, ID tracks are identified as muons based on the associated energy deposits in the calorimeter. These candidates must have $p_T > 15$ GeV. The inner detector tracks associated with muons that are identified inside the ID acceptance are required to have a minimum number of associated hits in each of the ID sub-detectors (to ensure good track reconstruction) and to have transverse (longitudinal) impact parameter d_0 (z_0), with respect to the primary vertex, smaller than 1 mm (10 mm).

Electrons and photons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter [54]. Tracks matched to electron candidates (and, for 8 TeV data, from photon conversions) and having enough associated hits in the silicon detectors are fitted using a Gaussian-Sum Filter, which accounts for bremsstrahlung energy loss [55].

Electron candidates are required to have a transverse energy greater than 10 GeV, pseudorapidity $|\eta| < 2.47$, and a well-reconstructed ID track pointing to the electromagnetic calorimeter cluster. The cluster should satisfy a set of identification criteria that require the longitudinal and transverse shower profiles to be consistent with those expected for electromagnetic showers [56]. The electron track is required to have a hit in the innermost pixel layer of the ID when passing through an active module and is also required to have a longitudinal impact parameter, with respect to the primary vertex, smaller than 10 mm.

Photon candidates are required to have a transverse energy greater than 15 GeV and pseudorapidity within the regions $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$, where the first calorimeter layer has high granularity. Photons reconstructed in or near regions of the calorimeter affected by read-out or high-voltage failures are not accepted. The identification of photons is performed through a cut-based selection based on shower shapes measured in the first two longitudinal layers of the electromagnetic calorimeter and on the leakage into the hadronic calorimeter [57]. To further suppress hadronic background, the calorimeter isolation transverse energy E_T^{iso} [1] in a cone of size $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the photon candidate is required to be lower than 4 GeV, after subtracting the contributions from the photon itself and from the underlying event and pile-up.

Removal of overlapping electrons and muons that satisfy all selection criteria and share the same inner detector track is performed: if the muon is identified by the MS, then the electron candidate is discarded; otherwise the muon candidate is rejected. Photon candidates within a $\Delta R = 0.3$ cone of a selected electron or muon candidate are also rejected, thus suppressing background from $Z \to \ell\ell\gamma$ events and signal from radiative Higgs boson decays to dileptons.

Z boson candidates are reconstructed from pairs of same-flavour, opposite-sign leptons passing the previous selections. At least one of the two muons from $Z \to \mu\mu$ must be reconstructed both in the ID and the MS.

Higgs boson candidates are reconstructed from the combination of a Z boson and a photon candidate. In each event only the Z candidate with invariant mass closest to the Z pole mass and the photon with largest transverse energy are retained. In the selected events, the triggering leptons are required to match one (or in the case of dilepton-triggered events, both) of the Z candidate's leptons. Track and calorimeter isolation requirements, as well as additional track impact parameter selections, are applied to the leptons forming the Z boson candidate [1]. The track isolation $\sum p_T$, inside a $\Delta R = 0.2$ cone around the lepton, excluding the lepton track, divided by the lepton p_T, must be smaller than 0.15. The calorimeter isolation for electrons, computed similarly to E_T^{iso} for photons but with $\Delta R = 0.2$, divided by the electron E_T, must be lower than 0.2. Muons are required to have a normalised calorimeter isolation E_T^{cone}/p_T less than 0.3 (0.15 in the case of muons without an ID track) inside a $\Delta R = 0.2$ cone around the muon direction. For both the track- and calorimeter-based isolation any contributions due to the other lepton from the candidate Z decay are subtracted. The transverse impact parameter significance $|d_0|/\sigma_{d_0}$ of the ID track associated with a lepton within the acceptance of the inner detector is required to be less than 3.5 and 6.5 for muons and electrons, respectively. The electron impact parameter is affected by bremsstrahlung and it thus has a broader distribution.

Finally, the dilepton invariant mass ($m_{\ell\ell}$) and the invariant mass of the $\ell\ell\gamma$ final-state particles ($m_{\ell\ell\gamma}$) are required to satisfy $m_{\ell\ell} > m_Z - 10$ GeV and $115 < m_{\ell\ell\gamma} < 170$ GeV, respectively. These criteria further suppress events from $Z \to \ell\ell\gamma$, as well as reducing the contribution to the signal from internal photon conversions in $H \to \gamma\gamma$ and radiation from leptons in $H \to \ell\ell$ to a negligible level [47]. The number of events satisfying all the selection criteria in $\sqrt{s} = 8$ TeV ($\sqrt{s} = 7$ TeV) data is 7798 (1041) in the $Z \to ee$ channel and 9530 (1400) in the $Z \to \mu\mu$ channel.

The same reconstruction algorithms and selection criteria are used for simulated events. The simulation is corrected to take into account measured data-MC differences in photon and lepton efficiencies and energy or momentum resolution. The acceptance of the kinematic requirements for simulated $H \to Z\gamma \to \ell\ell\gamma$ signal events at $m_H = 125.5$ GeV is 54% for $\ell = e$ and 57% for $\ell = \mu$, due to the larger acceptance in muon pseudorapidity. The average photon reconstruction and selection efficiency is 68% (61%) while the $Z \to \ell\ell$ reconstruction and selection efficiency is 74% (67%) and 88% (88%) for $\ell = e$ and $\ell = \mu$, respectively, at $\sqrt{s} = 8$ (7) TeV. The larger photon and electron efficiencies in 8 TeV data are due to a re-optimisation of the photon and electron identification criteria prior to the 8 TeV data taking. Including the acceptance and the reconstruction, selection and trigger efficiencies, the overall signal efficiency for $H \to Z\gamma \to \ell\ell\gamma$ events at $m_H = 125.5$ GeV is 27% (22%) for $\ell = e$ and 33% (27%) for $\ell = \mu$ at $\sqrt{s} = 8$ (7) TeV. The relative efficiency is about 5% higher in the VBF process and 5–10% lower in the W, Z, $t\bar{t}$-associated production modes, compared to signal events produced in the dominant gluon-fusion process. For m_H increasing between 120 and 150 GeV the overall signal efficiency varies from 0.87 to 1.25 times the efficiency at $m_H = 125.5$ GeV.

4.2. Invariant-mass calculation

In order to improve the three-body invariant-mass resolution of the Higgs boson candidate events and thus improve discrimination against non-resonant background events, three corrections are applied to the three-body mass $m_{\ell\ell\gamma}$. First, the photon pseudorapidity η^γ and its transverse energy $E_T^\gamma = E^\gamma / \cosh\eta^\gamma$ are recalculated using the identified primary vertex as the photon's origin, rather than the nominal interaction point (which is used in the standard ATLAS photon reconstruction). Second, the muon momenta are corrected for collinear final-state-radiation (FSR) by including any reconstructed electromagnetic cluster with E_T above 1.5 GeV lying close (typically with $\Delta R < 0.15$) to a muon track. Third, the lepton four-momenta are recomputed by means of a Z-mass-constrained kinematic fit previously used in the ATLAS $H \to 4\ell$ search [1]. The

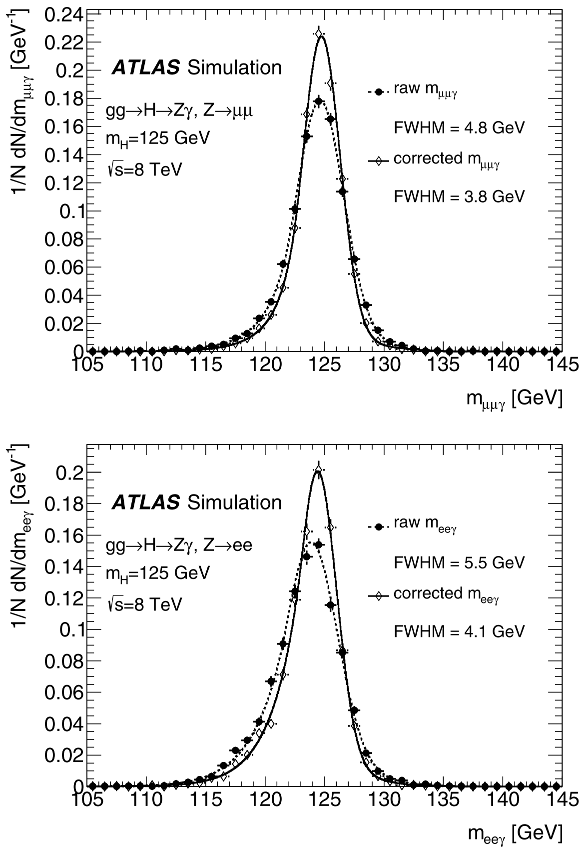

Fig. 1. Three-body invariant-mass distribution for $H \to Z\gamma$, $Z \to \mu\mu$ (top) or $Z \to ee$ (bottom) selected events in the 8 TeV, $m_H = 125$ GeV gluon-fusion signal simulation, after applying all analysis cuts, before (filled circles) and after (open diamonds) the corrections described in Section 4.2. The solid and dashed lines represent the fits of the points to the sum of a Crystal Ball and a Gaussian function.

photon direction and FSR corrections improve the invariant-mass resolution by about 1% each, while the Z-mass constraint brings an improvement of about 15–20%.

Fig. 1 illustrates the distributions of $m_{\mu\mu\gamma}$ and $m_{ee\gamma}$ for simulated signal events from $gg \to H$ at $m_H = 125$ GeV after all corrections. The $m_{ee\gamma}$ resolution is about 8% worse due to bremsstrahlung. The $m_{\ell\ell\gamma}$ distribution is modelled with the sum of a Crystal Ball function (a Gaussian with a power-law tail), representing the core of well-reconstructed events, and a small, wider Gaussian component describing the tails of the distribution. For $m_H = 125.5$ GeV the typical mass resolution σ_{CB} of the core component of the $m_{\mu\mu\gamma}$ distribution is 1.6 GeV.

4.3. Event classification

The selected events are classified into four categories, based on the pp centre-of-mass energy and the lepton flavour. To enhance the sensitivity of the analysis, each event class is further divided into categories with different signal-to-background ratios and invariant-mass resolutions, based on (i) the pseudorapidity difference $\Delta\eta_{Z\gamma}$ between the photon and the Z boson and (ii) p_{Tt},[3] the component of the Higgs boson candidate p_T that is orthogonal to the $Z\gamma$ thrust axis in the transverse plane [58]. Higgs boson candidates are classified as *high-* (*low-*)p_{Tt} candidates if their p_{Tt} is greater (smaller) than 30 GeV. In the analysis of $\sqrt{s} = 8$ TeV data, low-p_{Tt} candidates are further split into two classes, *high-* and *low-*$|\Delta\eta_{Z\gamma}|$, depending on whether $|\Delta\eta_{Z\gamma}|$ is greater or less than 2.0, yielding a total of ten event categories. Signal events are typically characterised by a larger p_{Tt} and a smaller $|\Delta\eta_{Z\gamma}|$ than background events, which are mostly due to $q\bar{q} \to Z + \gamma$ events in which the Z boson and the photon are back-to-back in the transverse plane. Signal events with high p_{Tt} or low $|\Delta\eta|$ are enriched in VBF, VH and ttH events, in which the Higgs boson is more boosted, and in gluon fusion events in which the leptons and the photon are harder or more central in the detector than in signal events with low p_{Tt} and high $|\Delta\eta|$. This results in a better $\ell\ell\gamma$ invariant mass resolution for the high p_{Tt} and low $|\Delta\eta|$ categories, which are also characterised by a better signal-to-background ratio.

As an example, the expected number of signal and background events in each category with invariant mass within a ±5 GeV window around $m_H = 125$ GeV, the observed number of events in data in the same region, and the full-width at half-maximum (FWHM) of the signal invariant-mass distribution, are summarised in Table 2. Using this classification improves the signal sensitivity of this analysis by 33% for a Higgs boson mass of 125.5 GeV compared to a classification based only on the centre-of-mass energy and lepton flavour categories.

Table 2
Expected signal (N_S) and background (N_B) yields in a ±5 GeV mass window around $m_H = 125$ GeV for each of the event categories under study. In addition, the observed number of events in data (N_D) and the FWHM of the signal invariant-mass distribution, modelled as described in Section 4.2, are given. The signal is assumed to have SM-like properties, including the production cross section times branching ratio. The background yield is extrapolated from the selected data event yield in the invariant-mass region outside the ±5 GeV window around $m_H = 125$ GeV, using an analytic background model described in Section 6. The uncertainty on the FWHM from the limited size of the simulated signal samples is negligible in comparison to the systematic uncertainties described in Section 5.

$\sqrt{s}$ [TeV]	ℓ	Category	N_S	N_B	N_D	$\frac{N_S}{\sqrt{N_B}}$	FWHM [GeV]
8	μ	high p_{Tt}	2.3	310	324	0.13	3.8
8	μ	low p_{Tt}, low $\|\Delta\eta\|$	3.7	1600	1587	0.09	3.8
8	μ	low p_{Tt}, high $\|\Delta\eta\|$	0.8	600	602	0.03	4.1
8	e	high p_{Tt}	1.9	260	270	0.12	3.9
8	e	low p_{Tt}, low $\|\Delta\eta\|$	2.9	1300	1304	0.08	4.2
8	e	low p_{Tt}, high $\|\Delta\eta\|$	0.6	430	421	0.03	4.5
7	μ	high p_{Tt}	0.4	40	40	0.06	3.9
7	μ	low p_{Tt}	0.6	340	335	0.03	3.9
7	e	high p_{Tt}	0.3	25	21	0.06	3.9
7	e	low p_{Tt}	0.5	240	234	0.03	4.0

4.4. Sample composition

The main backgrounds originate from continuum $Z+\gamma$, $Z \to \ell\ell$ production, from radiative $Z \to \ell\ell\gamma$ decays, and from Z + jet, $Z \to \ell\ell$ events in which a jet is misidentified as a photon. Small contributions arise from $t\bar{t}$ and WZ events. Continuum $Z+\gamma$ events are either produced by $q\bar{q}$ in the t- or u-channels, or from parton-to-photon fragmentation. The requirements $m_{\ell\ell} > m_Z - 10$ GeV, $m_{\ell\ell\gamma} > 115$ GeV and $\Delta R_{\ell\gamma} > 0.3$ suppress the contribution from $Z \to \ell\ell\gamma$, while the photon isolation requirement reduces the importance of the $Z+\gamma$ fragmentation component. The latter, together with the photon identification requirements, is also effective in reducing Z + jets events.

In this analysis, the estimated background composition is not used to determine the amount of expected background, which is directly fitted to the data mass spectrum, but is used to normalise the background Monte Carlo samples used for the optimisation of

[3] $p_{Tt} = |(\vec{p}_T^{\,\gamma} + \vec{p}_T^{\,Z}) \times \hat{t}|$ where $\hat{t} = (\vec{p}_T^{\,\gamma} - \vec{p}_T^{\,Z})/|\vec{p}_T^{\,\gamma} - \vec{p}_T^{\,Z}|$ denotes the thrust axis in the transverse plane, and $\vec{p}_T^{\,\gamma}$, $\vec{p}_T^{\,Z}$ are the transverse momenta of the photon and the Z boson.

the selection criteria and the choice of mass spectra background-fitting functions and the associated systematic uncertainties. Since the amplitudes for $Z+\gamma$, $Z \to \ell\ell$ and $Z \to \ell\ell\gamma$ interfere, only the total $\ell\ell\gamma$ background from the sum of the two processes is considered, and denoted with $Z\gamma$ in the following. A data-driven estimation of the background composition is performed, based on a two-dimensional sideband method [57,59] exploiting the distribution of the photon identification and isolation variables in control regions enriched in Z + jets events, to estimate the relative $Z\gamma$ and Z + jets fractions in the selected sample. The $Z\gamma$ and Z + jets contributions are estimated *in situ* by applying this technique to the data after subtracting the 1% contribution from the $t\bar{t}$ and WZ backgrounds. Simulated events are used to estimate the small backgrounds from $t\bar{t}$ and WZ production (normalised to the data luminosity using the NLO MC cross sections), on which a conservative uncertainty of ±50% accounts for observed data-MC differences in the rates of fake photons and leptons from misidentified jets as well as for the uncertainties on the MC cross section due to the missing higher orders of the perturbative expansion and the PDF uncertainties. Simulated events are also used to determine the $Z\gamma$ contamination in the Z + jet background control regions and the correlation between photon identification and photon isolation for Z + jet events. The contribution to the control regions from the $H \to Z\gamma$ signal is expected to be small compared to the background and is neglected in this study. The fractions of $Z\gamma$, Z + jets and other ($t\bar{t}+WZ$) backgrounds are estimated to be around 82%, 17% and 1% at both $\sqrt{s}=7$ and 8 TeV. The relative uncertainty on the $Z\gamma$ purity is around 5%, dominated by the uncertainty on the correlation between the photon identification and isolation in Z + jet events, which is estimated by comparing the ALPGEN and SHERPA predictions. Good agreement between data and simulation is observed in the distributions of $m_{\ell\ell\gamma}$, as well as in the distributions of several other kinematic quantities that were studied, including the dilepton invariant mass and the lepton and photon transverse momenta, pseudorapidity and azimuth.

5. Experimental systematic uncertainties

The following sources of experimental systematic uncertainties on the expected signal yields in each category were considered:

- The luminosity uncertainty is 1.8% for the 2011 data [19] and 2.8% for the 2012 data.[4]
- The uncertainty from the photon identification efficiency is obtained from a comparison between data-driven measurements and the simulated efficiencies in various photon and electron control samples [60] and varies between 2.6% and 3.1% depending on the category. The uncertainty from the photon reconstruction efficiency is negligible compared to that from the identification efficiency.
- The uncertainty from the electron trigger, reconstruction and identification efficiencies is estimated by varying the efficiency corrections applied to the simulation within the uncertainties of data-driven efficiency measurements. The total uncertainty, for events in which the Z boson candidate decays to electrons, varies between 2.5% and 3% depending on the category. The lepton reconstruction, identification and trigger efficiencies, as well as their energy and momentum scales and resolutions, are determined using large control samples of $Z \to \ell\ell$, $W \to \ell\nu$ and $J/\psi \to \ell\ell$ events [53,56].

Other sources of uncertainty (muon trigger, reconstruction and identification efficiencies, lepton energy scale, resolution, and impact parameter selection efficiencies, lepton and photon isolation efficiencies) were investigated and found to have a negligible impact on the signal yield compared to the mentioned sources of uncertainty. The total relative uncertainty on the signal efficiency in each category is less than 5%, more than twice as small as the corresponding theoretical systematic uncertainty on the SM production cross section times branching ratio, described in Section 3. The uncertainty in the population of the p_{Tt} categories due to the description of the Higgs boson p_{T} spectrum is determined by varying the QCD scales and PDFs used in the HRES2 program. It is estimated to vary between 1.8% and 3.6% depending on the category.

The following sources of experimental systematic uncertainties on the signal $m_{\ell\ell\gamma}$ distribution were considered:

- The uncertainty on the peak position (0.2 GeV) is dominated by the photon energy scale uncertainty, which arises from the following sources: the calibration of the electron energy scale from $Z \to ee$ events, the uncertainty on its extrapolation to the energy scale of photons, dominated by the description of the detector material, and imperfect knowledge of the energy scale of the presampler detector located in front of the electromagnetic calorimeter.
- The uncertainty from the photon and electron energy resolution is estimated as the relative variation of the width of the signal $m_{\ell\ell\gamma}$ distribution after varying the corrections to the resolution of the electromagnetic particle response in the simulation within their uncertainties. It amounts to 3% for events in which the Z boson candidate decays to muons and to 10% for events in which the Z boson candidate decays to electrons.
- The uncertainty from the muon momentum resolution is estimated as the relative variation of the width of the signal $m_{\ell\ell\gamma}$ distribution after varying the muon momentum smearing corrections within their uncertainties. It is smaller than 1.5%.

To extract the signal, the background is estimated from the observed $m_{\ell\ell\gamma}$ distribution by assuming an analytical model, chosen from several alternatives to provide the best sensitivity to the signal while limiting the possible bias in the fitted signal to be within 20% of the statistical uncertainty on the signal yield due to background fluctuations. The $m_{\ell\ell\gamma}$ range used for the fit is also chosen according to the same criteria. The models are tested by performing signal + background fits of the $m_{\ell\ell\gamma}$ distribution of large simulated background-only samples scaled to the luminosity of the data and evaluating the ratio of the fitted signal yield to the statistical uncertainty on the fitted signal itself. The largest observed bias in the fitted signal for any Higgs boson mass in the range 120–150 GeV is taken as an additional systematic uncertainty; it varies between 0.5 events in poorly populated categories and 8.3 events in highly populated ones.

All systematic uncertainties, except that on the luminosity, are taken as fully correlated between the $\sqrt{s}=7$ TeV and the $\sqrt{s}=8$ TeV analyses.

6. Results

6.1. Likelihood function

The final discrimination between signal and background events is based on a simultaneous likelihood fit to the $m_{\ell\ell\gamma}$ spectra in the invariant-mass region $115 < m_{\ell\ell\gamma} < 170$ GeV. The likelihood function depends on a single parameter of interest, the Higgs boson production signal strength μ, defined as the signal yield

[4] The luminosity of the 2012 data is derived, following the same methodology as that detailed in Ref. [19], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

normalised to the SM expectation, as well as on several nuisance parameters that describe the shape and normalisation of the background distribution in each event category and the systematic uncertainties. Results for the signal production cross section times branching ratio are also provided. In that case, the likelihood function depends on two parameters of interest, the signal cross sections times branching ratios at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, and the systematic uncertainties on the SM cross sections and branching ratios are removed.

The background model in each event category is chosen based on the studies of sensitivity versus bias described in the previous section. For 2012 data, fifth- and fourth-order polynomials are chosen to model the background in the low-p_{Tt} categories while an exponentiated second-order polynomial is chosen for the high-p_{Tt} categories. For 2011 data, a fourth-order polynomial is used for the low-p_{Tt} categories and an exponential function is chosen for the high-p_{Tt} ones. The signal resolution functions in each category are described by the model illustrated in Section 4.2, fixing the fraction of events in each category to the MC predictions. For each fixed value of the Higgs boson mass between 120 and 150 GeV, in steps of 0.5 GeV, the parameters of the signal model are obtained, separately for each event category, through interpolation of the fully simulated MC samples.

For each of the nuisance parameters describing systematic uncertainties the likelihood is multiplied by a constraint term for each of the experimental systematic uncertainties evaluated as described in Section 5. For systematic uncertainties affecting the expected total signal yields for different centre-of-mass or lepton flavour, a log-normal constraint is used while for the uncertainties on the fractions of signal events in different $p_{\mathrm{Tt}} - |\Delta\eta_{Z\gamma}|$ categories and on the signal $m_{\ell\ell\gamma}$ resolution a Gaussian constraint is used [61].

6.2. Statistical analysis

The data are compared to background and signal-plus-background hypotheses using a profile likelihood test statistic [61]. Higgs boson decays to final states other than $\ell\ell\gamma$ are expected to contribute negligibly to the background in the selected sample. For each fixed value of the Higgs boson mass between 120 and 150 GeV fits are performed in steps of 0.5 GeV to determine the best value of μ ($\hat{\mu}$) or to maximise the likelihood with respect to all the nuisance parameters for alternative values of μ, including $\mu = 0$ (background-only hypothesis) and $\mu = 1$ (background plus Higgs boson of that mass, with SM-like production cross section times branching ratio). The compatibility between the data and the background-only hypothesis is quantified by the p-value of the $\mu = 0$ hypothesis, p_0, which provides an estimate of the significance of a possible observation. Upper limits on the signal strength at 95% CL are set using a modified frequentist (CL_s) method [62], by identifying the value μ_{up} for which the CL_s is equal to 0.05. Closed-form asymptotic formulae [63] are used to derive the results. Fits to the data are performed to obtain observed results. Fits to Asimov pseudo-data [63], generated either according to the $\mu = 1$ or $\mu = 0$ hypotheses, are performed to compute expected p_0 and CL_s upper limits, respectively.

Fig. 2 shows the $m_{\ell\ell\gamma}$ distribution of all events selected in data, compared to the sum of the background-only fits to the data in each of the ten event categories. No significant excess with respect to the background is visible, and the observed p_0 is compatible with the data being composed of background only. The smallest p_0 (0.05), corresponding to a significance of 1.6σ, occurs for a mass of 141 GeV. The expected p_0 ranges between 0.34 and 0.44 for a Higgs boson with a mass $120 < m_H < 150$ GeV and SM-like cross section and branching ratio, corresponding to significances around

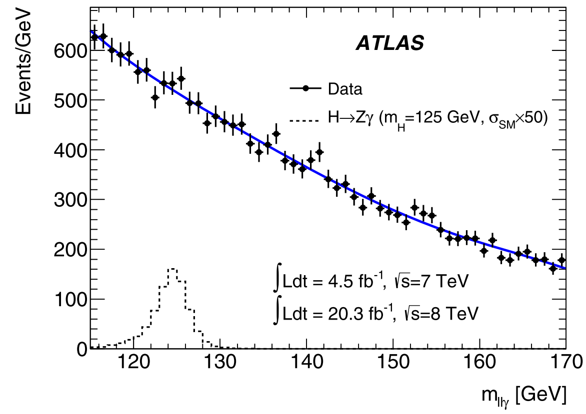

Fig. 2. Distribution of the reconstructed $\ell\ell\gamma$ invariant mass in data, after combining all the event categories (points with error bars). The solid dark grey (blue in the web version) line shows the sum of background-only fits to the data performed in each category. The dashed histogram corresponds to the signal expectation for a Higgs boson mass of 125 GeV decaying to $Z\gamma$ at 50 times the SM-predicted rate.

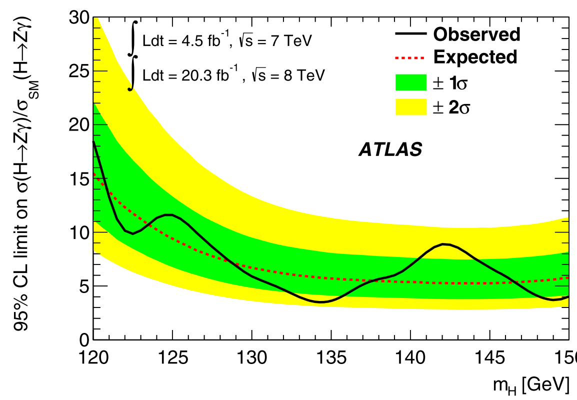

Fig. 3. Observed 95% CL limits (solid black line) on the production cross section of an SM Higgs boson decaying to $Z\gamma$ divided by the SM expectation. The limits are computed as a function of the Higgs boson mass. The median expected 95% CL exclusion limits (dashed red line), in the case of no expected signal, are also shown. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

0.2σ. The expected p_0 at $m_H = 125.5$ GeV is 0.42, corresponding to a significance of 0.2σ, while the observed p_0 at the same mass is 0.27 (0.6σ).

Observed and expected 95% CL upper limits on the value of the signal strength μ are derived and shown in Fig. 3. The expected limit ranges between 5 and 15 and the observed limit varies between 3.5 and 18 for a Higgs boson mass between 120 and 150 GeV. In particular, for a mass of 125.5 GeV, the observed and expected limits are equal to 11 and 9 times the Standard Model prediction, respectively. At the same mass the expected limit on μ assuming the existence of an SM ($\mu = 1$) Higgs boson with $m_H = 125.5$ GeV is 10. The results are dominated by the statistical uncertainties: neglecting all systematic uncertainties, the observed and expected 95% CL limits on the cross section at 125.5 GeV decrease by about 5%.

Upper limits on the $pp \to H \to Z\gamma$ cross section times branching ratio are also derived at 95% CL, for $\sqrt{s} = 7$ and 8 TeV. For $\sqrt{s} = 8$ TeV, the limit ranges between 0.13 and 0.5 pb; for $\sqrt{s} = 7$ TeV, it ranges between 0.20 and 0.8 pb. At $m_H = 125.5$ GeV the expected and observed limits are 0.33 pb and 0.45 pb, respectively, for $\sqrt{s} = 8$ TeV, and 0.7 pb and 0.5 pb, respectively, for $\sqrt{s} = 7$ TeV.

7. Conclusions

A search for a Higgs boson in the decay channel $H \to Z\gamma$, $Z \to \ell\ell$ ($\ell = e, \mu$), in the mass range 120–150 GeV, was performed using 4.5 fb^{-1} of proton–proton collisions at $\sqrt{s} = 7$ TeV and 20.3 fb^{-1} of proton–proton collisions at $\sqrt{s} = 8$ TeV recorded with the ATLAS detector at the LHC. No excess with respect to the background is found in the $\ell\ell\gamma$ invariant-mass distribution and 95% CL upper limits on the cross section times branching ratio are derived. For $\sqrt{s} = 8$ TeV, the limit ranges between 0.13 and 0.5 pb. Combining $\sqrt{s} = 7$ and 8 TeV data and dividing the cross section by the Standard Model expectation, for a mass of 125.5 GeV, the observed 95% confidence limit is 11 times the SM prediction.

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