Search for the Standard Model Higgs boson in the $H \to Z\gamma$ decay mode with $pp$ collisions at $\sqrt{s} = 7$ and 8 TeV

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Abstract

This note presents a search for the Standard Model Higgs boson in the decay channel $H \to Z\gamma$, $Z \to \ell^+\ell^-$, where $\ell = e$ or $\mu$, using 4.6 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV and 20.7 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 8$ TeV recorded with the ATLAS detector at the LHC. The distribution of the difference $\Delta m$ between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ is compared to Standard Model (SM) background expectations. No significant deviation from the SM prediction is observed and upper limits on the cross section of a Higgs boson with a mass between 120 and 150 GeV are derived. The expected exclusion limits at 95% confidence level range between 7.3 and 22 times the predicted Standard Model cross section. The observed exclusion limits range between 5.4 and 37 times the Standard Model cross section. For a Higgs boson mass of 125 GeV, the expected and observed limits are 13.5 and 18.2 times the Standard Model, respectively.
1 Introduction

In 2012 the ATLAS and CMS experiments announced the discovery of a Higgs-like boson [1, 2]. Its mass is measured by ATLAS to be close to 125 GeV [3]. In order to determine whether the newly discovered particle is the SM Higgs boson or a different object, it is fundamental to fully characterize its properties, including parity, spin, and decays to as many final states as possible. This note presents the search for the Standard Model Higgs boson in the decay channel \( H \rightarrow Z\gamma \), \( Z \rightarrow \ell^+\ell^- \), where \( \ell = e \) or \( \mu \), using 20.7 fb\(^{-1}\) of proton-proton collisions at \( \sqrt{s} = 8 \) TeV recorded with the ATLAS detector at the LHC. A similar search has recently been presented by the CMS Collaboration [4].

In the SM, the Higgs boson decays to \( Z\gamma \) via loop diagrams similar to \( H \rightarrow \gamma\gamma \) (Fig. 1) with the dominant contribution originating from the \( W \)-mediated amplitudes. For a Higgs boson mass of 125 GeV the predicted \( pp \rightarrow H \) cross section is \( \sigma = 17.5 (22.3) \) pb at 7 (8) TeV, and the branching ratio \( B(H \rightarrow Z\gamma) = 1.54 \times 10^{-3} [5, 6] \). Including \( B(Z \rightarrow \ell^+\ell^-) = 6.7% [7] \) reduces the total cross section to 1.8 (2.3) fb, roughly similar to that of \( pp \rightarrow H \rightarrow ZZ^* \rightarrow 4\ell \) and only 5% of that of \( pp \rightarrow H \rightarrow \gamma\gamma \). The reconstructed final state can be produced also from internal photon conversion in Higgs-boson decays to di-photons (\( H \rightarrow \gamma^*\gamma \rightarrow \ell\ell\gamma \)) or from radiation emission by leptons in Higgs-boson decays to di-leptons (\( H \rightarrow \ell\ell^* \rightarrow \ell\ell\gamma \)) [8]. The selection applied in this study suppresses these additional \( H \rightarrow \ell\ell\gamma \) decay processes.

![Figure 1: Leading Feynman diagrams for the \( H \rightarrow Z\gamma \) decay in the Standard Model. In the case of the fermion loop, top quarks dominate.](image)

The main backgrounds originate from \( Z+\gamma \) events, either from diboson production in the \( t, u \) channels (also referred to as initial-state-radiation), from final-state-radiation (FSR) in radiative \( Z \) boson decays (\( Z \rightarrow \ell\ell\gamma \)) or from parton-to-photon fragmentation, and production of a \( Z \) boson in association with jets, followed by a \( Z \rightarrow \ell\ell \) decay, and misidentification of a jet as a photon. Smaller contributions arise from other backgrounds (\( tt \) and \( W/Z \) processes). Although the background level for \( H \rightarrow Z\gamma \) is reduced compared to \( H \rightarrow \gamma\gamma \), it is orders of magnitude higher than that for \( H \rightarrow ZZ^* \rightarrow 4\ell \).

Measurements of (or limits on) the \( H \rightarrow Z\gamma \) decay rate can provide insight into models beyond the SM. The decay rate can help determine whether the new boson is the Higgs boson or a member of other electroweak singlets or triplets. Moreover, because the \( H \rightarrow Z\gamma \) decay proceeds via electroweak loop coupling to the Higgs boson, it can provide direct evidence of new heavy particles appearing there. Some models [9, 10, 11, 12] predict significant enhancements over the SM rate. However, many of these alternative hypotheses are already severely limited by the known \( H \rightarrow \gamma\gamma, H \rightarrow ZZ \), and SM \( Z\gamma \) measurements [13]. Nonetheless, the measurement of \( H \rightarrow Z\gamma \) (and its rate compared to \( H \rightarrow \gamma\gamma \) is important for extending our understanding of the Higgs mechanism.

In the following, the ATLAS detector is briefly described in Section 2, the signal and background simulation samples used in the analysis are presented in Section 3. The event selection criteria are described in Section 4. A comparison between the selected data sample and the simulation is presented in Section 5. The discrimination between signal and background events is performed by means of an

\[1\text{In the following the charge of the leptons will be omitted for simplicity.}\]
Monte Carlo (MC) samples are used to study the properties of signal and background events and to optimize the selection criteria. They are produced using the generators described below. Generated events are re-weighted to reproduce the observed distribution of the mean number of interactions per bunch crossing in the data and the size of the luminous beamspot. Samples of $H \rightarrow Z\gamma$ decays are generated with POWHEG [17, 18], interfaced to PYTHIA 8.170 [19] for showering and hadronization. Signal events are generated for Higgs boson masses between 120 and 150 GeV, in intervals of 5 GeV, at both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV. In each sample, the Z boson is forced to decay to charged lepton pairs. The CT10 [20] parton distribution functions (PDFs) are used. In addition, at $\sqrt{s} = 8$ TeV signal samples for the gluon fusion process for $m_H = 120, 125$ or 130 GeV are generated using MCFM 6.3 [21] interfaced to PYTHIA 8.165. The comparison between the MCFM and the POWHEG samples is used to assess systematic uncertainties related to the generator-level kinematic distributions of the final state particles.

Standard Model $Z+\gamma$ simulated events are generated with SHERPA 1.4.0 (at $\sqrt{s} = 7$ TeV) and 1.4.1 (at $\sqrt{s} = 8$ TeV) [22, 23], using the CT10 PDFs. Separate samples are produced for the $e\gamma$ and $\mu\gamma$ final states. Up to three additional partons are produced in the hard scattering processes, with matrix elements implemented at leading order (LO).

$Z$+jets events are generated with SHERPA 1.4.0 and ALPGEN 2.13 [24] interfaced to HERWIG 6.510 [25] for parton shower and fragmentation into particles and to JIMMY 4.31 [26] to model underlying event contributions, using the AUET2-CTEQ6L1 tune [27]. Separate samples are produced.

2 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates ($r, \phi$) are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = - \ln \tan(\theta/2)$.
for Z bosons decaying either to electron or muon pairs. The ALPGEN samples are generated using the CTEQ6L1 [28] PDFs, while the SHERPA samples use the CT10 ones. PHOTOS [29] is used to simulate final state QED radiation in the ALPGEN samples. In both samples the LO matrix elements for the production of up to 5 partons are used for the event generation.

Background events from the $t\bar{t}$ process are generated with MC@NLO [30, 31] interfaced to HERWIG 6.510 for parton shower and fragmentation and to JIMMY 4.31 for the underlying event. The CT10 PDFs are used.

Background events from the $WZ$ process at $\sqrt{s} = 7$ TeV are generated with SHERPA 1.3.1 using the CTEQ6L1 PDFs. Both the $W$ and the $Z$ decay leptonically. Up to three partons are produced in the hard scattering. At $\sqrt{s} = 8$ TeV, $WZ$ events are generated with POWHEG interfaced to PYTHIA 8.165.

4 Event Selection

The analyzed data are subjected to quality requirements: events in which the ATLAS detector is not fully operational, or show data quality problems, are excluded. The resulting integrated luminosity after the trigger and data quality requirements corresponds to 20.7 fb$^{-1}$ (4.6 fb$^{-1}$), with a relative uncertainty of 3.6% (1.8%) at $\sqrt{s} = 8$ TeV ($\sqrt{s} = 7$ TeV) [32, 33]. Unless explicitly specified, the selection criteria at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 7$ TeV are identical. Values quoted in parentheses correspond to the $\sqrt{s} = 7$ TeV run period.

Data are selected using the lowest threshold, unprescaled single-lepton or di-lepton triggers. For the single-muon trigger the transverse momentum, $p_T$, threshold is 24 (18) GeV, while for the single-electron trigger the transverse energy, $E_T$, threshold is 24 (20) GeV. For the di-muon triggers the thresholds are $p_T > 13$ (10) GeV for each muon, while for the di-electron triggers the thresholds are $E_T > 12$ GeV for each electron. At $\sqrt{s} = 8$ TeV an asymmetric di-muon trigger is also used with $p_{T1} > 18$ GeV and $p_{T2} > 8$ GeV. The trigger efficiency with respect to events passing the selection criteria is around 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 $|\eta| < 1.05$ region.

Primary vertices are determined from fits to 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 to it is considered as the primary vertex of the hard interaction.

Muons candidates are formed starting from tracks reconstructed either in the ID or in the MS [34]. The MS extends the muon reconstruction coverage to the forward region ($2.5 < |\eta| < 2.7$), which is outside of the ID acceptance. If a track is reconstructed both in the ID and in the MS, the two independent momentum measurements are combined; otherwise the momentum is measured using the ID or the MS information alone. In the center of the barrel region ($|\eta| < 0.1$), which lacks MS coverage, ID tracks with $p_T > 15$ GeV are identified as muons using the profile of the associated energy deposits in the calorimeter. All muon candidates identified using the information from the MS are required to have transverse momentum $p_T > 10$ GeV and $|\eta| < 2.7$, while the ones that are tagged by the calorimeters must have $p_T > 15$ GeV and $|\eta| < 0.1$. The inner detector tracks associated to 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).

The electron and photon reconstruction are seeded from clusters of energy deposits in the electromagnetic calorimeter. The reconstruction is designed to separate electrons, unconverted photons, and photons which have converted in the detector material to electron-positron pairs. The clusters are matched to tracks and to conversion vertex candidates, which have been reconstructed in the inner detector and extrapolated to the second layer of the calorimeter [35]. Clusters with a matching track are classified as electrons. Clusters without any matching track or conversion vertex are classified as unconverted photon.
candidates, while the ones with a matching vertex reconstructed from one or two tracks are converted photon candidates. 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 [36]. The energies of the clusters are calibrated, separately for electrons, unconverted and converted photon candidates, to account for energy losses upstream of the calorimeter and for energy leakage outside of the cluster. In data, the calibration is refined by applying $\eta$-dependent correction factors, which are of the order of $\pm1\%$, determined from data-to-MC comparisons of the $Z$ boson mass peak in $Z \rightarrow e^+e^-$ events [37]. In addition, the energy measurement of converted photons is improved with corrections, evaluated as a function of the conversion radius (i.e. the distance from the beamline at which the photon converts into an $e^+e^-$ pair) based on dedicated Monte Carlo simulation studies.

Electron candidates are required to have a transverse energy greater than 10 GeV, pseudorapidity $|\eta| < 2.47$, a well-reconstructed ID track pointing to an 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 [37]. The electron four-momentum is formed using the energy measured by the calorimeter and the track azimuth and pseudorapidity measured in the inner detector. The electron track is required to have a hit in the $b$-layer when passing through an active $b$-layer 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. In order to exploit the fine segmentation of the first layer of the electromagnetic calorimeter to discriminate between genuine prompt photons and fake photons within jets, the photon candidate pseudorapidity must satisfy $|\eta| < 1.37$ or $1.52 < |\eta| < 2.37$. The photon four-momentum is formed using the energy measured by the calorimeter and the direction determined by the nominal IP and the energy-weighted barycenter of all cluster cells in the second layer of the calorimeter. Photons reconstructed 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 in the hadronic calorimeter. To further suppress hadronic background, an isolation requirement is applied. The calorimeter isolation transverse energy $E_{T}^{iso}$ is estimated by summing the transverse energy of three-dimensional positive-energy topological clusters reconstructed in the electromagnetic and hadronic calorimeters in a cone of $\Delta R = 0.4$ around the photon candidate, where the region within $0.125 \times 0.175$ in $\eta \times \phi$ around the photon barycenter is excluded. The isolation energy is corrected by subtracting the estimated contributions from the leakage of the photon energy outside of the excluded region and, using the technique described in Refs. [38, 39], from the underlying event and additional $pp$ interactions. Photon candidates are required to have an isolation transverse energy of less than 4 GeV.

An overlap removal between electrons and muons that pass all selection criteria and share the same inner detector track within a cone of $\Delta R < 0.02$ is performed: if the muon is identified by the MS, then the electron candidate is discarded, otherwise the muon candidate is rejected. Photon candidates that are within $\Delta R < 0.3$ of a selected electron or muon candidate are also rejected, thus suppressing background from FSR $Z+\gamma$ events.

$Z$ boson candidates are reconstructed from pairs of same-flavor, opposite-sign leptons passing the previous selections. Muon pairs are required to have no more than one muon identified either without the MS or in the region outside the ID acceptance. In case of multiple $Z$ candidates in the same event, the candidate with the invariant mass closest to the $Z$ pole is selected.

Higgs boson candidates are reconstructed from the combination of the $Z$ candidate with invariant mass closest to the $Z$ pole and the photon with largest transverse energy. Track and calorimeter isolation requirements are applied to the leptons forming the Higgs boson candidate. The normalized track isola-
tion is defined as the sum of the transverse momenta of tracks, $\sum p_T$, inside a cone of $\Delta R < 0.2$ around the lepton, excluding the lepton track, divided by the lepton $p_T$. Each lepton is required to have a normalized track isolation smaller than 0.15. The normalized calorimetric isolation for electrons, computed as the sum of the positive-energy topological clusters with a reconstructed barycenter falling in a cone of $\Delta R < 0.2$ around the candidate electron topological cluster divided by the electron $E_T$, must be lower than 0.2. The cells within $0.125 \times 0.175$ in $\eta \times \phi$ around the electron barycenter are excluded. The calorimetric isolation $E_T^{\text{cone}}$ for muons is computed from the sum of the transverse energy of the calorimeter cells inside a cone of $\Delta R < 0.2$ around the muon direction. The transverse energy of the cells inside a predefined region around the points where the muon track crosses the different layers of the calorimeters and accounts for the muon energy loss itself is subtracted. Muons are required to have a normalized calorimetric isolation $E_T^{\text{cone}}/p_T$ less than 0.3 (0.15 in case of muons without an ID track). For both the track- and calorimeter-based isolation any contributions arising from the other lepton from the candidate $Z$ decay are subtracted. Additional track impact significance selections are also applied to the leptons from the $Z$ candidate decay. The transverse impact parameter significance $|d_0|/\sigma_{d_0}$ of the ID track associated to leptons 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. The isolation criteria, as well as the impact significance selections applied in this analysis, have been optimized in the search for the SM Higgs boson in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel [40].

Finally, to suppress events from FSR $Z \rightarrow \ell\ell\gamma$, the di-lepton invariant mass is required to be larger than the PDG value of the $Z$ boson mass minus 10 GeV. This requirement also reduces the contribution to the signal from internal photon conversions in $H \rightarrow \gamma\gamma$ to a negligible level [41].

After applying all selection criteria, the number of $H \rightarrow Z\gamma$ candidate events in the $\sqrt{s} = 8$ TeV ($\sqrt{s} = 7$ TeV) data sample is 13978 (1927) in the $Z \rightarrow e\gamma$ channel and 16678 (2621) in the $Z \rightarrow \mu\gamma$ channel. The same reconstruction algorithms and selection criteria are used for simulated events. The simulation is corrected to take into account known data-MC differences on photon and lepton efficiencies and energy or momentum resolution.

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, two corrections are applied to the three-body mass $m_{\ell\ell\gamma}$. First, the photon pseudorapidity $\eta^\gamma$ and its transverse energy $E_T^\gamma = E_T^\gamma / \cosh \eta^\gamma$ are recalculated from the identified primary vertex and the photon impact point in the calorimeter. Second, the lepton four-momenta are recomputed by means of the $Z$-mass constrained kinematic fit previously used in the $H \rightarrow 4\ell$ search [1]. The distribution of $m_{\ell\ell\gamma}$ for simulated signal events from $gg \rightarrow H$ at $m_H = 125$ GeV after all corrections is shown in Fig. 2.

5 Data-driven background estimation

The main backgrounds in the $H \rightarrow Z\gamma$ search originate from SM $Z+\gamma$ and $Z$+jets events, with small contributions from $t\bar{t}$ and $WZ$ events. In $Z+\gamma$ events, the requirements $m_{\ell\ell} > 81.2$ GeV and $\Delta R_{\ell\gamma} > 0.3$ suppress the contribution from FSR, while the photon isolation requirement reduces the importance of the fragmentation component. The latter, together with the photon identification requirements, is also effective in reducing $Z$+jets events.

In this analysis the background composition is not used to determine the amount of expected background, which is directly fitted to the data mass spectrum, but is needed to optimize the background modeling used in the signal extraction as described in Section 7. In this section a data-driven estimation of the background composition is performed, based on a two-dimensional sideband method 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. This technique was first used by ATLAS in the measurement of the Standard Model prompt photon production cross section [42].
and then exploited also in the $H \rightarrow \gamma\gamma$ [43] and SM $W/Z + \gamma$ [44] measurements. The $Z+\gamma$ and $Z$+jets contributions are estimated in situ applying the two-dimensional sideband technique to the data after subtracting the contribution from the $t\bar{t}$ and $WZ$ backgrounds. The simulation is used to estimate the small backgrounds from $t\bar{t}$ and $WZ$ (normalized to the data luminosity using the NLO MC cross sections, on which a conservative uncertainty of $\pm50\%$ is applied), as well as 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 from the $H \rightarrow Z\gamma$ 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 backgrounds are estimated to be around 82%, 17% and 1% at both $\sqrt{s} = 7$ and 8 TeV. The 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. A comparison between the three-body invariant mass distribution in data and in the simulation, where the MC background distributions have been normalized to the yields estimated with the previous procedure, is shown in Fig. 3. A 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 have also been studied.

6 Signal properties

The properties of the signal, in terms of expected yields and of the signal model used for the fit, are described in this section.

6.1 Expected signal yield

The Higgs boson cross sections, branching ratios [45, 46, 47] and their uncertainties are compiled in Refs. [5, 6]. The Higgs boson production cross sections are computed up to next-to-next-to-leading order (NNNLO) [48, 49, 50, 51, 52, 53] in $\alpha_s$ for the gluon fusion process. The next-to-leading order (NLO) EW corrections are applied [54, 55]. These results are compiled in Refs. [56, 57, 58] assuming factorization between QCD and EW corrections. The cross sections for the VBF process are calculated with full NLO QCD and EW corrections [59, 60, 61], and approximate NNLO QCD corrections are applied [62]. The $W/ZH$ processes are calculated at NLO [63] and at NNLO [64] in $\alpha_s$, and NLO EW radiative corrections [65] are applied. The full NLO QCD corrections for $t\bar{t}H$ are calculated [66, 67, 68, 69].
Figure 3: Three-body invariant mass ($m_{\ell\ell\gamma}$) distribution of selected events in data (dots) and from the various background sources (histograms, from the simulation) normalized to the yields determined as described in the text, for $Z \rightarrow ee$ (left) and $Z \rightarrow \mu\mu$ (right) channels. The small peak near $m_Z$ is from residual FSR $Z+\gamma$ contamination. The background uncertainty includes statistical uncertainties and systematic uncertainties from the inputs taken from the simulation, as detailed in the text.
The signal selection efficiency as a function of the Higgs boson mass, in steps of 0.5 GeV, is obtained through an interpolation of the values estimated using the simulated signal samples. Taking into account the signal production cross section and branching fraction, the signal selection efficiency, and $B(Z \rightarrow \ell\ell) = (3.3658 \pm 0.0023)\%$ [7], the number of signal events expected after the selection as a function of the Higgs boson mass is obtained. The contribution from $H \rightarrow \ell\ell\gamma$ decays proceeding through internal photon conversions in $H \rightarrow \gamma\gamma$ or FSR from leptons in $H \rightarrow \ell\ell$ is neglected in this calculation. The expected signal yields and selection efficiencies for Higgs boson masses between 120 and 150 GeV and for an integrated luminosity of 20.7 fb$^{-1}$ (4.6 fb$^{-1}$) at $\sqrt{s} = 8$ (7) TeV are shown in Table 1.

Table 1: Selection efficiency ($\varepsilon$) and number of expected $H \rightarrow Z\gamma$ signal events ($S$), for Higgs boson masses between 120 and 150 GeV, for the two reconstructed $Z$ boson final states and for 4.6 fb$^{-1}$ at $\sqrt{s} = 7$ TeV and 20.7 fb$^{-1}$ at $\sqrt{s} = 8$ TeV. The relative statistical uncertainty on the quoted numbers is around 1%.

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<th>$Z \rightarrow \mu\mu$, 7 TeV</th>
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6.2 Signal model

The search for the SM Higgs boson decay to $Z\gamma$ is performed through a fit to the distribution of an observable that discriminates between signal and background. Two observables have been studied: the three-body invariant mass of the final state particles, $m_{\ell\ell\gamma}$, and the difference between the three-body and the di-lepton invariant masses, $\Delta m = m_{\ell\ell\gamma} - m_{\ell\ell}$. Both $m_{\ell\ell\gamma}$ and $m_{\ell\ell}$ are computed using the $Z$-mass constraint described in Section 4, and $m_{\ell\ell\gamma}$ is also corrected to use the primary vertex as the photon origin. In the fit, a model for the signal and background probability density functions of the observable under study is needed. It has been found that both observables $m_{\ell\ell\gamma}$ and $\Delta m$ of signal events generated at a fixed Higgs boson nominal mass are well described by the sum of a Crystal Ball lineshape (a Gaussian with a power-law tail), representing the core of well-reconstructed events, and a small wide Gaussian component modeling poorly reconstructed events (outliers).

The final results, described in Section 9, are based on fits to the $\Delta m$ distributions. Fig. 4 shows the distribution of $\Delta m$ for signal events passing the full selection, for $m_H = 125$ GeV and $\sqrt{s} = 8$ TeV. The width of the $\Delta m$ distribution is dominated by the $Z$-boson intrinsic width, with a subleading contribution of $\approx 1$ GeV from the photon energy resolution (which is around 3%). Although the $Z$-mass constraint is applied, the $\Delta m$ resolution remains essentially unaffected.

The choice of $\Delta m$ over $m_{\ell\ell\gamma}$ as the discriminant observable has two advantages. First, it is almost unaffected by lepton energy scale uncertainties. Second, it is to a large extent insensitive to the contribution to the signal from FSR in $H \rightarrow \mu\mu$ decays ($H \rightarrow eee$ from FSR in $H \rightarrow ee$ in the SM is expected to be negligible due to the small electron mass). The $E_T^\gamma$ and $\Delta R_{\ell\gamma}$ requirements significantly suppress this contribution, which produces photons that are typically soft and collinear with the emitting lepton.
Figure 4: Distribution (normalized to unit area) of the difference $\Delta m$ between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ for signal events passing the full selection (dots), for $m_H = 125$ GeV and $\sqrt{s} = 7$ (top) or 8 (bottom) TeV. The line overlaid represents the fit of the distribution with a model composed of the sum of a Crystal Ball (CB) and a Gaussian (GA) function. Left: electron channel, right: muon channel.
However, studies performed at event-generator level, with both PYTHIA 8.150 interfaced to PHOTOS and MADGRAPH5 1.5.2 [70], indicate that after the selection there may be a non negligible residual contamination of $\mu^{+}\mu^{-}$, at the level of 5%. This could not be distinguished from $H \rightarrow Z\gamma$ if $m_{\ell\ell\gamma}$ were chosen as the discriminating variable, as $m_{\ell\ell\gamma}$ peaks at the Higgs boson mass $m_H$ for both $H \rightarrow Z\gamma$ and $H \rightarrow \mu\mu\gamma$. On the other hand, the $\Delta m$ distribution of $H \rightarrow \mu\mu\gamma$ decays does not produce a peak and the presence of a small residual $H \rightarrow \mu\mu\gamma$ contamination does not bias the fitted $H \rightarrow Z\gamma$ yield.

7 Background model

In order to distinguish the Higgs boson signal from the background using $\Delta m$ as a discriminant, a model for the background distribution is needed. The model has been chosen carefully so that it does not introduce significant biases ("spurious signal") on the fitted signal while at the same time preserving the sensitivity of the search.

Several functional forms have been tested, including polynomials of various orders, as well as non-polynomial functions such as exponential, Crystal Ball, Crystal Ball+Gaussian, and Crystal Ball+Landau distributions. The advantage of non-polynomial functions is that in general they do not follow local peaks and troughs in the mass distribution. The models have been tested by performing signal+background fits of the $\Delta m$ distribution of high-statistics simulated background-only samples and evaluating the ratio of the fitted spurious signal to the statistical uncertainty on the fitted signal itself. The model that was found to provide the best sensitivity to the signal while limiting the spurious signal to be within ±20% of the fitted signal uncertainty, for both 4.6 fb$^{-1}$ of 2011 data and 20.7 fb$^{-1}$ of 2012 data, is a third-order Chebychev polynomial in the fit range $24 < \Delta m < 64$ GeV. The spurious signal is treated as a systematic uncertainty on the fitted signal yield in the final statistical analysis described in Section 9.

8 Systematic Uncertainties

The theoretical and experimental systematic uncertainties are summarized in this section.

8.1 Theoretical uncertainties

The Higgs boson production cross sections and decay branching fractions as functions of the Higgs boson mass are compiled, together with their uncertainties, in Ref. [5]. Theoretical uncertainties on the production cross section are separated into two components: the uncertainty related to the energy scales used for the fixed-order calculation, and the uncertainty from the PDF eigenvalues and the value of $\alpha_s$ used in the perturbative calculation. The scale uncertainties are considered uncorrelated among the five Higgs boson production modes, while the PDF uncertainties are considered correlated among the gluon fusion and $t\bar{t}H$ processes, which are induced by $gq$ diagrams and thus sensitive to the uncertainty on the gluon PDF, and among the VBF and $WH/ZH$ processes, which are induced by $q\bar{q}$ diagrams. For each tested Higgs boson mass hypothesis the uncertainties from Ref. [5] are used. Table 2 summarizes the theoretical uncertainties for a Higgs boson mass of 125 GeV. They depend only mildly on $m_H$, for $120 < m_H < 150$ GeV, with the exception of the relative uncertainty on the $H \rightarrow Z\gamma$ branching fraction, which varies between 9.4% at 120 GeV and 6.2% at 150 GeV.

Theoretical uncertainties on the background cross sections do not affect the results shown in the next section, because the background normalization and shape are obtained through a fit to the data.
8.2 Experimental uncertainties

The following sources of experimental systematic uncertainties on the expected signal yields have been considered:

- Luminosity. The uncertainty on the integrated luminosity for the 2011 data is 1.8% [33]. The uncertainty on the integrated luminosity in 2012 is ±3.6%. It is derived, following the same methodology as that detailed in Ref. [33], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in April 2012.

- Acceptance of the kinematic requirements. The uncertainties related to the acceptance of the selection criteria are estimated by comparing the acceptance estimated with simulated signal events and the simulated efficiencies is used. This amounts to 2.5% for $E_T < 40$ GeV and for unconverted photons with $|\eta| > 1.81$, and to 1.5% otherwise. The resulting uncertainty on the $H \rightarrow Z\gamma$ selection efficiency is below 3%.

- Photon identification efficiency. At $\sqrt{s} = 7$ TeV, the signal yield is recomputed by varying the photon identification efficiency scale factors within their uncertainties and the relative variation is considered as a systematic uncertainty. At $\sqrt{s} = 8$ TeV a conservative estimate of the uncertainty on the photon identification efficiency obtained from a comparison between data-driven measurements and the simulated efficiencies is used. This amounts to 2.5% for $E_T < 40$ GeV and for unconverted photons with $|\eta| > 1.81$, and to 1.5% otherwise. The resulting uncertainty on the $H \rightarrow Z\gamma$ selection efficiency is below 3%.

- Photon and electron calorimeter isolation requirements. The signal efficiency is measured from simulated events. To estimate the systematic uncertainty due to the uncertainty on the efficiency of the isolation criteria, the signal efficiency is recomputed by shifting, in the simulation, the photon and electron calorimeter isolation energies by the average difference observed between data and Monte Carlo for photons and electrons, selected either in di-photon enriched events or in a control sample of electrons from $Z \rightarrow ee$. These differences are of the order of 100 MeV for the topological-cluster based isolation. The systematic uncertainty on the signal efficiency ranges between 0.2% and 0.4%.

- Photon and electron energy scales. The uncertainty from the electromagnetic (photon and electron) energy scales is assessed by varying the electromagnetic energy scale corrections (applied to the data) within their uncertainties. The effects of the uncertainty from the $Z \rightarrow ee$ control sample used to extract the scale factors, of the limited knowledge of the material, of the uncertainty on the presampler energy scale and of the low-$p_T$ scale factor uncertainties are evaluated. The total
uncertainty on the signal efficiency is around 0.2% for events in which the Z boson candidate decays to muons and between 0.4% and 1.2% for events in which the Z boson candidate decays to electrons.

- Photon and electron energy resolution. The uncertainty from the photon and electron energy resolution is estimated by varying the smearing correction within its uncertainties and observing the relative variation in the predicted signal yield. The estimated uncertainty is smaller than 0.2%.

- Electron trigger, reconstruction and identification efficiency. The electron trigger, reconstruction and identification efficiency uncertainties are estimated by varying the efficiency scale factors applied to the simulation within their uncertainties. The total uncertainty, for events in which the Z boson candidate decays to electrons, is around 3%.

- Muon momentum scale and resolution. The uncertainty of the efficiency of the $p_T > 10$ GeV cut (15 GeV for muons tagged in the calorimeters) is estimated by varying the muon momentum corrections in MC by their uncertainties. The effect is around 0.1%.

- Muon trigger, reconstruction and identification efficiency. The trigger, reconstruction and identification muon efficiency uncertainties are estimated by varying the efficiency scale factors within their uncertainties. The total uncertainty, for events in which the Z boson candidate decays to muons, is below 1%.

Other sources of uncertainties (the efficiency of the impact parameter and track isolation requirements for the leptons and of the calorimeter isolation selection for muons) have been estimated comparing the efficiencies in data and Monte Carlo for control samples of leptons from Z decays and found to be negligible. The total relative uncertainty on the signal efficiency is around 5%.

The following sources of experimental systematic uncertainties on the signal $\Delta m$ distribution have been considered:

- Photon and electron energy scales. The signal $\Delta m$ distribution is recomputed after varying the electromagnetic energy scale corrections within their uncertainties, and the shift of the peak position (0.2 GeV) is considered as the systematic uncertainty.

- Photon and electron energy resolution. The signal $\Delta m$ distribution is recomputed after varying the electromagnetic energy smearing corrections within their uncertainties, and the relative variation of its width is taken as a systematic uncertainty. It amounts to 2.4% for events in which the Z boson candidate decays to muons and to 5% for events in which the Z boson candidate decays to electrons.

- Muon momentum scale. The signal $\Delta m$ distribution is recomputed after varying the muon momentum scale within its uncertainties, and the shift of the peak position is considered as a systematic uncertainty. This uncertainty is found to be negligible.

- Muon momentum resolution. The signal $\Delta m$ distribution is recomputed after varying the muon momentum smearing corrections within their uncertainties, and the relative variation of its width (0-1.5%) is taken as a systematic uncertainty.

The list of the main sources of systematic uncertainties and their contributions to the $H \rightarrow Z\gamma$ expected signal yields and parameters of the signal $\Delta m$ distributions are listed in Table 3 for $m_H = 125$ GeV and $\sqrt{s} = 8(7)$ TeV. The systematic uncertainties are profiled in the final maximum likelihood fit to the data, as described in Section 9.3. All systematic uncertainties, except that on the luminosity, are treated as correlated between the $\sqrt{s} = 7$ TeV and the $\sqrt{s} = 8$ TeV analyses.
Table 3: Summary of the systematic uncertainties on the signal yield and invariant mass distribution for $m_H = 125$ GeV, at $\sqrt{s} = 8(7)$ TeV.

<table>
<thead>
<tr>
<th>Systematic Uncertainty</th>
<th>$H \rightarrow Z(ee)\gamma$ (%)</th>
<th>$H \rightarrow Z(\mu\mu)\gamma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity</td>
<td>3.6 (1.8)</td>
<td>3.6 (1.8)</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>0.4 (0.2)</td>
<td>0.8 (0.7)</td>
</tr>
<tr>
<td>Acceptance of kinematic selection</td>
<td>4.0 (4.0)</td>
<td>4.0 (4.0)</td>
</tr>
<tr>
<td>$\gamma$ identification efficiency</td>
<td>2.9 (2.9)</td>
<td>2.9 (2.9)</td>
</tr>
<tr>
<td>electron reconstruction and identification efficiency</td>
<td>2.7 (3.0)</td>
<td>0.6 (0.7)</td>
</tr>
<tr>
<td>$\mu$ reconstruction and identification efficiency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e/\gamma$ energy scale</td>
<td>1.4 (0.3)</td>
<td>0.3 (0.2)</td>
</tr>
<tr>
<td>$e/\gamma$ isolation</td>
<td>0.4 (0.3)</td>
<td>0.4 (0.2)</td>
</tr>
<tr>
<td>$e/\gamma$ energy resolution</td>
<td>0.2 (0.2)</td>
<td>0.0 (0.0)</td>
</tr>
<tr>
<td>$\mu$ momentum scale</td>
<td></td>
<td>0.1 (0.1)</td>
</tr>
<tr>
<td>$\mu$ momentum resolution</td>
<td></td>
<td>0.0 (0.1)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal $\Delta m$ resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e/\gamma$ energy resolution</td>
</tr>
<tr>
<td>$\mu$ momentum resolution</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Signal $\Delta m$ peak position</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e/\gamma$ energy scale</td>
</tr>
<tr>
<td>$\mu$ momentum scale</td>
</tr>
</tbody>
</table>

9 Results

In this section we present the expected and observed $p$-values for the compatibility of the data with the background-only hypothesis ($p_0$) and the 95% confidence level ($CL$) exclusion limits on the cross section of a Standard Model Higgs boson decaying to $Z\gamma$, for a possible Higgs boson mass between 120 and 150 GeV.

9.1 Likelihood

The results are obtained using an unbinned maximum likelihood $L$ depending on a single observable, the difference $\Delta m$ between the invariant mass of the three final state particles and the di-lepton invariant mass. The model includes a single parameter of interest, the signal strength $\mu$, defined as the ratio of the signal cross section to that predicted by the SM, and thus equal to the ratio between observed and expected signal events. In addition, several nuisance parameters are considered, which describe the normalization and $\Delta m$ distribution of the background and the systematic uncertainties. A simultaneous fit is performed to the four orthogonal categories defined by the lepton flavor and the center-of-mass energy of the dataset.

Systematic uncertainties are incorporated into the full likelihood by adding a nuisance parameter $\theta$ for each source of uncertainty, so that the signal and background expectations (yields or parameters of the model) become functions of $\theta$ (with $\theta = 0$ corresponding to the nominal value of the signal yield and resolution and $\theta = \pm 1$ corresponding to the $\pm 1\sigma$ variation of the yield or the resolution due to the source of the uncertainty). The global likelihood is then multiplied by a constraint term, i.e. a probability density function of $\theta$, and the nuisance parameters are then fitted (“profiled”) to the data, together with the parameters of interest ($\mu$), when minimizing $-\log L$. For systematic uncertainties affecting the expected yields, a log-normal constraint is used while for the uncertainty on the signal $\Delta m$ resolution a Gaussian constraint is used. Correlated uncertainties share the same nuisance parameter. In summary, the model includes eight nuisance parameters describing theory uncertainties (five for the scales, two for PDFs, one
for the $H \to Z\gamma$ branching fraction), 13 for the experimental uncertainties described in Section 8, and two for the spurious signal term described in Section 7. Including the background normalization parameters (four in total) and the background shape parameters (three for each category) the total number of nuisance parameters is thirty nine.

9.2 Background-only fits to the data

The shape parameters and the normalization of the background are determined by unbinned maximum likelihood fits to the data events selected in the range $24 \text{ GeV} < \Delta m < 64 \text{ GeV}$, performed separately for the two lepton categories and separately for the $\sqrt{s} = 7 \text{ TeV}$ and $\sqrt{s} = 8 \text{ TeV}$ data, using the parametrizations selected in Section 7. Fig. 5 shows the background-only fits to the data in the two categories for the $\sqrt{s} = 7 \text{ TeV}$ and the $\sqrt{s} = 8 \text{ TeV}$ data.

![Figure 5: Background-only fits to the distribution of the mass difference $\Delta m$ of selected events in data, for $Z \to ee$ (left) and $Z \to \mu\mu$ (right), at $\sqrt{s} = 7 \text{ TeV}$ (top) or $8 \text{ TeV}$ (bottom). For both 7 and 8 TeV, a third order polynomial is used for the fit. Dots correspond to data, the blue line is the fit result and the gray and light red bands are the 1$\sigma$ and 2$\sigma$ uncertainty bands from the statistical uncertainties on the fitted background model parameters. The dashed histograms correspond to the SM signal expectation, for a Higgs boson mass of 125 GeV, scaled by a factor 20 for clarity.](image)

14
9.3 Comparison to the background-only hypothesis and exclusion limits

The statistical procedures used to test the background-only hypothesis and to set exclusion limits are described in detail in Ref. [71]. The compatibility of the data with different values of the signal strength parameter \( \mu \) is tested as a function of the SM Higgs boson mass \( m_H \). In particular, for each value of \( m_H \), the (in)compatibility of the data with the background-only hypothesis (\( \mu = 0 \)) is tested in order to quantify the significance of a possible observation. In addition, the compatibility between the data and increasing non-zero values of \( \mu \) is used to set 95\% CL upper limits on the signal strength, using a modified frequentist (\( CL_s \)) [72] method.

The compatibility between the data and the background-only hypothesis is quantified by the \( p \)-value of the \( \mu = 0 \) hypothesis, \( p_0 \). In the following, \( p_0 \) values are computed from the \( q_0 \) values using closed-form asymptotic formulae [73]. Both observed \( p_0 \) results, computed using real data, and expected \( p_0 \) results, obtained from Asimov datasets [73] corresponding to the \( \mu = 1 \) hypothesis, are quoted.

The expected and observed \( p_0 \) values are shown in Fig. 6 as a function of the Higgs boson mass. Using the full 2011 and 2012 ATLAS data, corresponding to 4.6 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 7 \) TeV and 20.7 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 8 \) TeV, the expected \( p_0 \) ranges between 0.40 and 0.46 for \( 120 < m_H < 150 \) GeV, corresponding to significances around 0.25 \( \sigma \). The observed \( p_0 \) distribution is compatible with the data being composed of background only. The smallest \( p_0 \) (0.042), corresponding to a significance of 1.61 \( \sigma \), occurs for a mass of 141 GeV. The expected \( p_0 \) at \( m_H = 125 \) GeV is 0.443, corresponding to a significance of 0.14 \( \sigma \), while the observed one is 0.188 (0.89 \( \sigma \)).

![Figure 6: Expected (dashed blue line) and observed (solid black line) \( p_0 \) (compatibility of the data with the background-only hypothesis) as a function of the Higgs boson mass, using 4.6 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 7 \) TeV and 20.7 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 8 \) TeV.](image)

Subsequently, upper limits on the production cross section of \( H \to Z\gamma \) are set. The limits on the signal strength are computed with the \( CL_s \) technique. Limits at 95\% confidence level on the value of the signal strength \( \mu \) are computed by identifying the value \( \mu_{up} \) for which the \( CL_s \) exclusion is equal to 0.05. Both observed limits, computed using real data, and expected limits, computed using an Asimov dataset
generated in the $\mu = 0$ hypothesis, are shown in Fig. 7. The expected 95% CL limit ranges between 7.3 and 22 and the observed one varies between 5.4 and 37 for a Higgs boson mass between 120 and 150 GeV. In particular, for a mass of 125 GeV, consistent with the mass of the recently discovered Higgs-like boson, the expected and observed limits are equal to 13.5 and 18.2 times the Standard Model, respectively. The results are dominated by the statistical uncertainties: neglecting all systematic uncertainties, the observed (expected) 95% CL limit on the cross section at 125 GeV is 17.4 (12.9) times the Standard Model prediction.

Figure 7: Observed 95% CL limits (solid black line) on the production cross section of a SM Higgs boson decaying to $Z\gamma$, as a function of the Higgs boson mass, using 4.6 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV and 20.7 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV. The median expected 95% CL exclusion limits (dashed red line) are also shown. The green and yellow bands correspond to the $\pm 1\sigma$ and $\pm 2\sigma$ intervals.

10 Conclusions

In this note a search for the Standard Model Higgs boson in the decay channel $H \rightarrow Z\gamma$, $Z \rightarrow \ell\ell$, where $\ell = e$ or $\mu$, using 20.7 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 8$ TeV and 4.6 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 7$ TeV recorded with the ATLAS detector at the LHC, was presented. The distribution of the difference $\Delta m$ between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ was compared to Standard Model background expectations. No significant deviation from the SM prediction was observed and upper limits on the cross section of a Higgs boson with a mass between 120 and 150 GeV were derived. The expected exclusion limits at 95% confidence level range between 7.3 and 22 times the predicted Standard Model cross section. The observed exclusion limits range between 5.4 and 37 times the Standard Model cross section. In particular, for a mass of 125 GeV, corresponding to the mass of the recently discovered Higgs boson-like particle, the expected and observed limits are 13.5 and 18.2 times the Standard Model, respectively.
References


Figure 8: Distribution of the difference $\Delta m$ between the final state three-body invariant mass $m_{\ell\ell\gamma}$ and the di-lepton invariant mass $m_{\ell\ell}$ for selected events in data (dots) and from the various background sources (histograms) normalized to the yields determined as described in the text, for $Z \to ee$ (left) and $Z \to \mu\mu$ (right) channels. The background uncertainty includes statistical uncertainties and systematic uncertainties from the inputs taken from the simulation.