Abstract. In the low mass range (100 to 140 GeV) one of the most promising search channel for the Higgs boson at the LHC is the rare decay in a pair of photons. Photon identification and energy as well as direction measurements are key ingredients to reduce backgrounds and maximize the sensitivity to the Higgs boson signal. The analysis of the Higgs boson search in the two photon decay channel performed by the ATLAS experiment using 4.9 fb$^{-1}$ of proton-proton collisions data recorded in 2011 at the LHC is described. The role of the ATLAS Liquid Argon calorimeter in this analysis is emphasized.

1. Introduction

The Higgs mechanism [1] is one of the best-motivated processes to explain electroweak symmetry breaking. In the Standard Model, this mechanism explains the generation of the $W$ and $Z$ boson masses and predicts the existence of an elementary scalar particle, the Higgs boson. The search for the Higgs boson is one of the main goals of the Large Hadron Collider (LHC). The Higgs boson is copiously produced at the LHC via the gluon-fusion process. At large masses (above $\approx 140$ GeV mass), decays to vector bosons provide a clean signature with large branching ratio. At lower masses, the decay to $b\bar{b}$ pairs dominates and is difficult to observe in a hadron collider experiment. Thus rare decay modes have to be used. The decay in a pair of photons is considered as one of the most promising. This process was taken as a benchmark process for the optimization of the LHC detectors, especially the electromagnetic calorimeters. Figure 1 illustrates the cross-section times branching ratio as a function of the Higgs boson mass for decay modes considered as observables at the LHC [2]. With a branching ratio around 0.2%, the two photon decay mode gives a total rate of $\approx 40$ fb.

The ATLAS detector is described in Ref. [3]. The electromagnetic calorimeter is a lead-liquid argon sampling calorimeter with accordion geometry. It is divided into a barrel region, covering pseudorapidity ($\eta$) less than 1.475, and two end-caps covering 1.35 to 3.2. It is finely segmented in three longitudinal layers for $\eta$ less than 2.5. The first layer, around 4-5 radiation lengths thick, is finely segmented in the $\eta$ direction to provide $\gamma$-$\pi^0$ separation and $\gamma$ direction measurement. The cell size in $\eta$ is for instance 0.003125 in the barrel region. The second layer collects most of the shower energy and has a granularity of 0.025$\times$0.025 in $\eta \times \phi$. The last layer is used to correct for leakage beyond the electromagnetic calorimeter. In addition a thin presampler layer is located between the cryostat and the calorimeter, covering the region $\eta$ less than 1.8. It is used to correct for fluctuations in the energy loss upstream the calorimeter. A sketch of the calorimeter granularity in the barrel region can be seen in Figure 2. The electromagnetic
calorimeter comprises 173312 readout channels, 99.8% of them being operational during most of the 2011 data taking period. More details on the electromagnetic calorimeter and its operation in 2011 can be found in Ref. [4].

![Figure 1](image1.png)

**Figure 1.** The SM Higgs boson production cross-section times branching ratio at $\sqrt{s}=7$ TeV [2]

![Figure 2](image2.png)

**Figure 2.** Sketch of the electromagnetic calorimeter granularity in the barrel region

The recipe for the search of the Higgs boson decay into two photons consists in:

- Selecting events with two photon candidates. These events are “easy” to trigger on at the LHC. Jet-jet and $\gamma$-jet events should be reduced well below the level of the irreducible $\gamma$-jet continuum background and this requires rejection against jets of few thousands. To achieve this a rejection against high energies $\pi^0$, from tails of jet fragmentation, decaying into collimated photons is useful.

- Reconstructing the invariant mass of the photon pair as accurately as possible, to separate the signal from the continuum background. For the relevant Higgs boson mass range, the Higgs width is small thus the resolution is completely driven by the experimental resolution. To achieve a good mass resolution both a good energy resolution and angular resolution are needed.

- Optimizing the analysis to improve the sensitivity. This is done by splitting the data in different categories with different signal over background ratios or different mass resolutions. The classification is based on kinematical variables and on the expected photon energy resolution

The analysis described here is based on the full data set collected in 2011 by the ATLAS experiment at $\sqrt{s}=7$ TeV, corresponding to an integrated luminosity of 4.9 fb$^{-1}$ [5].

2. **Photon identification**

Photon candidates are seeded by energy clusters in the electromagnetic calorimeter. Clusters without matching inner detector tracks are classified as unconverted photon candidates. Clusters matched to either pairs of tracks which are consistent with the hypothesis of a photon conversion or single tracks without hits in the pixel layer nearest to the beam pipe are considered as converted photon candidates. The photon reconstruction efficiency is $\approx 98\%$.

Photon identification is based on the lateral and longitudinal energy profiles of the shower in the calorimeter. The photon candidate is required to deposit only a small fraction of its energy in
the hadronic calorimeter. The transverse shower shape in the second layer of the electromagnetic calorimeter needs to be consistent with that expected for a single electromagnetic shower. Using these variables, a set of loose identification criteria is defined. Finally, the high granularity first calorimeter layer is used to discriminate single photons from overlapping photon pairs from neutral meson decays produced in jet fragmentation, which are the main background source. Using cuts on all the shower shape variables, a tight identification selection is defined. This selection is different for converted photons and unconverted photons.

Figure 3 illustrates the distribution of two of the discriminating variables using the first layer of the calorimeter, for candidates fulfilling the loose identification selection. These variables are $E_{\text{ratio}}$, the asymmetry between the first and second maxima in the energy profile of the first layer along $\eta$, and $F_{\text{side}}$, the fraction of the energy in seven layer cells centered around the first maximum which is not contained in the three core cells centered around it. The separation between prompt photons and background can clearly be seen.

**Figure 3.** Examples of discriminating shower shape variables based on the energy deposit in the first longitudinal compartment of the electromagnetic calorimeter, for photon candidates passing the loose identification criteria. Left: $E_{\text{ratio}}$. Right: $F_{\text{side}}$. Photon candidates with pseudorapidity $|\eta| < 0.6$ [6].

Clean electron samples from $Z \rightarrow e^+ e^-$ are used to compare data and simulation for the distributions of the shower shape variables. An example is shown in Figure 4 for the $R_\eta$ variable, the ratio of the energy deposits in $3 \times 7$ over $7 \times 7$ cells in the second layer of the calorimeter. The shift between the data and the simulation corresponds to the fact that shower shape in data are somewhat broader than in the simulation. This difference is reduced in the latest simulation version.

To take into account these small differences, the shower shape variables are shifted in the simulation before the identification cuts are applied, by an amount corresponding to the average difference between data and simulation.

The photon identification efficiency ranges typically from 65% to 95% for transverse energies ($E_T$) in the range 25 to 80 GeV. The uncertainty on the identification efficiency is assessed using data control samples. Three different samples are used: photons from $Z \rightarrow \ell\ell\gamma$ decays, electrons from $Z \rightarrow e^+ e^-$ decays where electron shower shapes are extrapolated to photon shower shapes using simulation and loose photon candidates. The typical uncertainty on the photon identification efficiency is $\pm 5\%$, except at low $E_T$ ($< 30$ GeV) and high $|\eta|$ ($> 1.8$) for unconverted photons where it reaches $\pm 10\%$.

To further reduce the fake backgrounds, the photon candidates are required to be isolated. The isolation variable is computed by summing the transverse energy in calorimeter cells in a cone of radius 0.4 in the $\eta \times \phi$ space around the photon candidate. Cells in the electromagnetic calorimeter within $0.125 \times 0.175$ from the shower barycentre are excluded from the sum. The
small photon energy leakage outside the excluded cells is evaluated as a function of the transverse energy and is subtracted from the isolation variable. To mitigate the effect from the underlying event and pileup, the isolation is further corrected using a method suggested in Ref. [7]: for each of the two different pseudorapidity regions $|\eta| < 1.5$ and $1.5 < |\eta| < 3.0$, low energy jets are used to compute an ambient energy density which is then multiplied by the area of the isolation cone and subtracted from the isolation energy. Photon candidates are required to have an isolation variable less than 5 GeV. The isolation cut retains $\approx 87\%$ of the Higgs boson signal events, while rejecting $\approx 44\%$ of the data events.

The photon candidates are ordered in $E_T$ and the leading (subleading) candidate is required to have $E_T > 40$ GeV (25 GeV). Both photon candidates should be in the fiducial region $|\eta| < 2.37$, excluding the calorimeter barrel/end-cap transition region $1.37 < |\eta| < 1.52$. After all the identification steps, 22489 candidates are selected in the 2011 data sample. The composition of the sample (prompt diphoton pairs, photon-jet events where one jet fakes a photon, dijet events and residual Drell-Yan background with electrons misidentified as photons) is investigated using data-driven methods. A method based on the use of control regions for two discriminating variables is applied to measure the contributions of fake photon background. This method exploits relaxed isolation and photon identification cuts to estimate the fake component by relying on the fact that the rejection from these two cuts are almost independent. The Drell-Yan background is estimated by measuring the probability for an electron to be reconstructed as a photon candidate with $Z$ events and applying this probability to the observed yield of Drell-Yan events at high mass. The fraction of true diphoton events is estimated to be $(71 \pm 5)\%$. The photon-jet background is $(23 \pm 4)\%$, the dijet background $(5 \pm 3)\%$ and the Drell-Yan background $(0.7 \pm 0.1)\%$. The sample composition as a function of the diphoton invariant mass is shown in Figure 5. At this level, 69 signal events from Higgs boson decays into photon pairs are expected in the sample for a Higgs boson mass hypothesis of 125 GeV, assuming Standard Model production cross-section and branching ratio values. The acceptance of the kinematical cuts is around 60\% and the overall acceptance times efficiency of the full selection is 35\%. To isolate these signal events in the data sample (dominated by diphoton production) a good mass resolution is needed.

![Figure 4](image1.png)

Figure 4. $R_\eta$ shower shape variable. $Z^{\rightarrow\text{ee}}$ data (points) are compared to MC predictions using Geant4, with two different versions[8].

![Figure 5](image2.png)

Figure 5. Composition of the inclusive data sample as a function of $m_{\gamma\gamma}$. The various components are stacked on top of each other. The error bars correspond to the statistical uncertainties on each component separately. The gray bands show the overall uncertainty on each component[9].
3. Energy measurement

The LAr calorimeter cell signals are read out through 1524 Front-End Boards with 128 channels each. The FEBs perform analog processing (amplification and shaping), store the signal while waiting for the L1 trigger decision and digitize at 40 MHz the accepted signals [10] [11]. The digitized signals (5 time samples around the trigger time) are transmitted via optical fibers to the Readout Drivers where energy reconstruction is performed. For cells with enough energy, the digitized signals are also stored and energy can be re-computed offline. From the 5 digitized time samples, the cell energy is reconstructed with:

\[ E_{cell} = F_{\mu A \rightarrow MeV} \frac{M_{cal}}{M_{phys}} \sum a_i (ADC_i - P) \]  

where \(ADC_i\) are the digitized time samples, \(P\) is the pedestal, \(R\) the conversion factor from ADC to injected current (in \(\mu A\)), \(F_{\mu A \rightarrow MeV}\) is the conversion factor from current to energy deposited in the cell, \(a_i\) are optimal filter coefficients used to estimate the pulse amplitude while minimizing the noise contribution and \(\frac{M_{cal}}{M_{phys}}\) (typically few percent) accounts for the difference between electronics calibration injected signal and ionization signal in the maximum amplitude after shaping for the same initial current. \(P\) and \(R\) are computed using electronics calibration, injecting calibrated current to simulate energy deposits in the calorimeter. This is done typically once a week and these calibration constants are very stable with time. \(F_{\mu A \rightarrow MeV}\) was determined from test-beam calibration and adjusted with the first LHC collision data. This factor also accounts for difference between operating High Voltage and nominal values for few percent of the cells. \(\frac{M_{cal}}{M_{phys}}\) and differences between electronics calibration and ionization pulse shapes, important in the computation of the \(a_i\) factors, come from the different time shapes of these two signals (exponential for the electronics calibration, triangular for the ionization pulse shape) and from the electrical properties of the cells. The predicted ionization shapes are calculated from calibration pulses by modeling each readout cell as a resonant \(RLC\) circuit. The effective \(LC\) and \(RC\) are estimated from a frequency analysis of the output calibration pulse shape. The prediction of the ionization pulse also requires the knowledge of the electron drift time in liquid argon, which was directly measured from data [12].

To illustrate the good quality of the ionization pulse prediction, Figure 6 shows a comparison between a measured pulse (over 800 ns) from a radiating cosmics muon deposing few GeV in a cell with the pulse shape prediction, scaled to the measured cell energy. The agreement is at the few percent level, within the specifications to achieve the design constant term in the energy resolution of the calorimeter (0.7%).

The overall energy scale of the calorimeter, as measured with collision data using Z and W decays, is very stable with time, as shown in Figure 7.

Photon energy measurement is made using a cluster size which depends on the photon classification. In the barrel, a size of 0.075×0.125 in \(\eta \times \phi\) is used for unconverted photons, and 0.075×0.175 for converted photon candidates, to account for the larger spread of the shower in \(\phi\) for converted photons due to the magnetic field. In the end-cap, a cluster size of 0.125×0.125 is used for all candidates. A dedicated energy calibration [15] is applied to account for upstream energy loss, lateral leakage and longitudinal leakage, separately for converted and unconverted photon candidates. The correction for upstream energy loss is parametrized as a function of the energy deposited in the presampler for \(|\eta| < 1.8\). These corrections are derived from detailed full simulation samples. For 100 GeV photon energy, the energy resolution in the simulation varies from 1.2% to \(\approx 1.7\%\) as a function of \(\eta\), assuming the design constant term of 0.7%.

The final energy calibration is determined from \(Z \rightarrow ee\) decays, resulting in \(\eta\)-dependent correction factors of the order of \(\pm 1\%). After this calibration procedure, the constant term in the energy resolution is investigated from Z decays. Figure 8 shows the reconstructed Z invariant mass distribution when both electrons are in the barrel calorimeter and Figure 9 when
both electrons are in the end-cap calorimeter. The data are compared to simulation, without any additional energy smearing. This comparison leads to estimates of the constant term in the energy resolution which are found to be $1.2 \pm 0.5\%$ in the barrel calorimeter and $1.8 \pm 0.6\%$ in the end-cap calorimeter [17]. These constant terms are then applied to the Higgs boson signal simulated samples. The uncertainty on the photon energy resolution ($\pm 13\%$ relative) arises from the uncertainty on the sampling term of the energy resolution (from test-beam studies), the uncertainty in the constant term and the uncertainty in the electron to photon extrapolation (mostly from uncertainties in material upstream the calorimeter).

4. Direction measurement
In addition to the energies, the angle between the photons is needed for the computation of the diphoton invariant mass. This angle is determined from the interaction vertex position and the photon impact points in the calorimeter. The resolution of the angle measurement is dominated by the reconstruction of the primary vertex $z$ position. The RMS vertex spread in the $z$ direction is $\approx 5.5$ cm and a more accurate event-by-event estimate is performed to reduce the impact on the invariant mass resolution. Given the level of pileup, the determination of the vertex position is based only on the photon candidates, without relying on other charged particles.
tracks in the event. For converted photons with tracks having a precise measurement in the $z$ direction, the vertex position is estimated from the intercept of the line joining the reconstructed conversion position and the calorimeter impact point with the beam line. For all other photons, the vertex position is estimated from the shower position measurements in the first and second layers of the electromagnetic calorimeter, which can be used to calculate the photon direction. Finally the vertex positions from both photons are combined taking also into account the average beam spot position in $z$.

Figure 10 shows the difference between the estimates of the vertex positions from the two photons, when they are both unconverted in the barrel calorimeter. When both photons are unconverted, the typical final vertex position resolution is $\approx 1.6$ cm in $z$. The resolution is better in events with converted photons. The resulting impact of the angle measurement on the invariant mass resolution is negligible compared to the contribution from the photon energy resolution, as shown in Figure 11.

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5. Data analysis

The events are separated into nine mutually exclusive categories with different mass resolutions and signal-to-background ratios, to increase the sensitivity to a possible Higgs boson signal. Categories are defined by the conversion status, $\eta$ of the photons and $p_T^{\text{t}}$, the component of the diphoton transverse momentum that is orthogonal to the thrust axis. Events with two unconverted photons are separated into unconverted central ($|\eta| < 0.75$ for both candidates) and unconverted rest (all other events). Events with at least one converted photon are separated into converted central ($|\eta| < 0.75$ for both candidates), converted transition (at least one photon with $1.3 < |\eta| < 1.75$) and converted rest (all other events). Except the converted transition category, each category is further divided by a cut at $p_T^{\text{t}}=40$ GeV into two categories.

The invariant mass shape of the signal in each category is modeled by the sum of a Crystal Ball function describing the core of the distribution and of a wide Gaussian with a small amplitude describing the tails. In Figure 12, the sum of all signal processes in all categories is shown for a
Higgs mass boson of 120 GeV. The full-width-at-half maximum is 4.1 GeV and the core gaussian of the Crystal Ball function \(\sigma_{CB}\) is 1.7 GeV. \(\sigma_{CB}\) varies from 1.4 GeV (in the unconverted central categories) to 2.0 GeV (in the converted rest categories) and 2.3 GeV (in the converted transition category which is the one with the lowest sensitivity).

The background in each category is estimated from the data by fitting the diphoton mass spectrum in the range 100-160 GeV with an exponential function with free shape and normalization parameters. The distribution of the invariant mass of the diphoton events, summed over all categories is shown in Figure 13.

The dominant experimental uncertainty on the signal yield is the photon reconstruction and identification efficiency (±11% per event). Pileup also affects the identification efficiency and contributes to the uncertainty (±4%). Further uncertainties on the signal yield are related to the trigger (±1%), Higgs boson transverse momentum modeling (±1%), isolation (±5%), and luminosity (±3.9%). Uncertainties on the predicted cross-sections are due to uncertainties on the QCD renormalization and factorization scales (±12%) and on the parton density functions and \(\alpha_S\) (±8%). The total uncertainty on the signal yield is ±20% - 17%. The total uncertainty on the mass resolution is ±14%, dominated by the uncertainty on the energy resolution of the calorimeter (±12%). Further uncertainties on the mass resolution result from an imperfect knowledge of the material in front of the calorimeter affecting the extrapolation from electron to photon calibration (±6%), the impact of pileup (±3%) and the photon angle measurement (±1%). The uncertainty on the knowledge of the material in front of the calorimeter is used to derive the amount of event migration between the converted and unconverted categories (±4.5%). Uncertainty in the modeling of the Higgs transverse momentum distribution lead to a ±8% migration between the low and high \(p_T\) categories. Systematic uncertainties in the background modeling arise from possible deviations of the background shape from the assumed exponential shape. This has been estimated by checking how accurately the chosen model fits different predicted diphoton mass distributions, and comparing different function forms for the
background model. The uncertainties are $\pm (0.1 - 7.9)$ events in a 4 GeV signal mass window, depending on the category.

6. Results

The data are compared to background and signal-plus-background hypothesis using a profile likelihood test statistic. The exponentially falling invariant mass distribution used for the background model is determined by two nuisance parameters per category which are left free in the unbinned fit. The signal is modelled with the mass resolution functions described above, one per category, fixing the fraction of events in each category to the MC predictions, within the uncertainties discussed above. The fitted parameters for the signal are thus the overall signal strength relative to the Standard Model prediction and the nuisance parameters on the predicted event yield and mass resolution which have Gaussian constraints in the fit. The systematic uncertainty on the background shape is included as another nuisance parameter with a Gaussian constraint in the fit. From this fit, the best estimate of the signal yield is extracted, as well as the likelihood ratio (profile likelihood) between any assumed signal yield (leaving the nuisance parameters free to maximise the likelihood) and the best estimate. A modified frequentist approach ($\text{CL}_{S}$) for setting limits and a frequentist approach to calculate the $p_0$ value are used. The $p_0$ is the probability that the background fluctuates to the observed number of events or higher. The 95% confidence level (CL) limit on the cross-section relative to the Standard Model cross-section is shown in Figure 14. The median expected upper limit for background only experiments varies between 1.6 and 2.7 times the Standard Model cross-section in the mass range 110-150 GeV. The observed limit is between 0.83 and 3.6 times the Standard Model cross-section. A Standard Model Higgs boson is excluded at 95% CL in the mass ranges of 113-115 GeV and 134.5-136 GeV. The local $p_0$ value is shown in Figure 15. Around 126.5 GeV, an excess is observed in the data with a local significance of 2.8 standard deviations. This becomes 1.5 standard deviation when the look elsewhere effect for the mass range 110-150 GeV is included.

![Figure 14](image1.png)

**Figure 14.** Observed and expected 95% CL limits on the Standard Model Higgs boson production normalized to the predicted cross-section as a function of $m_H$ [5].

![Figure 15](image2.png)

**Figure 15.** The observed local $p_0$, the probability that the background fluctuates to the observed number of events or higher (solid line). The open points indicated the observed value when energy scale uncertainties are taken into account. The dotted line shows the expected median local $p_0$ for the signal hypothesis when tested at $m_H$ [5].

When combining with the other search channels in the 2011 dataset [19], the Standard Model
Higgs boson is excluded in the mass ranges 110-117.6 GeV, 118.5-122.5 GeV and 129-539 GeV. In the non-excluded mass range, an excess with a local significance of 2.5 standard deviations is observed corresponding to a mass hypothesis of 126 GeV. When taking into account the look elsewhere effect, the global $p_0$ is around 10%. The excess at low mass is compatible with the Standard Model Higgs boson but the statistical significance is not large enough to draw definitive conclusions.

Data taking in 2012 at 8 TeV centre of mass energy and higher luminosity started in April 2012 and, thanks to a very successful LHC operation, allowed ATLAS to observe shortly after this conference a significant signal for a new boson at a mass close to 126 GeV [20].

7. Conclusions
With the 2011 LHC data, the diphoton decay channel is already bringing an important sensitivity to the low mass Higgs boson search in ATLAS. This is possible thanks to the good performance of the liquid argon calorimeter and the ATLAS detector. With the 2011 data, the allowed mass range for the Standard Model Higgs boson has been reduced to a small range, with a small excess observed in the non-excluded mass range. The diphoton decay channel will also play an important role in the search of the Higgs boson with the 2012 data.

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