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Search for the Higgs boson decay to a Z boson and a photon in pp collisions at $\sqrt{s} = 13$ TeV and 13.6 TeV with the ATLAS detector

The ATLAS Collaboration

A search for the Higgs boson decay to a Z boson and a photon in the $\ell\ell\gamma$ ($\ell = e, \mu$) final state is performed using pp collisions at $\sqrt{s} = 13.6$ TeV recorded with the ATLAS detector at the Large Hadron Collider during 2022–2024, corresponding to an integrated luminosity of 165 fb^{-1}. The signal yield, normalised to the Standard Model prediction, is measured to be $\mu = 0.9^{+0.7}_{-0.6}$, compared to an expected value of $\mu = 1.0 \pm 0.7$. This corresponds to an observed (expected) signal significance of 1.4 (1.5) standard deviations for the background-only hypothesis. This result is combined with that of a similar search performed with 140 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions to provide the most stringent expected sensitivity to date to this rare decay, namely an observed (expected) signal strength of $\mu = 1.3^{+0.6}_{-0.5}$ ($\mu = 1.0^{+0.6}_{-0.5}$), corresponding to an observed (expected) significance of 2.5 (1.9) standard deviations. The measurement is consistent with the Standard Model expectation.

1 Introduction

A new boson with properties consistent with those of the Standard Model (SM) Higgs boson (H) was independently observed in 2012 by the ATLAS and CMS Collaborations [1, 2] at the Large Hadron Collider (LHC) [3]. Measurements of its couplings to SM particles, its spin, and its parity have, to date, shown no significant deviation from the SM predictions [4–7]. The combined ATLAS and CMS determination of its mass from LHC Run-1 data yields $m_H = 125.09 \pm 0.24$ GeV [8], a value that is consistent with recent Run-2 measurements [9–11].

Within the SM, the Higgs boson decay to a Z boson and a photon ($H \to Z\gamma$) proceeds via loop-induced processes, leading to a predicted branching ratio of $\mathrm{BR}(H \to Z\gamma) = (1.54^{+0.10}_{-0.11}) \times 10^{-3}$ for $m_H = 125.09$ GeV [12], similar to that for $H \to \gamma\gamma$, $\mathrm{BR}(H \to \gamma\gamma) = (2.27^{+0.07}_{-0.06}) \times 10^{-3}$ [12]. Extensions to the SM, such as models with additional colourless charged scalars, fermions, or vector bosons, can alter this rate via contributions in the loops [13–19], making the ratio $\mathrm{BR}(H \to Z\gamma)/\mathrm{BR}(H \to \gamma\gamma)$ a particularly sensitive probe of new physics. Similarly, scenarios in which the Higgs boson is composite or arises from alternative symmetry-breaking sectors may yield significantly different $H \to Z\gamma$ branching fractions [20–22]. Moreover, the observation of $H \to Z\gamma$ decay would complete the suite of established Higgs boson decays into pairs of electroweak gauge bosons ($\gamma\gamma$, ZZ^*, WW^*), consolidating the role played by the Higgs boson in electroweak symmetry breaking. Consequently, precise measurements of this rare decay provide a sensitive probe for the SM and its extensions.

The $Z(\to \ell\ell)\gamma$ final state ($\ell = e, \mu$), despite its reduced branching ratio, offers the best sensitivity to the $H \to Z\gamma$ process, as it can be efficiently triggered on and clearly distinguished from background events produced in proton–proton (pp) collisions. Furthermore, it benefits from full kinematic reconstruction and excellent invariant mass resolution. Both the ATLAS and CMS Collaborations have performed searches for the $H \to Z(\to \ell\ell)\gamma$ decay using the Run-2 pp collision dataset, corresponding to an integrated luminosity of about 140 fb^{-1} at $\sqrt{s} = 13$ TeV for each experiment. Compared to the background-only hypothesis, ATLAS observed a signal significance of 2.2σ (1.2σ expected) with a measured signal strength, defined by the ratio of the signal yield to the SM prediction, $\mu = 2.0^{+1.0}_{-0.9}$ [23], while CMS reported a signal significance of 2.7σ (1.2σ expected) with $\mu = 2.4 \pm 0.9$ [24]. The combination of these searches yielded the first evidence of $H \to Z\gamma$ decays with a significance of 3.4σ (1.6σ expected) with $\mu = 2.2 \pm 0.7$ [25]. All results were consistent with the SM expectation.

This letter presents a search for $H \to Z\gamma$ decays in the $\ell\ell\gamma$ final state using pp collision data collected with the ATLAS detector at $\sqrt{s} = 13.6$ TeV during 2022–2024 in Run 3, corresponding to an integrated luminosity of 165 fb^{-1}. Compared to the Run-2 analysis [23], this study benefits from an increased Higgs boson production cross-section at higher centre-of-mass energy, and from a larger data and simulated background samples. Furthermore, the event selection is optimised with relaxed transverse-momentum (p_{T}) thresholds for muons and photons. In addition, 13 mutually exclusive event categories are defined, including for the first time a dedicated multi-lepton category designed to target Higgs boson production in association with a vector boson or top quarks. The remaining 12 categories employ a multivariate classifier based on XGBoost [26] to maximise the sensitivity, replacing the previous approach mostly based on rectangular selections on simple kinematic variables. A simultaneous fit to the reconstructed $Z\gamma$ invariant mass distributions across all categories is performed to extract the overall $H \to Z\gamma$ signal yield. Finally, the result is combined with the Run-2 measurement to increase the sensitivity to this rare decay.

2 ATLAS detector

The ATLAS experiment [27, 28] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and near 4π coverage in solid angle[1]. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The inner tracking detector covers the pseudo-rapidity range $|\eta| < 2.5$. It consists of silicon pixels, silicon microstrips, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudo-rapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is primarily measured by the LUCID-2 detector, which is located close to the beam pipe. A two-level trigger system was used to select events [29, 30]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate close to 100 kHz. This is followed by a software-based trigger that reduced the accepted rate of complete events to 3 kHz on average, depending on the data-taking conditions. A software suite [31] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulation samples

The analysis presented in this letter uses pp collision data at $\sqrt{s} = 13.6$ TeV collected by the ATLAS experiment from 2022 to 2024 during LHC Run 3. Events were collected using unprescaled single- and dilepton triggers [32, 33] with a variety of p_{T} thresholds. The lowest-threshold single-electron and single-muon triggers required $p_{\mathrm{T}} > 26$ GeV and $p_{\mathrm{T}} > 24$ GeV, respectively. The dielectron trigger required two electrons with $p_{\mathrm{T}} > 17$ GeV each. The dimuon triggers employed a symmetric 14 GeV–14 GeV configuration in 2022–2024 and an asymmetric 22 GeV–8 GeV configuration in 2023–2024. To maintain high efficiency at high instantaneous luminosity, these low-threshold triggers were supplemented by higher-p_{T} triggers with looser identification or isolation requirements. The trigger selections yield an efficiency of 96% for the $ee\gamma$ final state and 93% for the $\mu\mu\gamma$ final state for events passing the offline selection requirements that will be described in Section 4. After data quality requirements, the total integrated luminosity amounts to 165 fb^{-1}. The average number of inelastic pp interactions per bunch crossing (pile-up) increased from 42 in 2022 to 58 in 2024, with the peak instantaneous luminosity reaching 2.3×10^{34} cm^{-2}s^{-1}.

The optimisation of the analysis strategy and the modelling of the relevant physics processes rely on simulation Monte Carlo (MC) samples that represent both the Higgs boson signal and the dominant

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

background processes. These samples, unless explicitly stated otherwise, undergo the full simulation of the ATLAS detector response using the GEANT4 framework [34], as implemented in the ATLAS simulation infrastructure [35].

The Higgs boson mass is set to $m_H = 125$ GeV for all simulated samples, with a corresponding total decay width of $\Gamma_H = 4.1$ MeV, as recommended in Ref. [12]. The simulated samples are normalised to the SM production cross-sections, evaluated at a Higgs boson mass of $m_H = 125.09$ GeV. These include production via gluon–gluon fusion (ggF) [12, 36–47], vector boson fusion (VBF) [12, 48–50], associated production with a vector boson (VH, where $V = W, Z$) [12, 51–58], associated production with a top-quark pair ($t\bar{t}H$) [12, 59–62], and associated production with a bottom-quark pair ($b\bar{b}H$) [63–65]. Other Higgs boson production mechanisms were not considered, as their contributions to the total Higgs boson production cross-section are at the level of 0.1% or less. The $H \to Z\gamma$ branching ratio and its uncertainty were taken from Ref. [12].

The production of the Higgs boson was simulated using the POWHEG BOX v2 MC event generator [66–70] and the PDF4LHC21 parton distribution functions (PDF) set [71], following the setup summarised in Table 1. The $H \to Z\gamma$ decay, as well as parton shower, hadronisation, and the modelling of the underlying event, were performed using PYTHIA 8 [72]. Contributions from $H \to \mu\mu$ decays, where the reconstructed photon originates from QED final-state radiation (FSR), were evaluated using samples produced with a similar setup and are considered as a potential background in this analysis. The impact of interference between Higgs boson decays with the same final-state signature ($H \to \ell\ell\gamma$ with non-resonant dilepton) is expected to be negligible in the SM [73]. Additional samples of the $H \to Z\gamma$ signals were generated using HERWIG 7 [74] for decay and parton shower simulation and are used to evaluate uncertainties associated with the parton shower modelling.

In this analysis, the dominant backgrounds arise from non-resonant production of a Z boson in association with a photon ($Z\gamma$) or jets, where a jet is misidentified as a photon (Z + jets). Additional background contributions stem from diboson (VV) production, where V denotes either a W or a Z boson. These additional background contributions are relevant only for the event category containing additional leptons.

A large $Z\gamma$ background sample was generated at next-to-leading-order (NLO) accuracy in QCD using the SHERPA 2.2.14 generator [75], with one to three additional partons in the final state at LO. The simulation employed the NNPDF3.0 next-to-next-to-leading-order (NNLO) PDF set [76], and a fast simulation of the calorimeter response was applied [77].

The EW production of a Z boson in association with a photon and two jets ($Z\gamma jj$) was simulated at LO accuracy in EW using MADGRAPH 3.5.5 [78] with the NNPDF2.3LO PDF set [79], where both jets originate from partons emitted at EW vertices. QCD-induced diagrams were explicitly excluded, resulting in no additional partons from QCD in the final state and ensuring orthogonality with the $Z\gamma$ sample generated with SHERPA. The hadronisation, parton shower, and the modelling of the underlying event were simulated using PYTHIA 8 with the A14 set of tuned parameters [80].

The background from Z + jets was estimated from data using a control region of events in which the photon candidates fail the nominal criteria and pass looser identification or isolation requirements.

Diboson backgrounds resulting in three- and four-lepton final states were also modelled using SHERPA 2.2.14, employing the NNPDF3.0NNLO PDF set. The sample was generated at NLO accuracy in QCD with up to three additional partons at LO accuracy.

The effect of pile-up was modeled by overlaying simulated hard-scattering events with inelastic pp interactions from a mix of EPOS 2.0.1.4 [81] and PYTHIA 8. EPOS events were generated with the LHC

tune[82], and Pythia with the A3 tune [83] and the NNPDF2.3LO PDF set. Pythia simulated pileup events containing high-p_{T} jets, prompt photons, or leptons from b-hadron decays, while Epos accounted for the remaining minimum–bias contribution. The individual samples were first reweighted to ensure a smooth transition across jet p_{T}, and the combined sample was reweighted to match the distribution of the number of interactions per bunch crossing observed in data. To improve the agreement between simulation and data, correction factors were applied to account for differences in reconstruction and identification efficiencies. These include corrections to the trigger, reconstruction, identification, and isolation efficiencies for electrons and muons, as well as the identification and selection of photons and jets. Additional corrections were applied to the energy and momentum scale and resolution of reconstructed objects to reflect the detector performance.

Table 1: Higgs boson signal MC samples produced with Powheg Box V2 along with the techniques used to generate the events and their precision in α_{s} for the event generation (gen.). The version of Pythia 8, its parameter tune, and the PDF set, which are used for modelling the Higgs boson decay, parton shower, hadronisation, and the underlying event, are listed. The precision of the total cross-section used in the sample normalisation is also reported.

Process	Technique	QCD (gen.)	Pythia 8 & tune	PDF set	Normalisation
ggF	Powheg [68, 69]	NNLO*	8.310 [72], A14 [80]	PDF4LHC21 [84]	NNLO (QCD), NLO (EW) [36–47]
VBF	Powheg	NLO	8.310, A14	PDF4LHC21	NNLO (QCD), NLO (EW) [48–50]
$q\bar{q} \to ZH$	Powheg & MiNLO [85]	NLO	8.310, A14	PDF4LHC21	NNLO (QCD), NLO (EW) [56, 58, 86]
$gg \to ZH$	Powheg	LO	8.310, A14	PDF4LHC21	NLO (EW) [58, 87, 88]
WH	Powheg & MiNLO [85]	NLO	8.310, A14	PDF4LHC21	NNLO (QCD), NLO (EW) [56, 58, 86]
$t\bar{t}H$	Powheg	NLO	8.310, A14	PDF4LHC21	NNLO (QCD), NLO (EW) [59–62, 89]
$b\bar{b}H$	Powheg (4FS)	NLO	8.310, A14	PDF4LHC21	NNLO (QCD), NLO (EW) [63–65, 90]

* NNLO accuracy achieved only for inclusive ggF observables.

4 Event selection and reconstruction

Events passing the trigger selection described in Section 3 are required to include at least one photon and two same-flavour, opposite-charge leptons, all associated with the primary vertex, defined as the inner-detector track vertex with the highest $\sum p_{\mathrm{T}}^2$ of tracks with $p_{\mathrm{T}} > 500$ MeV [91].

Muon candidates are reconstructed by combining the tracks in the ID and MS [92, 93]. They need to satisfy *medium* identification criteria, lie within $|\eta| < 2.5$, and have $p_{\mathrm{T}} > 5$ GeV. Electrons are reconstructed from topological clusters of EM calorimeter cells matched to ID tracks [94–96]. They are required to pass a *loose* identification selection based on a likelihood discriminant using calorimeter shower shapes and track parameters, lie within $|\eta| < 2.47$ (excluding the transition region between the barrel and endcap EM calorimeters $1.37 < |\eta| < 1.52$), and have $p_{\mathrm{T}} > 10$ GeV. To ensure leptons originate from the primary vertex and to suppress heavy-flavour backgrounds, all leptons are required to satisfy $|\Delta z_0 \cdot \sin\theta| < 0.5$ mm, where Δz_0 is the longitudinal impact parameter relative to the primary vertex and θ is the track polar angle. Moreover, the transverse-impact-parameter significance $|d_0|/\sigma_{d_0}$ needs to be < 3 for muons and < 5 for electrons, with d_0 measured relative to the beam line and σ_{d_0} its fit uncertainty.

Photon candidates are built from topological clusters of EM calorimeter cells [94–96]. They have to satisfy *tight* identification criteria based on calorimeter shower shape variables, $|\eta| < 2.37$ (excluding $1.37 < |\eta| < 1.52$), and have $p_{\mathrm{T}} > 10$ GeV (relaxed from 15 GeV in Run 2 [23]). To increase the rejection of background from non-prompt and hadronic production, the lepton and photon candidates are required to

pass isolation criteria, based on the energy deposits in the calorimeter and the total p_{T} of charged-particle tracks from the primary vertex, measured in cones surrounding the direction of the particle candidates.

Jets are reconstructed from particle flow objects [97] clustered via the anti-k_t algorithm ($R = 0.4$) [98–100]. They are required to satisfy $p_{\mathrm{T}} > 25$ GeV and $|y| < 4.4$. To suppress jets originating from pile-up, a central [101] or forward jet-vertex-tagger [102] is applied.

Overlap removal discards the lower-p_{T} electron when two electron candidates share the same track or satisfy $|\Delta\eta| < 0.075$ and $|\Delta\phi| < 0.125$. Electrons within $\Delta R < 0.02$ of muons are also removed. To suppress bremsstrahlung photons emitted by leptons, photons within $\Delta R < 0.3$ of leptons are discarded. Finally, jets within $\Delta R < 0.2$ of leptons or photons are removed.

Z boson candidates are reconstructed from opposite-charge and same-flavour lepton pairs. In the muon channel, the highest p_{T} collinear FSR photon ($\Delta R < 0.15$) is added to the corresponding muon to improve the di-muon mass resolution. A kinematic fit [23] then corrects the lepton four-momenta to constrain the dilepton mass to the known Z boson mass, accounting for its finite natural width. This procedure improves the $\ell\ell\gamma$ mass resolution of the signal MC samples by 17% for electrons and 11% for muons, including the effect of FSR. Candidates must satisfy $|m_{\ell\ell} - m_Z| < 10$ GeV, where $m_Z = 91.2$ GeV [103]. If multiple Z boson candidates are found, the dilepton pair with $m_{\ell\ell}$ closest to m_Z is selected, resulting in a 98% efficiency for correctly matching to the true Z boson in the ggF signal sample. The leptons associated with the Z boson candidate are additionally required to be geometrically matched to the corresponding trigger-level leptons that fired the event. They are required to satisfy an offline p_{T} threshold set 1–2 GeV above the nominal trigger requirement to ensure that the trigger is maximally efficient.

The Higgs boson candidate is reconstructed by combining the selected Z boson and the highest–p_{T} photon. The invariant mass of the $\ell\ell\gamma$ system ($m_{Z\gamma}$) must lie within 110–160 GeV to suppress contributions from on-shell Z boson events. In addition, the photon p_{T} is required to be larger than 0.09 times $m_{Z\gamma}$. This requirement further reduces the background, while not introducing a sharp turn-on in the $m_{Z\gamma}$ spectrum near m_H as would the use of an absolute minimum p_{T}^{γ} requirement with similar background rejection. This criterion, relaxed from the Run-2 value of 0.12 thanks to the calibrations of identification and isolation efficiencies for photons with lower p_{T}, enhances the selection efficiency. The overall reconstruction and selection efficiency (including detector acceptance) for the SM $H \to Z(\to \ell\ell)\gamma$ events ranges from 20% to 26%, depending on the production mode.

5 Event categorisation

To maximise the sensitivity to an $H \to Z\gamma$ signal, events are classified into 13 exclusive event categories. Events are first categorised into four primary regions: Lepton, VBF, High relative photon p_{T}, and Low relative photon p_{T}. This classification is based on lepton and jet multiplicities as well as kinematic properties. The VBF and both the High and Low relative photon p_{T} regions are further subdivided into mutually exclusive categories according to the output of XGBoost-based [26] boosted decision trees (BDT) and the lepton flavour. To avoid sculpting of the $m_{Z\gamma}$ distribution, the BDT inputs are selected to have minimal correlation with $m_{Z\gamma}$, and the classifiers are trained within narrow mass windows: 120–130 GeV for the VBF and High relative photon p_{T} regions, and 123–127 GeV for the Low relative photon p_{T} region. This categorisation strategy is designed to maximise the combined number counting significance, while requiring at least two background events in the signal region ($120 < m_{Z\gamma} < 130$ GeV) of each category. This requirement translates into a minimum number of background events in the full fit region that is

large enough to ensure sufficient statistical precision for the background estimate. The event classification scheme is illustrated in Figure 1 and more details are provided in the following paragraphs.

Events with at least three leptons ($N_{\text{lepton}} \geq 3$) are assigned to the Lepton category. This category is enriched in VH and $t\bar{t}H$ production modes, accounting for 56% and 35% of the signal yield in this category, respectively. The dominant backgrounds arise from Z + jets, multi-lepton diboson, and non-resonant $Z\gamma$ processes.

Events failing the Lepton region and containing at least two jets ($N_{\text{jet}} \geq 2$) are selected for the VBF region. If more than two jets are present in an event, the two highest-p_{T} jets are considered. A dedicated BDT was trained using 25 kinematic variables to separate the VBF signal from the non-resonant $Z\gamma$, and the EW $Zyjj$, as well as to reduce the contamination from ggF. The variables are summarised in Table 2. Events in the VBF region are classified into tight (VBFT) and loose (VBFL) categories based on the BDT score, with the VBFT category exhibiting higher significance. The VBF fraction of the total signal yield is 89% and 64%, respectively, in the VBFT and VBFL categories.

Table 2: Summary of input variables used in the BDT training for the VBF, HRelpT-ee, HRelpT-$\mu\mu$, LRelpT-ee, and LRelpT-$\mu\mu$ analysis regions. The same set of input variables is employed in the four relative photon p_{T} regions.

Input variable	Description	VBF	relative photon p_{T}
N_{jet}	Number of jets	✓	✓
$p_{\text{T}}^{j_1}$, η_{j_1}	p_{T}, and η of the leading jet (j_1)	✓	✓
m_{j_1}	Mass of the leading jet	✓	
ϕ_{j_1}	Azimuthal angle of the leading jet		✓
m_{j_2}, $p_{\text{T}}^{j_2}$, η_{j_2}	Mass, p_{T}, and η of the subleading jet (j_2)	✓	
$m_{j_1 j_2}$, $p_{\text{T}}^{j_1 j_2}$, $\Delta\eta_{j_1 j_2}$	Dijet invariant mass, p_{T}, and η separation	✓	
η_γ	Pseudorapidity of the photon	✓	✓
p_{T}^γ	Transverse momentum of the photon	✓	
$p_{\text{T}}^{\ell\ell}$	Transverse momentum of the dilepton system	✓	
$\eta_{\ell\ell}$, $\eta_{\ell\ell\gamma}$	Pseudorapidity of the dilepton and $\ell\ell\gamma$ systems	✓	✓
$p_{\text{T}}^{\ell\ell\gamma}$	Transverse momentum of the $\ell\ell\gamma$ system	✓	
$p_{\text{T}}^{\ell\ell\gamma}/m_{\ell\ell\gamma}$, $p_{\text{T}}^\gamma/m_{\ell\ell\gamma}$	Relative p_{T} of the $\ell\ell\gamma$ and the photon		✓
$p_{\text{T}}^{\ell\ell}/m_{\ell\ell\gamma}$	Relative p_{T} of the dilepton system		✓
p_{T}^t	Component of $\vec{p}_{\text{T}}^{\,\ell\ell\gamma}$ perpendicular to the difference between $\vec{p}_{\text{T}}^{\,\ell\ell}$ and $\vec{p}_{\text{T}}^{\,\gamma}$ ($p_{\text{T}}^t = \lvert\vec{p}_{\text{T}}^{\,\ell\ell\gamma} \times \hat{t}\rvert$, with $\hat{t} \propto \vec{p}_{\text{T}}^{\,\ell\ell} - \vec{p}_{\text{T}}^{\,\gamma}$) [104, 105]	✓	✓
$\Delta\phi_{\ell\ell,\gamma}$	Azimuthal separation between the $\ell\ell$ system and the photon	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1}$	Azimuthal separation between the $\ell\ell\gamma$ system and the leading jet	✓	✓
$\Delta\phi_{\ell\ell\gamma,j_1 j_2}$	Azimuthal separation between the $\ell\ell\gamma$ system and the dijet system	✓	
$\Delta\eta_{\ell\ell,\gamma}$	Pseudorapidity separation of the dilepton and the photon	✓	✓
$\Delta R_{\gamma \text{ or } \ell\ell,j}^{\text{min}}$	Minimum ΔR to j_1/j_2 from the photon or the dilepton system	✓	✓
$\cos\theta^*(\ell^+)$	Cosine of the polar angle of the ℓ^+ in the $\ell\ell$ rest frame	✓	✓
$\cos\theta(\ell\ell)$ in $\ell\ell\gamma$	Cosine of the polar angle of the $\ell\ell$ in the $\ell\ell\gamma$ rest frame	✓	✓
$\eta^{\text{Zeppenfeld}}$	Pseudorapidity difference between the $\ell\ell\gamma$ system and the dijet system, defined as $\lvert\eta_{\ell\ell\gamma} - (\eta_{j_1} + \eta_{j_2})/2\rvert$ [106]	✓	

Events not selected for the VBF region and satisfying $p_{\text{T}}^\gamma/m_{Z\gamma} \geq 0.4$ enter the High relative photon p_{T} region, dominated by ggF production. Separate BDTs are trained for the ee and $\mu\mu$ channels using

17 variables, as shown in Table 2. BDTs are trained using the simulated ggF and VBF signal events and the non-resonant $Z\gamma$ background events. For each lepton flavour, events are grouped into tight and loose categories using optimised BDT thresholds, yielding four categories (HRelpT-eeT, HRelpT-eeL, HRelpT-$\mu\mu$T, HRelpT-$\mu\mu$L) with ggF signal fractions above 70%.

Remaining events that are not selected in the VBF region and with $p_{\mathrm{T}}^{\gamma}/m_{Z\gamma} < 0.4$, are placed into the Low relative photon p_{T} region, where the signal yield is also dominated by ggF with a fraction above 90%. BDTs trained separately for ee and $\mu\mu$ channels use the same input variables as in the High relative photon p_{T} region. The training samples consist of the simulated ggF signal events, the non-resonant $Z\gamma$ background, and the data-driven Z+jets background events. Background components are constructed and normalised as detailed in Section 6. Each channel is split into tight, medium, and loose categories, according to their BDT score, forming six in total: LRelpT-eeT, LRelpT-eeM, LRelpT-eeL, LRelpT-$\mu\mu$T, LRelpT-$\mu\mu$M, and LRelpT-$\mu\mu$L.

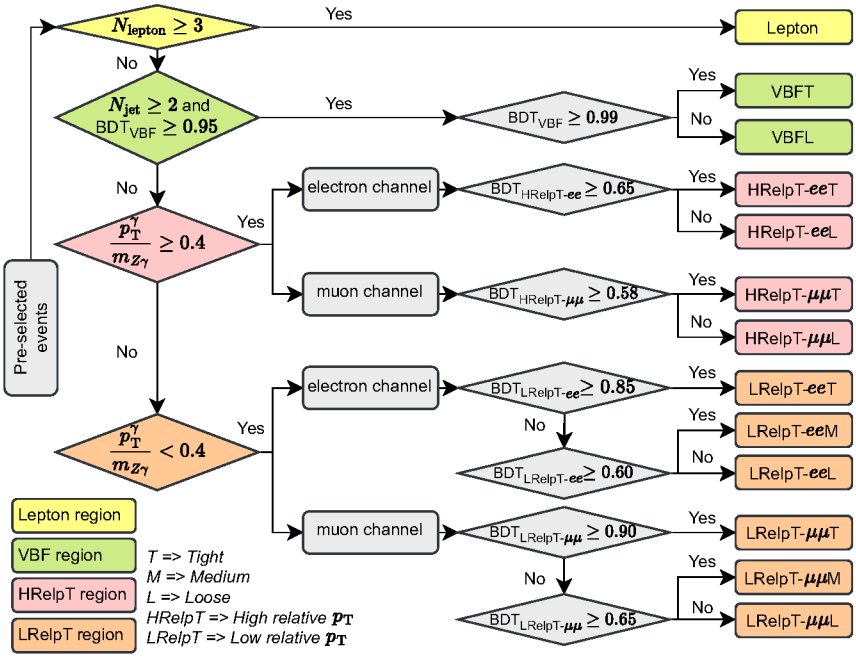


Figure 1: Schematic of the event categorisation based on kinematic selections and multivariate algorithms. Events are classified into four regions: Lepton (yellow), VBF (green), high relative photon p_{T} (HRelpT, pink), and low relative photon p_{T} (LRelpT, orange). The Lepton region is defined based on the number of lepton candidates, while the VBF region is split into loose and tight categories using a BDT output. The HRelpT and LRelpT regions are further divided into various categories based on the lepton flavour and dedicated BDT classifiers. In total, 13 mutually exclusive categories are defined.

Table 3 provides an overview of the expected signal and background composition in each analysis category, as determined from a signal-plus-background fit to the Asimov dataset (Section 8) to illustrate the sensitivity. The expected signal (S_{68}^{exp}), background (B_{68}^{exp}), and observed data (N_{68}) yields are quoted in an $m_{Z\gamma}$ window around the peak, with a width (w_{68}) corresponding to the interval expected to contain 68% of the signal. The resulting expected sensitivity, $S_{68}^{\mathrm{exp}}/\sqrt{S_{68}^{\mathrm{exp}} + B_{68}^{\mathrm{exp}}}$, varies across categories, reaching a maximum of 0.91 in the VBFT category. The combined sensitivity, obtained by summing the contributions from all categories in quadrature, is 1.81. The inclusive sensitivity is used solely for category optimisation and is not intended to represent the final sensitivity derived from the full statistical analysis.

Table 3: Expected signal (S_{68}^{exp}), background (B_{68}^{exp}) and observed event yields in data (N_{68}) in a window of width w_{68}, expected to contain 68% of the signal. The expected signal and backgrounds are extracted from a signal-plus-background fit to the Asimov dataset (Section 8). The signal uncertainty reflects the impact in μ, while the background uncertainty accounts for the statistical uncertainty from the fit. The expected sensitivity is given by $S_{68}^{\text{exp}}/\sqrt{S_{68}^{\text{exp}} + B_{68}^{\text{exp}}}$. The last row shows the inclusive results, calculated by summing the contributions from all categories. The inclusive sensitivity is derived by combining the category sensitivities in quadrature.

Category	S_{68}^{exp}	B_{68}^{exp}	N_{68}	w_{68} [GeV]	$S_{68}^{\text{exp}}/\sqrt{S_{68}^{\text{exp}} + B_{68}^{\text{exp}}}$
Lepton	1.5 ± 1.1	76.3 ± 2.8	78	4.4	0.17
VBFT	1.5 ± 1.1	1.2 ± 0.4	3	3.8	0.91
VBFL	2.8 ± 2.0	27.6 ± 1.8	23	4.0	0.51
HRelpT-eeT	1.2 ± 0.8	6.6 ± 0.9	11	3.1	0.43
HRelpT-eeL	3.0 ± 2.1	54.10 ± 1.8	77	4.0	0.40
HRelpT-$\mu\mu$T	2.4 ± 1.7	20.3 ± 1.7	33	3.9	0.50
HRelpT-$\mu\mu$L	2.4 ± 1.7	56.5 ± 1.7	72	4.1	0.31
LRelpT-eeT	9 ± 6	234 ± 6	251	3.8	0.57
LRelpT-eeM	29 ± 20	2 591 ± 19	3 806	4.1	0.56
LRelpT-eeL	24 ± 17	13 260 ± 50	17 435	4.5	0.21
LRelpT-$\mu\mu$T	4.9 ± 3.4	96 ± 4	127	3.9	0.49
LRelpT-$\mu\mu$M	34 ± 24	2 545 ± 19	3 133	4.1	0.67
LRelpT-$\mu\mu$L	37 ± 26	16 960 ± 40	19 331	4.4	0.28
Inclusive	150 ± 110	35 930 ± 70	44 380	4.0	1.81

6 Signal and background modelling

The signal and background yields are determined by an unbinned extended maximum-likelihood fit to the reconstructed $m_{Z\gamma}$ spectrum in data, employing analytic functions for both components. The shape of the $H \to Z\gamma$ signal is modelled by a double-sided Crystal Ball (DSCB) function, comprising a Gaussian core with power-law tails on both sides to capture both the detector resolution and non-Gaussian effects [107]. In each category, the DSCB parameters (mean μ_{CB}, width σ_{CB}, and four parameters describing the tails) are determined from a fit to a combination of all signal samples. The mean is shifted by 90 MeV to correct for the generated Higgs boson mass of 125 GeV to the measured value of 125.09 GeV. The overall signal normalisation and acceptance are taken directly from the same simulation. A small contribution from $H \to \mu\mu$ decays (up to 3.8% of $H \to Z\gamma$ signal in certain categories) is likewise modelled with its own DSCB template, with normalisation fixed to the SM prediction.

For all selected events, the backgrounds arise primarily from non-resonant $Z\gamma$ production and Z+jets events in which a jet is misidentified as a photon. The diboson contribution remains below 0.2% and is therefore neglected in the inclusive background estimate. The relative fractions of $Z\gamma$ and Z + jets components are determined inclusively via a two-dimensional sideband method, applied to a dataset obtained after loosening the nominal photon identification and isolation requirements. The sideband populations of the dataset are used to extract the $Z\gamma$ purity in data [108]. This yields a $Z\gamma$ fraction of $0.49^{+0.05}_{-0.10}$, compared to $0.78^{+0.04}_{-0.09}$ in Run 2 [23]. The reduction reflects three combined effects: the increased pile-up in Run 3, the lowered photon p_{T} threshold in the event selection, which admits more jets faking photons, and the smaller

ratio of SM $Z\gamma$ to Z + jets cross-sections at $\sqrt{s}$ = 13.6 TeV.

The background $m_{Z\gamma}$ distribution is modelled based on fits to a dedicated background template that combines the $Z\gamma$ and Z + jets components. After the inclusive fractions of $Z\gamma$ and Z + jets events are determined, they are extrapolated to each event category using efficiencies from the $Z\gamma$ fast-simulation MC and data-driven Z + jets samples. To reduce statistical fluctuations in the control region, the ratio of Z + jets to $Z\gamma$ shapes as a function of $m_{Z\gamma}$ is smoothed by fitting a low-order polynomial or exponential-polynomial function. This smoothed ratio is applied to the $Z\gamma$ template to define the Z + jets background shape. In the VBF categories, a similar smoothing is employed on the ratio of $Z\gamma$ + (Z + jets) to the larger EW $Z\gamma jj$ simulation to define the total background template. In the Lepton category, the 35% contribution from diboson backgrounds, taken from simulation, is added to the template. Finally, in each category, the overall background normalization is scaled to data in the $m_{Z\gamma}$ sidebands (excluding the interval 120–130 GeV). The resulting templates are compatible with the $m_{Z\gamma}$ distribution of data.

To determine the background model that accurately represents the data without inducing artificial signal features, a spurious signal (SS) study [23] is performed. In each category, several analytic function families, such as power laws, Bernstein polynomials, exponential polynomials, and logarithmic polynomials of the form $(1 - x^{1/3})^f x^{\Sigma_{i=0}^{N} p_i \log(x)^i}$, with $x = m_{Z\gamma}/\sqrt{\text{s}}$ and f a free parameter, are fitted to the background template. Each function is tested over three fit ranges (110–155 GeV, 115–160 GeV, 110–160 GeV). The function-range combinations are required to satisfy two criteria:

- The $|SS|$ is defined as the absolute value of the maximum fitted signal yield obtained from a background-only template when varying m_H between 120 and 130 GeV in steps of 1 GeV. It is required that one of $|SS - 1\sigma|$, SS, or $|SS + 1\sigma|$ is less than $0.2\Delta S$, where σ is the error of the SS, and ΔS is the expected signal statistical uncertainty.
- The χ^2-probability of the background-only fit > 1%.

When there is more than one function–range combination that passes these criteria, the one with the fewest free parameters is chosen. If more than one has the same number of parameters, the one with the smallest $|SS|$ is chosen. If no candidate satisfies both criteria, the fit window is progressively narrowed (to a minimum width of 35 GeV) until a valid model is found; if still unsuccessful, the combination with the lowest $|SS|$ is adopted. A Wald test [109, 110] is then applied to data sidebands to compare nested functions: if a lower-degree function is statistically compatible without significantly increasing $|SS|$, it replaces the nominal model to guard against over-fitting. To account for uncertainties in the relative $Z\gamma$ and Z + jets fractions, variations of those fractions by plus or minus their uncertainties are used to build alternative templates. Repeating the SS study on these templates leaves the chosen function–range combination unchanged in every category, and the maximum $|SS|$ across the three templates is assigned as the systematic uncertainty on the background model.

Once the function is selected, a smoothing technique based on Gaussian Process Regression [110, 111] is applied to each category's template. The $|SS|$ is then re-evaluated. This reduces the effect of residual statistical fluctuations without introducing any shape bias and does not affect the choice of any function–range combination in any categories. Unlike the signal models, whose parameters are fixed from simulation, the background model parameters are extracted directly from a fit to the $m_{Z\gamma}$ distribution in data. As an additional validation, a template is built as the sum of the SM signal template and the background template in each category, and is then fitted. The resulting best-fit signal strength in every category is compatible with the SM prediction, confirming the robustness of the background models.

7 Systematic uncertainties

Systematic uncertainties impact the fit results by affecting either the normalization or the shape of the $m_{Z\gamma}$ invariant mass distributions. Experimental uncertainties are evaluated using Run-3 data and MC events. Despite the large simulation background samples and smoothing procedures, the spurious signal, uncorrelated across event categories, retains a large contribution from statistical fluctuations of the input samples. It results in an 11% impact on the signal strength μ, which is small with respect to the statistical uncertainty.

Signal shape modelling uncertainties vary by category and are driven by the calibration of the electron and photon energy, as well as the muon momentum. The uncertainty in the electron and photon energy resolution and in the muon momentum resolution leads to a less than 5% mass resolution (σ_{CB}) uncertainty. The uncertainty in the electron and photon energy scale (and in the muon momentum scale) leads to a less than 0.3% (0.1%) uncertainty in the peak position (μ_{CB}). Overall, these uncertainties affect the measured signal strength by less than 2%.

The 60% uncertainty in the $H \to \mu\mu$ contribution, taken from the Run-2 ATLAS measurement [112], contributes a 2% uncertainty in the expected signal strength. Additional uncertainties in the signal yield arising from reconstruction, identification, and isolation corrections are smaller than 3% for photons, electrons, and muons [95, 96]. The jet-related uncertainties, including those from jet reconstruction and in situ calibration, are each below 2%. A conservative uncertainty of 10% is assigned to the reconstruction and calibration of forward jets. All of the jet uncertainties translate into a 4% impact on the signal strength. The uncertainty related to the pile-up effects is negligible. The overall uncertainty in the integrated luminosity for each dataset using the LUCID-2 detector [113] is 4%[2] for 2022–2024. Additional uncertainties arising from the triggers are below 2% across the analysis categories. Combining all experimental systematics, excluding the spurious signal uncertainty, yields a total 9% uncertainty in the signal strength.

Theory uncertainties affecting the expected signal yield arise from multiple sources. Uncertainties in the production cross-section and kinematic distributions, primarily due to missing higher-order QCD corrections, contribute up to 12%, depending on the analysis category, and are dominated by variations in the renormalisation and factorisation scales. Parton shower modelling introduces additional uncertainties ranging from 3% to 29%, with the largest values observed in VBF categories; in non-VBF categories, the uncertainty typically ranges from 0.3% to 10%. The uncertainty in the Higgs boson branching ratio to $Z\gamma$ is 7% [12]. The total impact of theory uncertainties on the signal strength is estimated to be 12%. Table 4 summarises the symmetrised impacts of individual uncertainty sources on the expected and observed signal strengths. The total uncertainty is dominated by the statistical component, with an expected impact of 0.70. Systematic uncertainties contribute 0.17, the spurious signal and theory modelling effects being the leading sources.

[2] The integrated luminosity for the 2024 dataset is derived from the relative yields of $Z \to ee$ and $Z \to \mu\mu$ events relative to those measured in 2022/2023, yielding a preliminary uncertainty of 5%. When combined with the 2% uncertainty assigned to the 2022/2023 integrated luminosity [114, 115], a luminosity-weighted uncertainty of 4% is obtained for the Run-3 dataset.

Table 4: Breakdown of the symmetrised impacts from individual sources of uncertainty on the expected and observed signal strengths. Uncertainties are grouped by source type to illustrate their relative contributions.

Uncertainty source	$\Delta\mu$	
	Expected	Observed
Statistical uncertainty	0.70	0.64
Systematic uncertainty	0.17	0.17
Spurious signal (background modelling)	0.11	0.10
QCD scale, PDF+α_S, parton shower	0.09	0.06
Branching ratio ($H \to Z\gamma$)	0.08	0.05
Luminosity	0.05	0.03
Photon efficiency	0.05	0.03
Jet	0.04	0.07
Electron and photon energy scale and resolution	0.02	0.02
Electron efficiency	0.02	0.02
Muon	0.02	< 0.01
Trigger	0.02	< 0.01
Total	0.72	0.67

8 Results

8.1 Run-3 only

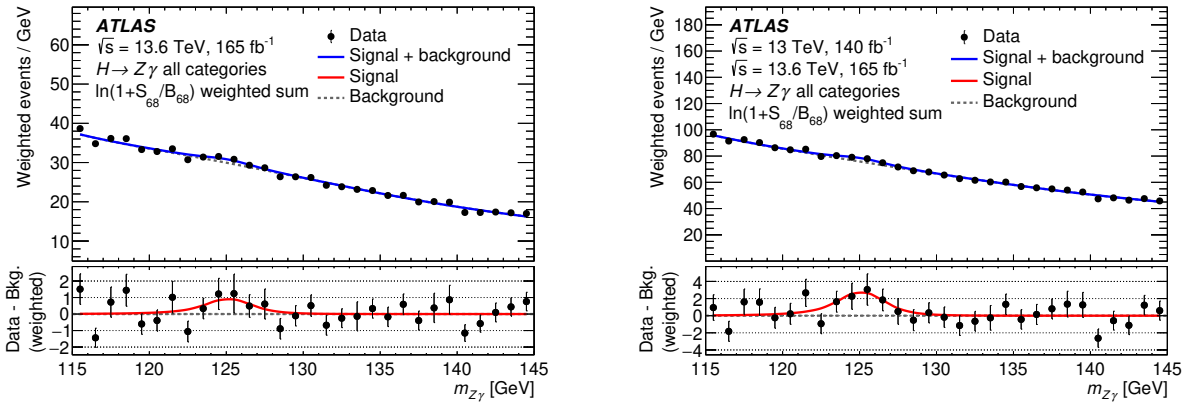
The results are extracted via an unbinned, simultaneous maximum-likelihood fit [116] to the $m_{Z\gamma}$ distributions across all categories, each with its own optimised mass window determined as described in Section 6, following the methodology of previous $H \to Z\gamma$ searches [23, 117]. The likelihood function is built by incorporating both the signal strength of $H \to Z\gamma$ and the nuisance parameters (NPs), which characterise the effects of systematic uncertainties on the signal normalisation and shape, as well as background normalisation and shape parameters.

The measured signal strength is $\mu = 0.9^{+0.7}_{-0.6}(\text{stat.})^{+0.2}_{-0.1}(\text{syst.}) = 0.9^{+0.7}_{-0.6}$ for $m_H = 125.09$ GeV. Under the SM signal hypothesis, the expected signal strength is $\mu_{\text{exp}} = 1.0 \pm 0.7(\text{stat.})^{+0.2}_{-0.1}(\text{syst.}) = 1.0 \pm 0.7$. The corresponding Asimov dataset [116] is generated under the hypothesis of SM signal plus background. The result is statistically compatible with the SM expectation. The observed significance under the background-only hypothesis is 1.4σ, close to the expected significance of 1.5σ. Among the event categories, the VBFT category provides the highest expected sensitivity. In all cases, the uncertainties are dominated by the statistical contribution, while the most significant systematic uncertainty impact arises from the modelling of the background (spurious signal). The measurement using individual signal strengths for each category is consistent with the result obtained from the global signal strength, with a p-value of 0.37.

Figure 2 (a) presents the $m_{Z\gamma}$ distribution of selected events in the Run-3 dataset, weighted by $\ln(1+S_{68}/B_{68})$, where S_{68} and B_{68} are the signal and background yields in each category, estimated from the fit to the data, in an $m_{Z\gamma}$ window expected to contain 68% of the signal. The combined models, obtained by weighting the individual category models, are overlaid. The negative profiled-likelihood-ratio values as a function of the signal strength μ are shown in Figure 3.

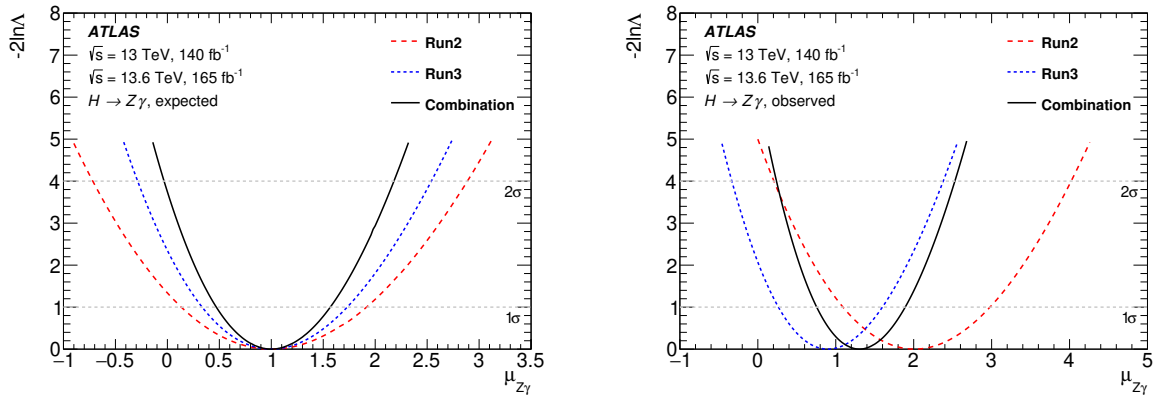
Overall, this analysis achieves an expected significance improvement of 28% relative to the previous ATLAS result [23]. This gain is primarily driven by the advanced event selection and categorisation,

which contributes 15%. The remaining improvement is from the larger dataset and a more favourable signal-to-background ratio at $\sqrt{s}$ = 13.6 TeV.



(a) (b)

Figure 2: $Z\gamma$ invariant mass distributions of weighted data events across all categories for (a) Run-3 only and (b) the combined Run-2 and Run-3 dataset. The black points represent the data, with statistical uncertainties shown as error bars. Each event is weighted by $\ln(1 + S_{68}/B_{68})$, where S_{68} and B_{68} are the signal and background yields in each category, estimated from the fit to the data, in an $m_{Z\gamma}$ window expected to contain 68% of the signal. The signal-plus-background fit (solid blue curve) and the background model (dashed line) are overlaid. In the bottom panels, the residuals between the data and the background model (black dots with error bars) are compared to the signal model (red solid line). All curves represent the weighted sum of the individual category models.



(a) (b)

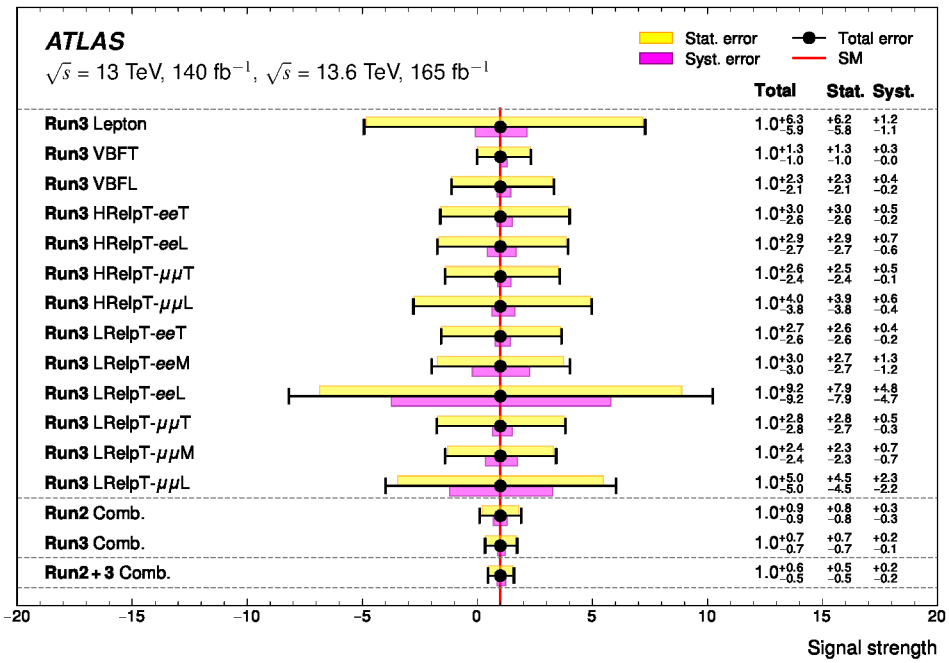
Figure 3: Profiled likelihood scan of the signal strength for the (a) expected and (b) observed results. Both plots show the results obtained by this analysis of the Run-3 dataset (dashed blue line), by the previous analysis of the Run-2 dataset [23] (long dashed red line), and their combination (solid black line).

8.2 Run-2 and Run-3 combination

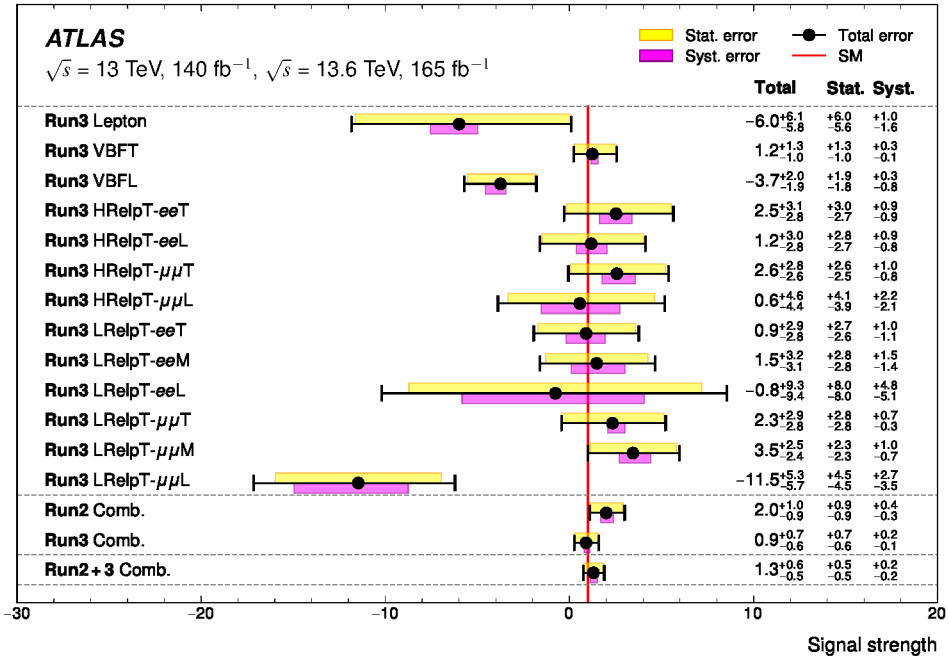
These results based on Run-3 data are combined with those from the previous ATLAS search for $H \to Z\gamma$ decays using Run-2 data [23]. The theoretical uncertainties, including branching ratios, QCD scale, and α_s

uncertainties, are treated as fully correlated across both datasets. The PDF uncertainties are uncorrelated due to the distinct PDF sets used in Run 2 and Run 3. Due to the different data-taking conditions, most experimental uncertainties are treated as uncorrelated between the two runs, in particular, the uncertainties related to the trigger, luminosity, electron, photon, and spurious signal. All of the uncertainty sources from muons and jets are correlated, except for the uncorrelated in situ calibration uncertainties. The impact of the correlation scheme on the final results was studied and found to be negligible, as the overall uncertainty is dominated by the statistical contributions. The joint likelihood is constructed as the product of the individual likelihood functions from the Run-2 and Run-3 analyses. Correlated systematic sources share a common NP with a Gaussian constraint in the combined fit.

Figure 2 (b) presents the weighted $m_{Z\gamma}$ distribution with the fitted signal and background models overlaid, and Figure 3 shows the likelihood scan of the combined signal strength. The observed combined fit has a best-fit signal strength of $\mu = 1.3 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.}) = 1.3^{+0.6}_{-0.5}$ with an expected $\mu = 1.0 \pm 0.5(\text{stat.}) \pm 0.2(\text{syst.}) = 1.0^{+0.6}_{-0.5}$. The significance of the observed (expected) excess above the background-only hypothesis is 2.5σ (1.9σ). Relative to the Run-2 analysis, the combined expected significance improves by 61%. Figure 4 shows the signal strength results in each Run-3 category, the stand-alone Run-2 and Run-3 measurements, and their combination. The Run-2 and Run-3 measurements are compatible, with a p-value of 0.33. Assuming the SM production cross-sections, the combination provides the most stringent expected sensitivity to date for determining the $H \to Z\gamma$ branching fraction, surpassing the ATLAS + CMS Run-2 combination [25]. Under this assumption, the observed (expected) branching fraction is $(2.0^{+0.9}_{-0.8}) \times 10^{-3}$ $((1.5^{+0.9}_{-0.8}) \times 10^{-3})$, compared with the SM prediction of $(1.54^{+0.10}_{-0.11}) \times 10^{-3}$.



(a)



(b)

Figure 4: (a) Expected and (b) observed best-fit signal strengths and corresponding uncertainties in each category of the Run-3 analysis, their combined values, the results of the previous Run-2 analysis, and the overall combination. The black points with horizontal error bars correspond to the central values and total uncertainties, while the upper yellow (lower magenta) bands indicate the statistical (systematic) uncertainties. The red vertical line denotes the SM prediction.

9 Conclusion

A search for the Higgs boson decay to $Z\gamma$ in the $\ell\ell\gamma$ final state is performed using proton–proton collision data recorded with the ATLAS detector at $\sqrt{s} = 13.6$ TeV during 2022–2024, corresponding to an integrated luminosity of 165 fb^{-1}. A simultaneous unbinned maximum-likelihood fit to the reconstructed invariant mass of the $Z\gamma$ system across all event categories gives an observed (expected) signal yield normalised to the SM prediction, $\mu = 0.9^{+0.7}_{-0.6}$ ($\mu = 1.0 \pm 0.7$). This corresponds to an observed (expected) signal significance of 1.4 (1.5) standard deviations. The statistical uncertainty is the dominant source of error. Compared to a similar search performed with Run-2 data [23], the expected significance improves by 28%, with 15% arising from the enhanced event selection and categorisation strategies, and the remainder from increased integrated luminosity and larger cross-sections.

This measurement is further combined with the Run-2 result to yield the most stringent expected sensitivity to date for the $H \to Z\gamma$ decay, surpassing the ATLAS + CMS Run-2 combination [25]. In the combined fit, the observed (expected) signal yield normalised to the SM prediction is $\mu = 1.3^{+0.6}_{-0.5}$ ($\mu = 1.0^{+0.6}_{-0.5}$), corresponding to an observed (expected) signal significance of 2.5 (1.9) standard deviations. The combination improves the expected significance by 61% with respect to the Run-2 measurement. The measurement is consistent with the SM expectation, indicating no significant deviation from the predicted Higgs boson behaviour in the $Z\gamma$ channel.

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The ATLAS Collaboration

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