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Search for the associated production of charm quarks and a Higgs boson decaying into a photon pair with the ATLAS detector

The ATLAS Collaboration

A search for the production of a Higgs boson and one or more charm quarks, in which the Higgs boson decays into a photon pair, is presented. This search uses $\sqrt{s} = 13$ TeV proton–proton collision data with an integrated luminosity of 140 fb^{-1} recorded by the ATLAS detector at the Large Hadron Collider. The analysis relies on the identification of charm-quark-containing jets, and adopts an approach based on Gaussian process regression to model the non-resonant di-photon background. The observed (expected, assuming the Standard Model signal) upper limit at the 95% confidence level on the cross-section for producing a Higgs boson and at least one charm quark is found to be 10.4 pb (8.6 pb). The observed (expected) measured cross-section for this process is 5.2 ± 3.0 pb (2.9 ± 2.8 pb).

1 Introduction and signal definition

The Higgs boson is the only scalar elementary particle in the Standard Model (SM) of particle physics, and is associated with a field with a non-zero vacuum expectation value. It arises from the Brout–Englert–Higgs mechanism [1–6], which generates the masses of all known fundamental particles except possibly for the neutrinos. Since its discovery in 2012 [7, 8], an extensive campaign of measurements [9, 10] has been underway at the Large Hadron Collider (LHC) [11] to understand its properties and test the SM.

The Yukawa sector of the SM [12] does not explain the structure of the fermion masses, and only predicts that their couplings to the Higgs boson are proportional to their masses. These masses take on hierarchical values, and span a wide range. This hierarchy may be explained by a mechanism beyond the SM [13–15]. Measuring these couplings is thus a crucial test of the SM, and can be sensitive to new physics. In particular, significant work has been dedicated to probing the coupling of the Higgs boson to charm quarks (y_c) [16–20], though this has so far been difficult due to its relatively low value in the SM and significant hadronic backgrounds at the LHC.

This paper presents the first search for inclusive Higgs boson plus charm-quark production, which uses decays of the Higgs boson to photon pairs, and the ATLAS detector at the LHC. This analysis searches for the inclusive production of a Higgs boson and at least one charm quark (the inclusive $H + c$ process), a component of which is a $g + c \to H + c$ process that is sensitive to y_c (the y_c-sensitive $H + c$ process). Despite the y_c-sensitive $H + c$ process amounting only to approximately 1% of the inclusive $H + c$ process, the quadratic dependence of its cross-section on y_c could lead to important effects on these signals in the case of deviations from the SM. This measurement thus provides an important step towards probing y_c using $H + c$ events [21], which complements the methods cited above.

The inclusive $H + c$ signal targeted herein is defined as any event including a Higgs boson and at least one anti-k_t jet [22, 23] with a radius parameter $R = 0.4$ formed from generator-level particles, which has $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$ and is matched to a charm hadron with $p_{\mathrm{T}} > 5$ GeV and $\Delta R < 0.3$, excluding the cascade decays from b-hadrons. Various Higgs boson production processes contribute to this signal, and the simulation of these processes is described in Section 2. The backgrounds considered are the dominant non-resonant $pp \to \gamma\gamma + n$ parton production background, and the largely irreducible Higgs boson–induced resonant background. The non-resonant background is estimated by using a data-driven approach. Events containing a Higgs boson that do not satisfy the signal criteria are considered as resonant backgrounds, these often have light-flavour-containing jets (light-flavour jets) or bottom-quark-containing jets (b-jets) mis-identified as charm-quark-induced jets (c-jets), and they are modelled using simulation.

2 The ATLAS detector, data and simulation

Proton–proton collision data collected at a centre-of-mass energy of $\sqrt{s} = 13$ TeV during Run 2 of the LHC, with an integrated luminosity of 140 fb^{-1}, are used. The data are recorded by the ATLAS detector [24], a multipurpose detector with forward–backward symmetric cylindrical geometry and nearly 4π coverage in solid angle[1]. ATLAS consists of an inner tracking detector, electromagnetic and hadronic calorimeters,

[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 $y = \frac{1}{2}\ln\left(\frac{E+p_z c}{E-p_z c}\right)$ in the relativistic limit.

and a muon spectrometer equipped with a two-level trigger system [25]. An extensive software suite [26] 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. The data were collected using di-photon and single-photon triggers, which have various minimum transverse energy (E_{T}) thresholds. Di-photon triggers are used, which require events to contain at least two photons that satisfy identification and isolation requirements that vary by data-taking year, and which have minimum E_{T} thresholds of 35 (25) GeV for the (second) highest E_{T} photon. Single-photon triggers with E_{T} thresholds of 120 GeV (140 GeV) are used to select the data collected in 2015 (2016–2018).

The inclusive $H + c$ signal and the resonant backgrounds containing a Higgs boson are simulated together, and then separated using a generator-level implementation of the signal definition stated above. The Higgs boson production modes simulated for these combined samples are gluon–gluon fusion (ggF), vector boson fusion (VBF), associated production with a vector boson (ZH and WH), with a top-quark pair ($t\bar{t}H$) and with a bottom-quark pair ($b\bar{b}H$), and the y_c-sensitive $H + c$ process. Some example Feynman diagrams of these processes are shown in Figure 1. The inclusive $H + c$ signal cross-section is about 2.9 pb in the SM, as determined using the simulation method described below, though this value is uncertain due to the difficulty in calculating the cross-section for Higgs bosons produced with jets containing a c-quark or b-quark (heavy-flavour jets). The event generation is performed using Powheg Box v2 [27–30] for all production modes, other than the y_c-sensitive $H+c$ process, which utilises MadGraph 5 [31], using matrix element calculations at the highest available order of accuracy in the strong coupling constant α_s. The ggF sample is generated at the next-to-next-to-leading order (NNLO), while next-to-leading order (NLO) accuracy is achieved for VBF, WH, $q\bar{q} \to ZH$, $t\bar{t}H$ and $b\bar{b}H$. The $gg \to ZH$ simulation is performed at leading order. The y_c-sensitive $H + c$ sample models the $g + c \to H + c$ process in which the Higgs boson couples directly to a charm quark, and it is simulated using MadGraph 5 at LO and Higgs Effective Couplings UFO [32], where generator-level jets are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 4.7$. All samples are interfaced with Pythia 8 [33, 34] to simulate the hadronisation, parton shower and underlying event. The PDF4LHC15 parton distribution function (PDF) set [35] and AZNLO CTEQ6L1 tuning parameters [36, 37] are used for all samples except for $t\bar{t}H$ and $b\bar{b}H$, which use the A14 NNPDF2.3lo tune [37, 38], and for the y_c-sensitive $H+c$ sample, which uses NNPDF3.0nlo [37] and A14 NNPDF2.3lo tune. The $H \to \gamma\gamma$ decays are modelled using Pythia 8 and include the small contribution from Dalitz decays ($H \to \gamma f\bar{f}$). In all samples, the Higgs boson mass and width are set to 125 GeV and 4.07 MeV, respectively, and the normalisations (except for the y_c-sensitive $H + c$ sample) use the latest theoretical calculations for SM production cross-sections [15]. The y_c-sensitive $H + c$ sample is normalised to the SM production cross-section of 0.028 pb, which is obtained from MadGraph 5 prediction calculated with $m_c(m_Z) = 0.63$ GeV. The branching fraction of Higgs boson decay into a photon pair ($H \to \gamma\gamma$) is assumed to be $2.27^{+0.07}_{-0.06} \times 10^{-3}$ [15]. The response of the ATLAS detector is modelled using Geant4 [39, 40]. The dominant non-resonant $pp \to \gamma\gamma + n$ parton production background is simulated to validate and evaluate an uncertainty in the data-driven method used to estimate this background. This sample is produced using Sherpa 2.2.4 [41] with NLO-accurate matrix elements for up to one parton, and LO accurate matrix elements for up to three partons, and was processed using a parameterised simulation of the ATLAS detector. All simulated events are reconstructed using the same algorithms that are applied to data [40], and include the effect of multiple proton–proton interactions per bunch crossing (pile-up), as well as the effect on the detector response due to interactions from bunch crossings before or after the one containing the hard interaction.

Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

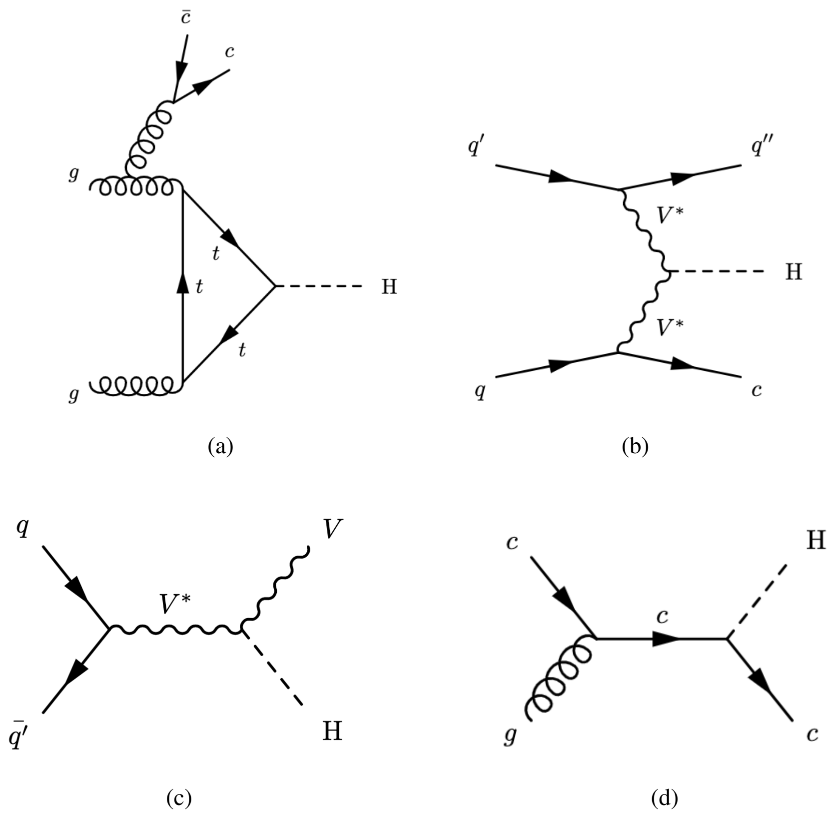


Figure 1: Example Feynman diagrams for processes contributing to the inclusive $H + c$ signal: (a) gluon–gluon fusion Higgs boson production with gluon radiation, which splits into $c\bar{c}$; (b) vector boson fusion Higgs boson production; (c) the VH processes, where V can be a W or Z boson decaying into one charm quark or a pair, respectively; and, (d) the y_c-sensitive $H + c$ signal.

3 Event reconstruction and selection

The event reconstruction and selection closely follows the recent Higgs boson production cross-section measurement analysis in the di-photon decay channel [42]. Photons are reconstructed from energy deposits in the calorimeter formed using a topological cell clustering algorithm [43]. The event selection is performed in two stages. The first stage constitutes a preselection, where the two highest-E_{T} preselected photon candidates are required to satisfy $E_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.37$, excluding the transition region $1.37 < |\eta| < 1.52$ between the barrel and endcap electromagnetic calorimeters, and to satisfy *loose* calorimeter-based identification criteria [44]. The accurate determination of the di-photon production vertex is crucial for measuring the di-photon invariant mass $m_{\gamma\gamma}$, selecting jets from the hard interaction, and calculating track-based isolation. To facilitate this, the preselected photon angular information and reconstructed vertex information are input to a neural network that is trained on simulated events to improve the determination of the primary vertex [45]. This vertex is then used to calculate properties of physics objects in the event. In the second selection stage, the two preselected photon candidates are required to satisfy *tight* identification criteria [44]. In addition, candidates must meet calorimeter- and track-based isolation criteria to minimise the misidentification of jets as photons. Calorimeter-based isolation refers to the total energy of calorimeter clusters within a cone of size $\Delta R = 0.2$ around the photon candidate. This excludes the energy in a fixed-size window containing the photon shower; the corrections for leakage, as well as subtraction of pile-up and underlying event contribution, are also performed [43]. The calorimeter-based isolation must be under 6.5% of the transverse energy of the photon. The track-based isolation is defined as the scalar sum of the transverse momenta of tracks within a cone of size $\Delta R = 0.2$ around the photon candidate. Only the tracks with transverse momenta $p_{\mathrm{T}} > 1$ GeV linked to the di-photon vertex and excluding those associated with photon conversions are used. The track isolation must be less than 5% of the photon transverse energy. The invariant mass of the di-photon system $m_{\gamma\gamma}$ must lie between 105 and 160 GeV. Finally, the leading (subleading) photon is required to satisfy $E_{\mathrm{T}}/m_{\gamma\gamma} > 0.35$ (0.25) [46].

Jet constituents are reconstructed using a particle-flow algorithm [47], from which jets are reconstructed using the anti-k_t algorithm with a radius parameter of $R = 0.4$. Events are required to have one or two jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$, and each jet is required to have $\Delta R(j, \gamma) > 1$ from both of the photons. The jets with $|\eta| < 2.4$ and $p_{\mathrm{T}} < 60$ GeV, originating from additional pp collisions in the same or neighbouring bunch crossings are suppressed by the use of the jet-vertex-tagger [48]. The flavour of the quark that initiates each reconstructed jet is identified using a deep learning–based algorithm called DL1r [49], which estimates the probabilities of a jet being a b-jet, a c-jet or a light-flavour jet. The output probabilities are combined with a parameter that regulates the discrimination between c-jets and b-jets or light-flavour jets. Finally, a requirement is made on this parameter to determine whether a jet should be considered as c-tagged. The average efficiencies are 30–40%, 10–13% and 1–2% for jets originating from c-quarks, b-quarks and light-flavour quarks, respectively, depending on the Higgs boson production mode [50]. The overlap removal procedure described in Ref. [42] is applied to avoid double-counting objects. To optimise the analysis sensitivity, selected events are split into two signal regions (SRs): the c-tag SR, where at least one c-tagged jet is present; and the non-c-tag SR, where no c-tagged jet is present. The non-c-tag SR provides significant sensitivity due to the low efficiency of the c-tagging criterion. Lastly, for an event to fall in a SR it must satisfy 120 GeV $< m_{\gamma\gamma} <$ 130 GeV, while events not meeting this requirement fall into the sidebands, which are later used to estimate the non-resonant background. The approximate expected yields of different physics processes contributing to the signal and resonant background are shown in Table 1, and these numbers are meant for illustrative purposes.

Table 1: Approximate expected yields of different physics processes contributing to the Standard Model signal and Standard Model Higgs boson–induced resonant background, in the c-tag and non-c-tag signal regions. The y_c-sensitive $H + c$ process assumes the Standard Model value of the coupling between the Higgs boson and charm quarks. The signal and background yields for the individual processes are estimated by using the simulation methods detailed in the main text.

Process	c-tag signal region		Non-c-tag signal region	
	Signal	Resonant background	Signal	Resonant background
ggF H	39	82	110	1800
VBF H	17	13	34	220
WH	9.5	4.7	23	59
ZH	4.5	5.1	7.8	50
$t\bar{t}H$	7.0	4.6	20	24
$b\bar{b}H$	0.11	1.9	0.35	16
y_c-sensitive $H + c$	0.37	0.046	0.78	0.48

4 Signal and background modelling

The inclusive $H + c$ signal and the total resonant and non-resonant background models are constructed in both of the SRs as $m_{\gamma\gamma}$ distributions with 0.5 GeV bins, in the mass range between 120 GeV and 130 GeV. The signal and total resonant background are modelled in each SR using simulation, as described above. The non-resonant background estimate employs a data-driven approach using Gaussian process regression (GPR) [51] to interpolate the data from the sidebands, defined as lower ($105 < m_{\gamma\gamma} < 120$ GeV) and upper ($130 < m_{\gamma\gamma} < 160$ GeV) mass regions, into the SRs. GPR is a non-parametric method that provides a Bayesian posterior distribution in the form of a functional over possible background functions. This approach provides a highly flexible background estimate, which explores a complete space of possible background shapes, and which has limited dependence on the choice of the prior distribution over possible background distributions [52]. Other implementation methods have been proposed in the particle physics literature [53] that use sidebands and the signal regions simultaneously to derive the GPR estimate, however, here a blinding and interpolation–based approach using the sidebands only is adopted. Histograms with 0.5 GeV bins in the sidebands are used to produce estimates of the non-resonant background distributions in each SR using a GPR-based interpolation. The GPR estimates use a Radial Basis Function kernel [54], which is motivated by the smoothness of these backgrounds, as can be established from both the simulation and the data sidebands. The histograms input to the GPR algorithm are pre-processed, and the parameters of the kernel are optimised by maximising the log-marginal-likelihood of the data in the sidebands. GPR is then implemented using `scikit-learn` [55] to provide posterior distributions over possible background distributions in the SRs, which are represented by multidimensional Gaussian distributions over the histogram bins contents. The means of the $m_{\gamma\gamma}$ histogram bin contents arising from the GPR estimates are shown in Figure 2, and the covariances of the bin contents in the SRs are shown in Figure 3. These posterior distributions are used to model the non-resonant backgrounds and the uncertainties arising from the GPR process in the statistical interpretation. These uncertainties arise from the GPR prior, the limited amount of data in the sidebands and the interpolation from the sidebands into the SRs, and they are largely statistical in nature. This method assumes that there is negligible signal in the sidebands, and this is confirmed to be the case using simulation. The robustness of the GPR-based background modelling strategy is confirmed using the Sherpa $\gamma\gamma + n$ parton simulated sample described above.

5 Systematic uncertainties

The inclusive $H + c$ signal and total resonant background, which are both modelled using simulation, are impacted by various theoretical and experimental systematic uncertainties. The data-driven non-resonant background model is unaffected by these uncertainties, but affected by dedicated modelling uncertainties described below.

Theoretical uncertainties in the signal and resonant background are assessed by varying the renormalisation and factorisation scales, and by calculating the impacts of uncertainties in the PDF, α_s and the branching fraction. Theoretical uncertainties related to the parton shower, hadronisation and underlying events are evaluated by comparing results obtained from the alternative generator `Herwig` 7.1.3 [56]. A 100% normalisation uncertainty is applied to resonant background events containing Higgs bosons with heavy-flavour jets from the ggF or VBF processes, to account for the difficulty in modelling these processes for events containing heavy-flavour jets, since these jets do not typically arise from the hard-scatter. This is motivated by data-to-simulation differences observed in other analyses, e.g., Refs. [57, 58]. The

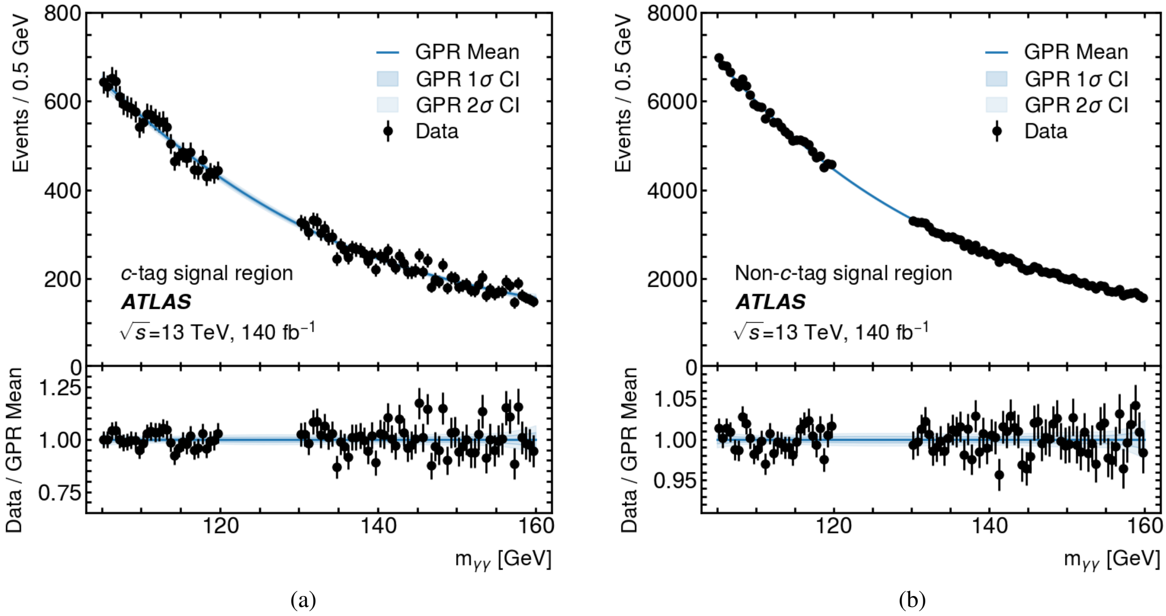


Figure 2: Gaussian process regression–based estimates of the non-resonant background derived from the data in the $m_{\gamma\gamma}$ sidebands as detailed in the main text in the (a) c-tag and (b) non-c-tag combined signal regions and sidebands. The 1σ and 2σ Bayesian credible intervals (CI) are shown by the darker and lighter shaded regions, respectively. The data in the sidebands, but not in the signal regions, is also shown.

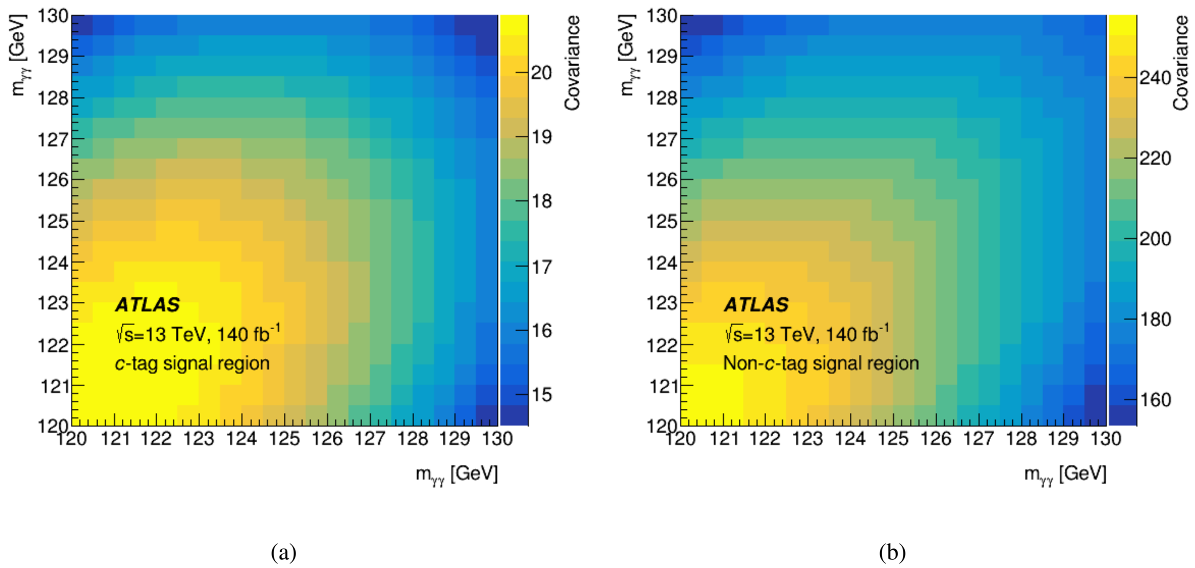


Figure 3: Covariance matrices of the Gaussian process regression–based estimates of the non-resonant background derived from the data in the $m_{\gamma\gamma}$ sidebands as detailed in the main text in the (a) c-tag and (b) non-c-tag signal regions.

signal efficiency has an overall theoretical uncertainty of less than 12% in both the SRs, while the theoretical uncertainty in the resonant background is less than 18% and 8% in the c-tag and non-c-tag SRs, respectively.

Experimental uncertainties arise from the modelling of the photon identification and isolation criteria and their energy scale and resolution [43], of the jet vertex tagger efficiency [48], energy scale and resolution [59], and of the c-tagging efficiency [50] and fake rates. An uncertainty is assigned to account for the different primary vertex definitions used in this analysis and the c-tagging calibration, which results in uncertainties of (16%) 16% for signal and (3.9%) 16% for resonant background in the (non-)c-tag SR. These uncertainties are uncorrelated between the signal and resonant backgrounds, and anti-correlated between the SRs. An additional uncertainty is assigned to events for which the c-tagged jet arises from the mis-tagging of a light-flavour jet to account for the fact that the calibration of the corresponding mis-tag rate is performed using $t\bar{t}$ events, which do not contain a pure component of light-jet events, unlike the samples that are usually adopted for this calibration task [60]. This uncertainty is designed to be approximately twice as large as it would need to be to make the scale factor from the calibration compatible with unity for light-flavour jets, providing a conservative uncertainty, and resulting in uncertainties of (0.36%) 0.72% for the signal and (2.2%) 30% for the resonant background in the (non-)c-tag SR. Further uncertainties in luminosity [61, 62] and trigger efficiency [25] are considered, impacting the event yield by 0.83% and 0.4%, respectively. An uncertainty in modelling of pile-up events is included, which is less than 1.1% [63]. Uncertainties in the non-resonant background estimate arise from its GPR-based estimation, and from a spurious signal test performed to quantify potential biases using an approach similar to that described in Ref. [52]. This spurious signal test uses pseudo-data events generated based on non-resonant simulated Sherpa sample with data-driven corrections [64], and results in an uncertainty of 12% (30%) of the expected signal in the c-tag (non-c-tag) category. The photon energy scale and resolution uncertainties and the GPR-based background estimation uncertainties affect the normalisations and shapes of the $m_{\gamma\gamma}$ distributions, while the other systematic uncertainties affect only the normalisations.

Uncertainties that do not affect the normalisation of the signal or the total resonant background by more than 1% in either SR are removed from the analysis. The breakdown of the expected inclusive $H + c$ signal uncertainty into various categories of uncertainty in this search, as obtained after the fit to the Asimov dataset described in Section 6, are summarised in Table 2.

6 Statistical interpretation

The statistical interpretation uses a binned likelihood fit to the $m_{\gamma\gamma}$ distributions, simultaneously in both the SRs in the range of 120–130 GeV. The signal and total resonant background are each modelled using one histogram per SR. The non-resonant background estimate consists of $m_{\gamma\gamma}$ bins in each SR determined from the GPR estimates performed before this fit, and are used in a similar way to other backgrounds in this analysis. However, as the GPR prediction is a posterior distribution over possible background estimates, the shapes and normalisations of this background are allowed to vary within the multi-dimensional Gaussian posterior distributions, which arise from these GPR estimates. Other systematic uncertainties are modelled as nuisance parameters and are profiled in the fit. The profile likelihood ratio test statistic [65] is used to perform a one-sided frequentist hypothesis test to constrain the inclusive $H + c$ cross-section under the asymptotic approximation [65] at the 95% confidence level using the $\mathrm{CL_s}$ formalism [66], and to calculate the statistical significance of the inclusive $H + c$ signal. This $H + c$ cross-section is inclusive of decay

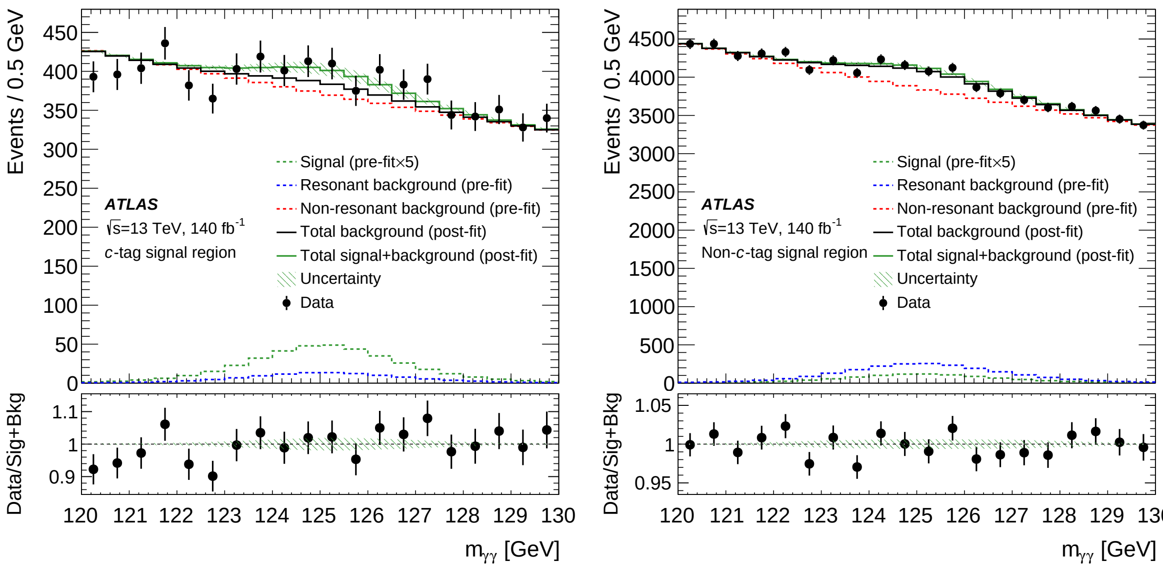
Table 2: Breakdown of the expected relative signal uncertainty into various categories, calculated by subtracting the uncertainty in the signal cross-section (with the relevant nuisance parameters fixed) in quadrature from the total signal uncertainty (with these nuisance parameters allowed to vary), and then dividing by the total uncertainty. The GPR posterior uncertainty is largely, but not entirely, statistical in nature. The "Theory" category consists of parton shower algorithm, parton distribution function, renormalisation and factorisation scales, α_s, $H \to \gamma\gamma$ branching fraction and Higgs boson+heavy-flavour jets cross-section uncertainties.

Uncertainty	$H + c$ uncertainty impact
Statistical (incl. GPR)	79%
GPR posterior	47%
Systematic (excl. GPR)	61%
Theory	40%
Photons	29%
c-tagging	29%
Jets	22%
Spurious signal	12%
Pile-up	5%

phase space, and does not include the branching fraction of the Higgs boson to photons. Expected results are calculated using an Asimov dataset [65] that includes the expected signal.

7 Results

The observed (expected) significance of the inclusive $H + c$ signal is 1.7σ (1.0σ), and so no significant excess above SM signal-plus-background expectation is observed in this search. The observed (expected) best-fit value of the inclusive $H + c$ signal cross-section is 5.2 ± 3.0 pb (2.9 ± 2.8 pb), and the post-fit $m_{\gamma\gamma}$ distributions are shown in Figure 4. Observed (expected) upper limits are set on the inclusive $H + c$ cross-section at the 95% confidence-level at 10.4 pb (8.6 pb) in the combined fit, and at 15 pb (9.6 pb) and 11 pb (14 pb) in the c-tag and non-c-tag SRs, respectively. The sensitivity of this result to the predicted normalisation of the total resonant Higgs boson background is tested by performing an additional fit in which this normalisation is left unconstrained, for which the limit deteriorates by 22% and the correlation between the signal and resonant background normalisation is −66%.



(a) (b)

Figure 4: Pre- and post-fit $m_{\gamma\gamma}$ distributions in the (a) the c-tag and (b) the non-c-tag signal regions. The pre-fit non-resonant background is estimated by using the Gaussian process regression–based interpolation, and the other pre-fit distributions are estimated by using simulation, as described in the main text. The hatched band represents the total post-fit uncertainty. The signal is scaled up by a factor of 5. The lower panel represents the ratio between the data and the total signal-plus-background prediction.

8 Conclusions

A search for the production of a Higgs boson and one or more charm quarks using Higgs boson decays into photon pairs is presented. The search uses a data sample of $\sqrt{s}$ = 13 TeV proton–proton collisions collected between 2015 and 2018 with the ATLAS detector at the CERN LHC, amounting to an integrated luminosity of 140 fb^{-1}. This result is the first direct constraint on the inclusive $H + c$ cross-section, and achieves an expected signal uncertainty at approximately the same level as the expected signal. This analysis also presents the first usage of Gaussian process regression for a direct background estimation in a particle physics data analysis, furthering pre-existing ideas of how to use this technique. The measurement of this process is an important step towards probing the coupling of the Higgs boson to the charm quark using $H + c$ events, which complements existing approaches.

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