A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

The standard model of particle physics describes the known fundamental particles and forces that make up our Universe, with the exception of gravity. One of the central features of the standard model is a field that permeates all of space and interacts with fundamental particles. The quantum excitation of this field, known as the Higgs field, manifests itself as the Higgs boson, the only fundamental particle with no spin. In 2012, a particle with properties consistent with the Higgs boson of the standard model was observed by the ATLAS and CMS experiments at the Large Hadron Collider at CERN. Since then, more than 30 times as many Higgs bosons have been recorded by the ATLAS experiment, enabling much more precise measurements and new tests of the theory. Here, on the basis of this larger dataset, we combine an unprecedented number of production and decay processes of the Higgs boson to scrutinize its interactions with elementary particles. Interactions with gluons, photons, and W and Z bosons—the carriers of the strong, electromagnetic and weak forces—are studied in detail. Interactions with three third-generation matter particles (bottom (b) and top (t) quarks, and tau leptons (τ)) are well measured and indications of interactions with a second-generation particle (muons, μ) are emerging. These tests reveal that the Higgs boson discovered ten years ago is remarkably consistent with the predictions of the theory and provide stringent constraints on many models of new phenomena beyond the standard model.

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each account for about 1% of the total rate. Processes is much smaller and experience.

The ATLAS detector at the LHC

The ATLAS experiment at the LHC is a multipurpose particle detector with a forward–backward symmetric, cylindrical geometry and a near 4π coverage in solid angle. The detector records digitized signals produced by the products of LHC’s proton bunch collisions, hereafter termed collision ‘events’. It is designed to identify a wide variety of particles and measure their momenta and energies. These particles include electrons, muons, τ leptons and photons, as well as gluons and quarks, which produce collimated jets of particles in the detector. Because the jets from b quarks and c quarks contain hadrons with relatively long lifetimes, they can be identified by observing a decay vertex, which typically occurs at a measurable distance from the collision point. The presence of particles that do not interact with the detector, such as neutrinos, can be inferred by summing the vector momenta of the visible particles in the plane transverse to the beam and imposing conservation of transverse momenta.

The detector components closest to the collision point measure charged-particle trajectories and momenta. This inner spectrometer is surrounded by calorimeters that are used in the identification of particles and in the measurement of their energies. The calorimeters are in turn surrounded by an outer spectrometer dedicated to measuring the trajectories and momenta of muons, the only charged particle to travel through the calorimeters. A two-level trigger system was optimized for Run 2 data-taking to select events of interest at a rate of about 1 kHz from the proton bunch collisions occurring at a rate of 40 MHz. An extensive software suite is used in the simulation, reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data-acquisition systems of the experiment.

Input measurements and combination procedure

Physics analyses typically focus on particular production and decay processes and measure the number of Higgs boson candidates observed after accounting for non-Higgs background processes. To determine
the strengths of the interactions of the Higgs boson, simultaneous fits with different physically motivated assumptions are performed on a combined set of complementary measurements. The relative weights of the input measurements in the combination depend on the analysis selection efficiencies, on the signal rates associated with the Higgs processes studied by the analysis, on the signal-to-background ratios, and on the associated systematic uncertainties.

For each decay mode entering the combination, the production process is assessed via event classification based on the properties of particles produced in association with the Higgs boson, mostly via dedicated machine-learning approaches. Unless stated otherwise, studies of each decay mode consider all individual or combined contributions from six production processes: ggF, VBF, WH, ZH, tH and tH. Higgs boson interactions are further explored via additional event classification of each production process based on the kinematic properties of the produced Higgs boson and the associated particles.

The input to the combined measurement includes the latest results from the decay modes that initially led to the Higgs boson discovery: $H \rightarrow Z\ell^+\ell^-$ decays with two $Z$ bosons that subsequently decay into a pair of oppositely charged electrons or muons; $H \rightarrow W^+W^- \rightarrow \ell^+\ell^\nu\nu$, $H \rightarrow Z\gamma \rightarrow \ell^+\ell^-\gamma$ decays targeting separately the ggF and VBF$^{27,30}$, and WH and ZH$^{31,32}$ production processes; and $H \rightarrow gg$ decays$^{33,34}$ with two high-energy photons. The latter is the only measurement used to discriminate between the $t\ell\ell$ and $t\ell$ processes. These diboson decay modes are for the first time complemented by a search for the rare $H \rightarrow Z\ell^\nu\ell^\nu$ decay$^{35}$. The decays of Higgs bosons to fermions are also extensively explored. The measurement of the dominant $H \rightarrow b\bar{b}$ decay mode is particularly challenging owing to a very large multi-jet background, which can be suppressed by requiring the presence of additional particles characteristic of the WH or ZH$^{33,34}$, VBF$^{30}$ and tH$^{35}$ production processes. As a new input, the fully hadronic $H \rightarrow b\bar{b}$ signal events with large Higgs boson transverse momentum are also considered$^{36}$, providing for the first time sensitivity to the ggF production process in this decay mode. The sensitivity of the latest measurement in the $H \rightarrow \tau\tau$ decay mode$^{37}$ is now extended to the tH and combined $t\ell\ell$ and $t\ell$ production processes. In addition to the $t\ell\ell$ measurements obtained in the $jj$, $\tau\tau$ and $ZZ$ decay modes, a complementary analysis that is sensitive to $\tau\tau$, $WW$ and $ZZ$ decays is performed using events with multiple leptons in the final state$^{38}$. The considerably more challenging measurements of Higgs boson couplings to second-generation fermions are explored via searches for the $H \rightarrow \mu^+\mu^-$ decay$^{39}$ and, included in the combination for the first time, $H \rightarrow c\bar{c}$ decay$^{40}$. Owing to the large multi-jet background, the latter decay mode is currently accessed only via WH and ZH production. Finally, the inputs to the combination are complemented by the latest direct searches in the VBF and ZH production processes for Higgs boson decays to invisible particles that escape the detector$^{41,42}$. A summary of these input measurements used in the combination is available in Extended Data Table 1.

All input measurements are performed with the full set of Run 2 data, except for the measurements of previous works$^{30,32,39–41}$, which use a partial Run 2 dataset collected during 2015 and 2016. The direct searches for invisible Higgs boson decays and the $H \rightarrow c\bar{c}$ measurements are employed only for measurements of the relevant Higgs boson coupling strengths, and the $H \rightarrow b\bar{b}$ measurements at high Higgs boson transverse momenta$^{42}$ are considered only when probing the kinematic properties of Higgs boson production. All other inputs are used for the measurements of production cross-sections, branching fractions and coupling strengths. The measurement of kinematic properties of Higgs boson production excludes input measurements from previous works$^{30,32,39–41}$, owing to their limited sensitivity.

Analyses performed with the Run 2 data introduce a number of improvements, often resulting in up to 50% better signal sensitivities compared to those expected from just the increase in the analysed amount of data. These improvements include better particle reconstruction (optimized to cope with an increased number of proton interactions per bunch crossing), dedicated reconstruction of highly Lorentz-boosted $H \rightarrow b\bar{b}$ decays, a greater number of simulated events, higher granularity of the kinematic regions that are probed in each production process, and improved signal and background theory predictions.

The standard model is tested by comparing the observed signal rates to theory predictions that require state-of-the-art calculations of Higgs boson production cross-sections and branching fractions$^{44–50}$. All signal reconstruction efficiencies and most background rates are predicted from the simulation. The simulation is complemented by the use of dedicated signal-depleted control data for measurements of selected background processes and to constrain signal-selection efficiencies. A common set of event generators were used in all analyses to describe the gluon and quark interactions in the proton–proton collisions. The generated particles were passed through a detailed simulation of the ATLAS detector response prior to their reconstruction and identification.

The statistical analysis of the data is described in more detail in Methods. It relies on a likelihood formalism, where the product of the likelihood functions describing each of the input measurements is calculated in order to obtain a combined likelihood$^{51}$. The effects of experimental and theoretical systematic uncertainties on the predicted signal and background yields are implemented by including nuisance parameters in the likelihood function. The values of those additional parameters are either fully determined by the included data, or constrained by Gaussian terms that multiply the likelihood. The effects of uncertainties that affect multiple measurements are propagated coherently through the fit by using common nuisance parameters.

The statistical test of a given signal hypothesis, used for the measurement of the parameters of interest, is performed with a test statistic that is based on the profile likelihood ratio$^{52}$. The confidence intervals of the measured parameters and the $p$ value used to test the compatibility of the results and the standard model predictions are constructed from the test statistic distribution, which is obtained using asymptotic formulae$^{52}$. The total uncertainty in the measurement of a given parameter of interest can be decomposed into different components. The statistical uncertainty is obtained from a fit with all externally constrained nuisance parameters set to their best-fit values. The systematic uncertainty, the squared value of which is evaluated as the difference between the squares of the total uncertainty and the statistical uncertainty, can be decomposed into categories by setting all relevant subsets of nuisance parameters to their best-fit values.

### Combined measurement with ATLAS Run 2 data

The Higgs boson production rates are probed by the likelihood fit to observed signal yields described earlier. Because the production cross-section $\sigma_i$ and the branching fraction $B_i$ for a specific production process $i$ and decay mode $f$ cannot be measured separately without further assumptions, the observed signal yield for a given process is expressed in terms of a single signal strength modifier $\mu_f = (\sigma_i/\sigma_{\text{SM}})(B_i/B_{\text{SM}}^f)$, where the superscript ‘SM’ denotes the corresponding standard model prediction. Assuming that all production and decay processes scale with the same global signal strength $\mu = \mu_f$, the inclusive Higgs boson production rate relative to the standard model prediction is measured to be

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03(\text{stat.}) \pm 0.03(\text{exp.}) \pm 0.04(\text{sig. th.}) \pm 0.02(\text{bkg. th.}).$$

The total measurement uncertainty is decomposed into components for statistical uncertainties, experimental systematic uncertainties, and theory uncertainties in both signal and background modelling. Both the experimental and the theoretical uncertainties are almost
production is low, making the ggF and VBF processes are therefore grouped together, predicting the decay mode is witharding model values, within the uncertainties specified previously. The Higgs boson decay branching fractions are set to their standard model values, with theory uncertainties. Results are obtained from the fit to the data, the total cross-section of each production process is a free parameter to be those from the standard model within corresponding uncertainties. Results are obtained from the fit to the data, where the cross-section of each production process is a free parameter of the fit. Higgs boson decay branching fractions are set to their standard model values, within the uncertainties specified previously. The results are shown in Fig. 2a.

All measurement results are compatible with the standard model predictions. For the ggF and VBF production processes, which were previously observed in Run 1 data, the cross-sections are measured with a precision of 7% and 12%, respectively. The following production processes are now also observed: WH with an observed (expected) signal significance of 5.8 (5.1) standard deviations (σ), ZH with 5.0σ (5.5σ) and the combined tH and tHH production processes with 6.4σ (6.6σ), where the expected signal significances are obtained under the standard model hypothesis. The separate tH and tH measurements lead to an observed (expected) upper limit on tH production of 15 (7) times the standard model prediction at the 95% confidence level (CL), with a relatively large negative correlation coefficient of 56% between the two measurements. This is due to cross-contamination between the tH and tH processes in the set of reconstructed events that provide the highest sensitivity to these production processes.

Branching fractions of individual Higgs boson decay modes are measured by setting the cross-sections for Higgs boson production processes to their respective standard model values. The results are shown in Fig. 2b. The branching fractions of the γγ, ZZ, WW, and ττ decays, which were already observed in the Run 1 data, are measured with a precision ranging from 10% to 12%. The bbH decay mode is observed with a signal significance of 7.0σ (expected 7.7σ), and the observed (expected) signal significances for the H → μμ and H → ττ decays are 2.0σ (1.7σ) and 2.3σ (1.1σ), respectively.

The assumptions about the relative contributions of different decay or production processes in the above measurements are relaxed by directly measuring the product of production cross-section and branching fraction for different combinations of production and decay processes. The corresponding results are shown in Fig. 3. The measurements are in agreement with the standard model prediction.

To determine the value of a particular Higgs boson coupling strength, a simultaneous fit of many individual production times branching fraction values is performed.

**Fig. 2** | Observed and predicted Higgs boson production cross-sections and branching fractions. a. Cross-sections for different Higgs boson production processes are measured assuming standard model (SM) values for the decay branching fractions. b. Branching fractions for different Higgs boson decay modes are measured assuming SM values for the production cross-sections.

**Fig. 3** | Ratio of observed rate to predicted standard model event rate for different combinations of Higgs boson production and decay processes. The horizontal bar on each point denotes the 68% confidence interval. The narrow grey bands indicate the theory uncertainties in the standard model (SM) cross-section multiplied by the branching fraction predictions. The p value for compatibility of the measurement and the SM prediction is 72%. α, β, is normalized to the SM prediction. Data are from ATLAS Run 2.
fraction measurements is required. The coupling fit presented here is performed within the $k$ framework with a set of parameters $k$ that affect the Higgs boson coupling strengths without altering any kinematic distributions of a given process.

Within this framework, the cross-section times the branching fraction for an individual measurement is parameterized in terms of the multiplicative coupling strength modifiers $k$. A coupling strength modifier $k_p$ for a production or decay process via the coupling to a given particle $p$ is defined as $k_p^2 = \sigma_p/\sigma_{SM}$ or $k_p^2 = \Gamma_p/\Gamma_{SM}$, respectively, where $\Gamma_p$ is the partial decay width into a pair of particles $p$. The parameterization takes into account that the total decay width depends on all decay modes included in the present measurements, as well as currently undetected or invisible, direct or indirect decays predicted by the standard model (such as those to gluons, light quarks or neutrinos) and the hypothetical decays into non-standard model particles. The decays to non-standard model particles are divided into decays to invisible particles and other decays that would be undetected owing to large backgrounds. The corresponding branching fractions for the two are denoted by $B_{\text{inv}}$ and $B_{\text{vis}}$, respectively.

In the following, three classes of models with progressively fewer assumptions about coupling strength modifiers $k$ are considered. Standard model values are assumed for the coupling strength modifiers of first-generation fermions, and the modifiers of the second-generation quarks are set to those of the third generation, except where $k_\tau$ is left free-floating in the fit. Owing to their small sizes, these couplings are not expected to noticeably affect any of the results. The ggF production and the $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ decays are loop-induced processes. They are either expressed in terms of the more fundamental coupling strength scale factors corresponding to the particles that contribute to the loop-induced processes in the standard model, or treated using effective coupling strength modifiers $k_\nu$, $k_\mu$, and $k_\tau$, respectively. The latter scenario accounts for possible loop contributions from particles beyond the standard model. The small contribution from the loop-induced $gg \rightarrow ZH$ process is always parameterized in terms of the couplings to the corresponding standard model particles.

The first model tests one scale factor for the vector bosons, $k_W = k_\nu = k_\mu$, and a second, $k_\tau$, which applies to all fermions. In general, the standard model prediction of $k_\tau = k_\nu = k_\mu = 1$ does not hold in extensions of the standard model. For example, the values of $k_\nu$ and $k_\tau$ would be less than 1 in models in which the Higgs boson is a composite particle. The effective couplings corresponding to the ggF, $H \rightarrow \gamma\gamma$ and $H \rightarrow Z\gamma$ loop-induced processes are parameterized in terms of the fundamental standard model couplings. It is assumed that there are no invisible or undetected Higgs boson decays beyond the standard model, that is, $B_{\text{inv}} = B_{\text{vis}} = 0$. As only the relative sign between $k_\nu$ and $k_\mu$ is physical and a negative relative sign has been excluded with a high level of confidence, $k_\nu \geq 0$ and $k_\mu \geq 0$ are assumed. Figure 4 shows the results of a combined fit in the $(k_\nu, k_\mu)$ plane. The best-fit values and their uncertainties from the combined fit are $k_\nu = 1.035 \pm 0.031$ and $k_\mu = 0.95 \pm 0.05$, compatible with the standard model predictions. A relatively large positive correlation of 39% is observed between the two fit parameters, because some of the most sensitive input measurements involve the ggF production process (that is, via couplings to fermions) with subsequent Higgs boson decays into vector bosons.

In the second class of models, the coupling strength modifiers for $W, Z, t, b, c, s, t$ and $\mu$ are treated independently. All modifiers are assumed to be positive. It is assumed that only standard model particles contribute to the loop-induced processes, and modifications of the fermion and vector boson couplings are propagated through the loop calculations. Invisible or undetected non-standard model Higgs boson decays are not considered. These models enable testing of the predicted scaling of the couplings of the Higgs boson to the standard model particles as a function of their mass using the reduced coupling strength modifiers $\sqrt{\kappa_{t, g_F}^2/2vev} = \sqrt{\kappa_{t, g_F}^2/(m_t/vev)}$ for weak bosons with a mass $m_t$ and $\sqrt{\kappa_{t, g_F}^2/2vev} = \sqrt{\kappa_{t, g_F}^2/(m_t/vev)}$ for fermions with a mass $m_t$, where $g_F$ and $g_t$ are the corresponding absolute coupling strengths and ‘vev’ is the vacuum expectation value of the Higgs field.

**Fig. 4** Negative log-likelihood contours corresponding to 68% and 95% CL in the $(k_\nu, k_\mu)$ plane. The data are obtained from a combined fit assuming no contributions from invisible or undetected non-standard model Higgs boson decays. The $p$ value for compatibility of the combined measurement and the standard model (SM) prediction is 14%. Data are from ATLAS Run 2.

**Fig. 5** Reduced Higgs boson coupling strength modifiers and their uncertainties. They are defined as $k_{F} m_{F}/vev$ for fermions ($F = t, b, \tau, \mu$) and $\sqrt{\kappa_{F} m_{F}/vev}$ for vector bosons as a function of their masses $m_{F}$ and $m_{V}$. Two fit scenarios with $k_{\nu} = k_{\mu}$ (coloured circle markers), or $k_{\nu}$ left free-floating in the fit (grey cross markers) are shown. Loop-induced processes are assumed to have the standard model (SM) structure, and Higgs boson decays to non-SM particles are not allowed. The vertical bar on each point denotes the 68% confidence interval. The $p$ values for compatibility of the combined measurement and the SM prediction are 56% and 65% for the respective scenarios. The lower panel shows the values of the coupling strength modifiers. The grey arrow points in the direction of the best-fit value and the corresponding grey uncertainty bar extends beyond the lower panel range. Data are from ATLAS Run 2.
In summary, the production and decay rates of the Higgs boson were measured using the dataset collected by the ATLAS experiment during Run 2 of the LHC from 2015 to 2018. The measurement results were found to be in excellent agreement with the predictions of the standard model. In different scenarios, the couplings to the three heaviest fermions, the top quark, the $b$ quark and the $t$ lepton, were measured with uncertainties ranging from about 7% to 12% and the couplings to the weak bosons ($Z$ and $W$) were measured with uncertainties of about 5%. In addition, indications are emerging of the presence of very rare Higgs boson decays into second-generation fermions and into a $Z$ boson and a photon. Finally, a comprehensive study of Higgs boson production kinematics was performed and the results were also found to be compatible with standard model predictions. In the ten years since its discovery, the Higgs boson has undergone many experimental tests that have demonstrated that, so far, its nature is remarkably consistent with the predictions of the standard model. However, some of its key properties—such as the coupling of the Higgs boson to itself—remain to be measured. In addition, some of its rare decay modes have not yet been observed and there is ample room for new phenomena beyond the standard model to be discovered. Substantial progress on these fronts is expected in the future, given that detector upgrades are planned for the coming years, that systematic uncertainties are expected to be reduced considerably, and that the size of the LHC’s dataset is projected to increase by a factor of 20.

Fig. 6 | Reduced coupling strength modifiers and their uncertainties per particle type with effective photon, $Z$, $W$ and gluon couplings. The horizontal bars on each point denote the 68% confidence interval. The scenario in which $B_{\text{inv.}} = B_{u.} = 0$ is assumed is shown as solid lines with circle markers. The p value for compatibility with the standard model (SM) prediction is 61% in this case. The scenario in which $B_{\text{inv.}}$ and $B_{u.}$ are allowed to contribute to the total Higgs boson decay width while assuming that $\kappa_{c} \leq 1$ and $B_{u.} \geq 0$ is shown as dashed lines with square markers. The lower panel shows the 95% CL upper limits on $B_{\text{inv.}}$ and $B_{u.}$ Data are from ATLAS Run 2.

Conclusion

In summary, the production and decay rates of the Higgs boson were measured using the dataset collected by the ATLAS experiment during Run 2 of the LHC from 2015 to 2018. The measurement results were found to be in excellent agreement with the predictions of the standard model. In different scenarios, the couplings to the three heaviest fermions, the top quark, the $b$ quark and the $t$ lepton, were measured with uncertainties ranging from about 7% to 12% and the couplings to the weak bosons ($Z$ and $W$) were measured with uncertainties of about 5%. In addition, indications are emerging of the presence of very rare Higgs boson decays into second-generation fermions and into a $Z$ boson and a photon. Finally, a comprehensive study of Higgs boson production kinematics was performed and the results were also found to be compatible with standard model predictions. In the ten years since its discovery, the Higgs boson has undergone many experimental tests that have demonstrated that, so far, its nature is remarkably consistent with the predictions of the standard model. However, some of its key properties—such as the coupling of the Higgs boson to itself—remain to be measured. In addition, some of its rare decay modes have not yet been observed and there is ample room for new phenomena beyond the standard model to be discovered. Substantial progress on these fronts is expected in the future, given that detector upgrades are planned for the coming years, that systematic uncertainties are expected to be reduced considerably, and that the size of the LHC’s dataset is projected to increase by a factor of 20.

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Experimental set-up
The ATLAS detector consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadron calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the z axis along the beam pipe. The x axis points from the interaction point to the centre of the LHC ring, and the y axis points upwards. Cylindrical 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 \( \eta = -\ln(\tan(\theta/2)) \).

The inner-detector (ID) system is immersed in a 2-T axial magnetic field and provides charged-particle tracking in the range |η| < 2.5. The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B-layer (IBL) installed before Run 2. It is followed by the silicon microstrip tracker (SCT), which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to |η| < 2.0. The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range |η| < 4.9. Within the region |η| < 3.2, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering |η| < 1.8 to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within |η| < 1.7, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for electromagnetic and hadronic energy measurements, respectively.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 Tm across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, covers the region |η| < 2.7, complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range |η| < 2.4 with resistive-plate chambers in the barrel, and thin-gap chambers in the endcap regions.

The performance of the vertex and track reconstruction in the inner detector, the calorimeter resolution in electromagnetic and hadronic calorimeters and the muon momentum resolution provided by the muon spectrometer are given previously.

Interesting events are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger. The first-level trigger accepts events from the 40-MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record events to disk at about 1 kHz.

Statistical framework
The results of the combination presented in this paper are obtained from a likelihood function defined as the product of the likelihoods of each input measurement. The observed yield in each category of reconstructed events follows a Poisson distribution the parameter of which is the sum of the expected signal and background contributions. The number of signal events in any category k is split into the different production and decay modes:
using the full Run 2 data and those using only the 2015 and 2016 data, owing to differences in their assessment, in the reconstruction algorithms and in software releases. Systematic uncertainties associated with the modelling of background processes, as well as uncertainties due to the limited number of simulated events used to estimate the expected signal and background yields, are treated as being uncorrelated between analyses.

Uncertainties in the parton distribution functions are implemented coherently in all input measurements and all analysis categories[75]. Uncertainties in modelling the parton showering into jets of particles affect the signal acceptances and efficiencies, and are common to all input measurements within a given production process. Similarly, uncertainties due to missing higher-order quantum chromodynamics (QCD) corrections are common to a given production process. Their implementation in the kinematic regions of the simplified template cross-sections framework results in a total of 66 uncertainty sources, where overall acceptance effects are separated from migrations between the various bins (for example, between jet multiplicity regions or between dijet invariant mass regions)[96]. Both the acceptance and signal yield uncertainties affect the signal strength modifier and coupling strength modifier results, which rely on comparisons of measured and expected yields. Only acceptance uncertainties affect the cross-section strength modifier results, which rely on comparisons of measured and expected yields. Measurements of kinematic uncertainties due to missing higher-order quantum chromodynamics (QCD) corrections are common to a given production process. Their implementation in the kinematic regions of the simplified template cross-sections framework results in a total of 66 uncertainty sources, where overall acceptance effects are separated from migrations between the various bins (for example, between jet multiplicity regions or between dijet invariant mass regions). Both the acceptance and signal yield uncertainties affect the signal strength modifier and coupling strength modifier results, which rely on comparisons of measured and expected yields. Only acceptance uncertainties affect the cross-section and branching fraction results. The uncertainties in the Higgs boson branching fractions due to dependencies on standard model parameter values (such as $b$ and $c$ quark masses) and missing higher-order effects are implemented using the correlation model described previously[44].

In total, over 2,600 sources of systematic uncertainty are included in the combined likelihood. For most of the presented measurements, the systematic uncertainty is expected to be of similar size or somewhat smaller than the corresponding statistical uncertainty. The systematic uncertainties are dominant for the parameters that are measured the most precisely, that is, the global signal strength and the production cross-sections for the ggF and VBF processes. The expected systematic uncertainty of the global signal strength measurement (about 5%) is larger than the statistical uncertainty (3%), with similar contributions from the theory uncertainties in signal (4%) and background modelling (1.7%), and from the experimental systematic uncertainty (3%). The latter is predominantly composed of the uncertainty in the luminosity measurement (1.7%), followed by the uncertainties in electron, jet and b-jet reconstruction, data-driven background modelling, as well as from the limited number of simulated events (about 1% each). All other sources of experimental uncertainty combined contribute an additional 1%. The systematic uncertainty in the production cross-section of the ggF process is dominated by experimental uncertainties (3.5%) followed by signal theory uncertainties (3%), compared to a statistical uncertainty of 4%. For the VBF process, where the statistical uncertainty is 8%, the experimental uncertainties are estimated to be 5%, and the signal theory uncertainties add up to 7%. Systematic uncertainties are also dominant over the statistical uncertainties in the measurements of the branching fractions into $W$ pairs and $Z$ lepton pairs.

Measurements of the parameters of interest use a statistical test based on the profile likelihood ratio[97]:

$$
\Lambda(\alpha) = \frac{L(\alpha, \hat{\theta}(\alpha))}{L(\hat{\alpha}, \hat{\theta})},
$$

where $\alpha$ are the parameters of interest and $\theta$ are the nuisance parameters. The $\hat{\theta}(\alpha)$ notation indicates that the nuisance parameters values are those that maximize the likelihood for given values of the parameters of interest. In the denominator, both the parameters of interest and the nuisance parameters are set to the values $\hat{\alpha}, \hat{\theta}$ that unconditionally maximize the likelihood. The estimates of the parameters $\alpha$ are these values $\hat{\alpha}$ that maximize the likelihood ratio.

Owing to the usually large number of events selected in the measurements, all results presented in this paper are obtained in the asymptotic regime where the likelihood approximately follows a Gaussian distribution. It was checked in previous iterations of the individual input measurements, for instance ref. [77], that this assumption also holds in cases with low event counts by comparing the results of the asymptotic formulae with those of pseudo-experiments. This confirmed the results from a previous work[98] that the Gaussian approximation becomes valid for as few as $\geq 5$ background events. In the asymptotic regime twice the negative logarithm of the profile likelihood $\Lambda(\alpha) = -2ln(\Lambda(\alpha))$ follows a $\chi^2$ distribution with a number of degrees of freedom equal to the number of parameters of interest. Confidence intervals for a given confidence level (CL), usually 68%, are then defined as the regions fulfilling $\Lambda(\alpha) < \chi^2_{n}(CL)$ where $\chi^2_{n}$ is the quantile function of the $\chi^2$ distribution with $n$ degrees of freedom, so $\chi^2_{n} = 1 (4)$ for a 68% (95%) CL with one degree of freedom. The values of the parameters $\alpha$ corresponding to these confidence intervals are obtained by scanning the profile likelihood. Similarly, the $p$ value $p_{\text{obs}} = 1 - F_{\Lambda}(\alpha_{\text{max}})$ is used to test the compatibility of the measurement and the standard model prediction. The correlations between the parameters are estimated by inverting the matrix of the second derivatives of the likelihood.

The expected significances and limits are determined using the ‘Asimov’ datasets, which are obtained by setting the observed yields to their expected values when the nuisance parameters are set to the values that maximize the likelihood.$^\theta$

**Parameterization within the $\kappa$ framework**

Within the $\kappa$ framework, the cross-section for an individual measurement is parameterized as

$$
\sigma(i \to H \to f) = \sigma_{0}B_{f} = \frac{\sigma_{\kappa}(\kappa)F_{h}(\kappa, B_{\text{inv}}, B_{u})}{\sigma_{\kappa}(\kappa, B_{\text{inv}}, B_{u})},
$$

where $F_{h}$ is the partial width for a Higgs boson decay to the final state $f$ and $\sigma_{\kappa}$ is the total decay width of the Higgs boson. The total width is given by the sum of the partial widths of all the decay modes included. Contributions to the total Higgs boson decay width owing to phenomena beyond the standard model may manifest themselves as a value of coupling strength modifier $\kappa$ differing from one, or a value of $B_{\text{inv}}$ or $B_{u}$ differing from zero. The Higgs boson total width is then expressed as $\sigma_{\kappa}(\kappa, B_{\text{inv}}, B_{u}) = \kappa_{\text{SM}}^{2}(\kappa, B_{\text{inv}}, B_{u}) \cdot \sigma_{\kappa}(\kappa, B_{\text{inv}}, B_{u})$ with

$$
\kappa_{\text{SM}}^{2}(\kappa, B_{\text{inv}}, B_{u}) = \frac{\sum_{i}B_{i}^{\text{SM}} k_{p}^{2}}{1 - B_{\text{inv}} - B_{u}}.
$$

Higgs boson production cross-sections and partial and total decay widths are parameterized in terms of the coupling strength modifiers as shown in table 9 of ref. [92]. An improved parameterization including additional sub-leading contributions is used in this paper to match the increased precision of the measurements.

**Kinematic regions probing Higgs boson production**

The definitions of kinematic regions for the precision study of Higgs boson production in the framework of simplified template cross-sections[44,50–58] are based on the predicted properties of particles generated in a given production process. The partitioning follows the so-called Stage-1.2 scheme, which features a slightly finer granularity than the Stage-1.1 scheme[57] and introduces the Higgs boson transverse momentum categories for the $t\bar{t}H$ production process. Higgs bosons are required to be produced with rapidity $|y| < 2.5$. Associated jets of particles are constructed from all stable particles with a lifetime greater than 10 ps, excluding the decay products of the Higgs boson and leptons from $W$ and $Z$ boson decays, using the anti-$k_{t}$ algorithm[96] with a jet radius parameter $R = 0.4$, and must have a transverse momentum $p_{T,\text{jet}} > 30$ GeV. Standard model predictions are assumed for the kinematic properties of Higgs boson decays. Phenomena beyond the
Higgs boson production is first classified according to the nature of the initial state and the associated particles, the latter including the decay products of W and Z bosons if they are present. These classes are: tH and tH processes; qq → Hqq processes, with contributions from both VBF and quark-initiated VH (where V = W, Z) production with a hadronic decay of the vector boson; pp → VH production with a leptonic decay of the vector boson (V(ℓℓ, ℓν)H), including gg → ZH → tH production; and finally the gg process combined with gg → ZH → q̄qH production to form a single gg → H process. The contribution of the bH production process is taken into account as a 1% increase of the gg → H yield in each kinematic region, because the acceptances for both processes are similar for all input analyses.

The input measurements in individual decay modes provide only limited sensitivity to the cross-section in some of the regions of the Stage-1.2 scheme, mainly because of the small number of events in some of these regions. In other cases, they only provide sensitivity to a combination of these regions, leading to strongly correlated measurements. To mitigate these effects, some of the Stage-1.2 kinematic regions were merged for the combined measurement.

Compared to individual input measurements, systematic theory uncertainties associated with the signal predictions have been updated for the combination to closely follow the granularity of the Stage-1.2 scheme. The QCD scale uncertainties in ggF production were updated for all input channels that are sensitive to this production process. Out of 18 uncertainty sources in total, two account for overall fixed-order and resummation effects, two cover the migrations between different multiplicity bins, seven are associated with the modelling of the Higgs boson transverse momentum (p_{T}^{H}) in different phase-space regions, four account for the uncertainty in the distribution of the dijet invariant mass (m_{jj}) variable, one covers the modelling of the Higgs boson plus two leading jets transverse momentum (p_{T}^{jj}) in the ≥2-jet region, one pertains to modelling of the distribution of the Higgs boson plus one jet transverse momentum (p_{T}^{j}) divided by p_{T}^{H} in the high-p_{T}^{H} region, and finally, the last takes into account the uncertainty from the choice of top quark mass scheme. Theory uncertainties for the qq → Hqq and tH processes are defined previously, and those of the V(ℓℓ, ℓν)H kinematic region follow the scheme described in an earlier work. For the kinematic regions defined by the merging of several Stage-1.2 regions, the signal acceptance factors are determined assuming that the relative fractions in each Stage-1.2 region are given by their standard model values, and the uncertainties predicted by the standard model in these fractions are taken into account.

Data availability

The experimental data that support the findings of this study are available in HEPData with the identifier https://doi.org/10.17182/hepdata.130266.

Code availability

The ATLAS data reduction software is available at the following link: https://zenodo.org/record/4772550. Statistical modelling and analysis is based on the ROOT software and its embedded RooFit and RooStats modules. Available at https://zenodo.org/record/3895852. Code to configure these statistical tools and to process their output is available upon request.

60. ATLAS Collaboration. ATLAS Invertible B-Layer. Technical Design Report Report No. CERN-LHCC-2010-013 (CERN, 2010). https://cds.cern.ch/record/1594633
61. Abbott, B. et al. Production and integration of the ATLAS Invertible B-Layer. J. Instrum. 13, T05008 (2018).
Extended Data Table 1 | Summary of the input measurements used for the combined fit results

| Decay mode | Targeted production processes | $L$ [fb$^{-1}$] | Ref. | Fits deployed in |
|------------|------------------------------|----------------|------|-----------------|
| $H \rightarrow \gamma\gamma$ | $ggF, VBF, WH, ZH, t\bar{t}H, tH$ | 139 | 31 | All |
| $H \rightarrow ZZ$ | $ggF, VBF, WH + ZH, t\bar{t}H + tH$ | 139 | 28 | All |
| | $t\bar{t}H + tH$ (multilepton) | 36.1 | 39 | All but fit of kinematics |
| $H \rightarrow WW$ | $ggF, VBF, WH, ZH$ | 139 | 29 | All |
| | $t\bar{t}H + tH$ (multilepton) | 36.1 | 30 | All but fit of kinematics |
| $H \rightarrow Z\gamma$ | inclusive | 139 | 31 | All but fit of kinematics |
| $H \rightarrow b\bar{b}$ | $WH, ZH$ | 139 | 32, 34 | All |
| | $VBF$ | 126 | 35 | All |
| | $t\bar{t}H + tH$ (multilepton) | 36.1 | 36 | All |
| | inclusive | 139 | 37 | Only for fit of kinematics |
| $H \rightarrow \tau\tau$ | $ggF, VBF, WH + ZH, t\bar{t}H + tH$ | 139 | 38 | All |
| | $t\bar{t}H + tH$ (multilepton) | 36.1 | 39 | All but fit of kinematics |
| $H \rightarrow \mu\mu$ | $ggF + t\bar{t}H + tH, VBF + WH + ZH$ | 139 | 40 | All but fit of kinematics |
| $H \rightarrow c\bar{c}$ | $WH + ZH$ | 139 | 41 | Only for free-floating $\kappa_C$ |
| $H \rightarrow$ invisible | $VBF$ | 139 | 42 | $\kappa$ models with $B_{\kappa, R_{\kappa}}$ |
| | $ZH$ | 139 | 43 | $\kappa$ models with $B_{\kappa, R_{\kappa}}$ |

Listed are the measured decay modes, targeted production processes and integrated luminosity ($L$) used for each input analysis of the combination. The references for the input measurements and information about which combined measurements they enter are also provided. The $q\bar{q}/gg + t\bar{t}H + tH$ measurement in the multilepton final state$^{35}$ is complementary to other $q\bar{q}/gg + t\bar{t}H + tH$ measurements in the $WW, ZZ$ and $\tau\tau$ decay modes, with no overlapping events selected by these measurements.