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Evidence of Higgs boson inclusive production at high transverse momentum decaying to a pair of b-quarks with the ATLAS detector

The ATLAS Collaboration

This letter reports on the first evidence of Higgs-boson production at high transverse momentum in the $b\bar{b}$ final state, reconstructed in a single large-radius jet. The results are based on proton proton collision data recorded by the ATLAS detector at the Large Hadron Collider at a centre-of-mass energies of 13 TeV and 13.6 TeV, corresponding to a total integrated luminosity of 301 fb^{-1}. The study profits from the large background suppression provided by the use of a new transformer-based algorithm for jet identification and the sharper mass and transverse momentum, p_{T}, resolution from a dedicated regression model. The yield relative to the Standard Model prediction, for Higgs bosons produced at p_{T} larger than 450 GeV is measured to be $1.53 \pm 0.27\,(\text{stat.})\,^{+0.33}_{-0.27}\,(\text{syst.}) \pm 0.17\,(\text{theo.})$ corresponding to an observed (expected) significance of 3.8σ (2.5σ) relative to the background-only hypothesis. Results are also obtained in three Higgs boson p_{T} intervals and found to be compatible with Standard Model predictions.

The steady increase in the amount of data collected in high-energy proton–proton (pp) collisions at the CERN Large Hadron Collider (LHC), together with advances in reconstruction techniques using transformer-based [1–3] models, opens new avenues for exploring phenomena at the TeV energy scale. Although measured production and decay rates are so far consistent with the Standard Model (SM) [4, 5], the study of Higgs-boson production at large transverse momentum (p_{T}) offers the opportunity to unveil or constrain new phenomena [6–9]. At high p_{T}, Higgs boson production becomes sensitive to the loop structure of gluon–gluon fusion (ggF). As a result of modified couplings from possible new physics contributions, effects from physics beyond the SM are typically enhanced by factors depending on the Higgs boson p_{T}. This motivates a dedicated study in the boosted regime with p_{T} up to and beyond 1 TeV. The $H \to b\bar{b}$ decay dominates the branching fractions and offers the best sensitivity of this rare process [10–14].

This letter reports a study of boosted inclusive Higgs boson production in pp collisions recorded by the ATLAS detector. Signal events feature a central high-p_{T} jet containing the two collimated b-hadrons from a $H \to b\bar{b}$ decay, recoiling against additional jets. Because of energy lost through neutrinos from b-hadron decays and of detector resolution effects, the Higgs boson candidate may be reconstructed as either the leading or subleading jet in p_{T}.

The Higgs boson yield is extracted from the jet mass m_J distribution, dominated by a smoothly falling non-resonant multijet QCD background with additional contributions from hadronic W/Z+jets and top-quark pair ($t\bar{t}$) production. The resonant $Z \to b\bar{b}$ and $H \to b\bar{b}$ rates are expressed in terms of signal-strength modifiers μ, defined as the ratio of the measured yields to their SM predictions, in a simultaneous fit that determines the multijet background entirely from data. The pronounced $Z \to b\bar{b}$ peak serves as an in-situ calibration of the jet tagging rates and the jet mass scale and resolution in the fit used to extract the Higgs boson signal.

Compared to an earlier Run 2 study [12], the analysis sensitivity improves by a factor of seven to ten. This improvement results from stronger multijet background suppression with a new transformer-based bb tagger, which also nearly removes the $V \to qq'$ and $t\bar{t}$ contributions from the signal region, leaving $Z \to b\bar{b}$ and $H \to b\bar{b}$ as the dominant resonant processes. Additional gains arise from the improved jet mass and p_{T} resolution from a transformer-based regression model, the simultaneous fit of signal and control regions to constrain the multijet background, and a larger analysed dataset.

The ATLAS experiment at the LHC is a multi-purpose particle detector with a forward-backward symmetric cylindrical geometry, described in detail in Refs. [15, 16]. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electro-magnetic and hadronic calorimeters, and a muon spectrometer. This analysis uses pp collision datasets recorded with the ATLAS detector totaling 140 fb^{-1} at $\sqrt{s}$ = 13 TeV during Run 2 (2015–2018) and 161 fb^{-1} at $\sqrt{s}$ = 13.6 TeV during the first three years of Run 3 (2022–2024) [17–19].

Monte Carlo (MC) simulated event samples are used to model Higgs boson production at next-to-leading-order (NLO) QCD accuracy using Powheg Box [20–22] with parton showering and hadronization provided by Pythia 8 [23]. Cross sections are normalized to state-of-the-art predictions, corresponding to NNLO QCD calculations for ggF including exact NLO top-mass effects, NNLO QCD for vector-boson-fusion (VBF), and NLO QCD for associated production with a vector boson (VH) or top-quarks ($t\bar{t}H$) [24]. The W/Z+jets and $t\bar{t}$ backgrounds are simulated using Sherpa 2.2.14 [25] and Powheg Box [20–22, 26], respectively. The detector response is modeled with Geant4 [27], including pile-up effects [28]. The effects of radiation damage in the Pixel detector [29, 30] are included for samples matching Run 3 data conditions.

Charged-particle tracks are reconstructed in the ID [31, 32] and used as components of the jet objects and for b-tagging. Jets are reconstructed from unified flow objects (UFO) [33] using the anti-k_t algorithm [34] with $R = 1.0$ and groomed with Soft-Drop [35, 36] and pile-up mitigation techniques [37, 38].

Transformer-based models are a key aspect of the analysis and used to identify and calibrate jets from resonances decaying to $b\bar{b}$ (bb-jet). These models are trained on samples of simulated events containing mixtures of jet flavors and exploit the kinematic and topological properties of UFO constituents and other charged particle tracks.

Jets containing two b-hadrons are identified using an improved version of the GN2X tagger [2] trained on simulated event samples corresponding to Run 2 and Run 3 conditions. The GN2X tagger output is rescaled in simulated Run 2 events to account for pixel radiation damage. Mass-dependent selections on the tagger output (working points, WPs) are defined independently for the leading and subleading jet *categories*, p_{T} ranges, and data-taking years using multijet events simulated with Pythia 8 [39]. These WPs suppress the multijet background by a nearly constant factor of about 500 across the jet-mass range, an improvement of more than four times compared to that of Ref. [12], with signal efficiencies of $\sim 45\%$ ($\sim 40\%$) for leading (subleading) Higgs jets. The efficiency for selecting $Z \to b\bar{b}$ or $H \to b\bar{b}$ jets is similar, and the suppression of top-quark jets is comparable to that of multijet background jets.

The reconstructed jet mass and p_{T} response [40] are improved using the bJR regression model [3], enhancing the jet mass and p_{T} resolution by approximately 30% and 20%, respectively, and thereby increasing the analysis sensitivity by nearly 30%. The p_{T} scale and resolution are validated using $Z \to \mu\mu$ +jet events by exploiting the balance between the recoil jet and the $\mu^+\mu^-$ system. Data and simulation agree at the 3% level, defining the associated energy scale (JES) and resolution (JER) uncertainty. Additionally, if a muon is associated to a subleading jet passing the GN2X requirement, its four-momentum is added to the jet, improving its mass resolution by about 12% in simulated Higgs boson events.

The simulation-to-data bb-tagging efficiency correction factors $\kappa_{bb}^{\mathrm{GN2X}}$, jet mass scale (JMS), and mass resolution (JMR) are determined in situ from the $Z \to b\bar{b}$ peak and applied to the Higgs boson signal templates. The factor $\kappa_{bb}^{\mathrm{GN2X}} \equiv \mu_{Z\to b\bar{b}}/\mu_{Z\to\mu\mu}$, where $\mu_{Z\to\mu\mu}$ is obtained from an independent fit to $Z \to \mu\mu$+ jet(s) data, ensures that common Z + jets production uncertainties versus jet p_{T} cancel in the ratio [41].

Data events are selected using a combination of unprescaled high-level triggers requiring a jet with online p_{T} thresholds from 420 GeV, with additional jet mass requirements used from 2018 [42, 43]. Events are required to contain at least one *candidate* jet spatially matched to the jet in the trigger system, pseudorapidity $|\eta| < 2.0$, transverse momentum on the trigger efficiency plateau of $p_{\mathrm{T}} > 450$ GeV, m_J in excess of 45 GeV and satisfying $2m_J/p_{\mathrm{T}} < 1$, ensuring well-contained boosted topologies. After applying the jet corrections above, the study focuses on the jet mass range 55–160 GeV.

Candidate jets are organized into *regions* according to the GN2X tagger output. If the leading jet passes the GN2X requirement, it enters the leading-jet signal region (SRL). Otherwise, if the subleading jet is tagged, it enters the subleading-jet signal region (SRS). Jets failing the tagger requirement have an m_J distribution that closely resemble that of the SR due to the definition of the GN2X WPs. These jets are partitioned into a control region (CR), used to constrain the multijet background shape in the SR, and a validation region (VR) used to test the multijet model. The CR is selected to have ten times the SR yield, proportionally across data-taking periods to preserve the time-dependent detector and pile-up conditions; the remaining 97.5% of anti-tagged jets form the VR. Anti-tagged leading (subleading) candidate jets populate the CRL and VRL (CRS and VRS). All regions are studied in three candidate-jet p_{T} bins: 450–650 GeV, 650–1000 GeV, and above 1000 GeV.

Within the SR, the SM predicts that ggF production constitutes about 50% of the selected signal in the 450–650 GeV p_{T} interval, decreasing to ~40% above 1 TeV, while the VH fraction increases from ~25% to nearly 40%, whereas VBF and $t\bar{t}H$ remain subleading at the ~20% and ~5% level, respectively.

For the bJR validation, trigger efficiency studies, and for an input to $\kappa_{bb}^{\mathrm{GN2X}}$, the $Z \to \mu\mu+$jet(s) sample is selected by requiring two oppositely charged muons with $p_{\mathrm{T}} > 50$ GeV and a high-p_{T} recoiling jet, using the same jet trigger requirements discussed above. The $Z \to \mu\mu$ signal rate is measured in the same three p_{T} intervals considering a full suite of systematic uncertainties. The jet trigger efficiency is studied using $Z \to \mu\mu$ events collected by a muon trigger [44].

The m_J spectrum of the multijet background in each SR and the corresponding CR is described by an exponentiated polynomial of order N (f_N), while residual SR–CR shape differences are absorbed by a multiplicative transfer function of order M (t_M) multiplied to the CR m_J spectrum,

$$f_N(x|\vec{\phi}) = \phi_0 \exp\left(\sum_{i=1}^{N} \phi_i x^i\right), \quad t_M(x|\vec{\psi}) = 1 + \sum_{j=1}^{M} \psi_j x^j$$

where $x = (m_J - 140\text{ GeV})/70\text{ GeV}$, ϕ_i and ψ_j are free parameters fitted independently to data for each jet category, p_{T} bin, and dataset. The ϕ_0 normalizations are treated independently in the SR and CR. Studies conducted with a set of MC generators and fragmentation models indicate that SR–CR m_J shape variations can arise from differences in the flavor composition and jet substructure and can be well described by the transfer function. More details are given in the Appendix. Compared to fits to the SRs alone, the use of the CRs helps to constrain the multijet background model. The uncertainties on the f_N parameters are reduced by 20–30%, improving the statistical precision on μ_H by ≃15–20%. The correlations between μ_H and the dominant systematic uncertainties, JMS and JMR, are also reduced by 15–40%, leading to smaller systematic uncertainties.

The VR mass spectrum provides a good approximation of the SR multijet background. The determination of the multijet background is studied using VR events divided into statistically independent subsets, or *slices*, with event counts comparable to the SR. After subtracting the W, Z and $t\bar{t}$ resonant contributions, these slices are reweighted to match the SR multijet shape using the ratio of f_N functions obtained from independent fits to the SR and CR spectra. $Z \to b\bar{b}$ and $H \to b\bar{b}$ templates are then injected at varying signal rates to evaluate the linearity of the fit response and the presence of spurious signal effects [45]. An ensemble of these slices are used to perform fits with $3 \leq N \leq 5$ and $0 \leq M \leq 2$ for the multijet parametrization.

The N and M orders are determined using these fits [12]. They are chosen such that the average bias of the extracted signal strength is small and the fraction of fits in which μ deviates by more than twice the fit statistical uncertainty $\sigma_{\mathrm{fit}}^{\mathrm{stat}}$ from the mean is approximately 5%. In each region, these studies show that $N = 4$ and $M = 2$ provide stable behavior. Small residual biases of 0.1–0.3 $\sigma_{\mathrm{fit}}^{\mathrm{stat}}$ in the extracted Higgs boson signal strength are incorporated as a spurious-signal uncertainty, with a minor effect on the total uncertainty. For the $Z \to b\bar{b}$ rate, the residual bias is $\sim 0.15\sigma_{\mathrm{fit}}^{\mathrm{stat}}$.

The strong rejection of multi-prong jets by the GN2X tagger and the m_J <160 GeV requirement greatly reduce the top-quark background. A boosted semi-leptonic $t\bar{t}$ control region is used to extract simulation-to-data correction factors from m_J fits and are applied separately in the SRs and CRs with a 25% uncertainty [46], leading to a 5% uncertainty on μ_H.

Signal yields are extracted using a simultaneous profile likelihood fit [47, 48] to the jet mass distributions in the SRL, SRS, CRL, and CRS categories divided into the three jet p_{T} bins separately for the Run 2 and

Run 3 datasets. In total, 12 pairs of signal and control regions are included in the fit. The $Z \to b\bar{b}$ event rates in the $\kappa_{bb}^{\mathrm{GN2X}}$ factors are treated as independent free parameters for each jet category, p_{T} bin, and dataset. The likelihood depends on $H \to b\bar{b}$ signal strength parameters $\vec{\mu}_H$, 12 $\kappa_{bb}^{\mathrm{GN2X}}$ factors, over 100 systematic uncertainty parameters, and 96 free parameters $\vec{\phi}$ and $\vec{\psi}$ modeling the multijet background.

Higgs boson cross section uncertainties are taken from Ref. [24], with additional top-quark-mass scheme effects from Ref. [49]. Acceptance uncertainties (scale, PDF, and parton shower variations) are evaluated from simulation, yielding an uncertainty of 17–18% depending on p_{T}. These uncertainties are fully correlated across regions and are the only systematic uncertainties correlated between datasets.

The dominant experimental uncertainties arise from the JMS and JMR, shared between the $Z \to b\bar{b}$ and $H \to b\bar{b}$ templates within a region but treated independently across jet categories, p_{T} bins, and datasets. Conservative prior uncertainties of 5% (JMS) and 25% (JMR) are assigned and are strongly constrained by the data: the $Z \to b\bar{b}$ peak position is determined to better than 1% precision in the lowest p_{T} bin and about 2% at the highest p_{T}, while the mass resolution is constrained to 3–18% depending on p_{T}. These constraints are propagated to the $H \to b\bar{b}$ template. Separate JMS and JMR parameters are used for the $W/Z \to q\bar{q}$ contribution in the CRs to account for flavor-composition differences. The full list of systematic uncertainties is given in the Appendix.

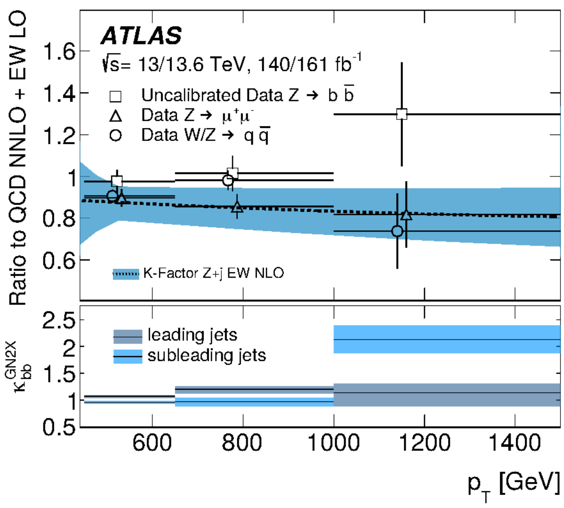
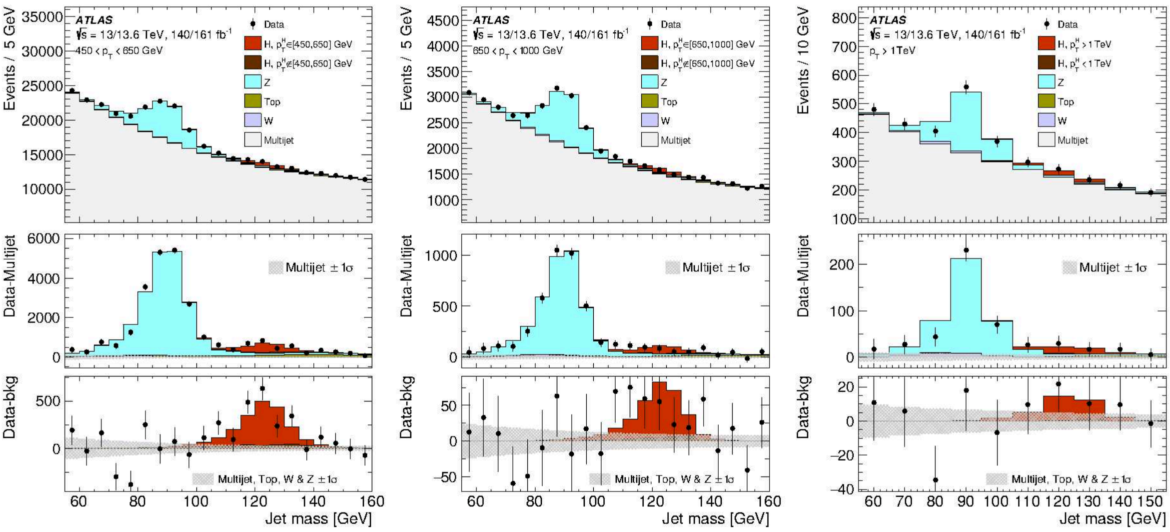


Figure 1: Observed $Z \to \mu\mu$+jet(s) event rate as a function of jet p_{T} compared to theoretical predictions from Sherpa 2.2.14 including QCD NNLO corrections from NNLOJET [50, 51] and EW NLO corrections from Sherpa with uncertainties estimates from Ref. [52]. The $W/Z \to q\bar{q}$ and $Z \to b\bar{b}$ rates, the latter uncalibrated for GN2X efficiency, are overlaid for comparison (upper panel). Fitted values of the leading and subleading $\kappa_{bb}^{\mathrm{GN2X}}$ factors averaged over datasets are shown within each p_{T} bin in the lower panel.

As part of the validation of the analysis strategy and the determination of the GN2X tagging efficiency, the Z + jets event rate is probed in three complementary final states (see Figure 1). The $Z \to \mu\mu$ event rate is extracted from the 96%-pure $Z \to \mu\mu$+jet(s) sample with a relative precision of 3–14%. The excellent agreement with state-of-the-art theory predictions [50, 51] across the full p_{T} range validates the denominator of $\kappa_{bb}^{\mathrm{GN2X}}$. The inclusive $W/Z \to q\bar{q}$ event rate derived from fits to the (anti-tagged) VR, which contains 99.8% of the selected jets, is also consistent. The uncalibrated $Z \to b\bar{b}$ rate, without $\kappa_{bb}^{\mathrm{GN2X}}$ applied, extracted simultaneously with the Higgs boson signal strength, is averaged and overlaid for comparison. With increasing p_{T}, it exhibits a mild upward trend, consistent with residual differences



(a) (b) (c)

Figure 2: Post-fit jet mass distributions in the (a) $450 < p_{\mathrm{T}} < 650$ GeV, (b) $650 < p_{\mathrm{T}} < 1000$ GeV, and (c) $p_{\mathrm{T}} > 1000$ GeV signal regions, summed over jet categories and datasets. The middle panel shows the data with the multijet background subtracted, and the bottom panel shows the data with all backgrounds subtracted. The fit is performed simultaneously across the twelve signal–control region pairs, with the Higgs boson contribution scaled to the fitted μ_H.

in the GN2X tagging efficiency between data and simulation. This behavior is captured in the in-situ determination of the twelve $\kappa_{bb}^{\mathrm{GN2X}}$ factors, represented in the lower panel of Figure 1 after averaging over datasets. For $p_{\mathrm{T}} > 1$ TeV, the $Z \to b\bar{b}$ signal is observed with a significance exceeding five standard deviations from the background-only hypothesis (see Figure 2), demonstrating the performance of boosted bb reconstruction and flavor tagging in the TeV regime.

The signal strength for Higgs bosons with reconstructed jet $p_{\mathrm{T}} \geq 450$ GeV extracted across all signal regions is $\mu_H = 1.53 \pm 0.27\,(\text{stat.})\,^{+0.33}_{-0.27}\,(\text{syst.}) \pm 0.17\,(\text{theo.})$ and corresponds to an observed (expected) significance of 3.8 (2.5) σ relative to the background-only hypothesis. Among the experimental uncertainties, the JMR and JMS parameters contribute ± 0.20 to the uncertainty on μ_H, while the $\kappa_{bb}^{\mathrm{GN2X}}$ parameters contribute ± 0.17, as determined from the impact method [53]. These are largely statistical in origin, reflecting the finite precision of the $Z \to b\bar{b}$ sample that constrains them, and are expected to decrease with increasing data. The combined post-fit distributions are shown in Figure 2 and exhibit good agreement between the fitted model and the data for all p_{T} bins.

The Higgs boson yield is also extracted with three independent signal strengths corresponding to intervals of its truth transverse momentum p_{T}^H in a simplified template cross section STXS-like framework [54–56]. The yield of migrated Higgs boson events with truth $p_{\mathrm{T}}^H < 450$ GeV are constrained to the results from Ref. [57]. The fitted μ_H values are $1.98 \pm 0.36\,(\text{stat.})\,^{+0.53}_{-0.40}\,(\text{syst.}) \pm 0.17\,(\text{theo.})$, $0.23 \pm 0.67\,(\text{stat.}) \pm 0.49\,(\text{syst.}) \pm 0.17\,(\text{theo.})$, and $2.3 \pm 1.4\,(\text{stat.})\,^{+1.3}_{-1.1}\,(\text{syst.}) \pm 0.2\,(\text{theo.})$ for p_{T}^H intervals of 450–650 GeV, 650–1000 GeV, and > 1000 GeV, respectively, corresponding to observed (expected) significances of 3.9 (1.9) σ, 0.3 (1.3) σ, and 1.3 (0.5) σ. The measurements are compatible with the SM expectations at the 16% level. Signal strengths extracted separately in Run 2 and Run 3, and in individual signal regions, are compatible with the reported results, with p-values of ~40–80%. The stability of the results has been tested under variations of the fit configuration. Changing the order of f_N by ±1, correlating $\kappa_{bb}^{\mathrm{GN2X}}$ across runs or jet categories, and decorrelating the JMS and JMR parameters between the Z and H components result in shifts in the measured μ_H that are compatible with the reported results.

Measured inclusive Higgs boson production signal strengths for the combined Run 2 and Run 3 dataset are shown in Figure 3 as a function of p_{T}^{H}. The EW NLO corrections derived using the HAWK package [58] are shown for the average of the VH, VBF and $t\bar{t}H$ Higgs boson production processes, for which they are known, weighted by their acceptance in this analysis.

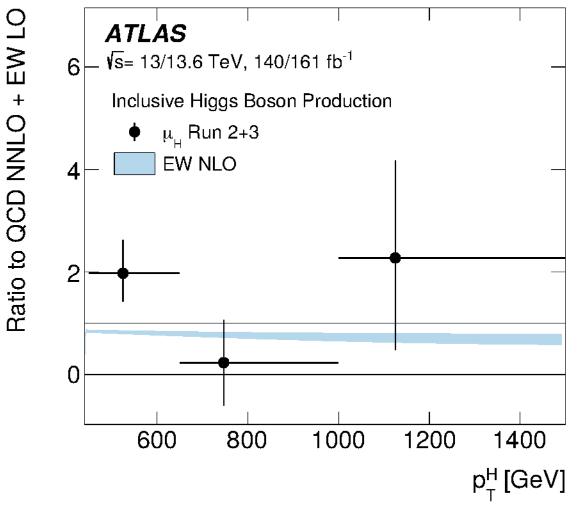


Figure 3: Measured inclusive Higgs boson production signal strengths for the Run 2 and Run 3 datasets as a function of p_{T}^{H}. The EW NLO corrections [58], averaged over the VH, VBF and $t\bar{t}H$ Higgs production processes, are also shown.

Separately measuring μ_H in Run 2 and Run 3 data with the same fit, yields $\sigma \times \mathrm{B}(H \rightarrow b\bar{b})$ values at 13 TeV of 40^{+21}_{-16} fb, 2.6 ± 1.7 fb, and $1.0^{+1.0}_{-0.8}$ fb for increasing p_{T}^{H} intervals of 450–650 GeV, 650–1000 GeV, and > 1000 GeV, respectively. At 13.6 TeV the corresponding values are 43^{+22}_{-17} fb for 450–650 GeV, < 8.7 fb at 95% confidence level for 650–1000 GeV, and 0.36 ± 0.72 fb for > 1000 GeV [59].

In conclusion, the ATLAS experiment reports a study of inclusive Higgs boson production at large transverse momentum using the $H \rightarrow b\bar{b}$ decay channel. Evidence is observed for $p_{\mathrm{T}} \geq 450$ GeV with a signal strength of 1.53 ± 0.27 (stat.) $^{+0.33}_{-0.27}$ (syst.) ± 0.17 (theo.), corresponding to an observed (expected) significance of 3.8 (2.5) σ relative to the background-only hypothesis. Measurements in three p_{T}^{H} intervals are consistent with Standard Model predictions. This result is enabled by advances in transformer-based jet reconstruction and a simultaneous fit strategy that determines the multijet background from data. It provides the most precise determination to date of Higgs boson production at high transverse momentum and extends sensitivity to potential deviations from the SM at the TeV scale.

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End Matter

A Analysis selection

Candidate jets are organized into regions according to the GN2X tagger output. The SRs are populated with leading or subleading candidate jets passing the GN2X tagger requirements. Anti-tagged jets populate either the CR or the VR. Jets are sorted into the various regions according to criteria given in Table 1.

Table 1: Assignment of events to analysis signal or control/validation regions based on the GN2X tagging decisions of the leading and subleading candidate jets. The symbol '–' indicates the jet is not included in the jet mass distribution of any region.

GN2X tagging decision		Jet's assigned region	
Leading jet	Subleading jet	Leading jet	Subleading jet
Pass	Pass	SRL	–
Pass	Fail	SRL	CRS/VRS
Fail	Pass	CRL/VRL	SRS
Fail	Fail	CRL/VRL	CRS/VRS

B Higgs boson sample generation and theory uncertainty

Higgs boson ggF production was simulated at next-to-leading-order (NLO) QCD accuracy with finite mass effects by using the Hj-MiNLO [61–64] prescription with the Powheg Box program [20–22] and NNPDF3.0nnlo [65] parton distribution function (PDF). NLO QCD accuracy for VBF and $t\bar{t}H$ production and LO accuracy for $gg \to VH$ (where V is a W or Z boson) production was achieved using the Powheg Box [20–22, 66, 67] program and NNPDF3.0nlo [65] PDF. The Higgs boson production cross sections were scaled to match predictions at next-to-next-to-leading order (NNLO) in QCD using the heavy-top effective field theory combined with exact NLO top quark mass effects for ggF production, NNLO for VBF production, and NLO for VH and $t\bar{t}H$ production [24]. The reweighting is performed in bins of Higgs boson transverse momentum using scale factors defined as the ratio of the higher-order calculation values to the corresponding generator predictions. The resulting corrections are typically at the 5–10% level for ggF and VBF, at the few-percent level for $t\bar{t}H$, and up to $\sim$ 10% for VH at high p_{T}. As differential predictions at $\sqrt{s}$ = 13.6 TeV are not yet available at the same perturbative accuracy, the p_{T}-dependent scale factors derived at 13 TeV are applied to the Run 3 samples. Corrections for EW NLO effects are derived using the HAWK package [58] for VH, VBF and $t\bar{t}H$ Higgs production processes.

The theoretical cross section uncertainties are taken from Ref. [24]. The accuracy for the different production processes, known at different order in QCD, varies considerably. They are included conservatively applying the scale variation uncertainty estimated for the approximate NNLO calculation of the ggF cross section to all Higgs boson production modes (11%). Top-quark mass scheme uncertainties, estimated at 10–18% for the ggF process [49], are included. In addition the PDF uncertainty for ggF is derived comparing to the alternative PDF4LHC15nlo PDF set [68]. A flat 10% difference is observed in p_{T}^{H} and m_J. Acceptance effects from the variation of the p_{T}^{H} distribution from a seven-point scale variation is estimated and found to vary with p_{T}^{H} between 2 and 5%. No substantial differences are observed in the mass shape when jet shower systematics are evaluated by comparing Pythia to Herwig. These uncertainties are propagated to the total signal yield according to the relative contribution of each production mode, resulting in an overall uncertainty of approximately 17–18% depending on p_{T}.

C Multijet modeling

The modeling of the multijet background was validated using simulated QCD samples produced with different generators and fragmentation models, namely Pythia 8 with the Lund string fragmentation model [69, 70], Herwig 7 [71] with the cluster [72] and Lund fragmentation models, Sherpa with the native Ahadic fragmentation model [72] and Powheg +Pythia 8. These studies show generator-dependent differences in the shape of the tagged and anti-tagged jet mass spectra, driven primarily by variations in heavy-flavor composition and parton-shower modeling. The ratio of the normalized SR and CR spectra is well described by a second order function in all tested models, supporting the robustness of the parametrization used in the fit to data.

D Systematic uncertainties and stability tests

The in-situ determinations of the simulation-to-data bb tagging efficiency correction factors $\kappa_{bb}^{\mathrm{GN2X}}$ and the jet mass scale (JMS) and resolution (JMR) factors require the transfer of results on jet tagging and mass performance from the Z to the Higgs. This assumes coherence in response and simulation modeling between the two resonant states.

Several checks were performed to ensure the validity of this procedure. Possible generator-related differences between $H \to b\bar{b}$ (Powheg +Pythia) and $Z \to b\bar{b}$ (Sherpa) production are evaluated through MC-to-MC comparisons.

Variations of the Sherpa fragmentation model change from the native Ahadic to the Lund string model induce a change of the $Z \to b\bar{b}$ tagging efficiency by about 5%, which is small compared to the uncertainty from the GN2X data-to-simulation efficiency correction factors (± 0.17 on μ_H). No additional uncertainty is assigned.

Compatible JMS and JMR behavior for $p_{\mathrm{T}} > 450$ GeV is seen in studies of boosted $V \to qq'$ jets from $t\bar{t}$ events generated with Powheg +Pythia and Sherpa. As a cross-check, the JMS and JMR parameters are decorrelated between the $Z \to b\bar{b}$ and $H \to b\bar{b}$ templates in the fit; the resulting μ_H values remain consistent with the baseline result within uncertainties. The JES and JER uncertainties are derived from measurements in Z + jet, $Z \to \mu\mu$ events dominated by light-flavor jets and applied to the b-tagged jets used in this analysis. The bJR response correction is consistent between simulated $Z \to q\bar{q}$ and $Z \to b\bar{b}$ events, indicating that the regression is largely flavor independent, as expected from its training dataset including all jet flavors in multijet samples.

The full set of systematic uncertainties is summarized in Table 2.

Table 2: Summary of the systematic uncertainties used in the fit model. Ranges in the magnitude column describe the envelope of uncertainty size across p_{T}, where larger uncertainties usually affect the highest p_{T} bin. Magnitudes for shape-only variations represent effective up and down variations of the involved quantity, i.e. the Jet mass resolution (scale) changes the peak width (position) by the relative amount shown in the table. The uncertainty contribution on the Higgs boson signal strength from the given source of systematic uncertainty is noted in the last column labeled $\delta\mu_H$ as calculated with the impact method [53].

Systematic	Magnitude (%)	Effect on observable		Processes concerned	$\delta\mu_H$
		Norm.	Shape		
Experimental systematics					
SR Jet Mass Resolution (JMR)	25	✗	✓	$Z \to b\bar{b}$, $H \to b\bar{b}$	
SR Jet Mass Scale (JMS)	5	✗	✓	$Z \to b\bar{b}$, $H \to b\bar{b}$	
CR Jet Mass Resolution	25	✗	✓	W/Z+jets	
CR Jet Mass Scale	5	✗	✓	W/Z+jets	
JMR+JMS					±0.19
$Z \to \mu\mu$ normalization	3–14	✓	✗	$Z \to b\bar{b}$	
$\kappa_{bb}^{\mathrm{GN2X}}$	5–30	✓	✗	$Z \to b\bar{b}$, $H \to b\bar{b}$	±0.17
p_{T} resolution	1 – 7	✓	✗	$H \to b\bar{b}$	±0.02
Trigger efficiency	2	✓	✗	all MC	±0.02
$t\bar{t}$ normalization	25	✓	✗	$t\bar{t}$	±0.05
CR W/Z+jets normalization	10	✓	✗	$V = W + Z \to q\bar{q}$	±0.07
Higgs spurious signal	0.1–0.3 $\sigma_{\mathrm{fit}}^{\mathrm{stat}}$	✓	✗	$H \to b\bar{b}$	±0.15
Theoretical systematics					
Higgs cross section	11	✓	✗	$H \to b\bar{b}$	
top-quark mass scheme	10–18	✓	✗	ggF $\to H$	
Higgs PDFs	10	✓	✗	$H \to b\bar{b}$	
Higgs scale variations (acc. only)	2-5	✓	✗	$H \to b\bar{b}$	
Higgs theory uncert.					±0.17 – 0.18

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