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Evidence for the Dimuon Decay of the Higgs Boson in *pp* Collisions with the ATLAS Detector

G. Aad *et al.*[*]
(ATLAS Collaboration)

(Received 8 July 2025; accepted 22 September 2025; published 3 December 2025)

A search for the dimuon decay of the Higgs boson is presented based on pp collision data recorded by ATLAS during Run 3 of the Large Hadron Collider, corresponding to an integrated luminosity of 165 fb^{-1} at $\sqrt{s} = 13.6$ TeV. To enhance the sensitivity, the results are combined with those from Run 2. An excess of events over the background is observed with a significance of 3.4σ (2.5σ expected). The best-fit signal strength is $\mu = 1.4 \pm 0.4$. This result provides evidence for the $H \to \mu\mu$ decay with ATLAS data and offers a direct probe of the Higgs-boson Yukawa coupling to second-generation fermions.

DOI: 10.1103/gzdh-p159

A wealth of information about the nature of the Higgs boson, H, discovered in 2012 by the ATLAS and CMS Collaborations [1,2], has been reaped by leveraging the Run-1 and Run-2 proton-proton (pp) collision datasets collected at the Large Hadron Collider (LHC) [3–5]. With these data, the Yukawa interactions of the Higgs boson to third-generation charged fermions have been firmly established. However, its Yukawa coupling to second-generation fermions has yet to be conclusively determined. Notably, the Higgs-boson interactions are the only ones in the standard model (SM) that distinguish between the fermion generations. The decay of the Higgs boson to two oppositely charged muons, $H \to \mu\mu$, provides an excellent opportunity for a first observation of this coupling to a second-generation fermion. The SM $H \to \mu\mu$ branching ratio is 2.17×10^{-4} [6] assuming a Higgs-boson mass of $m_H = 125.09$ GeV [7].

The most recent ATLAS search for the $H \to \mu\mu$ decay employed the full Run-2 dataset [8]. Assuming $m_H = 125.09$ GeV, the observed (expected) significance over the background-only hypothesis was 2.0σ (1.7σ). The comparable result by CMS [9], assuming $m_H = 125.38$ GeV, had an observed (expected) significance of 3.0σ (2.5σ).

A new ATLAS search for $H \to \mu\mu$ is presented targeting the gluon-fusion (ggF), vector-boson-fusion (VBF), associated vector-boson (VH), and associated top-quark-pair ($t\bar{t}H$) production modes. This analysis uses Run-3 pp collision data with an integrated luminosity of 165 fb^{-1}, collected in 2022–2024 at a center-of-mass energy $\sqrt{s} = 13.6$ TeV. The result is combined with the ATLAS Run-2 13 TeV result [8], with an integrated luminosity of 140 fb^{-1}. Apart from more than doubling the statistics of the previous result, several enhancements have been made to make the analysis more robust and performant, and include a five-billion event next-to-leading-order (NLO) Drell-Yan fully simulated sample, an improvement of the mass resolution through a $H \to \mu\mu$ decay vertex fit, the inclusion of a two-lepton VH category, the use of fully hadronic $t\bar{t}H$ decays, and the recategorization of $t\bar{t}H$ using a distance-correlation neural network [10].

The ATLAS experiment [11,12] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near 4π coverage in solid angle [13]. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer based on three large superconducting air-core toroidal magnets. The data used in this analysis [14] were collected with triggers that require at least one high-transverse-momentum muon: $p_{\mathrm{T}} > 24$ GeV and isolated, or $p_{\mathrm{T}} > 50$ GeV without isolation requirement [15,16]. The trigger efficiency for the sum of all $H \to \mu\mu$ signal processes is about 91% relative to the common event selection described in Table I.

Simulated Monte Carlo (MC) samples are used to optimize the event selection, model the signal processes, and develop analytic functions to describe the dimuon invariant-mass distributions, $m_{\mu\mu}$, for background estimation. Both the signal and a comprehensive set of background processes are produced using the full ATLAS detector simulation [17], based on Geant4 [18], and are corrected to match the number of interactions per bunch crossing (in-time pileup) observed in data. Further details are in the End Matter.

The physics objects necessary to reconstruct the searched-for final states consist of muons arising from

[*]Full author list given at the end of the Letter.

TABLE I. Event selection criteria and basic requirements on leptons, b-tagged jets, and $E_T^{\rm miss}$ for the categories targeting Higgs-boson production processes.

	Selection
Common preselection	Primary vertex Two opposite-charge muons Muons: $\lvert\eta\rvert < 2.5$, $p_{\rm T}^{\rm lead} > 27$ GeV, $p_{\rm T}^{\rm sublead} > 15$ GeV
Fit region	$m_{\mu\mu} = 110$–160 GeV
Jets	$p_{\rm T} > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_{\rm T} > 30$ GeV and $2.4 < \lvert\eta\rvert < 4.5$
b-tagged jets	$p_{\rm T} > 25$ GeV and $\lvert\eta\rvert < 2.4$ or with $p_{\rm T} > 30$ GeV and $2.4 < \lvert\eta\rvert < 2.5$ Tagging efficiency working point of 85%
$t\bar{t}H$ categories	At least one b jet
VH four-lepton category	Exactly two additional e or μ with $p_{\rm T} > 8$ GeV, 5 GeV(μ)/7 GeV(e), no b jets
VH three-lepton categories	Exactly one additional e or μ with $p_{\rm T} > 15$ GeV, no b jets
VH two-lepton categories	No additional lepton, no b jets, $E_T^{\rm miss} > 120$ GeV
VBF and ggF categories	No additional lepton, no b jets, $E_T^{\rm miss} < 120$ GeV

the $H \to \mu\mu$ decay as well as other particles or objects produced in association with the Higgs-boson candidate, such as other muons, electrons, photons, jets, and neutrinos characterized by missing transverse momentum, $\vec{p}_{\rm T}^{\rm miss}$. The main selection requirements are summarized in Table I.

Muon candidates must satisfy loose identification criteria [19], and have $p_{\rm T} > 5$ GeV and pseudorapidity $\lvert\eta\rvert < 2.5$. The muon inner-detector track must be matched to the primary vertex by having a longitudinal impact parameter $\lvert z_0 \sin(\theta)\rvert < 0.5$ mm, where θ is the track polar angle, and a significance of the transverse impact parameter, d_0, calculated relative to the measured beam-line position, of $\lvert d_0\rvert/\sigma(d_0) < 3$, where $\sigma(d_0)$ is the uncertainty in d_0. Particle-flow-based isolation criteria [19] are applied to suppress muons from hadron decays. There are known correlations between $m_{\mu\mu}$ and the muon-track orientation [9]. By fitting the Higgs-boson decay vertex, a more precise value for d_0 can be determined, yielding a better estimate of $m_{\mu\mu}$. This decay vertex is fitted with a least-squares method, that minimizes a set of estimators related to the muon tracks (track θ and ϕ, and the charge-to-momentum ratio, q/p) and vertex parameters (x, y, z position) with respect to the measured values, taking into account their covariances and a constraint to keep the fitted decay vertex within the beamspot envelope. This procedure is applied to categories requiring exactly two muons, resulting in an improvement of the $m_{\mu\mu}$ resolution of nearly 2%. This methodology was developed with signal ggF/VBF and background Drell-Yan MC samples, and validated using Z-boson resonance-peak 2018 data.

Muons from the $H \to \mu\mu$ decay can lose a fraction of their energy by QED final-state radiation (FSR), impacting the $m_{\mu\mu}$ shape and peak position. Photon candidates [20,21] are included in the $m_{\mu\mu}$ calculation if they are found in categories requiring exactly two muons and meet a minimum-energy requirement dependent on their closeness to the muon. An FSR photon is found for 5% of the events.

Electrons must satisfy medium likelihood-based identification criteria [20,21], and have $p_{\rm T} > 7$ GeV and $\lvert\eta\rvert < 2.47$. They must be isolated from additional nearby inner-detector tracks and energy deposits in the calorimeters [22]. Electrons must satisfy $\lvert z_0 \sin(\theta)\rvert < 0.5$ mm and $\lvert d_0\rvert/\sigma(d_0) < 5$.

Jets are reconstructed from particle-flow objects [23] using the anti-k_t algorithm [24,25] with radius $R = 0.4$. To suppress contributions from pileup, separate jet-vertex-tagging [26,27] requirements are applied to central and forward jets. Jets containing b hadrons are tagged using a transformer-based neural-network discriminant GN2 tagger [28]. The $E_T^{\rm miss}$ of the event is defined as the magnitude of the negative vectorial sum of the transverse momenta of the selected and calibrated physics objects and other inner-detector tracks from the primary vertex not associated with any of these objects [29].

Events with candidate $H \to \mu\mu$ decays are selected if they contain at least two opposite-charge muons. The signal-plus-background fits are performed in the mass range $m_{\mu\mu} = 110$–160 GeV. In the mass window $m_{\mu\mu} = 120$–130 GeV, which contains about 85% of the signal, approximately 1000 $H \to \mu\mu$ events with the 13.6 TeV data are expected, corresponding to a total efficiency times acceptance of 47% with respect to all $H \to \mu\mu$ produced in the $t\bar{t}H$, VH, VBF, and ggF processes. The leading sources of loss arise from the geometrical acceptance of the detector, the trigger, and requiring that there be at least two identified muons in the event.

Events satisfying the criteria of Table I are classified into 23 mutually exclusive categories (see Table II) constructed to exploit the topological and kinematic differences between the background processes and the Higgs-boson production modes under consideration: $t\bar{t}H$, VH, VBF, and ggF. For most categories, boosted decision tree (BDT) discriminants are built using the XGBoost package [30], though the toolkit for multivariate analysis (TMVA) [31] is

TABLE II. For the $m_{\mu\mu} = 120$–130 GeV window, the number of observed events and the fitted number of signal (S) and background (B) events from the combined fit to 165 fb^{-1} of Run-3 data with a signal strength of $\mu = 1.6 \pm 0.6$. The signal uncertainty reflects the uncertainty in μ, while the background uncertainty is given by the sum in quadrature of the fit statistical uncertainty and the spurious-signal uncertainty. Also shown are the number of signal events divided by the square root of the number of background events ($S/\sqrt{B}$) and signal-to-background ratio (S/B).

Category	Data	S	B	$S/\sqrt{B}$	S/B [%]
$t\bar{t}H$-High	12	1.9 ± 0.7	15.5 ± 2.3	0.49	12.5
$t\bar{t}H$-Medium	117	3.9 ± 1.4	115 ± 7	0.36	3.4
VH4L	11	0.78 ± 0.29	12.2 ± 1.8	0.22	6.4
VH3L-High	25	1.4 ± 0.5	17.4 ± 2.9	0.33	8.0
VH3L-Medium	143	3.7 ± 1.4	136 ± 10	0.31	2.7
VH2L-High	19	1.0 ± 0.4	18.3 ± 2.9	0.23	5.3
VH2L-Medium	30	0.38 ± 0.14	31.7 ± 3.1	0.07	1.2
VBF High	9	4.3 ± 1.6	10.5 ± 1.8	1.34	41.2
VBF Medium	28	5.3 ± 2.0	25.8 ± 2.7	1.04	20.5
VBF Low	69	7.2 ± 2.7	62 ± 4	0.91	11.6
VBF Very low	217	11 ± 4	225 ± 8	0.76	5.1
2-jet High	1399	31 ± 12	1367 ± 25	0.84	2.3
2-jet Medium	5657	69 ± 26	5560 ± 50	0.92	1.2
2-jet Low	17 684	110 ± 40	17300 ± 70	0.87	0.7
2-jet Very low	35 147	110 ± 40	35160 ± 140	0.59	0.3
1-jet High	708	17 ± 6	710 ± 16	0.65	2.4
1-jet Medium	7166	80 ± 30	7140 ± 70	0.95	1.1
1-jet Low	31 761	180 ± 70	31510 ± 120	1.00	0.6
1-jet Very low	73 578	200 ± 80	73330 ± 200	0.75	0.3
0-jet High	19 445	120 ± 50	19260 ± 90	0.89	0.6
0-jet Medium	50 742	200 ± 80	50830 ± 190	0.90	0.4
0-jet Low	94 032	240 ± 90	93770 ± 210	0.78	0.3
0-jet Very low	136 762	170 ± 60	136510 ± 290	0.47	0.1

used for the four-lepton VH category and a neural network is trained using Keras [32] and TensorFlow [33] in the $t\bar{t}H$ categories. The training is performed using variables sensitive to the kinematics of the final-state particles and their relations to other objects. The resulting discriminants are used to define category boundaries optimized to maximize the total number-counting significance. To minimize biases in the categorization process, all trainings are performed using k-fold cross validation, where $k = 4$ different partitions are used in turn for training, validation, and testing.

For each training, the targeted simulated Higgs-boson production process is considered as the signal, whereas other simulated SM processes relevant to the event-categorization topology, including other signal production modes, are used as the background. Overall, the Drell-Yan process comprises the dominant background. Other background processes such as diboson, $t\bar{t}$, and single-top production, and rarer processes such as $t\bar{t}V$ or electroweak production of Z bosons in association with jets play significant roles in specific categories. The background MC is scaled so that the number of events in the sidebands ($m_{\mu\mu} = 110$–120 GeV and $m_{\mu\mu} = 130$–160 GeV) matches the number of events in the data sidebands. The background yield is then taken as the number of reweighted background MC events in the window $m_{\mu\mu} = 120$–130 GeV where the expected signal-to-background ratio is computed. The category selections are performed in the same order as presented in this Letter: $t\bar{t}H$, VH, VBF, and ggF.

The $t\bar{t}H$ category targets both hadronic and leptonic final states arising from the decay of the Z boson produced in the top-quark decay. The two highest-p_{T} muons with opposite charge are chosen as the Higgs-boson decay candidate. This procedure correctly selects the Higgs-boson muon pair in 91% of the cases. Thirty variables are used as input to train a neural network that uses a custom loss function consisting of a term that calculates the binary cross-entropy between the neural network predictions and assigns each event as signal or background, and a term that measures the distance correlation between the neural-network predictions and the dimuon invariant mass of background events [10]. This latter term suppresses the shaping of the mass spectrum when defining categories based on the neural-network score, by penalizing any correlation between the scores and the mass. The resulting output-score distribution is used to define two regions with the highest significance: $t\bar{t}H$-High (99% purity) and $t\bar{t}H$-Medium (96% purity), where the quoted purity is with respect to all Higgs-boson signals.

Events not selected in the $t\bar{t}H$ category are considered for the VH-enriched categories targeting events where the Higgs boson is produced in association with a leptonically decaying vector boson, $W \to \ell\nu$ or $Z \to \ell\ell$, where $\ell = e$,

μ, and $Z \to \nu\nu$ decays. BDTs are trained separately to select five categories according to the lepton multiplicity: four, three, or two. Events entering the four-lepton category must contain exactly four well-separated and isolated leptons, either four muons or two muons and two electrons. The opposite-charge same-flavor dilepton pair with mass closest to the Z boson is labeled as the Z-boson candidate, and the remaining opposite-charge pair is labeled as the Higgs-boson candidate, if these leptons are muons. The accuracy of the Higgs-boson muon-pair assignment is estimated to be nearly 99% within $m_{\mu\mu} = 120$–130 GeV. Fifteen variables are used as input for the BDT training. In the three-lepton channel for the case where the additional lepton is a muon, the assignment of leptons to either Higgs-boson or W-boson decay candidates is based on a χ^2 minimization criterion that takes into account the lepton charge, the difference between the reconstructed and expected Higgs-boson mass and W-boson transverse mass (built from the lepton $\vec{p}_{\mathrm{T}}$ and the event $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$), and their expected experimental resolutions. The correct pairing is obtained in 96% of the cases. Isolation requirements are tightened on the lepton assigned to the W-boson candidate. Twelve variables are used as input for the BDT. The two-lepton channel must contain exactly two well-isolated muons and uses nine variables as input for the BDT training. In the end, five VH categories are defined by applying requirements on the BDT scores: one for the four-lepton channel (VH4L) and two each for the three- and two-lepton channels (VH3L-High, VH3L-Medium, VH2L-High, and VH2L-Medium). The expected $H \to \mu\mu$ signal purity for the VH production process ranges from 99% in VH4L to 63% for VH2L-Medium.

The events not selected in the $t\bar{t}H$ or VH categories are further classified according to the number of reconstructed jets in the event: 0-jet, 1-jet, and ≥ 2-jet (the latter referred to as "2-jet"). The BDT training applied to each jet-multiplicity category uses 17 variables. A VBF classifier is built from 2-jet events and four categories with the highest BDT scores are defined VBF High, Medium, Low, and Very Low, with purity ranging from 96% (High) to 76% (Very Low). The remaining events are considered for classification with BDTs split by jet multiplicity, and selected on the BDT scores, to yield 12 mutually exclusive categories: N-jet High, Medium, Low, and Very Low, where $N = 0, 1, 2$. The expected purity for ggF production ranges from $> 99\%$ to 67%.

Signal extraction is performed with a binned maximum-likelihood fit to $m_{\mu\mu}$ in the 110–160 GeV interval. Analytical models are used in the fit to describe both signal and background, following the methodology used in the corresponding ATLAS Run-2 search [8].

The Higgs-boson signal is modeled using a double-sided Crystal Ball [34,35] probability density function (pdf), fitted to the total expected signal in each category. The width of the Gaussian core, parametrizing the $m_{\mu\mu}$ resolution, changes with kinematics from 2.8 GeV in the 0-jet categories to 3.2 GeV in the VH and $t\bar{t}H$ categories.

Systematic uncertainties in the signal modeling arise from both theory and experimental sources, and are incorporated into the signal-extraction fit via nuisance parameters that affect the signal yields and mass distributions in each category. Theory uncertainties primarily affect the expected number of signal events. Uncertainties in the predicted SM production cross sections and branching ratios follow the recommendations of Refs. [36,37]. Uncertainties due to missing higher orders in Quantum chromodynamic (QCD) calculations are estimated based on the Stage 1.2 simplified template cross-sections (STXS) scheme [36,38,39]. For all signal processes, parton distribution function (PDF) uncertainties are evaluated by using eigenvector variations of the NNPDF2.3LO set [40]. For the ggF and VBF processes, modeling uncertainties related to the underlying event and parton showers are assessed by comparing simulations from PYTHIA 8 [41] and Herwig7 [42,43].

Experimental systematic uncertainties arise from muon-related efficiency uncertainties associated with reconstruction, identification, trigger, isolation, and impact-parameter requirements [19,44] and uncertainties in the muon momentum scale and resolution [45], both of which significantly affect the shape of the signal mass distribution.

Additional experimental uncertainties include those related to $E_{\mathrm{T}}^{\mathrm{miss}}$ [29], the b-tagging efficiency [46–48], the modeling of pile-up interactions [49], the measurement of electron reconstruction and identification efficiencies [20,21], the calibration of photon energy scale [20,21], and the data luminosity estimation [50,51]. Furthermore, uncertainties in the jet-reconstruction efficiency, energy scale, and resolution [52] are included. To account for observed mismodeling of jets at large pseudorapidity ($|\eta| > 3.2$), an additional systematic uncertainty is introduced, defined as five times the difference between data and Monte Carlo event yields resulting from the application of the energy shift measured in the forward calorimeters.

The $m_{\mu\mu}$ background-modeling strategy and the extraction of the main systematic uncertainty (spurious signal) follow Ref. [8]. The main differences with respect to this reference are the use of high-statistics, fully-simulated NLO samples as the sole background template, and an improved core function—based on an analytical leading-order (LO) Drell-Yan line shape—that includes a more accurate treatment of experimental dimuon mass-resolution effects and accounts for parton luminosity contributions from b- and c-quark initial states. Typical background parametrizations include exponentials of polynomials and power-law functions, with degrees of freedom ranging from 1 to 4, and the spurious signal is generally within the range of 5%–40% of the expected signal statistical uncertainty.

The search is dominated by statistical uncertainties, with systematic uncertainties accounting for approximately 5%

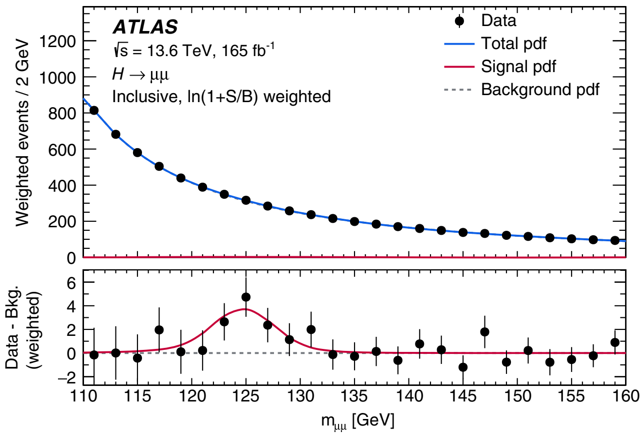

FIG. 1. Observed dimuon invariant mass spectrum combining all of the Run-3 categories. The events and probability density functions (pdfs) are weighted by $\ln(1+S/B)$, where S and B are the signal and background yields, respectively, evaluated in the $m_{\mu\mu} = 120$–130 GeV window. These yields are extracted from the fit performed in the mass range $m_{\mu\mu} = 110$–160 GeV, providing a signal strength of $\mu = 1.6 \pm 0.6$. The background and signal pdfs are obtained from the fit to the data. The lower panel shows the data with the background model subtracted, and the fitted signal pdf, normalized to the signal best-fit value. Error bars represent the data statistical uncertainties.

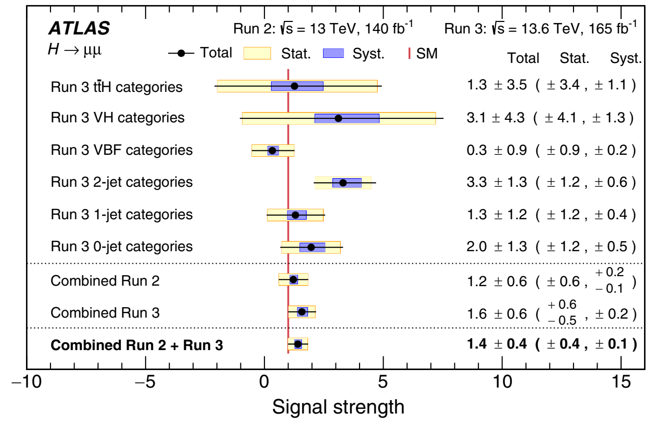

FIG. 2. Best-fit values of the signal-strength parameters for the analysis of the Run-3 data and the full Run-2 dataset. Results are first shown for Run 3 by grouping the signal strength parameters into six major categories ($t\bar{t}H$, VH, VBF, 2-jet, 1-jet, and 0-jet), where the systematic uncertainties reported in the legend are symmetrized. In the lower part of the plot, the full Run-2 and Run-3 results are given, as well as their combination.

of the total. The leading systematic contribution arises from background modeling, followed by theory uncertainties, muon-related effects, and the knowledge of the integrated luminosity.

The signal-plus-background model is used to fit to the observed $m_{\mu\mu}$ spectra in the 23 categories simultaneously. Events in Fig. 1 are weighted by $\ln(1+S/B)$, with S and B denoting the observed signal and background yields, respectively, as extracted from the fit to data in the $m_{\mu\mu} = 120$–130 GeV range. The corresponding values for S, B, and other relevant quantities for each category are summarized in Table II.

The best-fit value of the signal-strength parameter, defined as the ratio of the observed signal yield to the SM expectation, is $\mu = 1.6 \pm 0.6$, and corresponds to an observed (expected) significance of 2.8 (1.8) standard deviations, σ, with respect to the background-only hypothesis. The measured signal strengths in each group of categories, together with the combined Run-3 result, are shown in Fig. 2. The compatibility of the measured signal strengths between the 23 categories is tested by repeating the fit after allowing each category to have its own signal strength parameter. The probability of compatibility is at the 68% level. Using the same methodology, the probability of compatibility between the signal strengths of the six groups of categories shown in Fig. 2 is 54%.

The results presented in this Letter are combined with the analysis of the full ATLAS Run-2 dataset [8]. Experimental uncertainties are taken as uncorrelated between the two datasets, while theory sources are treated as fully correlated, except for those related to PDFs. An excess of events over background is observed with an observed (expected) significance of 3.4 (2.5)σ. The measured signal strength in the combined fit is $\mu = 1.4 \pm 0.4$, and the individual results for Run 2 and Run 3 are compatible within 68%. The measured signal strengths for the Run-2 and Run-3 datasets, as well as their combination, are shown in Fig. 2. Assuming the SM values for the Higgs-boson production cross sections, this result corresponds to a branching fraction of $\mathrm{B}(H \to \mu\mu) = (3.0 \pm 0.9) \times 10^{-4}$.

In conclusion, the ATLAS experiment sees evidence for the rare decay of the Higgs boson into two muons, and hence for the Higgs-boson Yukawa coupling to second-generation fermions, with an observed (expected) significance over the background-only hypothesis of 3.4 (2.5)σ. The result is obtained by analyzing 165 fb^{-1} of pp data collected at $\sqrt{s} = 13.6$ TeV and combining with the results from 140 fb^{-1} of data collected at $\sqrt{s} = 13$ TeV. This result is compatible with the SM expectation.

Acknowledgments—We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [53]. We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMFTR, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, USA. Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom. In addition, individual members wish to acknowledge support from CERN: European Organization for Nuclear Research (CERN DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1240864, Fondecyt 3240661); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), National Natural Science Foundation of China (NSFC—12175119, NSFC 12275265); Czech Republic: Czech Science Foundation (GACR—24-11373S), Ministry of Education Youth and Sports (ERC-CZ-LL2327, FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC—101002463); European Union: European Research Council (BARD No. 101116429, ERC—948254, ERC 101089007), European Regional Development Fund (SMASH COFUND 101081355, SLO ERDF), Horizon 2020 Framework Programme (MUCCA—CHIST-ERA-19-XAI-00), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG—469666862, DFG—CR 312/5-2); China: Research Grants Council (GRF); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (NextGenEU 153D23001490006 M4C2.1.1, NextGenEU I53D23000820006 M4C2.1.1, NextGenEU I53D23001490006 M4C2.1.1, SOE2024_0000023); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP24K23939, JSPS KAKENHI JP24KK0251, JSPS KAKENHI JP25H00650, JSPS KAKENHI JP25H01291, JSPS KAKENHI JP25K01023); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920, UMO-2024/53/N/ST2/00869); Portugal: Foundation for Science and Technology (FCT); Spain: Ministry of Science and Innovation (MCIN and NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2021-03651, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR 2024-05451), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2022.0358, KAW 2023.0366); Switzerland: Swiss National Science Foundation (SNSF—PCEFP2_194658); United Kingdom: Royal Society (NIF-R1-231091); USA: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

Data availability—The public release of data supporting the findings of this article will follow the CERN Open Data Policy [54]. Inquiries about plots and tables associated with this article can be addressed to atlas.publications@cern.ch.

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End Matter

Simulated samples—Signal samples are generated for the primary Higgs-boson production modes, with $m_H = 125$ GeV and $\Gamma_H = 4.07$ MeV [55], using the POWHEG [56–63] program and employing the NNPDF2.3LO parton distribution function set [40]. Parton-level events are processed with PYTHIA 8 [41] to perform Higgs-boson decays, parton showering, final-state QED photon radiation, hadronization, and modeling of the underlying event, using the A14 tune of parameters [64]. These samples are normalized using the most up-to-date theory predictions for the SM production cross sections, as summarized in Ref. [36]. The normalization also includes the $H \to \mu\mu$ branching ratio of 2.17×10^{-4}, computed using HDECAY [65–68] and PROPHECY4F [69–71].

The simulation of Higgs-boson production via the gluon-fusion process attains next-to-next-to-leading-order (NNLO) QCD accuracy for inclusive observables using the NNLOPS prescription and after reweighting the Higgs-boson rapidity spectrum [72]. The sample normalization is based on a next-to-NNLO QCD calculation including next-to-leading-order (NLO) electroweak corrections [73–84].

Samples for Higgs-boson production via the vector-boson-fusion process and in association with a vector boson, $q\bar{q}/qg \to VH$ with $V = W$ or Z, are generated using the POWHEG BOX program [85–87] at NLO accuracy, with the sole exception of the loop-induced process $gg \to ZH$, which is generated at leading order (LO). VBF samples are normalized to an approximate-NNLO QCD cross section with NLO electroweak corrections [88–90], while VH samples are normalized to cross sections calculated at NNLO in QCD with NLO electroweak corrections for $q\bar{q}/qg \to VH$ and at NLO and next-to-leading-logarithm accuracy in QCD for $gg \to ZH$ [91–98].

Higgs-boson production in association with a top-quark pair, $t\bar{t}H$, is simulated at NLO accuracy in QCD and is normalized using a cross-section calculation that is accurate to NLO in QCD with NLO electroweak corrections [99–102].

Higgs-boson production in association with a bottom-quark pair, $b\bar{b}H$, is simulated at NLO accuracy in QCD using the four-flavor scheme. The simulation is normalized using a cross section computed at NNLO in the five-flavor scheme and at NLO in QCD in the four-flavor scheme, including NLO electroweak corrections [103].

Background events from the Drell-Yan $Z/\gamma^* \to \mu\mu$ process are generated with Sherpa 2.2.14 [104]. Drell-Yan events are generated using NLO-accurate matrix elements for up to two partons, and LO-accurate matrix elements for up to five partons calculated with the Comix [105] and OpenLoops [106,107] libraries and the NNPDF3.0 NNLO set [108]. The events are matched to the Sherpa parton shower [109] using the MEPS@NLO prescription [110–113]. Diboson (WW, WZ, and ZZ) and electroweak Zjj events are produced with Sherpa 2.2.14 and Sherpa 2.2.16, with a similar setup as Drell-Yan and NLO-accurate matrix elements for up to one parton and LO-accurate matrix elements for up to three partons.

The $t\bar{t}$ and single-top-quark samples are generated at NLO accuracy with POWHEG BOX [114,115] using the NNPDF3.0NLO PDF set. They are interfaced to PYTHIA 8 for parton showering and hadronization using the A14 parameter set and the NNPDF2.3LO PDF set.

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Smith,[149] H. Smitmanns,[102] M. Smizanska,[93] K. Smolek,[135] P. Smolyanskiy,[135] A. A. Snesarev,[39] H. L. Snoek,[117] S. Snyder,[30] R. Sobie,[171,o] A. Soffer,[157] C. A. Solans Sanchez,[37] E. Yu. Soldatov,[39] U. Soldevila,[169] A. A. Solodkov,[34h] S. Solomon,[27] A. Soloshenko,[39] K. Solovieva,[54] O. V. Solovyanov,[41] P. Sommer,[50] A. Sonay,[13] A. Sopczak,[135] A. L. Sopio,[52] F. Sopkova,[29b] J. D. Sorenson,[115] I. R. Sotarriva Alvarez,[141] V. Sothilingam,[63a] O. J. Soto Sandoval,[140c,140b] S. Sottocornola,[68] R. Soualah,[85a] Z. Soumaimi,[36e] D. South,[48] N. Soybelman,[175] S. Spagnolo,[70a,70b] M. Spalla,[112] D. Sperlich,[54] B. Spisso,[72a,72b] D. P. Spiteri,[59] L. Splendori,[104] M. Spousta,[136] E. J. Staats,[35] R. Stamen,[63a] E. Stanecka,[88] W. Stanek-Maslouska,[48] M. V. Stange,[50] B. Stanislaus,[18a] M. M. Stanitzki,[48] B. Stapf,[48] E. A. Starchenko,[38] G. H. Stark,[139] J. Stark,[91] P. Staroba,[134] P. Starovoitov,[85b] R. Staszewski,[88] C. Stauch,[111] G. Stavropoulos,[46] A. Stefl,[37] A. Stein,[102] P. Steinberg,[30] B. Stelzer,[148,162a] H. J. Stelzer,[132] O. Stelzer,[162a] H. Stenzel,[58] T. J. Stevenson,[152] G. A. Stewart,[37] J. R. Stewart,[124] G. Stoicea,[28b] M. Stolarski,[133a] S. Stonjek,[112] A. Straessner,[50] J. Strandberg,[150] S. Strandberg,[47a,47b] M. Stratmann,[177] M. Strauss,[123] T. Strebler,[104] P. Strizenec,[29b] R. Ströhmer,[172] D. M. Strom,[126] R. Stroynowski,[45] A. Strubig,[47a,47b] S. A. Stucci,[30] B. Stugu,[17] J. Stupak,[123] N. A. Styles,[48] D. Su,[149] S. Su,[62] X. Su,[62] D. Suchy,[29a] A. D. Sudhakar Ponnu,[55] K. Sugizaki,[131] V. V. Sulin,[38] D. M. S. Sultan,[129] L. Sultanaliyeva,[25] S. Sultansoy,[3b] S. Sun,[176] W. Sun,[14] N. Sur,[100] M. R. Sutton,[152] M. Svatos,[134] P. N. Swallow,[33] M. Swiatlowski,[162a] T. Swirski,[172] A. Swoboda,[37] I. Sykora,[29a] M. Sykora,[136] T. Sykora,[136] D. Ta,[102] K. Tackmann,[48,hh] A. Taffard,[165] R. Tafirout,[162a] Y. Takubo,[84] M. Talby,[104] A. A. Talyshev,[38] K. C. Tam,[64b] N. M. Tamir,[157] A. Tanaka,[159] J. Tanaka,[159] R. Tanaka,[66] M. Tanasini,[151] Z. Tao,[170] S. Tapia Araya,[140g] S. Tapprogge,[102] A. Tarek Abouelfadl Mohamed,[37] S. Tarem,[156] K. Tariq,[14] G. Tarna,[37] G. F. Tartarelli,[71a] M. J. Tartarin,[91] P. Tas,[136] M. Tasevsky,[134] E. Tassi,[44b,44a] A. C. Tate,[168] Y. Tayalati,[36e,ll] G. N. Taylor,[107] W. Taylor,[162b] R. J. Taylor Vara,[169] A. S. Tegetmeier,[91] P. Teixeira-Dias,[97] J. J. Teoh,[161] K. Terashi,[159] J. Terron,[101] S. Terzo,[13] M. Testa,[53] R. J. Teuscher,[161,o] A. Thaler,[79] O. Theiner,[56] T. Theveneaux-Pelzer,[104] D. W. Thomas,[97] J. P. Thomas,[21] E. A. Thompson,[18a] P. D. Thompson,[21] E. Thomson,[131] R. E. Thornberry,[45] C. Tian,[62] Y. Tian,[56] V. Tikhomirov,[82] Yu. A. Tikhonov,[39] S. Timoshenko,[38] D. Timoshyn,[136] E. X. L. Ting,[1] P. Tipton,[178] A. Tishelman-Charny,[30] K. Todome,[141] S. Todorova-Nova,[136] L. Toffolin,[69a,69c] M. Togawa,[84] J. Tojo,[90] S. Tokár,[29a] O. Toldaiev,[68] G. Tolkachev,[104] M. Tomoto,[84] L. Tompkins,[149,mm] E. Torrence,[126] H. Torres,[91] D. I. Torres Arza,[140g] E. Torró Pastor,[169] M. Toscani,[31] C. Tosciri,[40] M. Tost,[11] D. R. Tovey,[145] T. Trefzger,[172] P. M. Tricarico,[13] A. Tricoli,[30] I. M. Trigger,[162a] S. Trincaz-Duvoid,[130] D. A. Trischuk,[27] A. Tropina,[39] L. Truong,[34c] M. Trzebinski,[88] A. Trzupek,[88] F. Tsai,[151] M. Tsai,[108] A. Tsiamis,[158] P. V. Tsiareshka,[39] S. Tsigaridas,[162a] A. Tsirigotis,[158,bb] V. Tsiskaridze,[155a] E. G. Tskhadadze,[155a] Y. Tsujikawa,[89] I. I. Tsukerman,[38] V. Tsulaia,[18a] S. Tsuno,[84] K. Tsuri,[121] D. Tsybychev,[151] Y. Tu,[64b] A. Tudorache,[28b] V. Tudorache,[28b] S. B. Tuncay,[129] S. Turchikhin,[57b,57a] I. Turk Cakir,[3a] R. Turra,[71a] T. Turtuvshin,[39,nn] P. M. Tuts,[42] S. Tzamarias,[158,aa] Y. Uematsu,[84] F. Ukegawa,[163] P. A. Ulloa Poblete,[140c,140b] E. N. Umaka,[30] G. Unal,[37] A. Undrus,[30] G. Unel,[165] J. Urban,[29b] P. Urrejola,[140e] G. Usai,[8] R. Ushioda,[160] M. Usman,[110] F. Ustuner,[52] Z. Uysal,[82] V. Vacek,[135] B. Vachon,[106] T. Vafeiadis,[37] A. Vaitkus,[98] C. Valderanis,[111] E. Valdes Santurio,[47a,47b] M. Valente,[37] S. Valentinetti,[24b,24a] A. Valero,[169] E. Valiente Moreno,[169] A. Vallier,[91] J. A. Valls Ferrer,[169] D. R. Van Arneman,[117] A. Van Der Graaf,[49] H. Z. Van Der Schyf,[34h] P. Van Gemmeren,[6] M. Van Rijnbach,[37] S. Van Stroud,[98] I. Van Vulpen,[117] P. Vana,[136] M. Vanadia,[76a,76b] U. M. Vande Voorde,[150] W. Vandelli,[37] E. R. Vandewall,[124] D. Vannicola,[157] L. Vannoli,[53] R. Vari,[75a] M. Varma,[178] E. W. Varnes,[7] C. Varni,[118] D. Varouchas,[66] L. Varriale,[169] K. E. Varvell,[153] M. E. Vasile,[28b] L. Vaslin,[84] M. D. Vassilev,[149] A. Vasyukov,[39]

L. M. Vaughan,[124] R. Vavricka,[136] T. Vazquez Schroeder,[13] J. Veatch,[32] V. Vecchio,[103] M. J. Veen,[105] I. Veliscek,[30] I. Velkovska,[95] L. M. Veloce,[161] F. Veloso,[133a,133c] S. Veneziano,[75a] A. Ventura,[70a,70b] A. Verbytskyi,[112] M. Verducci,[74a,74b] C. Vergis,[96] M. Verissimo De Araujo,[83b] W. Verkerke,[117] J. C. Vermeulen,[117] C. Vernieri,[149] M. Vessella,[165] M. C. Vetterli,[148,u] A. Vgenopoulos,[102] N. Viaux Maira,[140g,oo] T. Vickey,[145] O. E. Vickey Boeriu,[145] G. H. A. Viehhauser,[129] L. Vigani,[63b] M. Vigl,[112] M. Villa,[24b,24a] M. Villaplana Perez,[169] E. M. Villhauer,[40] E. Vilucchi,[53] M. Vincent,[169] M. G. Vincter,[35] A. Visibile,[117] A. Visive,[117] C. Vittori,[37] I. Vivarelli,[24b,24a] M. I. Vivas Albornoz,[48] E. Voevodina,[112] F. Vogel,[111] J. C. Voigt,[50] P. Vokac,[135] Yu. Volkotrub,[87b] L. Vomberg,[25] E. Von Toerne,[25] B. Vormwald,[37] K. Vorobev,[51] M. Vos,[169] K. Voss,[147] M. Vozak,[37] L. Vozdecky,[123] N. Vranjes,[16] M. Vranjes Milosavljevic,[16] M. Vreeswijk,[117] N. K. Vu,[144b,144a] R. Vuillermet,[37] O. Vujinovic,[102] I. Vukotic,[40] I. K. Vyas,[35] J. F. Wack,[33] A. Wada,[113] S. Wada,[163] C. Wagner,[149] J. M. Wagner,[18a] W. Wagner,[177] S. Wahdan,[177] H. Wahlberg,[92] C. H. Waits,[123] J. Walder,[137] R. Walker,[111] K. Walkingshaw Pass,[59] W. Walkowiak,[147] A. Wall,[131] E. J. Wallin,[100] T. Wamorkar,[18a] K. Wandall-Christensen,[169] A. Wang,[62] A. Z. Wang,[139] C. Wang,[102] C. Wang,[11] H. Wang,[18a] J. Wang,[64c] P. Wang,[103] P. Wang,[98] R. Wang,[61] R. Wang,[6] S. M. Wang,[154] S. Wang,[14] T. Wang,[116] T. Wang,[62] W. T. Wang,[129] W. Wang,[14] X. Wang,[168] X. Wang,[144a] X. Wang,[48] Y. Wang,[114a] Y. Wang,[62] Z. Wang,[108] Z. Wang,[144b] Z. Wang,[108] C. Wanotayaroj,[84] A. Warburton,[106] A. L. Warnerbring,[147] S. Waterhouse,[97] A. T. Watson,[21] H. Watson,[52] M. F. Watson,[21] E. Watton,[37] G. Watts,[142] B. M. Waugh,[98] J. M. Webb,[54] C. Weber,[30] H. A. Weber,[19] M. S. Weber,[20] S. M. Weber,[63a] C. Wei,[62] Y. Wei,[54] A. R. Weidberg,[129] E. J. Weik,[120] J. Weingarten,[49] C. Weiser,[54] C. J. Wells,[48] T. Wenaus,[30] T. Wengler,[37] N. S. Wenke,[112] N. Wermes,[25] M. Wessels,[63a] A. M. Wharton,[93] A. S. White,[61] A. White,[8] M. J. White,[1] D. Whiteson,[165] L. Wickremasinghe,[127] W. Wiedenmann,[176] M. Wielers,[137] R. Wierda,[150] C. Wiglesworth,[43] H. G. Wilkens,[37] J. J. H. Wilkinson,[33] D. M. Williams,[42] H. H. Williams,[131] S. Williams,[33] S. Willocq,[105] B. J. Wilson,[103] D. J. Wilson,[103] P. J. Windischhofer,[40] F. I. Winkel,[31] F. Winklmeier,[126] B. T. Winter,[54] M. Wittgen,[149] M. Wobisch,[99] T. Wojtkowski,[60] Z. Wolffs,[117] J. Wollrath,[37] M. W. Wolter,[88] H. Wolters,[133a,133c] M. C. Wong,[139] E. L. Woodward,[42] S. D. Worm,[48] B. K. Wosiek,[88] K. W. Woźniak,[88] S. Wozniewski,[55] K. Wraight,[59] C. Wu,[161] C. Wu,[21] J. Wu,[159] M. Wu,[114b] M. Wu,[116] S. L. Wu,[176] S. Wu,[14,pp] X. Wu,[62] Y. Q. Wu,[161] Y. Wu,[62] Z. Wu,[4] Z. Wu,[114a] J. Wuerzinger,[112] T. R. Wyatt,[103] B. M. Wynne,[52] S. Xella,[43] L. Xia,[114a] M. Xie,[62] A. Xiong,[126] D. Xu,[14] H. Xu,[62] L. Xu,[62] R. Xu,[131] T. Xu,[108] Y. Xu,[142] Z. Xu,[52] R. Xue,[132] B. Yabsley,[153] S. Yacoob,[34a] Y. Yamaguchi,[84] E. Yamashita,[159] H. Yamauchi,[163] T. Yamazaki,[18a] Y. Yamazaki,[86] S. Yan,[59] Z. Yan,[105] H. J. Yang,[144a,144b] H. T. Yang,[62] S. Yang,[62] T. Yang,[64c] X. Yang,[37] X. Yang,[14] Y. Yang,[159] Y. Yang,[62] W-M. Yao,[18a] C. L. Yardley,[152] J. Ye,[14] S. Ye,[30] X. Ye,[62] Y. Yeh,[98] I. Yeletskikh,[39] B. Yeo,[18b] M. R. Yexley,[98] T. P. Yildirim,[129] K. Yorita,[174] C. J. S. Young,[37] C. Young,[149] N. D. Young,[126] Y. Yu,[62] J. Yuan,[14,114c] M. Yuan,[108] R. Yuan,[144b,144a] L. Yue,[98] M. Zaazoua,[62] B. Zabinski,[88] I. Zahir,[36a] A. Zaio,[57b,57a] Z. K. Zak,[88] T. Zakareishvili,[169] S. Zambito,[56] J. A. Zamora Saa,[140d] J. Zang,[159] R. Zanzottera,[71a,71b] O. Zaplatilek,[135] C. Zeitnitz,[177] H. Zeng,[14] J. C. Zeng,[168] D. T. Zenger Jr.,[27] O. Zenin,[38] T. Ženiš,[29a] S. Zenz,[96] D. Zerwas,[66] M. Zhai,[14,114c] D. F. Zhang,[145] G. Zhang,[14,pp] J. Zhang,[143a] J. Zhang,[6] K. Zhang,[14,114c] L. Zhang,[62] L. Zhang,[114a] P. Zhang,[14,114c] R. Zhang,[114a] S. Zhang,[91] T. Zhang,[159] Y. Zhang,[142] Y. Zhang,[98] Y. Zhang,[62] Y. Zhang,[114a] Z. Zhang,[18a] Z. Zhang,[143a] Z. Zhang,[66] H. Zhao,[142] T. Zhao,[143a] Y. Zhao,[35] Z. Zhao,[62] Z. Zhao,[62] A. Zhemchugov,[39] J. Zheng,[114a] K. Zheng,[168] L. Zheng,[143a] X. Zheng,[62] Z. Zheng,[149] D. Zhong,[168] B. Zhou,[108] H. Zhou,[7] N. Zhou,[144a] Y. Zhou,[15] Y. Zhou,[114a] Y. Zhou,[7] C. G. Zhu,[143a] J. Zhu,[108] X. Zhu,[144b] Y. Zhu,[144a] Y. Zhu,[62] X. Zhuang,[14] K. Zhukov,[68] N. I. Zimine,[39] J. Zinsser,[63b] M. Ziolkowski,[147] L. Živković,[16] A. Zoccoli,[24b,24a] K. Zoch,[61] A. Zografos,[37] T. G. Zorbas,[145] O. Zormpa,[46] and L. Zwalinski[37]

(ATLAS Collaboration)

[1]*Department of Physics, University of Adelaide, Adelaide, Australia*
[2]*Department of Physics, University of Alberta, Edmonton, Alberta, Canada*
[3a]*Department of Physics, Ankara University, Ankara, Türkiye*
[3b]*Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*

[4]LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
[5]APC, Université Paris Cité, CNRS/IN2P3, Paris, France
[6]High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
[7]Department of Physics, University of Arizona, Tucson, Arizona, USA
[8]Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
[9]Physics Department, National and Kapodistrian University of Athens, Athens, Greece
[10]Physics Department, National Technical University of Athens, Zografou, Greece
[11]Department of Physics, University of Texas at Austin, Austin, Texas, USA
[12]Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[13]Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
[14]Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[15]Physics Department, Tsinghua University, Beijing, China
[16]Institute of Physics, University of Belgrade, Belgrade, Serbia
[17]Department for Physics and Technology, University of Bergen, Bergen, Norway
[18a]Physics Division, Lawrence Berkeley National Laboratory, Berkeley, California, USA
[18b]University of California, Berkeley, California, USA
[19]Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
[20]Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[21]School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[22a]Department of Physics, Bogazici University, Istanbul, Türkiye
[22b]Department of Physics Engineering, Gaziantep University, Gaziantep, Türkiye
[22c]Department of Physics, Istanbul University, Istanbul, Türkiye
[23a]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá, Colombia
[23b]Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[24a]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna, Italy
[24b]INFN Sezione di Bologna, Italy
[25]Physikalisches Institut, Universität Bonn, Bonn, Germany
[26]Department of Physics, Boston University, Boston, Massachusetts, USA
[27]Department of Physics, Brandeis University, Waltham, Massachusetts, USA
[28a]Transilvania University of Brasov, Brasov, Romania
[28b]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[28c]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania
[28d]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
[28e]National University of Science and Technology Politechnica, Bucharest, Romania
[28f]West University in Timisoara, Timisoara, Romania
[28g]Faculty of Physics, University of Bucharest, Bucharest, Romania
[29a]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
[29b]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[30]Physics Department, Brookhaven National Laboratory, Upton, New York, USA
[31]Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
[32]California State University, Fresno, California, USA
[33]Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[34a]Department of Physics, University of Cape Town, Cape Town, South Africa
[34b]iThemba Labs, Western Cape, South Africa
[34c]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
[34d]National Institute of Physics, University of the Philippines Diliman, Quezon City, Philippines
[34e]Department of Physics, Stellenbosch University, Matieland, South Africa
[34f]University of South Africa, Department of Physics, Pretoria, South Africa
[34g]University of Zululand, KwaDlangezwa, South Africa
[34h]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[35]Department of Physics, Carleton University, Ottawa, Ontario, Canada
[36a]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca, Casablanca, Morocco
[36b]Faculté des Sciences, Université Ibn-Tofail, Kénitra, Morocco
[36c]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Morocco
[36d]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda, Morocco
[36e]Faculté des sciences, Université Mohammed V, Rabat, Morocco
[36f]Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
[37]CERN, Geneva, Switzerland

[38]Affiliated with an institute formerly covered by a cooperation agreement with CERN
[39]Affiliated with an international laboratory covered by a cooperation agreement with CERN
[40]Enrico Fermi Institute, University of Chicago, Chicago, Illinois, USA
[41]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
[42]Nevis Laboratory, Columbia University, Irvington, New York, USA
[43]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[44a]Dipartimento di Fisica, Università della Calabria, Rende, Italy
[44b]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy
[45]Physics Department, Southern Methodist University, Dallas, Texas, USA
[46]National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece
[47a]Department of Physics, Stockholm University, Stockholm, Sweden
[47b]Oskar Klein Centre, Stockholm, Sweden
[48]Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
[49]Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany
[50]Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
[51]Department of Physics, Duke University, Durham, North Carolina, USA
[52]SUPA—School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
[53]INFN e Laboratori Nazionali di Frascati, Frascati, Italy
[54]Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
[55]II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
[56]Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[57a]Dipartimento di Fisica, Università di Genova, Genova, Italy
[57b]INFN Sezione di Genova, Genova, Italy
[58]II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[59]SUPA—School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
[60]LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France
[61]Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, Massachusetts, USA
[62]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China
[63a]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[63b]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[64a]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong, China
[64b]Department of Physics, University of Hong Kong, Hong Kong, China
[64c]Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
[65]Department of Physics, National Tsing Hua University, Hsinchu, Taiwan
[66]IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France
[67]Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain
[68]Department of Physics, Indiana University, Bloomington, Indiana, USA
[69a]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy
[69b]ICTP, Trieste, Italy
[69c]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy
[70a]INFN Sezione di Lecce, Lecce, Italy
[70b]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[71a]INFN Sezione di Milano, Milano, Italy
[71b]Dipartimento di Fisica, Università di Milano, Milano, Italy
[72a]INFN Sezione di Napoli, Napoli, Italy
[72b]Dipartimento di Fisica, Università di Napoli, Napoli, Italy
[73a]INFN Sezione di Pavia, Pavia, Italy
[73b]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[74a]INFN Sezione di Pisa, Pisa, Italy
[74b]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[75a]INFN Sezione di Roma, Roma, Italy
[75b]Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
[76a]INFN Sezione di Roma Tor Vergata, Roma, Italy
[76b]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[77a]INFN Sezione di Roma Tre, Roma, Italy
[77b]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
[78a]INFN-TIFPA, Trento, Italy
[78b]Università degli Studi di Trento, Trento, Italy

[79]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria
[80]University of Iowa, Iowa City, Iowa, USA
[81]Department of Physics and Astronomy, Iowa State University, Ames, Iowa, USA
[82]Istinye University, Sariyer, Istanbul, Türkiye
[83a]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora, Brazil
[83b]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro, Brazil
[83c]Instituto de Física, Universidade de São Paulo, São Paulo, Brazil
[83d]Rio de Janeiro State University, Rio de Janeiro, Brazil
[83e]Federal University of Bahia, Bahia, Brazil
[84]KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[85a]Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates
[85b]University of Sharjah, Sharjah, United Arab Emirates
[86]Graduate School of Science, Kobe University, Kobe, Japan
[87a]AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow, Poland
[87b]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
[88]Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
[89]Faculty of Science, Kyoto University, Kyoto, Japan
[90]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan
[91]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France
[92]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[93]Physics Department, Lancaster University, Lancaster, United Kingdom
[94]Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
[95]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia
[96]Department of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
[97]Department of Physics, Royal Holloway University of London, Egham, United Kingdom
[98]Department of Physics and Astronomy, University College London, London, United Kingdom
[99]Louisiana Tech University, Ruston, Louisiana, USA
[100]Fysiska institutionen, Lunds universitet, Lund, Sweden
[101]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain
[102]Institut für Physik, Universität Mainz, Mainz, Germany
[103]School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
[104]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
[105]Department of Physics, University of Massachusetts, Amherst, Massachusetts, USA
[106]Department of Physics, McGill University, Montreal, Quebec, Canada
[107]School of Physics, University of Melbourne, Victoria, Australia
[108]Department of Physics, University of Michigan, Ann Arbor, Michigan, USA
[109]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA
[110]Group of Particle Physics, University of Montreal, Montreal, Quebec, Canada
[111]Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[112]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[113]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[114a]Department of Physics, Nanjing University, Nanjing, China
[114b]School of Science, Shenzhen Campus of Sun Yat-sen University, China
[114c]University of Chinese Academy of Science (UCAS), Beijing, China
[115]Department of Physics and Astronomy, University of New Mexico, Albuquerque, New Mexico, USA
[116]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands
[117]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
[118]Department of Physics, Northern Illinois University, DeKalb, Illinois, USA
[119a]New York University Abu Dhabi, Abu Dhabi, United Arab Emirates
[119b]United Arab Emirates University, Al Ain, United Arab Emirates
[120]Department of Physics, New York University, New York, New York, USA
[121]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan
[122a]Ohio State University, Columbus, Ohio, USA
[122b]Washington College, Chestertown, Maryland, USA
[123]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA
[124]Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA
[125]Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic
[126]Institute for Fundamental Science, University of Oregon, Eugene, Oregon, USA
[127]Graduate School of Science, University of Osaka, Osaka, Japan

[128]Department of Physics, University of Oslo, Oslo, Norway
[129]Department of Physics, Oxford University, Oxford, United Kingdom
[130]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France
[131]Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA
[132]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA
[133a]Laboratório de Instrumentação e Física Experimental de Partículas—LIP, Lisboa, Portugal
[133b]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal
[133c]Departamento de Física, Universidade de Coimbra, Coimbra, Portugal
[133d]Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal
[133e]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga, Portugal
[133f]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain
[133g]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal
[134]Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[135]Czech Technical University in Prague, Prague, Czech Republic
[136]Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic
[137]Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
[138]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
[139]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA
[140a]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile
[140b]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile
[140c]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena, La Serena, Chile
[140d]Universidad Andres Bello, Department of Physics, Santiago, Chile
[140e]Universidad San Sebastian, Recoleta, Chile
[140f]Instituto de Alta Investigación, Universidad de Tarapacá, Arica, Chile
[140g]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
[141]Department of Physics, Institute of Science, Tokyo, Japan
[142]Department of Physics, University of Washington, Seattle, Washington, USA
[143a]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao, China
[143b]School of Physics, Zhengzhou University, Zhengzhou, China
[144a]State Key Laboratory of Dark Matter Physics, School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai, China
[144b]State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai, China
[145]Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
[146]Department of Physics, Shinshu University, Nagano, Japan
[147]Department Physik, Universität Siegen, Siegen, Germany
[148]Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada
[149]SLAC National Accelerator Laboratory, Stanford, California, USA
[150]Department of Physics, Royal Institute of Technology, Stockholm, Sweden
[151]Departments of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA
[152]Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
[153]School of Physics, University of Sydney, Sydney, Australia
[154]Institute of Physics, Academia Sinica, Taipei, Taiwan
[155a]E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia
[155b]High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[155c]University of Georgia, Tbilisi, Georgia
[156]Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel
[157]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
[158]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
[159]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan
[160]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[161]Department of Physics, University of Toronto, Toronto, Ontario, Canada
[162a]TRIUMF, Vancouver, British Columbia, Canada
[162b]Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
[163]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[164]Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
[165]Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
[166]University of West Attica, Athens, Greece

[167]Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[168]Department of Physics, University of Illinois, Urbana, Illinois, USA
[169]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia—CSIC, Valencia, Spain
[170]Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
[171]Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
[172]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[173]Department of Physics, University of Warwick, Coventry, United Kingdom
[174]Waseda University, Tokyo, Japan
[175]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[176]Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
[177]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[178]Department of Physics, Yale University, New Haven, Connecticut, USA
[179]Yerevan Physics Institute, Yerevan, Armenia

[a]Deceased.
[b]Also at Department of Physics, King's College London, London, United Kingdom.
[c]Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
[d]Also at Imam Mohammad Ibn Saud Islamic University, Riyadh, Saudi Arabia.
[e]Also at Department of Physics, University of Thessaly, Volos, Greece.
[f]Also at An-Najah National University, Nablus, Palestine.
[g]Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
[h]Also at Department of Physics, Westmont College, Santa Barbara, California, USA.
[i]Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain.
[j]Also at University of Sienna, Sienna, Italy.
[k]Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[l]Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
[m]Also at Faculty of Physics, Sofia University, "St. Kliment Ohridski", Sofia, Bulgaria.
[n]Also at Università di Napoli Parthenope, Napoli, Italy.
[o]Also at Institute of Particle Physics (IPP), Canada.
[p]Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu, Türkiye.
[q]Also at Faculty of Physics, University of Bucharest, Romania.
[r]Also at Borough of Manhattan Community College, City University of New York, New York, New York, USA.
[s]Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Quezon City, Philippines.
[t]Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
[u]Also at TRIUMF, Vancouver, British Columbia, Canada.
[v]Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
[w]Also at Henan University, Kaifeng, China.
[x]Also at Yeditepe University, Physics Department, Istanbul, Türkiye.
[y]Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
[z]Also at CERN, Geneva, Switzerland.
[aa]Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece.
[bb]Also at Hellenic Open University, Patras, Greece.
[cc]Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei, China.
[dd]Also at Department of Mathematical Sciences, University of South Africa, Johannesburg, South Africa.
[ee]Also at Department of Physics, Stellenbosch University, South Africa.
[ff]Also at University of Colorado Boulder, Department of Physics, Boulder, Colorado, USA.
[gg]Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland.
[hh]Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.
[ii]Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP), Braga, Portugal.
[jj]Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.
[kk]Also at Washington College, Chestertown, Maryland, USA.
[ll]Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco.
[mm]Also at Department of Physics, Stanford University, Stanford, California, USA.
[nn]Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia.
[oo]Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago, Chile.
[pp]Also at University of Chinese Academy of Sciences (UCAS), Beijing, China.