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Search for $H \to c\bar{c}$ and measurement of $H \to b\bar{b}$ in vector-boson fusion production with the ATLAS detector

The ATLAS Collaboration

A search for Standard Model (SM) Higgs bosons produced via vector-boson fusion at the Large Hadron Collider and decaying into a charm quark–antiquark pair ($H \to c\bar{c}$) is presented. The datasets used correspond to integrated luminosities of 37.5 and 51.5 fb^{-1} and were collected by the ATLAS detector from proton–proton collisions at $\sqrt{s}$ = 13 and 13.6 TeV respectively. The observed (expected) upper limit on the $H \to c\bar{c}$ production cross-section times branching ratio is 41 (28) times the SM prediction at 95% confidence level. Combining this search with the previous $H \to c\bar{c}$ search in associated production with a W or Z boson yields an observed (expected) limit on the Higgs–charm Yukawa coupling modifier of $|\kappa_c| < 4.7$ (3.9). Higgs bosons decaying into a bottom quark–antiquark pair ($H \to b\bar{b}$) is measured simultaneously using the 51.5 fb^{-1} dataset at $\sqrt{s}$ = 13.6 TeV, with an observed signal strength of $0.97^{+0.57}_{-0.50}$ relative to the SM expectation. When combined with previous $H \to b\bar{b}$ results at 13 TeV, the observed (expected) significance reaches 3.2 (3.6) standard deviations, providing evidence for $H \to b\bar{b}$ events from vector-boson fusion.

The discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) [1, 2] was a landmark achievement in particle physics, confirming the existence of the last missing piece of the Standard Model (SM). Since the discovery, properties of the Higgs boson have been studied extensively. These include its mass [3–9], spin [10–15], and couplings to gauge bosons [16–26] and third-generation fermions [27–31], which are all found to align with the SM predictions. More recently, both ATLAS and CMS have reported evidence for the coupling of the Higgs boson to muons [32, 33], providing the first direct probe of Higgs boson interactions with second-generation fermions. However, in the quark sector, one of the key properties that remains to be explored is the coupling of the Higgs boson to charm quarks.

The search for Higgs boson decay into a charm quark–antiquark pair ($H \to c\bar{c}$) remains challenging because of the Higgs boson's smaller Yukawa coupling to charm quarks than to bottom quarks, the overwhelming quantum chromodynamics (QCD) multijet backgrounds, and the challenges in experimentally distinguishing charm jets from light-flavor or bottom jets. Both the ATLAS [34] and CMS [35] collaborations have constrained the Higgs–charm Yukawa coupling through searches for $H \to c\bar{c}$ in associated production with a vector boson (VH, $V = W, Z$). In addition, the CMS Collaboration [36] has also performed a search in associated production with a top-quark pair ($t\bar{t}H$). The most stringent observed (expected) limits are 11.5 (10.6) times the SM prediction, from ATLAS in the VH production mode, and 9.3 (5.6) times the SM prediction, from CMS using a combination of VH and $t\bar{t}H$ production modes.

This Letter presents a search for $H \to c\bar{c}$ by exploiting the second-largest Higgs boson production mode, vector-boson fusion (VBF). In parallel, the analysis also targets $H \to b\bar{b}$ decays in VBF production. The bottom-quark Yukawa coupling plays a central role in the Higgs sector, and while $H \to b\bar{b}$ has been measured in associated-production modes (VH and $t\bar{t}H$) [29, 34, 37, 38], it has not yet been observed in the VBF production mode. Measuring the VBF production cross-section in the $H \to b\bar{b}$ decay mode is also important for Higgs boson measurements within kinematic fiducial regions [39], particularly at high transverse momentum [40].

The VBF production mode is characterized by the presence of two forward jets with large invariant mass and rapidity separation, produced via the exchange of a virtual vector boson between the two initial-state quarks. A new inclusive trigger exploiting this topology [41] was deployed in ATLAS partway through 2018, during Run 2 of the LHC. It achieves an efficiency for VBF $H \to b\bar{b}$ events comparable to that of the b-tagging-based trigger used in the Run-2 VBF $H \to b\bar{b}$ analysis [40], while also enabling the first search for the VBF $H \to c\bar{c}$ process. The $H \to c\bar{c}$ search utilizes proton–proton collision data collected by the ATLAS detector at two center-of-mass energies: 37.5 fb^{-1} at $\sqrt{s}$ = 13 TeV from part of the 2018 Run-2 period and 51.5 fb^{-1} at $\sqrt{s}$ = 13.6 TeV during 2022–2023 in Run 3, yielding a total integrated luminosity of 89.0 fb^{-1}. The $H \to b\bar{b}$ process is measured only with the Run-3 data, allowing direct combination with the analysis performed on full Run-2 dataset [40]. The analysis strategy follows Ref. [40], with improvements in multivariate techniques, the adoption of the inclusive VBF trigger, and the use of a novel transformer-based flavor-tagging algorithm [42] for jet flavor identification.

The ATLAS detector [43] is a multipurpose particle detector designed to investigate a wide range of physics processes at the LHC. It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer. Events are triggered by a two-level trigger system, with the first level implemented in hardware and the second level in software [41, 44]. An extensive software suite [45] is used in data simulation, in the reconstruction and analysis of real and simulated data, and in detector operations and the trigger and data acquisition systems of the experiment. All simulated Monte Carlo (MC) events are passed through a full simulation of the ATLAS detector response [46] using Geant4 [47], and are corrected to match the number of interactions per bunch crossing (pile-up) observed in data. Only events satisfying requirements ensuring good detector operating conditions are analyzed.

Simulated VBF signal events were generated at next-to-leading order (NLO) in QCD with Powheg Box v2 [48–51], using the NNPDF3.0nlo [52] parton distribution functions (PDFs). NLO electroweak (EW) corrections were calculated using MadGraph5_aMC@NLO [53] and applied as a function of the generated Higgs boson's transverse momentum (p_{T}). The gluon–gluon fusion (ggF) process can produce events with two energetic forward jets, resulting in a topology similar to that of VBF, and such events are treated as part of the signal. Simulated ggF events were generated at next-to-next-to-leading order (NNLO) in QCD with Powheg Box v2 [54–56] using the NNPDF3.0nlo PDFs. Both the VBF and ggF samples used Pythia 8 [57] with the A14 set of tuned parameters [58] and the NNPDF2.3lo PDF set [59] for parton showering and fragmentation. For the VBF sample, the Pythia dipole-recoil scheme [60] was used to improve the modeling of radiation in the central region. Other Higgs boson production modes, including both those with an associated vector boson (VH), top quark (tH) or top-quark pair ($t\bar{t}H$) and QCD-induced $b\bar{b}H$ production, are not considered due to their negligible contributions.

The dominant background, non-resonant QCD multijet production (Non-res. bkgd), is estimated using a data-driven method and accounts for about 99% of the total background. Simulated multijet events are used only to derive the systematic uncertainty of this estimate. The multijet samples were generated with Pythia 8 at leading order (LO) in QCD for inclusive $2 \to 2$ dijet production, using the NNPDF2.3lo PDF set and the A14 tune. A filter was applied at generator level to enhance the fraction of events with a VBF-like topology.

The hadronic resonant background from V+jets consists of QCD and EW components. The QCD V+jets contribution was modeled at LO in QCD using MadGraph5_aMC@NLO with the NNPDF3.0nlo PDF set and includes matrix elements with up to two partons at the Born level. The events were interfaced to Pythia 8 for parton showering and hadronization. The EW V+jets processes were modeled at LO in the EW coupling ($O(\alpha_{\mathrm{EW}}^4)$) by Sherpa 2.2.14 [61] with the NNPDF3.0nlo PDF set and include matrix elements with up to three partons at the Born level. The same filter as for the QCD multijet sample was applied at generator level to enhance the fraction of VBF-like events. The EW V+jets component contributes most of the V+jets background in the most sensitive regions. In the $H \to b\bar{b}$ regions, $Z \to b\bar{b}$ dominates, while in the $H \to c\bar{c}$ regions, $W \to cs$ and $Z \to c\bar{c}$ are the main backgrounds, with the $W \to cs$ to $Z \to c\bar{c}$ ratio increasing from 0.40 in the most signal-like regions to 1.7 in the most background-like regions. A small contribution from top-quark pair ($t\bar{t}$) production was modeled using Powheg Box v2 interfaced with Pythia 8. The $t\bar{t}$ background contributes less than 10% of the total V+jets yield in the most sensitive analysis regions. Except for Sherpa samples, the decay of b and c hadrons was performed using EvtGen1.6.0 [62].

Jet reconstruction uses the particle-flow algorithm [63], which combines calorimeter energy deposits and inner-detector tracks into particle-flow objects that are clustered into jets using the anti-k_t algorithm [64, 65] with a radius parameter $R = 0.4$. To mitigate the impact of pileup, dedicated jet-vertex-tagging (JVT) requirements [66] are applied. Jets with pseudorapidity $|\eta| < 2.5$ are required to have $p_{\mathrm{T}} > 20$ GeV, whereas jets with $|\eta| > 2.5$ must satisfy $p_{\mathrm{T}} > 30$ GeV.

Selected events must pass the inclusive VBF trigger [41, 44], which requires at least two jets: one with $p_{\mathrm{T}} > 70$ GeV and $|\eta| < 3.2$, and another with $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 4.9$. Additional dijet requirements are imposed, namely $|\Delta\eta_{jj}| > 4$, $|\Delta\phi_{jj}| < 2$, and $m_{jj} > 1000$ (1100) GeV for Run 3 (Run 2). To avoid inefficiencies near the trigger threshold, the offline selection applies stricter requirements to the two VBF candidate jets (denoted by j_1 and j_2, ordered in decreasing jet p_{T}). Both jets must have $p_{\mathrm{T}} > 75$ GeV, with j_1 restricted to $|\eta| < 3.2$ and j_2 to $|\eta| < 4.5$. The dijet system is also required to satisfy $|\Delta\eta_{jj}| > 4$, $|\Delta\phi_{jj}| < 2$, and $m_{jj} > 1200$ GeV. When multiple jet pairs pass the requirements, the one with the largest m_{jj} is chosen.

The trigger efficiency is evaluated in data from a $Z \to \mu\bar{\mu}$ region, where events are first selected using a single-muon trigger [67]. This region is defined with selection criteria similar to those for the signal regions (SRs), except it requires two opposite-sign muons with $p_{\mathrm{T}} > 7$ GeV and $|\eta| < 2.5$, whose reconstruction and identification are described further below, instead of two b-tagged or c-tagged jets from Higgs boson decay. To emulate the kinematic topology of the signal region, events must also have $p_{\mathrm{T},\ell\ell} > 150$ GeV and $|\Delta\phi_{\ell\ell}| < 2$. In these regions, the trigger efficiency is found to be above 90% (95%) in Run 2 (Run 3), with negligible dependence on jet kinematics.

Jets not identified as VBF candidate jets are considered for the selection of Higgs candidate jets (denoted by j_{h1} and j_{h2}), originating from the $H \to c\bar{c}$ or $H \to b\bar{b}$ decay. Both j_{h1} and j_{h2} are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$. To suppress shape distortions in the background invariant-mass distributions, the Higgs candidate jets must also satisfy $p_{\mathrm{T},j_h j_h} > 150$ GeV and $|\Delta\phi_{j_h j_h}| < 2$. If multiple jets satisfy these criteria, the pair maximizing $p_{\mathrm{T},j_h j_h}$ is selected.

The two Higgs candidate jets must be either b-tagged or c-tagged. Flavor identification is performed using the transformer-based GN2 algorithm [42], which exploits charged-track information and achieves better separation of b-jets, c-jets, and light-flavor jets than the previous DL1r tagger [68]. The calibrated tagger output defines working points corresponding to various b- and c-jet efficiency targets, using established calibration methods consistent with those described in Refs. [69–71]. To identify b-jets, this analysis uses the 77% b-tagging-efficiency working point, which has a c-jet (light-flavor jet) efficiency of 6% (0.24%). Jets failing this requirement are classified as c-tagged if they satisfy the 50% c-tagging-efficiency working point, which has a b-jet (light-flavor jet) efficiency of 13% (5.3%). Two tighter working points, corresponding to 30% and 10% c-jet efficiencies, provide additional inputs to the neural network. All quoted efficiency values are derived from simulated $t\bar{t}$ events.

Events with one or more isolated electrons or muons are vetoed to avoid overlap with other $H \to b\bar{b}$ and $H \to c\bar{c}$ channels. Electrons are reconstructed by matching inner-detector tracks to electromagnetic-calorimeter energy clusters, while muons are reconstructed by combining inner-detector and muon-spectrometer tracks. Both electrons and muons must have $p_{\mathrm{T}} > 7$ GeV, $|\eta| < 2.5$, be matched to the primary vertex, and satisfy the loose identification and isolation criteria, as described in Refs. [72, 73].

To recover energy lost in semileptonic heavy-flavor decays, the four-momentum of any muons with $p_{\mathrm{T}} > 3$ GeV that are reconstructed within the b- or c-tagged jet, prior to the muon isolation requirement, is added to the jet [34]. For b-jets, an additional p_{T}-dependent calibration is applied to account for residual response differences [34].

Events are categorized into three channels: the $b\bar{b}$ Run-3 channel, where both Higgs candidate jets are b-tagged, and the $c\bar{c}$ Run-2 and Run-3 channels, where both are c-tagged.

The overall analysis strategy is similar to that in Ref. [40]. A neural-network classifier is used to separate events into different analysis regions, and the signal yield is extracted from a simultaneous fit to the Higgs candidate mass ($m_{j_h j_h}$) distribution in all regions. The dominant Non-res. bkgd is estimated from data; its shape is determined from the lowest-score region, assuming it is largely identical across all regions. To realize this strategy, an adversarial neural network (ANN), similar to that in Ref. [40], is trained separately for each analysis channel in order to decorrelate the neural-network classifier output from $m_{j_h j_h}$. The networks are implemented in PyTorch [74] and optimized using the Adam algorithm [75]. Inputs comprise event and jet kinematics and jet flavor-tagging information. For training, signal events are taken from VBF MC samples, while background events are drawn from data sidebands on either side of the Higgs boson mass window ($100 < m_{j_h j_h} < 140$ GeV) but within the range $50 < m_{j_h j_h} < 200$ GeV. Further details of the ANN are provided in the End Matter. The number of regions and their boundaries are optimized for maximum sensitivity, resulting in six signal regions per channel (SR1–SR6), ordered by decreasing signal purity, which ranges from 2% to 0.02%. The least pure region, SR6, is used as a control region.

The $H \to c\bar{c}$ contamination in the $H \to b\bar{b}$ channel is negligible, whereas the expected $H \to b\bar{b}$ yield in the $H \to c\bar{c}$ channel increases from about 40% to 100% of the $H \to c\bar{c}$ signal across SR1–SR5 and is approximately 1.4 times larger in SR6. The expected ggF-to-VBF yield ratio increases from about 1% in SR1 to 8% in SR5, and reaches about 45% in SR6 in all channels; the ggF ANN distribution closely resembles that of the backgrounds, explaining the weak sensitivity of the measurement to ggF.

Signal production rates are extracted from a binned maximum-likelihood fit to the $m_{j_h j_h}$ distributions in all regions and channels, using 5 GeV bins over the range $50 < m_{j_h j_h} < 200$ GeV, resulting in a total of 30 bins per region. The expected $H \to c\bar{c}$ and $H \to b\bar{b}$ yields are scaled by independent signal-strength modifiers, $\mu^{c\bar{c}}$ and $\mu^{b\bar{b}}$, defined as the ratios of the observed to the SM-expected signal yields; being inclusive in production mode, they scale both the VBF and ggF contributions. These modifiers are treated as parameters of interest (POIs) and are extracted by maximizing the likelihood. Systematic uncertainties affecting both the normalization and shape of the fitted distributions are incorporated through nuisance parameters (NPs). Systematic variations with large statistical fluctuations are smoothed, while those with negligible impact are pruned region-by-region.

The Non-res. bkgd is modeled using a data-driven approach. For each channel, its shape in the high-score regions (SR1–SR5) is taken from the signal-depleted low-score region (SR6). This strategy is motivated by the ANN design, which aims to decorrelate the reconstructed mass and classifier score. Technically, one unconstrained parameter is assigned per mass bin, correlated across all regions within a given channel, resulting in 90 such floating normalizations in total (one per bin per channel). Since SR6 contains a much larger number of events and is signal-depleted relative to SR1–SR5, it effectively constrains the multijet background shape in the high-score regions. In addition, 15 unconstrained normalization factors (one per high-score region per channel) are introduced, allowing the fit to freely adjust the QCD background yield in each region.

Two sets of systematic uncertainties are introduced to account for possible Non-res. bkgd shape differences between signal regions, arising from an imperfect decorrelation of the ANN score and $m_{j_h j_h}$. The *residual uncertainties* capture potential correlations: for each signal region, an uncertainty is derived from $m_{j_h j_h}$ sidebands and applied across the full mass range. A fit to the ratio of the $m_{j_h j_h}$ distributions in the sidebands of SR6 to those in each of SR1–SR5 is performed, where a linear function adequately describes the observed differences; higher-order polynomials were tested but did not provide any significant improvement. The fitted slopes are implemented as unconstrained shape variations in the likelihood, while the offsets are absorbed by the normalization factors.

The *bias uncertainties* quantify possible distortions of the $m_{j_h j_h}$ spectrum within the Higgs mass window ($100 < m_{j_h j_h} < 140$ GeV) that may arise because the ANN is trained only on sideband events and may bias the signal extraction. They are estimated by performing signal-plus-background fits on multijet MC samples, which are treated as data after being reweighted using sideband data information to improve the modelling. The resulting bias in the fitted signal strength, computed as the quadrature sum of the extracted signal yield and its statistical uncertainty, is taken as a systematic uncertainty. The bias amounts to about 27%–51% of the expected statistical uncertainty in the $H \to b\bar{b}$ signal and 26%–56% of that in the

$H \to c\bar{c}$ signal. Both the *bias* and *residual* uncertainties are applied in SR1–SR5, treated as uncorrelated across regions, leading to 15 nuisance parameters for each set.

Normalization factors for the V+jets backgrounds are extracted from the Run-2 and Run-3 $Z \to \mu\bar{\mu}$ regions. The $Z \to \mu\bar{\mu}$+jets MC samples are simulated using the same setup as for the hadronic V+jets samples. The ANNs trained in the $H \to c\bar{c}$ channels are applied to these regions, replacing the c-jet candidates with the muon pair (with a fixed value of the c-tagging score to mimic c-jets), to define 12 score regions (6 in each Run). A dedicated statistical-only, normalization-only fit is performed simultaneously across all these regions to extract normalization factors for the QCD and EW V+jets components, corresponding to the background- and signal-like contributions, respectively. The resulting normalization factors are applied to simulated V+jets templates in the signal regions. A 50% normalization uncertainty is applied to the sum of EW and QCD components, treated as uncorrelated between the Z+jets and W+jets backgrounds. The size of this uncertainty corresponds to the largest data–MC discrepancy observed in the $Z \to \mu\bar{\mu}$ region after the fit. A 50% normalization uncertainty is also assigned to the $t\bar{t}$ background. These uncertainties are treated as uncorrelated across regions.

An overall 7% (4%) uncertainty in the VBF trigger selection efficiency, derived from a comparison between data and simulation in the $Z \to \mu\bar{\mu}$ region, is applied to the Run-2 (Run-3) simulated events. Systematic uncertainties considered for the jets include those for the energy scale and resolution [76], the vertex-tagging efficiency [66, 77], and the b/c-tagging efficiency for b-jets [69], c-jets [71], and light-flavor jets [70]. Uncertainties of 0.83% and 2% are applied to the integrated luminosity of the Run-2 and Run-3 datasets, respectively [78].

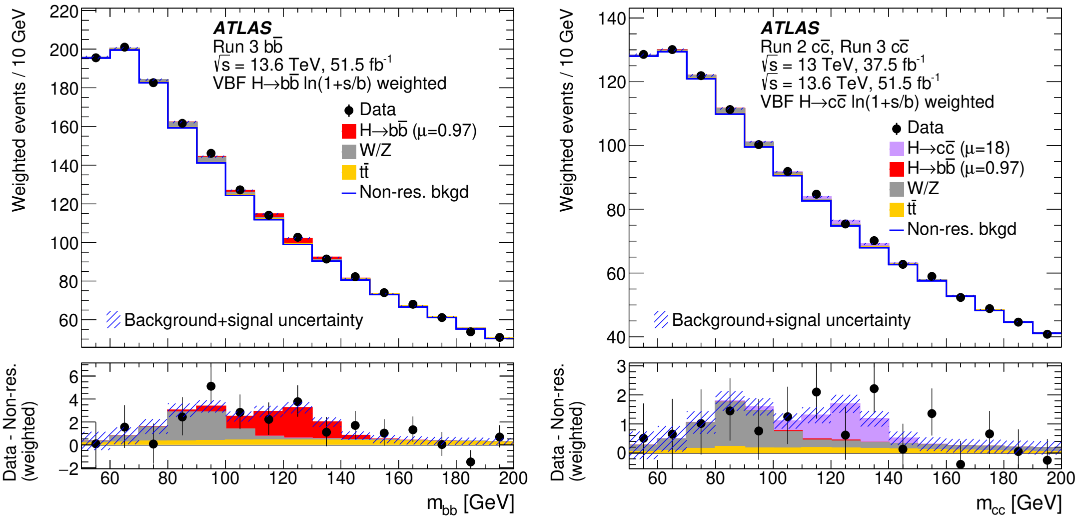
For both VBF and ggF signal, uncertainties in the predicted SM production cross-sections and branching ratios follow the recommendations of Ref. [39]. PDF uncertainties are evaluated by using eigenvector variations of the NNPDF2.3LO set [59]. The impact of the ggF process modeling in the VBF phase space was evaluated and found to be negligible. Consequently, no associated uncertainties are considered. In addition, for the VBF signal, QCD scale uncertainties are estimated by varying the renormalization and factorization scales, while underlying-event and parton-shower uncertainties are assessed by comparing simulations from Pythia 8 and Herwig 7 [57, 79]. The uncertainty from the EW NLO reweighting of the VBF signal was evaluated and found to have a negligible impact on the results.

Figure 1 shows the observed data together with the signal and background estimates in each bin of the Higgs candidate mass discriminant. All SRs are weighted by $\ln(1 + s/b)$ and summed; here b and s denote the total background and signal yields, respectively. The distributions are shown separately for the $H \to b\bar{b}$ and $H \to c\bar{c}$ channels, with the signal definition restricted to one Higgs boson decay mode at a time.

The measured signal strengths for the $H \to b\bar{b}$ and $H \to c\bar{c}$ signals are:

$$\mu^{b\bar{b}} = 0.97^{+0.57}_{-0.50} = 0.97 \pm 0.45\ (\text{stat.})^{+0.35}_{-0.22}\ (\text{syst.})$$
$$\mu^{c\bar{c}} = 18 \pm 13 = 18 \pm 12\ (\text{stat.}) \pm 7\ (\text{syst.})$$

with a correlation of −4.5% between the two measurements. The measurement of $\mu^{b\bar{b}}$ yields an observed (expected) significance of 2.0 (2.1) standard deviations over the background-only prediction. No significant excess over the background-only hypothesis is observed in the search for $H \to c\bar{c}$. An upper limit on $\mu^{c\bar{c}}$ is calculated using the CL_s method [80], with the profile-likelihood ratio as the test statistic [81]. The observed 95% confidence level (CL) upper limit on $\mu^{c\bar{c}}$ is 41, while a limit of 28 is expected in the case of no $H \to c\bar{c}$ process. The result is also interpreted in the “kappa framework” [39, 82] by reparameterizing $\mu^{c\bar{c}}$ in terms of the charm Yukawa coupling modifier κ_c, defined as $\kappa_c^2 = \Gamma_c/\Gamma_c^{\text{SM}}$, where Γ_c is the partial



(a) (b)

Figure 1: Higgs candidate mass distribution with all SRs weighted by $\ln(1 + s/b)$ and summed for the (a) $H \to b\bar{b}$ channel and (b) $H \to c\bar{c}$ channel. The value of s (b) is calculated from the observed Higgs boson signal (post-fit background yields) in each region. The bottom panel shows the difference between the weighted data and the Non-res. bkgd. The diagonally striped band represents the total uncertainty of the fitted background and signal.

decay width into a charm-quark pair. Assuming that all other couplings follow their SM predictions and only SM decays are considered, the parameterization is:

$$\mu^{c\bar{c}} = \frac{\kappa_c^2}{1 + B^{\rm SM}_{H\to c\bar{c}}(\kappa_c^2 - 1)}$$

where $B^{\rm SM}_{H\to c\bar{c}}$ is the SM $H \to c\bar{c}$ branching fraction. The expected 95% CL constraint on the modifier is $|\kappa_c| < 11.6$. No observed constraint can be set at 95% CL due to the large observed value of $\mu^{c\bar{c}}$. Instead, a 68% CL interval of $2.3 < |\kappa_c| < 18.4$ is obtained. An additional fit, performed by considering only the VBF process as signal, while fixing the ggF contribution to its SM prediction within uncertainties, yields a nearly identical result for both the $H \to b\bar{b}$ and $H \to c\bar{c}$ measurements.

The contributions of each uncertainty source to the total uncertainty in the fitted $\mu^{c\bar{c}}$ and $\mu^{b\bar{b}}$ values are summarized in Table 1. Both measurements are statistically limited. In both cases, the dominant systematic uncertainties arise from the Non-res. bkgd bias uncertainty and the effects of limited MC sample size (particularly those from the QCD V+jets samples), followed by the detector-related uncertainties, primarily those associated with jets.

Two combined analyses are performed: one combining the $H \to c\bar{c}$ result with the Run-2 VH-channel results [34], and another combining the Run-3 $H \to b\bar{b}$ result with the Run-2 result in the VBF channel [40] and a recently reported Run-2 photon-associated VBF (VBF+γ) result [83]. For the $H \to c\bar{c}$ combination, $\mu^{b\bar{b}}$ is also allowed to float. For the $H \to b\bar{b}$ combination, the $H \to c\bar{c}$ channels from this analysis are excluded and $\mu^{c\bar{c}}$ is fixed to 1, with the ggF contributions fixed to their SM predictions within uncertainties. For both combinations, jet-related experimental uncertainties are correlated, except for those related to jet flavor tagging, where different algorithms and calibration procedures are used; background modeling

Table 1: Breakdown of contributions to the uncertainty in the fitted signal strengths for $H \to c\bar{c}$ and $H \to b\bar{b}$. All values correspond to absolute uncertainties in $\mu^{c\bar{c}}$ and $\mu^{b\bar{b}}$. The sum in quadrature of uncertainties from different sources may differ from the total because of correlations. The mean of the absolute values of the upward and downward systematic variations is shown. "Other Higgs signal normalization" indicates an effect of $\mu^{b\bar{b}}$ ($\mu^{c\bar{c}}$) on the $\mu^{c\bar{c}}$ ($\mu^{b\bar{b}}$) measurement.

Source of uncertainty	$\sigma(\mu^{c\bar{c}})$	$\sigma(\mu^{b\bar{b}})$
Total	13	0.53
Statistical	12	0.45
Data statistical	8.7	0.32
Non-res. bkgd normalization	4.9	0.19
Non-res. bkgd shape	4.6	0.20
Non-res. bkgd residual uncertainty	1.4	0.05
Other Higgs signal normalization	0.3	0.01
Systematic	6.5	0.28
Non-res. bkgd bias uncertainty	5.8	0.19
Simulation sample sizes	3.4	0.21
Experimental	1.8	0.18
Jet	1.8	0.18
Flavor tagging	0.3	0.01
Trigger	0.3	0.02
Other	0.06	0.02
V+jets and $t\bar{t}$ background estimate	0.7	0.03
Signal theory	0.8	0.04

uncertainties are treated as uncorrelated, while theory uncertainties in signal production cross-sections and branching ratios are correlated.

From the first combination, the observed $\mu^{c\bar{c}}_{\text{Comb.}}$ signal strength relative to the SM prediction is $3.3^{+5.2}_{-5.0}$, assuming SM VBF, ggF, and VH production rates. The observed (expected) 95% CL upper limit on $\mu^{c\bar{c}}_{\text{Comb.}}$ is 13 (10), corresponding to an observed (expected) constraint of $|\kappa_c| < 4.7$ (3.9). This represents an 8% improvement in the expected limit and a 5% improvement in the expected $|\kappa_c|$ constraint relative to the VH-only result. The observed result is slightly weaker than that from the VH channel, owing to an upward fluctuation in $\mu^{c\bar{c}}_{\text{Comb.}}$ driven by the VBF contribution. From the second combination, the observed $\mu^{b\bar{b}}_{\text{VBF}}$ signal strength relative to the SM prediction is 0.87 ± 0.28, corresponding to an observed (expected) significance of 3.2 (3.6) standard deviations, thus providing the first evidence for the VBF $H \to b\bar{b}$ process. The p-value for compatibility of the signal-strength parameters among the three analyses is 65%, and 95% between the Run-2 and Run-3 VBF $H \to b\bar{b}$ analyses.

In summary, this Letter presents the first search for SM Higgs boson decay into a pair of charm quarks in the VBF production mode in the ATLAS experiment at the LHC, together with a simultaneous measurement of Higgs boson decay into a bottom quark–antiquark pair. The VBF $H \to c\bar{c}$ search is enabled by a new trigger designed to exploit the VBF topology. The observed signal strengths relative to the SM predictions are $\mu^{b\bar{b}} = 0.97^{+0.57}_{-0.50}$ and $\mu^{c\bar{c}} = 18 \pm 13$. For the $H \to c\bar{c}$ process, this corresponds to an observed (expected) 95% CL upper limit of 41 (28) on $\mu^{c\bar{c}}$. When combined with previous Run-2 results, these measurements improve the expected constraint on the Higgs–charm coupling and both the expected and observed constraints on the Higgs–bottom coupling.

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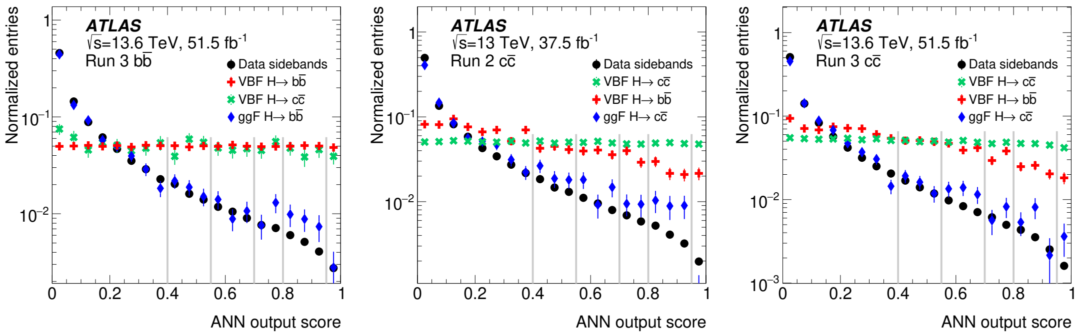
End Matter

The input variables used in ANN training are listed in Table 2. The $H \to b\bar{b}$ and $H \to c\bar{c}$ channels use almost identical sets of variables, differing only by the inclusion of tagging-related inputs in the $H \to c\bar{c}$ channels, which improve discrimination between c-jets and background, and the $p_{\mathrm{T}}^{\mathrm{AddJet}}$ variable, defined as the transverse momentum of the leading additional jet, in the $H \to b\bar{b}$ channel. The $c\bar{c}$ Run-2 and Run-3 channels share an identical input set. Figure 2 shows the ANN score distributions for the VBF signal, ggF events, and the data sidebands. As a post-training step, the classifier scores are scaled to quantiles of the signal distribution with the output values ranging from 0 to 1. Clear separation is visible between the VBF signal and the data sidebands, while the ggF events exhibit a score distribution similar to that of the data sidebands. The variables that contribute most significantly to the ANN's discriminating power are m_{jj}, $p_{\mathrm{T},jj}$, $p_{\mathrm{T}}^{\mathrm{balance}}$ and $n_{\mathrm{Jets}}^{\mathrm{Rap}}$.

Table 2: The input variables used for ANN training in each of the channels. The ✓ symbol indicates the inclusion of a variable.

Variable	$H \to c\bar{c}$	$H \to b\bar{b}$	Description
m_{jj}	✓	✓	Invariant mass of the VBF candidate jet pair.
$p_{\mathrm{T},jj}$	✓	✓	Transverse momentum of the VBF candidate jet pair.
$p_{\mathrm{T},j_h j_h}$	✓	✓	Transverse momentum of the Higgs jet pair.
$p_{\mathrm{T}}^{\mathrm{balance}}$	✓	✓	The ratio of the vectorial to scalar sums of the transverse momenta of j_{h1}, j_{h2}, j_1 and j_2.
$\theta_{j_h j_h}$	✓	✓	Defined as $\tan^{-1}\left[\tan\left(\frac{\Delta\eta(j_h j_h)}{2}\right)/\tanh\left(\frac{\Delta\phi(j_h j_h)}{2}\right)\right]$, a measure of the relative angle of $\Delta\eta$ and $\Delta\phi$ between the two tagged jets.
$n_{\mathrm{Jets}}^{\mathrm{Rap}}$	✓	✓	The number of jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and η between η_{j_1} and η_{j_2}.
$\lvert\Delta\phi(j_h j_h, jj)\rvert$	✓	✓	The separation in ϕ between the Higgs jet pair and the VBF candidate jet pair.
$N_{\mathrm{trk}}^{j_1}$	✓	✓	The number of tracks matched to the leading VBF candidate jet.
$N_{\mathrm{trk}}^{j_2}$	✓	✓	The number of tracks matched to the sub-leading VBF candidate jet.
$D_{\mathrm{GN2}}^{j_{h1}}$	✓		Binned output of the GN2 tagging algorithm for the leading c-tagged jet, with bin boundaries corresponding to 50%, 30%, and 10% c-tagging efficiencies.
$D_{\mathrm{GN2}}^{j_{h2}}$	✓		Binned output of the GN2 tagging algorithm for the sub-leading c-tagged jet, with bin boundaries corresponding to 50%, 30%, and 10% c-tagging efficiencies.
$p_{\mathrm{T}}^{\mathrm{AddJet}}$		✓	Transverse momentum of the additional jet with the highest transverse momentum that does not belong to either the VBF candidate jets or the Higgs jets, and satisfies $\lvert\eta\rvert < 2.5$. If no such jet exists, the value is set to 0 by default.



(a) (b) (c)

Figure 2: Distributions of ANN output scores for the VBF $H \to c\bar{c}$ signal MC events, VBF $H \to b\bar{b}$ signal MC events, ggF MC events, and data sidebands in the (a) $b\bar{b}$ Run-3, (b) $c\bar{c}$ Run-2, and (c) $c\bar{c}$ Run-3 channels. The errors are statistical only. Vertical lines indicate the ANN score thresholds defining the six signal regions (SR1–SR6), in right-to-left order, with the rightmost region SR1 being the most signal-like. No separation between $b\bar{b}$ and $c\bar{c}$ signals is expected in the $b\bar{b}$ ANN since tagging information is not used in this channel, while such separation is visible in the $c\bar{c}$ ANN, which includes tagging inputs.

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The ATLAS Collaboration

G. Aad[103], E. Aakvaag[17], B. Abbott[122], S. Abdelhameed[118a], K. Abeling[55], N.J. Abicht[49],
S.H. Abidi[30], M. Aboelela[45], A. Aboulhorma[36e], H. Abramowicz[156], B.S. Acharya[69a,69b,l],
A. Ackermann[63a], C. Adam Bourdarios[4], L. Adamczyk[86a], S.V. Addepalli[148],
M.J. Addison[102], J. Adelman[117], A. Adiguzel[22c], T. Adye[136], A.A. Affolder[138], Y. Afik[40],
M.N. Agaras[13], A. Aggarwal[101], C. Agheorghiesei[28c], F. Ahmadov[39,ac], S. Ahuja[96],
S. Ahuja[168], X. Ai[142b], G. Aielli[76a,76b], A. Aikot[168], M. Ait Tamlihat[36e], B. Aitbenchikh[36a],
T.P.A. Åkesson[99], D. Akiyama[173], N.N. Akolkar[25], S. Aktas[171], G.L. Alberghi[24b],
J. Albert[170], U. Alberti[20], P. Albicocco[53], G.L. Albouy[60], S. Alderweireldt[52],
Z.L. Alegria[123], M. Aleksa[37], I.N. Aleksandrov[39], C. Alexa[28b], T. Alexopoulos[10],
F. Alfonsi[24b], M. Algren[56], M. Alhroob[172], B. Ali[134], H.M.J. Ali[92,u], S. Ali[32],
S.W. Alibocus[93], M. Aliev[34c], G. Alimonti[71a], W. Alkakhi[55], C. Allaire[66],
B.M.M. Allbrooke[151], D.R. Allen[123], J.S. Allen[102], J.F. Allen[52], C.S. Alley[1],
A. Aloisio[72a,72b], F. Alonso[91], C. Alpigiani[141], Z.M.K. Alsolami[92], A. Alvarez Fernandez[101],
M. Alves Cardoso[56], M.G. Alviggi[72a,72b], M. Aly[102], Y. Amaral Coutinho[82b], A. Ambler[105],
C. Amelung[37], M. Amerl[102], C.G. Ames[110], T. Amezza[129], B. Amini[54], K. Amirie[160],
A. Amirkhanov[39], S.P. Amor Dos Santos[132a], D. Amperiadou[157], S. An[83], C. Anastopoulos[144],
T. Andeen[11], J.K. Anders[93], A.C. Anderson[59], A. Andreazza[71a,71b], S. Angelidakis[9],
A. Angerami[42], A.V. Anisenkov[39], A. Annovi[74a], C. Antel[37], E. Antipov[150],
M. Antonelli[53], F. Anulli[75a], M. Aoki[83], T. Aoki[158], M.A. Aparo[13], L. Aperio Bella[48],
M. Apicella[31], C. Appelt[156], A. Apyan[27], M. Arampatzi[10], S.J. Arbiol Val[87],
C. Arcangeletti[53], A.T.H. Arce[51], J-F. Arguin[109], S. Argyropoulos[157], J.-H. Arling[48],
O. Arnaez[4], H. Arnold[150], G. Artoni[75a,75b], H. Asada[112], K. Asai[120], S. Asatryan[178],
N.A. Asbah[37], R.A. Ashby Pickering[172], A.M. Aslam[96], K. Assamagan[30], R. Astalos[29a],
K.S.V. Astrand[99], S. Atashi[164], R.J. Atkin[34a], H. Atmani[36f], P.A. Atmasiddha[130],
K. Augsten[134], A.D. Auriol[41], V.A. Austrup[102], A.S. Avad[95], G. Avolio[37], K. Axiotis[56],
A. Azzam[13], D. Babal[29b], H. Bachacou[137], K. Bachas[157,o], A. Bachiu[35], E. Bachmann[50],
M.J. Backes[63a], A. Badea[40], T.M. Baer[107], P. Bagnaia[75a,75b], M. Bahmani[19], D. Bahner[54],
K. Bai[125], J.T. Baines[136], L. Baines[95], O.K. Baker[177], E. Bakos[16], D. Bakshi Gupta[8],
L.E. Balabram Filho[82b], V. Balakrishnan[122], R. Balasubramanian[4], E.M. Baldin[38],
P. Balek[86a], E. Ballabene[24b,24a], F. Balli[137], L.M. Baltes[63a], W.K. Balunas[33], J. Balz[101],
I. Bamwidhi[118b], E. Banas[87], M. Bandieramonte[131], A. Bandyopadhyay[25], S. Bansal[25],
L. Barak[156], M. Barakat[48], E.L. Barberio[106], D. Barberis[18b], M. Barbero[103], M.Z. Barel[116],
T. Barillari[111], M-S. Barisits[37], T. Barklow[148], P. Baron[135], D.A. Baron Moreno[102],
A. Baroncelli[62], A.J. Barr[128], J.D. Barr[97], F. Barreiro[100], J. Barreiro Guimarães da Costa[14],
M.G. Barros Teixeira[132a], S. Barsov[38], F. Bartels[63a], R. Bartoldus[148], A.E. Barton[92],
P. Bartos[29a], M. Baselga[49], S. Bashiri[87], A. Bassalat[66,b], M.J. Basso[161a], S. Bataju[45],
R. Bate[169], R.L. Bates[59], S. Batlamous[100], M. Battaglia[138], D. Battulga[19], M. Bauce[75a,75b],
L. Bauckhage[48], P. Bauer[25], L.T. Bayer[48], L.T. Bazzano Hurrell[31], J.B. Beacham[111],
T. Beau[129], J.Y. Beaucamp[91], P.H. Beauchemin[163], P. Bechtle[25], H.P. Beck[20,n],
K. Becker[172], A.J. Beddall[81], V.A. Bednyakov[39], C.P. Bee[150], L.J. Beemster[16],
M. Begalli[82d], M. Begel[30], J.K. Behr[48], J.F. Beirer[37], F. Beisiegel[25], M. Belfkir[118b],
G. Bella[156], L. Bellagamba[24b], A. Bellerive[35], C.D. Bellgraph[68], P. Bellos[21],
K. Beloborodov[38], I. Benaoumeur[21], D. Benchekroun[36a], F. Bendebba[36a], Y. Benhammou[156],
K.C. Benkendorfer[61], L. Beresford[48], M. Beretta[53], E. Bergeaas Kuutmann[166], N. Berger[4],

B. Bergmann [134], J. Beringer [18a], G. Bernardi [5], C. Bernius [148], F.U. Bernlochner [25], A. Berrocal Guardia [13], T. Berry [96], P. Berta [135], A. Berti [132a], R. Bertrand [103], S. Bethke [111], A. Betti [75a,75b], A.J. Bevan [95], L. Bezio [56], N.K. Bhalla [54], S. Bharthuar [111], S. Bhatta [150], P. Bhattarai [148], Z.M. Bhatti [119], K.D. Bhide [54], V.S. Bhopatkar [123], R.M. Bianchi [131], G. Bianco [24b,24a], O. Biebel [110], M. Biglietti [77a], P. Bijl [54], C.S. Billingsley [45], Y. Bimgdi [36f], M. Bindi [55], A. Bingham [176], A. Bingul [22b], C. Bini [75a,75b], G.A. Bird [33], M. Birman [174], M. Biros [135], S. Biryukov [151], T. Bisanz [49], E. Bisceglie [24b,24a], J.P. Biswal [136], D. Biswas [146], I. Bloch [48], A. Blue [59], U. Blumenschein [95], V.S. Bobrovnikov [39], L. Boccardo [57b,57a], M. Boehler [54], B. Boehm [171], D. Bogavac [13], A.G. Bogdanchikov [38], L.S. Boggia [129], V. Boisvert [96], P. Bokan [166], T. Bold [86a], M. Bomben [5], M. Bona [95], M. Boonekamp [137], A.G. Borbély [59], I.S. Bordulev [38], G. Borissov [92], D. Bortoletto [128], D. Boscherini [24b], M. Bosman [13], K. Bouaouda [36a], N. Bouchhar [168], L. Boudet [4], J. Boudreau [131], E.V. Bouhova-Thacker [92], D. Boumediene [41], R. Bouquet [57b,57a], A. Boveia [121], J. Boyd [37], D. Boye [30], I.R. Boyko [39], L. Bozianu [56], J. Bracinik [21], N. Brahimi [4], G. Brandt [176], O. Brandt [33], B. Brau [104], R. Brener [174], L. Brenner [116], R. Brenner [166], S. Bressler [174], G. Brianti [116], D. Britton [59], D. Britzger [111], I. Brock [25], R. Brock [108], H. Bronson [130], G. Brooijmans [42], A.J. Brooks [68], E.M. Brooks [161b], E. Brost [30], L.M. Brown [170,161a], L.E. Bruce [61], T.L. Bruckler [128], P.A. Bruckman de Renstrom [87], B. Brüers [48], A. Bruni [24b], G. Bruni [24b], D. Brunner [47a,47b], M. Bruschi [24b], N. Bruscino [75a,75b], T. Buanes [17], Q. Buat [141], D. Buchin [111], A.G. Buckley [59], M. Buhring [50], O. Bulekov [81], B.A. Bullard [148], S. Burdin [93], C.D. Burgard [49], A.M. Burger [90], B. Burghgrave [8], O. Burlayenko [54], J. Burleson [167], J.C. Burzynski [147], V. Büscher [101], P.J. Bussey [59], O. But [25], J.M. Butler [26], C.M. Buttar [59], J.M. Butterworth [97], P. Butti [37], W. Buttinger [136], C.J. Buxo Vazquez [108], A.R. Buzykaev [39], S. Cabrera Urbán [168], L. Cadamuro [66], H. Cai [37], Y. Cai [24b,113c,24a], Y. Cai [113a], V.M.M. Cairo [37], O. Cakir [3a], N. Calace [37], P. Calafiura [18a], G. Calderini [129], P. Calfayan [35], L. Calic [99], G. Callea [59], L.P. Caloba [82b], D. Calvet [41], S. Calvet [41], R. Camacho Toro [129], S. Camarda [37], D. Camarero Munoz [27], P. Camarri [76a,76b], C. Camincher [37], M. Campanelli [97], A. Camplani [43], V. Canale [72a,72b], A.C. Canbay [3a], E. Canonero [96], J. Cantero [168], Y. Cao [167], F. Capocasa [27], M. Capua [44b,44a], A. Carbone [71a,71b], R. Cardarelli [76a], J.C.J. Cardenas [8], M.P. Cardiff [27], G. Carducci [44b,44a], T. Carli [37], G. Carlino [72a], J.I. Carlotto [13], B.T. Carlson [131,p], E.M. Carlson [170], L. Carminati [71a,71b], A. Carnelli [4], M. Carnesale [37], S. Caron [115], E. Carquin [139g], I.B. Carr [106], S. Carrá [73a,73b], G. Carratta [24b,24a], C. Carrion Martinez [168], A.M. Carroll [125], M.P. Casado [13,h], P. Casolaro [72a,72b], M. Caspar [48], W.R. Castiglioni [40], F.L. Castillo [4], L. Castillo Garcia [13], V. Castillo Gimenez [168], N.F. Castro [132a,132e], A. Catinaccio [37], J.R. Catmore [127], T. Cavaliere [4], V. Cavaliere [30], L.J. Caviedes Betancourt [23b], E. Celebi [81], S. Cella [156], V. Cepaitis [56], K. Cerny [124], A.S. Cerqueira [82a], A. Cerri [74a,al], L. Cerrito [76a,76b], F. Cerutti [18a], B. Cervato [71a,71b], A. Cervelli [24b], G. Cesarini [53], S.A. Cetin [81], P.M. Chabrillat [129], R. Chakkappai [66], S. Chakraborty [172], A. Chambers [61], J. Chan [18a], W.Y. Chan [158], J.D. Chapman [33], E. Chapon [137], B. Chargeishvili [154b], D.G. Charlton [21], C. Chauhan [133], Y. Che [113a], S. Chekanov [6], G.A. Chelkov [39,a], B. Chen [170], H. Chen [30], J. Chen [143a], J. Chen [147], M. Chen [128], S. Chen [88], S.J. Chen [113a], X. Chen [143a], X. Chen [15,ag], Z. Chen [62], C.L. Cheng [175], H.C. Cheng [64a], S. Cheong [148], A. Cheplakov [39], E. Cherepanova [116], E. Cheu [7], K. Cheung [65], L. Chevalier [137], V. Chiarella [53], G. Chiarelli [74a], G. Chiodini [70a], A.S. Chisholm [21], A. Chitan [28b], M. Chitishvili [168], M.V. Chizhov [39,q], K. Choi [11], Y. Chou [141], E.Y.S. Chow [115], K.L. Chu [174], M.C. Chu [64a], Z. Chubinidze [53], J. Chudoba [133], J.J. Chwastowski [87], D. Cieri [111], K.M. Ciesla [86a], V. Cindro [94], A. Ciocio [18a], F. Cirotto [72a,72b], Z.H. Citron [174], M. Citterio [71a], D.A. Ciubotaru[28b], A. Clark [56], P.J. Clark [52], N. Clarke Hall [97], C. Clarry [160], S.E. Clawson [48], C. Clement [47a,47b], L. Clissa [24b,24a], Y. Coadou [103], M. Cobal [69a,69c], A. Coccaro [57b], R.F. Coelho Barrue [132a], R. Coelho Lopes De Sa [104], S. Coelli [71a], M.M. Cohen [130], L.S. Colangeli [160], B. Cole [42], P. Collado Soto [100], J. Collot [60], R. Coluccia[70a,70b], P. Conde Muiño [132a,132g], M.P. Connell [34c], S.H. Connell [34c], E.I. Conroy [128], M. Contreras Cossio [11], F. Conventi [72a,ai], A.M. Cooper-Sarkar [128], L. Corazzina [75a,75b], F.A. Corchia [24b,24a], A. Cordeiro Oudot Choi [141], L.D. Corpe [41], M. Corradi [75a,75b], F. Corriveau [105,aa], A. Cortes-Gonzalez [158], M.J. Costa [168], F. Costanza [4], D. Costanzo [144], J. Couthures [4], G. Cowan [96], K. Cranmer [175], L. Cremer [49], D. Cremonini [24b,24a], S. Crépé-Renaudin [60], F. Crescioli [129], T. Cresta [73a,73b], M. Cristinziani [146], M. Cristoforetti [78a,78b], E. Critelli [97], G. Crosetti [44b,44a], A. Cueto [100], H. Cui [97], Z. Cui [7], B.M. Cunnett [151], W.R. Cunningham [59], F. Curcio [168], J.R. Curran [52], M.J. Da Cunha Sargedas De Sousa [57b,57a], J.V. Da Fonseca Pinto [82b], C. Da Via [102], W. Dabrowski [86a], T. Dado [37], S. Dahbi [153], T. Dai [107], D. Dal Santo [20], C. Dallapiccola [104], M. Dam [43], G. D'amen [30], V. D'Amico [110], J.R. Dandoy [35], M. D'Andrea [57b,57a], D. Dannheim [37], G. D'anniballe [74a,74b], M. Danninger [147], V. Dao [150], G. Darbo [57b], S.J. Das [30], F. Dattola [48], S. D'Auria [71a,71b], A. D'Avanzo [72a,72b], T. Davidek [135], J. Davidson [172], I. Dawson [95], K. De [8], C. De Almeida Rossi [160], R. De Asmundis [72a], N. De Biase [48], S. De Castro [24b,24a], N. De Groot [115], P. de Jong [116], H. De la Torre [117], A. De Maria [113a], A. De Salvo [75a], U. De Sanctis [76a,76b], F. De Santis [70a,70b], A. De Santo [151], J.B. De Vivie De Regie [60], J. Debevc [94], D.V. Dedovich[39], J. Degens [93], A.M. Deiana [45], J. Del Peso [100], L. Delagrange [129], F. Deliot [137], C.M. Delitzsch [49], M. Della Pietra [72a,72b], D. Della Volpe [56], A. Dell'Acqua [37], L. Dell'Asta [71a,71b], M. Delmastro [4], C.C. Delogu [57b,57a], P.A. Delsart [60], S. Demers [177], M. Demichev [39], S.P. Denisov [38], H. Denizli [22a,k], M.G. Depala [93], L. D'Eramo [41], D. Derendarz [87], F. Derue [129], P. Dervan [93,*], A.M. Desai [1], K. Desch [25], F.A. Di Bello [74a,74b], A. Di Ciaccio [76a,76b], L. Di Ciaccio [4], A. Di Domenico [75a,75b], C. Di Donato [72a,72b], A. Di Girolamo [37], G. Di Gregorio [66], A. Di Luca [78a,78b], B. Di Micco [77a,77b], R. Di Nardo [77a,77b], K.F. Di Petrillo [40], M. Diamantopoulou [35], F.A. Dias [116], M.A. Diaz [139a,139b], A.R. Didenko [39], M. Didenko [168], S.D. Diefenbacher [18a], E.B. Diehl [107], S. Díez Cornell [48], C. Diez Pardos [146], C. Dimitriadi [149], A. Dimitrievska [21], A. Dimri [150], Y. Ding[62], J. Dingfelder [25], T. Dingley [128], I-M. Dinu [28b], S.J. Dittmeier [63b], F. Dittus [37], M. Divisek [135], B. Dixit [93], F. Djama [103], T. Djobava [154b], C. Doglioni [102,99], A. 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Sperlich [54], B. Spisso [72a,72b], L. Splendori [103], M. Spousta [135], E.J. Staats [35], R. Stamen [63a], E. Stanecka [87], W. Stanek-Maslouska [48], M.V. Stange [50], B. Stanislaus [18a], M.M. Stanitzki [48], E.A. Starchenko [38], G.H. Stark [138], J. Stark [90], P. Staroba [133], P. Starovoitov [84b], R. Staszewski [87], C. Stauch [110], G. Stavropoulos [46], A. Stefl [37], A. Stein [101], P. Steinberg [30], B. Stelzer [147,161a], H.J. Stelzer [131], O. Stelzer [161a], H. Stenzel [58], T.J. Stevenson [151], G.A. Stewart [48], G. Stoicea [28b], M. Stolarski [132a], S. Stonjek [111], A. Straessner [50], J. Strandberg [149], S. Strandberg [47a,47b], M. Stratmann [176], M. Strauss [122], T. Strebler [103], P. Strizenec [29b], R. Ströhmer [171], D.M. Strom [125], R. Stroynowski [45], A. Strubig [47a,47b], S.A. Stucci [30], B. Stugu [17], J. Stupak [122], N.A. Styles [48], D. Su [148], S. Su [62], X. Su [62], D. Suchy [29a], A.D. Sudhakar Ponnu [55], L. Sudit [174], Y. Sue [83], K. Sugizaki [130], V.V. Sulin [38], D.M.S. Sultan [128], L. Sultanaliyeva [25], S. Sultansoy [3b], S. Sun [175], W. Sun [14], S. Sundar Raman [169], N. Sur [99], N. Suri Jr [177], M.R. Sutton [151], M. Svatos [133], P.N. Swallow [33], M. Swiatlowski [161a], A. Swoboda [37], I. Sykora [29a], M. Sykora [135], T. Sykora [135], D. Ta [101], K. Tackmann [48,x], A. Taffard [164], R. Tafirout [161a], Y. Takubo [83], M. Talby [103], A.A. Talyshev [38], N.M. Tamir [156], A. Tanaka [158], J. Tanaka [158], R. Tanaka [66], M. Tanasini [150], Z. Tao [169], S. Tapia Araya [139g], S. Tapprogge [101], A. Tarek Abouelfadl Mohamed [37], S. Tarem [155], K. Tariq [14], G. Tarna [37], G.F. Tartarelli [71a], M.J. Tartarin [90], P. Tas [135], M. Tasevsky [133], E. Tassi [44b,44a], A.C. Tate [167], Y. Tayalati [36e,z], G.N. Taylor [106], W. Taylor [161b], R.J. Taylor Vara [168], A.S. Tegetmeier [90], P. Teixeira-Dias [96], J.J. Teoh [160], K. Terashi [158], J. Terron [100], S. Terzo [13], M. Testa [53], R.J. Teuscher [160,aa], A. Thaler [79], O. Theiner [56], T. Theveneaux-Pelzer [103], J.P. Thomas [21], E.A. Thompson [18a], P.D. Thompson [21], E. Thomson [130], R.E. Thornberry [45], C. Tian [62], Y. Tian [56], V. Tikhomirov [81], Yu.A. Tikhonov [39], S. Timoshenko[38], D. Timoshyn [135], E.X.L. Ting [1], P. Tipton [177], A. Tishelman-Charny [30], K. Todome [140], S. Todorova-Nova [135], L. Toffolin [69a,69c], M. Togawa [83], J. Tojo [89], S. Tokár [29a], O. Toldaiev [68], G. Tolkachev [103], M. Tomoto [83], L. Tompkins [148], E. Torrence [125], H. Torres [90], D.I. Torres Arza [139g], E. Torró Pastor [168], M. Toscani [31], C. Tosciri [40], M. Tost [11], D.R. Tovey [144], T. Trefzger [171], P.M. Tricarico [13], A. Tricoli [30], I.M. Trigger[161a], S. Trincaz-Duvoid[129], D.A. Trischuk[170], A. Tropina[39], D. Truncali[76a,76b], L. Truong[34c], M. Trzebinski[87], A. Trzupek[87], F. Tsai[150], M. Tsai[107], A. Tsiamis[157], P.V. Tsiareshka[39], S. Tsigaridas[161a], A. Tsirigotis[157,s], V. Tsiskaridze[154a], E.G. Tskhadadze[154a], Y. Tsujikawa[88], I.I. Tsukerman[38], V. Tsulaia[18a], K. Tsuri[120], D. Tsybychev[150], Y. Tu[64b], A. Tudorache[28b], V. Tudorache[28b], S.B. Tuncay[128], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[39,ab], P.M. Tuts[42], Y. Uematsu[83], F. Ukegawa[162], P.A. Ulloa Poblete[139c,139b], G. Unal[37], A. Undrus[30], J. Urban[29b], P. Urrejola[139e], G. Usai[8], R. Ushioda[159], M. Usman[109], F. Ustuner[52], Z. Uysal[81], V. Vacek[134], B. Vachon[105], T. Vafeiadis[37], A. Vaitkus[97], C. Valderanis[110], E. Valdes Santurio[47a,47b], M. Valente[37], S. Valentinetti[24b,24a], A. Valero[168], E. Valiente Moreno[168], A. Vallier[90], J.A. Valls Ferrer[168], D.R. Van Arneman[116], R. Van Den Broucke[129], A. Van Der Graaf[49], H.Z. Van Der Schyf[34j], P. Van Gemmeren[6], M. Van Rijnbach[37], S. Van Stroud[97], I. Van Vulpen[116], P. Vana[135], M. Vanadia[76a,76b], U.M. Vande Voorde[149], W. Vandelli[37], E.R. Vandewall[148], D. Vannicola[156], L. Vannoli[53], R. Vari[75a], M. Varma[177], E.W. Varnes[7], C. Varni[79], D. Varouchas[66], L. Varriale[168], K.E. Varvell[152], M.E. Vasile[28b], L. Vaslin[83], M.D. Vassilev[148], A. Vasyukov[39], L.M. Vaughan[123], R. Vavricka[135], T. Vazquez Schroeder[13], J. Veatch[32], V. Vecchio[102], M.J. Veen[104], I. Veliscek[30], I. Velkovska[94], L.M. Veloce[160], F. Veloso[132a,132c], A.G. Veltman[52], S. Veneziano[75a], A. Ventura[70a,70b], A. Verbytskyi[111], M. Verducci[74a,74b], C. Vergis[95], M. Verissimo De Araujo[82b], W. Verkerke[116], J.C. Vermeulen[116], C. Vernieri[148], M. Vessella[164], M.C. Vetterli[147,ah], A. Vgenopoulos[101], N. Viaux Maira[139g,ae], T. Vickey[144], O.E. Vickey Boeriu[144], G.H.A. Viehhauser[128], L. Vigani[63b], M. Vigl[111], M. Villa[24b,24a], M. Villaplana Perez[168], E.M. Villhauer[40], E. Vilucchi[53], M. Vincent[168], M.G. Vincter[35], A. Visibile[116], A. Visive[116], C. Vittori[37], I. Vivarelli[24b,24a], M.I. Vivas Albornoz[48], E. Voevodina[111], F. Vogel[110], J.C. Voigt[50], P. Vokac[134], Yu. Volkotrub[86b], L. Vomberg[25], E. Von Toerne[25], B. Vormwald[37], K. Vorobev[51], M. Vos[168], K. Voss[146], M. Vozak[37], L. Vozdecky[122], N. Vranjes[16], M. Vranjes Milosavljevic[16], M. Vreeswijk[116], N.K. Vu[143b,143a], R. Vuillermet[37], O. Vujinovic[101], I. Vukotic[40], I.K. Vyas[35], J.F. Wack[33], A. Wada[112], S. Wada[162], C. Wagner[148], J.M. Wagner[18a], W. Wagner[176], S. Wahdan[176], H. Wahlberg[91], C.H. Waits[122], J. Walder[136], R. Walker[110], K. Walkingshaw Pass[59], W. Walkowiak[146], A. Wall[130], E.J. Wallin[99], T. Wamorkar[148], K. Wandall-Christensen[168], A. Wang[62], A.Z. Wang[138], C. Wang[48], C. Wang[11], H. Wang[18a], J. Wang[64c], P. Wang[102], P. Wang[97], R. Wang[61], R. Wang[107], R. Wang[6], S.M. Wang[153], S. Wang[14], T. Wang[115], T. Wang[62], W.T. Wang[128], X. Wang[167], X. Wang[143a], X. Wang[48], Y. Wang[150], Y. Wang[114], Z. Wang[107], Z. Wang[143b], Z. Wang[107], C. Wanotayaroj[83], A. Warburton[105], A.L. Warnerbring[146], S. Waterhouse[96], A.T. Watson[21], H. Watson[52], M.F. Watson[21], E. Watton[37], G. Watts[141], B.M. Waugh[97], J.M. Webb[54], C. Weber[30], M.S. Weber[20], C. Wei[62], Y. Wei[54], A.R. Weidberg[128], E.J. Weik[119], J. Weingarten[49], C. Weiser[54], C.J. Wells[48], T. Wenaus[30], T. Wengler[37], N.S. Wenke[111], N. Wermes[25], M. Wessels[63a], A.M. Wharton[92], A.S. White[37], A. White[8], M.J. White[1], D. Whiteson[164], L. Wickremasinghe[126], W. Wiedenmann[175], M. Wielers[136], R. Wierda[149], C. Wiglesworth[43], H.G. Wilkens[37], J.J.H. Wilkinson[33], S. Williams[33], S. Willocq[104], B.J. Wilson[102], D.J. Wilson[102], P.J. Windischhofer[40], F.I. Winkel[31], F. Winklmeier[125], B.T. Winter[54], M. Wittgen[148], M. Wobisch[98], T. Wojtkowski[60], Z. Wolffs[116], J. Wollrath[37], M.W. Wolter[87], H. Wolters[132a,132c], M.C. Wong[138], E.L. Woodward[42], S.D. Worm[48], B.K. Wosiek[87], K.W. Woźniak[87], S. Wozniewski[55], K. Wraight[59], C. Wu[160], C. Wu[21], J. Wu[158], M. Wu[113b], M. Wu[115], S.L. Wu[175], S. Wu[14], X. Wu[62], Y.Q. Wu[160], Y. Wu[62], Z. Wu[4], Z. Wu[113a], J. Wuerzinger[111], T.R. Wyatt[102], B.M. Wynne[52], S. Xella[43], L. Xia[113a],

M. Xie[62], A. Xiong[125], D. Xu[14], H. Xu[62], L. Xu[62], R. Xu[130], T. Xu[107], W. Xu[113a], Y. Xu[141], Z. Xu[52], R. Xue[131], B. Yabsley[152], S. Yacoob[11], Y. Yamaguchi[83], E. Yamashita[158], H. Yamauchi[162], T. Yamazaki[18a], Y. Yamazaki[85], S. Yan[59], Z. Yan[104], H.J. Yang[143a], H.T. Yang[62], S. Yang[62], X. Yang[37], X. Yang[14], Y. Yang[158], Y. Yang[62], W-M. Yao[18a], C.L. Yardley[151], J. Ye[14], S. Ye[30], X. Ye[62], Y. Yeh[97], I. Yeletskikh[39], B. Yeo[18b], M.R. Yexley[97], T.P. Yildirim[128], K. Yorita[173], C.J.S. Young[37], C. Young[148], I.N.L. Young[59], N.D. Young[125], Y. Yu[62], J. Yuan[14,113c], M. Yuan[107], R. Yuan[143b], L. Yue[97], M. Zaazoua[62], B. Zabinski[87], I. Zahir[36a], A. Zaio[57b,57a], Z.K. Zak[87], T. Zakareishvili[168], S. Zambito[56], J.A. Zamora Saa[139d], J. Zang[158], R. Zanzottera[71a,71b], O. Zaplatilek[134], C. Zeitnitz[176], H. Zeng[14], D.T. Zenger Jr[27], O. Zenin[38], T. Ženiš[29a], S. Zenz[95], D. Zerwas[66], B. Zhang[172], D.F. Zhang[144], G. Zhang[14,aj], J. Zhang[142a], J. Zhang[6], L. Zhang[62], L. Zhang[113a], P. Zhang[14,113c], R. Zhang[113a], S. Zhang[90], T. Zhang[158], Y. Zhang[141], Y. Zhang[97], Y. Zhang[62], Y. Zhang[113a], Z. Zhang[18a], Z. Zhang[142a], Z. Zhang[66], H. Zhao[141], T. Zhao[142a], Y. Zhao[35], Z. Zhao[62], Z. Zhao[62], A. Zhemchugov[39], J. Zheng[113a], K. Zheng[167], L. Zheng[142a], X. Zheng[62], Z. Zheng[148], D. Zhong[167], B. Zhou[107], B. Zhou[143b,143a], H. Zhou[7], N. Zhou[143a], Y. Zhou[15], Y. Zhou[113a], Y. Zhou[7], J. Zhu[107], X. Zhu[143b], Y. Zhu[143a], X. Zhuang[14], K. Zhukov[68], N.I. Zimine[39], J. Zinsser[63b], M. Ziolkowski[146], L. Živković[16], A. Zoccoli[24b,24a], K. Zoch[61], A. Zografos[37], T.G. Zorbas[144], O. Zormpa[46], L. Zwalinski[37].

[1]Department of Physics, University of Adelaide, Adelaide; Australia.
[2]Department of Physics, University of Alberta, Edmonton AB; Canada.
[3] $^{(a)}$Department of Physics, Ankara University, Ankara; $^{(b)}$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 IL; United States of America.
[7]Department of Physics, University of Arizona, Tucson AZ; United States of America.
[8]Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
[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 TX; United States of America.
[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.
[18] $^{(a)}$Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; $^{(b)}$University of California, Berkeley CA; United States of America.
[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.
[22] $^{(a)}$Department of Physics, Bogazici University, Istanbul; $^{(b)}$Department of Physics Engineering, Gaziantep University, Gaziantep; $^{(c)}$Department of Physics, Istanbul University, Istanbul; Türkiye.

[23(a)]Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá;[(b)]Departamento de Física, Universidad Nacional de Colombia, Bogotá; Colombia.
[24(a)]Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna;[(b)]INFN Sezione di Bologna; Italy.
[25]Physikalisches Institut, Universität Bonn, Bonn; Germany.
[26]Department of Physics, Boston University, Boston MA; United States of America.
[27]Department of Physics, Brandeis University, Waltham MA; United States of America.
[28(a)]Transilvania University of Brasov, Brasov;[(b)]Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest;[(c)]Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi;[(d)]National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca;[(e)]National University of Science and Technology Politechnica, Bucharest;[(f)]West University in Timisoara, Timisoara;[(g)]Faculty of Physics, University of Bucharest, Bucharest; Romania.
[29(a)]Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava;[(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
[30]Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
[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, CA; United States of America.
[33]Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
[34(a)]Department of Physics, University of Cape Town, Cape Town;[(b)]iThemba Labs, Western Cape;[(c)]Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg;[(d)]National Institute of Physics, University of the Philippines Diliman (Philippines);[(e)]Department of Physics, Stellenbosch University, Matieland;[(f)]University of KwaZulu-Natal, School of Agriculture and Science, Mathematics, Westville;[(g)]University of South Africa, Department of Physics, Pretoria;[(h)]University of Pretoria, Department of Mechanical and Aeronautical Engineering, Pretoria;[(i)]University of Zululand, KwaDlangezwa;[(j)]School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
[35]Department of Physics, Carleton University, Ottawa ON; Canada.
[36(a)]Faculté des Sciences Ain Chock, Université Hassan II de Casablanca;[(b)]Faculté des Sciences, Université Ibn-Tofail, Kénitra;[(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;[(d)]LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda;[(e)]Faculté des sciences, Université Mohammed V, Rabat;[(f)]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 IL; United States of America.
[41]LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.
[42]Nevis Laboratory, Columbia University, Irvington NY; United States of America.
[43]Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.
[44(a)]Dipartimento di Fisica, Università della Calabria, Rende;[(b)]INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.
[45]Physics Department, Southern Methodist University, Dallas TX; United States of America.
[46]National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.
[47(a)]Department of Physics, Stockholm University;[(b)]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 NC; United States of America.
[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.
[57][(a)]Dipartimento di Fisica, Università di Genova, Genova;[(b)]INFN Sezione di 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 MA; United States of America.
[62]Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.
[63][(a)]Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;[(b)]Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.
[64][(a)]Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;[(b)]Department of Physics, University of Hong Kong, Hong Kong;[(c)]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 IN; United States of America.
[69][(a)]INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;[(b)]ICTP, Trieste;[(c)]Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
[70][(a)]INFN Sezione di Lecce;[(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
[71][(a)]INFN Sezione di Milano;[(b)]Dipartimento di Fisica, Università di Milano, Milano; Italy.
[72][(a)]INFN Sezione di Napoli;[(b)]Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
[73][(a)]INFN Sezione di Pavia;[(b)]Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
[74][(a)]INFN Sezione di Pisa;[(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
[75][(a)]INFN Sezione di Roma;[(b)]Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
[76][(a)]INFN Sezione di Roma Tor Vergata;[(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
[77][(a)]INFN Sezione di Roma Tre;[(b)]Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
[78][(a)]INFN-TIFPA;[(b)]Università degli Studi di Trento, Trento; Italy.
[79]Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria.
[80]Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
[81]Istinye University, Sariyer, Istanbul; Türkiye.
[82][(a)]Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;[(b)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;[(c)]Instituto de Física, Universidade de São Paulo, São Paulo;[(d)]Rio de Janeiro State University, Rio de Janeiro;[(e)]Federal University of Bahia, Bahia; Brazil.
[83]KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
[84][(a)]Khalifa University of Science and Technology, Abu Dhabi;[(b)]University of Sharjah, Sharjah; United

Arab Emirates.
[85]Graduate School of Science, Kobe University, Kobe; Japan.
[86(a)]AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;[(b)]Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
[87]Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
[88]Faculty of Science, Kyoto University, Kyoto; Japan.
[89]Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka ; Japan.
[90]L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse; France.
[91]Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
[92]Physics Department, Lancaster University, Lancaster; United Kingdom.
[93]Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
[94]Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
[95]Department of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
[96]Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
[97]Department of Physics and Astronomy, University College London, London; United Kingdom.
[98]Louisiana Tech University, Ruston LA; United States of America.
[99]Fysiska institutionen, Lunds universitet, Lund; Sweden.
[100]Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
[101]Institut für Physik, Universität Mainz, Mainz; Germany.
[102]School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
[103]CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
[104]Department of Physics, University of Massachusetts, Amherst MA; United States of America.
[105]Department of Physics, McGill University, Montreal QC; Canada.
[106]School of Physics, University of Melbourne, Victoria; Australia.
[107]Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
[108]Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
[109]Group of Particle Physics, University of Montreal, Montreal QC; Canada.
[110]Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
[111]Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
[112]Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
[113(a)]Department of Physics, Nanjing University, Nanjing;[(b)]School of Science, Shenzhen Campus of Sun Yat-sen University;[(c)]University of Chinese Academy of Science (UCAS), Beijing; China.
[114]Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
[115]Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen; Netherlands.
[116]Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
[117]Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
[118(a)]New York University Abu Dhabi, Abu Dhabi;[(b)]United Arab Emirates University, Al Ain; United Arab Emirates.
[119]Department of Physics, New York University, New York NY; United States of America.
[120]Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
[121]Ohio State University, Columbus OH; United States of America.

[122]Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
[123]Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
[124]Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic.
[125]Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America.
[126]Graduate School of Science, University of Osaka, Osaka; Japan.
[127]Department of Physics, University of Oslo, Oslo; Norway.
[128]Department of Physics, Oxford University, Oxford; United Kingdom.
[129]LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris; France.
[130]Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
[131]Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
[132(a)]Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;[(b)]Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;[(c)]Departamento de Física, Universidade de Coimbra, Coimbra;[(d)]Centro de Física Nuclear da Universidade de Lisboa, Lisboa;[(e)]Departamento de Física, Escola de Ciências, Universidade do Minho, Braga;[(f)]Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);[(g)]Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
[133]Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
[134]Czech Technical University in Prague, Prague; Czech Republic.
[135]Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
[136]Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
[137]IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
[138]Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
[139(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;[(b)]Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;[(c)]Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;[(d)]Universidad Andres Bello, Department of Physics, Santiago;[(e)]Universidad San Sebastian, Recoleta;[(f)]Instituto de Alta Investigación, Universidad de Tarapacá, Arica;[(g)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
[140]Department of Physics, Institute of Science, Tokyo; Japan.
[141]Department of Physics, University of Washington, Seattle WA; United States of America.
[142(a)]Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;[(b)]School of Physics, Zhengzhou University; China.
[143(a)]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;[(b)]State Key Laboratory of Dark Matter Physics, Tsung-Dao Lee Institute, Shanghai Jiao Tong University, Shanghai; China.
[144]Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
[145]Department of Physics, Shinshu University, Nagano; Japan.
[146]Department Physik, Universität Siegen, Siegen; Germany.
[147]Department of Physics, Simon Fraser University, Burnaby BC; Canada.
[148]SLAC National Accelerator Laboratory, Stanford CA; United States of America.
[149]Department of Physics, Royal Institute of Technology, Stockholm; Sweden.
[150]Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

[151]Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
[152]School of Physics, University of Sydney, Sydney; Australia.
[153]Institute of Physics, Academia Sinica, Taipei; Taiwan.
[154](a)E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;(b)High Energy Physics Institute, Tbilisi State University, Tbilisi;(c)University of Georgia, Tbilisi; Georgia.
[155]Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
[156]Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
[157]Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
[158]International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
[159]Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
[160]Department of Physics, University of Toronto, Toronto ON; Canada.
[161](a)TRIUMF, Vancouver BC;(b)Department of Physics and Astronomy, York University, Toronto ON; Canada.
[162]Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
[163]Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
[164]Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
[165]University of West Attica, Athens; Greece.
[166]Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
[167]Department of Physics, University of Illinois, Urbana IL; United States of America.
[168]Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
[169]Department of Physics, University of British Columbia, Vancouver BC; Canada.
[170]Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
[171]Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.
[172]Department of Physics, University of Warwick, Coventry; United Kingdom.
[173]Waseda University, Tokyo; Japan.
[174]Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel.
[175]Department of Physics, University of Wisconsin, Madison WI; United States of America.
[176]Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany.
[177]Department of Physics, Yale University, New Haven CT; United States of America.
[178]Yerevan Physics Institute, Yerevan; Armenia.
[a] Also at Affiliated with an institute formerly covered by a cooperation agreement with CERN.
[b] Also at An-Najah National University, Nablus; Palestine.
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY; United States of America.
[d] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[e] Also at Centre of Physics of the Universities of Minho and Porto (CF-UM-UP); Portugal.
[f] Also at CERN, Geneva; Switzerland.
[g] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[h] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[i] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[j] Also at Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; China.

[k] Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu; Türkiye.
[l] Also at Department of Physics, King's College London, London; United Kingdom.
[m] Also at Department of Physics, Stellenbosch University; South Africa.
[n] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[o] Also at Department of Physics, University of Thessaly; Greece.
[p] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[q] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
[r] Also at Faculty of Physics, University of Bucharest; Romania.
[s] Also at Hellenic Open University, Patras; Greece.
[t] Also at Henan University; China.
[u] Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
[v] Also at Indian Institute of Technology (IIT), Jodhpur; India.
[w] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
[x] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[y] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[z] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[aa] Also at Institute of Particle Physics (IPP); Canada.
[ab] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[ac] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ad] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ae] Also at Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago; Chile.
[af] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ag] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[ah] Also at TRIUMF, Vancouver BC; Canada.
[ai] Also at Università di Napoli Parthenope, Napoli; Italy.
[aj] Also at University of Chinese Academy of Sciences (UCAS), Beijing; China.
[ak] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[al] Also at University of Siena; Italy.
[am] Also at Washington College, Chestertown, MD; United States of America.
[an] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased