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Letter

Constraint on the total width of the Higgs boson from Higgs boson and four-top-quark measurements in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration *

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ABSTRACT

This Letter presents a constraint on the total width of the Higgs boson (Γ_H) using a combined measurement of on-shell Higgs boson production and the production of four top quarks, which involves contributions from off-shell Higgs boson-mediated processes. This method relies on the assumption that the tree-level Higgs-top Yukawa coupling strength is the same for on-shell and off-shell Higgs boson production processes, thereby avoiding any assumptions about the relationship between on-shell and off-shell gluon fusion Higgs production rates, which were central to previous measurements. The result is based on up to 140 fb^{-1} of proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the Large Hadron Collider. The observed (expected) 95% confidence level upper limit on Γ_H is 450 MeV (75 MeV). Additionally, considering the constraint on the Higgs-top Yukawa coupling from loop-induced Higgs boson production and decay processes further yields an observed (expected) upper limit of 160 MeV (55 MeV).

1. Introduction

The discovery of the Higgs boson [1–6] by the ATLAS [7] and CMS [8] collaborations at the Large Hadron Collider (LHC) has ushered in a new era for particle physics, marked by precision measurements in the Higgs sector. The total width of the Higgs boson (Γ_H) is sensitive to the potential presence of beyond the Standard Model (SM) Higgs boson decays that are not covered by direct experimental searches, making it a crucial parameter for exploring new phenomena. The Higgs boson mass has been measured to be 125.09 ± 0.24 GeV based on LHC Run 1 data collected by the ATLAS and CMS experiments [9], and more recently to be 125.11 ± 0.11 GeV based on Run 1 and Run 2 data collected by the ATLAS experiment [10]. At the measured Higgs boson mass value around 125 GeV, the SM predicts the value of Γ_H to be only 4.1 MeV [11]. Due to limited detector resolution, the total width of the Higgs boson is inaccessible via direct measurement of the Higgs boson line shape or flight distance [12] at the LHC experiments. However, a combined measurement of on-shell and off-shell Higgs boson production processes can constrain the total width of the Higgs boson based on specific model assumptions [13–16]. The on-shell Higgs boson production and decay rates depend on both the Higgs boson coupling strength to particles involved in the production and decay processes, and the total width of the Higgs boson. In contrast, the off-shell Higgs boson production and decay depend only on the off-shell Higgs coupling strength. If the relation between the on-shell and off-shell Higgs boson couplings is known, the combined measurement of on-shell and off-shell Higgs boson production processes allows the determination of Γ_H.

Recently, both the ATLAS and CMS experiments placed constraints on Γ_H using combined measurements of on-shell and off-shell Higgs boson production processes in the $ZZ^{(*)}$ final states, yielding 95% confidence level (CL) upper limits of 10.2 MeV [17] and 8.5 MeV [18], respectively, superseding earlier constraints obtained by the two experiments with Run 1 data using the same assumptions [19,20]. These measurements assume that the strength modifiers, which are multiplicative factors of the Higgs boson couplings, are the same between off-shell and on-shell production processes specifically for its interactions with gluons and vector bosons. However, the loop-induced effective Higgs-gluon coupling could vary differently between on-shell and off-shell production processes if not-yet-detected coloured beyond SM (BSM) particles are contributing to the Higgs-gluon coupling [21–23].

This Letter presents a constraint on Γ_H using a combined measurement of on-shell Higgs boson production in association with a top-quark pair ($t\bar{t}H$) and the simultaneous production of four top quarks ($t\bar{t}t\bar{t}$), which involves contributions from off-shell Higgs boson-mediated processes through the Higgs-top Yukawa coupling. Fig. 1 shows representative Feynman diagrams of those processes involving a Higgs boson in the final state or a virtual Higgs boson mediator. This measurement assumes that the tree-level Higgs-top Yukawa coupling strength is the same for

* *E-mail address:* atlas.publications@cern.ch.

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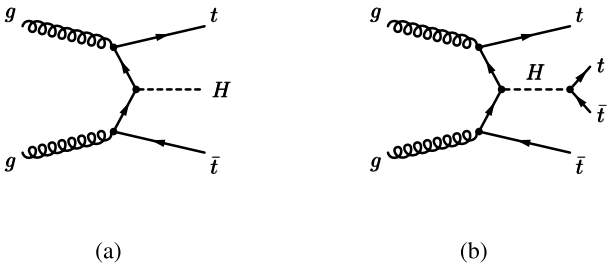


Fig. 1. Example leading-order Feynman diagrams for the (a) $t\bar{t}H$ and (b) Higgs-mediated $t\bar{t}t\bar{t}$ processes.

Table 1
Summary of on-shell and off-shell measurements used as input for the total width measurement. For the on-shell analyses, this table specifically breaks down the processes targeted by the measurement into production and decay modes. The off-shell measurement is included but not broken down in this manner.

Target processes		Reference
Off-shell measurement		
$pp \to t\bar{t}t\bar{t}$		[26]
On-shell measurement		
Production	Decay	
ggF, VBF, WH, ZH, $t\bar{t}H$, tH	$H \to \gamma\gamma$	[31]
$t\bar{t}H + tH$	$H \to b\bar{b}$	[32]
WH, ZH	$H \to b\bar{b}$	[33,34]
VBF	$H \to b\bar{b}$	[35]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to ZZ$	[36]
ggF, VBF	$H \to WW$	[37]
WH, ZH	$H \to WW$	[38]
ggF, VBF, $WH + ZH$, $t\bar{t}H + tH$	$H \to \tau\tau$	[39]
ggF+ $t\bar{t}H + tH$, VBF+ $WH + ZH$	$H \to \mu\mu$	[40]
Inclusive	$H \to Z\gamma$	[41]

on-shell and off-shell Higgs boson production processes [24,25]. Different from the Higgs-gluon coupling, the presence of unknown coloured particles would not modify the tree-level Higgs-top Yukawa coupling and its scale dependence. Another assumption made in this study is that no BSM contributions affect the $t\bar{t}t\bar{t}$ production. Both ATLAS and CMS experiments have observed $t\bar{t}t\bar{t}$ production in proton–proton (pp) collisions at $\sqrt{s} = 13$ TeV and used the measurements to set constraints on possible BSM contributions that may affect this process [26,27]. In summary, the constraint on Γ_H derived from the combined measurement of the $t\bar{t}H$ and $t\bar{t}t\bar{t}$ processes represents a complementary approach based on different assumptions from existing studies [17,18].

2. Input measurements

This combined measurement uses results from individual measurements performed by the ATLAS experiment [28] as input, summarised in Table 1. The sensitivity to the total width of the Higgs boson primarily comes from the $t\bar{t}H$ and $t\bar{t}t\bar{t}$ processes. However, measurements targeting other Higgs boson production modes are also included to constrain contributions from Higgs boson couplings beyond its top Yukawa coupling. These additional modes include gluon–gluon fusion (ggF), vector boson fusion (VBF), associated production with a vector boson (WH/ZH), and associated production with a single top quark (tH), which also contributes to the Higgs-top Yukawa coupling measurement.

The input measurements rely on the two-level trigger system used to select the events [29], and a software suite [30] that is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

An overview of the on-shell Higgs boson measurements is detailed in Ref. [42]. Based on pp collision data collected by the ATLAS experiment during LHC Run 2 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV, corresponding to integrated luminosities ranging from 36.1 fb^{-1} to 139 fb^{-1}, the $t\bar{t}H$ cross-section is determined to be 0.37 ± 0.12 pb assuming SM Higgs boson decay branching ratios. The measured value is in agreement with the SM prediction of 0.50 ± 0.05 pb [11]. The sensitivity is mainly contributed by the $H \to \gamma\gamma$ [31], $H \to b\bar{b}$ [32], and multi-lepton [43] final states. In the $H \to \gamma\gamma$ analysis, a multi-class Boosted Decision Trees (BDT) classifier is first used to divide data into regions enriched with $t\bar{t}H$ or Higgs bosons produced through other modes. Then binary BDT classifiers are deployed to further discriminate the target signal from background processes. The $t\bar{t}H$ signal is extracted by fitting the diphoton invariant mass spectra in categories defined by the multi-class and binary BDT boundaries. The background is estimated from data-driven interpolation in the data side-band. The $H \to b\bar{b}$ analysis, on the other hand, first separates data into one-lepton and dilepton final states (electrons or muons), with the presence of b-tagged jets, then uses either a BDT or a Deep Neural Network (DNN) algorithm to reconstruct the Higgs boson. A classification BDT is used to further separate the $t\bar{t}H$ signal from background processes. The $t\bar{t}H$ signal cross-section is extracted by fitting the classification BDT score distribution to data in most analysis categories. The dominant background is from the $t\bar{t}(+ \geq 1b)$ process, which is modelled by Monte Carlo (MC) simulation with its normalisation determined from data. Finally, the measurement from the multi-lepton final states [43], which includes contributions from $H \to ZZ$, $H \to WW$, and $H \to \tau\tau$ decays, is removed from the work reported in this Letter due to its partial overlap with the $t\bar{t}t\bar{t}$ data set [26]. After the removal, the overlap of data sets between the on-shell measurement and the $t\bar{t}t\bar{t}$ measurement is negligible.

The measurement of $t\bar{t}t\bar{t}$ production is detailed in Ref. [26]. It uses pp collision data at $\sqrt{s} = 13$ TeV from LHC Run 2, corresponding to an integrated luminosity of 140 fb^{-1}. Events with multi-lepton final states are selected, specifically those with two leptons of the same electric charge or at least three leptons (electrons or muons). These events are also required to have at least two b-tagged jets. Major background processes include $t\bar{t}W$, $t\bar{t}Z$, and $t\bar{t}H$ processes, with dedicated control regions defined to constrain the corresponding templates built from MC simulation. The rates of fake and non-prompt lepton background and charge mis-assignment background are also estimated and corrected using data-driven methods. A Graph Neural Network (GNN) classifier is used to further separate the $t\bar{t}t\bar{t}$ signal from background processes. The $t\bar{t}t\bar{t}$ cross-section is measured by fitting the GNN score distribution to data. The observed significance of the $t\bar{t}t\bar{t}$ signal is 6.1 standard deviations (σ), with an expected significance of $4.3\,\sigma$. The measured $t\bar{t}t\bar{t}$ production cross-section is $22.5^{+6.6}_{-5.5}$ fb, consistent with the SM prediction of 12.0 ± 2.4 fb [44–46] within $1.8\,\sigma$.

3. Combination framework

The combined measurement uses the profile likelihood ratio and its asymptotic distribution to set upper limits on the total width of the Higgs boson [47,48]. The likelihood function of this combined measurement incorporates systematic uncertainties as constrained nuisance parameters and correlates those consistently defined between input measurements. To incorporate the updated ATLAS integrated luminosity measurement [49] since the publication of Ref. [42], the luminosity uncertainties in the on-shell measurement are revised and correlated with the $t\bar{t}t\bar{t}$ measurement. In addition, the uncertainties in the reconstruction and calibration of electrons, muons, jets, and missing transverse momentum, the uncertainty in the pile-up modelling by the MC simulation, and the theory uncertainties in $t\bar{t}H$, $t\bar{t}t\bar{t}$, and $t\bar{t}Z$ MC modelling are all treated as correlated between the on-shell and $t\bar{t}t\bar{t}$ measurements. The impact from the potential correlation in other systematic uncertainties between the on-shell and $t\bar{t}t\bar{t}$ measurements on the upper limit of Γ_H is checked and found to be negligible. The expected results corresponding to the SM prediction are evaluated based on an Asimov data set [48], which is generated with a set of nuisance parameters deter-

mined by a fit to data where the signal cross-sections are fixed to their SM values.

To parameterise the event rates of on-shell and off-shell Higgs boson production processes, the so-called κ-framework [50] is adopted. The signal strength of any Higgs boson production and decay process $i \to H \to f$ in the on-shell measurement, defined as the ratio of the total Higgs boson signal yield to its SM prediction, is parameterised as $\kappa_i^2 \kappa_f^2 / (\Gamma_H / \Gamma_H^{SM})$ under the narrow-width approximation, where κ_i and κ_f are the coupling strength parameters modifying the production and decay rates, respectively, and Γ_H^{SM} is the SM value of the total width of the Higgs boson. The strength parameters for the tree-level couplings to top quark (κ_t), bottom quark (κ_b), tau-lepton (κ_τ), muon (κ_μ), and weak bosons (κ_Z and κ_W) are free parameters determined by the data. The strength parameters for the three loop-induced effective couplings, namely, the Higgs-gluon coupling (κ_g), the Higgs-photon coupling (κ_γ), and the Higgs-Z-photon coupling ($\kappa_{(Z\gamma)}$), are free parameters in the fit as well. The coupling for the $gg \to ZH$ process $\kappa_{(ggZH)}$, on the other hand, is parameterised as a function of κ_Z and κ_t. The current data set does not have the statistical power to constrain the $gg \to ZH$ process. The $t\bar{t}t\bar{t}$ process is a minor background in the $t\bar{t}H$, $H \to b\bar{b}$ measurement, and its normalisation is fixed to the SM prediction within uncertainties. The constraint on the Higgs-top Yukawa coupling strength κ_t primarily comes from the $t\bar{t}H$ production cross-section measurement. As a cross-check of this constraint, a fit is performed by parameterising Γ_H as a function of coupling strengths for SM particles based on the data used in the on-shell measurement. The fit yields κ_t to be 0.86 ± 0.13. This is 9% lower than the value reported in Ref. [42] due to the removal of the $t\bar{t}H$ multi-lepton final states from the on-shell measurement. The uncertainty in κ_t also increases by 18% when removing the $t\bar{t}H$ multi-lepton final state.

For the $t\bar{t}t\bar{t}$ measurement, the expected signal production rate in each bin of the GNN classifier discriminant is parameterised as a polynomial in κ_t, up to $\mathcal{O}(\kappa_t^4)$. The constant term arises from $t\bar{t}t\bar{t}$ production mediated by gluons or Z/γ^*, the $\mathcal{O}(\kappa_t^2)$ term arises from the interference between off-shell Higgs boson-mediated production and gluon- or Z/γ^*-mediated production, and the $\mathcal{O}(\kappa_t^4)$ term represents the contribution from off-shell Higgs boson-mediated production. There are no terms at odd orders of κ_t since there are always two Higgs-top Yukawa coupling vertices in the Higgs-mediated $t\bar{t}t\bar{t}$ production diagrams. The polynomial is derived based on leading-order MC simulation samples [26]. The $t\bar{t}H$ process is included in the $t\bar{t}t\bar{t}$ measurement as a background, and its normalisation is a free parameter determined from data. As discussed in Section 4, this treatment has a small impact on the determination of Γ_H. Using this configuration, the $t\bar{t}t\bar{t}$ measurement yields an observed (expected) 95% CL upper limit on $|\kappa_t|$ of 2.3 (1.9) [26]. This observation is consistent with the SM at 1.8 standard deviations.

4. Results

With κ_t and other Higgs boson coupling strength parameters as described in Section 3 profiled, the observed (expected) combined 95% CL upper limit on Γ_H is 450 MeV (75 MeV), corresponding to 110 (18) times the SM prediction. The profile likelihood ratio as a function of Γ_H is shown in Fig. 2. The observed value of the total width of the Higgs boson is $\Gamma_H = 86^{+110}_{-49}$ MeV, which is $2.0\,\sigma$ away from the SM expectation. The tension with the SM prediction arises primarily from the $1.8\,\sigma$ difference between data and SM prediction in the $t\bar{t}t\bar{t}$ measurement. Assuming the loop-induced ggF, $H \to \gamma\gamma$, and $H \to Z\gamma$ rates can be modelled as a function of κ_t and other SM coupling strengths [42,50], the observed (expected) 95% CL upper limit on Γ_H becomes 160 MeV (55 MeV) owing to the better constraint on κ_t contributed by these loop-induced processes. The deviation from the SM expectation in Γ_H under this alternative scenario remains $2.0\,\sigma$.

The 68% and 95% CL contours in the Γ_H and κ_t plane are shown in Fig. 3. Because of the degeneracy among coupling strength parameters and Γ_H in the on-shell measurement, the best-fit value of $\kappa_t = 1.9$ is

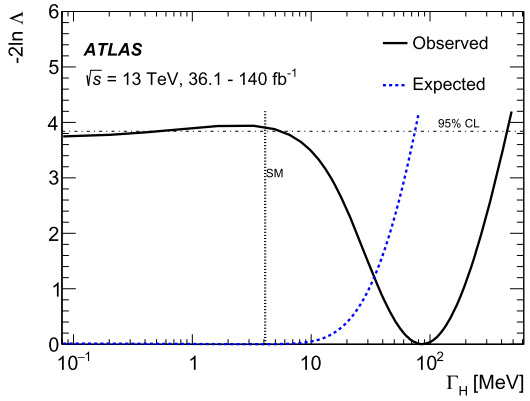


Fig. 2. The observed (expected) profile likelihood ratio, $-2\ln\Lambda$, as a function of Γ_H is shown as a solid (dashed) line. The Higgs-top Yukawa coupling strength κ_t and other Higgs boson coupling strength parameters as described in Section 3 are profiled. The 95% confidence interval is indicated by the intersections of the horizontal line with the $-2\ln\Lambda$ curves. The vertical line indicates the SM prediction.

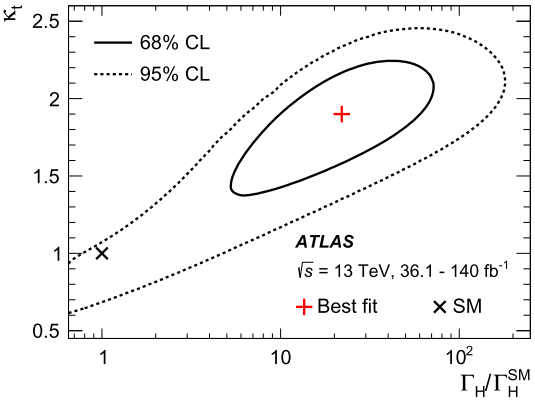


Fig. 3. The 68% CL (solid line) and 95% CL (dashed line) contours for a simultaneous measurement of Γ_H normalised to the SM prediction and κ_t. The best-fit value and the SM prediction are also indicated in the figure.

determined by the measurement of $t\bar{t}t\bar{t}$ cross-section that is larger than the SM prediction. The best-fit value of Γ_H is in turn scaled together with κ_t and other coupling strengths parameters along the flat direction of the likelihood function for the on-shell measurement.

The Higgs boson decay contributions from the minor $t\bar{t}H$ background in the $t\bar{t}t\bar{t}$ measurement were not incorporated into the κ-framework based event rate parameterisation because the input measurement did not preserve information about the relative fractions of various Higgs decay final states in the signal region. However, this has minimal impacts on the interpretation. Up to a 6% (2%) decrease in the observed (expected) limit on Γ_H is estimated when the $t\bar{t}H$ background in the $t\bar{t}t\bar{t}$ measurement is parameterised as functions of Γ_H and κ_t in the combined fit, assuming either a 100% $H \to WW$ or a 100% $H \to \tau\tau$ branching ratio. Note that the $H \to WW$ and $H \to \tau\tau$ are the two leading Higgs boson decay channels that contribute to the multi-lepton final state targeted by the $t\bar{t}t\bar{t}$ measurement. The assumption of full branching ratios is expected to provide a maximum estimate of the impact. Similarly, the input on-shell measurement did not consider the contribution from the $t\bar{t}t\bar{t}$ process in constraining κ_t. When the $t\bar{t}t\bar{t}$ normalisation in the $t\bar{t}H$, $H \to b\bar{b}$ measurement is parameterised as a function of κ_t [24] in the combined fit, the observed (expected) limit on Γ_H changes by 0.6% (0.5%).

The impact of various groups of systematic uncertainties in Γ_H is evaluated by individually removing each group from the fit. This is achieved by fixing the associated nuisance parameters to their best-fit

Table 2
Impact of the main sources of systematic uncertainties in the expected and observed 95% CL upper limit on the total width of the Higgs boson Γ_H. The impact is quantified as the reduction of the upper limit when the corresponding systematic uncertainties are removed from consideration by fixing the associated nuisance parameters at the best-fit values. The impacts shown here are not a breakdown of uncertainties, and one does not expect that the quadratic sum of individual impact values will be the same as the total impact value.

Systematic uncertainty	Impact on 95% CL upper limit on Γ_H	
	Expected [%]	Observed [%]
Theory	37	33
$t\bar{t}t\bar{t}$ production	25	13
Higgs boson production/decay	5	6
Other processes	10	16
Experimental	2	2
Jet flavour tagging	2	1
Jet and missing transverse energy	< 1	< 1
Leptons and photons	< 1	< 1
All other systematic uncertainties	< 1	< 1

values and then quantifying the change in the upper limit on Γ_H. As shown in Table 2, theory uncertainties have the most significant impact on the result. The largest impact on the expected limit, at 25%, comes from the theory uncertainties in the $t\bar{t}t\bar{t}$ process, which include missing higher-order QCD corrections evaluated from varying renormalisation and factorisation scales, MC generator choices, and the parton shower modelling. Details of the $t\bar{t}t\bar{t}$ MC simulated sample are provided in Ref. [26]. Conversely, the largest impact on the observed limit, at 16%, arises from the theory uncertainty in other physics processes, notably the $t\bar{t}(+\geq 1b)$ background in the $t\bar{t}H$, $H \to b\bar{b}$ measurement. Due to a larger-than-SM best-fit value, the uncertainty in the $t\bar{t}t\bar{t}$ cross-section measurement has a smaller observed impact on the Γ_H measurement than in the expected case, owing to the non-linear mapping between the two measurements. Experimental uncertainties, such as those in jet energy calibration and flavour tagging, contribute only a 2% impact on the limit. Removing all systematic uncertainties would decrease the observed (expected) upper limit to 280 MeV (44 MeV).

5. Conclusions

In this Letter a constraint on the total width of the Higgs boson Γ_H is obtained through a combination of measurements of on-shell Higgs boson production and $t\bar{t}t\bar{t}$ production with contribution from the off-shell $H \to t\bar{t}$ process. The input analyses are based on up to 140 fb^{-1} of pp collisions at a centre-of-mass energy of $\sqrt{s}$ =13 TeV, collected with the ATLAS detector at the LHC. The study assumes that the Higgs-top Yukawa coupling strength κ_t remains the same between the on-shell and off-shell regimes. The resulting 95% CL upper limit on Γ_H is 450 MeV, corresponding to 110 times the SM prediction, while the expected upper limit is 75 MeV, corresponding to 18 times the SM prediction. Assuming that only SM particles contribute to the loop-induced gluon–gluon fusion, $H \to \gamma\gamma$, and $H \to Z\gamma$ processes, the observed (expected) upper limit decreases to 160 MeV (55 MeV). The tension between the data and the SM prediction is $2.0\,\sigma$ in both scenarios, driven by the $1.8\,\sigma$ difference between data and SM in the $t\bar{t}t\bar{t}$ measurement. This result represents the first constraint on the total width of the Higgs boson using both on-shell and off-shell production processes involving the Higgs-top Yukawa coupling. It explores model assumptions distinct from those employed in similar studies based on diboson final states, thereby testing the robustness of our current understanding of the Higgs boson total width.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data for this manuscript are not available. The values in the plots and tables associated to this article are stored in HEPDATA (http://hepdata.cedar.ac.uk)

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P. Bartos [29a], A. Basan [102], M. Baselga [50], A. Bassalat [67,b], M.J. Basso [159a], S. Bataju [45], R. Bate [167], R.L. Bates [60], S. Batlamous [101], B. Batool [145], M. Battaglia [139], D. Battulga [19], M. Bauce [76a,76b], M. Bauer [80], P. Bauer [25], L.T. Bazzano Hurrell [31], J.B. Beacham [52], T. Beau [130], J.Y. Beaucamp [92], P.H. Beauchemin [161], P. Bechtle [25], H.P. Beck [20,o], K. Becker [170], A.J. Beddall [83], V.A. Bednyakov [39], C.P. Bee [149], L.J. Beemster [16], T.A. Beermann [37], M. Begalli [84d], M. Begel [30], A. Behera [149], J.K. Behr [49], J.F. Beirer [37], F. Beisiegel [25], M. Belfkir [119b], G. Bella [155], L. Bellagamba [24b], A. Bellerive [35], P. Bellos [21], K. Beloborodov [38], D. Benchekroun [36a], F. Bendebba [36a], Y. Benhammou [155], K.C. Benkendorfer [62], L. Beresford [49], M. Beretta [54], E. Bergeaas Kuutmann [164], N. Berger [4], B. Bergmann [135], J. Beringer [18a], G. Bernardi [5], C. Bernius [147], F.U. Bernlochner [25], F. Bernon [37], A. Berrocal Guardia [13], T. Berry [97], P. Berta [136], A. Berthold [51], S. Bethke [112], A. Betti [76a,76b], A.J. Bevan [96], N.K. Bhalla [55], S. Bhatta [149], D.S. Bhattacharya [169], P. Bhattarai [147], K.D. Bhide [55], V.S. Bhopatkar [124], R.M. Bianchi [132], G. Bianco [24b,24a], O. Biebel [111], R. Bielski [126], M. Biglietti [78a], C.S. Billingsley [45], Y. Bimgdi [36f], M. Bindi [56], A. Bingul [22b], C. Bini [76a,76b], G.A. Bird [33], M. Birman [172], M. Biros [136], S. Biryukov [150], T. Bisanz [50], E. Bisceglie [44b,44a], J.P. Biswal [137], D. Biswas [145], I. Bloch [49], A. Blue [60], U. Blumenschein [96], J. Blumenthal [102], V.S. Bobrovnikov [38], M. Boehler [55], B. Boehm [169], D. Bogavac [37], A.G. Bogdanchikov [38], L.S. Boggia [130], C. Bohm [48a], V. Boisvert [97], P. Bokan [37], T. Bold [87a], M. Bomben [5], M. Bona [96], M. Boonekamp [138], C.D. Booth [97], A.G. Borbély [60], I.S. Bordulev [38], G. Borissov [93], D. Bortoletto [129], D. Boscherini [24b], M. Bosman [13], J.D. Bossio Sola [37], K. Bouaouda [36a], N. Bouchhar [166], L. Boudet [4], J. Boudreau [132], E.V. Bouhova-Thacker [93], D. Boumediene [41], R. Bouquet [58b,58a], A. Boveia [122], J. Boyd [37], D. Boye [30], I.R. Boyko [39], L. Bozianu [57], J. Bracinik [21], N. Brahimi [4], G. Brandt [174], O. Brandt [33], F. Braren [49], B. Brau [105], J.E. Brau [126], R. Brener [172], L. Brenner [117], R. Brenner [164], S. Bressler [172], G. Brianti [79a,79b], D. Britton [60], D. Britzger [112], I. Brock [25], R. Brock [109], G. Brooijmans [42], E.M. Brooks [159b], E. Brost [30], L.M. Brown [168], L.E. Bruce [62], T.L. Bruckler [129], P.A. Bruckman de Renstrom [88], B. Brüers [49], A. Bruni [24b], G. Bruni [24b], M. Bruschi [24b], N. Bruscino [76a,76b], T. Buanes [17], Q. Buat [142], D. Buchin [112], A.G. Buckley [60], O. Bulekov [38], B.A. Bullard [147], S. Burdin [94], C.D. Burgard [50], A.M. Burger [37], B. Burghgrave [8], O. Burlayenko [55], J. Burleson [165], J.T.P. Burr [33], J.C. Burzynski [146], E.L. Busch [42], V. Büscher [102], P.J. Bussey [60], J.M. Butler [26], C.M. Buttar [60], J.M. Butterworth [98], W. Buttinger [137], C.J. Buxo Vazquez [109], A.R. Buzykaev [38], S. Cabrera Urbán [166], L. Cadamuro [67], D. Caforio [59], H. Cai [132], Y. Cai [14,114c], Y. Cai [114a], V.M.M. Cairo [37], O. Cakir [3a], N. Calace [37], P. Calafiura [18a], G. Calderini [130], P. Calfayan [69], G. Callea [60], L.P. Caloba [84b], D. Calvet [41], S. Calvet [41], M. Calvetti [75a,75b], R. Camacho Toro [130], S. Camarda [37], D. Camarero Munoz [27], P. Camarri [77a,77b], M.T. Camerlingo [73a,73b], D. Cameron [37], C. Camincher [168], M. Campanelli [98], A. Camplani [43], V. Canale [73a,73b], A.C. Canbay [3a], E. Canonero [97], J. Cantero [166], Y. Cao [165], F. Capocasa [27], M. Capua [44b,44a], A. Carbone [72a,72b], R. Cardarelli [77a], J.C.J. Cardenas [8], G. Carducci [44b,44a], T. Carli [37], G. Carlino [73a], J.I. Carlotto [13], B.T. Carlson [132,q], E.M. Carlson [168,159a], J. Carmignani [94], L. Carminati [72a,72b], A. Carnelli [138], M. Carnesale [37], S. Caron [116], E. Carquin [140f], I.B. Carr [107], S. Carrá [72a], G. Carratta [24b,24a], A.M. Carroll [126], M.P. Casado [13,i], M. Caspar [49], F.L. Castillo [4], L. Castillo Garcia [13], V. Castillo Gimenez [166], N.F. Castro [133a,133e], A. Catinaccio [37], J.R. Catmore [128], T. Cavaliere [4], V. Cavaliere [30], N. Cavalli [24b,24a], L.J. Caviedes Betancourt [23b], Y.C. Cekmecelioglu [49], E. Celebi [83], S. Cella [37], M.S. Centonze [71a,71b], V. Cepaitis [57], K. Cerny [125], A.S. Cerqueira [84a],

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P. Urrejola [140a], G. Usai [8], R. Ushioda [141], M. Usman [110], F. Ustuner [53], Z. Uysal [83], V. Vacek [135], B. Vachon [106], T. Vafeiadis [37], A. Vaitkus [98], C. Valderanis [111], E. Valdes Santurio [48a,48b], M. Valente [159a], S. Valentinetti [24b,24a], A. Valero [166], E. Valiente Moreno [166], A. Vallier [91], J.A. Valls Ferrer [166], D.R. Van Arneman [117], T.R. Van Daalen [142], A. Van Der Graaf [50], P. Van Gemmeren [6], M. Van Rijnbach [37], S. Van Stroud [98], I. Van Vulpen [117], P. Vana [136], M. Vanadia [77a,77b], U.M. Vande Voorde [148], W. Vandelli [37], E.R. Vandewall [124], D. Vannicola [155], L. Vannoli [54], R. Vari [76a], E.W. Varnes [7], C. Varni [18b], T. Varol [152], D. Varouchas [67], L. Varriale [166], K.E. Varvell [151], M.E. Vasile [28b], L. Vaslin [85], G.A. Vasquez [168], A. Vasyukov [39], L.M. Vaughan [124], R. Vavricka [102], T. Vazquez Schroeder [37], J. Veatch [32], V. Vecchio [103], M.J. Veen [105], I. Veliscek [30], L.M. Veloce [158], F. Veloso [133a,133c], S. Veneziano [76a], A. Ventura [71a,71b], S. Ventura Gonzalez [138], A. Verbytskyi [112], M. Verducci [75a,75b], C. Vergis [96], M. Verissimo De Araujo [84b], W. Verkerke [117], J.C. Vermeulen [117], C. Vernieri [147], M. Vessella [105], M.C. Vetterli [146,af], A. Vgenopoulos [102], N. Viaux Maira [140f], T. Vickey [143], O.E. Vickey Boeriu [143], G.H.A. Viehhauser [129], L. Vigani [64b], M. Vigl [112], M. Villa [24b,24a], M. Villaplana Perez [166], E.M. Villhauer [53], E. Vilucchi [54], M.G. Vincter [35], A. Visibile [117], C. Vittori [37], I. Vivarelli [24b,24a], E. Voevodina [112], F. Vogel [111], J.C. Voigt [51], P. Vokac [135], Yu. Volkotrub [87b], E. Von Toerne [25], B. Vormwald [37], V. Vorobel [136], K. Vorobev [38], M. Vos [166], K. Voss [145], M. Vozak [117], L. Vozdecky [123], N. Vranjes [16], M. Vranjes Milosavljevic [16], M. Vreeswijk [117], N.K. Vu [63d,63c], R. Vuillermet [37], O. Vujinovic [102], I. Vukotic [40], I.K. Vyas [35], S. Wada [160], C. Wagner [147], J.M. Wagner [18a], W. Wagner [174], S. Wahdan [174], H. Wahlberg [92], C.H. Waits [123], J. Walder [137], R. Walker [111], W. Walkowiak [145], A. Wall [131], E.J. Wallin [100], T. Wamorkar [6], A.Z. Wang [139], C. Wang [102], C. Wang [11], H. Wang [18a], J. Wang [65c], P. Wang [98], R. Wang [62], R. Wang [6], S.M. Wang [152], S. Wang [63b], S. Wang [14], T. Wang [63a], W.T. Wang [81], W. Wang [14], X. Wang [114a], X. Wang [165], X. Wang [63c], Y. Wang [63d], Y. Wang [114a], Y. Wang [63a], Z. Wang [108], Z. Wang [63d,52,63c], Z. Wang [108], A. Warburton [106], R.J. Ward [21], N. Warrack [60], S. Waterhouse [97], A.T. Watson [21], H. Watson [53], M.F. Watson [21], E. Watton [60,137], G. Watts [142], B.M. Waugh [98], J.M. Webb [55], C. Weber [30], H.A. Weber [19], M.S. Weber [20], S.M. Weber [64a], C. Wei [63a], Y. Wei [55], A.R. Weidberg [129], E.J. Weik [120], J. Weingarten [50], C. Weiser [55], C.J. Wells [49], T. Wenaus [30], B. Wendland [50], T. Wengler [37], N.S. Wenke [112], N. Wermes [25], M. Wessels [64a], A.M. Wharton [93], A.S. White [62], A. White [8], M.J. White [1], D. Whiteson [162], L. Wickremasinghe [127], W. Wiedenmann [173], M. Wielers [137], C. Wiglesworth [43], D.J. Wilbern [123], 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], P.J. Windischhofer [40], F.I. Winkel [31], F. Winklmeier [126], B.T. Winter [55], J.K. Winter [103], M. Wittgen [147], M. Wobisch [99], T. Wojtkowski [61], Z. Wolffs [117], J. Wollrath [162], M.W. Wolter [88], H. Wolters [133a,133c], M.C. Wong [139], E.L. Woodward [42], S.D. Worm [49], B.K. Wosiek [88], K.W. Woźniak [88], S. Wozniewski [56], K. Wraight [60], C. Wu [21], M. Wu [114b], M. Wu [116], S.L. Wu [173], X. Wu [57], Y. Wu [63a], Z. Wu [4], J. Wuerzinger [112,ad], T.R. Wyatt [103], B.M. Wynne [53], S. Xella [43], L. Xia [114a], M. Xia [15], M. Xie [63a], S. Xin [14,114c], A. Xiong [126], J. Xiong [18a], D. Xu [14], H. Xu [63a], L. Xu [63a], R. Xu [131], T. Xu [108], Y. Xu [15], Z. Xu [53], Z. Xu [114a], B. Yabsley [151], S. Yacoob [34a], Y. Yamaguchi [85], E. Yamashita [157], H. Yamauchi [160], T. Yamazaki [18a], Y. Yamazaki [86], S. Yan [60], Z. Yan [105], H.J. Yang [63c,63d], H.T. Yang [63a], S. Yang [63a], T. Yang [65c], X. Yang [37], X. Yang [14], Y. Yang [45], Y. Yang [63a], Z. Yang [63a], W-M. Yao [18a], H. Ye [114a], H. Ye [56], J. Ye [14], S. Ye [30], X. Ye [63a], Y. Yeh [98], I. Yeletskikh [39], B. Yeo [18b], M.R. Yexley [98],

T.P. Yildirim [129], P. Yin [42], K. Yorita [171], S. Younas [28b], C.J.S. Young [37], C. Young [147], C. Yu [14,114c], Y. Yu [63a], J. Yuan [14,114c], M. Yuan [108], R. Yuan [63d,63c], L. Yue [98], M. Zaazoua [63a], B. Zabinski [88], E. Zaid [53], Z.K. Zak [88], T. Zakareishvili [166], S. Zambito [57], J.A. Zamora Saa [140d,140b], J. Zang [157], D. Zanzi [55], O. Zaplatilek [135], C. Zeitnitz [174], H. Zeng [14], J.C. Zeng [165], D.T. Zenger Jr [27], O. Zenin [38], T. Ženiš [29a], S. Zenz [96], S. Zerradi [36a], D. Zerwas [67], M. Zhai [14,114c], D.F. Zhang [143], J. Zhang [63b], J. Zhang [6], K. Zhang [14,114c], L. Zhang [63a], L. Zhang [114a], P. Zhang [14,114c], R. Zhang [173], S. Zhang [108], S. Zhang [91], T. Zhang [157], X. Zhang [63c], X. Zhang [63b], Y. Zhang [142], Y. Zhang [98], Y. Zhang [63a], Y. Zhang [114a], Z. Zhang [18a], Z. Zhang [63b], Z. Zhang [67], H. Zhao [142], T. Zhao [63b], Y. Zhao [139], Z. Zhao [63a], Z. Zhao [63a], A. Zhemchugov [39], J. Zheng [114a], K. Zheng [165], X. Zheng [63a], Z. Zheng [147], D. Zhong [165], B. Zhou [108], H. Zhou [7], N. Zhou [63c], Y. Zhou [15], Y. Zhou [114a], Y. Zhou [7], C.G. Zhu [63b], J. Zhu [108], X. Zhu [63d], Y. Zhu [63c], Y. Zhu [63a], X. Zhuang [14], K. Zhukov [69], N.I. Zimine [39], J. Zinsser [64b], M. Ziolkowski [145], L. Živković [16], A. Zoccoli [24b,24a], K. Zoch [62], T.G. Zorbas [143], O. Zormpa [47], W. Zou [42], 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)] *University of South Africa, Department of Physics, Pretoria;* [(f)] *University of Zululand, KwaDlangezwa;* [(g)] *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 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] *Physics Department, University of Texas at Dallas, Richardson TX; United States of America*
[47] *National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece*
[48] [(a)] *Department of Physics, Stockholm University;* [(b)] *Oskar Klein Centre, Stockholm; Sweden*

[49] Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany
[50] Fakultät Physik, Technische Universität Dortmund, Dortmund; Germany
[51] Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany
[52] Department of Physics, Duke University, Durham NC; United States of America
[53] SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom
[54] INFN e Laboratori Nazionali di Frascati, Frascati; Italy
[55] Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany
[56] II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany
[57] Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland
[58] [(a)] Dipartimento di Fisica, Università di Genova, Genova; [(b)] INFN Sezione di Genova; Italy
[59] II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany
[60] SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom
[61] LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France
[62] Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America
[63] [(a)] Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; [(b)] Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; [(c)] School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai; [(d)] Tsung-Dao Lee Institute, Shanghai; [(e)] School of Physics, Zhengzhou University; China
[64] [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany
[65] [(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
[66] Department of Physics, National Tsing Hua University, Hsinchu; Taiwan
[67] IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay; France
[68] Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona; Spain
[69] Department of Physics, Indiana University, Bloomington IN; United States of America
[70] [(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
[71] [(a)] INFN Sezione di Lecce; [(b)] Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy
[72] [(a)] INFN Sezione di Milano; [(b)] Dipartimento di Fisica, Università di Milano, Milano; Italy
[73] [(a)] INFN Sezione di Napoli; [(b)] Dipartimento di Fisica, Università di Napoli, Napoli; Italy
[74] [(a)] INFN Sezione di Pavia; [(b)] Dipartimento di Fisica, Università di Pavia, Pavia; Italy
[75] [(a)] INFN Sezione di Pisa; [(b)] Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy
[76] [(a)] INFN Sezione di Roma; [(b)] Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy
[77] [(a)] INFN Sezione di Roma Tor Vergata; [(b)] Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy
[78] [(a)] INFN Sezione di Roma Tre; [(b)] Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy
[79] [(a)] INFN-TIFPA; [(b)] Università degli Studi di Trento, Trento; Italy
[80] Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck; Austria
[81] University of Iowa, Iowa City IA; United States of America
[82] Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America
[83] Istinye University, Sariyer, Istanbul; Türkiye
[84] [(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
[85] KEK, High Energy Accelerator Research Organization, Tsukuba; Japan
[86] Graduate School of Science, Kobe University, Kobe; Japan
[87] [(a)] AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow; [(b)] 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] School 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 LA; United States of America
[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 MA; United States of America
[106] Department of Physics, McGill University, Montreal QC; Canada
[107] School of Physics, University of Melbourne, Victoria; Australia
[108] Department of Physics, University of Michigan, Ann Arbor MI; United States of America
[109] Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America
[110] Group of Particle Physics, University of Montreal, Montreal QC; 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
[114] [(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
[115] Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America
[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 IL; United States of America
[119] [(a)] New York University Abu Dhabi, Abu Dhabi; [(b)] United Arab Emirates University, Al Ain; United Arab Emirates
[120] Department of Physics, New York University, New York NY; United States of America
[121] Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan
[122] Ohio State University, Columbus OH; United States of America
[123] Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America
[124] Department of Physics, Oklahoma State University, Stillwater OK; United States of America

[125] Palacký University, Joint Laboratory of Optics, Olomouc; Czech Republic
[126] Institute for Fundamental Science, University of Oregon, Eugene, OR; United States of America
[127] Graduate School of Science, Osaka University, 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 PA; United States of America
[132] Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America
[133] [(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, 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
[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 CA; United States of America
[140] [(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)] Instituto de Alta Investigación, Universidad de Tarapacá, Arica; [(f)] 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 WA; United States of America
[143] Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom
[144] Department of Physics, Shinshu University, Nagano; Japan
[145] Department Physik, Universität Siegen, Siegen; Germany
[146] Department of Physics, Simon Fraser University, Burnaby BC; Canada
[147] SLAC National Accelerator Laboratory, Stanford CA; United States of America
[148] Department of Physics, Royal Institute of Technology, Stockholm; Sweden
[149] Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America
[150] Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom
[151] School of Physics, University of Sydney, Sydney; Australia
[152] Institute of Physics, Academia Sinica, Taipei; Taiwan
[153] [(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
[154] Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel
[155] Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel
[156] Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece
[157] International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan
[158] Department of Physics, University of Toronto, Toronto ON; Canada
[159] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON; Canada
[160] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan
[161] Department of Physics and Astronomy, Tufts University, Medford MA; United States of America
[162] Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America
[163] University of Sharjah, Sharjah; United Arab Emirates
[164] Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden
[165] Department of Physics, University of Illinois, Urbana IL; United States of America
[166] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia – CSIC, Valencia; Spain
[167] Department of Physics, University of British Columbia, Vancouver BC; Canada
[168] Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada
[169] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany
[170] Department of Physics, University of Warwick, Coventry; United Kingdom
[171] Waseda University, Tokyo; Japan
[172] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot; Israel
[173] Department of Physics, University of Wisconsin, Madison WI; United States of America
[174] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal; Germany
[175] Department of Physics, Yale University, New Haven CT; United States of America
[176] Yerevan Physics Institute, Yerevan; Armenia

[a] Also Affiliated with an institute 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 High Energy Physics, Peking University; China.
[e] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki; Greece.
[f] Also at CERN, Geneva; Switzerland.
[g] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC); Azerbaijan.
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona; Spain.
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
[k] Also at Department of Physics, California State University, Sacramento; United States of America.
[l] Also at Department of Physics, King's College London, London; United Kingdom.
[m] Also at Department of Physics, Stanford University, Stanford CA; United States of America.
[n] Also at Department of Physics, Stellenbosch University; South Africa.
[o] Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
[p] Also at Department of Physics, University of Thessaly; Greece.
[q] Also at Department of Physics, Westmont College, Santa Barbara; United States of America.
[r] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia; Bulgaria.
[s] Also at Hellenic Open University, Patras; Greece.
[t] Also at Imam Mohammad Ibn Saud Islamic University; Saudi Arabia.
[u] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.

[v] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
[w] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia; Bulgaria.
[x] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir; Morocco.
[y] Also at Institute of Particle Physics (IPP); Canada.
[z] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar; Mongolia.
[aa] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
[ab] Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
[ac] Also at National Institute of Physics, University of the Philippines Diliman (Philippines); Philippines.
[ad] Also at Technical University of Munich, Munich; Germany.
[ae] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
[af] Also at TRIUMF, Vancouver BC; Canada.
[ag] Also at Università di Napoli Parthenope, Napoli; Italy.
[ah] Also at University of Colorado Boulder, Department of Physics, Colorado; United States of America.
[ai] Also at Washington College, Chestertown, MD; United States of America.
[aj] Also at Yeditepe University, Physics Department, Istanbul; Türkiye.
[*] Deceased.