

Search for Higgs Boson and Observation of Z Boson through Their Decay into a Charm Quark-Antiquark Pair in Boosted Topologies in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

A. Tumasyan *et al.**
(CMS Collaboration)

 (Received 25 November 2022; revised 9 April 2023; accepted 11 April 2023; published 26 July 2023)

A search for the standard model (SM) Higgs boson (H) produced with transverse momentum (p_T) greater than 450 GeV and decaying to a charm quark-antiquark ($c\bar{c}$) pair is presented. The search is performed using proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment at the LHC, corresponding to an integrated luminosity of 138 fb^{-1} . Boosted $H \rightarrow c\bar{c}$ decay products are reconstructed as a single large-radius jet and identified using a deep neural network charm tagging technique. The method is validated by measuring the $Z \rightarrow c\bar{c}$ decay process, which is observed in association with jets at high p_T for the first time with a signal strength of $1.00^{+0.17}_{-0.14}(\text{syst}) \pm 0.08(\text{theo}) \pm 0.06(\text{stat})$, defined as the ratio of the observed process rate to the SM expectation. The observed (expected) upper limit on $\sigma(H)B(H \rightarrow c\bar{c})$ is set at 47 (39) times the SM prediction at 95% confidence level.

DOI: [10.1103/PhysRevLett.131.041801](https://doi.org/10.1103/PhysRevLett.131.041801)

The standard model (SM) Higgs boson (H) has been observed at the LHC [1–3] in all its expected primary production modes and most of its dominant decay channels. With the observations of direct couplings to τ leptons [4,5], top quarks [6,7], and bottom quarks [8,9] confirming that the SM Yukawa sector gives rise to the masses of third-generation fermions, attention naturally turns to probing the second generation, specifically muons and charm quarks.

The search for H decays to muon pairs is the most experimentally accessible channel, and has been explored by the ATLAS [10,11] and CMS [12] Collaborations. The latter recently found evidence of the H coupling to muons [13].

In contrast, the search for H decays to charm quark-antiquark pairs ($H \rightarrow c\bar{c}$) is considerably more challenging, because of the difficulty of identifying such decays and due to the enormous multijet background. However, recent advances in jet substructure and flavor tagging techniques [14] have greatly improved the experimental sensitivity to this decay mode. Prior searches by ATLAS [15,16] and CMS [17,18] have focused on H production in association with a vector boson (VH , where V stands for a W or Z boson), which benefits from strong background rejection thanks to leptonic decays of the vector bosons. The

gluon-gluon fusion (ggF) and vector boson fusion (VBF) production modes have larger cross sections, but have yet to be explored.

This letter reports on the first search for the $H \rightarrow c\bar{c}$ decay at the LHC, where the H is produced with transverse momentum (p_T) greater than 450 GeV, enriched in events from the ggF production. The search employs the same general strategy as earlier CMS searches for boosted H in the $b\bar{b}$ decay channel [19,20], but uses new mass decorrelated discriminators to define a charm-enriched signal region. This search strategy provides an additional constraint on the decay process to the existing ATLAS and CMS measurements, in terms of production mode and H p_T .

The search is performed using a dataset of proton-proton collisions at $\sqrt{s} = 13$ TeV, collected with the CMS detector at the LHC, and corresponding to an integrated luminosity of 138 fb^{-1} . Candidate events are selected by requiring a high- p_T , large-radius jet with substructure observables compatible with those expected from an $H \rightarrow c\bar{c}$ decay. Deep neural network (DNN) discriminators are employed to separate the H signal events from the dominant background, specifically quantum chromodynamics (QCD)-induced multijet events. The discriminators are designed to be independent of jet mass, which allows for both an estimation of the QCD background from control samples in data and for the validation of the analysis procedure through a search for $Z \rightarrow c\bar{c}$ decays. A model of the jet mass distributions for the $H \rightarrow c\bar{c}$ and $Z \rightarrow c\bar{c}$ signals, QCD multijet events, and other background processes is fit simultaneously in several disjoint signal and control regions to extract the signal production cross sections.

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

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International license](https://creativecommons.org/licenses/by/4.0/). Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by SCOAP³.

The CMS apparatus [21] is a multipurpose, nearly hermetic detector, designed to trigger on [22,23] and identify electrons, muons, photons, and (charged and neutral) hadrons [24–26]. A global “particle-flow” (PF) algorithm [27] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic and brass-scintillator hadron calorimeters, operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ leptons, jets, and missing transverse momentum (p_T^{miss}) [28–30].

Simulated samples of signal and background events are produced at the matrix element level using various Monte Carlo (MC) event generators. The QCD multijet, Z + jets, and W + jets processes are modeled at QCD leading order (LO) accuracy using the MADGRAPH5_aMC@NLO v2.4.2 generator [31]. The vector boson samples contain decays to all flavors of quarks, and include up to 3 (4) extra partons at the matrix element level for V + jets events. Jets from the matrix element calculations and the parton shower description are matched using the MLM prescription [32]. The $t\bar{t}$ and single top quark processes are modeled at next-to-LO (NLO) using POWHEG 2.0 [33–38]. The diboson processes are modeled at LO accuracy with PYTHIA8.226 [39]. For 2016 data-taking conditions, QCD samples are modeled with MADGRAPH5_aMC@NLO v2.2.2, and diboson samples are modeled with PYTHIA8.205.

The differential cross sections for the Z + jets and W + jets (V + jets) samples are corrected with boson p_T -dependent functions for higher-order QCD and electroweak (EW) effects. The QCD NLO corrections are derived using MADGRAPH5_aMC@NLO, simulating W and Z production with up to two additional partons and the FxFx matching to the parton shower [40]. The EW NLO corrections are taken from theoretical calculations of Refs. [41–44]. Additionally, the total cross sections for the diboson samples are corrected to next-to-NLO (NNLO) accuracy with the MCFM 7.0 program [45].

The ggF H production process is simulated using the HJ-MiNLO [35,46–48] event generator with mass $m_H = 125$ GeV and including finite top quark mass effects, following the recommendation in Ref. [48]. The POWHEG [49] generator is used to model the H production through the VBF, VH , and $t\bar{t}H$ processes [47,50,51].

For parton showering and hadronization, the POWHEG and MADGRAPH5_aMC@NLO samples are interfaced with PYTHIA8.205 (8.230) for 2016 (2017–2018) running conditions. The corresponding PYTHIA parameters for the underlying event description are set to the CUETP8M1 [52] (CP5 [53]) tune. For 2016 samples the parton distribution function (PDF) set NNPDF3.0 [54] is used, with either LO or NLO accuracy, corresponding to that used in the matrix element calculations, while for 2017–2018 samples

NNPDF3.1 [55] at NNLO accuracy is used for all processes. The detector response is modeled with GEANT4 [56].

Reconstructed particles are clustered into jets using the anti- k_T algorithm [57,58]. Small-radius jets are clustered with a distance parameter of 0.4 (AK4 jets). Large-radius jets arising from the decays of boosted heavy particles are reconstructed with a distance parameter of 0.8 (AK8 jets). The effect of particles from additional proton-proton interactions within the same or nearby bunch crossings (pileup) is mitigated through the charged hadron subtraction [27] and pileup-per-particle identification [59] algorithms for AK4 and AK8 jets, respectively. Additional corrections are applied to the jet energy as functions of jet pseudorapidity (η) and p_T to account for the detector response.

The H candidate is reconstructed as a single AK8 jet with $p_T > 450$ GeV. A mix of triggers using jet p_T or a scalar sum of the jet p_T in the event is employed for online selection. At $p_T = 450$ GeV, the online selection is 90% efficient with respect to the offline selection, reaching full efficiency by 500 GeV. The soft-drop (SD) algorithm [60] with parameters $\beta = 0$ and $z = 0.1$ is applied to the jet mass (m_{SD}) to remove soft and wide-angle radiation, which reduces the mass of jets originating from QCD background events while preserving the mass of jets originating from heavy boson decays. The range of interest is set to $40 < m_{\text{SD}} < 201$ GeV. To match the tracker acceptance region, jets are required to have $|\eta| < 2.5$. In case of several jets in the event passing the criteria, the jet with the highest charm versus light tagging score, defined below, is taken to be the H candidate.

After the above selections, the dominant background is the QCD multijet production, which accounts for more than 95% of the expected yield and is estimated from data. The V + jets processes are significant resonant backgrounds at approximately 4%, and are estimated from simulation. The $t\bar{t}$ process constitutes a subdominant nonresonant background across the m_{SD} spectrum, the shape of which is taken from simulation, while the total yield is estimated from data. Other EW processes, including diboson, triboson, and $t\bar{t}V$ processes, are estimated from simulation and found to be negligible.

Events containing leptons are vetoed to reduce SM EW backgrounds. The selection criteria for electrons, muons, and hadronic τ leptons are $p_T > 10$, 10, and 20 GeV and $|\eta| < 2.5$, 2.4, and 2.3, along with “veto,” “loose,” and “very loose” identification requirements [24,28,61], respectively. In addition, muons are required to have a relative isolation (scalar p_T sum of the PF candidates within a cone with a distance parameter of 0.4, divided by the lepton p_T) of less than 0.25. Events with $p_T^{\text{miss}} > 140$ GeV, as well as events with AK4 b -tagged jets with $p_T > 30$ GeV opposite in azimuth to the H candidate jet [$\Delta\phi(\text{AK4}, \text{AK8}) > \pi/2$], are removed to reduce the top quark background. The AK4

b jet identification is performed using the DEEPCSV DNN algorithm [62] with a working point corresponding to a 1% misidentification probability for light (u , d , s quark, or gluon) jets.

The dimensionless mass scale variable $\rho = 2 \ln(m_{\text{SD}}/p_T)$ [63,64] is used to parametrize the QCD background model (described below) as its distribution is approximately invariant versus jet p_T , unlike jet m_{SD} . A selection of $-6.0 < \rho < -2.1$ is imposed to avoid instabilities and edge effects from the SD algorithm and jet clustering [65]. The lower ρ threshold implies an upper jet p_T threshold, which is made explicit by requiring $p_T < 1200$ GeV. In simulation, less than 1% of signal events are found above this upper bound.

The N_2^1 variable [66], a ratio of energy correlation functions [67], is a powerful way to identify two-pronged signatures. However, using it for selection distorts the background jet mass distribution as a function of p_T . To mitigate this effect, the designing decorrelated taggers (DDT) technique [64], effectively a sliding selection, is applied. The selection is on $N_2^{1,\text{DDT}} \equiv N_2^1 - q_{0.26}(p_T, \rho) < 0$, where $q_{0.26}(p_T, \rho)$ is the N_2^1 value corresponding to the 26% efficiency for the QCD background, as a function of jet p_T and ρ . The target percentile is chosen to optimize the $H \rightarrow c\bar{c}$ expected significance.

Finally, jet flavor is determined by the DEEPDOUBLEX DNN algorithm [68]. The model comprises convolutional and recurrent units processing low-level features of secondary vertices and PF candidates, the outputs of which are joined with expert variables [62] in a fully connected layer. The application of feature importance ranking techniques, such as integrated gradients [69] and deep Taylor decomposition [70], indicates the key features to be the angular distances of the PF candidates from both the jet and 2-subjetness [71] axes. The kinematic properties of the PF candidates defined relative to the parent jet have subleading importance. The model is trained to distinguish between two-pronged H -like signatures of bottom and charm flavors, as well as the QCD background, yielding two per-jet classifiers: charm versus light, referred to as DEEPDOUBLECVL (DDCvL), and charm versus bottom, referred to as DEEPDOUBLECVB (DDCvB). The performance of the two classifiers is shown, prior to any analysis-specific selection, in Fig. 1. The optimal working point, maximizing the $H \rightarrow c\bar{c}$ expected significance after all previous selections are applied, is found with respect to both classifiers at a QCD efficiency of 0.5% and a $H \rightarrow c\bar{c}$ efficiency of 20.6%. The corresponding efficiency for $H \rightarrow b\bar{b}$ events is 4.8%. As the classifiers are mass independent, the quoted efficiencies also apply to $Z \rightarrow c\bar{c}$ and $Z \rightarrow b\bar{b}$.

The relative contributions of H production modes to the overall signal yield are 55%, 25%, and 20% for

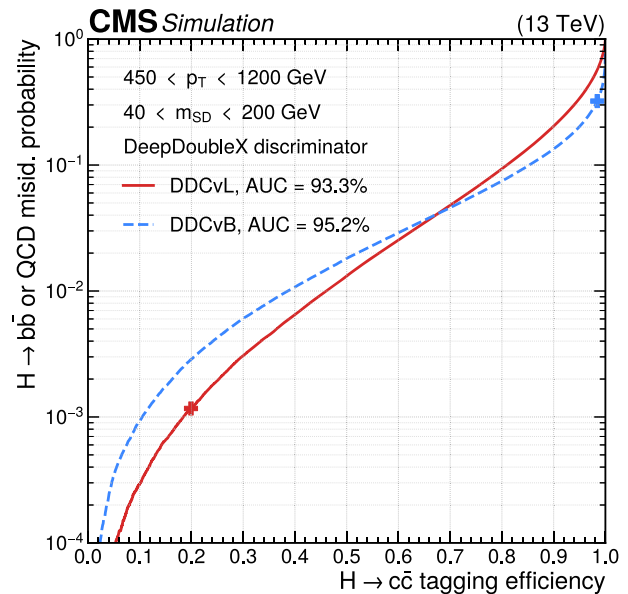


FIG. 1. The DDCvL and DDCvB performance for $H \rightarrow c\bar{c}$ identification versus QCD and $H \rightarrow b\bar{b}$ processes, respectively. No selection apart from the displayed m_{SD} and p_T requirements is applied. The working points used in this search are marked with a cross. The AUC is the area-under-curve metric.

ggF , VBF, and VH , respectively, and are similar for both $c\bar{c}$ and $b\bar{b}$ decay modes. The $t\bar{t}H$ contribution is suppressed due to the top veto and found to be negligible. Events passing all of the selection requirements described above constitute the signal or “passing” region (SR), whereas events failing the DDCvL requirement while passing the rest, including the DDCvB requirement, constitute the control or “failing” region (CR). Both the SR and CR are subdivided into 23 evenly spaced bins of jet m_{SD} in the range 40–201 GeV and 6 p_T bins from 450 (or 475) to 1200 GeV. Additionally, all regions are subdivided according to the three data-taking years (2016–2018).

The QCD background is not accurately predicted in simulation. Since the flavor discrimination is nearly independent of the jet p_T and mass, the ratio of the passing and failing region distributions, $R_{\text{p/f}}$, is expected to be approximately flat with respect to the jet p_T and m_{SD} . This can be exploited to obtain an SR prediction of the QCD background from the CR via an appropriate efficiency scaling. A residual difference in shapes can be accounted for by parametrizing the $R_{\text{p/f}}$ shape in the two dimensions. In order to take into account a potential mass dependence of the flavor selection efficiency, a correction factor, $R_{\text{p/f}}^{\text{QCD}}(p_T, \rho)$, is fit to the simulated QCD background shapes. Then, a second correction factor of the same functional form, $R^{\text{data}}(p_T, \rho)$, accounts for mismodelings

in simulation. Both are parametrized in terms of Bernstein polynomials [72] in p_T and ρ :

$$R(p_T, \rho) = \sum_{k=0}^{n_p} \sum_{\ell=0}^{n_{p_T}} a_{k,\ell} b_{\ell,n_{p_T}}(p_T) b_{k,n_p}(\rho), \quad (1)$$

where n_{p_T} is the degree of the polynomial in p_T , n_p is the degree of the polynomial in ρ , $a_{k,\ell}$ is a Bernstein coefficient, and $b_{\nu,n}$ is a Bernstein basis polynomial of degree n . The coefficients $a_{k,\ell}$ of $R_{p/f}^{\text{QCD}}(p_T, \rho)$ are determined in a fit to simulated QCD background events; $a_{k,\ell}$ of $R_{p/f}^{\text{data}}(p_T, \rho)$ are unconstrained and are determined during the maximum likelihood fit to data. The total effective $R_{p/f}$ is then expressed as

$$R_{p/f}(p_T, \rho) = R_{p/f}^{\text{QCD}}(p_T, \rho) R_{p/f}^{\text{data}}(p_T, \rho). \quad (2)$$

The $R_{p/f}$ are expected to vary between data-taking years because of changes in detector conditions, and are thus fit independently for each year. The minimal degree of the polynomials necessary to fit the QCD simulation and the data is determined by a Fisher F-test [73] and found to be $(n_{p_T}, n_p) = (0, 2), (1, 2),$ and $(0, 2)$ for $R_{p/f}^{\text{QCD}}(p_T, \rho)$ and $(1, 0), (0, 0),$ and $(1, 0)$ for $R_{p/f}^{\text{data}}(p_T, \rho)$ for the years 2016, 2017, and 2018, respectively. Bias tests were performed with respect to the choice of parametrization, and no significant bias was found.

The $V + \text{jets}$ processes are modeled using simulation. The differential $t\bar{t}$ contribution is taken from simulation; however, the normalizations in the SR and CR are corrected via two scale factors measured in a dedicated $t\bar{t}$ -enriched control region, parametrizing the overall normalization and the efficiency of the DDCvL selection between the SR and CR. This control region is adapted from the SR selection by lowering the H candidate p_T threshold, requiring exactly one muon, and inverting the selection requirements on p_T^{miss} and b -tagged AK4 jets. The scale factor measurement is performed *in situ* during the signal extraction, separately for each data-taking period, and the values are given in Table I. The $H \rightarrow b\bar{b}$ contribution is taken from the simulation and is fixed to the SM expectation. While its expected SR yield is greater by approximately a factor of 5 than that of the $H \rightarrow c\bar{c}$ signal, its impact is negligible with respect to the overall background uncertainty.

The dominant systematic uncertainties for this search are related to the flavor tagging efficiency and jet mass shape. Corrections of the jet mass, jet mass resolution, and $N_2^{1,\text{DDT}}$ and DDCvB efficiencies are derived from data using W boson jets from semileptonic $t\bar{t}$ events. These corrections are measured independently of jet flavor, and as such are correlated among all considered resonant (H, Z, W) production and decay processes. The DDCvL misidentification efficiency of the W process is measured here as well. The corrections and their associated uncertainties are given in Table I.

The efficiency of the DDCvL selection for the signal processes is estimated using data and simulation samples enriched in $c\bar{c}$ pairs from gluon splitting [62]. Signal-like events are selected by requiring each of the two SD subjects of an AK8 jet to contain a muon, targeting semileptonic decays of b/c hadrons. The efficiency is extracted from a template fit to the combined mass of all matched secondary vertices; the measured correction factors are given in Table I. The relative uncertainty of the misidentification efficiency of $b\bar{b}$ decays is assigned to be 30%. Varying this value from 10% to 50% has a negligible effect on reported results.

Other systematic uncertainties are assigned to cover potential mismodeling of the H signal, in particular for the ggF and VBF production modes [48], and higher-order corrections to the W and Z processes [44]. Finally, systematic uncertainties for experimental effects, including jet energy scale and resolution [74], trigger and veto efficiencies [75,76], variations in the measured pileup [77], finite simulated sample size [78], and an integrated luminosity measurement [79–81], are also included, but are found to have a comparatively small effect.

The parameter of interest in this analysis is the signal strength μ_H or μ_Z , defined as the ratio of the observed to the SM expected H or Z boson production cross section times the $H \rightarrow c\bar{c}$ or $Z \rightarrow c\bar{c}$ branching fraction, respectively. These parameters are extracted from a binned (m_{SD}, p_T) maximum likelihood fit to the observed data, where the expected value is the sum of the signal contribution (scaled by the signal strength parameter) and the background contributions, each modified by nuisance parameters to account for the previously discussed systematic effects. The magnitude of each systematic uncertainty is encoded in the likelihood model as an additional constraint, treated

TABLE I. Summary of the applied data-to-simulation scale factors for the jet mass, jet mass resolution, $N_2^{1,\text{DDT}}$ selection, $t\bar{t}$ normalization, and DEEPDOUBLEX selections for different data-taking periods. The jet mass correction is additive, in units of GeV.

| Data period | Jet mass correction (GeV) | Jet mass resolution | $N_2^{1,\text{DDT}}$, CvB selection | $t\bar{t}$ normalization | CvL selection $t\bar{t}$ | CvL selection ($W + \text{jets}$) | CvL selection (signal) |
|-------------|---------------------------|---------------------|--------------------------------------|--------------------------|--------------------------|-------------------------------------|------------------------|
| 2016 | -1.17 ± 0.22 | 1.021 ± 0.017 | 0.89 ± 0.02 | 0.84 ± 0.05 | 0.93 ± 0.15 | 0.62 ± 0.09 | 1.15 ± 0.25 |
| 2017 | -1.19 ± 0.23 | 1.019 ± 0.016 | 0.90 ± 0.02 | 0.86 ± 0.09 | 0.93 ± 0.15 | 0.64 ± 0.09 | 0.85 ± 0.16 |
| 2018 | -0.12 ± 0.21 | 1.090 ± 0.031 | 0.92 ± 0.02 | 0.86 ± 0.08 | 1.00 ± 0.14 | 0.72 ± 0.08 | 0.74 ± 0.20 |

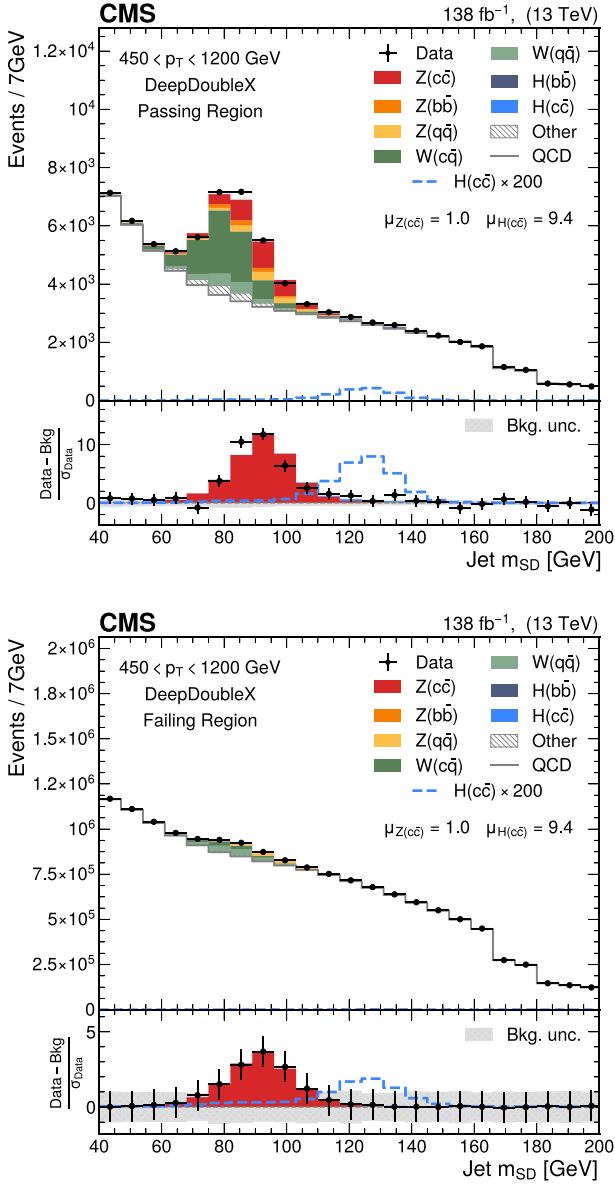


FIG. 2. The observed and fitted m_{SD} distributions for the passing (left) and failing (right) regions, combining all p_T categories and the three data-taking years. The fit is performed under the signal-plus-background hypothesis with a single inclusive $H \rightarrow c\bar{c}$ signal strength parameter. The $t\bar{t}$ background yields and the QCD background yields and shapes are estimated from data. The $t\bar{t}$ process constitutes the majority of contributions labeled “other.” The dashed line represents the $H \rightarrow c\bar{c}$ expectation, multiplied by a factor of 200. The steplike features at 166 and 180 GeV are due to the ρ acceptance upper bound, which excludes bins with high m_{SD} and low p_T from the analysis. The lower panel shows the residual difference between the data and the overall background (excluding $Z \rightarrow c\bar{c}$), divided by the statistical uncertainty in the data. The near perfect model agreement with data in the failing region (right) is by construction.

according to the frequentist paradigm [82]. The fit is performed simultaneously across all subdivisions of the SR and CR described previously, as well as the per-year $t\bar{t}$ background enriched CRs.

To validate the analysis strategy, and to confirm the presence of $Z \rightarrow c\bar{c}$ decays, the Z signal strength μ_Z is measured via a profile likelihood fit, treating μ_H as a nuisance parameter, and is found to be $1.00^{+0.17}_{-0.14}(\text{syst}) \pm 0.08(\text{theo}) \pm 0.06(\text{stat})$. This corresponds to an excess, both observed and expected, over the $\mu_Z = 0$ hypothesis with a significance of well over 5 standard deviations. The precision of the μ_Z measurement is primarily limited by the systematic uncertainty in the DDCvL signal tagging efficiency. The subleading uncertainty comes from the modeling of the $Z + \text{jets}$ production cross section.

For the extraction of μ_H , since the Z cross section has been measured in leptonic decay channels and found to agree with theoretical predictions within 5% in this p_T regime [83] and since the $Z \rightarrow c\bar{c}$ branching ratio is known to 2% precision [84], we fix $\mu_Z \equiv 1$, constraining the expected Z contribution to be within the applicable uncertainties of its SM value. This serves to further constrain *in situ* the DDCvL signal tagging efficiency uncertainty. The measured efficiencies are compatible with the values quoted in Table I and have approximately 30% lower uncertainty.

An observed (expected) upper limit is placed on the signal strength μ_H using the profile likelihood ratio test statistic [82], CL_s criterion [85,86], and asymptotic formulas [87], and found to be 47 (39) at 95% confidence level. For the best fit value of $\mu_H = 9.4^{+20.3}_{-19.9}$, the total m_{SD} distributions in the passing and failing regions are shown in Fig. 2, and a

TABLE II. Sources of uncertainty in the measurement of the signal strength $\mu_H = 9.4^{+20.3}_{-19.9}$, and their observed impact ($\Delta\mu_H$) in the fit to the full dataset. The impact of each uncertainty is evaluated by computing the uncertainty excluding that source and subtracting it in quadrature from the total uncertainty. The total uncertainty does not match the sum in quadrature of each source because of correlations among the components.

| Uncertainty source | $\Delta\mu_H$ | |
|--|---------------|-------|
| <i>Statistical</i> | +16.7 | -16.6 |
| Signal extraction | +14.2 | -14.1 |
| QCD pass-fail ratio (data correction) | +7.4 | -7.4 |
| $t\bar{t}$ normalization and misidentification | +0.9 | -0.7 |
| <i>Systematic</i> | +10.5 | -10.4 |
| QCD pass-fail ratio (simulation) | +9.7 | -9.8 |
| Flavor (mis-)tagging efficiency | +1.7 | -2.2 |
| Simulated sample size | +4.2 | -3.6 |
| Other experimental uncertainties | +2.1 | -1.4 |
| <i>Theoretical</i> | +3.9 | -1.6 |
| $V + \text{jets}$ modeling | +2.3 | -1.2 |
| H modeling | +3.2 | -1.0 |
| <i>Total</i> | +20.3 | -19.9 |

breakdown of the sources of uncertainty affecting the measurement is shown in Table II. Tabulated results are provided in the HEPData record for this analysis [88].

In conclusion, a search for standard model (SM) Z and Higgs bosons produced with transverse momenta greater than 450 GeV and decaying to charm quark-antiquark ($c\bar{c}$) pairs has been performed in a data sample corresponding to an integrated luminosity of 138 fb⁻¹ at $\sqrt{s} = 13$ TeV. New algorithms based on deep neural networks have been developed to identify jets originating from charm quark pairs. The $Z \rightarrow c\bar{c}$ process is observed in association with jets at a hadron collider for the first time, with a signal strength of $1.00^{+0.19}_{-0.17}$ relative to the SM prediction. This observation establishes $Z \rightarrow c\bar{c}$ as an important reference for future $X \rightarrow c\bar{c}$ searches. An observed (expected) upper limit on the product of the Higgs boson production cross section and branching fraction to $c\bar{c}$ of 47 (39) times the SM expectation is set at 95% confidence level.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); MoER, ERC PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES and NSC (Poland); FCT (Portugal); MESTD (Serbia); MCIN/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI and NSTDA (Thailand); TUBITAK and TENMAK (Turkey); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

[1] ATLAS Collaboration, Observation of a new particle in the search for the standard model Higgs boson with the ATLAS detector at the LHC, *Phys. Lett. B* **716**, 1 (2012).

- [2] CMS Collaboration, Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC, *Phys. Lett. B* **716**, 30 (2012).
- [3] CMS Collaboration, Observation of a new boson with mass near 125 GeV in pp collisions at $\sqrt{s} = 7$ and 8 TeV, *J. High Energy Phys.* **06** (2013) 081.
- [4] CMS Collaboration, Observation of the Higgs boson decay to a pair of τ leptons with the CMS detector, *Phys. Lett. B* **779**, 283 (2018).
- [5] ATLAS Collaboration, Measurements of Higgs boson production cross-sections in the $H \rightarrow \tau^+\tau^-$ decay channel in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector, *J. High Energy Phys.* **08** (2022) 175.
- [6] CMS Collaboration, Observation of $t\bar{t}H$ Production, *Phys. Rev. Lett.* **120**, 231801 (2018).
- [7] ATLAS Collaboration, Observation of Higgs boson production in association with a top quark pair at the LHC with the ATLAS detector, *Phys. Lett. B* **784**, 173 (2018).
- [8] ATLAS Collaboration, Observation of $H \rightarrow b\bar{b}$ decays and VH production with the ATLAS detector, *Phys. Lett. B* **786**, 59 (2018).
- [9] CMS Collaboration, Observation of Higgs Boson Decay to Bottom Quarks, *Phys. Rev. Lett.* **121**, 121801 (2018).
- [10] CMS Collaboration, Search for the Higgs Boson Decaying to Two Muons in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV, *Phys. Rev. Lett.* **122**, 021801 (2019).
- [11] ATLAS Collaboration, A search for the dimuon decay of the standard model Higgs boson with the ATLAS detector, *Phys. Lett. B* **812**, 135980 (2021).
- [12] ATLAS Collaboration, Search for the Dimuon Decay of the Higgs Boson in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector, *Phys. Rev. Lett.* **119**, 051802 (2017).
- [13] CMS Collaboration, Evidence for Higgs boson decay to a pair of muons, *J. High Energy Phys.* **01** (2021) 148.
- [14] CMS Collaboration, Performance of deep tagging algorithms for boosted double quark jet topology in proton-proton collisions at 13 TeV with the Phase-0 CMS detector, CMS Detector Performance Note, Report No. CMS-DP-2018-046, 2018, <https://cds.cern.ch/record/2630438>.
- [15] ATLAS Collaboration, Search for the Decay of the Higgs Boson to Charm Quarks with the ATLAS Experiment, *Phys. Rev. Lett.* **120**, 211802 (2018).
- [16] ATLAS Collaboration, Direct constraint on the Higgs-charm coupling from a search for Higgs boson decays into charm quarks with the ATLAS detector, *Eur. Phys. J. C* **82**, 717 (2022).
- [17] CMS Collaboration, A search for the standard model Higgs boson decaying to charm quarks, *J. High Energy Phys.* **03** (2020) 131.
- [18] CMS Collaboration, Search for Higgs boson decay to a charm quark-antiquark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV, [arXiv:2205.05550](https://arxiv.org/abs/2205.05550) [Phys. Rev. Lett. (to be published)].
- [19] CMS Collaboration, Inclusive Search for a Highly Boosted Higgs Boson Decaying to a Bottom Quark-Antiquark Pair, *Phys. Rev. Lett.* **120**, 071802 (2018).
- [20] CMS Collaboration, Inclusive search for highly boosted Higgs bosons decaying to bottom quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **12** (2020) 085.

- [21] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* **3**, S08004 (2008).
- [22] CMS Collaboration, The CMS trigger system, *J. Instrum.* **12**, P01020 (2017).
- [23] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* **15**, P10017 (2020).
- [24] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, *J. Instrum.* **16**, P05014 (2021).
- [25] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* **13**, P06015 (2018).
- [26] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* **9**, P10009 (2014).
- [27] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, *J. Instrum.* **12**, P10003 (2017).
- [28] CMS Collaboration, Performance of reconstruction and identification of τ leptons decaying to hadrons and ν_τ in pp collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* **13**, P10005 (2018).
- [29] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, *J. Instrum.* **12**, P02014 (2017).
- [30] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, *J. Instrum.* **14**, P07004 (2019).
- [31] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H. S. Shao, T. Stelzer, P. Torrielli, and M. Zaro, The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations, *J. High Energy Phys.* **07** (2014) 079.
- [32] J. Alwall, S. S. Hoeche, F. Krauss, N. Lavesson, L. Lonnblad, F. Maltoni, M. L. Mangano, M. Moretti, C. G. Papadopoulos, F. Piccinini, S. Schumann, M. Treccani, J. Winter, and M. Worek, Comparative study of various algorithms for the merging of parton showers and matrix elements in hadronic collisions, *Eur. Phys. J. C* **53**, 473 (2008).
- [33] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, *J. High Energy Phys.* **11** (2004) 040.
- [34] S. Frixione, P. Nason, and G. Ridolfi, A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction, *J. High Energy Phys.* **09** (2007) 126.
- [35] S. Frixione, P. Nason, and C. Oleari, Matching NLO QCD computations with parton shower simulations: The POWHEG method, *J. High Energy Phys.* **11** (2007) 070.
- [36] S. Alioli, P. Nason, C. Oleari, and E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: The POWHEG BOX, *J. High Energy Phys.* **06** (2010) 043.
- [37] E. Re, Single-top Wt -channel production matched with parton showers using the POWHEG method, *Eur. Phys. J. C* **71**, 1547 (2011).
- [38] R. Frederix, E. Re, and P. Torrielli, Single-top t -channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO, *J. High Energy Phys.* **09** (2012) 130.
- [39] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [40] R. Frederix and S. Frixione, Merging meets matching in MC@NLO, *J. High Energy Phys.* **12** (2012) 061.
- [41] S. Kallweit, J. M. Lindert, P. Maierhöfer, S. Pozzorini, and M. Schönherr, NLO electroweak automation and precise predictions for $W +$ multijet production at the LHC, *J. High Energy Phys.* **04** (2015) 012.
- [42] S. Kallweit, J. M. Lindert, S. Pozzorini, M. Schönherr, and P. Maierhöfer, NLO QCD + EW automation and precise predictions for $V +$ multijet production, in *50th Rencontres de Moriond, QCD and high energy interactions* (2015), p. 121, [arXiv:1505.05704](https://arxiv.org/abs/1505.05704).
- [43] S. Kallweit, J. M. Lindert, P. Maierhöfer, S. Pozzorini, and M. Schönherr, NLO QCD + EW predictions for $V +$ jets including off-shell vector-boson decays and multijet merging, *J. High Energy Phys.* **04** (2016) 021.
- [44] J. M. Lindert *et al.*, Precise predictions for $V +$ jets dark matter backgrounds, *Eur. Phys. J. C* **77**, 829 (2017).
- [45] J. M. Campbell and R. K. Ellis, MCFM for the Tevatron and the LHC, *Nucl. Phys. B, Proc. Suppl.* **205–206**, 10 (2010).
- [46] K. Hamilton, P. Nason, C. Oleari, and G. Zanderighi, Merging $H/W/Z + 0$ and 1 jet at NLO with no merging scale: A path to parton shower + NNLO matching, *J. High Energy Phys.* **05** (2013) 082.
- [47] G. Luisoni, P. Nason, C. Oleari, and F. Tramontano, $HW \pm /HZ + 0$ and 1 jet at NLO with the POWHEG box interfaced to GoSam and their merging within MiNLO, *J. High Energy Phys.* **10** (2013) 083.
- [48] K. Becker *et al.*, Precise predictions for boosted Higgs production, [arXiv:2005.07762](https://arxiv.org/abs/2005.07762).
- [49] E. Bagnaschi, G. Degrassi, P. Slavich, and A. Vicini, Higgs production via gluon fusion in the POWHEG approach in the SM and in the MSSM, *J. High Energy Phys.* **02** (2012) 088.
- [50] P. Nason and C. Oleari, NLO Higgs boson production via vector-boson fusion matched with shower in POWHEG, *J. High Energy Phys.* **02** (2010) 037.
- [51] H. B. Hartanto, B. Jäger, L. Reina, and D. Wackerroth, Higgs boson production in association with top quarks in the POWHEG BOX, *Phys. Rev. D* **91**, 094003 (2015).
- [52] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* **76**, 155 (2016).
- [53] CMS Collaboration, Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements, *Eur. Phys. J. C* **80**, 4 (2020).
- [54] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions for the LHC run II, *J. High Energy Phys.* **04** (2015) 040.
- [55] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, *Eur. Phys. J. C* **77**, 663 (2017).
- [56] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—a simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [57] M. Cacciari, G. P. Salam, and G. Soyez, The anti- k_T jet clustering algorithm, *J. High Energy Phys.* **04** (2008) 063.

- [58] M. Cacciari, G. P. Salam, and G. Soyez, FastJet user manual, *Eur. Phys. J. C* **72**, 1896 (2012).
- [59] D. Bertolini, P. Harris, M. Low, and N. Tran, Pileup per particle identification, *J. High Energy Phys.* **10** (2014) 059.
- [60] A. J. Larkoski, S. Marzani, G. Soyez, and J. Thaler, Soft drop, *J. High Energy Phys.* **05** (2014) 146.
- [61] CMS Collaboration, Performance of the reconstruction and identification of high-momentum muons in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. Instrum.* **15**, P02027 (2020).
- [62] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, *J. Instrum.* **13**, P05011 (2018).
- [63] M. Dasgupta, A. Fregoso, S. Marzani, and G. P. Salam, Towards an understanding of jet substructure, *J. High Energy Phys.* **09** (2013) 029.
- [64] J. Dolen, P. Harris, S. Marzani, S. Rappoccio, and N. Tran, Thinking outside the ROCs: Designing decorrelated taggers (DDT) for jet substructure, *J. High Energy Phys.* **05** (2016) 156.
- [65] ATLAS Collaboration, Measurement of soft-drop jet observables in pp collisions with the ATLAS detector at $\sqrt{s} = 13$ TeV, *Phys. Rev. D* **101**, 052007 (2020).
- [66] I. Moutl, L. Necib, and J. Thaler, New angles on energy correlation functions, *J. High Energy Phys.* **12** (2016) 153.
- [67] A. J. Larkoski, G. P. Salam, and J. Thaler, Energy correlation functions for jet substructure, *J. High Energy Phys.* **06** (2013) 108.
- [68] CMS Collaboration, Performance of the mass-decorrelated DEEPDOUBLEX classifier for double- b and double- c large-radius jets with the CMS detector, CMS Detector Performance Note Report No. CMS-DP-2022-041, 2022, <https://cds.cern.ch/record/2839736>.
- [69] M. Sundararajan, A. Taly, and Q. Yan, Axiomatic attribution for deep networks, in *Proceedings of the 34th International Conference on Machine Learning* (PMLR, 2017), p. 3319.
- [70] G. Montavon, S. Lapuschkin, A. Binder, W. Samek, and K. R. Müller, Explaining nonlinear classification decisions with deep Taylor decomposition, *Pattern Recognit.* **65**, 211 (2017).
- [71] J. Thaler and K. Van Tilburg, Identifying boosted objects with N-subjettiness, *J. High Energy Phys.* **03** (2011) 015.
- [72] S. Bernstein, Démonstration du théorème de Weierstrass fondée sur le calcul des probabilités, *Comm. Kharkov Math. Soc.* **13**, 01 (1912).
- [73] R. A. Fisher, On the interpretation of χ^2 from contingency tables, and the calculation of P, *J. R. Stat. Soc.* **85**, 87 (1922).
- [74] CMS Collaboration, Jet energy scale and resolution performance with 13 TeV data collected by CMS in 2016–2018, CMS Detector Performance Note Report No. CMS-DP-2020-019, 2020, <https://cds.cern.ch/record/2715872>.
- [75] CMS Collaboration, Performance of heavy flavour identification algorithms in proton-proton collisions at 13 TeV at the CMS experiment, CMS Detector Performance Note, Report No. CMS-DP-2017-012, 2017, <http://cds.cern.ch/record/2263801>.
- [76] CMS Collaboration, Performance of b -tagging algorithms in proton-proton collisions at 13 TeV with Phase 1 CMS detector, CMS Detector Performance Note, Report No. CMS-DP-2018-033, 2018, <https://cds.cern.ch/record/2627468>.
- [77] CMS Collaboration, Performance of the pile up jet identification in CMS for Run 2, CMS Detector Performance Note, Report No. CMS-DP-2020-020, 2020, <https://cds.cern.ch/record/2715906>.
- [78] R. J. Barlow and C. Beeston, Fitting using finite Monte Carlo samples, *Comput. Phys. Commun.* **77**, 219 (1993).
- [79] CMS Collaboration, Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS, *Eur. Phys. J. C* **81**, 800 (2021).
- [80] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-17-004, 2018, <http://cds.cern.ch/record/2621960>.
- [81] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-18-002, 2019, <http://cds.cern.ch/record/2676164>.
- [82] The ATLAS Collaboration, The CMS Collaboration, The LHC Higgs Combination Group, Procedure for the LHC Higgs boson search combination in Summer 2011, Technical Reports No. CMS-NOTE-2011-005, No. ATL-PHYS-PUB-2011-11, 2011, <https://cds.cern.ch/record/1379837>.
- [83] CMS Collaboration, Measurement of the Z boson differential production cross section using its invisible decay mode ($Z \rightarrow \nu\bar{\nu}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV, *J. High Energy Phys.* **05** (2021) 205.
- [84] Particle Data Group, Review of particle physics, *Prog. Theor. Exp. Phys.* **2022**, 083C01 (2022).
- [85] T. Junk, Confidence level computation for combining searches with small statistics, *Nucl. Instrum. Methods Phys. Res., Sect. A* **434**, 435 (1999).
- [86] A. L. Read, Presentation of search results: the CL_s technique, *J. Phys. G* **28**, 2693 (2002).
- [87] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, Asymptotic formulae for likelihood-based tests of new physics, *Eur. Phys. J. C* **71**, 1554 (2011); **73**, 2501(E) (2013).
- [88] HEPData record for this analysis (2022), [10.17182/hepdata.139717](https://cds.cern.ch/record/139717).

A. Tumasyan^{1,b}, W. Adam², J. W. Andrejkovic², T. Bergauer², S. Chatterjee², K. Damanakis², M. Dragicevic², A. Escalante Del Valle², P. S. Hussain², M. Jeitler^{2,c}, N. Krammer², L. Lechner², D. Liko², I. Mikulec², P. Paulitsch², J. Schieck^{2,c}, R. Schöfbeck², D. Schwarz², M. Sonawane², S. Templ², W. Waltenberger², C.-E. Wulz^{2,c}, M. R. Darwish^{3,d}, T. Janssen³, T. Kello^{3,c}, H. Rejeb Sfar³, P. Van Mechelen³, E. S. Bols⁴, J. D'Hondt⁴, A. De Moor⁴, M. Delcourt⁴, H. El Faham⁴, S. Lowette⁴, A. Morton⁴, D. Müller⁴

A. R. Sahasransu⁴, S. Tavernier⁴, W. Van Doninck⁴, S. Van Putte⁴, D. Vannerom⁴, B. Clerbaux⁵, G. De Lentdecker⁵, L. Favart⁵, D. Hohov⁵, J. Jaramillo⁵, K. Lee⁵, M. Mahdavihorrani⁵, I. Makarenko⁵, A. Malara⁵, S. Paredes⁵, L. Pétré⁵, N. Postiau⁵, L. Thomas⁵, M. Vanden Bemden⁵, C. Vander Velde⁵, P. Vanlaer⁵, D. Dobur⁶, J. Knolle⁶, L. Lambrecht⁶, G. Mestdach⁶, C. Rendón⁶, A. Samalan⁶, K. Skovpen⁶, M. Tytgat⁶, N. Van Den Bossche⁶, B. Vermassen⁶, L. Wezenbeek⁶, A. Benecke⁷, G. Bruno⁷, F. Bury⁷, C. Caputo⁷, P. David⁷, C. Delaere⁷, I. S. Donertas⁷, A. Giammanco⁷, K. Jaffel⁷, Sa. Jain⁷, V. Lemaitre⁷, K. Mondal⁷, A. Taliercio⁷, T. T. Tran⁷, P. Vischia⁷, S. Wertz⁷, G. A. Alves⁸, E. Coelho⁸, C. Hensel⁸, A. Moraes⁸, P. Rebello Teles⁸, W. L. Aldá Júnior⁹, M. Alves Gallo Pereira⁹, M. Barroso Ferreira Filho⁹, H. Brandao Malbouisson⁹, W. Carvalho⁹, J. Chinellato^{9,f}, E. M. Da Costa⁹, G. G. Da Silveira^{9,g}, D. De Jesus Damiao⁹, V. Dos Santos Sousa⁹, S. Fonseca De Souza⁹, J. Martins^{9,h}, C. Mora Herrera⁹, K. Mota Amarilo⁹, L. Mundim⁹, H. Nogima⁹, A. Santoro⁹, S. M. Silva Do Amaral⁹, A. Sznajder⁹, M. Thiel⁹, A. Vilela Pereira⁹, C. A. Bernardes^{10,g}, L. Calligaris¹⁰, T. R. Fernandez Perez Tomei¹⁰, E. M. Gregores¹⁰, P. G. Mercadante¹⁰, S. F. Novaes¹⁰, Sandra S. Padula¹⁰, A. Aleksandrov¹¹, G. Antchev¹¹, R. Hadjiiska¹¹, P. Iaydjiev¹¹, M. Misheva¹¹, M. Rodozov¹¹, M. Shopova¹¹, G. Sultanov¹¹, A. Dimitrov¹², T. Ivanov¹², L. Litov¹², B. Pavlov¹², P. Petkov¹², A. Petrov¹², E. Shumka¹², S. Thakur¹³, T. Cheng¹⁴, T. Javaid^{14,i}, M. Mittal¹⁴, L. Yuan¹⁴, M. Ahmad¹⁵, G. Bauer^{15,j}, Z. Hu¹⁵, S. Lezki¹⁵, K. Yi^{15,k,j}, G. M. Chen^{16,i}, H. S. Chen^{16,i}, M. Chen^{16,i}, F. Iemmi¹⁶, C. H. Jiang¹⁶, A. Kapoor¹⁶, H. Liao¹⁶, Z.-A. Liu^{16,l}, V. Milosevic¹⁶, F. Monti¹⁶, R. Sharma¹⁶, J. Tao¹⁶, J. Thomas-Wilsker¹⁶, J. Wang¹⁶, H. Zhang¹⁶, J. Zhao¹⁶, A. Agapitos¹⁷, Y. An¹⁷, Y. Ban¹⁷, A. Levin¹⁷, C. Li¹⁷, Q. Li¹⁷, X. Lyu¹⁷, Y. Mao¹⁷, S. J. Qian¹⁷, X. Sun¹⁷, D. Wang¹⁷, J. Xiao¹⁷, H. Yang¹⁷, M. Lu¹⁸, Z. You¹⁸, N. Lu¹⁹, X. Gao^{20,e}, D. Leggat²⁰, H. Okawa²⁰, Y. Zhang²⁰, Z. Lin²¹, C. Lu²¹, M. Xiao²¹, C. Avila²², D. A. Barbosa Trujillo²², A. Cabrera²², C. Florez²², J. Fraga²², J. Mejia Guisao²³, F. Ramirez²³, M. Rodriguez²³, J. D. Ruiz Alvarez²³, D. Giljanovic²⁴, N. Godinovic²⁴, D. Lelas²⁴, I. Puljak²⁴, Z. Antunovic²⁵, M. Kovac²⁵, T. Sculac²⁵, V. Brigljevic²⁶, B. K. Chitroda²⁶, D. Ferencek²⁶, S. Mishra²⁶, M. Roguljic²⁶, A. Starodumov^{26,m}, T. Susa²⁶, A. Attikis²⁷, K. Christoforou²⁷, S. Konstantinou²⁷, J. Mousa²⁷, C. Nicolaou²⁷, F. Ptochos²⁷, P. A. Razis²⁷, H. Rykaczewski²⁷, H. Saka²⁷, A. Stepanov²⁷, M. Finger²⁸, M. Finger Jr.²⁸, A. Kveton²⁸, E. Ayala²⁹, E. Carrera Jarrin³⁰, Y. Assran^{31,o,n}, S. Elgammal^{31,n}, M. Abdullah Al-Mashad³², M. A. Mahmoud³², S. Bhowmik³³, R. K. Dewanjee³³, K. Ehattaht³³, M. Kadastik³³, T. Lange³³, S. Nandan³³, C. Nielsen³³, J. Pata³³, M. Raidal³³, L. Tani³³, C. Veelken³³, P. Eerola³⁴, H. Kirschenmann³⁴, K. Osterberg³⁴, M. Voutilainen³⁴, S. Bharthuar³⁵, E. Brücken³⁵, F. Garcia³⁵, J. Havukainen³⁵, M. S. Kim³⁵, R. Kinnunen³⁵, T. Lampén³⁵, K. Lassila-Perini³⁵, S. Lehti³⁵, T. Lindén³⁵, M. Lotti³⁵, L. Martikainen³⁵, M. Myllymäki³⁵, M. m. Rantanen³⁵, H. Siikonen³⁵, E. Tuominen³⁵, J. Tuominiemi³⁵, P. Luukka³⁶, H. Petrow³⁶, T. Tuuva^{36,a}, C. Amendola³⁷, M. Besancon³⁷, F. Couderc³⁷, M. DeJardin³⁷, D. Denegri³⁷, J. L. Faure³⁷, F. Ferri³⁷, S. Ganjour³⁷, P. Gras³⁷, G. Hamel de Monchenault³⁷, V. Lohezic³⁷, J. Malcles³⁷, J. Rander³⁷, A. Rosowsky³⁷, M. Ö. Sahin³⁷, A. Savoy-Navarro^{37,p}, P. Simkina³⁷, M. Titov³⁷, C. Baldenegro Barrera³⁸, F. Beaudette³⁸, A. Buchot Perraguin³⁸, P. Busson³⁸, A. Cappati³⁸, C. Charlot³⁸, F. Damas³⁸, O. Davignon³⁸, B. Diab³⁸, G. Falmagne³⁸, B. A. Fontana Santos Alves³⁸, S. Ghosh³⁸, R. Granier de Cassagnac³⁸, A. Hakimi³⁸, B. Harikrishnan³⁸, G. Liu³⁸, J. Motta³⁸, M. Nguyen³⁸, C. Ochando³⁸, L. Portales³⁸, R. Salerno³⁸, U. Sarkar³⁸, J. B. Sauvan³⁸, Y. Sirois³⁸, A. Tarabini³⁸, E. Vernazza³⁸, A. Zabi³⁸, A. Zghiche³⁸, J.-L. Agram^{39,q}, J. Andrea³⁹, D. Apparu³⁹, D. Bloch³⁹, G. Bourgatte³⁹, J.-M. Brom³⁹, E. C. Chabert³⁹, C. Collard³⁹, D. Darej³⁹, U. Goerlach³⁹, C. Grimault³⁹, A.-C. Le Bihan³⁹, P. Van Hove³⁹, S. Beauceron⁴⁰, B. Blancon⁴⁰, G. Boudoul⁴⁰, A. Carle⁴⁰, N. Chanon⁴⁰, J. Choi⁴⁰, D. Contardo⁴⁰, P. Depasse⁴⁰, C. Dozen^{40,r}, H. El Mamouni⁴⁰, J. Fay⁴⁰, S. Gascon⁴⁰, M. Gouzevitch⁴⁰, G. Grenier⁴⁰, B. Ille⁴⁰, I. B. Laktineh⁴⁰, M. Lethuillier⁴⁰, L. Mirabito⁴⁰, S. Perries⁴⁰, L. Torterotot⁴⁰, M. Vander Donckt⁴⁰, P. Verdier⁴⁰, S. Viret⁴⁰, A. Khvedelidze^{41,m}, I. Lomidze⁴¹, Z. Tsamalaidze^{41,m}, V. Botta⁴², L. Feld⁴², K. Klein⁴², M. Lipinski⁴², D. Meuser⁴², A. Pauls⁴², N. Röwert⁴², M. Teroerde⁴², S. Diekmann⁴³, A. Dodonova⁴³, N. Eich⁴³, D. Eliseev⁴³, M. Erdmann⁴³, P. Fackeldey⁴³, D. Fasanella⁴³, B. Fischer⁴³, T. Hebbeker⁴³, K. Hoepfner⁴³, F. Ivone⁴³, M. y. Lee⁴³, L. Mastrolorenzo⁴³, M. Merschmeyer⁴³, A. Meyer⁴³, S. Mondal⁴³, S. Mukherjee⁴³, D. Noll⁴³, A. Novak⁴³, F. Nowotny⁴³, A. Pozdnyakov⁴³, Y. Rath⁴³, W. Redjeb⁴³, H. Reithler⁴³, A. Schmidt⁴³, S. C. Schuler⁴³

A. Sharma⁴³, A. Stein⁴³, F. Torres Da Silva De Araujo^{43,s}, L. Vigilante⁴³, S. Wiedenbeck⁴³, S. Zaleski⁴³, C. Dziwok⁴⁴, G. Flügge⁴⁴, W. Haj Ahmad^{44,t}, O. Hlushchenko⁴⁴, T. Kress⁴⁴, A. Nowack⁴⁴, O. Pooth⁴⁴, A. Stahl⁴⁴, T. Ziemons⁴⁴, A. Zotz⁴⁴, H. Aarup Petersen⁴⁵, M. Aldaya Martin⁴⁵, J. Alimena⁴⁵, P. Asmuss⁴⁵, S. Baxter⁴⁵, M. Bayatmakou⁴⁵, H. Becerril Gonzalez⁴⁵, O. Behnke⁴⁵, A. Bermúdez Martínez⁴⁵, S. Bhattacharya⁴⁵, A. A. Bin Anuar⁴⁵, F. Blekman^{45,u}, K. Borrás^{45,v}, D. Brunner⁴⁵, A. Campbell⁴⁵, A. Cardini⁴⁵, C. Cheng⁴⁵, F. Colombina⁴⁵, S. Consuegra Rodríguez⁴⁵, G. Correia Silva⁴⁵, M. De Silva⁴⁵, G. Eckerlin⁴⁵, D. Eckstein⁴⁵, L. I. Estevez Banos⁴⁵, O. Filatov⁴⁵, E. Gallo^{45,w}, A. Geiser⁴⁵, A. Giraldi⁴⁵, G. Greau⁴⁵, A. Grohsjean⁴⁵, V. Guglielmi⁴⁵, M. Guthoff⁴⁵, A. Jafari^{45,w}, N. Z. Jomhari⁴⁵, B. Kaech⁴⁵, M. Kasemann⁴⁵, H. Kaveh⁴⁵, C. Kleinwort⁴⁵, R. Kogler⁴⁵, M. Komm⁴⁵, D. Krücker⁴⁵, W. Lange⁴⁵, D. Leyva Pernia⁴⁵, K. Lipka^{45,x}, W. Lohmann^{45,y}, R. Mankel⁴⁵, I.-A. Melzer-Pellmann⁴⁵, M. Mendizabal Morentin⁴⁵, J. Metwally⁴⁵, A. B. Meyer⁴⁵, G. Milella⁴⁵, M. Mormile⁴⁵, A. Mussgiller⁴⁵, A. Nürnberg⁴⁵, Y. Otari⁴⁵, D. Pérez Adán⁴⁵, E. Ranken⁴⁵, A. Raspereza⁴⁵, B. Ribeiro Lopes⁴⁵, J. Rübenach⁴⁵, A. Saggio⁴⁵, M. Savitskyi⁴⁵, M. Scham^{45,v,z}, V. Scheurer⁴⁵, S. Schnake^{45,v}, P. Schütze⁴⁵, C. Schwanenberger^{45,u}, M. Shchedrolosiev⁴⁵, R. E. Sosa Ricardo⁴⁵, D. Stafford⁴⁵, N. Tonon^{45,a}, M. Van De Klundert⁴⁵, F. Vazzoler⁴⁵, A. Ventura Barroso⁴⁵, R. Walsh⁴⁵, D. Walter⁴⁵, Q. Wang⁴⁵, Y. Wen⁴⁵, K. Wichmann⁴⁵, L. Wiens^{45,v}, C. Wissing⁴⁵, S. Wuchterl⁴⁵, Y. Yang⁴⁵, A. Zimmermann Castro Santos⁴⁵, A. Albrecht⁴⁶, S. Albrecht⁴⁶, M. Antonello⁴⁶, S. Bein⁴⁶, L. Benato⁴⁶, M. Bonanomi⁴⁶, P. Connor⁴⁶, K. De Leo⁴⁶, M. Eich⁴⁶, K. El Morabit⁴⁶, F. Feindt⁴⁶, A. Fröhlich⁴⁶, C. Garbers⁴⁶, E. Garutti⁴⁶, M. Hajheidari⁴⁶, J. Haller⁴⁶, A. Hinzmann⁴⁶, H. R. Jabusch⁴⁶, G. Kasieczka⁴⁶, P. Keicher⁴⁶, R. Klanner⁴⁶, W. Korcari⁴⁶, T. Kramer⁴⁶, V. Kutzner⁴⁶, F. Labe⁴⁶, J. Lange⁴⁶, A. Lobanov⁴⁶, C. Matthies⁴⁶, A. Mehta⁴⁶, L. Moureaux⁴⁶, M. Mrowietz⁴⁶, A. Nigamova⁴⁶, Y. Nissan⁴⁶, A. Paasch⁴⁶, K. J. Pena Rodriguez⁴⁶, T. Quadfasel⁴⁶, M. Rieger⁴⁶, O. Rieger⁴⁶, D. Savoie⁴⁶, J. Schindler⁴⁶, P. Schleper⁴⁶, M. Schröder⁴⁶, J. Schwandt⁴⁶, M. Sommerhalder⁴⁶, H. Stadie⁴⁶, G. Steinbrück⁴⁶, A. Tews⁴⁶, M. Wolf⁴⁶, S. Brommer⁴⁷, M. Burkart⁴⁷, E. Butz⁴⁷, T. Chwalek⁴⁷, A. Dierlamm⁴⁷, A. Droll⁴⁷, N. Faltermann⁴⁷, M. Giffels⁴⁷, J. O. Gosewisch⁴⁷, A. Gottmann⁴⁷, F. Hartmann^{47,aa}, M. Horzela⁴⁷, U. Husemann⁴⁷, M. Klute⁴⁷, R. Koppenhöfer⁴⁷, M. Link⁴⁷, A. Lintuluoto⁴⁷, S. Maier⁴⁷, S. Mitra⁴⁷, Th. Müller⁴⁷, M. Neukum⁴⁷, M. Oh⁴⁷, G. Quast⁴⁷, K. Rabbertz⁴⁷, J. Rauser⁴⁷, I. Shvetsov⁴⁷, H. J. Simonis⁴⁷, N. Trevisani⁴⁷, R. Ulrich⁴⁷, J. van der Linden⁴⁷, R. F. Von Cube⁴⁷, M. Wassmer⁴⁷, S. Wieland⁴⁷, R. Wolf⁴⁷, S. Wozniowski⁴⁷, S. Wunsch⁴⁷, X. Zuo⁴⁷, G. Anagnostou⁴⁸, P. Assiouras⁴⁸, G. Daskalakis⁴⁸, A. Kyriakis⁴⁸, A. Stakia⁴⁸, M. Diamantopoulou⁴⁹, D. Karasavvas⁴⁹, P. Kontaxakis⁴⁹, A. Manousakis-Katsikakis⁴⁹, A. Panagiotou⁴⁹, I. Papavergou⁴⁹, N. Saoulidou⁴⁹, K. Theofilatos⁴⁹, E. Tziaferi⁴⁹, K. Vellidis⁴⁹, I. Zisopoulos⁴⁹, G. Bakas⁵⁰, T. Chatzistavrou⁵⁰, K. Kousouris⁵⁰, I. Papakrivopoulos⁵⁰, G. Tsipolitis⁵⁰, A. Zacharopoulou⁵⁰, K. Adamidis⁵¹, I. Bestintzanos⁵¹, I. Evangelou⁵¹, C. Foudas⁵¹, P. Gianneios⁵¹, C. Kamtsikis⁵¹, P. Katsoulis⁵¹, P. Kokkas⁵¹, P. G. Kosmoglou Kioseoglou⁵¹, N. Manthos⁵¹, I. Papadopoulos⁵¹, J. Strologas⁵¹, M. Csanád⁵², K. Farkas⁵², M. M. A. Gadallah^{52,bb}, S. Lökös^{52,cc}, P. Major⁵², K. Mandal⁵², G. Pásztor⁵², A. J. Rádl^{52,dd}, O. Surányi⁵², G. I. Veres⁵², M. Bartók^{53,ee}, G. Bencze⁵³, C. Hajdu⁵³, D. Horvath^{53,ff,gg}, F. Sikler⁵³, V. Veszpremi⁵³, N. Beni⁵⁴, S. Czellar⁵⁴, J. Karancsi^{54,ee}, J. Molnar⁵⁴, Z. Szillasi⁵⁴, D. Teyssier⁵⁴, P. Raics⁵⁵, B. Ujvari^{55,hh}, G. Zilizi⁵⁵, T. Csorgo^{56,dd}, F. Nemes^{56,dd}, T. Novak⁵⁶, J. Babbar⁵⁷, S. Bansal⁵⁷, S. B. Beri⁵⁷, V. Bhatnagar⁵⁷, G. Chaudhary⁵⁷, S. Chauhan⁵⁷, N. Dhingra^{57,ii}, R. Gupta⁵⁷, A. Kaur⁵⁷, A. Kaur⁵⁷, H. Kaur⁵⁷, M. Kaur⁵⁷, S. Kumar⁵⁷, P. Kumari⁵⁷, M. Meena⁵⁷, K. Sandeep⁵⁷, T. Sheokand⁵⁷, J. B. Singh^{57,ji}, A. Singla⁵⁷, A. K. Viridi⁵⁷, A. Ahmed⁵⁸, A. Bhardwaj⁵⁸, A. Chhetri⁵⁸, B. C. Choudhary⁵⁸, A. Kumar⁵⁸, M. Naimuddin⁵⁸, K. Ranjan⁵⁸, S. Saumya⁵⁸, S. Baradia⁵⁹, S. Barman^{59,kk}, S. Bhattacharya⁵⁹, D. Bhowmik⁵⁹, S. Dutta⁵⁹, S. Dutta⁵⁹, B. Gomber^{59,ll}, M. Maity^{59,kk}, P. Palit⁵⁹, G. Saha⁵⁹, B. Sahu⁵⁹, S. Sarkar⁵⁹, P. K. Behera⁶⁰, S. C. Behera⁶⁰, S. Chatterjee⁶⁰, P. Kalbhor⁶⁰, J. R. Komaragiri^{60,mmm}, D. Kumar^{60,mmm}, A. Muhammad⁶⁰, L. Panwar^{60,mmm}, R. Pradhan⁶⁰, P. R. Pujahari⁶⁰, N. R. Saha⁶⁰, A. Sharma⁶⁰, A. K. Sikdar⁶⁰, S. Verma⁶⁰, K. Naskar^{61,nn}, T. Aziz⁶², I. Das⁶², S. Dugad⁶², M. Kumar⁶², G. B. Mohanty⁶², P. Suryadevara⁶², S. Banerjee⁶³, M. Guchait⁶³, S. Karmakar⁶³, S. Kumar⁶³, G. Majumder⁶³, K. Mazumdar⁶³, S. Mukherjee⁶³, A. Thachayath⁶³, S. Bahinipati^{64,oo}, A. K. Das⁶⁴, C. Kar⁶⁴, P. Mal⁶⁴, T. Mishra⁶⁴, V. K. Muraleedharan Nair Bindhu^{64,pp}, A. Nayak^{64,pp}, P. Saha⁶⁴, S. K. Swain⁶⁴, D. Vats^{64,pp}, A. Alpna⁶⁵, S. Dube⁶⁵, B. Kansal⁶⁵, A. Laha⁶⁵, S. Pandey⁶⁵, A. Rastogi⁶⁵, S. Sharma⁶⁵, H. Bakhshiansohi^{66,qq}, E. Khazaie⁶⁶, M. Zeinali^{66,rr}, S. Chenarani^{67,ss}

S. M. Etesami⁶⁷, M. Khakzad⁶⁷, M. Mohammadi Najafabadi⁶⁷, M. Grunewald⁶⁸, M. Abbrescia^{69a,69b},
R. Aly^{69a,69c,tt}, C. Aruta^{69a,69b}, A. Colaleo^{69a}, D. Creanza^{69a,69c}, L. Cristella^{69a,69b}, N. De Filippis^{69a,69c},
M. De Palma^{69a,69b}, A. Di Florio^{69a,69b}, W. Elmetenawee^{69a,69b}, F. Errico^{69a,69b}, L. Fiore^{69a}, G. Iaselli^{69a,69c},
G. Maggi^{69a,69c}, M. Maggi^{69a}, I. Margjeka^{69a,69b}, V. Mastrapasqua^{69a,69b}, S. My^{69a,69b}, S. Nuzzo^{69a,69b},
A. Pellecchia^{69a,69b}, A. Pompili^{69a,69b}, G. Pugliese^{69a,69c}, R. Radogna^{69a}, D. Ramos^{69a}, A. Ranieri^{69a},
G. Selvaggi^{69a,69b}, L. Silvestris^{69a}, F. M. Simone^{69a,69b}, Ü. Sözbilir^{69a}, A. Stamerra^{69a}, R. Venditti^{69a},
P. Verwilligen^{69a}, G. Abbiendi^{70a}, C. Battilana^{70a,70b}, D. Bonacorsi^{70a,70b}, L. Borgonovi^{70a}, L. Brigliadori^{70a},
R. Campanini^{70a,70b}, P. Capiluppi^{70a,70b}, A. Castro^{70a,70b}, F. R. Cavallo^{70a}, M. Cuffiani^{70a,70b}, G. M. Dallavalle^{70a},
T. Diotallevi^{70a,70b}, F. Fabbri^{70a}, A. Fanfani^{70a,70b}, P. Giacomelli^{70a}, L. Giommi^{70a,70b}, C. Grandi^{70a},
L. Guiducci^{70a,70b}, S. Lo Meo^{70a,uu}, L. Lunerti^{70a,70b}, S. Marcellini^{70a}, G. Masetti^{70a}, F. L. Navarra^{70a,70b},
A. Perrotta^{70a}, F. Primavera^{70a,70b}, A. M. Rossi^{70a,70b}, T. Rovelli^{70a,70b}, G. P. Siroli^{70a,70b}, S. Costa^{71a,71b,vv},
A. Di Mattia^{71a}, R. Potenza^{71a,71b}, A. Tricomi^{71a,71b,vv}, C. Tuve^{71a,71b}, G. Barbagli^{72a}, G. Bardelli^{72a,72b},
B. Camaiani^{72a,72b}, A. Cassese^{72a}, R. Ceccarelli^{72a,72b}, V. Ciulli^{72a,72b}, C. Civinini^{72a}, R. D'Alessandro^{72a,72b},
E. Focardi^{72a,72b}, G. Latino^{72a,72b}, P. Lenzi^{72a,72b}, M. Lizzo^{72a,72b}, M. Meschini^{72a}, S. Paoletti^{72a}, G. Sguazzoni^{72a},
L. Viliani^{72a}, L. Benussi⁷³, S. Bianco⁷³, S. Meola^{73,ww}, D. Piccolo⁷³, M. Bozzo^{74a,74b}, P. Chatagnon^{74a},
F. Ferro^{74a}, E. Robutti^{74a}, S. Tosi^{74a,74b}, A. Benaglia^{75a}, G. Boldrini^{75a}, F. Brivio^{75a,75b}, F. Cetorelli^{75a,75b},
F. De Guio^{75a,75b}, M. E. Dinardo^{75a,75b}, P. Dini^{75a}, S. Gennai^{75a}, A. Ghezzi^{75a,75b}, P. Govoni^{75a,75b}, L. Guzzi^{75a,75b},
M. T. Lucchini^{75a,75b}, M. Malberti^{75a}, S. Malvezzi^{75a}, A. Massironi^{75a}, D. Menasce^{75a}, L. Moroni^{75a},
M. Paganoni^{75a,75b}, D. Pedrini^{75a}, B. S. Pinolini^{75a}, S. Ragazzi^{75a,75b}, N. Redaelli^{75a}, T. Tabarelli de Fatis^{75a,75b},
D. Zuolo^{75a,75b}, S. Buontempo^{76a}, F. Carnevali^{76a,76b}, N. Cavallo^{76a,76c}, A. De Iorio^{76a,76b}, F. Fabozzi^{76a,76c},
A. O. M. Iorio^{76a,76b}, L. Lista^{76a,76b,xx}, P. Paolucci^{76a,aa}, B. Rossi^{76a}, C. Sciacca^{76a,76b}, P. Azzi^{77a},
N. Bacchetta^{77a,yy}, M. Bellato^{77a}, M. Benettoni^{77a}, D. Bisello^{77a,77b}, P. Bortignon^{77a}, A. Bragagnolo^{77a,77b},
R. Carlin^{77a,77b}, P. Checchia^{77a}, T. Dorigo^{77a}, U. Gasparini^{77a,77b}, G. Grosso^{77a}, L. Layer^{77a,zz}, E. Lusiani^{77a},
M. Margoni^{77a,77b}, J. Pazzini^{77a,77b}, P. Ronchese^{77a,77b}, R. Rossin^{77a,77b}, F. Simonetto^{77a,77b}, G. Strong^{77a},
M. Tosi^{77a,77b}, H. Yarar^{77a,77b}, M. Zanetti^{77a,77b}, P. Zotto^{77a,77b}, A. Zucchetta^{77a,77b}, G. Zumerle^{77a,77b},
S. Abu Zeid^{78a,aaa}, C. Aimè^{78a,78b}, A. Braghieri^{78a}, S. Calzaferri^{78a,78b}, D. Fiorina^{78a,78b}, P. Montagna^{78a,78b},
V. Re^{78a}, C. Riccardi^{78a,78b}, P. Salvini^{78a}, I. Vai^{78a}, P. Vitulo^{78a,78b}, P. Asenov^{79a,bbb}, G. M. Bilei^{79a},
D. Ciangottini^{79a,79b}, L. Fanò^{79a,79b}, M. Magherini^{79a,79b}, G. Mantovani^{79a,79b}, V. Mariani^{79a,79b}, M. Menichelli^{79a},
F. Moscatelli^{79a,bbb}, A. Piccinelli^{79a,79b}, M. Presilla^{79a,79b}, A. Rossi^{79a,79b}, A. Santocchia^{79a,79b}, D. Spiga^{79a},
T. Tedeschi^{79a,79b}, P. Azzurri^{80a}, G. Bagliesi^{80a}, V. Bertacchi^{80a,80c}, R. Bhattacharya^{80a}, L. Bianchini^{80a,80b},
T. Boccali^{80a}, E. Bossini^{80a,80b}, D. Bruschini^{80a,80c}, R. Castaldi^{80a}, M. A. Ciocci^{80a,80b}, V. D'Amante^{80a,80d},
R. Dell'Orso^{80a}, S. Donato^{80a}, A. Giassi^{80a}, F. Ligabue^{80a,80c}, D. Matos Figueiredo^{80a}, A. Messineo^{80a,80b},
M. Musich^{80a,80b}, F. Palla^{80a}, S. Parolia^{80a}, G. Ramirez-Sanchez^{80a,80c}, A. Rizzi^{80a,80b}, G. Rolandi^{80a,80c},
S. Roy Chowdhury^{80a}, T. Sarkar^{80a}, A. Scribano^{80a}, P. Spagnolo^{80a}, R. Tenchini^{80a}, G. Tonelli^{80a,80b},
N. Turini^{80a,80d}, A. Venturi^{80a}, P. G. Verdini^{80a}, P. Barria^{81a}, M. Campana^{81a,81b}, F. Cavallari^{81a}, D. Del Re^{81a,81b},
E. Di Marco^{81a}, M. Diemoz^{81a}, E. Longo^{81a,81b}, P. Meridiani^{81a}, G. Organtini^{81a,81b}, F. Pandolfi^{81a},
R. Paramatti^{81a,81b}, C. Quaranta^{81a,81b}, S. Rahatlou^{81a,81b}, C. Rovelli^{81a}, F. Santanastasio^{81a,81b}, L. Soffi^{81a},
R. Tramontano^{81a,81b}, N. Amapane^{82a,82b}, R. Arcidiacono^{82a,82c}, S. Argiro^{82a,82b}, M. Arneodo^{82a,82c}, N. Bartosik^{82a},
R. Bellan^{82a,82b}, A. Bellora^{82a,82b}, C. Biino^{82a}, N. Cartiglia^{82a}, M. Costa^{82a,82b}, R. Covarelli^{82a,82b}, N. Demaria^{82a},
M. Grippo^{82a,82b}, B. Kiani^{82a,82b}, F. Legger^{82a}, C. Mariotti^{82a}, S. Maselli^{82a}, A. Mecca^{82a,82b}, E. Migliore^{82a,82b},
M. Monteno^{82a}, R. Mulargia^{82a}, M. M. Obertino^{82a,82b}, G. Ortona^{82a}, L. Pacher^{82a,82b}, N. Pastrone^{82a},
M. Pelliccioni^{82a}, M. Ruspà^{82a,82c}, K. Shchelina^{82a}, F. Siviero^{82a,82b}, V. Sola^{82a,82b}, A. Solano^{82a,82b},
D. Soldi^{82a,82b}, A. Staiano^{82a}, M. Tornago^{82a,82b}, D. Trocino^{82a}, G. Umoret^{82a,82b}, A. Vagnerini^{82a,82b},
E. Vlasov^{82a,82b}, S. Belforte^{83a}, V. Candelise^{83a,83b}, M. Casarsa^{83a}, F. Cossutti^{83a}, G. Della Ricca^{83a,83b},
G. Sorrentino^{83a,83b}, S. Dogra⁸⁴, C. Huh⁸⁴, B. Kim⁸⁴, D. H. Kim⁸⁴, G. N. Kim⁸⁴, J. Kim⁸⁴, J. Lee⁸⁴,
S. W. Lee⁸⁴, C. S. Moon⁸⁴, Y. D. Oh⁸⁴, S. I. Pak⁸⁴, M. S. Ryu⁸⁴, S. Sekmen⁸⁴, Y. C. Yang⁸⁴, H. Kim⁸⁵,
D. H. Moon⁸⁵, E. Asilar⁸⁶, T. J. Kim⁸⁶, J. Park⁸⁶, S. Choi⁸⁷, S. Han⁸⁷, B. Hong⁸⁷, K. Lee⁸⁷, K. S. Lee⁸⁷,
J. Lim⁸⁷, J. Park⁸⁷, S. K. Park⁸⁷, J. Yoo⁸⁷, J. Goh⁸⁸, H. S. Kim⁸⁹, Y. Kim⁸⁹, S. Lee⁸⁹, J. Almond⁹⁰, J. H. Bhyun⁹⁰

J. Choi⁹⁰, S. Jeon⁹⁰, J. Kim⁹⁰, J. S. Kim⁹⁰, S. Ko⁹⁰, H. Kwon⁹⁰, H. Lee⁹⁰, S. Lee⁹⁰, B. H. Oh⁹⁰, S. B. Oh⁹⁰,
H. Seo⁹⁰, U. K. Yang⁹⁰, I. Yoon⁹⁰, W. Jang⁹¹, D. Y. Kang⁹¹, Y. Kang⁹¹, D. Kim⁹¹, S. Kim⁹¹, B. Ko⁹¹,
J. S. H. Lee⁹¹, Y. Lee⁹¹, J. A. Merlin⁹¹, I. C. Park⁹¹, Y. Roh⁹¹, D. Song⁹¹, I. J. Watson⁹¹, S. Yang⁹¹, S. H. Ha⁹²,
H. D. Yoo⁹², M. Choi⁹³, M. R. Kim⁹³, H. Lee⁹³, Y. Lee⁹³, I. Yu⁹³, T. Beyrouthy⁹⁴, Y. Maghrbi⁹⁴,
K. Dreimanis⁹⁵, G. Pikurs⁹⁵, A. Potrebko⁹⁵, M. Seidel⁹⁵, V. Veckalns⁹⁵, M. Ambrozas⁹⁶,
A. Carvalho Antunes De Oliveira⁹⁶, A. Juodagalvis⁹⁶, A. Rinkevicius⁹⁶, G. Tamulaitis⁹⁶, N. Bin Norjoharuddeen⁹⁷,
S. Y. Hoh^{97,ccc}, I. Yusuff^{97,ccc}, Z. Zolkapli⁹⁷, J. F. Benitez⁹⁸, A. Castaneda Hernandez⁹⁸, H. A. Encinas Acosta⁹⁸,
L. G. Gallegos Maríñez⁹⁸, M. León Coello⁹⁸, J. A. Murillo Quijada⁹⁸, A. Sehrawat⁹⁸, L. Valencia Palomo⁹⁸,
G. Ayala⁹⁹, H. Castilla-Valdez⁹⁹, I. Heredia-De La Cruz^{99,ddd}, R. Lopez-Fernandez⁹⁹, C. A. Mondragon Herrera⁹⁹,
D. A. Perez Navarro⁹⁹, A. Sánchez Hernández⁹⁹, C. Oropeza Barrera¹⁰⁰, F. Vazquez Valencia¹⁰⁰, I. Pedraza¹⁰¹,
H. A. Salazar Ibarguen¹⁰¹, C. Uribe Estrada¹⁰¹, I. Bujanja¹⁰², J. Mijuskovic^{102,eee}, N. Raicevic¹⁰², A. Ahmad¹⁰³,
M. I. Asghar¹⁰³, A. Awais¹⁰³, M. I. M. Awan¹⁰³, M. Gul¹⁰³, H. R. Hoorani¹⁰³, W. A. Khan¹⁰³, V. Avati¹⁰⁴,
L. Grzanka¹⁰⁴, M. Malawski¹⁰⁴, H. Bialkowska¹⁰⁵, M. Bluj¹⁰⁵, B. Boimska¹⁰⁵, M. Górski¹⁰⁵, M. Kazana¹⁰⁵,
M. Szeleper¹⁰⁵, P. Zalewski¹⁰⁵, K. Bunkowski¹⁰⁶, K. Doroba¹⁰⁶, A. Kalinowski¹⁰⁶, M. Konecki¹⁰⁶,
J. Krolikowski¹⁰⁶, M. Araujo¹⁰⁷, P. Bargassa¹⁰⁷, D. Bastos¹⁰⁷, A. Boletti¹⁰⁷, P. Faccioli¹⁰⁷, M. Gallinaro¹⁰⁷,
J. Hollar¹⁰⁷, N. Leonardo¹⁰⁷, T. Niknejad¹⁰⁷, M. Pisano¹⁰⁷, J. Seixas¹⁰⁷, J. Varela¹⁰⁷, P. Adzic^{108,fff},
M. Dordevic¹⁰⁸, P. Milenovic¹⁰⁸, J. Milosevic¹⁰⁸, M. Aguilar-Benitez¹⁰⁹, J. Alcaraz Maestre¹⁰⁹, M. Barrio Luna¹⁰⁹,
Cristina F. Bedoya¹⁰⁹, M. Cepeda¹⁰⁹, M. Cerrada¹⁰⁹, N. Colino¹⁰⁹, B. De La Cruz¹⁰⁹, A. Delgado Peris¹⁰⁹,
D. Fernández Del Val¹⁰⁹, J. P. Fernández Ramos¹⁰⁹, J. Flix¹⁰⁹, M. C. Fouz¹⁰⁹, O. Gonzalez Lopez¹⁰⁹,
S. Goy Lopez¹⁰⁹, J. M. Hernandez¹⁰⁹, M. I. Josa¹⁰⁹, J. León Holgado¹⁰⁹, D. Moran¹⁰⁹, C. Perez Dengra¹⁰⁹,
A. Pérez-Calero Yzquierdo¹⁰⁹, J. Puerta Pelayo¹⁰⁹, I. Redondo¹⁰⁹, D. D. Redondo Ferrero¹⁰⁹, L. Romero¹⁰⁹,
S. Sánchez Navas¹⁰⁹, J. Sastre¹⁰⁹, L. Urda Gómez¹⁰⁹, J. Vazquez Escobar¹⁰⁹, C. Willmott¹⁰⁹, J. F. de Trocóniz¹¹⁰,
B. Alvarez Gonzalez¹¹¹, J. Cuevas¹¹¹, J. Fernandez Menendez¹¹¹, S. Folgueras¹¹¹, I. Gonzalez Caballero¹¹¹,
J. R. González Fernández¹¹¹, E. Palencia Cortezon¹¹¹, C. Ramón Álvarez¹¹¹, V. Rodríguez Bouza¹¹¹,
A. Soto Rodríguez¹¹¹, A. Trapote¹¹¹, C. Vico Villalba¹¹¹, J. A. Brochero Cifuentes¹¹², I. J. Cabrillo¹¹²,
A. Calderon¹¹², J. Duarte Campderros¹¹², M. Fernandez¹¹², C. Fernandez Madrazo¹¹², A. García Alonso¹¹²,
G. Gomez¹¹², C. Lasasoa García¹¹², C. Martinez Rivero¹¹², P. Martinez Ruiz del Arbol¹¹², F. Matorras¹¹²,
P. Matorras Cuevas¹¹², J. Piedra Gomez¹¹², C. Prieels¹¹², L. Scodellaro¹¹², I. Vila¹¹², J. M. Vizan Garcia¹¹²,
M. K. Jayananda¹¹³, B. Kailasapathy^{113,ggg}, D. U. J. Sonnadara¹¹³, D. D. C. Wickramaratna¹¹³,
W. G. D. Dharmaratna¹¹⁴, K. Liyanage¹¹⁴, N. Perera¹¹⁴, N. Wickramage¹¹⁴, D. Abbaneo¹¹⁵, E. Auffray¹¹⁵,
G. Auzinger¹¹⁵, J. Baechler¹¹⁵, P. Baillon^{115,a}, D. Barney¹¹⁵, J. Bendavid¹¹⁵, M. Bianco¹¹⁵, B. Bilin¹¹⁵,
A. Bocci¹¹⁵, E. Brondolin¹¹⁵, C. Caillol¹¹⁵, T. Camporesi¹¹⁵, G. Cerminara¹¹⁵, N. Chernyavskaya¹¹⁵,
S. S. Chhibra¹¹⁵, S. Choudhury¹¹⁵, M. Cipriani¹¹⁵, D. d'Enterria¹¹⁵, A. Dabrowski¹¹⁵, A. David¹¹⁵,
A. De Roeck¹¹⁵, M. M. Defranchis¹¹⁵, M. Deile¹¹⁵, M. Dobson¹¹⁵, M. Dünser¹¹⁵, N. Dupont¹¹⁵,
F. Fallavollita^{115,hhh}, A. Florent¹¹⁵, L. Forthomme¹¹⁵, G. Franzoni¹¹⁵, W. Funk¹¹⁵, S. Ghosh¹¹⁵, S. Giani¹¹⁵,
D. Gigi¹¹⁵, K. Gill¹¹⁵, F. Glege¹¹⁵, L. Gouskos¹¹⁵, E. Govorkova¹¹⁵, M. Haranko¹¹⁵, J. Hegeman¹¹⁵,
V. Innocente¹¹⁵, T. James¹¹⁵, P. Janot¹¹⁵, J. Kaspar¹¹⁵, J. Kieseler¹¹⁵, N. Kratochwil¹¹⁵, S. Laurila¹¹⁵,
P. Lecoq¹¹⁵, E. Leutgeb¹¹⁵, C. Lourenço¹¹⁵, B. Maier¹¹⁵, L. Malgeri¹¹⁵, M. Mannelli¹¹⁵, A. C. Marini¹¹⁵,
F. Meijers¹¹⁵, S. Mersi¹¹⁵, E. Meschi¹¹⁵, F. Moortgat¹¹⁵, M. Mulders¹¹⁵, S. Orfanelli¹¹⁵, L. Orsini¹¹⁵,
F. Pantaleo¹¹⁵, E. Perez¹¹⁵, M. Peruzzi¹¹⁵, A. Petrilli¹¹⁵, G. Petrucciani¹¹⁵, A. Pfeiffer¹¹⁵, M. Pierini¹¹⁵,
D. Piparo¹¹⁵, M. Pitt¹¹⁵, H. Qu¹¹⁵, T. Quast¹¹⁵, D. Rabady¹¹⁵, A. Racz¹¹⁵, G. Reales Gutiérrez¹¹⁵, M. Rovere¹¹⁵,
H. Sakulin¹¹⁵, J. Salfeld-Nebgen¹¹⁵, S. Scarfi¹¹⁵, M. Selvaggi¹¹⁵, A. Sharma¹¹⁵, P. Silva¹¹⁵, P. Sphicas^{115,iii},
A. G. Stahl Leitner¹¹⁵, S. Summers¹¹⁵, K. Tatar¹¹⁵, D. Treille¹¹⁵, P. Tropea¹¹⁵, A. Tsirou¹¹⁵, J. Wanczyk^{115,jjj},
K. A. Wozniak¹¹⁵, W. D. Zeuner¹¹⁵, L. Caminada^{116,kkk}, A. Ebrahimi¹¹⁶, W. Erdmann¹¹⁶, R. Horisberger¹¹⁶,
Q. Ingram¹¹⁶, H. C. Kaestli¹¹⁶, D. Kotlinski¹¹⁶, C. Lange¹¹⁶, M. Missiroli^{116,kkk}, L. Nohte^{116,kkk}, T. Rohe¹¹⁶,
T. K. Aarrestad¹¹⁷, K. Androsov^{117,jjj}, M. Backhaus¹¹⁷, A. Calandri¹¹⁷, K. Datta¹¹⁷, A. De Cosa¹¹⁷,
G. Dissertori¹¹⁷, M. Dittmar¹¹⁷, M. Donegà¹¹⁷, F. Eble¹¹⁷, M. Galli¹¹⁷, K. Gedia¹¹⁷, F. Glessgen¹¹⁷,
T. A. Gómez Espinosa¹¹⁷, C. Grab¹¹⁷, D. Hits¹¹⁷, W. Lustermaier¹¹⁷, A.-M. Lyon¹¹⁷, R. A. Manzoni¹¹⁷,
L. Marchese¹¹⁷, C. Martin Perez¹¹⁷, A. Mascellani^{117,jjj}, F. Nessi-Tedaldi¹¹⁷, J. Niedziela¹¹⁷, F. Pauss¹¹⁷

V. Perovic¹¹⁷ S. Pigazzini¹¹⁷ M. G. Ratti¹¹⁷ M. Reichmann¹¹⁷ C. Reissel¹¹⁷ T. Reitenspiess¹¹⁷ B. Ristic¹¹⁷ F. Riti¹¹⁷ D. Ruini¹¹⁷ D. A. Sanz Becerra¹¹⁷ R. Seidita¹¹⁷ J. Steggemann^{117,ijj} D. Valsecchi^{117,aa} R. Wallny¹¹⁷ C. Amsler^{118,lll} P. Bäertschi¹¹⁸ C. Botta¹¹⁸ D. Brzhechko¹¹⁸ M. F. Canelli¹¹⁸ K. Cormier¹¹⁸ A. De Wit¹¹⁸ R. Del Burgo¹¹⁸ J. K. Heikkilä¹¹⁸ M. Huwiler¹¹⁸ W. Jin¹¹⁸ A. Jofrehei¹¹⁸ B. Kilminster¹¹⁸ S. Leontsinis¹¹⁸ S. P. Liechti¹¹⁸ A. Macchiolo¹¹⁸ P. Meiring¹¹⁸ V. M. Mikuni¹¹⁸ U. Molinatti¹¹⁸ I. Neutelings¹¹⁸ A. Reimers¹¹⁸ P. Robmann¹¹⁸ S. Sanchez Cruz¹¹⁸ K. Schweiger¹¹⁸ M. Senger¹¹⁸ Y. Takahashi¹¹⁸ C. Adloff^{119,mmm} C. M. Kuo¹¹⁹ W. Lin¹¹⁹ P. K. Rout¹¹⁹ P. C. Tiwari^{119,nnn} S. S. Yu¹¹⁹ L. Ceard¹²⁰ Y. Chao¹²⁰ K. F. Chen¹²⁰ P. s. Chen¹²⁰ H. Cheng¹²⁰ W.-S. Hou¹²⁰ R. Khurana¹²⁰ G. Kole¹²⁰ Y. y. Li¹²⁰ R.-S. Lu¹²⁰ E. Paganis¹²⁰ A. Psallidas¹²⁰ A. Steen¹²⁰ H. y. Wu¹²⁰ E. Yazgan¹²⁰ C. Asawatangtrakuldee¹²¹ N. Srimanobhas¹²¹ V. Wachirapusanand¹²¹ D. Agyel¹²² F. Boran¹²² Z. S. Demiroglu¹²² F. Dolek¹²² I. Dumanoglu^{122,nnn} E. Eskut¹²² Y. Guler^{122,ooo} E. Gurpinar Guler^{122,ooo} C. Isik¹²² O. Kara¹²² A. Kayis Topaksu¹²² U. Kiminsu¹²² G. Onengut¹²² K. Ozdemir^{122,ppp} A. Polatoz¹²² A. E. Simsek¹²² B. Tali^{122,qqq} U. G. Tok¹²² S. Turkcapar¹²² E. Uslan¹²² I. S. Zorbakir¹²² G. Karapinar^{123,rrr} K. Ocalan^{123,sss} M. Yalvac^{123,ttt} B. Akgun¹²⁴ I. O. Atakisi¹²⁴ E. Gülmez¹²⁴ M. Kaya^{124,uuu} O. Kaya^{124,vvv} S. Tekten^{124,www} A. Cakir¹²⁵ K. Cankocak^{125,nnn} Y. Komurcu¹²⁵ S. Sen^{125,xxx} O. Aydilek¹²⁶ S. Cerci^{126,qqq} B. Haciasahinoglu¹²⁶ I. Hos^{126,yyy} B. Isildak^{126,zzz} B. Kaynak¹²⁶ S. Ozkorucuklu¹²⁶ C. Simsek¹²⁶ D. Sunar Cerci^{126,qqq} B. Grynyov¹²⁷ L. Levchuk¹²⁸ D. Anthony¹²⁹ J. J. Brooke¹²⁹ A. Bundock¹²⁹ E. Clement¹²⁹ D. Cussans¹²⁹ H. Flacher¹²⁹ M. Glowacki¹²⁹ J. Goldstein¹²⁹ H. F. Heath¹²⁹ L. Kreczko¹²⁹ B. Krikler¹²⁹ S. Paramesvaran¹²⁹ S. Seif El Nasr-Storey¹²⁹ V. J. Smith¹²⁹ N. Stylianou^{129,aaaa} K. Walkingshaw Pass¹²⁹ R. White¹²⁹ A. H. Ball¹³⁰ K. W. Bell¹³⁰ A. Belyaev^{130,bbbb} C. Brew¹³⁰ R. M. Brown¹³⁰ D. J. A. Cockerill¹³⁰ C. Cooke¹³⁰ K. V. Ellis¹³⁰ K. Harder¹³⁰ S. Harper¹³⁰ M.-L. Holmberg^{130,cccc} Sh. Jain¹³⁰ J. Linacre¹³⁰ K. Manolopoulos¹³⁰ D. M. Newbold¹³⁰ E. Olaiya¹³⁰ D. Petyt¹³⁰ T. Reis¹³⁰ G. Salvi¹³⁰ T. Schuh¹³⁰ C. H. Shepherd-Themistocleous¹³⁰ I. R. Tomalin¹³⁰ T. Williams¹³⁰ R. Bainbridge¹³¹ P. Bloch¹³¹ S. Bonomally¹³¹ J. Borg¹³¹ C. E. Brown¹³¹ O. Buchmuller¹³¹ V. Cacchio¹³¹ C. A. Carrillo Montoya¹³¹ V. Cepaitis¹³¹ G. S. Chahal^{131,dddd} D. Colling¹³¹ J. S. Dancu¹³¹ P. Dauncey¹³¹ G. Davies¹³¹ J. Davies¹³¹ M. Della Negra¹³¹ S. Fayer¹³¹ G. Fedi¹³¹ G. Hall¹³¹ M. H. Hassanshahi¹³¹ A. Howard¹³¹ G. Iles¹³¹ J. Langford¹³¹ L. Lyons¹³¹ A.-M. Magnan¹³¹ S. Malik¹³¹ A. Martelli¹³¹ M. Mieskolainen¹³¹ D. G. Monk¹³¹ J. Nash^{131,eeee} M. Pesaresi¹³¹ B. C. Radburn-Smith¹³¹ D. M. Raymond¹³¹ A. Richards¹³¹ A. Rose¹³¹ E. Scott¹³¹ C. Seez¹³¹ R. Shukla¹³¹ A. Tapper¹³¹ K. Uchida¹³¹ G. P. Uttley¹³¹ L. H. Vage¹³¹ T. Virdee^{131,aa} M. Vojinovic¹³¹ N. Wardle¹³¹ S. N. Webb¹³¹ D. Winterbottom¹³¹ K. Coldham¹³² J. E. Cole¹³² A. Khan¹³² P. Kyberd¹³² I. D. Reid¹³² S. Abdullin¹³³ A. Brinkerhoff¹³³ B. Caraway¹³³ J. Dittmann¹³³ K. Hatakeyama¹³³ A. R. Kanuganti¹³³ B. McMaster¹³³ M. Saunders¹³³ S. Sawant¹³³ C. Sutantawibul¹³³ M. Toms¹³³ J. Wilson¹³³ R. Bartek¹³⁴ A. Dominguez¹³⁴ C. Huerta Escamilla¹³⁴ R. Uniyal¹³⁴ A. M. Vargas Hernandez¹³⁴ R. Chudasama¹³⁵ S. I. Cooper¹³⁵ D. Di Croce¹³⁵ S. V. Gleyzer¹³⁵ C. Henderson¹³⁵ C. U. Perez¹³⁵ P. Rumerio^{135,fff} C. West¹³⁵ A. Akpinar¹³⁶ A. Albert¹³⁶ D. Arcaro¹³⁶ C. Cosby¹³⁶ Z. Demiragli¹³⁶ C. Erice¹³⁶ E. Fontanesi¹³⁶ D. Gastler¹³⁶ S. May¹³⁶ J. Rohlf¹³⁶ K. Salyer¹³⁶ D. Sperka¹³⁶ D. Spitzbart¹³⁶ I. Suarez¹³⁶ A. Tsatsos¹³⁶ S. Yuan¹³⁶ G. Benelli¹³⁷ B. Burkle¹³⁷ X. Coubez^{137,v} D. Cutts¹³⁷ M. Hadley¹³⁷ U. Heintz¹³⁷ J. M. Hogan^{137,gggg} T. Kwon¹³⁷ G. Landsberg¹³⁷ K. T. Lau¹³⁷ D. Li¹³⁷ J. Luo¹³⁷ M. Narain¹³⁷ N. Pervan¹³⁷ S. Sagir^{137,hhhh} F. Simpson¹³⁷ E. Usai¹³⁷ W. Y. Wong¹³⁷ X. Yan¹³⁷ D. Yu¹³⁷ W. Zhang¹³⁷ M. S. Abbott¹³⁸ J. Bonilla¹³⁸ C. Brainerd¹³⁸ R. Breedon¹³⁸ M. Calderon De La Barca Sanchez¹³⁸ M. Chertok¹³⁸ J. Conway¹³⁸ P. T. Cox¹³⁸ R. Erbacher¹³⁸ G. Haza¹³⁸ F. Jensen¹³⁸ O. Kukral¹³⁸ G. Mocellin¹³⁸ M. Mulhearn¹³⁸ D. Pellett¹³⁸ B. Regnery¹³⁸ Y. Yao¹³⁸ F. Zhang¹³⁸ M. Bachtis¹³⁹ R. Cousins¹³⁹ A. Datta¹³⁹ J. Hauser¹³⁹ M. Ignatenko¹³⁹ M. A. Iqbal¹³⁹ T. Lam¹³⁹ E. Manca¹³⁹ W. A. Nash¹³⁹ D. Saltzberg¹³⁹ B. Stone¹³⁹ V. Valuev¹³⁹ R. Clare¹⁴⁰ J. W. Gary¹⁴⁰ M. Gordon¹⁴⁰ G. Hanson¹⁴⁰ G. Karapostoli¹⁴⁰ O. R. Long¹⁴⁰ N. Manganelli¹⁴⁰ W. Si¹⁴⁰ S. Wimpenny¹⁴⁰ J. G. Branson¹⁴¹ S. Cittolin¹⁴¹ S. Cooperstein¹⁴¹ D. Diaz¹⁴¹ J. Duarte¹⁴¹ R. Gerosa¹⁴¹ L. Giannini¹⁴¹ J. Guiang¹⁴¹ R. Kansal¹⁴¹ V. Krutelyov¹⁴¹ R. Lee¹⁴¹ J. Letts¹⁴¹ M. Masciovecchio¹⁴¹ F. Mokhtar¹⁴¹ M. Pieri¹⁴¹ M. Quinnan¹⁴¹ B. V. Sathia Narayanan¹⁴¹ V. Sharma¹⁴¹ M. Tadel¹⁴¹ E. Vourliotis¹⁴¹ F. Würthwein¹⁴¹ Y. Xiang¹⁴¹ A. Yagil¹⁴¹ N. Amin¹⁴² C. Campagnari¹⁴²

M. Citron¹⁴², G. Collura¹⁴², A. Dorsett¹⁴², J. Incandela¹⁴², M. Kilpatrick¹⁴², J. Kim¹⁴², A. J. Li¹⁴²,
P. Masterson¹⁴², H. Mei¹⁴², M. Oshiro¹⁴², J. Richman¹⁴², U. Sarica¹⁴², R. Schmitz¹⁴², F. Setti¹⁴²,
J. Sheplock¹⁴², P. Siddireddy¹⁴², D. Stuart¹⁴², S. Wang¹⁴², A. Bornheim¹⁴³, O. Cerri¹⁴³, I. Dutta¹⁴³, A. Latorre¹⁴³,
J. M. Lawhorn¹⁴³, J. Mao¹⁴³, H. B. Newman¹⁴³, T. Q. Nguyen¹⁴³, M. Spiropulu¹⁴³, J. R. Vlimant¹⁴³,
C. Wang¹⁴³, S. Xie¹⁴³, R. Y. Zhu¹⁴³, J. Alison¹⁴⁴, S. An¹⁴⁴, M. B. Andrews¹⁴⁴, P. Bryant¹⁴⁴, V. Dutta¹⁴⁴,
T. Ferguson¹⁴⁴, A. Harilal¹⁴⁴, C. Liu¹⁴⁴, T. Mudholkar¹⁴⁴, S. Murthy¹⁴⁴, M. Paulini¹⁴⁴, A. Roberts¹⁴⁴,
A. Sanchez¹⁴⁴, W. Terrill¹⁴⁴, J. P. Cumalat¹⁴⁵, W. T. Ford¹⁴⁵, A. Hassani¹⁴⁵, G. Karathanasis¹⁴⁵, E. MacDonald¹⁴⁵,
F. Marini¹⁴⁵, A. Perloff¹⁴⁵, C. Savard¹⁴⁵, N. Schonbeck¹⁴⁵, K. Stenson¹⁴⁵, K. A. Ulmer¹⁴⁵, S. R. Wagner¹⁴⁵,
N. Zipper¹⁴⁵, J. Alexander¹⁴⁶, S. Bright-Thonney¹⁴⁶, X. Chen¹⁴⁶, D. J. Cranshaw¹⁴⁶, J. Fan¹⁴⁶, X. Fan¹⁴⁶,
D. Gadhari¹⁴⁶, S. Hogan¹⁴⁶, J. Monroy¹⁴⁶, J. R. Patterson¹⁴⁶, J. Reichert¹⁴⁶, M. Reid¹⁴⁶, A. Ryd¹⁴⁶, J. Thom¹⁴⁶,
P. Wittich¹⁴⁶, R. Zou¹⁴⁶, M. Albrow¹⁴⁷, M. Alyari¹⁴⁷, G. Apollinari¹⁴⁷, A. Apresyan¹⁴⁷, L. A. T. Bauerdick¹⁴⁷,
D. Berry¹⁴⁷, J. Berryhill¹⁴⁷, P. C. Bhat¹⁴⁷, K. Burkett¹⁴⁷, J. N. Butler¹⁴⁷, A. Canepa¹⁴⁷, G. B. Cerati¹⁴⁷,
H. W. K. Cheung¹⁴⁷, F. Chlebana¹⁴⁷, K. F. Di Petrillo¹⁴⁷, J. Dickinson¹⁴⁷, V. D. Elvira¹⁴⁷, Y. Feng¹⁴⁷,
J. Freeman¹⁴⁷, A. Gandrakota¹⁴⁷, Z. Gecse¹⁴⁷, L. Gray¹⁴⁷, D. Green¹⁴⁷, S. Grünendahl¹⁴⁷, D. Guerrero¹⁴⁷,
O. Gutsche¹⁴⁷, R. M. Harris¹⁴⁷, R. Heller¹⁴⁷, T. C. Herwig¹⁴⁷, J. Hirschauer¹⁴⁷, L. Horyn¹⁴⁷, B. Jayatilaka¹⁴⁷,
S. Jindariani¹⁴⁷, M. Johnson¹⁴⁷, U. Joshi¹⁴⁷, T. Klijnsma¹⁴⁷, B. Klima¹⁴⁷, K. H. M. Kwok¹⁴⁷, S. Lammel¹⁴⁷,
D. Lincoln¹⁴⁷, R. Lipton¹⁴⁷, T. Liu¹⁴⁷, C. Madrid¹⁴⁷, K. Maeshima¹⁴⁷, C. Mantilla¹⁴⁷, D. Mason¹⁴⁷,
P. McBride¹⁴⁷, P. Merkel¹⁴⁷, S. Mrenna¹⁴⁷, S. Nahn¹⁴⁷, J. Ngadiuba¹⁴⁷, D. Noonan¹⁴⁷, V. Papadimitriou¹⁴⁷,
N. Pastika¹⁴⁷, K. Pedro¹⁴⁷, C. Pena^{147,iiii}, F. Ravera¹⁴⁷, A. Reinsvold Hall^{147,iiij}, L. Ristori¹⁴⁷,
E. Sexton-Kennedy¹⁴⁷, N. Smith¹⁴⁷, A. Soha¹⁴⁷, L. Spiegel¹⁴⁷, J. Strait¹⁴⁷, L. Taylor¹⁴⁷, S. Tkaczyk¹⁴⁷,
N. V. Tran¹⁴⁷, L. Uplegger¹⁴⁷, E. W. Vaandering¹⁴⁷, I. Zoi¹⁴⁷, P. Avery¹⁴⁸, D. Bourilkov¹⁴⁸, L. Cadamuro¹⁴⁸,
P. Chang¹⁴⁸, V. Cherepanov¹⁴⁸, R. D. Field¹⁴⁸, E. Koenig¹⁴⁸, M. Kolosova¹⁴⁸, J. Konigsberg¹⁴⁸, A. Korytov¹⁴⁸,
E. Kuznetsova¹⁴⁸, K. H. Lo¹⁴⁸, K. Matchev¹⁴⁸, N. Menendez¹⁴⁸, G. Mitselmakher¹⁴⁸, A. Muthirakalayil Madhu¹⁴⁸,
N. Rawal¹⁴⁸, D. Rosenzweig¹⁴⁸, S. Rosenzweig¹⁴⁸, K. Shi¹⁴⁸, J. Wang¹⁴⁸, Z. Wu¹⁴⁸, T. Adams¹⁴⁹,
A. Askew¹⁴⁹, N. Bower¹⁴⁹, R. Habibullah¹⁴⁹, V. Hagopian¹⁴⁹, T. Kolberg¹⁴⁹, G. Martinez¹⁴⁹, H. Prosper¹⁴⁹,
O. Viazlo¹⁴⁹, M. Wulansatiti¹⁴⁹, R. Yohay¹⁴⁹, J. Zhang¹⁴⁹, M. M. Baarmand¹⁵⁰, S. Butalla¹⁵⁰, T. Elkafrawy^{150,aaa},
M. Hohmann¹⁵⁰, R. Kumar Verma¹⁵⁰, M. Rahmani¹⁵⁰, F. Yumiceva¹⁵⁰, M. R. Adams¹⁵¹, R. Cavanaugh¹⁵¹,
S. Dittmer¹⁵¹, O. Evdokimov¹⁵¹, C. E. Gerber¹⁵¹, D. J. Hofman¹⁵¹, D. S. Lemos¹⁵¹, A. H. Merrit¹⁵¹, C. Mills¹⁵¹,
G. Oh¹⁵¹, T. Roy¹⁵¹, S. Rudrabhatla¹⁵¹, M. B. Tonjes¹⁵¹, N. Varelas¹⁵¹, X. Wang¹⁵¹, Z. Ye¹⁵¹, J. Yoo¹⁵¹,
M. Alhusseini¹⁵², K. Dilsiz^{152,kkkk}, L. Emediato¹⁵², G. Karaman¹⁵², O. K. Köseyan¹⁵², J.-P. Merlo¹⁵²,
A. Mestvirishvili^{152,llll}, J. Nachtman¹⁵², O. Neogi¹⁵², H. Ogul^{152,mmmm}, Y. Onel¹⁵², A. Penzo¹⁵², C. Snyder¹⁵²,
E. Tiras^{152,nnnn}, O. Amram¹⁵³, B. Blumenfeld¹⁵³, L. Corcodilos¹⁵³, J. Davis¹⁵³, A. V. Gritsan¹⁵³, S. Kyriacou¹⁵³,
P. Maksimovic¹⁵³, J. Roskes¹⁵³, S. Sekhar¹⁵³, M. Swartz¹⁵³, T. Á. Vámi¹⁵³, A. Abreu¹⁵⁴,
L. F. Alcerro Alcerro¹⁵⁴, J. Anguiano¹⁵⁴, P. Baringer¹⁵⁴, A. Bean¹⁵⁴, Z. Flowers¹⁵⁴, J. King¹⁵⁴, G. Krintiras¹⁵⁴,
M. Lazarovits¹⁵⁴, C. Le Mahieu¹⁵⁴, C. Lindsey¹⁵⁴, J. Marquez¹⁵⁴, N. Minafra¹⁵⁴, M. Murray¹⁵⁴, M. Nickel¹⁵⁴,
C. Rogan¹⁵⁴, C. Royon¹⁵⁴, R. Salvatico¹⁵⁴, S. Sanders¹⁵⁴, C. Smith¹⁵⁴, Q. Wang¹⁵⁴, G. Wilson¹⁵⁴,
B. Allmond¹⁵⁵, S. Duric¹⁵⁵, A. Ivanov¹⁵⁵, K. Kaadze¹⁵⁵, A. Kalogeropoulos¹⁵⁵, D. Kim¹⁵⁵, Y. Maravin¹⁵⁵,
T. Mitchell¹⁵⁵, A. Modak¹⁵⁵, K. Nam¹⁵⁵, D. Roy¹⁵⁵, F. Rebassoo¹⁵⁶, D. Wright¹⁵⁶, E. Adams¹⁵⁷, A. Baden¹⁵⁷,
O. Baron¹⁵⁷, A. Belloni¹⁵⁷, A. Bethani¹⁵⁷, S. C. Eno¹⁵⁷, N. J. Hadley¹⁵⁷, S. Jabeen¹⁵⁷, R. G. Kellogg¹⁵⁷,
T. Koeth¹⁵⁷, Y. Lai¹⁵⁷, S. Lascio¹⁵⁷, A. C. Mignerey¹⁵⁷, S. Nabili¹⁵⁷, C. Palmer¹⁵⁷, C. Papageorgakis¹⁵⁷,
L. Wang¹⁵⁷, K. Wong¹⁵⁷, W. Busza¹⁵⁸, I. A. Cali¹⁵⁸, Y. Chen¹⁵⁸, M. D'Alfonso¹⁵⁸, J. Eysermans¹⁵⁸,
C. Freer¹⁵⁸, G. Gomez-Ceballos¹⁵⁸, M. Goncharov¹⁵⁸, P. Harris¹⁵⁸, M. Hu¹⁵⁸, D. Kovalskyi¹⁵⁸, J. Krupa¹⁵⁸,
Y.-J. Lee¹⁵⁸, K. Long¹⁵⁸, C. Mironov¹⁵⁸, C. Paus¹⁵⁸, D. Rankin¹⁵⁸, C. Roland¹⁵⁸, G. Roland¹⁵⁸, Z. Shi¹⁵⁸,
G. S. F. Stephans¹⁵⁸, J. Wang¹⁵⁸, Z. Wang¹⁵⁸, B. Wyslouch¹⁵⁸, T. J. Yang¹⁵⁸, R. M. Chatterjee¹⁵⁹, B. Crossman¹⁵⁹,
J. Hiltbrand¹⁵⁹, B. M. Joshi¹⁵⁹, C. Kapsiak¹⁵⁹, M. Krohn¹⁵⁹, Y. Kubota¹⁵⁹, D. Mahon¹⁵⁹, J. Mans¹⁵⁹,
M. Revering¹⁵⁹, R. Rusack¹⁵⁹, R. Saradhy¹⁵⁹, N. Schroeder¹⁵⁹, N. Strobbe¹⁵⁹, M. A. Wadud¹⁵⁹,
L. M. Cremaldi¹⁶⁰, K. Bloom¹⁶¹, M. Bryson¹⁶¹, D. R. Claes¹⁶¹, C. Fangmeier¹⁶¹, L. Finco¹⁶¹, F. Golf¹⁶¹,
C. Joo¹⁶¹, R. Kamalieddin¹⁶¹, I. Kravchenko¹⁶¹, I. Reed¹⁶¹, J. E. Siado¹⁶¹, G. R. Snow^{161,a}, W. Tabb¹⁶¹

A. Wightman¹⁶¹, F. Yan¹⁶¹, A. G. Zecchinelli¹⁶¹, G. Agarwal¹⁶², H. Bandyopadhyay¹⁶², L. Hay¹⁶², I. Iashvili¹⁶², A. Kharchilava¹⁶², C. McLean¹⁶², M. Morris¹⁶², D. Nguyen¹⁶², J. Pekkanen¹⁶², S. Rappoccio¹⁶², A. Williams¹⁶², G. Alverson¹⁶³, E. Barberis¹⁶³, Y. Haddad¹⁶³, Y. Han¹⁶³, A. Krishna¹⁶³, J. Li¹⁶³, J. Lidrych¹⁶³, G. Madigan¹⁶³, B. Marzocchi¹⁶³, D. M. Morse¹⁶³, V. Nguyen¹⁶³, T. Orimoto¹⁶³, A. Parker¹⁶³, L. Skinnari¹⁶³, A. Tishelman-Charny¹⁶³, T. Wamorkar¹⁶³, B. Wang¹⁶³, A. Wisecarver¹⁶³, D. Wood¹⁶³, S. Bhattacharya¹⁶⁴, J. Bueghly¹⁶⁴, Z. Chen¹⁶⁴, A. Gilbert¹⁶⁴, K. A. Hahn¹⁶⁴, Y. Liu¹⁶⁴, N. Odell¹⁶⁴, M. H. Schmitt¹⁶⁴, M. Velasco¹⁶⁴, R. Band¹⁶⁵, R. Bucci¹⁶⁵, M. Cremonesi¹⁶⁵, A. Das¹⁶⁵, R. Goldouzian¹⁶⁵, M. Hildreth¹⁶⁵, K. Hurtado Anampa¹⁶⁵, C. Jessop¹⁶⁵, K. Lannon¹⁶⁵, J. Lawrence¹⁶⁵, N. Loukas¹⁶⁵, L. Lutton¹⁶⁵, J. Mariano¹⁶⁵, N. Marinelli¹⁶⁵, I. Mcalister¹⁶⁵, T. McCauley¹⁶⁵, C. Mcgrady¹⁶⁵, K. Mohrman¹⁶⁵, C. Moore¹⁶⁵, Y. Musienko^{165,m}, R. Ruchti¹⁶⁵, A. Townsend¹⁶⁵, M. Wayne¹⁶⁵, H. Yockey¹⁶⁵, M. Zarucki¹⁶⁵, L. Zygala¹⁶⁵, B. Bylsma¹⁶⁶, M. Carrigan¹⁶⁶, L. S. Durkin¹⁶⁶, C. Hill¹⁶⁶, M. Joyce¹⁶⁶, A. Lesauvage¹⁶⁶, M. Nunez Ornelas¹⁶⁶, K. Wei¹⁶⁶, B. L. Winer¹⁶⁶, B. R. Yates¹⁶⁶, F. M. Addesa¹⁶⁷, P. Das¹⁶⁷, G. Dezoort¹⁶⁷, P. Elmer¹⁶⁷, A. Frankenthal¹⁶⁷, B. Greenberg¹⁶⁷, N. Haubrich¹⁶⁷, S. Higginbotham¹⁶⁷, G. Kopp¹⁶⁷, S. Kwan¹⁶⁷, D. Lange¹⁶⁷, A. Loeliger¹⁶⁷, D. Marlow¹⁶⁷, I. Ojalvo¹⁶⁷, J. Olsen¹⁶⁷, D. Stickland¹⁶⁷, C. Tully¹⁶⁷, S. Malik¹⁶⁸, S. Norberg¹⁶⁸, A. S. Bakshi¹⁶⁹, V. E. Barnes¹⁶⁹, R. Chawla¹⁶⁹, S. Das¹⁶⁹, L. Gutay¹⁶⁹, M. Jones¹⁶⁹, A. W. Jung¹⁶⁹, D. Kondratyev¹⁶⁹, A. M. Koshy¹⁶⁹, M. Liu¹⁶⁹, G. Negro¹⁶⁹, N. Neumeister¹⁶⁹, G. Paspalaki¹⁶⁹, S. Piperov¹⁶⁹, A. Purohit¹⁶⁹, J. F. Schulte¹⁶⁹, M. Stojanovic¹⁶⁹, J. Thieman¹⁶⁹, F. Wang¹⁶⁹, R. Xiao¹⁶⁹, W. Xie¹⁶⁹, J. Dolen¹⁷⁰, N. Parashar¹⁷⁰, D. Acosta¹⁷¹, A. Baty¹⁷¹, T. Carnahan¹⁷¹, S. Dildick¹⁷¹, K. M. Ecklund¹⁷¹, P. J. Fernández Manteca¹⁷¹, S. Freed¹⁷¹, P. Gardner¹⁷¹, F. J. M. Geurts¹⁷¹, A. Kumar¹⁷¹, W. Li¹⁷¹, B. P. Padley¹⁷¹, R. Redjimi¹⁷¹, J. Rotter¹⁷¹, S. Yang¹⁷¹, E. Yigitbasi¹⁷¹, Y. Zhang¹⁷¹, A. Bodek¹⁷², P. de Barbaro¹⁷², R. Demina¹⁷², J. L. Dulemba¹⁷², C. Fallon¹⁷², A. Garcia-Bellido¹⁷², O. Hindrichs¹⁷², A. Khukhunaishvili¹⁷², P. Parygin¹⁷², E. Popova¹⁷², R. Taus¹⁷², G. P. Van Onsem¹⁷², K. Goulianos¹⁷³, B. Chiarito¹⁷⁴, J. P. Chou¹⁷⁴, Y. Gershtein¹⁷⁴, E. Halkiadakis¹⁷⁴, A. Hart¹⁷⁴, M. Heindl¹⁷⁴, D. Jaroslowski¹⁷⁴, O. Karacheban^{174,y}, I. Laflotte¹⁷⁴, A. Lath¹⁷⁴, R. Montalvo¹⁷⁴, K. Nash¹⁷⁴, M. Osherson¹⁷⁴, H. Routray¹⁷⁴, S. Salur¹⁷⁴, S. Schnetzer¹⁷⁴, S. Somalwar¹⁷⁴, R. Stone¹⁷⁴, S. A. Thayil¹⁷⁴, S. Thomas¹⁷⁴, H. Wang¹⁷⁴, H. Acharya¹⁷⁵, A. G. Delannoy¹⁷⁵, S. Fiorendi¹⁷⁵, T. Holmes¹⁷⁵, E. Nibigira¹⁷⁵, S. Spanier¹⁷⁵, O. Bouhali^{176,oooo}, M. Dalchenko¹⁷⁶, A. Delgado¹⁷⁶, R. Eusebi¹⁷⁶, J. Gilmore¹⁷⁶, T. Huang¹⁷⁶, T. Kamon^{176,pppp}, H. Kim¹⁷⁶, S. Luo¹⁷⁶, S. Malhotra¹⁷⁶, R. Mueller¹⁷⁶, D. Overton¹⁷⁶, D. Rathjens¹⁷⁶, A. Safonov¹⁷⁶, N. Akchurin¹⁷⁷, J. Damgov¹⁷⁷, V. Hegde¹⁷⁷, K. Lamichhane¹⁷⁷, S. W. Lee¹⁷⁷, T. Mengke¹⁷⁷, S. Muthumuni¹⁷⁷, T. Peltola¹⁷⁷, I. Volobouev¹⁷⁷, A. Whitbeck¹⁷⁷, E. Appelt¹⁷⁸, S. Greene¹⁷⁸, A. Gurrola¹⁷⁸, W. Johns¹⁷⁸, A. Melo¹⁷⁸, F. Romeo¹⁷⁸, P. Sheldon¹⁷⁸, S. Tuo¹⁷⁸, J. Velkovska¹⁷⁸, J. Viinikainen¹⁷⁸, B. Cardwell¹⁷⁹, B. Cox¹⁷⁹, G. Cummings¹⁷⁹, J. Hakala¹⁷⁹, R. Hirosky¹⁷⁹, A. Ledovskoy¹⁷⁹, A. Li¹⁷⁹, C. Neu¹⁷⁹, C. E. Perez Lara¹⁷⁹, P. E. Karchin¹⁸⁰, A. Aravind¹⁸¹, S. Banerjee¹⁸¹, K. Black¹⁸¹, T. Bose¹⁸¹, S. Dasu¹⁸¹, I. De Bruyn¹⁸¹, P. Everaerts¹⁸¹, C. Galloni¹⁸¹, H. He¹⁸¹, M. Herndon¹⁸¹, A. Herve¹⁸¹, C. K. Koraka¹⁸¹, A. Lanaro¹⁸¹, R. Loveless¹⁸¹, J. Madhusudanan Sreekala¹⁸¹, A. Mallampalli¹⁸¹, A. Mohammadi¹⁸¹, S. Mondal¹⁸¹, G. Parida¹⁸¹, D. Pinna¹⁸¹, A. Savin¹⁸¹, V. Shang¹⁸¹, V. Sharma¹⁸¹, W. H. Smith¹⁸¹, D. Teague¹⁸¹, H. F. Tsoi¹⁸¹, W. Vetens¹⁸¹, A. Warden¹⁸¹, S. Afanasiev¹⁸², V. Andreev¹⁸², Yu. Andreev¹⁸², T. Aushev¹⁸², M. Azarkin¹⁸², A. Babaev¹⁸², A. Belyaev¹⁸², V. Blinov^{182,m}, E. Boos¹⁸², V. Borschch¹⁸², D. Budkouski¹⁸², V. Bunichev¹⁸², V. Chekhovskiy¹⁸², R. Chistov^{182,m}, M. Danilov^{182,m}, A. Dermenev¹⁸², T. Dimova^{182,m}, I. Dremin¹⁸², M. Dubinin^{182,iiii}, L. Dudko¹⁸², V. Epshteyn¹⁸², A. Ershov¹⁸², G. Gavrilo¹⁸², V. Gavrilo¹⁸², S. Gninenko¹⁸², V. Golovtsov¹⁸², N. Golubev¹⁸², I. Golutvin¹⁸², I. Gorbunov¹⁸², Y. Ivanov¹⁸², V. Kachanov¹⁸², L. Kardapoltsev^{182,m}, V. Karjavine¹⁸², A. Karneyev¹⁸², V. Kim^{182,m}, M. Kirakosyan¹⁸², D. Kirpichnikov¹⁸², M. Kirsanov¹⁸², V. Klyukhin¹⁸², O. Kodolova^{182,qqqq}, D. Konstantinov¹⁸², V. Korenkov¹⁸², A. Kozyrev^{182,m}, N. Krasnikov¹⁸², A. Lanev¹⁸², P. Levchenko¹⁸², A. Litomin¹⁸², N. Lychkovskaya¹⁸², V. Makarenko¹⁸², A. Malakhov¹⁸², V. Matveev^{182,m}, V. Murzin¹⁸², A. Nikitenko^{182,mrr}, S. Obraztsov¹⁸², I. Ovtin^{182,m}, V. Palichik¹⁸², V. Perelygin¹⁸², M. Perfilov¹⁸², S. Petrushanko¹⁸², S. Polikarpov^{182,m}, V. Popov¹⁸², O. Radchenko^{182,m}, M. Savina¹⁸², V. Savrin¹⁸², D. Selivanova¹⁸², V. Shalae¹⁸², S. Shmatov¹⁸², S. Shulha¹⁸², Y. Skovpen^{182,m}, S. Slabospitskii¹⁸², V. Smirnov¹⁸², D. Sosnov¹⁸², V. Sulimov¹⁸²

E. Tcherniaev¹⁸², A. Terkulov¹⁸², O. Teryaev¹⁸², I. Tlisova¹⁸², A. Toropin¹⁸², L. Uvarov¹⁸², A. Uzunian¹⁸²,
A. Vorobyev^{182,a}, N. Voytishin¹⁸², B. S. Yuldashev^{182,ssss}, A. Zarubin¹⁸², I. Zhizhin¹⁸² and A. Zhokin¹⁸²

(CMS Collaboration)

- ¹Yerevan Physics Institute, Yerevan, Armenia
²Institut für Hochenergiephysik, Vienna, Austria
³Universiteit Antwerpen, Antwerpen, Belgium
⁴Vrije Universiteit Brussel, Brussel, Belgium
⁵Université Libre de Bruxelles, Bruxelles, Belgium
⁶Ghent University, Ghent, Belgium
⁷Université Catholique de Louvain, Louvain-la-Neuve, Belgium
⁸Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
⁹Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
¹⁰Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
¹¹Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
¹²University of Sofia, Sofia, Bulgaria
¹³Instituto de Alta Investigación, Universidad de Tarapaca, Casilla 7 D, Arica, Chile
¹⁴Beihang University, Beijing, China
¹⁵Department of Physics, Tsinghua University, Beijing, China
¹⁶Institute of High Energy Physics, Beijing, China
¹⁷State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
¹⁸Sun Yat-Sen University, Guangzhou, China
¹⁹University of Science and Technology of China, Hefei, China
²⁰Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
²¹Zhejiang University, Hangzhou, Zhejiang, China
²²Universidad de Los Andes, Bogota, Colombia
²³Universidad de Antioquia, Medellín, Colombia
²⁴University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
²⁵University of Split, Faculty of Science, Split, Croatia
²⁶Institute Rudjer Boskovic, Zagreb, Croatia
²⁷University of Cyprus, Nicosia, Cyprus
²⁸Charles University, Prague, Czech Republic
²⁹Escuela Politécnica Nacional, Quito, Ecuador
³⁰Universidad San Francisco de Quito, Quito, Ecuador
³¹Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
³²Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
³³National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
³⁴Department of Physics, University of Helsinki, Helsinki, Finland
³⁵Helsinki Institute of Physics, Helsinki, Finland
³⁶Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
³⁷IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
³⁸Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
³⁹Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
⁴⁰Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
⁴¹Georgian Technical University, Tbilisi, Georgia
⁴²RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
⁴³RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
⁴⁴RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
⁴⁵Deutsches Elektronen-Synchrotron, Hamburg, Germany
⁴⁶University of Hamburg, Hamburg, Germany
⁴⁷Karlsruher Institut fuer Technologie, Karlsruhe, Germany
⁴⁸Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
⁴⁹National and Kapodistrian University of Athens, Athens, Greece
⁵⁰National Technical University of Athens, Athens, Greece
⁵¹University of Ioánnina, Ioánnina, Greece

- ⁵²*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*
- ⁵³*Wigner Research Centre for Physics, Budapest, Hungary*
- ⁵⁴*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁵⁵*Institute of Physics, University of Debrecen, Debrecen, Hungary*
- ⁵⁶*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
- ⁵⁷*Panjab University, Chandigarh, India*
- ⁵⁸*University of Delhi, Delhi, India*
- ⁵⁹*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁶⁰*Indian Institute of Technology Madras, Madras, India*
- ⁶¹*Bhabha Atomic Research Centre, Mumbai, India*
- ⁶²*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶³*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶⁴*National Institute of Science Education and Research,
An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
- ⁶⁵*Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁶⁶*Isfahan University of Technology, Isfahan, Iran*
- ⁶⁷*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁶⁸*University College Dublin, Dublin, Ireland*
- ^{69a}*INFN Sezione di Bari, Bari, Italy*
- ^{69b}*Università di Bari, Bari, Italy*
- ^{69c}*Politecnico di Bari, Bari, Italy*
- ^{70a}*INFN Sezione di Bologna, Bologna, Italy*
- ^{70b}*Università di Bologna, Bologna, Italy*
- ^{71a}*INFN Sezione di Catania, Catania, Italy*
- ^{71b}*Università di Catania, Catania, Italy*
- ^{72a}*INFN Sezione di Firenze, Firenze, Italy*
- ^{72b}*Università di Firenze, Firenze, Italy*
- ⁷³*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ^{74a}*INFN Sezione di Genova, Genova, Italy*
- ^{74b}*Università di Genova, Genova, Italy*
- ^{75a}*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ^{75b}*Università di Milano-Bicocca, Milano, Italy*
- ^{76a}*INFN Sezione di Napoli, Napoli, Italy*
- ^{76b}*Università di Napoli 'Federico II', Napoli, Italy*
- ^{76c}*Università della Basilicata, Potenza, Italy*
- ^{76d}*Università G. Marconi, Roma, Italy*
- ^{77a}*INFN Sezione di Padova, Padova, Italy*
- ^{77b}*Università di Padova, Padova, Italy*
- ^{77c}*Università di Trento, Trento, Italy*
- ^{78a}*INFN Sezione di Pavia, Pavia, Italy*
- ^{78b}*Università di Pavia, Pavia, Italy*
- ^{79a}*INFN Sezione di Perugia, Perugia, Italy*
- ^{79b}*Università di Perugia, Perugia, Italy*
- ^{80a}*INFN Sezione di Pisa, Pisa, Italy*
- ^{80b}*Università di Pisa, Pisa, Italy*
- ^{80c}*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ^{80d}*Università di Siena, Siena, Italy*
- ^{81a}*INFN Sezione di Roma, Roma, Italy*
- ^{81b}*Sapienza Università di Roma, Roma, Italy*
- ^{82a}*INFN Sezione di Torino, Torino, Italy*
- ^{82b}*Università di Torino, Torino, Italy*
- ^{82c}*Università del Piemonte Orientale, Novara, Italy*
- ^{83a}*INFN Sezione di Trieste, Trieste, Italy*
- ^{83b}*Università di Trieste, Trieste, Italy*
- ⁸⁴*Kyungpook National University, Daegu, Korea*
- ⁸⁵*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ⁸⁶*Hanyang University, Seoul, Korea*
- ⁸⁷*Korea University, Seoul, Korea*
- ⁸⁸*Kyung Hee University, Department of Physics, Seoul, Korea*
- ⁸⁹*Sejong University, Seoul, Korea*

- ⁹⁰Seoul National University, Seoul, Korea
⁹¹University of Seoul, Seoul, Korea
⁹²Yonsei University, Department of Physics, Seoul, Korea
⁹³Sungkyunkwan University, Suwon, Korea
⁹⁴College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
⁹⁵Riga Technical University, Riga, Latvia
⁹⁶Vilnius University, Vilnius, Lithuania
⁹⁷National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
⁹⁸Universidad de Sonora (UNISON), Hermosillo, Mexico
⁹⁹Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
¹⁰⁰Universidad Iberoamericana, Mexico City, Mexico
¹⁰¹Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
¹⁰²University of Montenegro, Podgorica, Montenegro
¹⁰³National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
¹⁰⁴AGH University of Science and Technology Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
¹⁰⁵National Centre for Nuclear Research, Swierk, Poland
¹⁰⁶Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
¹⁰⁷Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
¹⁰⁸VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
¹⁰⁹Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
¹¹⁰Universidad Autónoma de Madrid, Madrid, Spain
¹¹¹Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
¹¹²Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
¹¹³University of Colombo, Colombo, Sri Lanka
¹¹⁴University of Ruhuna, Department of Physics, Matara, Sri Lanka
¹¹⁵CERN, European Organization for Nuclear Research, Geneva, Switzerland
¹¹⁶Paul Scherrer Institut, Villigen, Switzerland
¹¹⁷ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
¹¹⁸Universität Zürich, Zurich, Switzerland
¹¹⁹National Central University, Chung-Li, Taiwan
¹²⁰National Taiwan University (NTU), Taipei, Taiwan
¹²¹Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
¹²²Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
¹²³Middle East Technical University, Physics Department, Ankara, Turkey
¹²⁴Bogazici University, Istanbul, Turkey
¹²⁵Istanbul Technical University, Istanbul, Turkey
¹²⁶Istanbul University, Istanbul, Turkey
¹²⁷Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
¹²⁸National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
¹²⁹University of Bristol, Bristol, United Kingdom
¹³⁰Rutherford Appleton Laboratory, Didcot, United Kingdom
¹³¹Imperial College, London, United Kingdom
¹³²Brunel University, Uxbridge, United Kingdom
¹³³Baylor University, Waco, Texas, USA
¹³⁴Catholic University of America, Washington, DC, USA
¹³⁵The University of Alabama, Tuscaloosa, Alabama, USA
¹³⁶Boston University, Boston, Massachusetts, USA
¹³⁷Brown University, Providence, Rhode Island, USA
¹³⁸University of California, Davis, Davis, California, USA
¹³⁹University of California, Los Angeles, California, USA
¹⁴⁰University of California, Riverside, Riverside, California, USA
¹⁴¹University of California, San Diego, La Jolla, California, USA
¹⁴²University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
¹⁴³California Institute of Technology, Pasadena, California, USA
¹⁴⁴Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
¹⁴⁵University of Colorado Boulder, Boulder, Colorado, USA
¹⁴⁶Cornell University, Ithaca, New York, USA
¹⁴⁷Fermi National Accelerator Laboratory, Batavia, Illinois, USA
¹⁴⁸University of Florida, Gainesville, Florida, USA
¹⁴⁹Florida State University, Tallahassee, Florida, USA

- ¹⁵⁰Florida Institute of Technology, Melbourne, Florida, USA
¹⁵¹University of Illinois at Chicago (UIC), Chicago, Illinois, USA
¹⁵²The University of Iowa, Iowa City, Iowa, USA
¹⁵³Johns Hopkins University, Baltimore, Maryland, USA
¹⁵⁴The University of Kansas, Lawrence, Kansas, USA
¹⁵⁵Kansas State University, Manhattan, Kansas, USA
¹⁵⁶Lawrence Livermore National Laboratory, Livermore, California, USA
¹⁵⁷University of Maryland, College Park, Maryland, USA
¹⁵⁸Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹⁵⁹University of Minnesota, Minneapolis, Minnesota, USA
¹⁶⁰University of Mississippi, Oxford, Mississippi, USA
¹⁶¹University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁶²State University of New York at Buffalo, Buffalo, New York, USA
¹⁶³Northeastern University, Boston, Massachusetts, USA
¹⁶⁴Northwestern University, Evanston, Illinois, USA
¹⁶⁵University of Notre Dame, Notre Dame, Indiana, USA
¹⁶⁶The Ohio State University, Columbus, Ohio, USA
¹⁶⁷Princeton University, Princeton, New Jersey, USA
¹⁶⁸University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁶⁹Purdue University, West Lafayette, Indiana, USA
¹⁷⁰Purdue University Northwest, Hammond, Indiana, USA
¹⁷¹Rice University, Houston, Texas, USA
¹⁷²University of Rochester, Rochester, New York, USA
¹⁷³The Rockefeller University, New York, New York, USA
¹⁷⁴Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁷⁵University of Tennessee, Knoxville, Tennessee, USA
¹⁷⁶Texas A&M University, College Station, Texas, USA
¹⁷⁷Texas Tech University, Lubbock, Texas, USA
¹⁷⁸Vanderbilt University, Nashville, Tennessee, USA
¹⁷⁹University of Virginia, Charlottesville, Virginia, USA
¹⁸⁰Wayne State University, Detroit, Michigan, USA
¹⁸¹University of Wisconsin—Madison, Madison, Wisconsin, USA

¹⁸²Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN

^aDeceased.

^bAlso at Yerevan State University, Yerevan, Armenia.

^cAlso at TU Wien, Vienna, Austria.

^dAlso at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt.

^eAlso at Université Libre de Bruxelles, Bruxelles, Belgium.

^fAlso at Universidade Estadual de Campinas, Campinas, Brazil.

^gAlso at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.

^hAlso at UFMS, Nova Andradina, Brazil.

ⁱAlso at University of Chinese Academy of Sciences, Beijing, China.

^jAlso at Nanjing Normal University Department of Physics, Nanjing, China.

^kAlso at The University of Iowa, Iowa City, Iowa, USA.

^lAlso at University of Chinese Academy of Sciences, Beijing, China.

^mAlso at Another institute or international laboratory covered by a cooperation agreement with CERN.

ⁿAlso at British University in Egypt, Cairo, Egypt.

^oAlso at Suez University, Suez, Egypt.

^pAlso at Purdue University, West Lafayette, Indiana, USA.

^qAlso at Université de Haute Alsace, Mulhouse, France.

^rAlso at Department of Physics, Tsinghua University, Beijing, China.

^sAlso at The University of the State of Amazonas, Manaus, Brazil.

^tAlso at Erzincan Binali Yildirim University, Erzincan, Turkey.

^uAlso at University of Hamburg, Hamburg, Germany.

^vAlso at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

^wAlso at Isfahan University of Technology, Isfahan, Iran.

^xAlso at Bergische University Wuppertal (BUW), Wuppertal, Germany.

^yAlso at Brandenburg University of Technology, Cottbus, Germany.

- ^z Also at Forschungszentrum Jülich, Juelich, Germany.
- ^{aa} Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
- ^{bb} Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
- ^{cc} Also at Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary.
- ^{dd} Also at Wigner Research Centre for Physics, Budapest, Hungary.
- ^{ee} Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
- ^{ff} Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
- ^{gg} Also at Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
- ^{hh} Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.
- ⁱⁱ Also at Punjab Agricultural University, Ludhiana, India.
- ^{jj} Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
- ^{kk} Also at University of Visva-Bharati, Santiniketan, India.
- ^{ll} Also at University of Hyderabad, Hyderabad, India.
- ^{mm} Also at Indian Institute of Science (IISc), Bangalore, India.
- ⁿⁿ Also at Indian Institute of Technology (IIT), Mumbai, India.
- ^{oo} Also at IIT Bhubaneswar, Bhubaneswar, India.
- ^{pp} Also at Institute of Physics, Bhubaneswar, India.
- ^{qq} Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
- ^{rr} Also at Sharif University of Technology, Tehran, Iran.
- ^{ss} Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ^{tt} Also at Helwan University, Cairo, Egypt.
- ^{uu} Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ^{vv} Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ^{ww} Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ^{xx} Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
- ^{yy} Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- ^{zz} Also at Università di Napoli 'Federico II', Napoli, Italy.
- ^{aaa} Also at Ain Shams University, Cairo, Egypt.
- ^{bbb} Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
- ^{ccc} Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- ^{ddd} Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{eee} Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
- ^{fff} Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{ggg} Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ^{hhh} Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ⁱⁱⁱ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{jjj} Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ^{kkk} Also at Universität Zürich, Zurich, Switzerland.
- ^{lll} Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ^{mmm} Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ⁿⁿⁿ Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ^{ooo} Also at Konya Technical University, Konya, Turkey.
- ^{ppp} Also at Izmir Bakircay University, Izmir, Turkey.
- ^{qqq} Also at Adiyaman University, Adiyaman, Turkey.
- ^{rrr} Also at Istanbul Gedik University, Istanbul, Turkey.
- ^{sss} Also at Necmettin Erbakan University, Konya, Turkey.
- ^{ttt} Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ^{uuu} Also at Marmara University, Istanbul, Turkey.
- ^{vvv} Also at Milli Savunma University, Istanbul, Turkey.
- ^{www} Also at Kafkas University, Kars, Turkey.
- ^{xxx} Also at Hacettepe University, Ankara, Turkey.
- ^{yyy} Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ^{zzz} Also at Yildiz Technical University, Istanbul, Turkey.
- ^{aaaa} Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ^{bbbb} Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{cccc} Also at University of Bristol, Bristol, United Kingdom.
- ^{dddd} Also at IPPP Durham University, Durham, United Kingdom.
- ^{eeee} Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{fff} Also at Università di Torino, Torino, Italy.
- ^{gggg} Also at Bethel University, St. Paul, Minnesota, USA.

^{hhhh} Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.

ⁱⁱⁱⁱ Also at California Institute of Technology, Pasadena, California, USA.

^{jjjj} Also at United States Naval Academy, Annapolis, Maryland, USA.

^{kkkk} Also at Bingol University, Bingol, Turkey.

^{llll} Also at Georgian Technical University, Tbilisi, Georgia.

^{mmmm} Also at Sinop University, Sinop, Turkey.

ⁿⁿⁿⁿ Also at Erciyes University, Kayseri, Turkey.

^{oooo} Also at Texas A&M University at Qatar, Doha, Qatar.

^{pppp} Also at Kyungpook National University, Daegu, Korea.

^{qqqq} Also at Yerevan Physics Institute, Yerevan, Armenia.

^{rrrr} Also at Imperial College, London, United Kingdom.

^{ssss} Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.