Simultaneous Probe of the Charm and Bottom Quark Yukawa Couplings Using $t\bar{t}H$ Events

A. Hayrapetyan *et al.*[*]
(CMS Collaboration)

(Received 26 September 2025; accepted 7 November 2025; published 2 January 2026)

A search for the standard model Higgs boson decaying to a charm quark-antiquark pair, $H \to c\bar{c}$, produced in association with a top quark-antiquark pair ($t\bar{t}H$) is presented. The search is performed with data from proton-proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1}. Advanced machine learning techniques are employed for jet flavor identification and event classification. The Higgs boson decay to a bottom quark-antiquark pair is measured simultaneously and the observed $t\bar{t}H(H \to b\bar{b})$ event rate relative to the standard model expectation is $0.91^{+0.26}_{-0.22}$. The observed (expected) upper limit on the product of production cross section and branching fraction $\sigma(t\bar{t}H)\mathcal{B}(H \to c\bar{c})$ is 0.11 (0.13) pb at 95% confidence level, corresponding to 7.8 (8.7) times the standard model prediction. When combined with the previous search for $H \to c\bar{c}$ via associated production with a W or Z boson, the observed (expected) 95% confidence interval on the Higgs-charm Yukawa coupling modifier, κ_c, is $|\kappa_c| <$ 3.5 (2.7), the most stringent constraint to date.

DOI: 10.1103/9nwb-splk

The discovery of a Higgs boson (H) by the ATLAS [1] and CMS [2,3] experiments was a landmark achievement in understanding electroweak (EW) symmetry breaking. With a measured mass of 125.38 ± 0.14 GeV [4], the Higgs boson's observed interactions with gauge bosons and third-generation fermions [5–15], as well as all its measured properties [16–24], align with the standard model (SM) predictions. Following the first evidence of Higgs boson decays to muons, i.e., second-generation leptons [25], another important milestone is to observe its couplings to second-generation quarks.

The charm quark Yukawa coupling, y_c, can be significantly modified in the presence of physics beyond the SM [26–34]. Searches for Higgs boson decays to a charm quark-antiquark pair, $c\bar{c}$, provide direct access to y_c. To date, the most sensitive approach at the LHC exploits associated production of a Higgs boson with a V (W or Z) boson. Using proton-proton (pp) collision data at 13 TeV, corresponding to an integrated luminosity of about 140 fb^{-1}, the ATLAS [35] and CMS [36] Collaborations reported observed (expected) 95% confidence level (CL) intervals on $\kappa_c = y_c/y_c^{\mathrm{SM}}$ of $|\kappa_c| < 4.2$ (4.1) and $1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$), respectively. The search in the dominant gluon fusion production mode yields lower sensitivity because of the overwhelming $c\bar{c}$ background from quantum chromodynamics (QCD) multijet production [37]. Despite these advancements, projections for the high-luminosity LHC [38] indicate that current approaches may prove insufficient to achieve evidence of $H \to c\bar{c}$ decay within the experiment's lifetime.

In this Letter, we present a new approach: to search for $H \to c\bar{c}$ via associated production of a Higgs boson with a top quark-antiquark pair ($t\bar{t}H$) and to measure simultaneously the $H \to b\bar{b}$ decay. We use pp collision data at $\sqrt{s} = 13$ TeV, collected with the CMS detector in 2016–2018, and corresponding to an integrated luminosity of 138 fb^{-1} [39–41]. The analogous processes $t\bar{t}Z(Z \to c\bar{c})$ and $t\bar{t}Z(Z \to b\bar{b})$ are measured to validate the analysis strategy. For $t\bar{t}H(H \to c\bar{c})$ and $t\bar{t}H(H \to b\bar{b})$, the presence of multiple jets, including several b and c jets, poses significant challenges in identifying the jet origins and in reconstructing the top quark and Higgs boson decays. To address this, we employ advanced machine learning algorithms, ParticleNet [42] for jet flavor identification and Particle Transformer (ParT) [43] for event classification. The resulting sensitivity is comparable to the best achieved in the VH channel [36].

The CMS apparatus [44,45] is a multipurpose, nearly hermetic detector, designed to trigger on [46–48] and identify electrons, muons, photons, and hadrons [49–51]. A global "particle-flow" algorithm [52] 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

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

data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build jets, employing the anti-k_T algorithm [53,54] with a distance parameter $R = 0.4$, and to compute missing transverse momentum [55,56].

Signal and background processes are simulated using various Monte Carlo event generators. The $t\bar{t}H$ signal process is generated at next-to-leading order (NLO) accuracy in QCD using POWHEG v2 [57–59], with the Higgs boson and top quark masses set to 125 and 172.5 GeV, respectively. The main background is $t\bar{t}$ production with additional jets ($t\bar{t}$ + jets), particularly when these additional jets originate from the hadronization of b or c quarks, as such events closely resemble the signal topology. This background is categorized based on the flavor of the additional jets, i.e., those that do not originate from top quark decays. Jets containing at least one b hadron (at least one c hadron and no b hadron) are defined as b (c) jets, following the ghost association procedure [60]. The remaining jets are labeled as light jets. Events containing one extra b jet are labeled as $t\bar{t} + b$, while those with two or more are labeled as $t\bar{t}+ \geq 2b$. Similarly, events with no b jets but one (two or more) extra c jet are labeled as $t\bar{t} + c$ ($t\bar{t}+ \geq 2c$). The remaining $t\bar{t}$ + jets events, containing no b or c jets other than those from top quark decays, are labeled $t\bar{t}$ + light. To achieve the highest available accuracy in modeling the $t\bar{t}$ + jets components, a dedicated $t\bar{t}b\bar{b}$ sample is used to predict the $t\bar{t} + b$ and $t\bar{t}+ \geq 2b$ backgrounds. This sample is generated at NLO in QCD in the four-flavor scheme using POWHEG-BOX-RES [61,62] and OpenLoops [63], explicitly including additional b quarks in the matrix element calculation. Contributions to $t\bar{t} + b$ and $t\bar{t}+ \geq 2b$ from double parton scattering—amounting to ≈15% of the $t\bar{t}b\bar{b}$ production cross section—are not included in the $t\bar{t}b\bar{b}$ sample and are modeled separately. The remaining components, $t\bar{t} + c$, $t\bar{t}+ \geq 2c$, and $t\bar{t}$ + light, are modeled using an inclusive $t\bar{t}$ sample simulated with POWHEG v2 at NLO in QCD in the five-flavor scheme [64]. Measurements of $t\bar{t}+ \geq 1b$ and $t\bar{t}+ \geq 1c$ production [65–68] indicate moderate mismodeling in simulation, necessitating corrections of the background estimates based on control samples in data.

Single top quark production in the t channel (s channel) and in association with a W boson is simulated at NLO accuracy with POWHEG v2 [69–71] (MadGraph5_aMC@NLO v2.6.5 [72]). The production cross sections for the $t\bar{t}$ and single top quark samples are computed at next-to-NLO (NNLO) [73,74]. For $t\bar{t}$, the differential cross section as a function of top quark p_T is corrected to the NNLO QCD + NLO EW prediction [75]. The $t\bar{t}W$ and $t\bar{t}Z$ (tWZ) processes are simulated at NLO (leading order, LO) accuracy in QCD using MadGraph5_aMC@NLO. The matching of jets from matrix element calculations and those from parton showers is done with the FxFx [76] (MLM [77]) prescription for NLO (LO) samples. For all samples, the proton structure is described by the NNLO NNPDF3.1 parton distribution function (PDF) set [78]. Parton showering and hadronization are handled by PYTHIA v8.240 [79] with the CP5 underlying event tune [80]. Additional pp interactions within the same or nearby bunch crossings (pileup) are simulated with PYTHIA and added to the hard-scattering process, with events reweighted to match the pileup profile observed in data. The detector response is modeled with Geant4 [81].

The analysis is carried out in three mutually exclusive channels targeting the fully hadronic (0L), single-lepton (1L), and dilepton (2L) decays of the top quark-antiquark pair. Events are collected using triggers based on high jet and b jet multiplicities, or on the presence of one or two well-identified and isolated leptons (electrons or muons). In the offline selection, only jets with transverse momentum $p_T > 25$ GeV and pseudorapidity $|\eta| < 2.4$ are considered. In the 0L channel, events must contain at least seven jets, of which at least six have $p_T > 40$ GeV, and have a jet p_T scalar sum exceeding 500 GeV to satisfy trigger requirements. The 1L channel selects events with one isolated electron or muon with a minimum p_T of 26 to 30 GeV, depending on the lepton flavor and the trigger requirements in each data-taking year, along with at least five jets. The 2L channel selects events with two oppositely charged leptons, at least one with $p_T > 25$ GeV, and at least four jets. To suppress the Drell-Yan background, events with a dielectron or dimuon invariant mass below 20 GeV or within the Z boson mass window (76–106 GeV) are excluded. Across all channels, events must contain at least three jets tagged as either b or c jets, with at least one tagged as a b jet, using criteria corresponding to tagging efficiencies of approximately 70% (50%) for b (c) jets. Additional details of the event selection criteria are provided in Supplemental Material [82], which includes references [83–90].

A key challenge in this analysis is accurately identifying jet flavor—not only efficiently tagging heavy-flavor jets initiated by b or c quarks but also distinguishing between them. To address this, ParticleNet [42], a dynamic graph convolutional neural network [93], is employed to classify jet flavors by leveraging spatial and kinematic correlations of individual particles and secondary vertices associated with the jets. Two discriminants are constructed from the ParticleNet outputs: p_{B+C}, which differentiates heavy-flavor from light jets, and $p_{B\mathrm{vs}C}$, which distinguishes b from c jets. Based on these, 11 mutually exclusive tagging categories are defined as shown in Fig. 1: five b-tagging categories (`B0`–`B4`), five c-tagging categories (`C0`–`C4`), and one untagged category (`L0`) enriched in light jets. Compared to the previously used DeepJet algorithm [94], ParticleNet improves background jet rejection by up to a factor of 2 at the same signal jet efficiency, demonstrating superior performance in distinguishing jet flavors.

To correct for potential mismodeling of tagging efficiencies in simulation, flavor-dependent scale factors are

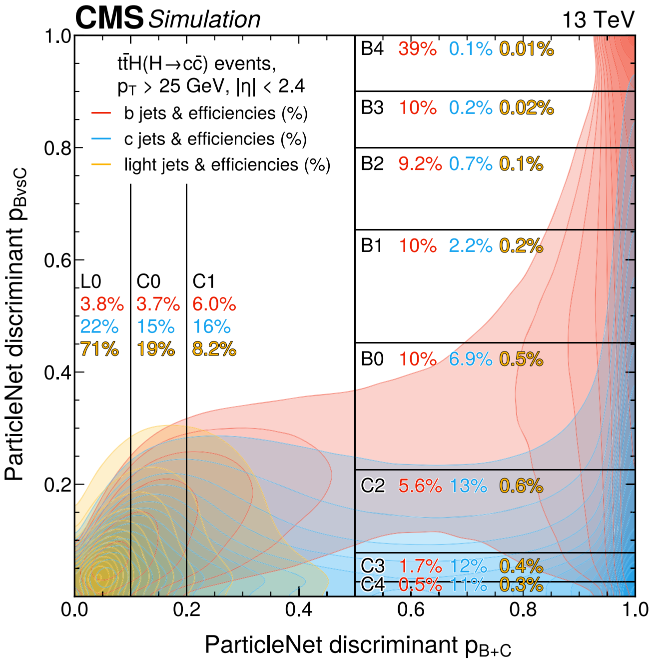

FIG. 1. Distribution of b, c, and light jets in the two-dimensional ParticleNet discriminant plane. The vertical and horizontal lines correspond to the edges of the tagging categories. The numbers in each bin correspond to the tagging efficiencies for b (red), c (blue), and light (yellow) jets, evaluated on a sample of simulated $t\bar{t}H(H \to c\bar{c})$ events. The contour lines represent constant density values for each jet type in steps of 5%.

derived using data samples targeting the production of $W +$ jets, dileptonic $t\bar{t}$, and $Z +$ jets, which are enriched in c, b, and light jets, respectively. These scale factors, defined as data-to-simulation efficiency ratios for each jet type in the 11 tagging categories as functions of jet p_{T}, are extracted via a simultaneous profile likelihood fit to all three data samples. Further details about the tagger performance and calibration are provided in Supplemental Material [82]. The scale factors typically range from 0.75 to 1.5, with uncertainties of up to ≈15% for b jets and up to ≈50% for c and light jets.

A further challenge involves distinguishing the $t\bar{t}H$ signal from the $t\bar{t} +$ jets background. Both processes produce numerous jets, including multiple b and c jets, which may originate from top quark or Higgs boson decays, or from additional quark or gluon radiation. This complexity hinders precise jet origin identification and full decay chain reconstruction. To overcome this, a multiclass event classifier based on ParT [43] is developed to classify events directly from final-state objects—jets, leptons, and missing transverse momentum—without requiring explicit reconstruction of the top quarks or the Higgs boson. For every object, the classifier receives kinematic inputs in terms of $\ln(p_{\mathrm{T}}/\mathrm{GeV})$, $\ln(E/\mathrm{GeV})$, and η. Jet flavor is encoded via ten boolean values corresponding to the tagging categories `B0`–`B4` and `C0`–`C4`. For each lepton, a flag is included to distinguish between electrons and muons. To better capture event kinematic values and object correlations, ParT constructs pairwise features (e.g., angular separation and invariant mass) for all object pairs using their four-momenta. The classifier is trained to assign likelihood scores across ten (nine) classes in the 0L (1L, 2L) channel—two $t\bar{t}H$ classes: $t\bar{t}H(H \to c\bar{c})$, $t\bar{t}H(H \to b\bar{b})$; two $t\bar{t}Z$ classes: $t\bar{t}Z(Z \to c\bar{c})$, $t\bar{t}Z(Z \to b\bar{b})$; five $t\bar{t} +$ jets classes: $t\bar{t} + b$, $t\bar{t} + \geq 2b$, $t\bar{t} + c$, $t\bar{t} + \geq 2c$, $t\bar{t} +$ light; and (only in the 0L channel) one class for QCD multijet.

The ParT classifier is used to refine event selection and categorization. In the 0L channel, a stringent requirement on the QCD multijet discriminant suppresses this background by nearly 4 orders of magnitude, allowing it to be neglected relative to $t\bar{t} +$ jets and enabling a uniform event categorization strategy across all three channels, as depicted in Fig. 5 in the End Matter. Only events with a high $t\bar{t}H$ or $t\bar{t}Z$ likelihood—defined as $\mathcal{D}_{t\bar{t}X} > 0.6$, where $\mathcal{D}_{t\bar{t}X}$ is the sum of all four $t\bar{t}H$ and $t\bar{t}Z$ discriminants—are retained for signal extraction and background estimation. A requirement on the $t\bar{t} +$ light discriminant, $\mathcal{D}_{t\bar{t}+\mathrm{light}} < 0.05$ (0.02) in the 0L and 2L (1L) channels, further reduces $t\bar{t} +$ light contamination. Events passing these criteria are categorized into four signal regions (SRs) with $\mathcal{D}_{t\bar{t}X} > 0.85$, each enriched in $t\bar{t}H(H \to c\bar{c})$, $t\bar{t}H(H \to b\bar{b})$, $t\bar{t}Z(Z \to c\bar{c})$, and $t\bar{t}Z(Z \to b\bar{b})$, along with five control regions (CRs) with $0.6 < \mathcal{D}_{t\bar{t}X} < 0.85$, which are used to estimate the normalizations of various $t\bar{t} +$ jets background components in a phase space similar to that of the SRs. Additional requirements on heavy-flavor jet multiplicity enhance purity: at least three b jets are required in the b-enriched regions [$t\bar{t}H(H \to b\bar{b})$, $t\bar{t}Z(Z \to b\bar{b})$, $t\bar{t} + \geq 2b$, and $t\bar{t} + b$], at least two c jets in the c-enriched $t\bar{t}H(H \to c\bar{c})$, $t\bar{t}Z(Z \to c\bar{c})$, and $t\bar{t} + \geq 2c$ regions, and at least one c jet in the $t\bar{t} + c$ region. A signal-depleted sideband region, defined by $0.4 < \mathcal{D}_{t\bar{t}X} < 0.6$ with an analogous SR and CR structure, is used to validate the background estimation strategy.

Production rates of the signal processes are determined via a binned profile likelihood fit to data. The fitted variable is the ParT classifier discriminant for each category. For each of the $t\bar{t}H(H \to c\bar{c})$, $t\bar{t}H(H \to b\bar{b})$, $t\bar{t}Z(Z \to c\bar{c})$, and $t\bar{t}Z(Z \to b\bar{b})$ processes, the expected yield is scaled by an independent signal strength modifier μ, defined as $(\sigma\mathcal{B})_{\mathrm{obs}}/(\sigma\mathcal{B})_{\mathrm{SM}}$. Here σ is the production cross section and $\mathcal{B}$ is the branching fraction, which is allowed to freely float in the fit, following the procedure in Ref. [17]. The dominant background, $t\bar{t} +$ jets, is estimated by including CRs in the fit, with the normalizations of the $t\bar{t} + c$, $t\bar{t} + \geq 2c$, $t\bar{t} + b$, $t\bar{t} + \geq 2b$, and $t\bar{t} +$ light components allowed to float independently. The normalization factors for each $t\bar{t} +$ jets component are shared between the 1L and 2L channels but not with the 0L channel, to account for potential phase space differences due to the requirement of more energetic jets in the 0L case. Minor backgrounds, such as single top quark production, $t\bar{t}W$, and tWZ, are estimated directly from simulations assuming SM production rates. Results are obtained using COMBINE [95], the CMS statistical analysis tool based on the RooFit [96] and RooStats [97] frameworks.

Systematic uncertainties affecting normalizations and shapes of fitted variables are incorporated via nuisance parameters that encode the appropriate correlations across channels. The contributions of each uncertainty source to the total uncertainty in the fitted $\mu_{t\bar{t}H(H\to c\bar{c})}$ and $\mu_{t\bar{t}H(H\to b\bar{b})}$ are summarized in Table II in the End Matter. For $\mu_{t\bar{t}H(H\to c\bar{c})}$, the leading uncertainty is statistical because of the limited number of events in the SRs as well as in the CRs used to extract background normalizations. The main systematic uncertainty arises from the theoretical modeling of the $t\bar{t}+c$ and $t\bar{t}+$ light processes, contributing ≈32% and ≈29% of the total uncertainty, respectively. For $\mu_{t\bar{t}H(H\to b\bar{b})}$, the largest uncertainties are theoretical, including those associated with the renormalization and factorization scales, flavor scheme, and parton shower modeling in the $t\bar{t}b\bar{b}$ simulation, representing ≈60% of the total uncertainty. Theoretical uncertainties in the $t\bar{t}H$ signal simulation contribute an additional ≈47%. For both measurements, the primary experimental uncertainty is associated with jet flavor identification efficiencies, representing ≈39% (≈28%) of the total uncertainty in $\mu_{t\bar{t}H(H\to c\bar{c})}$ ($\mu_{t\bar{t}H(H\to b\bar{b})}$).

The analysis is validated by measuring the $t\bar{t}Z$ signal strengths:

$$\mu_{t\bar{t}Z(Z\to c\bar{c})} = 1.02^{+0.79}_{-0.84},$$
$$\mu_{t\bar{t}Z(Z\to b\bar{b})} = 1.47^{+0.45}_{-0.41}, \qquad (1)$$

which are consistent with the SM prediction within uncertainties and with measurements in the leptonic decay channel [98–100]. The significance of the excess over the background-only hypothesis is computed using the asymptotic distribution of a test statistic based on the profile likelihood ratio [101,102]. The observed (expected) significance is 1.2 (1.3) standard deviations for $t\bar{t}Z(Z\to c\bar{c})$ and 3.5 (2.4) standard deviations for $t\bar{t}Z(Z\to b\bar{b})$.

Figure 2 shows the observed and expected event yields from all CRs and SRs as a function of $\log_{10}(S/B)$, the logarithm of the ratio of $t\bar{t}H(H\to c\bar{c})$ [or $t\bar{t}H(H\to b\bar{b})$] and background yields. The best fit signal strengths for $t\bar{t}H$ production are

$$\mu_{t\bar{t}H(H\to c\bar{c})} = -1.6 \pm 4.5,$$
$$\mu_{t\bar{t}H(H\to b\bar{b})} = 0.91^{+0.26}_{-0.22}, \qquad (2)$$

with an observed (expected) significance of 4.4 (4.5) standard deviations for the $t\bar{t}H(H\to b\bar{b})$ process. The best fit $\mu_{t\bar{t}H(H\to b\bar{b})}$ value is closer to the SM prediction than was the previous measurement [103], with a compatibility

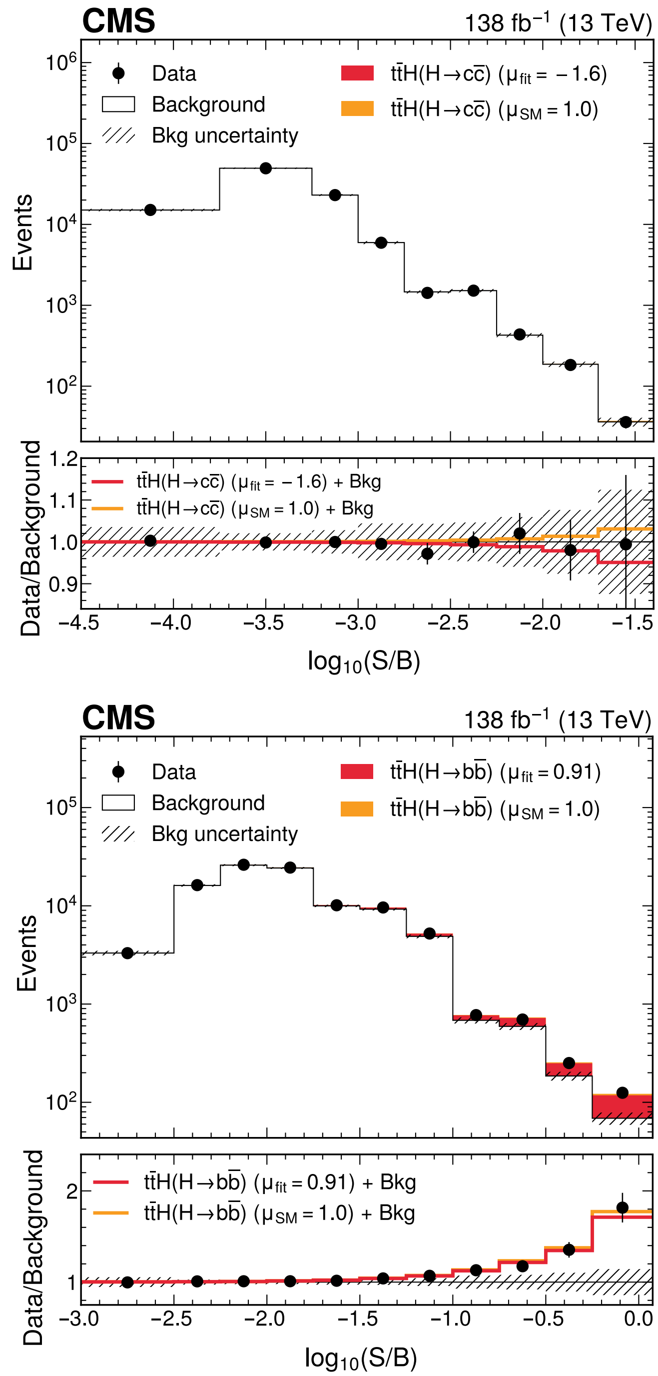

FIG. 2. Observed and expected event yields from all SRs and CRs as a function of $\log_{10}(S/B)$, where S are the expected $t\bar{t}H(H\to c\bar{c})$ (upper) and $t\bar{t}H(H\to b\bar{b})$ (lower) yields, and B are the post-fit total background yields. Signal contributions are shown for the best fit signal strength (red) and for the SM prediction, $\mu = 1$ (orange). The lower panel shows the ratio of the data to the post-fit background predictions, compared to the signal-plus-background predictions.

p value of 10% (3%) between the two measurements, assuming uncorrelated (50% correlated) systematic uncertainties. Because of a very different background model, a more inclusive event selection, and a low correlation of the

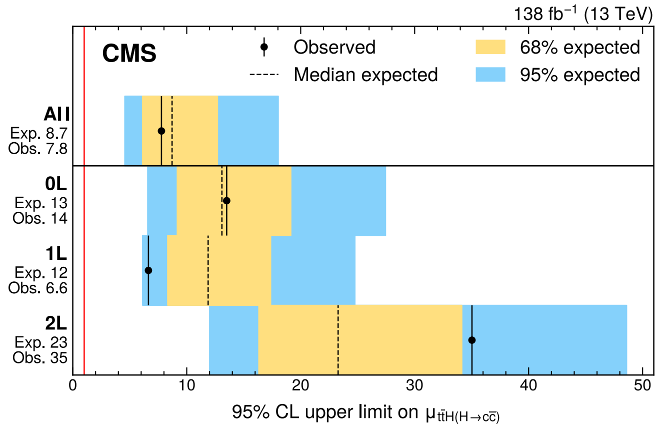

FIG. 3. The 95% CL upper limits on $\mu_{t\bar{t}H(H\to c\bar{c})}$. The yellow and blue bands indicate the expected 68% and 95% CL regions, respectively, under the background-only hypothesis. The vertical red line indicates the SM value $\mu_{t\bar{t}H(H\to c\bar{c})} = 1$.

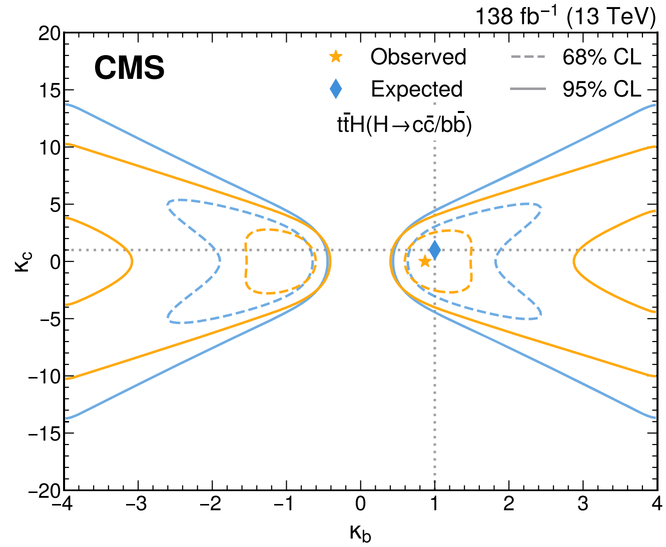

FIG. 4. Constraints on the Higgs boson coupling modifiers κ_c and κ_b. The 68% (95%) CL intervals are indicated by the dashed (solid) lines. The observed (expected) best fit values are shown by the orange (blue) markers.

neural network scores, the total systematic uncertainty can be considered mostly uncorrelated. No excess over the background-only hypothesis is observed in the search for $t\bar{t}H(H\to c\bar{c})$. An upper limit on $\mu_{t\bar{t}H(H\to c\bar{c})}$ is extracted using the CL_s criterion [104,105]. The test statistic is the profile likelihood ratio modified for upper limits [101], with the asymptotic approximation [102] used in the limit setting procedure. The observed (expected) 95% CL upper limit on $\mu_{t\bar{t}H(H\to c\bar{c})}$ is 7.8 (8.7), corresponding to an observed (expected) upper limit on $\sigma(t\bar{t}H)\mathcal{B}(H\to c\bar{c})$ of 0.11 (0.13) pb. The contributions from the individual channels are summarized in Fig. 3. Tabulated results are provided in the HEPData record for this analysis [106].

The result is interpreted in the κ framework [107,108] by reparameterizing $\mathcal{B}(H\to c\bar{c})$ and $\mathcal{B}(H\to b\bar{b})$ in terms of the charm and bottom quark Yukawa coupling modifiers κ_c and κ_b, assuming that only the Higgs boson decay widths are altered:

$$\mathcal{B}(H\to c\bar{c}) = \frac{\kappa_c^2\mathcal{B}_{\mathrm{SM}}^{H\to c\bar{c}}}{1+(\kappa_c^2-1)\mathcal{B}_{\mathrm{SM}}^{H\to c\bar{c}}+(\kappa_b^2-1)\mathcal{B}_{\mathrm{SM}}^{H\to b\bar{b}}},$$
$$\mathcal{B}(H\to b\bar{b}) = \frac{\kappa_b^2\mathcal{B}_{\mathrm{SM}}^{H\to b\bar{b}}}{1+(\kappa_c^2-1)\mathcal{B}_{\mathrm{SM}}^{H\to c\bar{c}}+(\kappa_b^2-1)\mathcal{B}_{\mathrm{SM}}^{H\to b\bar{b}}}. \quad (3)$$

Figure 4 shows the two-dimensional profile likelihood scan of κ_c and κ_b. When fixing κ_b to the SM expectation, the observed (expected) 95% CL interval is $|\kappa_c| < 3.0$ (3.3).

A combined analysis with the previous search in the VH channel [36] is performed. Common experimental uncertainties are correlated, except for jet flavor tagging, which differs in algorithms and calibration methods. Background modeling uncertainties are uncorrelated because of differing dominant backgrounds, while theoretical uncertainties in Higgs boson production and decay for the same processes are correlated. The expected 95% CL upper limit on $\mu_{H\to c\bar{c}}$, assuming SM production rates for $t\bar{t}H$ and VH, is 5.6, representing a 36% (26%) improvement over the $t\bar{t}H$ (VH) channel alone. The observed limit is 9.3, driven by a small upward statistical fluctuation in the VH channel. For κ_c, the combination improves the expected 95% CL interval to $|\kappa_c| < 2.7$, while the observed is $|\kappa_c| < 3.5$.

In summary, a search for the SM Higgs boson decaying to a charm quark-antiquark pair via $t\bar{t}H$ production is presented, alongside a simultaneous measurement of the Higgs boson decay to a bottom quark-antiquark pair. Novel jet flavor identification tools and event classification techniques using advanced machine learning algorithms are developed for this analysis. The observed $t\bar{t}H$ signals relative to the SM predictions are $\mu_{t\bar{t}H(H\to c\bar{c})} = -1.6 \pm 4.5$ and $\mu_{t\bar{t}H(H\to b\bar{b})} = 0.91^{+0.26}_{-0.22}$, with an observed (expected) significance of 4.4 (4.5) standard deviations for the $t\bar{t}H(H\to b\bar{b})$ process. The observed (expected) upper limit on $\sigma(t\bar{t}H)\mathcal{B}(H\to c\bar{c})$ is 0.11 (0.13) pb, corresponding to 7.8 (8.7) times the theoretical prediction for an SM Higgs boson mass of 125.38 GeV. When combined with the previous search for $H\to c\bar{c}$ via associated production with a W or Z boson, the observed (expected) 95% CL interval on the charm quark Yukawa coupling modifier, κ_c, is $|\kappa_c| < 3.5$ (2.7). This represents the most stringent constraint on κ_c to date.

Acknowledgments—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: SC (Armenia), 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); ERC PRG, TARISTU24-TK10, and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); BMFTR, DFG, and HGF (Germany); GSRI (Greece); NKFIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIT and NRF (Republic of Korea); MES (Latvia); LMTLT (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MES, NSC, and NAWA (Poland); FCT (Portugal); MESTD (Serbia); MICIU/AEI and PCTI (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); MHESI (Thailand); TUBITAK and TENMAK (Türkiye); NASU (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Data availability—Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, reuse, and open access policy [91]. In addition, the statistical model for this analysis has been posted at [92].

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End Matter

Analysis strategy and event selection—The ParT event classifier is used to select and categorize events, as illustrated in Fig. 5. The classifier outputs ten (nine) likelihood scores that sum to unity for the 0L (1L and 2L) channel. These include four scores for the signal processes, $\mathcal{D}_{t\bar{t}H(H\to c\bar{c})}$, $\mathcal{D}_{t\bar{t}H(H\to b\bar{b})}$, $\mathcal{D}_{t\bar{t}Z(Z\to c\bar{c})}$, and $\mathcal{D}_{t\bar{t}Z(Z\to b\bar{b})}$, and six (five) for the background processes, $\mathcal{D}_{t\bar{t}+\mathrm{light}}$, $\mathcal{D}_{t\bar{t}+c}$, $\mathcal{D}_{t\bar{t}+\geq 2c}$, $\mathcal{D}_{t\bar{t}+b}$, $\mathcal{D}_{t\bar{t}+\geq 2b}$, and $\mathcal{D}_{\mathrm{QCD}}$ (the last applies only to the 0L channel). The sum of the four signal scores is defined as $\mathcal{D}_{t\bar{t}X}$, while the sum of the five $t\bar{t}+$jets background scores is defined as $\mathcal{D}_{t\bar{t}+\mathrm{jets}}$.

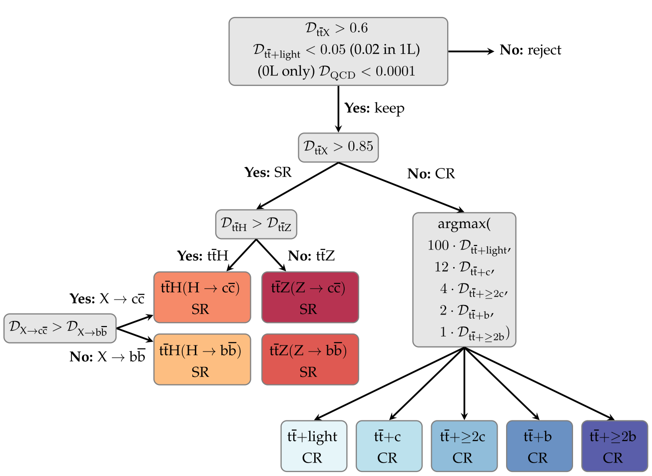

FIG. 5. Event categorization flowchart.

In the 0L channel, an initial requirement of $\mathcal{D}_{\mathrm{QCD}} < 0.0001$ suppresses the QCD multijet background to below 1% of the $t\bar{t}+$jets background, allowing the QCD multijet contribution to be neglected. To reduce the $t\bar{t}+$light background, a requirement of $\mathcal{D}_{t\bar{t}+\mathrm{light}} < 0.05$ (0.02) is applied in the 0L and 2L (1L) channels. Events with $\mathcal{D}_{t\bar{t}X} > 0.85$ are assigned to one of four SRs based on two pairs of signal discriminants, $\mathcal{D}_{t\bar{t}H}$ *vs* $\mathcal{D}_{t\bar{t}Z}$ and $\mathcal{D}_{X\to c\bar{c}}$ *vs* $\mathcal{D}_{X\to b\bar{b}}$, where $\mathcal{D}_{t\bar{t}H} = \mathcal{D}_{t\bar{t}H(H\to c\bar{c})} + \mathcal{D}_{t\bar{t}H(H\to b\bar{b})}$, $\mathcal{D}_{t\bar{t}Z} = \mathcal{D}_{t\bar{t}Z(Z\to c\bar{c})} + \mathcal{D}_{t\bar{t}Z(Z\to b\bar{b})}$, $\mathcal{D}_{X\to c\bar{c}} = \mathcal{D}_{t\bar{t}H(H\to c\bar{c})} + \mathcal{D}_{t\bar{t}Z(Z\to c\bar{c})}$, and $\mathcal{D}_{X\to b\bar{b}} = \mathcal{D}_{t\bar{t}H(H\to b\bar{b})} + \mathcal{D}_{t\bar{t}Z(Z\to b\bar{b})}$. Events with $0.6 < \mathcal{D}_{t\bar{t}X} < 0.85$ are categorized into one of the five CRs, determined by the background class with the highest weighted score. The weights—100, 12, 4, 2, and 1 for $\mathcal{D}_{t\bar{t}+\mathrm{light}}$, $\mathcal{D}_{t\bar{t}+c}$, $\mathcal{D}_{t\bar{t}+\geq 2c}$, $\mathcal{D}_{t\bar{t}+b}$, $\mathcal{D}_{t\bar{t}+\geq 2b}$, respectively—are optimized to enhance the purity of each CR.

Figure 6 shows the fitted event yields in each bin for the CRs and SRs.

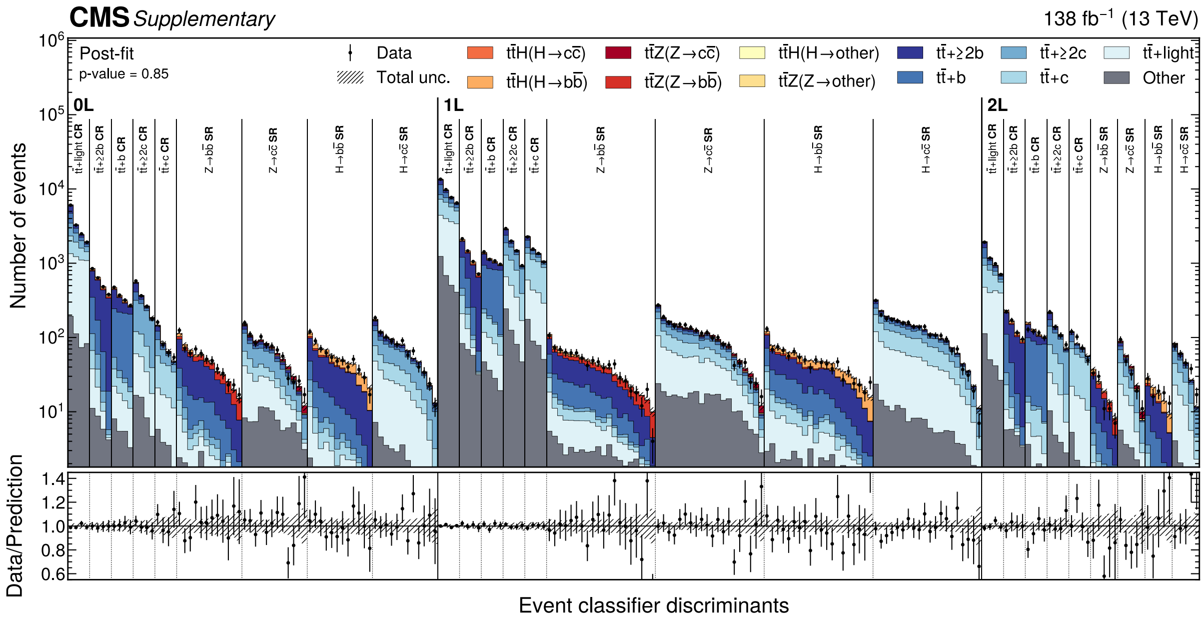

FIG. 6. Distributions of the ParT discriminants in data (points) and predicted signal and backgrounds (colored histograms) after the fit to data. The vertical bars on the points represent the statistical uncertainties in data. The hatched band represents the total uncertainty in the sum of the signal and background predictions. The lower panel shows the ratio of the data to the sum of the signal and background predictions.

The $t\bar{t}+$jets *background model*—Simulated $t\bar{t}+$jets events are divided into five mutually exclusive components: $t\bar{t}+\geq 2b$, $t\bar{t}+b$, $t\bar{t}+\geq 2c$, $t\bar{t}+c$, and $t\bar{t}+$light. The $t\bar{t}+\geq 2b$ and $t\bar{t}+b$ events are taken from a dedicated $t\bar{t}b\bar{b}$ sample, where the $t\bar{t}b\bar{b}$ matrix elements are calculated at NLO in QCD using the

TABLE I. Best fit values of the $t\bar{t}+$jets background normalization factors for each analysis category (Cat.).

Cat.	$t\bar{t}+\geq 2b$	$t\bar{t}+b$	$t\bar{t}+\geq 2c$	$t\bar{t}+c$	$t\bar{t}+$light
2L/1L	0.88 ± 0.07	0.92 ± 0.16	1.39 ± 0.23	1.41 ± 0.36	0.89 ± 0.11
0L	1.12 ± 0.11	0.89 ± 0.18	2.03 ± 0.41	0.95 ± 0.34	0.89 ± 0.17

TABLE II. The absolute (relative) contributions to the total uncertainties, $\Delta\mu$ ($\Delta\mu/\Delta\mu_{\mathrm{tot}}$).

Uncertainty source	$\Delta\mu$ ($\Delta\mu/\Delta\mu_{\mathrm{tot}}$)			
	$\mu_{t\bar{t}H(H\to c\bar{c})}$		$\mu_{t\bar{t}H(H\to b\bar{b})}$	
Statistical	3.3	(74%)	0.14	(57%)
$t\bar{t}+$jets normalizations	1.4	(32%)	0.06	(26%)
$t\bar{t}Z$ normalizations	0.4	(8.4%)	0.06	(30%)
Theory	2.1	(47%)	0.18	(75%)
Signal	0.7	(15%)	0.11	(47%)
$t\bar{t}+\geq 1b$	0.7	(15%)	0.14	(60%)
$t\bar{t}+\geq 1c$	1.4	(32%)	0.01	(5.8%)
$t\bar{t}+$light	1.3	(29%)	0.01	(5.2%)
Minor backgrounds	0.2	(4.6%)	0.01	(4.6%)
Experimental	2.0	(47%)	0.07	(31%)
Jet flavor tagging	1.7	(39%)	0.07	(28%)
Size of the simulated samples	1.1	(24%)	0.05	(21%)
Jet energy scale and resolution	0.8	(18%)	0.02	(8.6%)
Lepton identification	0.3	(6.0%)	0.02	(6.3%)
Integrated luminosity	0.1	(2.0%)	0.02	(6.2%)
Total	4.5	(100%)	0.24	(100%)

four-flavor scheme (4FS). The b quark mass is set to 4.75 GeV, and the 4FS NNLO NNPDF3.1 PDF set is used to describe the proton structure. The $t\bar{t}b\bar{b}$ production cross section is computed at NLO in 4FS. The $t\bar{t}+\geq 2c$, $t\bar{t}+c$, and $t\bar{t}+\text{light}$ components are extracted from the inclusive $t\bar{t}$ simulation after removing the $t\bar{t}+\geq 2b$ and $t\bar{t}+b$ contributions, thereby avoiding double counting. This inclusive $t\bar{t}$ sample is generated at NLO in QCD with up to one additional parton included at the matrix-element level, while additional emissions are modeled via parton showering with PYTHIA. The matrix element calculation is performed in the five-flavor scheme (5FS) using the 5FS NNLO NNPDF3.1 PDF set, where the b quarks are treated as massless. A subcomponent of $t\bar{t}+b$ ($t\bar{t}+c$), referred to as $t\bar{t}+j_{bb}$ ($t\bar{t}+j_{cc}$), consists of events where the additional b (c) jet contains two or more b (c) hadrons. These events predominantly arise from collinear $g\to b\bar{b}$ ($g\to c\bar{c}$) splittings, which are not well modeled in simulation. To account for this modeling limitation, an additional 50% uncertainty is assigned to the $t\bar{t}+j_{bb}$ and $t\bar{t}+j_{cc}$ contributions in the background estimation.

Production of $t\bar{t}b\bar{b}$ via double parton scattering (DPS) also contributes to the $t\bar{t}+\geq 2b$ and $t\bar{t}+b$ categories. This contribution is included in the inclusive $t\bar{t}$ sample but not in the dedicated $t\bar{t}b\bar{b}$ sample. It is therefore modeled separately by generating $t\bar{t}$ production at NLO in QCD using POWHEG, with additional $b\bar{b}$ production simulated by PYTHIA at LO in QCD using the `SecondHard` option. The cross section for this process is estimated to be 8 pb, assuming an effective DPS cross section of 30 mb [109] and an inclusive $b\bar{b}$ cross section of 0.3 mb, the latter estimated from simulation. In the background estimation, the DPS contributions are included in the corresponding $t\bar{t}+\geq 2b$ and $t\bar{t}+b$ categories, with a 50% uncertainty assigned to the normalization of the DPS components.

Table I summarizes the best fit values of the $t\bar{t}+\text{jets}$ background normalization factors obtained from a simultaneous fit to all CRs and SRs.

Uncertainty breakdown—The contributions of individual uncertainty sources to the total uncertainties in the fitted $\mu_{t\bar{t}H(H\to c\bar{c})}$ and $\mu_{t\bar{t}H(H\to b\bar{b})}$ are summarized in Table II. The values are determined by repeating the fit with the nuisance parameters associated with each category fixed to their best fit values, and then subtracting the resulting uncertainty in quadrature from the total uncertainty. The total uncertainty differs from the quadrature sum of the individual components because of correlations among nuisance parameters in the fit.

A. Hayrapetyan,[1] V. Makarenko,[1] A. Tumasyan,[1,b] W. Adam,[2] J. W. Andrejkovic,[2] L. Benato,[2] T. Bergauer,[2] M. Dragicevic,[2] C. Giordano,[2] P. S. Hussain,[2] M. Jeitler,[2,c] N. Krammer,[2] A. Li,[2] D. Liko,[2] M. Matthewman,[2] I. Mikulec,[2] J. Schieck,[2,c] R. Schöfbeck,[2,c] D. Schwarz,[2] M. Shooshtari,[2] M. Sonawane,[2] W. Waltenberger,[2] C.-E. Wulz,[2,c] T. Janssen,[3] H. Kwon,[3] D. Ocampo Henao,[3] T. Van Laer,[3] P. Van Mechelen,[3] J. Bierkens,[4] N. Breugelmans,[4] J. D'Hondt,[4] S. Dansana,[4] A. De Moor,[4] M. Delcourt,[4] F. Heyen,[4] Y. Hong,[4] P. Kashko,[4] S. Lowette,[4] I. Makarenko,[4] D. Müller,[4] J. Song,[4] S. Tavernier,[4] M. Tytgat,[4,d] G. P. Van Onsem,[4] S. Van Putte,[4] D. Vannerom,[4] B. Bilin,[5] B. Clerbaux,[5] A. K. Das,[5] I. De Bruyn,[5] G. De Lentdecker,[5] H. Evard,[5] L. Favart,[5] P. Gianneios,[5] A. Khalilzadeh,[5] F. A. Khan,[5] A. Malara,[5] M. A. Shahzad,[5] L. Thomas,[5] M. Vanden Bemden,[5] C. Vander Velde,[5] P. Vanlaer,[5] F. Zhang,[5] M. De Coen,[6] D. Dobur,[6] G. Gokbulut,[6] J. Knolle,[6] D. Marckx,[6] K. Skovpen,[6] N. Van Den Bossche,[6] J. van der Linden,[6] J. Vandenbroeck,[6] L. Wezenbeek,[6] S. Bein,[7] A. Benecke,[7] A. Bethani,[7] G. Bruno,[7] A. Cappati,[7] J. De Favereau De Jeneret,[7] C. Delaere,[7] A. Giammanco,[7] A. O. Guzel,[7] V. Lemaitre,[7] J. Lidrych,[7] P. Malek,[7] P. Mastrapasqua,[7] S. Turkcapar,[7] G. A. Alves,[8] M. Barroso Ferreira Filho,[8] E. Coelho,[8] C. Hensel,[8] T. Menezes De Oliveira,[8] C. Mora Herrera,[8,e] P. Rebello Teles,[8] M. Soeiro,[8] E. J. Tonelli Manganote,[8,f] A. Vilela Pereira,[8,e] W. L. Aldá Júnior,[9] H. Brandao Malbouisson,[9] W. Carvalho,[9] J. Chinellato,[9,g] M. Costa Reis,[9] E. M. Da Costa,[9] G. G. Da Silveira,[9,h] D. De Jesus Damiao,[9] S. Fonseca De Souza,[9] R. Gomes De Souza,[9] S. S. Jesus,[9] T. Laux Kuhn,[9,h] M. Macedo,[9] K. Mota Amarilo,[9] L. Mundim,[9] H. Nogima,[9] J. P. Pinheiro,[9] A. Santoro,[9] A. Sznajder,[9] M. Thiel,[9] F. Torres Da Silva De Araujo,[9,i] C. A. Bernardes,[10,h] F. Damas,[10] T. R. Fernandez Perez Tomei,[10] E. M. Gregores,[10] B. Lopes Da Costa,[10] I. Maietto Silverio,[10] P. G. Mercadante,[10] S. F. Novaes,[10] B. Orzari,[10] Sandra S. Padula,[10] V. Scheurer,[10] A. Aleksandrov,[11] G. Antchev,[11] P. Danev,[11] R. Hadjiiska,[11] P. Iaydjiev,[11] M. Shopova,[11] G. Sultanov,[11] A. Dimitrov,[12] L. Litov,[12] B. Pavlov,[12]

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Barbosa Trujillo,[25] A. Cabrera,[25] C. Florez,[25] J. Fraga,[25] J. A. Reyes Vega,[25] C. Rendón,[26] M. Rodriguez,[26] A. A. Ruales Barbosa,[26] J. D. Ruiz Alvarez,[26] N. Godinovic,[27] D. Lelas,[27] A. Sculac,[27] M. Kovac,[28] A. Petkovic,[28] T. Sculac,[28] P. Bargassa,[29] V. Brigljevic,[29] B. K. Chitroda,[29] D. Ferencek,[29] K. Jakovcic,[29] A. Starodumov,[29] T. Susa,[29] A. Attikis,[30] K. Christoforou,[30] A. Hadjiagapiou,[30] C. Leonidou,[30] C. Nicolaou,[30] L. Paizanos,[30] F. Ptochos,[30] P. A. Razis,[30] H. Rykaczewski,[30] H. Saka,[30] A. Stepennov,[30] M. Finger,[31,a] M. Finger Jr.,[31] E. Ayala,[32] E. Carrera Jarrin,[33] A. A. Abdelalim,[34,r,s] R. Aly,[34,t,r] M. Abdullah Al-Mashad,[35] A. Hussein,[35] H. Mohammed,[35] K. Ehataht,[36] M. Kadastik,[36] T. Lange,[36] C. Nielsen,[36] J. Pata,[36] M. Raidal,[36] N. Seeba,[36] L. Tani,[36] A. Milieva,[37] K. Osterberg,[37] M. Voutilainen,[37] N. Bin Norjoharuddeen,[38] E. Brücken,[38] F. Garcia,[38] P. 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Mokhtar,[157] S. Mukherjee,[157] M. Pieri,[157] D. Primosch,[157] M. Quinnan,[157] V. Sharma,[157] M. Tadel,[157] E. Vourliotis,[157] F. Würthwein,[157] A. Yagil,[157] Z. Zhao,[157] A. Barzdukas,[158] L. Brennan,[158] C. Campagnari,[158] S. Carron Montero,[158,gggg] K. Downham,[158] C. Grieco,[158] M. M. Hussain,[158] J. Incandela,[158] M. W. K. Lai,[158] A. J. Li,[158] P. Masterson,[158] J. Richman,[158] S. N. Santpur,[158] U. Sarica,[158] R. Schmitz,[158] F. Setti,[158] J. Sheplock,[158] D. Stuart,[158] T. Á. Vámi,[158] X. Yan,[158] D. Zhang,[158] A. Albert,[159] S. Bhattacharya,[159] A. Bornheim,[159] O. Cerri,[159] R. Kansal,[159] J. Mao,[159] H. B. Newman,[159] G. Reales Gutiérrez,[159] T. Sievert,[159] M. Spiropulu,[159] J. R. Vlimant,[159] R. A. Wynne,[159] S. Xie,[159] J. Alison,[160] S. An,[160] M. Cremonesi,[160] V. Dutta,[160] E. Y. Ertorer,[160] T. Ferguson,[160] T. A. Gómez Espinosa,[160] A. Harilal,[160]

A. Kallil Tharayil,[160] M. Kanemura,[160] C. Liu,[160] P. Meiring,[160] T. Mudholkar,[160] S. Murthy,[160] P. Palit,[160] K. Park,[160] M. Paulini,[160] A. Roberts,[160] A. Sanchez,[160] W. Terrill,[160] J. P. Cumalat,[161] W. T. Ford,[161] A. Hart,[161] A. Hassani,[161] S. Kwan,[161] J. Pearkes,[161] C. Savard,[161] N. Schonbeck,[161] K. Stenson,[161] K. A. Ulmer,[161] S. R. Wagner,[161] N. Zipper,[161] D. Zuolo,[161] J. Alexander,[162] X. Chen,[162] J. Dickinson,[162] A. Duquette,[162] J. Fan,[162] X. Fan,[162] J. Grassi,[162] S. Hogan,[162] P. Kotamnives,[162] J. Monroy,[162] G. Niendorf,[162] M. Oshiro,[162] J. R. Patterson,[162] A. Ryd,[162] J. Thom,[162] P. Wittich,[162] R. Zou,[162] L. Zygala,[162] M. Albrow,[163] M. Alyari,[163] O. Amram,[163] G. Apollinari,[163] A. Apresyan,[163] L. A. T. Bauerdick,[163] D. Berry,[163] J. Berryhill,[163] P. C. Bhat,[163] K. Burkett,[163] J. N. Butler,[163] A. Canepa,[163] G. B. Cerati,[163] H. W. K. Cheung,[163] F. Chlebana,[163] C. Cosby,[163] G. Cummings,[163] I. Dutta,[163] V. D. Elvira,[163] J. Freeman,[163] A. Gandrakota,[163] Z. Gecse,[163] L. Gray,[163] D. Green,[163] A. Grummer,[163] S. Grünendahl,[163] D. Guerrero,[163] O. Gutsche,[163] R. M. Harris,[163] T. C. Herwig,[163] J. Hirschauer,[163] B. Jayatilaka,[163] S. Jindariani,[163] M. Johnson,[163] U. Joshi,[163] T. Klijnsma,[163] B. Klima,[163] K. H. M. Kwok,[163] S. Lammel,[163] C. Lee,[163] D. Lincoln,[163] R. Lipton,[163] T. Liu,[163] K. Maeshima,[163] D. Mason,[163] P. McBride,[163] P. Merkel,[163] S. Mrenna,[163] S. Nahn,[163] J. Ngadiuba,[163] D. Noonan,[163] S. Norberg,[163] V. Papadimitriou,[163] N. Pastika,[163] K. Pedro,[163] C. Pena,[163,hhhh] C. E. Perez Lara,[163] F. Ravera,[163] A. Reinsvold Hall,[163,iiii] L. Ristori,[163] M. Safdari,[163] E. Sexton-Kennedy,[163] N. Smith,[163] A. Soha,[163] L. Spiegel,[163] S. Stoynev,[163] J. Strait,[163] L. Taylor,[163] S. Tkaczyk,[163] N. V. Tran,[163] L. Uplegger,[163] E. W. Vaandering,[163] C. Wang,[163] I. Zoi,[163] C. Aruta,[164] P. Avery,[164] D. Bourilkov,[164] P. Chang,[164] V. Cherepanov,[164] R. D. Field,[164] C. Huh,[164] E. Koenig,[164] M. Kolosova,[164] J. Konigsberg,[164] A. Korytov,[164] N. Menendez,[164] G. Mitselmakher,[164] K. Mohrman,[164] A. Muthirakalayil Madhu,[164] N. Rawal,[164] S. Rosenzweig,[164] V. Sulimov,[164] Y. Takahashi,[164] J. Wang,[164] T. Adams,[165] A. Al Kadhim,[165] A. Askew,[165] S. Bower,[165] R. Goff,[165] R. Hashmi,[165] R. S. Kim,[165] T. Kolberg,[165] G. Martinez,[165] M. Mazza,[165] H. Prosper,[165] P. R. Prova,[165] R. Yohay,[165] B. Alsufyani,[166] S. Butalla,[166] S. Das,[166] M. Hohlmann,[166] M. Lavinsky,[166] E. Yanes,[166] M. R. Adams,[167] N. Barnett,[167] A. Baty,[167] C. Bennett,[167] R. Cavanaugh,[167] R. Escobar Franco,[167] O. Evdokimov,[167] C. E. Gerber,[167] H. Gupta,[167] M. Hawksworth,[167] A. Hingrajiya,[167] D. J. Hofman,[167] J. h. Lee,[167] C. Mills,[167] S. Nanda,[167] G. Nigmatkulov,[167] B. Ozek,[167] T. Phan,[167] D. Pilipovic,[167] R. Pradhan,[167] E. Prifti,[167] P. Roy,[167] T. Roy,[167] N. Singh,[167] M. B. Tonjes,[167] N. Varelas,[167] M. A. Wadud,[167] J. Yoo,[167] M. Alhusseini,[168] D. Blend,[168] K. Dilsiz,[168,jjjj] O. K. Köseyan,[168] A. Mestvirishvili,[168,kkkk] O. Neogi,[168] H. Ogul,[168,llll] Y. Onel,[168] A. Penzo,[168] C. Snyder,[168] E. Tiras,[168,mmmm] B. Blumenfeld,[169] J. Davis,[169] A. V. Gritsan,[169] L. Kang,[169] S. Kyriacou,[169] P. Maksimovic,[169] M. Roguljic,[169] S. Sekhar,[169] M. V. Srivastav,[169] M. Swartz,[169] A. Abreu,[170] L. F. Alcerro Alcerro,[170] J. Anguiano,[170] S. Arteaga Escatel,[170] P. Baringer,[170] A. Bean,[170] Z. Flowers,[170] D. Grove,[170] J. King,[170] G. Krintiras,[170] M. Lazarovits,[170] C. Le Mahieu,[170] J. Marquez,[170] M. Murray,[170] M. Nickel,[170] S. Popescu,[170,nnnn] C. Rogan,[170] C. Royon,[170] S. Rudrabhatla,[170] S. Sanders,[170] C. Smith,[170] G. Wilson,[170] B. Allmond,[171] N. Islam,[171] A. Ivanov,[171] K. Kaadze,[171] Y. Maravin,[171] J. Natoli,[171] G. G. Reddy,[171] D. Roy,[171] G. Sorrentino,[171] A. Baden,[172] A. Belloni,[172] J. Bistany-riebman,[172] S. C. Eno,[172] N. J. Hadley,[172] S. Jabeen,[172] R. G. Kellogg,[172] T. Koeth,[172] B. Kronheim,[172] S. Lascio,[172] P. Major,[172] A. C. Mignerey,[172] C. Palmer,[172] C. Papageorgakis,[172] M. M. Paranjpe,[172] E. Popova,[172,oooo] A. Shevelev,[172] L. Zhang,[172] C. Baldenegro Barrera,[173] H. Bossi,[173] S. Bright-Thonney,[173] I. A. Cali,[173] Y. c. Chen,[173] P. c. Chou,[173] M. D'Alfonso,[173] J. Eysermans,[173] C. Freer,[173] G. Gomez-Ceballos,[173] M. Goncharov,[173] G. Grosso,[173] P. Harris,[173] D. Hoang,[173] G. M. Innocenti,[173] D. Kovalskyi,[173] J. Krupa,[173] L. Lavezzo,[173] Y.-J. Lee,[173] K. Long,[173] C. Mcginn,[173] A. Novak,[173] M. I. Park,[173] C. Paus,[173] C. Reissel,[173] C. Roland,[173] G. Roland,[173] S. Rothman,[173] T. a. Sheng,[173] G. S. F. Stephans,[173] D. Walter,[173] Z. Wang,[173] B. Wyslouch,[173] T. J. Yang,[173] B. Crossman,[174] W. J. Jackson,[174] C. Kapsiak,[174] M. Krohn,[174] D. Mahon,[174] J. Mans,[174] B. Marzocchi,[174] R. Rusack,[174] O. Sancar,[174] R. Saradhy,[174] N. Strobbe,[174] K. Bloom,[175] D. R. Claes,[175] G. Haza,[175] J. Hossain,[175] C. Joo,[175] I. Kravchenko,[175] A. Rohilla,[175] J. E. Siado,[175] W. Tabb,[175] A. Vagnerini,[175] A. Wightman,[175] F. Yan,[175] H. Bandyopadhyay,[176] L. Hay,[176] H. w. Hsia,[176] I. Iashvili,[176] A. Kalogeropoulos,[176] A. Kharchilava,[176] A. Mandal,[176] M. Morris,[176] D. Nguyen,[176] S. Rappoccio,[176] H. Rejeb Sfar,[176] A. Williams,[176] P. Young,[176] D. Yu,[176] G. Alverson,[177] E. Barberis,[177] J. Bonilla,[177] B. Bylsma,[177] M. Campana,[177] J. Dervan,[177] Y. Haddad,[177] Y. Han,[177] I. Israr,[177] A. Krishna,[177] M. Lu,[177] N. Manganelli,[177] R. Mccarthy,[177] D. M. Morse,[177] T. Orimoto,[177] A. Parker,[177] L. Skinnari,[177]

C. S. Thoreson,[177] E. Tsai,[177] D. Wood,[177] S. Dittmer,[178] K. A. Hahn,[178] Y. Liu,[178] M. Mcginnis,[178] Y. Miao,[178] D. G. Monk,[178] M. H. Schmitt,[178] A. Taliercio,[178] M. Velasco,[178] J. Wang,[178] G. Agarwal,[179] R. Band,[179] R. Bucci,[179] S. Castells,[179] A. Das,[179] A. Ehnis,[179] R. Goldouzian,[179] M. Hildreth,[179] K. Hurtado Anampa,[179] T. Ivanov,[179] C. Jessop,[179] A. Karneyeu,[179] K. Lannon,[179] J. Lawrence,[179] N. Loukas,[179] L. Lutton,[179] J. Mariano,[179] N. Marinelli,[179] I. Mcalister,[179] T. McCauley,[179] C. Mcgrady,[179] C. Moore,[179] Y. Musienko,[179,oooo] H. Nelson,[179] M. Osherson,[179] A. Piccinelli,[179] R. Ruchti,[179] A. Townsend,[179] Y. Wan,[179] M. Wayne,[179] H. Yockey,[179] A. Basnet,[180] M. Carrigan,[180] R. De Los Santos,[180] L. S. Durkin,[180] C. Hill,[180] M. Joyce,[180] M. Nunez Ornelas,[180] D. A. Wenzl,[180] B. L. Winer,[180] B. R. Yates,[180] H. Bouchamaoui,[181] P. Das,[181] G. Dezoort,[181] P. Elmer,[181] A. Frankenthal,[181] M. Galli,[181] B. Greenberg,[181] N. Haubrich,[181] K. Kennedy,[181] G. Kopp,[181] Y. Lai,[181] D. Lange,[181] A. Loeliger,[181] D. Marlow,[181] I. Ojalvo,[181] J. Olsen,[181] F. Simpson,[181] D. Stickland,[181] C. Tully,[181] S. Malik,[182] R. Sharma,[182] S. Chandra,[183] R. Chawla,[183] A. Gu,[183] L. Gutay,[183] M. Jones,[183] A. W. Jung,[183] D. Kondratyev,[183] M. Liu,[183] G. Negro,[183] N. Neumeister,[183] G. Paspalaki,[183] S. Piperov,[183] N. R. Saha,[183] J. F. Schulte,[183] F. Wang,[183] A. Wildridge,[183] W. Xie,[183] Y. Yao,[183] Y. Zhong,[183] N. Parashar,[184] A. Pathak,[184] E. Shumka,[184] D. Acosta,[185] A. Agrawal,[185] C. Arbour,[185] T. Carnahan,[185] K. M. Ecklund,[185] S. Freed,[185] P. Gardner,[185] F. J. M. Geurts,[185] T. Huang,[185] I. Krommydas,[185] N. Lewis,[185] W. Li,[185] J. Lin,[185] O. Miguel Colin,[185] B. P. Padley,[185] R. Redjimi,[185] J. Rotter,[185] M. Wulansatiti,[185] E. Yigitbasi,[185] Y. Zhang,[185] O. Bessidskaia Bylund,[186] A. Bodek,[186] P. de Barbaro,[186,a] R. Demina,[186] A. Garcia-Bellido,[186] H. S. Hare,[186] O. Hindrichs,[186] N. Parmar,[186] P. Parygin,[186,oooo] H. Seo,[186] R. Taus,[186] B. Chiarito,[187] J. P. Chou,[187] S. V. Clark,[187] S. Donnelly,[187] D. Gadkari,[187] Y. Gershtein,[187] E. Halkiadakis,[187] C. Houghton,[187] D. Jaroslawski,[187] A. Kobert,[187] S. Konstantinou,[187] I. Laflotte,[187] A. Lath,[187] J. Martins,[187] M. Perez Prada,[187] B. Rand,[187] J. Reichert,[187] P. Saha,[187] S. Salur,[187] S. Schnetzer,[187] S. Somalwar,[187] R. Stone,[187] S. A. Thayil,[187] S. Thomas,[187] J. Vora,[187] D. Ally,[188] A. G. Delannoy,[188] S. Fiorendi,[188] J. Harris,[188] T. Holmes,[188] A. R. Kanuganti,[188] N. Karunarathna,[188] J. Lawless,[188] L. Lee,[188] E. Nibigira,[188] B. Skipworth,[188] S. Spanier,[188] D. Aebi,[189] M. Ahmad,[189] T. Akhter,[189] K. Androsov,[189] A. Bolshov,[189] O. Bouhali,[189,pppp] A. Cagnotta,[189] V. D'Amante,[189] R. 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Lomte,[194] R. Loveless,[194] A. Mallampalli,[194] A. Mohammadi,[194] S. Mondal,[194] T. Nelson,[194] G. Parida,[194] L. Pétré,[194] D. Pinna,[194] A. Savin,[194] V. Shang,[194] V. Sharma,[194] W. H. Smith,[194] D. Teague,[194] H. F. Tsoi,[194] W. Vetens,[194] A. Warden,[194] S. Afanasiev,[195] V. Alexakhin,[195] Yu. Andreev,[195] T. Aushev,[195] D. Budkouski,[195] R. Chistov,[195,oooo] M. Danilov,[195,oooo] T. Dimova,[195,oooo] A. Ershov,[195,oooo] S. Gninenko,[195] I. Gorbunov,[195] A. Gribushin,[195,oooo] A. Kamenev,[195] V. Karjavine,[195] M. Kirsanov,[195] V. Klyukhin,[195,oooo] O. Kodolova,[195,qqqq] V. Korenkov,[195] I. Korsakov,[195] A. Kozyrev,[195,oooo] N. Krasnikov,[195] A. Lanev,[195] A. Malakhov,[195] V. Matveev,[195,oooo] A. Nikitenko,[195,rrrr,qqqq] V. Palichik,[195] V. Perelygin,[195] S. Petrushanko,[195,oooo] S. Polikarpov,[195,oooo] O. Radchenko,[195,oooo] M. Savina,[195] V. Shalaev,[195] S. Shmatov,[195] S. Shulha,[195] Y. Skovpen,[195,oooo] K. Slizhevskiy,[195] V. Smirnov,[195] O. Teryaev,[195] I. Tlisova,[195,oooo] A. Toropin,[195] N. Voytishin,[195] B. S. Yuldashev,[195,a,ssss] A. Zarubin,[195] I. Zhizhin,[195] L. Dudko,[196] K. Ivanov,[196] V. Kim,[196,oooo] V. Murzin,[196] V. Oreshkin,[196] D. Sosnov,[196] E. Boos,[196] V. Bunichev,[196] M. Dubinin,[196,hhhh] V. Savrin,[196] and A. Snigirev[196]

(CMS Collaboration)

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

[58]*Faculty of Informatics, University of Debrecen, Debrecen, Hungary*
[59]*HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary*
[60]*Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary*
[61]*Panjab University, Chandigarh, India*
[62]*University of Delhi, Delhi, India*
[63]*University of Hyderabad, Hyderabad, India*
[64]*Indian Institute of Technology Kanpur, Kanpur, India*
[65]*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
[66]*Indian Institute of Technology Madras, Madras, India*
[67]*IISER Mohali, India, Mohali, India*
[68]*Tata Institute of Fundamental Research-A, Mumbai, India*
[69]*Tata Institute of Fundamental Research-B, Mumbai, India*
[70]*National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India*
[71]*Indian Institute of Science Education and Research (IISER), Pune, India*
[72]*Indian Institute of Technology Hyderabad, Telangana, India*
[73]*Isfahan University of Technology, Isfahan, Iran*
[74]*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
[75]*University College Dublin, Dublin, Ireland*
[76a]*INFN Sezione di Bari, Bari, Italy*
[76b]*Università di Bari, Bari, Italy*
[76c]*Politecnico di Bari, Bari, Italy*
[77a]*INFN Sezione di Bologna, Bologna, Italy*
[77b]*Università di Bologna, Bologna, Italy*
[78a]*INFN Sezione di Catania, Catania, Italy*
[78b]*Università di Catania, Catania, Italy*
[79a]*INFN Sezione di Firenze, Firenze, Italy*
[79b]*Università di Firenze, Firenze, Italy*
[80]*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
[81a]*INFN Sezione di Genova, Genova, Italy*
[81b]*Università di Genova, Genova, Italy*
[82a]*INFN Sezione di Milano-Bicocca, Milano, Italy*
[82b]*Università di Milano-Bicocca, Milano, Italy*
[83a]*INFN Sezione di Napoli, Napoli, Italy*
[83b]*Università di Napoli "Federico II," Napoli, Italy*
[83c]*Università della Basilicata, Potenza, Italy*
[83d]*Scuola Superiore Meridionale (SSM), Napoli, Italy*
[84a]*INFN Sezione di Padova, Padova, Italy*
[84b]*Università di Padova, Padova, Italy*
[84c]*Universita degli Studi di Cagliari, Cagliari, Italy*
[85a]*INFN Sezione di Pavia, Pavia, Italy*
[85b]*Università di Pavia, Pavia, Italy*
[86a]*INFN Sezione di Perugia, Perugia, Italy*
[86b]*Università di Perugia, Perugia, Italy*
[87a]*INFN Sezione di Pisa, Pisa, Italy*
[87b]*Università di Pisa, Pisa, Italy*
[87c]*Scuola Normale Superiore di Pisa, Pisa, Italy*
[87d]*Università di Siena, Siena, Italy*
[88a]*INFN Sezione di Roma, Roma, Italy*
[88b]*Sapienza Università di Roma, Roma, Italy*
[89a]*INFN Sezione di Torino, Torino, Italy*
[89b]*Università di Torino, Torino, Italy*
[89c]*Università del Piemonte Orientale, Novara, Italy*
[90a]*INFN Sezione di Trieste, Trieste, Italy*
[90b]*Università di Trieste, Trieste, Italy*
[91]*Kyungpook National University, Daegu, Korea*
[92]*Department of Mathematics and Physics—GWNU, Gangneung, Korea*
[93]*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
[94]*Hanyang University, Seoul, Korea*
[95]*Korea University, Seoul, Korea*
[96]*Kyung Hee University, Department of Physics, Seoul, Korea*

[97]Sejong University, Seoul, Korea
[98]Seoul National University, Seoul, Korea
[99]University of Seoul, Seoul, Korea
[100]Yonsei University, Department of Physics, Seoul, Korea
[101]Sungkyunkwan University, Suwon, Korea
[102]College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
[103]Kuwait University, College of Science, Department of Physics, Safat, Kuwait
[104]Riga Technical University, Riga, Latvia
[105]University of Latvia (LU), Riga, Latvia
[106]Vilnius University, Vilnius, Lithuania
[107]National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
[108]Universidad de Sonora (UNISON), Hermosillo, Mexico
[109]Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
[110]Universidad Iberoamericana, Mexico City, Mexico
[111]Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
[112]University of Montenegro, Podgorica, Montenegro
[113]University of Canterbury, Christchurch, New Zealand
[114]National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
[115]AGH University of Krakow, Krakow, Poland
[116]National Centre for Nuclear Research, Swierk, Poland
[117]Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
[118]Warsaw University of Technology, Warsaw, Poland
[119]Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
[120]Faculty of Physics, University of Belgrade, Belgrade, Serbia
[121]VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[122]Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[123]Universidad Autónoma de Madrid, Madrid, Spain
[124]Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
[125]Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
[126]University of Colombo, Colombo, Sri Lanka
[127]University of Ruhuna, Department of Physics, Matara, Sri Lanka
[128]CERN, European Organization for Nuclear Research, Geneva, Switzerland
[129]PSI Center for Neutron and Muon Sciences, Villigen, Switzerland
[130]ETH Zurich—Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
[131]Universität Zürich, Zurich, Switzerland
[132]National Central University, Chung-Li, Taiwan
[133]National Taiwan University (NTU), Taipei, Taiwan
[134]High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
[135]Tunis El Manar University, Tunis, Tunisia
[136]Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
[137]Middle East Technical University, Physics Department, Ankara, Turkey
[138]Bogazici University, Istanbul, Turkey
[139]Istanbul Technical University, Istanbul, Turkey
[140]Istanbul University, Istanbul, Turkey
[141]Yildiz Technical University, Istanbul, Turkey
[142]Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
[143]National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
[144]University of Bristol, Bristol, United Kingdom
[145]Rutherford Appleton Laboratory, Didcot, United Kingdom
[146]Imperial College, London, United Kingdom
[147]Brunel University, Uxbridge, United Kingdom
[148]Baylor University, Waco, Texas, USA
[149]Bethel University, St. Paul, Minnesota, USA
[150]Catholic University of America, Washington, DC, USA
[151]The University of Alabama, Tuscaloosa, Alabama, USA
[152]Boston University, Boston, Massachusetts, USA
[153]Brown University, Providence, Rhode Island, USA
[154]University of California, Davis, Davis, California, USA
[155]University of California, Los Angeles, California, USA
[156]University of California, Riverside, Riverside, California, USA

[157]*University of California, San Diego, La Jolla, California, USA*
[158]*University of California, Santa Barbara, Department of Physics, Santa Barbara, California, USA*
[159]*California Institute of Technology, Pasadena, California, USA*
[160]*Carnegie Mellon University, Pittsburgh, Pennsylvania, USA*
[161]*University of Colorado Boulder, Boulder, Colorado, USA*
[162]*Cornell University, Ithaca, New York, USA*
[163]*Fermi National Accelerator Laboratory, Batavia, Illinois, USA*
[164]*University of Florida, Gainesville, Florida, USA*
[165]*Florida State University, Tallahassee, Florida, USA*
[166]*Florida Institute of Technology, Melbourne, Florida, USA*
[167]*University of Illinois Chicago, Chicago, Illinois, USA*
[168]*The University of Iowa, Iowa City, Iowa, USA*
[169]*Johns Hopkins University, Baltimore, Maryland, USA*
[170]*The University of Kansas, Lawrence, Kansas, USA*
[171]*Kansas State University, Manhattan, Kansas, USA*
[172]*University of Maryland, College Park, Maryland, USA*
[173]*Massachusetts Institute of Technology, Cambridge, Massachusetts, USA*
[174]*University of Minnesota, Minneapolis, Minnesota, USA*
[175]*University of Nebraska-Lincoln, Lincoln, Nebraska, USA*
[176]*State University of New York at Buffalo, Buffalo, New York, USA*
[177]*Northeastern University, Boston, Massachusetts, USA*
[178]*Northwestern University, Evanston, Illinois, USA*
[179]*University of Notre Dame, Notre Dame, Indiana, USA*
[180]*The Ohio State University, Columbus, Ohio, USA*
[181]*Princeton University, Princeton, New Jersey, USA*
[182]*University of Puerto Rico, Mayaguez, Puerto Rico, USA*
[183]*Purdue University, West Lafayette, Indiana, USA*
[184]*Purdue University Northwest, Hammond, Indiana, USA*
[185]*Rice University, Houston, Texas, USA*
[186]*University of Rochester, Rochester, New York, USA*
[187]*Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA*
[188]*University of Tennessee, Knoxville, Tennessee, USA*
[189]*Texas A&M University, College Station, Texas, USA*
[190]*Texas Tech University, Lubbock, Texas, USA*
[191]*Vanderbilt University, Nashville, Tennessee, USA*
[192]*University of Virginia, Charlottesville, Virginia, USA*
[193]*Wayne State University, Detroit, Michigan, USA*
[194]*University of Wisconsin—Madison, Madison, Wisconsin, USA*
[195]*An institute or international laboratory covered by a cooperation agreement with CERN*
[196]*An institute formerly covered by a cooperation agreement with CERN*

[a]Deceased.
[b]Also at Yerevan State University, Yerevan, Armenia.
[c]Also at TU Wien, Vienna, Austria.
[d]Also at Ghent University, Ghent, Belgium.
[e]Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[f]Also at FACAMP—Faculdades de Campinas, Sao Paulo, Brazil.
[g]Also at Universidade Estadual de Campinas, Campinas, Brazil.
[h]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[i]Also at The University of the State of Amazonas, Manaus, Brazil.
[j]Also at University of Chinese Academy of Sciences, Beijing, China.
[k]Also at China Center of Advanced Science and Technology, Beijing, China.
[l]Also at University of Chinese Academy of Sciences, Beijing, China.
[m]Also at School of Physics, Zhengzhou University, Zhengzhou, China.
[n]Present address: Henan Normal University, Xinxiang, China.
[o]Also at University of Shanghai for Science and Technology, Shanghai, China.
[p]Present address: The University of Iowa, Iowa City, Iowa, USA.
[q]Also at Center for High Energy Physics, Peking University, Beijing, China.
[r]Also at Helwan University, Cairo, Egypt.
[s]Present address: Zewail City of Science and Technology, Zewail, Egypt.

[t]Also at British University in Egypt, Cairo, Egypt.
[u]Also at Purdue University, West Lafayette, Indiana, USA.
[v]Also at Université de Haute Alsace, Mulhouse, France.
[w]Also at Tbilisi State University, Tbilisi, Georgia.
[x]Also at Another institute or international laboratory covered by a cooperation agreement with CERN.
[y]Also at University of Hamburg, Hamburg, Germany.
[z]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[aa]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[bb]Also at Brandenburg University of Technology, Cottbus, Germany.
[cc]Also at Forschungszentrum Jülich, Juelich, Germany.
[dd]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[ee]Also at HUN-REN ATOMKI—Institute of Nuclear Research, Debrecen, Hungary.
[ff]Present address: Universitatea Babes-Bolyai—Facultatea de Fizica, Cluj-Napoca, Romania.
[gg]Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[hh]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[ii]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[jj]Also at The University of Kansas, Lawrence, Kansas, USA.
[kk]Also at Punjab Agricultural University, Ludhiana, India.
[ll]Also at University of Hyderabad, Hyderabad, India.
[mm]Also at Indian Institute of Science (IISc), Bangalore, India.
[nn]Also at University of Visva-Bharati, Santiniketan, 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 Isfahan University of Technology, Isfahan, Iran.
[ss]Also at Sharif University of Technology, Tehran, Iran.
[tt]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[uu]Also at Department of Physics, Faculty of Science, Arak University, Arak, Iran.
[vv]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[ww]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[xx]Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[yy]Also at Scuola Superiore Meridionale, Università di Napoli "Federico II," Napoli, Italy.
[zz]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[aaa]Also at Lulea University of Technology, Lulea, Sweden.
[bbb]Also at Consiglio Nazionale delle Ricerche—Istituto Officina dei Materiali, Perugia, Italy.
[ccc]Also at UPES—University of Petroleum and Energy Studies, Dehradun, India.
[ddd]Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[eee]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[fff]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[ggg]Also at Saegis Campus, Nugegoda, Sri Lanka.
[hhh]Also at National and Kapodistrian University of Athens, Athens, Greece.
[iii]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[jjj]Also at Universität Zürich, Zurich, Switzerland.
[kkk]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[lll]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[mmm]Also at Konya Technical University, Konya, Turkey.
[nnn]Also at Izmir Bakircay University, Izmir, Turkey.
[ooo]Also at Adiyaman University, Adiyaman, Turkey.
[ppp]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[qqq]Also at Istanbul Sabahattin Zaim University, Istanbul, Turkey.
[rrr]Also at Marmara University, Istanbul, Turkey.
[sss]Also at Milli Savunma University, Istanbul, Turkey.
[ttt]Also at Informatics and Information Security Research Center, Gebze/Kocaeli, Turkey.
[uuu]Also at Kafkas University, Kars, Turkey.
[vvv]Present address: Istanbul Okan University, Istanbul, Turkey.
[www]Also at Hacettepe University, Ankara, Turkey.
[xxx]Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[yyy]Also at Istanbul University—Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[zzz]Also at Istinye University, Istanbul, Turkey.
[aaaa]Also at Yildiz Technical University, Istanbul, Turkey.

[bbbb]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[cccc]Also at Monash University, Faculty of Science, Clayton, Australia.
[dddd]Also at Bethel University, St. Paul, Minnesota, USA.
[eeee]Also at Università di Torino, Torino, Italy.
[ffff]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[gggg]Also at California Lutheran University;, Thousand Oaks, California, USA.
[hhhh]Also at California Institute of Technology, Pasadena, California, USA.
[iiii]Also at United States Naval Academy, Annapolis, Maryland, USA.
[jjjj]Also at Bingol University, Bingol, Turkey.
[kkkk]Also at Georgian Technical University, Tbilisi, Georgia.
[llll]Also at Sinop University, Sinop, Turkey.
[mmmm]Also at Erciyes University, Kayseri, Turkey.
[nnnn]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
[oooo]Present address: Another institute formerly covered by a cooperation agreement with CERN.
[pppp]Also at Hamad Bin Khalifa University (HBKU), Doha, Qatar.
[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.