Phys. Lett. B 868 (2025) 139754

Contents lists available at ScienceDirect

Physics Letters B

journal homepage: www.elsevier.com/locate/physletb

Letter

Measurement of the W boson decay branching fraction ratio $\mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration *

CERN, Geneva, Switzerland

ARTICLE INFO

Editor: M. Doser

Keywords:
CMS
SMP
Charm

ABSTRACT

The most precise measurement to date of the W boson hadronic decay branching fraction ratio $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ is presented. The measurement is based on a sample of proton-proton collision data from the CERN LHC collected by the CMS experiment at a center-of-mass energy of 13 TeV in 2016–2018 with an integrated luminosity of 138 fb^{-1}. The large cross section of top quark-antiquark production at the LHC offers a sizable high-purity sample of W bosons suitable for this measurement. Events with one charged lepton (electron or muon) and at least four jets, two tagged as bottom quark jets, are analyzed. Charm jets are tagged using the presence of a muon inside the jet. The result, $R_c^W = 0.489 \pm 0.020$, is consistent with the standard model prediction and is twice as precise as the current world-average value.

1. Introduction

In this Letter, we present a measurement of the rate of charm (c) quark production in W boson decays relative to the rate of W hadronic decays to various quark flavors, $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$. Here $W \to cq$ stands for both $W^+ \to c\bar{q}$ (with $\bar{q} = \bar{d}$, $\bar{s}$, or $\bar{b}$) and $W^- \to \bar{c}q$ (with q = d, s, or b). The $W \to q\bar{q}'$ hadronic decays include $W \to uq$ and $W \to cq$ contributions.

This measurement tests the universality of the weak interaction in the quark sector, a fundamental property of the standard model (SM) that assumes the sum of the couplings of any up-type quark to all down-type quarks is the same for all generations. This property is encoded in the Cabibbo–Kobayashi–Maskawa (CKM) matrix [1,2] through the unitarity condition $\sum_j |V_{ij}|^2 = 1$, separately for each generation *i*.

The R_c^W ratio can be expressed as a function of the CKM matrix elements through the relation

$$R_c^W = \frac{\mathcal{B}(W \to cq)}{\mathcal{B}(W \to uq) + \mathcal{B}(W \to cq)} = \frac{|V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}{|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 + |V_{cd}|^2 + |V_{cs}|^2 + |V_{cb}|^2}. \quad (1)$$

Assuming the unitarity of the CKM matrix, R_c^W is expected to be equal to 1/2. Therefore, a measurement of R_c^W is a direct test of this assumption. Furthermore, a value of $|V_{cs}|$ can be determined from Eq. (1) using the R_c^W measurement and the world-average values of the other CKM matrix elements [3].

Previous measurements of R_c^W were performed by the LEP2 experiments [4,5] analyzing $e^+e^- \to W^+W^-$ events. The current world-average value [3] derived from these measurements is $R_c^W = 0.49 \pm 0.04$, corresponding to an uncertainty of 8%.

This Letter describes a measurement of R_c^W that is twice as precise as that value. The analysis is based on proton-proton (pp) collision data from the CERN LHC at a center-of-mass energy $\sqrt{s} = 13\,\text{TeV}$, collected by the CMS experiment in the period 2016–2018. The large cross section at the LHC for the production of top quark-antiquark pairs ($t\bar{t}$), each decaying into a W boson and a bottom (b) quark, offers a sizable high-purity sample of W bosons suitable for a high-precision study of their decays. Jets are tagged as originating from the hadronization of c quarks by the presence of a muon, which comes from the semileptonic decay of a c hadron, inside the jet. The efficiency of this muon-based c-tagging method, employed in previous CMS publications [6–9], can be precisely calibrated using data, enabling a precision measurement of R_c^W.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

https://doi.org/10.1016/j.physletb.2025.139754
Received 20 December 2024; Received in revised form 7 July 2025; Accepted 21 July 2025

Available online 23 July 2025
0370-2693/© 2025 CERN for the benefit of the CMS Collaboration. Published by Elsevier B.V. Funded by SCOAP³. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

2. The CMS detector and object reconstruction

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, along with a definition of the coordinate system used and the relevant kinematic variables, is reported in Ref. [10].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz, within a fixed latency of about 4 μs [11]. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing and reduces the event rate to around 1 kHz before data storage [12].

A global particle-flow (PF) algorithm [13] reconstructs and identifies each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. Photons are identified as ECAL energy clusters not linked to the extrapolation of any charged-particle trajectory. Electrons are identified as a charged-particle track with many ECAL energy clusters, corresponding to the extrapolation of this track to the ECAL and possible bremsstrahlung photons emitted along the path through the tracker material. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Charged hadrons are identified as charged-particle tracks identified neither as electrons nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged-hadron trajectory, or as a combined ECAL and HCAL energy excess relative to the expected charged-hadron energy deposit.

The energy of photons is obtained from the ECAL measurement. The energy of electrons is obtained from a combination of the electron momentum at the primary vertex (PV) derived using the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy resolution of reconstructed photons ranges from 1% in the barrel section of the ECAL to approximately 3% in the endcaps [14]. For electrons with transverse momentum (p_{T}) around 45 GeV from $\mathrm{Z} \to \mathrm{ee}$ decays, the p_{T} resolution varies between 1.6% and 5%, with generally better performance in the barrel region than in the endcaps [14]. The energy of muons is obtained from the curvature of the corresponding track. Matching muons to tracks measured in the silicon tracker results in a p_{T} resolution of 1% in the barrel and 3% in the endcaps for muons with p_{T} up to 100 GeV [15]. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching calorimeter energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected calorimeter energies. The PV is taken to be the vertex corresponding to the hardest scattering in the event, as described in Section 9.4.1 of Ref. [16].

Hadronic jets are clustered from the PF objects using the infrared- and collinear-safe anti-k_{T} algorithm [17,18] with a distance parameter of 0.4. The jet momentum is determined as the vector sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the entire transverse momentum spectrum and detector acceptance. Additional pp interactions within the same or nearby bunch crossings (pileup) can contribute additional tracks and calorimetric energy deposits, increasing the apparent jet momentum. To mitigate this effect, charged particles identified as originating from pileup vertices are discarded, and an offset correction is applied to account for remaining contributions from neutral hadrons [19]. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle level jets on average. In situ measurements of the momentum balance in dijet, photon + jet, Z + jet, and multijet events are used to correct for any residual differences in the jet energy scale (JES) between data and simulation [20]. The jet energy resolution (JER) typically amounts to 15–20% at 30 GeV and 10% at 100 GeV. A spreading procedure is applied to match the JER in simulation to that in data [20]. Additional selection criteria are applied to each jet to remove jets potentially dominated by anomalous contributions from various subdetector components or reconstruction failures.

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is computed as the negative vector sum of the p_{T} of all the PF objects from the PV, including unclustered energy from the PF objects not associated with any reconstructed lepton, photon, or jet [21]. Its magnitude is denoted as $p_{\mathrm{T}}^{\mathrm{miss}}$, and it is a measure of the transverse momentum of particles leaving the detector undetected. The $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ is modified to correct the energy scale of the reconstructed jets in the event. Anomalous high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events can be due to a variety of reconstruction failures, detector malfunctions, or noncollision backgrounds. Such events are rejected by event filters that are designed to identify more than 85–90% of the spurious high-$p_{\mathrm{T}}^{\mathrm{miss}}$ events with a mistagging rate of less than 0.1% [21].

The trigger, reconstruction, and selection efficiencies are corrected in simulation to match those observed in the data. Lepton efficiencies (ϵ_{ℓ}) are evaluated using data samples of dilepton events in the Z boson mass peak region with the tag-and-probe method [22], and correction factors $\epsilon_{\ell}^{\mathrm{data}}/\epsilon_{\ell}^{\mathrm{MC}}$, binned in p_{T}^{ℓ} and η^{ℓ} of the leptons, are implemented.

3. Data and simulated event samples

This measurement is performed using a data sample of pp collisions at $\sqrt{s} = 13$ TeV collected by the CMS experiment during the 2016 (36.3 fb^{-1}), 2017 (41.5 fb^{-1}), and 2018 (59.8 fb^{-1}) data-taking periods with a total integrated luminosity of approximately 138 fb^{-1}.

The signal process, referred to as semileptonic $\mathrm{t\bar{t}}$, occurs in events where one of the W bosons produced in the decay of the $\mathrm{t\bar{t}}$ pair, decays leptonically, whereas the second W boson decays hadronically into two jets. The high transverse momentum lepton (electron or muon) is used for the online selection of signal events, and the identification of a c jet enables the measurement of $R_{\mathrm{c}}^{\mathrm{W}}$. The presence of two additional b jets from the decay of the $\mathrm{t\bar{t}}$ pair efficiently suppresses the background from events where a vector boson (W , Z /γ^{*}) is produced in association with jets (collectively denoted as V + jets). Other background processes are $\mathrm{t\bar{t}}$ events where the two W bosons decay leptonically (referred to as dileptonic $\mathrm{t\bar{t}}$) and single top quark production. The background of diboson (WW, WZ, and ZZ, collectively denoted as VV) events is negligible.

The Monte Carlo (MC) event generator POWHEG v2.0 [23–25] is used to simulate the production of $\mathrm{t\bar{t}}$ and single top quark (s-, t-, and tW channels) events at next-to-leading-order (NLO) accuracy in quantum chromodynamics (QCD). The renormalization and factorization scales are set to the transverse mass $m_{\mathrm{T}}^{\mathrm{t}} = \sqrt{m_{\mathrm{t}}^2 + p_{\mathrm{T}}^2}$ of the top quark, where $m_{\mathrm{t}} = 172.5$ GeV is used. Simulated samples of V + jets are generated at NLO accuracy with the MADGRAPH5_aMC@NLO [26] (version 2.6.3) matrix element generator. The diboson production process is modeled at leading order with samples of events generated with PYTHIA8 [27] (version 8.219). The parton distribution functions (PDFs) NNPDF3.1 NNLO [28] are used. The output of the event generators is combined with the parton shower (PS) and hadronization simulation of PYTHIA8 using the underlying event tune CP5 [29]. Pileup collisions are overlaid in each simulated event, and the generated distribution of the number

of events per bunch crossing is matched to that observed in data. The detector response is simulated using GEANT4 [30].

4. Event selection

The event sample is collected with a trigger algorithm [12] that requires the presence of an electron (muon) candidate with a minimum p_T of 27, 32, and 32 GeV (24, 27, and 24 GeV) during the 2016, 2017, and 2018 data-taking periods, respectively. Electrons and muons are selected using tight identification criteria following the reconstruction algorithms discussed in Refs. [14,15]. We select electrons (muons) with $p_T^{\ell} > 35$ (30) GeV and $|\eta^{\ell}| < 2.4$. The isolation I^{ℓ} of a lepton is defined as the scalar p_T sum of all PF particles within a distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ (0.4) around the electron (muon). Electrons are identified using gradient-boosted decision trees, where isolation is one of the included observables. The muon candidate is isolated if $I^{\ell}/p_T^{\ell} < 0.15$. Events with an additional isolated lepton with $p_T^{\ell} > 20$ GeV are rejected.

The transverse mass (m_T) of the lepton and $\vec{p}_T^{\,\text{miss}}$ is defined as

$$m_T \equiv \sqrt{2\, p_T^{\ell}\, p_T^{\text{miss}}\, [1 - \cos(\phi_{\ell} - \phi_{p_T^{\text{miss}}})]},$$

where ϕ_{ℓ} and $\phi_{p_T^{\text{miss}}}$ are the azimuthal angles of the lepton and the $\vec{p}_T^{\,\text{miss}}$ vector, respectively. Events with $m_T < 20$ GeV or $p_T^{\text{miss}} < 20$ GeV are discarded to suppress the contamination from events composed uniquely of jets produced through the strong interaction.

In addition to the requirements above that are designed to select events with a W boson decaying leptonically with an electron or a muon in the final state, we require the presence of at least four jets with $p_T^{\text{jet}} > 25$ GeV and $|\eta^{\text{jet}}| < 2.4$. Jets with a low angular separation between the jet axis and the selected isolated lepton, $\Delta R(\text{jet}, \ell) < 0.4$, are not considered.

Two of the selected jets must be identified as originating from the hadronization of a b quark. The b tagging algorithm employs a deep neural network multiclassification algorithm (DEEPJET [31]) that considers the full information of all jet constituents, charged and neutral particles, secondary vertices, and global event variables, simultaneously [32]. The chosen working point of the algorithm corresponds to a misidentification rate of 1% for light-quark and gluon jets (evaluated together and referred to as "light jets" in the following), and an identification efficiency of around 70% for bottom quark jets.

To further reduce the background and to improve the efficiency in the identification and classification of the four jets coming from the decay of the $t\bar{t}$ pair, we impose additional kinematic constraints. We calculate the invariant mass of the prompt lepton and either of the two b-tagged jets ($m_{\ell b}$) and discard events if $m_{\ell b} > 150$ GeV for both b jet combinations. In addition, we use the W boson and top quark mass constraints to perform a χ^2 test evaluating the compatibility of three-jet combinations with the expectation from simulation for jets originating from the decay of a top quark. The W boson invariant mass (m_{jj}^{W}) is determined from the two highest p_T jets, excluding the b jet candidates, and the top quark mass (m_{jjb}^{t}) is calculated using those two jets along with one of the b-tagged jets. The expected average values for m_{jj}^{W} and m_{jjb}^{t}, and its covariance matrix, are computed with the semileptonic $t\bar{t}$ simulation. An event is discarded if the two possible three-jet combinations yield a p-value in the χ^2 test smaller than 0.2. We also require that the b jet passing the χ^2 test is different than the one fulfilling the $m_{\ell b}$ requirement. According to the simulation, after applying these kinematic requirements, the two b jets are correctly matched in 98% of cases, and the two jets from the W boson decay are correctly assigned in 81%.

The data sample selected with the above criteria, referred to as ℓ + jets, consists of 916 680 events. According to the simulation, the data sample is composed of 45% semileptonic $t\bar{t}$ events with $W \to cq$, 45% semileptonic $t\bar{t}$ with $W \to uq$, 6% dileptonic $t\bar{t}$, 3% single top quark, and 1% V + jets.

4.1. Identification of charm jets

The accurate identification of c jets from the decay of W bosons, the precise calibration of the charm tagging efficiency, and the estimation of the associated systematic uncertainties are key ingredients of the R_c^W measurement. In a sizable fraction of the charm hadron decays (≈9% [3]) there is a muon in the final state. The presence of the muon inside the jet provides a high-purity signature to identify c jets. Semileptonic c quark decays into electrons are not considered because of the high background in identifying electrons inside jets. The muon-based charm tagging method provides a clean selection of c jets with a low misidentification rate for light jets, which is precisely determined from data, as described below. This allows a precision measurement of R_c^W with reduced systematic uncertainties.

Charm jets are tagged requiring a reconstructed muon among the constituents of either of the two selected jets associated with the W boson candidate decaying hadronically. The muon must satisfy the same tight reconstruction and identification quality criteria as those imposed on the muons from the W boson decaying leptonically, except for isolation, which is inverted requiring a minimum nonisolation of $I^{\mu} > 2.5$ GeV. The muon must be reconstructed in the region $|\eta^{\mu}| < 2.4$, with $5 < p_T^{\mu} < 25$ GeV, and $p_T^{\mu}/p_T^{\text{jet}} < 0.5$. The upper p_T requirement and the $p_T^{\mu}/p_T^{\text{jet}}$ condition significantly reduce the contamination from prompt muons overlapping with or misreconstructed as jets. The lower p_T threshold ensures a sufficiently high muon reconstruction efficiency (70% at $p_T^{\mu} = 5$ GeV) since the muon must traverse the material in front of the muon detector and penetrate deep enough into the muon system to be reconstructed and satisfy the identification criteria. If more than one such muon is identified, the one with the highest p_T is selected.

In the semileptonic $t\bar{t}$ charm signal events, the electric charges of the isolated lepton and the muon from the c hadron decay are opposite. We refer to these events as opposite-sign (OS) events. We impose the OS condition as an additional selection requirement for the c-tagged data sample.

In most of the backgrounds, the number of OS events is the same as the number of events for which the charges of the isolated lepton and the muon in the jet are the same, which we refer to as same-sign (SS) events. This applies to events c-tagged by the presence of a muon from the decay of a pion or a kaon within a jet, or to events c-tagged by muons from b jets in $t\bar{t}$ events, where the production of a $b\bar{b}$ pair from the $t\bar{t}$ decay ensures symmetric contributions from OS and SS events. Additionally, heavy quark-antiquark pairs, generated, for example, by gluon splitting in the PS and involving muons in their decay chain, also produce charge-symmetric events. These charge-symmetric backgrounds can be estimated from the SS data sample leveraging the OS = SS background symmetry. For this reason, in the statistical analysis described in Section 6, the expectation for OS events in data will be modeled by the sum of the OS − SS subtracted simulation yields and the SS data events. This approach removes the need for the simulation to estimate the charge-symmetric background contribution. The SS data and MC yields differ by approximately 10%.

The selected data sample containing one c-tagged jet consists of 17 973 OS and 4097 SS events. Fig. 1 shows relevant kinematic distributions of the muon inside the tagged c jets, illustrating the good agreement between data and simulation. In this figure, the normalization of the semileptonic $t\bar{t}$ simulation, after applying the ℓ + jets selection criteria and before charm tagging, has been scaled to match the data. The displayed distributions correspond to OS − SS subtracted yields, both for the data and the simulations. The gray band in the predictions accounts for the systematic uncertainties discussed in Section 5. The c-tagged jet sample has a high purity of 97% in c jets. The only significant residual

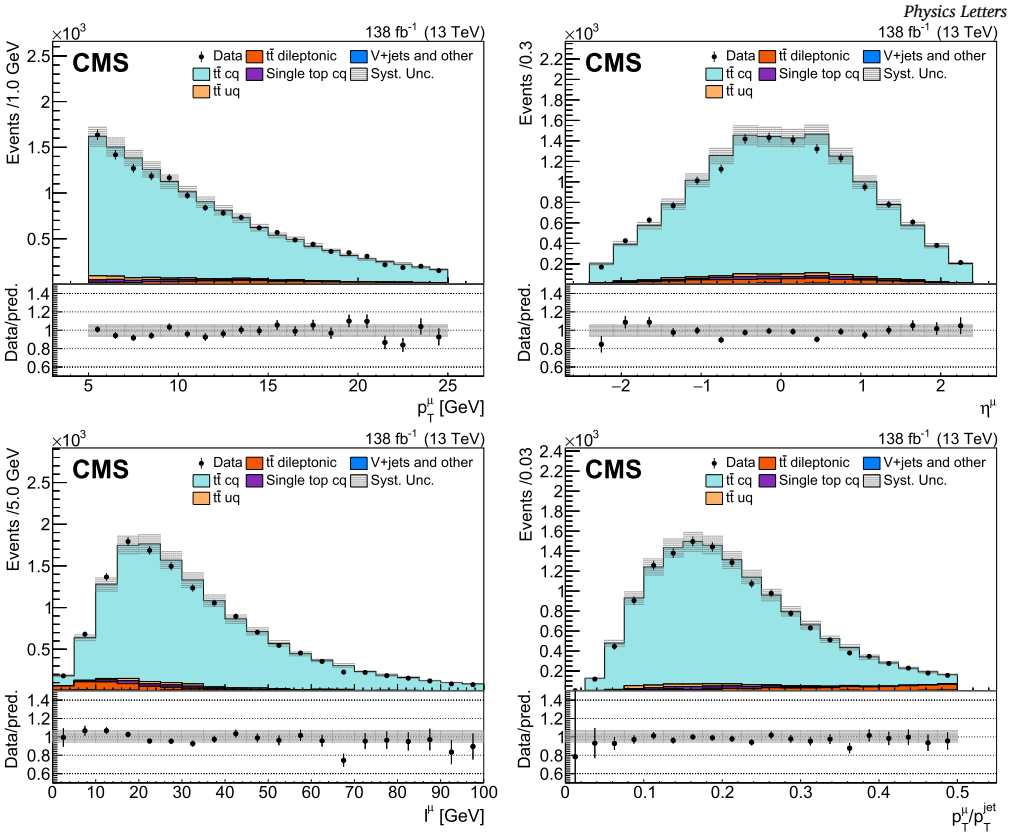

Fig. 1. Kinematic distributions of the muon inside the c-tagged jets: transverse momentum p_{T}^{μ} (upper left), pseudorapidity η^{μ} (upper right), isolation I^{μ} (lower left), and $p_{\mathrm{T}}^{\mu}/p_{\mathrm{T}}^{\mathrm{jet}}$ (lower right). Histograms show OS − SS yields for both data and simulations. Events with a prompt electron or muon are considered. The data are displayed as points with statistical error bars. The gray band in the predictions represents the systematic uncertainties. The ratios of data to the expected yields are given at the bottom of each panel, together with the statistical and systematic uncertainties.

contribution after OS − SS subtraction arises from dileptonic $\mathrm{t\bar{t}}$ events, where a muon from the decay of one W boson overlaps with a light jet. This contribution is inherently OS, since the muon inside the jet carries a charge opposite to that of the isolated lepton from the decay of the other W boson.

4.1.1. Calibration of muons inside charm jets

The modeling of the muon-based charm tagging relies on the accurate simulation of the production of c hadrons from the hadronization of c quarks, and their leptonic and semileptonic decays with a muon in the final state. The QCD PS, hadronization, and particle decay in the simulated samples are performed by PYTHIA8. The charm fragmentation fractions (FFs), defined as the probabilities for c quarks to hadronize as particular c hadrons, corresponding to $\mathrm{D}^{\pm}$, $\mathrm{D}^{0}/\overline{\mathrm{D}}^{0}$, $\mathrm{D}_{\mathrm{s}}^{\pm}$, and $\Lambda_{\mathrm{c}}^{\pm}$ hadrons, are reweighted in the MC samples to match the measured values reported in Ref. [33]. These values, derived from a combination of $\mathrm{e^{+}e^{-}}$, ep, and pp collision data, are well suited to the charm production mechanism and kinematic regime relevant to this study. In addition, the leptonic and semileptonic branching fractions (BFs) of the c hadrons are adjusted to agree with more recent measurements [3]. The overall correction reduces the rate of muons originating from c hadron decays in the simulation by 4.5%.

The reconstruction and identification efficiency of muons inside jets in the simulation is calibrated with data. The b jets in the ℓ + jets selected sample, identified with very high purity, provide a suitable source of muons for calibration. These muons, originating from the semileptonic decays of b hadrons or c hadrons produced in the hadronic decay of b hadrons, are kinematically similar to those found in c jets. The rate of muons in b jets depends on several factors: the relative production rate of b hadrons from b quarks (i.e., the b-quark FFs), the muonic BFs of b hadrons, the BFs of b hadrons decaying into c hadrons, and the muonic BFs of the resulting c hadrons. After applying the aforementioned corrections to the muonic BFs of c hadrons, the muon rate in b jets in the simulation aligns with experimental measurements [3], and no additional corrections are required. A correction factor for the identification efficiency of muons within jets is determined by comparing the rate of reconstructed muons inside b jets in data and simulation, using the ℓ + jets selected sample as a starting point. The correction factor, which ranges from 1.0 to 0.85, is independent of p_T^{μ} but varies with muon isolation I^{μ} and pseudorapidity $|\eta^{\mu}|$. The correction deviates from 1 as the muon becomes less isolated and also with increasing $|\eta^{\mu}|$. The dependence on I^{μ} ensures that the correction derived from muons in b jets remains applicable to muons in c jets, which typically have lower particle multiplicity. The distributions shown in Fig. 1 are generated using calibrated muon efficiencies.

5. Systematic uncertainties

Several sources of systematic uncertainty affect the predicted event yields of the various signal and background processes used to extract the $R_{\mathrm{c}}^{\mathrm{W}}$ measurement. For all the uncertainties, those originating from the same source are considered fully correlated between channels, and those arising from different sources are considered uncorrelated.

The high-p_{T} prompt muons and electrons in the simulated samples have uncertainties associated with the high-level trigger, reconstruction, and identification efficiencies (1–2%). These uncertainties are uncorrelated across lepton flavors but correlated across data-taking years and are parameterized as functions of the lepton p_{T} and η. The uncertainty associated with the possible misidentification of the sign of the lepton electric charge is negligible.

JES and JER uncertainties are accounted for by varying the energy of reconstructed jets in simulated events. These variations incorporate

Table 1
Summary of the main systematic uncertainties affecting the R_c^W measurement. The quoted numbers are the percentage change in the predicted yields of the samples with no charm and with a charm tag, and the last column reflects the impacts in percentage of the measured R_c^W value from each uncertainty source. The total systematic uncertainty, calculated from the various sources of uncertainty and their correlations, is given in the last row.

	No charm tag	Charm tag	Impact on R_c^W
Source	Uncertainty [%]		
Charm tagging: muon identification	—	2.7	2.6
Charm tagging: muon rate in simulation	—	2.2	2.1
Parton shower final state radiation	4.0	6.0	1.9
Jet energy scale	4.0	4.0	0.6
SS data statistical uncertainty	—	1.6	0.5
Charm fragmentation modeling	—	0.4	0.3
Jet energy resolution	1.0	1.0	0.3
b tagging	2.5	2.5	0.2
MC background normalization	5.0	5.0	0.1
Integrated luminosity	1.6	1.6	0.1
Total			3.9

Table 2
Observed and predicted event yields input to the fit for the four categories. Predictions are separated by process. For the two categories with charm tag, the yields predicted by the simulations correspond to OS − SS subtracted events, the SS contamination is estimated with data, and the number of observed events in data corresponds to OS events. The relative uncertainties shown in parenthesis for the predictions are based on the statistical uncertainties of the MC samples and the systematic uncertainties and their correlations discussed in Section 5. Correlated systematic effects dominate the uncertainties.

Process	Prompt μ no charm tag	Prompt e no charm tag	Prompt μ charm tag	Prompt e charm tag
$t\bar{t}$, W → cq	245 816(7%)	151 570(7%)	8172(9%)	4993(9%)
$t\bar{t}$, W → uq	257 789(7%)	159 146(7%)	150(9%)	84(9%)
Dileptonic $t\bar{t}$	31 343(7%)	19 219(7%)	299(8%)	188(8%)
Single top, W → cq	5060(7%)	3085(7%)	133(10%)	93(10%)
Single top, W → uq	4772(7%)	2948(7%)	2(50%)	2(50%)
Single top, no W → $q\bar{q}'$	3620(13%)	1884(13%)	15(20%)	9(50%)
V + jets	5005(12%)	3687(12%)	43(30%)	9(50%)
Diboson	299(12%)	142(12%)	1(50%)	1(50%)
Total predictions OS − SS			8815(9%)	5379(9%)
Data SS			2551(2%)	1546(2%)
Total predictions	553 705(7%)	341 681(7%)	11 366(7%)	6925(7%)
Data OS	553 378	341 232	11 167	6806

multiple uncertainty sources, which are categorized by detector regions and data-taking years [20]. The JES variations are also propagated to the p_T^{miss}. The resulting uncertainties in the predicted yields are 4% (1%) for JES (JER). The b tagging identification and mistagging efficiencies in the simulation are calibrated to match the corresponding efficiencies in data [34]. Separate uncertainties in the tagging and mistagging corrections are assigned resulting in an overall yield uncertainty from b tagging of 2.5%.

All MC samples are reweighted to match the pileup distribution in data, assuming a total inelastic cross section of 69.2 mb, with a 4.6% uncertainty [35]. The statistical uncertainty of the charm-tagged SS data sample, which is used as the prediction for the mistag contamination of the OS signal sample, is taken as the systematic uncertainty (1.6%) of this component. Additionally, the measured integrated luminosity values for the three data-taking years have uncertainties between 1.2% and 2.5% [36–38], while the overall uncertainty for the combined data set is 1.6%, affecting the predictions from the simulations.

In addition to the experimental sources, we consider theoretical uncertainties affecting the MC simulations. All MC samples are normalized according to their respective SM cross section values, and uncertainties in the rates of each process are assigned using the precision of CMS cross section measurements or theoretical calculations. A 5% uncertainty is assigned to $t\bar{t}$ production [39]; 1%, 2%, and 4% to single top quark *s*-, *t*-, and tW-channel production [40,41]; 2% to V + jets [42]; and 6%, 5%, and 7% to diboson WW, ZZ, and WZ [43–45]. The uncertainty from the choice of PDF is estimated from the Hessian NNPDF3.1 sets according to the procedure described in Ref. [28]; the resulting uncertainty is negligible. For the PS simulation, uncertainties are separately assessed for initial- and final-state radiation (ISR and FSR), by varying the respective scales up and down by factors of two. The effect of the ISR uncertainty is negligible but the FSR uncertainty changes the predicted yields of the samples with and without c tagging by 6% and 4%, respectively, producing a significant impact on the R_c^W uncertainty of 1.9%. An additional uncertainty is included, which is estimated by reweighting the simulation to the measured top quark p_T in Ref. [46]. The effect of this uncertainty is negligible.

The systematic effects discussed so far (except for the effect of the PS FSR uncertainty) have a minimal impact on the uncertainty of the R_c^W measurement since they affect the predictions for the W → cq and W → uq contributions in approximately the same way. The dominant source of uncertainty in R_c^W arises from systematic effects related to c tagging, which influence the predicted yields of the c -tagged sample. The correction of the muon rate in the decay of c hadrons in the simulation, described in Section 4.1.1, introduces an uncertainty of 2.2% in the

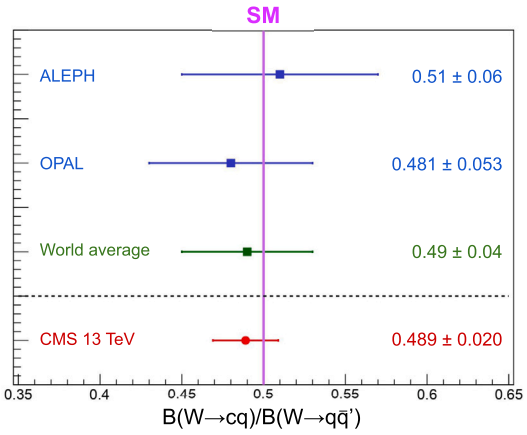

Fig. 2. Comparison of the measured value of R_c^W with previous LEP2 measurements [4,5], and the world-average value [3]. Horizontal bars represent the total uncertainty of the measurements.

W → cq rate, reflecting the precision of the charm FF and semileptonic decay BF measurements. The scale factor correcting the reconstruction and identification efficiency of muons inside jets in the simulation, determined by comparing the rate of muons in b jets in data and simulation, as detailed in Section 4.1.1, brings in an uncertainty of 2.7%. This value mostly arises from the uncertainty in the measurements of the b quark FFs to $B^{\pm}$, $B^0/\overline{B}^0$, B_s^0, and Λ_b^0 hadrons, the semileptonic decay BFs of these b hadrons, the decay BFs of b hadrons into $D^{\pm}$, $D^0/\overline{D}^0$, $D_s^{\pm}$, and $\Lambda_c^{\pm}$ hadrons, and the semileptonic decay BFs of these c hadrons. It also includes uncertainties related to the calculation of the correction, such as residual kinematic differences between muons in b jets and c jets. The effect of modeling the charm quark fragmentation in the simulation is evaluated by varying ±5% the p_T of the muon in the c-tagged jets, resulting in a systematic yield uncertainty of 0.4%. The variation considered for p_T^{μ} corresponds to the dispersion and uncertainty in the measurements at LEP of the average energy fraction of D mesons in charm quark fragmentation [47–49].

The main systematic uncertainties affecting the R_c^W measurement are summarized in Table 1. Relative changes in the predicted event yields of the samples with and without charm tagging are given together

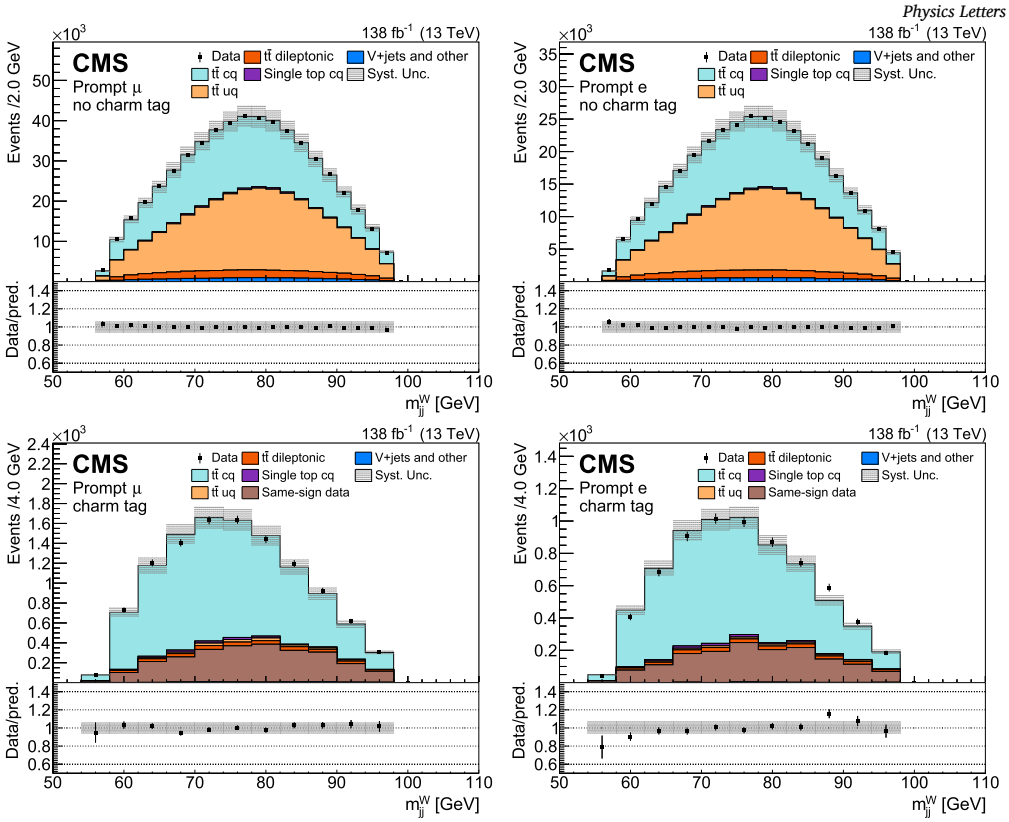

Fig. 3. Invariant mass of the two jets associated with the W boson, for the four event categories entering the fit: prompt muon and no charm tag (upper left), prompt electron and no charm tag (upper right), prompt muon and charm tag (lower left), prompt electron and charm tag (lower right). The measured data correspond to OS events, whereas the predictions from the simulations are OS − SS subtracted yields on top of the background prediction using the SS data. The data are displayed as points with statistical error bars. The gray band in the predictions represents the pre-fit systematic uncertainties. The ratios of data to the expected yields are given at the bottom of each panel together with the statistical and systematic uncertainties.

with the impact of each uncertainty source on the measured value of R_c^W. The total systematic uncertainty is 3.9%.

6. Results

For the extraction of the R_c^W BF ratio, the observed and predicted global event yields, split into four exclusive categories, are used to make a fit with the CMS statistical analysis and combination tool, COMBINE [50]. The four event categories are constructed depending on the flavor of the prompt lepton (electron or muon) and the charm tagging (tag or no tag) of one of the jets associated with the W boson. The predicted input yields from the simulation are separated between $W \to cq$ and $W \to uq$ contributions (from both semileptonic $t\bar{t}$ and single top quark production with a hadronically decaying W boson) and are varied in an anticorrelated manner in the fit. The fit also determines the global normalization of the combined $W \to cq + W \to uq$ contributions. The small background contributions from dileptonic $t\bar{t}$ and V + jets events are taken from the simulation. The effects of systematic uncertainties and their correlations are included by incorporating nuisance parameters into the fit model. As noted in Section 5, many of the systematic effects influence the normalization of the $W \to uq$ and $W \to cq$ contributions in the same way and therefore do not impact the uncertainty of the measured R_c^W ratio.

The observed data yields entering the fit for the two categories with a charm tag are OS events. The predicted yields are constructed using the OS − SS subtracted yields from the MC simulations and the observed SS data representing the remaining background contributions, as described in Section 4.1. This procedure has the advantage that the prediction for the background contribution to $W \to cq$ relies only on the simulation for a small fraction of the events (3%). The remaining backgrounds are accurately characterized by data, significantly reducing the systematic uncertainty in their prediction. Table 2 lists the observed and predicted event yields for the four categories used in the fit. The uncertainties are primarily driven by correlated systematic effects, which cancel out in the determination of R_c^W.

The fit yields a value $R_c^W = 0.489 \pm 0.005\,(\text{stat}) \pm 0.019\,(\text{syst})$, with a total uncertainty of ±0.020, in good agreement with the prediction of the SM. The precision of the measurement, limited by the systematic uncertainty in the charm tagging efficiency, is improved by more than a factor of two compared with the world-average value, as shown in Fig. 2.

To illustrate the good description of the data by the simulation, we display in Figs. 3 and 4, for the four event categories used in the fit, the post-fit distributions of the invariant mass of the two jets associated with the W boson, and the invariant mass of the three jets associated with the top quark. The counting fit slightly adjusts the normalization of the simulation predictions while leaving the shapes of the distributions unchanged.

Using Eq. (1) and the CMS measurement of the sum of squared elements in the first two rows of the CKM matrix (1.984 ± 0.021, determined from the measured W boson leptonic decay BFs [51]), the sum of squared elements in the second row of the CKM matrix can be derived. The obtained value, $\Sigma = 0.970 \pm 0.041$, provides a consistency test of the CKM matrix unitarity. In addition, using the measured value of Σ and the world-average values of $|V_{cd}| = 0.221 \pm 0.004$ and $|V_{cb}| = 0.0408 \pm 0.0014$ [3], a value of $|V_{cs}| = 0.959 \pm 0.021$ is obtained. This value is less precise than the current world-average value, $|V_{cs}| = 0.975 \pm 0.006$ [3], determined from leptonic and semileptonic

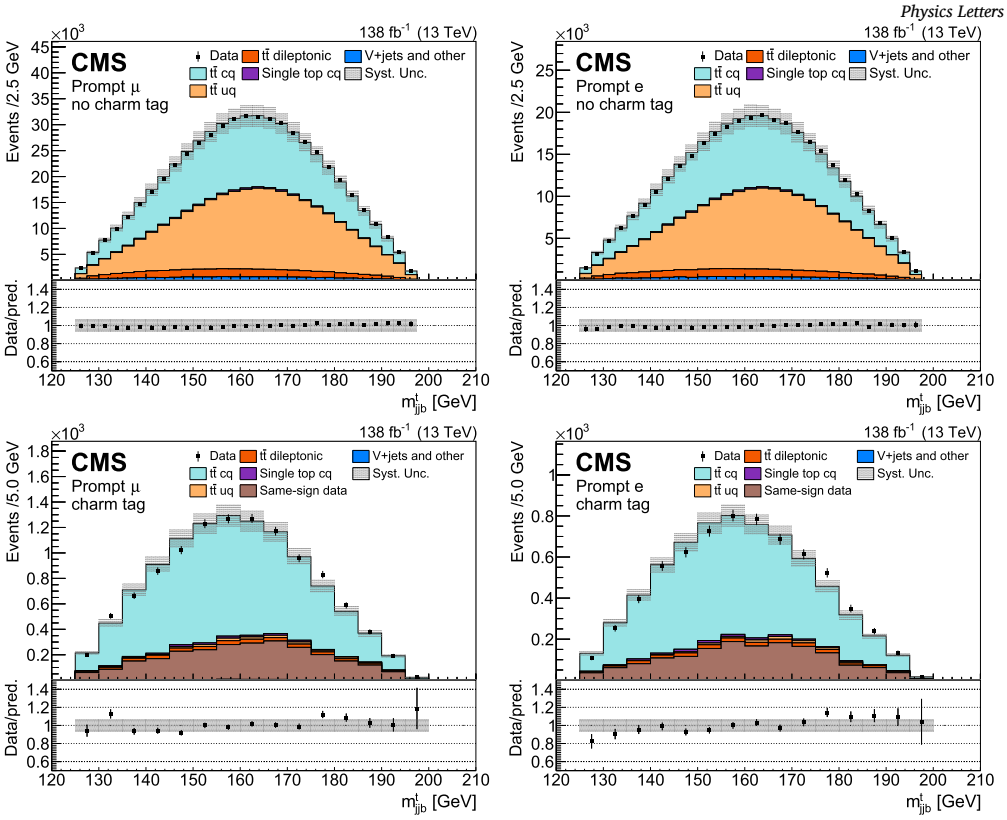

Fig. 4. Invariant mass of the three jets associated with the top quark, for the four event categories entering the fit: prompt muon and no charm tag (upper left), prompt electron and no charm tag (upper right), prompt muon and charm tag (lower left), prompt electron and charm tag (lower right). The measured data correspond to OS events, whereas the predictions from the simulations are OS − SS subtracted yields on top of the background prediction using the SS data. The data are displayed as points with statistical error bars. The gray band in the predictions represents the pre-fit systematic uncertainties. The ratios of data to the expected yields are given at the bottom of each panel together with the statistical and systematic uncertainties.

charm hadron decays, but it provides an independent measurement from hadronic W boson decays.

7. Summary

The most precise measurement to date of the W boson hadronic decay branching fraction ratio $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ is reported. The measurement is based on a data sample collected by the CMS experiment at a center-of-mass energy of 13 TeV in 2016–2018 at the CERN LHC with an integrated luminosity of 138 fb^{-1}. The large cross section of top quark-antiquark production at the LHC offers a sizable high-purity sample of W bosons suitable for this measurement. Events with one prompt charged lepton (electron or muon) and at least four jets, two of them tagged as bottom quark jets, are analyzed. Charm jets are tagged using the presence of a muon inside the jet. This charm tagging method enables the selection of a sample of charm jets with a low level of background that is precisely determined from data. The measured R_c^W value is 0.489 ± 0.020, in good agreement with the standard model prediction. The relative precision of the measurement of 4%, limited by the systematic uncertainty in the charm tagging efficiency, is improved by a factor of two compared with the current world-average value.

From the R_c^W measurement, the sum of squared elements in the second row of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, 0.970 ± 0.041, and the CKM matrix element $|V_{cs}| = 0.959 \pm 0.021$ are derived. These results provide a consistency test of the CKM unitarity and a measurement of $|V_{cs}|$ from hadronic W boson decays.

Declaration of competing interest

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

Acknowledgements

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, RVTT3 and MoER TK202 (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); SRNSF (Georgia); 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); LMTLT (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).

Individuals have received support from the Marie-Curie program and The European Research Council and Horizon 2020 Grant, contract Nos. 675440, 724704, 752730, 758316, 765710, 824093, 101115353, 101002207, and COST Action CA16108 (European Union); the Leventis Foundation; the Alfred P. Sloan Foundation; the Alexander von Humboldt Foundation; the Science Committee, project no. 22rl-037 (Armenia); the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science – EOS" – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); The Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), among others, under Germany's Excellence Strategy – EXC 2121 "Quantum Universe" – 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, TKP2021-NKTA-64, and 2021-4.1.2-NEMZ_KI-2024-00036 (Hungary); the Council of Science and Industrial Research, India; ICSC – National Research Center for High Performance Computing, Big Data and Quantum Computing and FAIR – Future Artificial Intelligence Research, funded by the NextGenerationEU program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência e a Tecnologia, grant CEECIND/01334/2018 (Portugal); the National Priorities Research Program by Qatar National Research Fund; MCIN/AEI/10.13039/501100011033, ERDF "a way of making Europe", and the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2017-0765 and Programa Severo Ochoa del Principado de Asturias (Spain); the Chulalongkorn Academic into Its 2nd Century Project Advancement Project, and the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation, grant B39G670016 (Thailand); the Kavli Foundation; the Nvidia Corporation; the SuperMicro Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (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, re-use and open access policy.

References

[1] N. Cabibbo, Unitary symmetry and leptonic decays, Phys. Rev. Lett. 10 (1963) 531, https://doi.org/10.1103/PhysRevLett.10.531.

[2] M. Kobayashi, T. Maskawa, CP violation in the renormalizable theory of weak interaction, Prog. Theor. Phys. 49 (1973) 652, https://doi.org/10.1143/PTP.49.652.

[3] Particle Data Group, S. Navas, et al., Review of particle physics, Phys. Rev. D 110 (2024) 030001, https://doi.org/10.1103/PhysRevD.110.030001.

[4] R. Barate, et al., ALEPH, A direct measurement of $|V_{cs}|$ in hadronic W decays using a charm tag, Phys. Lett. B 465 (1999) 349, https://doi.org/10.1016/S0370-2693(99)01088-6.

[5] G. Abbiendi, et al., OPAL, A measurement of the rate of charm production in W decays, Phys. Lett. B 490 (2000) 71, https://doi.org/10.1016/S0370-2693(00)00971-0, arXiv:hep-ex/0009020.

[6] CMS Collaboration, Measurement of associated Z + charm production in proton-proton collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 78 (2018) 287, https://doi.org/10.1140/epjc/s10052-018-5752-x, arXiv:1711.02143.

[7] CMS Collaboration, Measurement of associated W + charm production in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 02 (2014) 013, https://doi.org/10.1007/JHEP02(2014)013, arXiv:1310.1138.

[8] CMS Collaboration, Measurements of the production of a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s} = 8$ TeV, Eur. Phys. J. C 82 (2022) 1094, https://doi.org/10.1140/epjc/s10052-022-10897-7, arXiv:2112.00895.

[9] CMS Collaboration, Measurements of the production cross section for a W boson in association with a charm quark in proton-proton collisions at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 84 (2024) 27, https://doi.org/10.1140/epjc/s10052-023-12258-4, arXiv:2308.02285v2.

[10] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.

[11] CMS Collaboration, Performance of the CMS Level-1 trigger in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 15 (2020) P10017, https://doi.org/10.1088/1748-0221/15/10/P10017, arXiv:2006.10165.

[12] CMS Collaboration, The CMS trigger system, J. Instrum. 12 (2017) P01020, https://doi.org/10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[13] CMS Collaboration, Particle-flow reconstruction and global event description with the CMS detector, J. Instrum. 12 (2017) P10003, https://doi.org/10.1088/1748-0221/12/10/P10003, arXiv:1706.04965.

[14] CMS Collaboration, Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC, J. Instrum. 16 (2021) P05014, https://doi.org/10.1088/1748-0221/16/05/P05014, arXiv:2012.06888.

[15] CMS Collaboration, Performance of the CMS muon detector and muon reconstruction with proton-proton collisions at $\sqrt{s} = 13$ TeV, J. Instrum. 13 (2018) P06015, https://doi.org/10.1088/1748-0221/13/06/P06015, arXiv:1804.04528.

[16] CMS Collaboration, Technical proposal for the phase-II upgrade of the Compact Muon Solenoid, CMS Technical Proposal, 2015, http://cds.cern.ch/record/2020886, CERN-LHCC-2015-010, CMS-TDR-15-02.

[17] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_T jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, https://doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[18] M. Cacciari, G.P. Salam, G. Soyez, FastJet user manual, Eur. Phys. J. C 72 (2012) 1896, https://doi.org/10.1140/epjc/s10052-012-1896-2, arXiv:1111.6097.

[19] CMS Collaboration, Pileup mitigation at CMS in 13 TeV data, J. Instrum. 15 (2020) P09018, https://doi.org/10.1088/1748-0221/15/09/p09018, arXiv:2003.00503.

[20] CMS Collaboration, Jet energy scale and resolution in the CMS experiment in pp collisions at 8 TeV, J. Instrum. 12 (2017) P02014, https://doi.org/10.1088/1748-0221/12/02/P02014, arXiv:1607.03663.

[21] CMS Collaboration, Performance of missing transverse momentum reconstruction in proton-proton collisions at $\sqrt{s} = 13$ TeV using the CMS detector, J. Instrum. 14 (2019) P07004, https://doi.org/10.1088/1748-0221/14/07/P07004, arXiv:1903.06078.

[22] CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the CMS experiment, J. High Energy Phys. 10 (2011) 132, https://doi.org/10.1007/JHEP10(2011)132, arXiv:1107.4789.

[23] P. Nason, A new method for combining NLO QCD with shower Monte Carlo algorithms, J. High Energy Phys. 11 (2004) 40, https://doi.org/10.1088/1126-6708/2004/11/040, arXiv:hep-ph/0409146.

[24] S. Frixione, P. Nason, C. Oleari, Matching NLO QCD computations with parton shower simulations: the POWHEG method, J. High Energy Phys. 11 (2007) 70, https://doi.org/10.1088/1126-6708/2007/11/070, arXiv:0709.2092.

[25] S. Alioli, P. Nason, C. Oleari, E. Re, A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX, J. High Energy Phys. 06 (2010) 043, https://doi.org/10.1007/JHEP06(2010)043, arXiv:1002.2581.

[26] J. Alwall, R. Frederix, S. Frixione, V. Hirschi, F. Maltoni, O. Mattelaer, H.-S. Shao, T. Stelzer, P. Torrielli, 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, https://doi.org/10.1007/JHEP07(2014)079, arXiv:1405.0301.

[27] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[28] R.D. Ball, et al., NNPDF Collaboration, Parton distributions from high-precision collider data, Eur. Phys. J. C 77 (2017) 663, https://doi.org/10.1140/epjc/s10052-017-5199-5, arXiv:1706.00428.

[29] CMS Collaboration, Extraction and validation of a new set of CMS Pythia8 tunes from underlying-event measurements, Eur. Phys. J. C 80 (2020) 4, https://doi.org/10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[30] S. Agostinelli, et al., (GEANT4), GEANT4–a simulation toolkit, Nucl. Instrum. Methods A 506 (2003) 250, https://doi.org/10.1016/S0168-9002(03)01368-8.

[31] CMS Collaboration, Identification of heavy-flavour jets with the CMS detector in pp collisions at 13 TeV, J. Instrum. 13 (2018) P05011, https://doi.org/10.1088/1748-0221/13/05/P05011, arXiv:1712.07158.

[32] E. Bols, J. Kieseler, M. Verzetti, M. Stoye, A. Stakia, Jet flavour classification using DeepJet, J. Instrum. 15 (2020) P12012, https://doi.org/10.1088/1748-0221/15/12/P12012, arXiv:2008.10519.

[33] M. Lisovyi, A. Verbytskyi, O. Zenaiev, Combined analysis of charm-quark fragmentation-fraction measurements, Eur. Phys. J. C 76 (2016) 397, https://doi.org/10.1140/epjc/s10052-016-4246-y, arXiv:1509.01061.
[34] CMS Collaboration, Performance of the DeepJet b tagging algorithm using 41.9/fb of data from proton-proton collisions at 13 TeV with Phase 1 CMS detector, CMS detector performance summary CMS-DP-2018-058, http://cds.cern.ch/record/2646773, 2018.
[35] CMS Collaboration, Measurement of the inelastic proton-proton cross section at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2018) 161, https://doi.org/10.1007/JHEP07(2018)161, arXiv:1802.02613.
[36] 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 (2021) 800, https://doi.org/10.1140/epjc/s10052-021-09538-2, arXiv:2104.01927.
[37] CMS Collaboration, CMS luminosity measurement for the 2017 data-taking period at $\sqrt{s} = 13$ TeV, CMS physics analysis summary, https://cds.cern.ch/record/2621960, 2018, CMS-PAS-LUM-17-004.
[38] CMS Collaboration, CMS luminosity measurement for the 2018 data-taking period at $\sqrt{s} = 13$ TeV, CMS physics analysis summary, https://cds.cern.ch/record/2676164, 2019, CMS-PAS-LUM-18-002.
[39] M. Czakon, A. Mitov, Top++: a program for the calculation of the top-pair cross-section at hadron colliders, Comput. Phys. Commun. 185 (2014) 2930, https://doi.org/10.1016/j.cpc.2014.06.021, arXiv:1112.5675.
[40] J. Campbell, T. Neumann, Z. Sullivan, Single-top-quark production in the t-channel at NNLO, J. High Energy Phys. 02 (2021) 040, https://doi.org/10.1007/JHEP02(2021)040, arXiv:2012.01574.
[41] N. Kidonakis, N. Yamanaka, Higher-order corrections for tW production at high-energy hadron colliders, J. High Energy Phys. 05 (2021) 278, https://doi.org/10.1007/JHEP05(2021)278, arXiv:2102.11300.
[42] CMS Collaboration, Measurement of the inclusive cross sections for W and Z boson production in proton-proton collisions at $\sqrt{s} = 5.02$ and 13 TeV, J. High Energy Phys. 10 (2025) 162, https://doi.org/10.1007/JHEP04(2025)162, arXiv:2408.03744.
[43] CMS Collaboration, W^+W^- boson pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D 102 (2020) 092001, https://doi.org/10.1103/PhysRevD.102.092001, arXiv:2009.00119.
[44] CMS Collaboration, Measurements of pp → ZZ production cross sections and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV, Eur. Phys. J. C 81 (2021) 200, https://doi.org/10.1140/epjc/s10052-020-08817-8, arXiv:2009.01186.
[45] CMS Collaboration, Measurement of the inclusive and differential WZ production cross sections, polarization angles, and triple gauge couplings in pp collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 07 (2022) 32, https://doi.org/10.1007/JHEP07(2022)032, arXiv:2110.11231.
[46] V. Khachatryan, et al., CMS Collaboration, Measurement of differential cross sections for top quark pair production using the lepton+jets final state in proton-proton collisions at 13 tev, Phys. Rev. D 95 (2017) 092001, https://doi.org/10.1103/PhysRevD.95.092001, arXiv:1610.04191v2.
[47] P. Abreu, et al., DELPHI, A measurement of D meson production in Z^0 hadronic decays, Z. Phys. C 59 (1993) 533, https://doi.org/10.1007/BF01562545.
[48] R. Akers, et al., OPAL, A measurement of the production of $D^{*\pm}$ mesons on the Z^0 resonance, Z. Phys. C 67 (1995) 27, https://doi.org/10.1007/BF01564819.
[49] R. Barate, et al., ALEPH, Study of charm production in Z decays, Eur. Phys. J. C 16 (2000) 597, https://doi.org/10.1007/s100520000421, arXiv:hep-ex/9909032.
[50] CMS Collaboration, The CMS statistical analysis and combination tool: *Combine*, Comput. Softw. Big Sci. 8 (2024) 19, https://doi.org/10.1007/s41781-024-00121-4, arXiv:2404.06614.
[51] CMS Collaboration, Precision measurement of the W boson decay branching fractions in proton-proton collisions at $\sqrt{s} = 13$ TeV, Phys. Rev. D 105 (2022) 072008, https://doi.org/10.1103/PhysRevD.105.072008, arXiv:2201.07861.

The CMS collaboration

A. Hayrapetyan, A. Tumasyan [1]

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, J.W. Andrejkovic, L. Benato, T. Bergauer, S. Chatterjee, K. Damanakis, M. Dragicevic, P.S. Hussain, M. Jeitler [2], N. Krammer, A. Li, D. Liko, I. Mikulec, J. Schieck [2], R. Schöfbeck [2], D. Schwarz, M. Sonawane, W. Waltenberger, C.-E. Wulz [2]

Institut für Hochenergiephysik, Vienna, Austria

T. Janssen, T. Van Laer, P. Van Mechelen

Universiteit Antwerpen, Antwerpen, Belgium

N. Breugelmans, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, F. Heyen, S. Lowette, I. Makarenko, D. Müller, S. Tavernier, M. Tytgat [3], G.P. Van Onsem, S. Van Putte, D. Vannerom

Vrije Universiteit Brussel, Brussel, Belgium

B. Bilin, B. Clerbaux, A.K. Das, I. De Bruyn, G. De Lentdecker, H. Evard, L. Favart, P. Gianneios, J. Jaramillo, A. Khalilzadeh, F.A. Khan, K. Lee, A. Malara, M.A. Shahzad, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Université Libre de Bruxelles, Bruxelles, Belgium

M. De Coen, D. Dobur, G. Gokbulut, Y. Hong, J. Knolle, L. Lambrecht, D. Marckx, K. Mota Amarilo, K. Skovpen, N. Van Den Bossche, J. van der Linden, L. Wezenbeek

Ghent University, Ghent, Belgium

Physics Letters B 868 (2025) 139754

A. Benecke, A. Bethani, G. Bruno, C. Caputo, J. De Favereau De Jeneret, C. Delaere, I.S. Donertas, A. Giammanco, A.O. Guzel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, T.T. Tran, S. Turkcapar

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

G.A. Alves, E. Coelho, G. Correia Silva, C. Hensel, T. Menezes De Oliveira, C. Mora Herrera [4], P. Rebello Teles, M. Soeiro, E.J. Tonelli Manganote [5], A. Vilela Pereira [4]

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato [6], E.M. Da Costa, G.G. Da Silveira [7], D. De Jesus Damiao, S. Fonseca De Souza, R. Gomes De Souza, T. Laux Kuhn [7], M. Macedo, J. Martins, L. Mundim, H. Nogima, J.P. Pinheiro, A. Santoro, A. Sznajder, M. Thiel

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

C.A. Bernardes [7], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, I. Maietto Silverio, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil

A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

University of Sofia, Sofia, Bulgaria

S. Keshri, D. Laroze, S. Thakur

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile

T. Cheng, T. Javaid, L. Yuan

Beihang University, Beijing, China

Z. Hu, Z. Liang, J. Liu

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen [8], H.S. Chen [8], M. Chen [8], F. Iemmi, C.H. Jiang, A. Kapoor [9], H. Liao, Z.-A. Liu [10], R. Sharma [11], J.N. Song [10], J. Tao, C. Wang [8], J. Wang, Z. Wang [8], H. Zhang, J. Zhao

Institute of High Energy Physics, Beijing, China

A. Agapitos, Y. Ban, A. Carvalho Antunes De Oliveira, S. Deng, B. Guo, C. Jiang, A. Levin, C. Li, Q. Li, Y. Mao, S. Qian, S.J. Qian, X. Qin, X. Sun, D. Wang, H. Yang, L. Zhang, Y. Zhao, C. Zhou

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

S. Yang

Guangdong Provincial Key Laboratory of Nuclear Science and Guangdong-Hong Kong Joint Laboratory of Quantum Matter, South China Normal University, Guangzhou, China

Z. You

Sun Yat-Sen University, Guangzhou, China

K. Jaffel, N. Lu

University of Science and Technology of China, Hefei, China

G. Bauer [12], B. Li [13], K. Yi [14], J. Zhang

Nanjing Normal University, Nanjing, China

Y. Li

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China

Z. Lin, C. Lu, M. Xiao

Zhejiang University, Hangzhou, Zhejiang, China

C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Los Andes, Bogota, Colombia

C. Rendón, M. Rodriguez, A.A. Ruales Barbosa, J.D. Ruiz Alvarez

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

M. Kovac, A. Petkovic, T. Sculac

University of Split, Faculty of Science, Split, Croatia

P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, K. Jakovcic, A. Starodumov [15], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis, K. Christoforou, A. Hadjiagapiou, C. Leonidou, J. Mousa, C. Nicolaou, L. Paizanos, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

University of Cyprus, Nicosia, Cyprus

M. Finger, M. Finger Jr., A. Kveton

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

B. El-mahdy, S. Khalil [16], E. Salama [17,18]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

M. Abdullah Al-Mashad, M.A. Mahmoud

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt

K. Ehataht, M. Kadastik, T. Lange, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann, K. Osterberg, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar, N. Bin Norjoharuddeen, E. Brücken, F. Garcia, P. Inkaew, K.T.S. Kallonen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Myllymäki, M.m. Rantanen, H. Siikonen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka, H. Petrow

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, M. Kumar, V. Lohezic, J. Malcles, F. Orlandi, L. Portales, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[19], P. Simkina, M. Titov, M. Tornago

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

F. Beaudette, G. Boldrini, P. Busson, A. Cappati, C. Charlot, M. Chiusi, T.D. Cuisset, F. Damas, O. Davignon, A. De Wit, I.T. Ehle, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, M. Nguyen, C. Ochando, R. Salerno, J.B. Sauvan, Y. Sirois, L. Urda Gómez, E. Vernazza, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France

J.-L. Agram[20], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, R. Haeberle, A.-C. Le Bihan, M. Meena, O. Poncet, G. Saha, M.A. Sessini, P. Van Hove, P. Vaucelle

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

A. Di Florio

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

D. Amram, S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, D. Contardo, P. Depasse, C. Dozen[21], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, E. Jourd'huy, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France

G. Adamov, I. Lomidze, Z. Tsamalaidze[22]

Georgian Technical University, Tbilisi, Georgia

V. Botta, S. Consuegra Rodríguez, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, D. Pérez Adán, N. Röwert, M. Teroerde

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, J. Erdmann, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, F. Mausolf, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, C. Seth, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[23], S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

C. Dziwok, G. Flügge, T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, J. Bach, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, F. Blekman[24], K. Borras[25], A. Campbell, A. Cardini, C. Cheng, F. Colombina, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, E. Gallo[24], A. Geiser, V. Guglielmi, M. Guthoff, A. Hinzmann, L. Jeppe, B. Kaech, M. Kasemann, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[26], W. Lohmann[27], F. Lorkowski, R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, A.B. Meyer, G. Milella, K. Moral Figueroa, A. Mussgiller, L.P. Nair, J. Niedziela, A. Nürnberg, Y. Otarid, J. Park, E. Ranken, A. Raspereza, D. Rastorguev, J. Rübenach, L. Rygaard, A. Saggio, M. Scham[28,25], S. Schnake[25], P. Schütze, C. Schwanenberger[24], D. Selivanova, K. Sharko, M. Shchedrolosiev, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, D. Wang, Q. Wang, K. Wichmann, L. Wiens[25], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht, S. Albrecht, M. Antonello, S. Bein, S. Bollweg, M. Bonanomi, P. Connor, K. El Morabit, Y. Fischer, E. Garutti, A. Grohsjean, J. Haller, D. Hundhausen, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, C.c. Kuo, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, L. Moureaux, M. Mrowietz, A. Nigamova, Y. Nissan, A. Paasch, K.J. Pena Rodriguez, T. Quadfasel, B. Raciti, M. Rieger, D. Savoiu, J. Schindler, P. Schleper, M. Schröder, J. Schwandt, M. Sommerhalder, H. Stadie, G. Steinbrück, A. Tews, B. Wiederspan, M. Wolf

University of Hamburg, Hamburg, Germany

S. Brommer, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, U. Elicabuk, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[29], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, O. Lavoryk, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, E. Pfeffer, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, L. Sowa, L. Stockmeier, K. Tauqeer, M. Toms, B. Topko, N. Trevisani, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, X. Zuo

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, A. Kyriakis, A. Papadopoulos[29], A. Stakia

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Melachroinos, Z. Painesis, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

Physics Letters B 868 (2025) 139754

I. Bestintzanos, I. Evangelou, C. Foudas, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

University of Ioánnina, Ioánnina, Greece

C. Hajdu, D. Horvath[30,31], K. Márton, A.J. Rádl[32], F. Sikler, V. Veszpremi

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary

M. Csanád, K. Farkas, A. Fehérkuti[33], M.M.A. Gadallah[34], Á. Kadlecsik, P. Major, G. Pásztor, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

B. Ujvari, G. Zilizi

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G. Bencze, S. Czellar, J. Molnar, Z. Szillasi

HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary

T. Csorgo[33], F. Nemes[33], T. Novak

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary

S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[35], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, T. Sheokand, J.B. Singh, A. Singla

Panjab University, Chandigarh, India

A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, M.K. Saini, S. Saumya

University of Delhi, Delhi, India

S. Baradia, S. Barman[36], S. Bhattacharya, S. Das Gupta, S. Dutta, S. Dutta, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, G. Dash, P. Jana, P. Kalbhor, S. Kamble, J.R. Komaragiri[37], D. Kumar[37], T. Mishra, B. Parida[38], P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, R.K. Singh, P. Verma, S. Verma, A. Vijay

Indian Institute of Technology Madras, Madras, India

S. Dugad, G.B. Mohanty, M. Shelake, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

A. Bala, S. Banerjee, R.M. Chatterjee, M. Guchait, Sh. Jain, A. Jaiswal, S. Kumar, G. Majumder, K. Mazumdar, S. Parolia, A. Thachayath

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati[39], C. Kar, D. Maity[40], P. Mal, K. Naskar[40], A. Nayak[40], S. Nayak, K. Pal, P. Sadangi, S.K. Swain, S. Varghese[40], D. Vats[40]

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India

S. Acharya[41], A. Alpana, S. Dube, B. Gomber[41], P. Hazarika, B. Kansal, A. Laha, B. Sahu[41], S. Sharma, K.Y. Vaish

Indian Institute of Science Education and Research (IISER), Pune, India

Physics Letters B 868 (2025) 139754

H. Bakhshiansohi [42], A. Jafari [43], M. Zeinali [44]

Isfahan University of Technology, Isfahan, Iran

S. Bashiri, S. Chenarani [45], S.M. Etesami, Y. Hosseini, M. Khakzad, E. Khazaie, M. Mohammadi Najafabadi, S. Tizchang [46]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], A. Colaleo [a,b], D. Creanza [a,c], B. D'Anzi [a,b], N. De Filippis [a,c], M. De Palma [a,b], W. Elmetenawee [a,b,47], N. Ferrara [a,b], L. Fiore [a], G. Iaselli [a,c], L. Longo [a], M. Louka [a,b], G. Maggi [a,c], M. Maggi [a], I. Margjeka [a], V. Mastrapasqua [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pellecchia [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a,b], D. Ramos [a], A. Ranieri [a], L. Silvestris [a], F.M. Simone [a,c], Ü. Sözbilir [a], A. Stamerra [a,b], D. Troiano [a,b], R. Venditti [a,b], P. Verwilligen [a], A. Zaza [a,b]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], P. Capiluppi [a,b], A. Castro [a,b,†], F.R. Cavallo [a], M. Cuffiani [a,b], G.M. Dallavalle [a], T. Diotalevi [a,b], F. Fabbri [a], A. Fanfani [a,b], D. Fasanella [a], P. Giacomelli [a], L. Giommi [a,b], C. Grandi [a], L. Guiducci [a,b], S. Lo Meo [a,48], M. Lorusso [a,b], L. Lunerti [a], S. Marcellini [a], G. Masetti [a], F.L. Navarria [a,b], G. Paggi [a,b], A. Perrotta [a], F. Primavera [a,b], A.M. Rossi [a,b], S. Rossi Tisbeni [a,b], T. Rovelli [a,b], G.P. Siroli [a,b]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Costa [a,b,49], A. Di Mattia [a], A. Lapertosa [a], R. Potenza [a,b], A. Tricomi [a,b,49], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

P. Assiouras [a], G. Barbagli [a], G. Bardelli [a,b], B. Camaiani [a,b], A. Cassese [a], R. Ceccarelli [a], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], T. Kello [a], G. Latino [a,b], P. Lenzi [a,b], M. Lizzo [a], M. Meschini [a], S. Paoletti [a], A. Papanastassiou [a,b], G. Sguazzoni [a], L. Viliani [a]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, S. Meola [50], D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

M. Alves Gallo Pereira [a], F. Ferro [a], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia [a], F. Brivio [a], F. Cetorelli [a,b], F. De Guio [a,b], M.E. Dinardo [a,b], P. Dini [a], S. Gennai [a], R. Gerosa [a,b], A. Ghezzi [a,b], P. Govoni [a,b], L. Guzzi [a], M.T. Lucchini [a,b], M. Malberti [a], S. Malvezzi [a], A. Massironi [a], D. Menasce [a], L. Moroni [a], M. Paganoni [a,b], S. Palluotto [a,b], D. Pedrini [a], A. Perego [a,b], B.S. Pinolini [a], G. Pizzati [a,b], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*

[b] Università di Milano-Bicocca, Milano, Italy

S. Buontempo [a], A. Cagnotta [a,b], F. Carnevali [a,b], N. Cavallo [a,c], F. Fabozzi [a,c], A.O.M. Iorio [a,b], L. Lista [a,b,51], P. Paolucci [a,29], B. Rossi [a]

[a] INFN Sezione di Napoli, Napoli, Italy
[b] Università di Napoli 'Federico II', Napoli, Italy
[c] Università della Basilicata, Potenza, Italy
[d] Scuola Superiore Meridionale (SSM), Napoli, Italy

R. Ardino [a], P. Azzi [a], N. Bacchetta [a,52], M. Bellato [a], M. Benettoni [a], P. Bortignon [a], G. Bortolato [a,b], A. Bragagnolo [a,b], A.C.M. Bulla [a], R. Carlin [a,b], P. Checchia [a], T. Dorigo [a,53], U. Gasparini [a,b], S. Giorgetti [a], E. Lusiani [a], M. Margoni [a,b], A.T. Meneguzzo [a,b], M. Migliorini [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], M. Tosi [a,b], A. Triossi [a,b], S. Ventura [a], M. Zanetti [a,b], P. Zotto [a,b], A. Zucchetta [a,b], G. Zumerle [a,b]

[a] INFN Sezione di Padova, Padova, Italy
[b] Università di Padova, Padova, Italy
[c] Università di Trento, Trento, Italy

A. Braghieri [a], S. Calzaferri [a], D. Fiorina [a], P. Montagna [a,b], V. Re [a], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] INFN Sezione di Pavia, Pavia, Italy
[b] Università di Pavia, Pavia, Italy

S. Ajmal [a,b], M.E. Ascioti [a,b], G.M. Bilei [a], C. Carrivale [a,b], D. Ciangottini [a,b], L. Fanò [a,b], M. Magherini [a,b], V. Mariani [a,b], M. Menichelli [a], F. Moscatelli [a,54], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a], T. Tedeschi [a,b]

[a] INFN Sezione di Perugia, Perugia, Italy
[b] Università di Perugia, Perugia, Italy

C. Aimè [a], C.A. Alexe [a,c], P. Asenov [a,b], P. Azzurri [a], G. Bagliesi [a], R. Bhattacharya [a], L. Bianchini [a,b], T. Boccali [a], E. Bossini [a], D. Bruschini [a,c], R. Castaldi [a], M.A. Ciocci [a,b], M. Cipriani [a,b], V. D'Amante [a,d], R. Dell'Orso [a], S. Donato [a], A. Giassi [a], F. Ligabue [a,c], A.C. Marini [a], D. Matos Figueiredo [a], A. Messineo [a,b], S. Mishra [a], V.K. Muraleedharan Nair Bindhu [a,b,40], M. Musich [a,b], S. Nandan [a,b], F. Palla [a], A. Rizzi [a,b], G. Rolandi [a,c], S. Roy Chowdhury [a], T. Sarkar [a], A. Scribano [a], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], N. Turini [a,d], F. Vaselli [a,c], A. Venturi [a], P.G. Verdini [a]

[a] INFN Sezione di Pisa, Pisa, Italy
[b] Università di Pisa, Pisa, Italy
[c] Scuola Normale Superiore di Pisa, Pisa, Italy
[d] Università di Siena, Siena, Italy

C. Baldenegro Barrera [a,b], P. Barria [a], C. Basile [a,b], F. Cavallari [a], L. Cunqueiro Mendez [a,b], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], F. Errico [a,b], R. Gargiulo [a,b], E. Longo [a,b], L. Martikainen [a,b], J. Mijuskovic [a,b], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], C. Quaranta [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b], L. Soffi [a], V. Vladimirov [a,b]

[a] INFN Sezione di Roma, Roma, Italy
[b] Sapienza Università di Roma, Roma, Italy

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], A. Bellora [a,b], C. Biino [a], C. Borca [a,b], N. Cartiglia [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], L. Finco [a], M. Grippo [a,b], B. Kiani [a,b], F. Legger [a], F. Luongo [a,b], C. Mariotti [a], L. Markovic [a,b],

Physics Letters B 868 (2025) 139754

S. Maselli [a], A. Mecca [a,b], L. Menzio [a,b], P. Meridiani [a], E. Migliore [a,b], M. Monteno [a], R. Mulargia [a], M.M. Obertino [a,b], G. Ortona [a], L. Pacher [a,b], N. Pastrone [a], M. Pelliccioni [a], M. Ruspa [a,c], F. Siviero [a,b], V. Sola [a,b], A. Solano [a,b], A. Staiano [a], C. Tarricone [a,b], D. Trocino [a], G. Umoret [a,b], R. White [a,b]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, Italy

J. Babbar [a,b], S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], K. De Leo [a], G. Della Ricca [a,b]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

S. Dogra, J. Hong, B. Kim, J. Kim, D. Lee, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, B. Tae, Y.C. Yang

Kyungpook National University, Daegu, Korea

M.S. Kim

Department of Mathematics and Physics - GWNU, Gangneung, Korea

G. Bak, P. Gwak, H. Kim, D.H. Moon

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

E. Asilar, J. Choi [55], D. Kim, T.J. Kim, J.A. Merlin, Y. Ryou

Hanyang University, Seoul, Korea

S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Yoo

Korea University, Seoul, Korea

J. Goh, S. Yang

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim, Y. Kim, S. Lee

Sejong University, Seoul, Korea

J. Almond, J.H. Bhyun, J. Choi, J. Choi, W. Jun, J. Kim, Y.W. Kim, S. Ko, H. Kwon, H. Lee, J. Lee, J. Lee, B.H. Oh, S.B. Oh, H. Seo, U.K. Yang, I. Yoon

Seoul National University, Seoul, Korea

W. Jang, D.Y. Kang, Y. Kang, S. Kim, B. Ko, J.S.H. Lee, Y. Lee, I.C. Park, Y. Roh, I.J. Watson

University of Seoul, Seoul, Korea

S. Ha, K. Hwang, H.D. Yoo

Yonsei University, Department of Physics, Seoul, Korea

M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy, Y. Gharbia

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait

F. Alazemi

Kuwait University - College of Science - Department of Physics, Safat, Kuwait

K. Dreimanis, A. Gaile, C. Munoz Diaz, D. Osite, G. Pikurs, A. Potrebko, M. Seidel, D. Sidiropoulos Kontos

Riga Technical University, Riga, Latvia

N.R. Strautnieks

University of Latvia (LU), Riga, Latvia

M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

Vilnius University, Vilnius, Lithuania

I. Yusuff[56], Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, H.A. Encinas Acosta, L.G. Gallegos Maríñez, M. León Coello, J.A. Murillo Quijada, A. Sehrawat, L. Valencia Palomo

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala, H. Castilla-Valdez, H. Crotte Ledesma, E. De La Cruz-Burelo, I. Heredia-De La Cruz[57], R. Lopez-Fernandez, J. Mejia Guisao, C.A. Mondragon Herrera, A. Sánchez Hernández

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

C. Oropeza Barrera, D.L. Ramirez Guadarrama, M. Ramírez García

Universidad Iberoamericana, Mexico City, Mexico

I. Bautista, F.E. Neri Huerta, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja, N. Raicevic

University of Montenegro, Podgorica, Montenegro

P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

V. Avati, L. Grzanka, M. Malawski

AGH University of Krakow, Krakow, Poland

H. Bialkowska, M. Bluj, M. Górski, M. Kazana, M. Szleper, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

P. Fokow, K. Pozniak, W. Zabolotny

Warsaw University of Technology, Warsaw, Poland

M. Araujo, D. Bastos, C. Beirão Da Cruz E Silva, A. Boletti, M. Bozzo, T. Camporesi, G. Da Molin, P. Faccioli, M. Gallinaro, J. Hollar, N. Leonardo, G.B. Marozzo, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

P. Adzic, P. Milenovic

Faculty of Physics, University of Belgrade, Belgrade, Serbia

D. Devetak, M. Dordevic, J. Milosevic, L. Nadderd, V. Rekovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia

J. Alcaraz Maestre, Cristina F. Bedoya, J.A. Brochero Cifuentes, Oliver M. Carretero, M. Cepeda, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, A. Escalante Del Valle, D. Fernández Del Val, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, J. Llorente Merino, C. Martin Perez, E. Martin Viscasillas, D. Moran, C.M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, S. Sánchez Navas, J. Sastre, J. Vazquez Escobar

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, P. Leguina, E. Palencia Cortezon, J. Prado Pico, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain

S. Bhowmik, S. Blanco Fernández, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, G. Gomez, C. Lasaosa García, R. Lopez Ruiz, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, P. Matorras Cuevas, E. Navarrete Ramos, J. Piedra Gomez, L. Scodellaro, I. Vila, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

B. Kailasapathy[58], D.D.C. Wickramarathna

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna[59], K. Liyanage, N. Perera

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, A.A. Bin Anuar, A. Bocci, L. Borgonovi, C. Botta, E. Brondolin, C.E. Brown, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, J. Hegeman, J.K. Heikkilä, B. Huber, V. Innocente, T. James, P. Janot, O. Kaluzinska, O. Karacheban[27], S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, L. Malgeri, M. Mannelli, M. Matthewman, A. Mehta, F. Meijers,

S. Mersi, E. Meschi, V. Milosevic, F. Monti, F. Moortgat, M. Mulders, I. Neutelings, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, H. Qu, D. Rabady, B. Ribeiro Lopes, F. Riti, M. Rovere, H. Sakulin, R. Salvatico, S. Sanchez Cruz, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[60], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, D. Walter, J. Wanczyk[61], J. Wang, S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua[62], L. Caminada[62], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[62], L. Noehte[62], T. Rohe, A. Samalan

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T.K. Aarrestad, M. Backhaus, G. Bonomelli, A. Calandri, C. Cazzaniga, K. Datta, P. De Bryas Dexmiers D'archiac[61], A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, N. Härringer, T.G. Harte, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, A. Mascellani[61], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, B. Ristic, R. Seidita, J. Steggemann[61], A. Tarabini, D. Valsecchi, R. Wallny

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

C. Amsler[63], P. Bärtschi, M.F. Canelli, K. Cormier, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, F. Meng, J. Motta, A. Reimers, P. Robmann, M. Senger, E. Shokr, F. Stäger, R. Tramontano

Universität Zürich, Zurich, Switzerland

C. Adloff[64], D. Bhowmik, C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[37]

National Central University, Chung-Li, Taiwan

L. Ceard, K.F. Chen, Z.g. Chen, A. De Iorio, W.-S. Hou, T.h. Hsu, Y.w. Kao, S. Karmakar, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, D. Tsionou, H.y. Wu, E. Yazgan

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand

Y. Maghrbi

Tunis El Manar University, Tunis, Tunisia

D. Agyel, F. Boran, F. Dolek, I. Dumanoglu[65], E. Eskut, Y. Guler[66], E. Gurpinar Guler[66], C. Isik, O. Kara, A. Kayis Topaksu, Y. Komurcu, G. Onengut, K. Ozdemir[67], A. Polatoz, B. Tali[68], U.G. Tok, E. Uslan, I.S. Zorbakir

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

G. Sokmen, M. Yalvac[69]

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[70], O. Kaya[71], S. Tekten[72]

Bogazici University, Istanbul, Turkey

A. Cakir, K. Cankocak[65,73], G.G. Dincer[65], S. Sen[74]

Istanbul Technical University, Istanbul, Turkey

O. Aydilek[75], B. Hacisahinoglu, I. Hos[76], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, C. Zorbilmez

Istanbul University, Istanbul, Turkey

S. Cerci, B. Isildak[77], D. Sunar Cerci, T. Yetkin

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev, B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine

L. Levchuk

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine

D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, M.-L. Holmberg, L. Kreczko, S. Paramesvaran, L. Robertshaw, V.J. Smith, K. Walkingshaw Pass

University of Bristol, Bristol, United Kingdom

A.H. Ball, K.W. Bell, A. Belyaev[78], C. Brew, R.M. Brown, D.J.A. Cockerill, C. Cooke, A. Elliot, K.V. Ellis, K. Harder, S. Harper, J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, A.R. Sahasransu, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, K.C. Whalen, T. Williams

Rutherford Appleton Laboratory, Didcot, United Kingdom

I. Andreou, R. Bainbridge, P. Bloch, O. Buchmuller, C.A. Carrillo Montoya, G.S. Chahal[79], D. Colling, J.S. Dancu, I. Das, P. Dauncey, G. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, A. Howard, G. Iles, C.R. Knight, P. Krueper, J. Langford, K.H. Law, J. León Holgado, L. Lyons, A.-M. Magnan, B. Maier, S. Mallios, M. Mieskolainen, J. Nash[80], M. Pesaresi, P.B. Pradeep, B.C. Radburn-Smith, A. Richards, A. Rose, K. Savva, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, T. Virdee[29], M. Vojinovic, N. Wardle, D. Winterbottom

Imperial College, London, United Kingdom

J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Brunel University, Uxbridge, United Kingdom

S. Abdullin, A. Brinkerhoff, E. Collins, M.R. Darwish, J. Dittmann, K. Hatakeyama, V. Hegde, J. Hiltbrand, B. McMaster, J. Samudio, S. Sawant, C. Sutantawibul, J. Wilson

Baylor University, Waco, TX, USA

R. Bartek, A. Dominguez, A.E. Simsek, S.S. Yu

Catholic University of America, Washington, DC, USA

B. Bam, A. Buchot Perraguin, R. Chudasama, S.I. Cooper, C. Crovella, S.V. Gleyzer, E. Pearson, C.U. Perez, P. Rumerio[81], E. Usai, R. Yi

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar, C. Cosby, G. De Castro, Z. Demiragli, C. Erice, C. Fangmeier, C. Fernandez Madrazo, E. Fontanesi, D. Gastler, F. Golf, S. Jeon, J. O'cain, I. Reed, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, A.G. Zecchinelli

Boston University, Boston, MA, USA

G. Barone, G. Benelli, D. Cutts, L. Gouskos, M. Hadley, U. Heintz, K.W. Ho, J.M. Hogan[82], T. Kwon, G. Landsberg, K.T. Lau, J. Luo, S. Mondal, T. Russell, S. Sagir[83], X. Shen, F. Simpson, M. Stamenkovic, N. Venkatasubramanian

Brown University, Providence, RI, USA

S. Abbott, B. Barton, C. Brainerd, R. Breedon, H. Cai, M. Calderon De La Barca Sanchez, M. Chertok, M. Citron, J. Conway, P.T. Cox, R. Erbacher, F. Jensen, O. Kukral, G. Mocellin, M. Mulhearn, S. Ostrom, W. Wei, S. Yoo, F. Zhang

University of California, Davis, Davis, CA, USA

K. Adamidis, M. Bachtis, D. Campos, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, Y.f. Lo, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Los Angeles, CA, USA

R. Clare, J.W. Gary, G. Hanson

University of California, Riverside, Riverside, CA, USA

A. Aportela, A. Arora, J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, Y. Gu, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, S. Mukherjee, M. Pieri, D. Primosch, M. Quinnan, V. Sharma, M. Tadel, E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, San Diego, La Jolla, CA, USA

A. Barzdukas, L. Brennan, C. Campagnari, K. Downham, C. Grieco, M.M. Hussain, J. Incandela, J. Kim, A.J. Li, P. Masterson, H. Mei, J. Richman, S.N. Santpur, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, T.Á. Vámi, X. Yan, D. Zhang

University of California, Santa Barbara - Department of Physics, Santa Barbara, CA, USA

S. Bhattacharya, A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, G. Reales Gutiérrez, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

California Institute of Technology, Pasadena, CA, USA

J. Alison, S. An, P. Bryant, M. Cremonesi, V. Dutta, T. Ferguson, T.A. Gómez Espinosa, A. Harilal, A. Kallil Tharayil, C. Liu, T. Mudholkar, S. Murthy, P. Palit, K. Park, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat, W.T. Ford, A. Hart, A. Hassani, G. Karathanasis, N. Manganelli, J. Pearkes, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper, D. Zuolo

University of Colorado Boulder, Boulder, CO, USA

Physics Letters B 868 (2025) 139754

J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Dickinson, J. Fan, X. Fan, S. Hogan, P. Kotamnives, J. Monroy, M. Oshiro, J.R. Patterson, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Cornell University, Ithaca, NY, USA

M. Albrow, M. Alyari, O. Amram, G. Apollinari, A. Apresyan, L.A.T. Bauerdick, D. Berry, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, G. Cummings, I. Dutta, V.D. Elvira, Y. Feng, J. Freeman, A. Gandrakota, Z. Gecse, L. Gray, D. Green, A. Grummer, S. Grünendahl, D. Guerrero, O. Gutsche, R.M. Harris, T.C. Herwig, J. Hirschauer, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, C. Lee, D. Lincoln, R. Lipton, T. Liu, C. Madrid, K. Maeshima, C. Mantilla, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, J. Ngadiuba, D. Noonan, S. Norberg, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[84], F. Ravera, A. Reinsvold Hall[85], L. Ristori, M. Safdari, E. Sexton-Kennedy, N. Smith, A. Soha, L. Spiegel, S. Stoynev, J. Strait, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, I. Zoi

Fermi National Accelerator Laboratory, Batavia, IL, USA

C. Aruta, P. Avery, D. Bourilkov, P. Chang, V. Cherepanov, R.D. Field, C. Huh, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, S. Rosenzweig, Y. Takahashi, J. Wang

University of Florida, Gainesville, FL, USA

T. Adams, A. Al Kadhim, A. Askew, S. Bower, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, M. Wulansatiti, R. Yohay, J. Zhang

Florida State University, Tallahassee, FL, USA

B. Alsufyani, S. Butalla, S. Das, T. Elkafrawy[18], M. Hohlmann, E. Yanes

Florida Institute of Technology, Melbourne, FL, USA

M.R. Adams, A. Baty, C. Bennett, R. Cavanaugh, R. Escobar Franco, O. Evdokimov, C.E. Gerber, M. Hawksworth, A. Hingrajiya, D.J. Hofman, J.h. Lee, D.S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, R. Pradhan, E. Prifti, T. Roy, S. Rudrabhatla, N. Singh, M.B. Tonjes, N. Varelas, M.A. Wadud, Z. Ye, J. Yoo

University of Illinois Chicago, Chicago, IL, USA

M. Alhusseini, D. Blend, K. Dilsiz[86], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[87], O. Neogi, H. Ogul[88], Y. Onel, A. Penzo, C. Snyder, E. Tiras[89]

The University of Iowa, Iowa City, IA, USA

B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz

Johns Hopkins University, Baltimore, MD, USA

A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, S. Arteaga Escatel, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, J. Marquez,

M. Murray, M. Nickel, M. Pitt, S. Popescu[90], C. Rogan, C. Royon, S. Sanders, C. Smith, G. Wilson

The University of Kansas, Lawrence, KS, USA

B. Allmond, R. Gujju Gurunadha, A. Ivanov, K. Kaadze, Y. Maravin, J. Natoli, D. Roy, G. Sorrentino

Kansas State University, Manhattan, KS, USA

A. Baden, A. Belloni, J. Bistany-riebman, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, B. Kronheim, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, E. Popova[91], A. Shevelev, L. Wang

University of Maryland, College Park, MD, USA

J. Bendavid, I.A. Cali, P.c. Chou, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, G. Grosso, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mcginn, A. Novak, M.I. Park, C. Paus, C. Reissel, C. Roland, G. Roland, S. Rothman, G.S.F. Stephans, Z. Wang, B. Wyslouch, T.J. Yang

Massachusetts Institute of Technology, Cambridge, MA, USA

B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, M. Revering, R. Rusack, R. Saradhy, N. Strobbe

University of Minnesota, Minneapolis, MN, USA

K. Bloom, D.R. Claes, G. Haza, J. Hossain, C. Joo, I. Kravchenko, A. Rohilla, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu

University of Nebraska-Lincoln, Lincoln, NE, USA

H. Bandyopadhyay, L. Hay, H.w. Hsia, I. Iashvili, A. Kalogeropoulos, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams, P. Young

State University of New York at Buffalo, Buffalo, NY, USA

G. Alverson, E. Barberis, J. Bonilla, B. Bylsma, M. Campana, J. Dervan, Y. Haddad, Y. Han, I. Israr, A. Krishna, J. Li, M. Lu, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, E. Tsai, D. Wood

Northeastern University, Boston, MA, USA

J. Bueghly, S. Dittmer, K.A. Hahn, D. Li, Y. Li, M. Mcginnis, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

Northwestern University, Evanston, IL, USA

G. Agarwal, R. Band, R. Bucci, S. Castells, A. Das, R. Goldouzian, M. Hildreth, K. Hurtado Anampa, T. Ivanov, C. Jessop, K. Lannon, J. Lawrence, N. Loukas, L. Lutton, J. Mariano, N. Marinelli, I. Mcalister, T. McCauley, C. Mcgrady, C. Moore, Y. Musienko[22], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

University of Notre Dame, Notre Dame, IN, USA

A. Basnet, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, M. Nunez Ornelas, K. Wei, D.A. Wenzl, B.L. Winer, B.R. Yates

The Ohio State University, Columbus, OH, USA

H. Bouchamaoui, K. Coldham, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, K. Kennedy, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, D. Stickland, C. Tully, L.H. Vage

Princeton University, Princeton, NJ, USA

S. Malik, R. Sharma

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi, S. Chandra, R. Chawla, A. Gu, L. Gutay, M. Jones, A.W. Jung, A.M. Koshy, M. Liu, G. Negro, N. Neumeister, G. Paspalaki, S. Piperov, V. Scheurer, J.F. Schulte, M. Stojanovic, J. Thieman, A.K. Virdi, F. Wang, A. Wildridge, W. Xie, Y. Yao

Purdue University, West Lafayette, IN, USA

J. Dolen, N. Parashar, A. Pathak

Purdue University Northwest, Hammond, IN, USA

D. Acosta, A. Agrawal, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, I. Krommydas, W. Li, J. Lin, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

Rice University, Houston, TX, USA

A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, N. Parmar, P. Parygin[91], R. Taus

University of Rochester, Rochester, NY, USA

B. Chiarito, J.P. Chou, S.V. Clark, D. Gadkari, Y. Gershtein, E. Halkiadakis, M. Heindl, C. Houghton, D. Jaroslawski, S. Konstantinou, I. Laflotte, A. Lath, R. Montalvo, K. Nash, J. Reichert, P. Saha, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

Rutgers, The State University of New Jersey, Piscataway, NJ, USA

D. Ally, A.G. Delannoy, S. Fiorendi, S. Higginbotham, T. Holmes, A.R. Kanuganti, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

University of Tennessee, Knoxville, TN, USA

D. Aebi, M. Ahmad, T. Akhter, K. Androsov[61], O. Bouhali[92], R. Eusebi, J. Gilmore, T. Huang, T. Kamon[93], H. Kim, S. Luo, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas A&M University, College Station, TX, USA

N. Akchurin, J. Damgov, N. Gogate, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev

Texas Tech University, Lubbock, TX, USA

E. Appelt, Y. Chen, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

Vanderbilt University, Nashville, TN, USA

B. Cardwell, H. Chung, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu

University of Virginia, Charlottesville, VA, USA

S. Bhattacharya, P.E. Karchin

Wayne State University, Detroit, MI, USA

A. Aravind, S. Banerjee, K. Black, T. Bose, E. Chavez, S. Dasu, P. Everaerts, C. Galloni, H. He, M. Herndon, A. Herve, C.K. Koraka, A. Lanaro, R. Loveless, J. Madhusudanan Sreekala, A. Mallampalli, A. Mohammadi, S. Mondal, G. Parida, L. Pétré, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

University of Wisconsin - Madison, Madison, WI, USA

S. Afanasiev, V. Alexakhin, D. Budkouski, I. Golutvin[†], I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[94], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[95], A. Zarubin, I. Zhizhin, Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin

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

G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[96], P. Levchenko[97], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†], T. Aushev, K. Ivanov, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[98,99], V. Popov, A. Zhokin, M. Chadeeva[96], R. Chistov[96], S. Polikarpov[96], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, E. Boos, V. Bunichev, M. Dubinin[84], L. Dudko, V. Klyukhin, O. Kodolova[99], O. Lukina, S. Obraztsov, M. Perfilov, V. Savrin, A. Snigirev, G. Vorotnikov, V. Blinov[96], T. Dimova[96], A. Kozyrev[96], O. Radchenko[96], Y. Skovpen[96], V. Kachanov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN

[†] Deceased.
[1] Also at Yerevan State University, Yerevan, Armenia.
[2] Also at TU Wien, Vienna, Austria.
[3] Also at Ghent University, Ghent, Belgium.
[4] Also at Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil.
[5] Also at FACAMP - Faculdades de Campinas, Sao Paulo, Brazil.
[6] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[7] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[8] Also at University of Chinese Academy of Sciences, Beijing, China.
[9] Also at China Center of Advanced Science and Technology, Beijing, China.
[10] Also at University of Chinese Academy of Sciences, Beijing, China.
[11] Also at China Spallation Neutron Source, Guangdong, China.
[12] Now at Henan Normal University, Xinxiang, China.
[13] Also at University of Shanghai for Science and Technology, Shanghai, China.
[14] Now at The University of Iowa, Iowa City, Iowa, USA.
[15] Also at an institute formerly covered by a cooperation agreement with CERN.
[16] Also at Zewail City of Science and Technology, Zewail, Egypt.
[17] Also at British University in Egypt, Cairo, Egypt.
[18] Now at Ain Shams University, Cairo, Egypt.
[19] Also at Purdue University, West Lafayette, Indiana, USA.
[20] Also at Université de Haute Alsace, Mulhouse, France.

[21] Also at Istinye University, Istanbul, Turkey.
[22] Also at an international laboratory covered by a cooperation agreement with CERN.
[23] Also at The University of the State of Amazonas, Manaus, Brazil.
[24] Also at University of Hamburg, Hamburg, Germany.
[25] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[26] Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.
[27] Also at Brandenburg University of Technology, Cottbus, Germany.
[28] Also at Forschungszentrum Jülich, Juelich, Germany.
[29] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[30] Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary.
[31] Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania.
[32] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[33] Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.
[34] Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.
[35] Also at Punjab Agricultural University, Ludhiana, India.
[36] Also at University of Visva-Bharati, Santiniketan, India.
[37] Also at Indian Institute of Science (IISc), Bangalore, India.
[38] Also at Amity University Uttar Pradesh, Noida, India.
[39] Also at IIT Bhubaneswar, Bhubaneswar, India.
[40] Also at Institute of Physics, Bhubaneswar, India.
[41] Also at University of Hyderabad, Hyderabad, India.
[42] Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.
[43] Also at Isfahan University of Technology, Isfahan, Iran.
[44] Also at Sharif University of Technology, Tehran, Iran.
[45] Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
[46] Also at Department of Physics, Faculty of Science, Arak University, ARAK, Iran.
[47] Also at Helwan University, Cairo, Egypt.
[48] Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
[49] Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
[50] Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
[51] Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
[52] Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
[53] Also at Lulea University of Technology, Lulea, Sweden.
[54] Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy.
[55] Also at Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France.
[56] Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
[57] Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
[58] Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
[59] Also at Saegis Campus, Nugegoda, Sri Lanka.
[60] Also at National and Kapodistrian University of Athens, Athens, Greece.
[61] Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
[62] Also at Universität Zürich, Zurich, Switzerland.
[63] Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
[64] Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
[65] Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
[66] Also at Konya Technical University, Konya, Turkey.
[67] Also at Izmir Bakircay University, Izmir, Turkey.
[68] Also at Adiyaman University, Adiyaman, Turkey.
[69] Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey.
[70] Also at Marmara University, Istanbul, Turkey.
[71] Also at Milli Savunma University, Istanbul, Turkey.
[72] Also at Kafkas University, Kars, Turkey.
[73] Now at Istanbul Okan University, Istanbul, Turkey.
[74] Also at Hacettepe University, Ankara, Turkey.
[75] Also at Erzincan Binali Yildirim University, Erzincan, Turkey.
[76] Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
[77] Also at Yildiz Technical University, Istanbul, Turkey.
[78] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[79] Also at IPPP Durham University, Durham, United Kingdom.
[80] Also at Monash University, Faculty of Science, Clayton, Australia.
[81] Also at Università di Torino, Torino, Italy.
[82] Also at Bethel University, St. Paul, Minnesota, USA.
[83] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[84] Also at California Institute of Technology, Pasadena, California, USA.
[85] Also at United States Naval Academy, Annapolis, Maryland, USA.
[86] Also at Bingol University, Bingol, Turkey.
[87] Also at Georgian Technical University, Tbilisi, Georgia.
[88] Also at Sinop University, Sinop, Turkey.
[89] Also at Erciyes University, Kayseri, Turkey.
[90] Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.

[91] Now at another institute formerly covered by a cooperation agreement with CERN.
[92] Also at Texas A&M University at Qatar, Doha, Qatar.
[93] Also at Kyungpook National University, Daegu, Korea.
[94] Also at another international laboratory covered by a cooperation agreement with CERN.
[95] Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
[96] Also at another institute formerly covered by a cooperation agreement with CERN.
[97] Also at Northeastern University, Boston, Massachusetts, USA.
[98] Also at Imperial College, London, United Kingdom.
[99] Now at Yerevan Physics Institute, Yerevan, Armenia.