EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2024-135
2024/07/19

CMS-HIN-21-016

Multiplicity dependence of charm baryon and baryon meson production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

Measurements of the production yields of charm baryons (Λ_c^+) and charm mesons (D^0) in proton-lead collisions at a nucleon-nucleon center-of-mass energy of 8.16 TeV are presented. The data were collected in 2016 with the CMS experiment and correspond to an integrated luminosity of 186 nb^{-1}. The Λ_c^+ baryon is reconstructed from the decay channel $\Lambda_c^+ \to K_S^0 p$, while the D^0 meson is reconstructed via $D^0 \to K^- \pi^+$. The Λ_c^+ baryon and D^0 meson yields are extracted in several charged-particle multiplicity classes. No strong multiplicity dependence of the Λ_c^+-to-D^0 yield ratio is observed, unlike the observed strange baryon to strange meson yield ratio of $\Lambda/\overline{\Lambda}$ to K_S^0, which shows a strong multiplicity dependence. This observation indicates different mechanisms for the multiplicity evolution of hadronization processes for charm and strange quarks and provides new constraints to the understanding of heavy flavor production and collectivity in small collision systems.

Submitted to Physics Letters B

*See Appendix A for the list of collaboration members

1 Introduction

The quark-gluon plasma (QGP), a deconfined phase of quarks and gluons, is formed in ultra-relativistic heavy ion collisions. The collective flow motion ("collectivity") of this strongly coupled medium in nucleus-nucleus (AA) collisions has been observed at the CERN LHC [1–3] and the BNL RHIC [4–7]. The observed azimuthal anisotropies of the particles emitted [8–13], such as the "elliptic flow," result from strong interactions between constituents inside the medium that initially has an asymmetric geometrical shape and can be well described by hydrodynamic models [14–16]. Similar observations of a common collective signature for charm mesons [17–19] and bottom mesons [20–22] indicate that heavy quarks may also be strongly coupled to the QGP, even though their interactions with the medium are expected to be much less frequent than for light quarks.

In recent years, unexpected strong collective flow signals were also observed in small systems such as proton-proton (pp) [23–26] and proton-lead (pPb) [27–37] collisions. The elliptic flow for prompt D^0 [18, 38] and J/ψ [39, 40] mesons in pPb collisions was found to be comparable to that of light-flavor hadrons at a given particle transverse momentum (p_T). On the other hand, no evidence for bottom hadron collective flow has been observed yet in small systems, such as pPb collisions [38, 41]. Although effects of final-state partonic rescatterings in a dense medium can successfully explain a large variety of measurements for light quarks (see reviews in Refs. [42, 43]), they alone cannot describe the large flow for charm quarks [44]. Meanwhile, calculations based on initial-state effects, such as gluon saturation models, can successfully describe experimental measurements for several charm and bottom mesons [45].

The study of heavy flavor meson and baryon production yields provides a powerful means to further elucidate the origin of heavy flavor collectivity in small systems, as hadronization processes are also influenced by the presence of final-state rescattering effects. The abundant deconfined quarks in the QGP can coalesce into bound states before fragmenting to low-energy hadrons, resulting in a different modification of the yields for baryons and mesons [46, 47]. This parton coalescence effect is expected to be stronger with increasing system size and can enhance the baryon-to-meson yield ratio at an intermediate hadron p_T range (e.g., 2–6 GeV) [48, 49]. Models in AA collisions incorporating parton coalescence have been able to describe measurements of heavy-flavor hadrons, such as the Λ_c^+-to-D^0 production yield ratio, at both RHIC and the LHC [50–52]. Because of its dependence on final-state effects, the study of this baryon-to-meson enhancement effect may also contribute to our understanding of the origin of collectivity in small systems.

Measurements of the charged-particle multiplicity dependence of the baryon-to-meson ratio for strange particles show an increasing trend from low to high multiplicity in the intermediate hadron p_T range [53], which is qualitatively consistent with models including final-state effects. Therefore, an enhancement of charm baryon-to-meson yield ratios should be expected for high multiplicity events, if final state effects are the origin of heavy flavor quark collectivity. For inclusive pp and pPb collisions, models assuming the presence of a QGP [54, 55] are in agreement with measurements of Λ_c^+ baryon yields [56–58] when coalescence effects are incorporated. Over the limited range of charged multiplicities in pp collisions, the statistical hadronization model is able to describe the multiplicity dependence of the Λ_c^+-to-D^0 yield ratio as a function of p_T [59, 60].

In this Letter, the p_T spectra of the Λ_c^+ and D^0 particles and their ratios are measured in the range of 2–10 GeV in pPb collisions at a nucleon-nucleon center-of-mass energy $\sqrt{s_\mathrm{NN}} = 8.16$ TeV, for the first time in different multiplicity intervals. Tabulated results are provided in the HEPData record for this analysis [61].

2 The CMS detector

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. Hadron forward (HF) calorimeters [62], made of steel and quartz fibers, extend the pseudorapidity ($\eta = -\ln(\tan(\theta/2))$, where the polar angle θ is defined relative to the counterclockwise beam) 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, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [63].

The silicon tracker measures charged particles within the range $|\eta_{\text{lab}}| < 2.5$ in the laboratory frame. During the LHC running period when the data used in this Letter were recorded, the silicon tracker consisted of 1440 silicon pixel and 15 148 silicon strip detector modules. For particles of $1 < p_{\text{T}} < 10\,\text{GeV}$ and $|\eta_{\text{lab}}| < 1.4$, the track resolutions are typically 1.5% in p_{T} and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [64].

The event samples are collected by the CMS experiment with a two-level trigger system [65, 66]. At Level-1, events are selected by custom hardware processors, while the high-level trigger (HLT) uses fast versions of the offline software. The pPb data used in this analysis were collected in 2016 at $\sqrt{s_{\text{NN}}} = 8.16\,\text{TeV}$ and correspond to an integrated luminosity of $186.0 \pm 6.5\,\text{nb}^{-1}$ [67]. The beam energies were 6.5 TeV for the protons and 2.56 TeV per nucleon for the lead nuclei. Because of the asymmetric beam conditions, the midrapidity range of $|y_{\text{lab}}| < 1$, which is used for particle selections, corresponds to the rapidity range $-1.46 < y_{\text{cm}} < 0.54$ in the nucleon-nucleon center-of-mass frame, with positive rapidity corresponding to the proton beam direction.

The event reconstruction, event selections, and trigger requirements for minimum bias and high-multiplicity events are identical to those described in Refs. [26, 68, 69]. The minimum bias (MB) 8.16 TeV pPb events are triggered by requiring energy deposits above 1 GeV in at least one of the two HF calorimeters and the presence of at least one track with $p_{\text{T}} > 0.4\,\text{GeV}$ reconstructed using hits from the pixel tracker only. To collect a large sample of high-multiplicity pPb collisions, a dedicated trigger is implemented. At Level-1, the total number of ECAL+HCAL towers having deposited energy above a threshold of 0.5 GeV in transverse energy (E_{T}) is required to be greater than 150. As part of the HLT trigger, the track reconstruction is performed online with the identical reconstruction algorithm used offline [64]. For each event selected at Level-1, the reconstructed vertex with the highest number of associated tracks is selected as the primary vertex (PV) at the HLT. The number of online tracks with $|\eta| < 2.4$, $p_{\text{T}} > 0.4\,\text{GeV}$, and a distance of closest approach less than 0.12 cm along the beam axis to the PV is determined for each event and is required to exceed 185. The events are required to contain a PV within 15 cm of the nominal interaction point along the beam axis and 0.2 cm in the transverse direction. The integrated luminosity sampled by the minimum bias (high-multiplicity) trigger is 4.22 (97.8) nb^{-1}.

3 Data analysis

Similar to previous measurements [27, 30, 33, 34], hadronic events are selected by requiring the presence of at least one energy deposit greater than 3 GeV in each of the two HF calorimeters. The pPb data are analyzed in several charged-particle multiplicity classes, and defined accord-

ing to the number of selected offline tracks ($N_{\mathrm{trk}}^{\mathrm{offline}}$) with $|\eta_{\mathrm{lab}}| < 2.4$ and $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$ that originate from the PV [26, 64]. If more than one vertex is found in an event, the vertex associated with the highest number of offline tracks is considered as the PV. The average number of tracks in each $N_{\mathrm{trk}}^{\mathrm{offline}}$ range before and after correcting for inefficiencies and misidentification rates in the tracking system is denoted as $\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$ and $\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$, respectively. The statistical uncertainty in $\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$ has been found to be negligible, while the systematic uncertainty is 4% resulting from the uncertainty of tracking efficiency estimated based on simulated events. The $\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$ and $\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$ values in each $N_{\mathrm{trk}}^{\mathrm{offline}}$ range are summarized in Table 1. To optimize the signal significance and efficiency, a sample of simulated signal events is generated using hard processes in PYTHIA 8.209 [70], using the CUETP8M1 tune [71]. These signal events are embedded into pPb events generated with the EPOS LHC model [72]. The response of the CMS detector for generated events is simulated using the GEANT4 [73] toolkit. The decay kinematics for Λ_{c}^{+} and D^{0} particles are simulated using EVTGEN [74].

Table 1: The average multiplicity before (and after) corrections, $\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$ ($\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$) with track $p_{\mathrm{T}} > 0.4\,\mathrm{GeV}$ and $|\eta_{\mathrm{lab}}| < 2.4$ in each multiplicity interval. The uncertainties reported for $\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$ are systematic uncertainties, as the statistical uncertainties have been found to be negligible.

Multiplicity interval ($N_{\mathrm{trk}}^{\mathrm{offline}}$)	$\langle N_{\mathrm{trk}}^{\mathrm{offline}} \rangle$	$\langle N_{\mathrm{trk}}^{\mathrm{corrected}} \rangle$
$[2, 35)$	16.4	20.0 ± 0.8
$[35, 60)$	46.3	56.4 ± 2.3
$[60, 90)$	73.0	88.7 ± 3.5
$[90, 120)$	102	124 ± 5
$[120, 185)$	140	170 ± 7
$[185, 250)$	202	245 ± 10

The Λ_{c}^{+} baryons are reconstructed using the decay channel $\Lambda_{\mathrm{c}}^{+} \to \mathrm{K}_{\mathrm{S}}^{0}\mathrm{p}$ with the branching fraction of $(1.59 \pm 0.07)\%$ [75], where $\mathrm{K}_{\mathrm{S}}^{0}$ mesons are reconstructed via the $\mathrm{K}_{\mathrm{S}}^{0} \to \pi^{+}\pi^{-}$ decays with the branching fraction of $(69.20 \pm 0.05)\%$ [75]. Throughout this Letter, charge-conjugate modes are implied unless explicitly noted otherwise. The decay vertex for each $\mathrm{K}_{\mathrm{S}}^{0}$ meson is reconstructed by fitting a common vertex with two oppositely charged particles inside the CMS tracking detector using a Kalman filter. Selections based on topological information are also applied to optimize the $\mathrm{K}_{\mathrm{S}}^{0}$ signal yield significance (over the non-signal hypothesis) of these signals, following the same procedures as Ref. [18]. The invariant mass of each $\mathrm{K}_{\mathrm{S}}^{0}$ candidate ($M_{\pi^{+}\pi^{-}}$) is required to be within $|M_{\pi^{+}\pi^{-}} - M_{\mathrm{K}_{\mathrm{S}}^{0}}| < 0.02\,\mathrm{GeV}$, where $M_{\mathrm{K}_{\mathrm{S}}^{0}}$ is the $\mathrm{K}_{\mathrm{S}}^{0}$ meson mass [75]. The secondary decay vertices of the Λ_{c}^{+} baryon are reconstructed by combining a $\mathrm{K}_{\mathrm{S}}^{0}$ candidate with another charged track in the event. The Λ_{c}^{+} candidates (including signals and backgrounds) with invariant mass falling within $|M_{\mathrm{K}_{\mathrm{S}}^{0}\mathrm{p}} - M_{\Lambda_{\mathrm{c}}^{+}}| < 0.2\,\mathrm{GeV}$, are considered in this analysis, where $M_{\Lambda_{\mathrm{c}}^{+}}$ is the mass of the Λ_{c}^{+} baryon [75]. A multilayer perceptron (MLP) is trained with the Toolkit for Multivariate Data Analysis (TMVA) package [76] using simulated signal events to suppress the combinatorial background. The training variables are: the candidate proton track momentum and η; the energy loss of the candidate proton track per unit length inside the tracker normalized by the expected mean value for the proton at the corresponding momentum; and the cosine of the pointing angle defined as the angle in three dimensions between the vector connecting the PV with the secondary decay vertex of Λ_{c}^{+} baryons and the momentum of the Λ_{c}^{+} candidate. The energy loss per unit length for each track is calculated with the "generalized mean" of grade–2, as described in Ref. [77].

Events populating the sideband region, defined as $0.06 < |M_{K^0_S p} - M_{\Lambda_c^+}| < 0.11\,\text{GeV}$ that is at least four standard deviations away from the peak of the signal distribution, are used as background samples in the TMVA training. The optimization of the Λ_c^+ signal significance is performed separately for event classes $2 \leq N_{\text{trk}}^{\text{offline}} < 185$ (from the minimum bias trigger) and $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ (from the high-multiplicity trigger). The maximum statistical significance of these signals after optimization is much larger than 5 standard deviations.

The D^0 candidates are reconstructed using the decay channel $D^0 \to K^-\pi^+$ with the branching fraction of $(3.947 \pm 0.030)\%$ [75]. The boosted decision tree (BDT) method is used to reject combinatorial backgrounds and to optimize the D^0 signal yield significance. Details about the reconstruction, candidate selection, and correction are reported in Ref. [38].

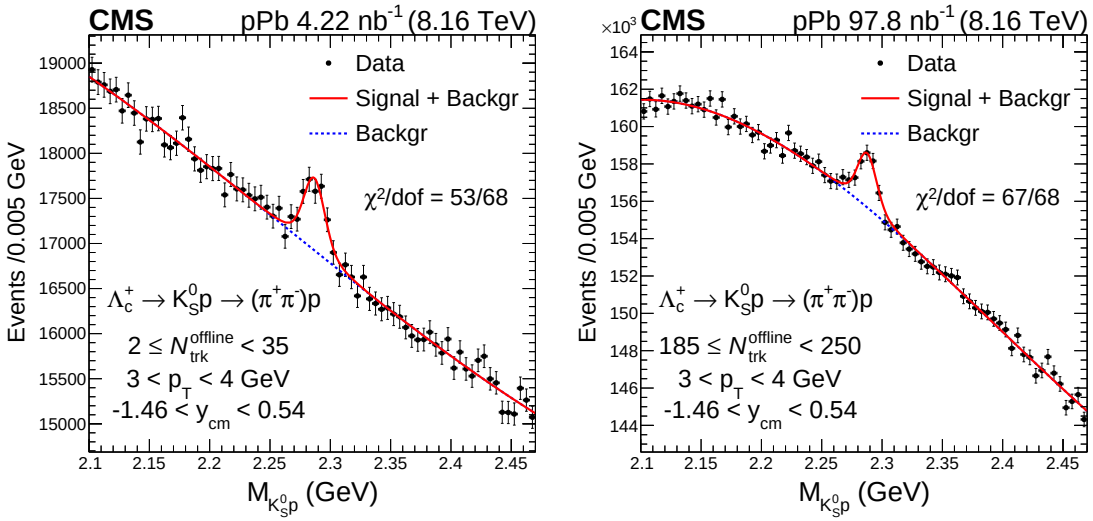

Figure 1: The fitted mass spectra, along with the goodness-of-fit values, for Λ_c^+ candidates with $3 < p_T < 4\,\text{GeV}$ and $-1.46 < y_{\text{cm}} < 0.54$. The spectrum for the multiplicity class with $2 \leq N_{\text{trk}}^{\text{offline}} < 35$ is shown in the left plot, and the spectrum for $185 \leq N_{\text{trk}}^{\text{offline}} < 250$ is shown in the right plot.

The Λ_c^+ candidate mass spectra are modeled by a double Gaussian function with a common mean and different widths for the signal contribution and a third-order Chebyshev polynomial for the background. The widths of the signal distributions are constrained to those found in simulation to improve the fit stability. Figure 1 shows the mass spectra of the Λ_c^+ candidates for the multiplicity ranges of $2 \leq N_{\text{trk}}^{\text{offline}} < 35$ and $185 \leq N_{\text{trk}}^{\text{offline}} < 250$. The invariant mass of D^0 candidates is modeled by several components: a double Gaussian function with a common mean for the D^0 signal; an additional Gaussian function to describe the invariant mass shape of D^0 candidates with swapped pion and kaon tracks ("swapped component"); two Crystal Ball (CB) functions [78] to describe the processes $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$; and a third-order polynomial to model the combinatorial background. Examples of fits to the D^0 invariant mass are shown in Ref. [38].

The differential yields for Λ_c^+ and D^0 particles are computed using

$$\frac{dN}{dp_T} = \frac{f^{\text{prompt}} N^{\text{sig}}}{2\alpha\epsilon\Delta p_T} \frac{1}{\mathcal{B}}, \tag{1}$$

where N^{sig} is the raw yield from the fit to the invariant mass in each p_T and multiplicity bin, α is the acceptance, ϵ is the reconstruction efficiency, Δp_T is the width of p_T interval, $\mathcal{B}$ is the

branching fraction, and f^{prompt} is the corresponding prompt component fraction for Λ_c^+ and D^0 hadrons, respectively. Prompt mesons are those directly produced in pPb collisions or from strong decays of excited charm hadrons, rather than from decays of bottom hadrons. The factor of two in the denominator takes into account the inclusion of both charge-conjugate particles in the raw yield. The acceptance and reconstruction efficiencies are obtained from simulated events in bins of p_T, where the resolution is much narrower than the bin width.

The fraction f^{prompt} for Λ_c^+ events is estimated following a procedure similar to the one described in Ref. [56]. The estimation of nonprompt Λ_c^+ contributions from bottom hadron decays considers inputs including the Λ_b^0 and B production cross sections and the inclusive decay branching fractions of Λ_b^0 and B (B^+, B^0) mesons to Λ_c^+, i.e., $\Lambda_b^0 \to \Lambda_c^+ + X$ and $B \to \Lambda_c^+ + X$. The Λ_b^0 production cross section is derived from that for B meson production, computed using the "fixed order next-to-leading logarithmic" (FONLL) perturbative quantum chromodynamics calculation [79] and rescaled according to the fragmentation fractions measured by the LHCb Collaboration [80]. It is then multiplied by $A = 208$, the atomic number of the lead nucleus, to map it to pPb collisions. Modifications due to nuclear effects are allowed at the level of 25% in the systematic uncertainties, as discussed in Section 4. The $\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ X)$ value is set to 83%, as in the EVTGEN package, and it includes the contributions from unobserved decay channels [81]. The corresponding branching fractions for the B mesons are set to 5% by summing over all channels reported in Ref. [75]. The correlations between the kinematic distributions of b hadrons and Λ_c^+ particles are simulated using EVTGEN. The cross section of nonprompt Λ_c^+ baryon production is further corrected for the acceptance and reconstruction efficiency. The fraction of feed-down contribution is assumed to be multiplicity independent in the range $2 \leq N_{\text{trk}}^{\text{offline}} < 185$, as the same candidate selection is applied in all the multiplicity ranges. A summary of the nonprompt Λ_c^+ baryon fraction (1-f^{prompt}), which has little dependence on p_T and $N_{\text{trk}}^{\text{offline}}$ within uncertainties, is given in Table 2.

Table 2: Summary table for the fraction of nonprompt Λ_c^+ baryons (1-f^{prompt}) relative to inclusive Λ_c^+ baryons. The fraction is evaluated in different multiplicity ranges. Details regarding the systematic uncertainties are described in Section 4.

p_T (GeV)	$2 \leq N_{\text{trk}}^{\text{offline}} < 185$ (%)	$185 \leq N_{\text{trk}}^{\text{offline}} < 250$ (%)
2–3	$6.8^{+11}_{-6.8}$	—
3–4	$4.1^{+5.8}_{-4.1}$	$4.3^{+6.0}_{-4.3}$
4–5	$3.3^{+5.5}_{-3.3}$	$3.4^{+5.7}_{-3.4}$
5–6	$3.6^{+2.9}_{-2.9}$	$3.6^{+3.0}_{-3.0}$
6–8	$3.5^{+3.8}_{-3.5}$	$3.1^{+3.4}_{-3.1}$
8–10	$3.9^{+5.5}_{-3.9}$	$4.3^{+6.2}_{-4.3}$

The f^{prompt} fraction for D^0 mesons is obtained using a template fit method. The prompt and nonprompt D^0 mesons can be distinguished based on the distributions of their distance of closest approach (DCA) with respect to the PV of the event. A two-component fit with DCA templates from simulated prompt and nonprompt D^0 samples is performed to the DCA distribution in data. Examples of the template fit to DCA distributions for D^0 mesons can be found in Ref. [38].

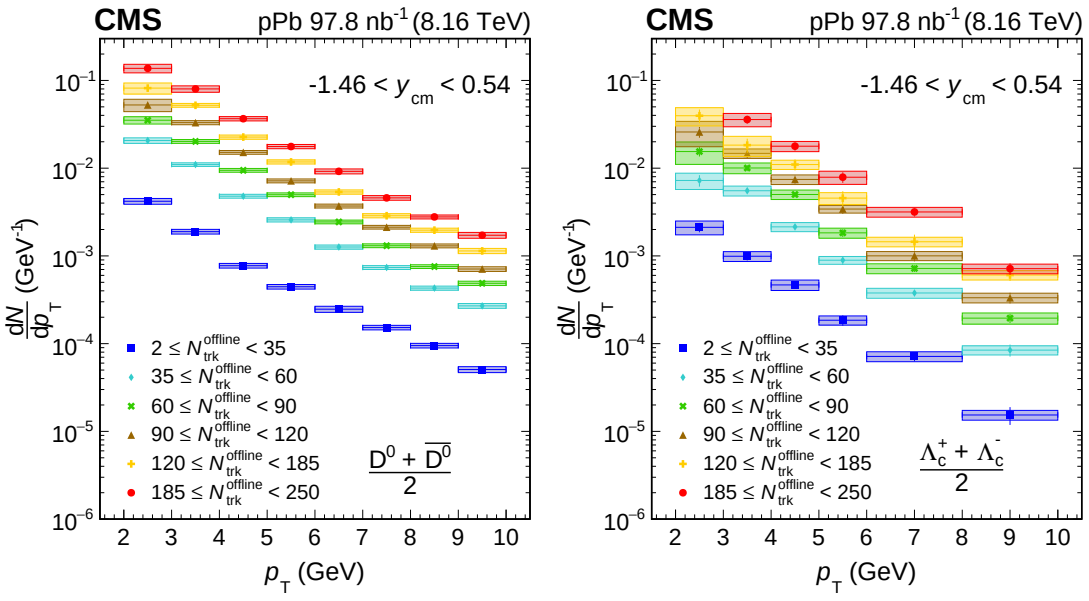

Figure 2: Transverse momentum spectra for Λ_c^+ baryons (left) and D^0 mesons (right) with $-1.46 < y_{cm} < 0.54$ in different multiplicity classes. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties.

4 Systematic uncertainties

The candidate selection uncertainty is estimated by varying the MLP or BDT classifier cut over a wide range, which yields a relative uncertainty of 2–6% for Λ_c^+ baryons and 1–5% for D^0 mesons, respectively, depending on the $N_{trk}^{offline}$ and charm hadron p_T. The uncertainty of the fit procedure is estimated by changing the signal shape from a double Gaussian to a Gaussian+CB function for the Λ_c^+ baryon, and via changing the background function to a second- and fourth-order polynomial for both Λ_c^+ and D^0 particles. These variations yield a relative uncertainty of 6–28% for Λ_c^+ baryons and less than 2% for D^0 mesons.

The uncertainty in feed-down from b hadrons for Λ_c^+ is estimated from the following components. The associated systematic uncertainty from FONLL calculations is evaluated by varying its central values by its uncertainties [79]. Another variation is performed by comparing the FONLL calculations with PYTHIA. The value of the Pb-normalized FONLL calculations is also varied by 25% to account for potential nuclear effects. No significant nuclear modifications to the b-hadrons production cross sections in pPb collisions are observed within ±25% [82]. The uncertainty from the LHCb fragmentation fraction measurements is also considered [80]. The assumption that the feed-down is uniform across multiplicities is studied using D^0 mesons and assumed to have similar behavior for Λ_c^+ baryons, because both nonprompt Λ_c^+ and D^0 production originates from b hadrons. The maximum of the difference of f^{prompt} for D^0 mesons between different multiplicity classes is taken as an estimate for the systematic uncertainty in the Λ_c^+ measurements. The sum in quadrature of these sources yields a total relative uncertainty of 4–12% for the feed-down estimation. The uncertainty related to template fits in DCA for D^0 mesons is estimated by varying the DCA resolution of simulated samples to explore the discrepancy between simulated samples and data. This source yields an uncertainty of less than 15%.

The systematic uncertainty from the tracking efficiency is 2.3% per track [83], which is propagated to 7% for Λ_c^+ baryon yields and 5% for D^0 meson yields since the former are reconstructed from three tracks and the latter are from two. The uncertainty related to trigger effi-

ciency is found to be negligible, as the main inefficiency affects mostly very low multiplicity events while those containing a heavy flavor hadron production are strongly biased toward higher average multiplicity within each class. Occasionally, there are multiple collisions per bunch crossing, and these additional collisions are referred to as pileup interactions. The pileup effects are studied by requiring different minimum distances between multiple reconstructed PVs according to the final-state track multiplicity. The systematic uncertainty due to pileup effects turns out to be 3–6% (from low to high $N_{\mathrm{trk}}^{\mathrm{offline}}$) for Λ_{c}^{+} baryons and $< 1\%$ for D^{0} mesons. The total systematic uncertainty of the production yields is calculated by assuming all sources are independent and adding them in quadrature.

The relative systematic uncertainty for the yield ratio of Λ_{c}^{+}-to-D^{0} is computed by adding in quadrature the relative Λ_{c}^{+} and D^{0} yield uncertainties including the effects of candidate selections, fit procedures, b hadron feed-down, and branching fractions. The uncertainties from tracking efficiency and pileup effects are taken to be fully correlated between the D^{0} and Λ_{c}^{+} samples, resulting in uncertainties of 2.3% and 2–4% for the Λ_{c}^{+}-to-D^{0} ratio, respectively.

A summary of systematic uncertainties in measurements of the Λ_{c}^{+} and D^{0} differential yields can be found in Table 3.

Table 3: Summary of relative uncertainties in the differential yields.

Source	Λ_{c}^{+} (%)	D^{0} (%)
Selections	2–6	1–5
Fit	6–28	<2
b feed-down	3–11	<15
Tracking efficiency	7	5
Pileup effects	3–6	<1
Branching fraction	5	1
Total	10–32	5–16

5 Results

The p_{T} spectra for Λ_{c}^{+} and D^{0} hadrons in each multiplicity class are shown in Fig. 2. The production of charm hadron yield per event increases with multiplicity. The p_{T} spectra follow approximately an exponential falling trend for all multiplicity classes.

The corresponding Λ_{c}^{+}-to-D^{0} ratios are presented in Fig 3. The Λ_{c}^{+}-to-D^{0} ratio tends to decrease with p_{T}, both for low- and high-multiplicity events. The ratios in Fig. 3 are also consistent with those obtained in inclusive pPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$ reported in Refs. [56, 58]. No strong multiplicity dependence is observed within one standard deviation, in contrast to the enhanced baryon-to-meson ratio for strange hadrons as the multiplicity increases [53].

To further investigate the system size dependence, the charm baryon-to-meson ratio is also plotted as a function of $N_{\mathrm{trk}}^{\mathrm{offline}}$ in Fig. 4. In contrast to what is observed in the strange-quark sector, the charm baryon-to-meson ratio is approximately constant over a large range of multiplicity. This may indicate a possible mass dependence for the particle hadronization mechanism. If a coalescence process is present, it may happen earlier for charm quarks than for light quarks during the system evolution.

The observed independence of the Λ_{c}^{+}-to-D^{0} ratio on the multiplicity might indicate a difference between heavy and light quarks, even though these particles show similar elliptic flow signals as a function of multiplicity [18, 40]. In models of QGP formation, charm quarks are

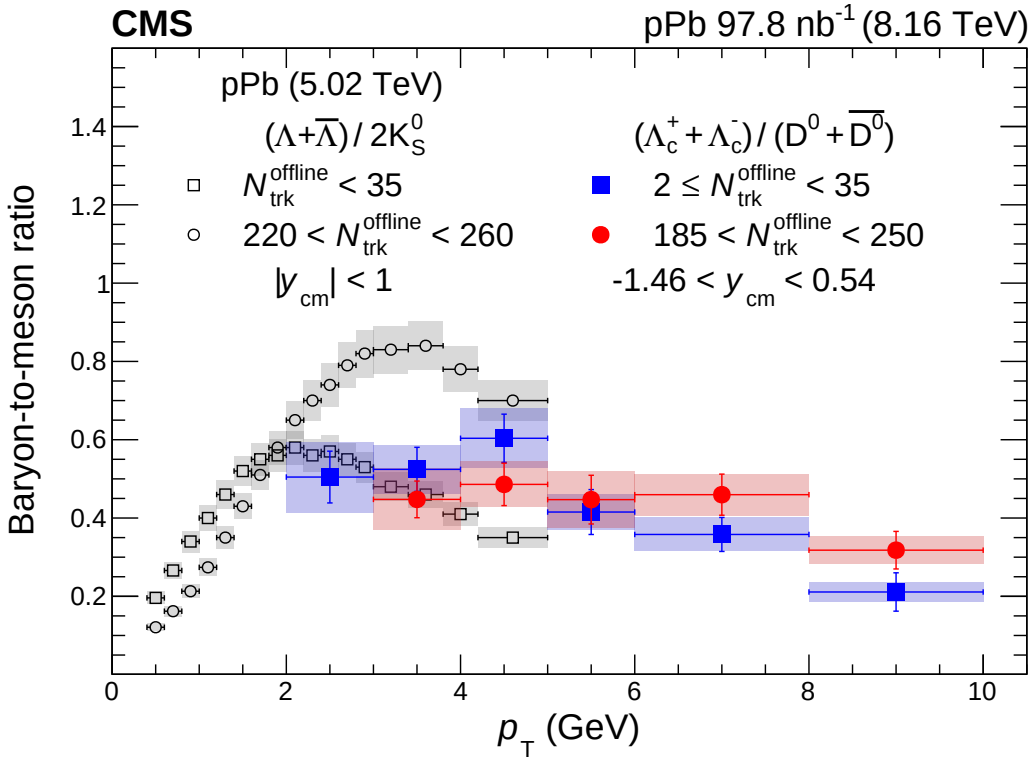

Figure 3: Ratio of Λ_c^+ baryons to D^0 mesons production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with $2 \leq N_{trk}^{offline} < 35$ and $185 \leq N_{trk}^{offline} < 250$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The grey markers are for Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV from Ref. [53].

expected to experience kinetic propagation inside the liquid QGP [49, 84], while light quarks are in general thermalized in the hot QGP. The larger mean free path of heavy quarks compared with light quarks in pPb collisions may lead to less pronounced effects from the dense medium. On the other hand, a model incorporating an initial-state gluon saturation scenario without QGP production shows agreement with the elliptic flow of D^0 mesons in pPb collisions [45, 85].

The charm baryon-to-meson ratio as a function of p_T in pPb collisions at 8.16 TeV is also compared with that in pp and PbPb collisions at 5.02 TeV [52, 86] in Fig. 5. The results in the range $2 < p_T < 10$ GeV are consistent with inclusive events in pp collisions and mid-central (e.g., 30–50% centrality) PbPb collisions. The decreasing trend with p_T for the charm baryon-to-meson ratio is also observed in these systems. Further studies of the multiplicity dependence of this ratio in pPb collisions for the very high-p_T regime are crucial to find out whether this convergence is universal across different colliding systems and event activities.

6 Summary

The first measurements of Λ_c^+ baryon and D^0 meson yields, as well as their yield ratios, as a function of the charged-particle multiplicity in proton-lead (pPb) collisions are presented. At a nucleon-nucleon center-of-mass energy of 8.16 TeV, the Λ_c^+ baryon is reconstructed using the decay channel $\Lambda_c^+ \to K_S^0 p$, while the D^0 meson is reconstructed from $D^0 \to K^- \pi^+$. The Λ_c^+ and D^0 production yields, and the Λ_c^+-to-D^0 yield ratio are studied as a function of transverse momentum and charged-particle multiplicity. No strong multiplicity dependence is observed

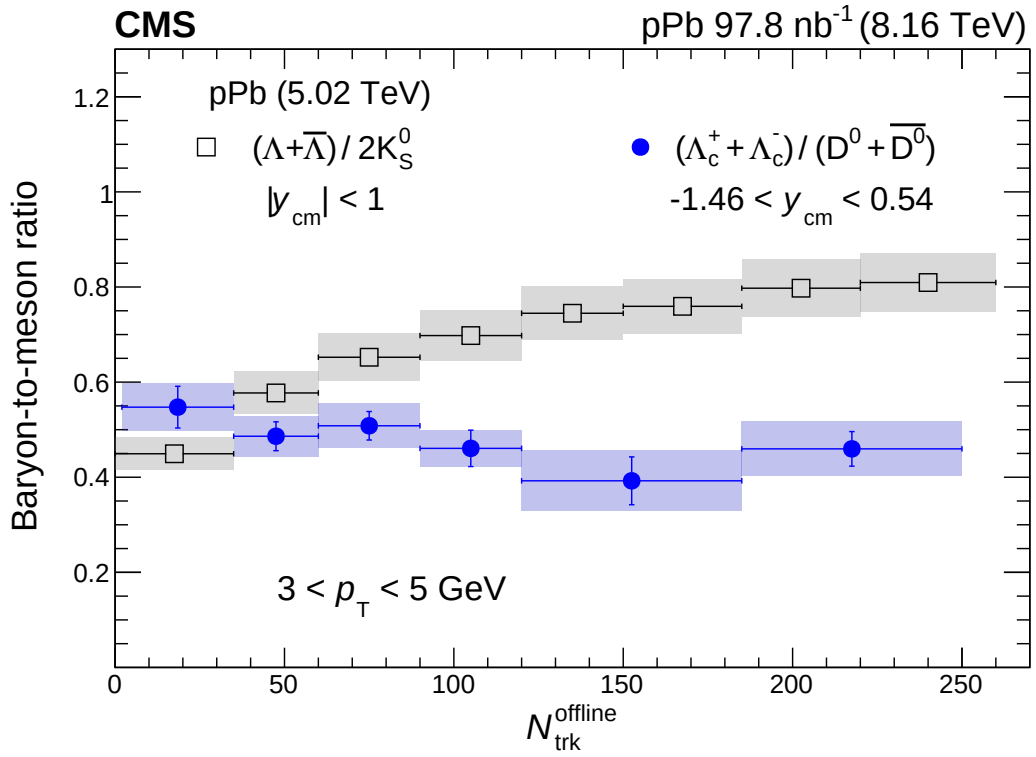

Figure 4: Ratio of Λ_c^+ baryon to D^0 meson production with $-1.46 < y_{cm} < 0.54$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV as a function of $N_{trk}^{offline}$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The ratio of Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV obtained from data in Ref. [53] is also shown for comparisons, denoted by grey markers.

within the experimental uncertainties. The absence of any significant multiplicity dependence of the yield ratio differs strikingly from that for strange hadrons, which is observed to increase with multiplicity. The difference between these results for charm quarks and those for strange quarks might indicate that the conjectured coalescence processes of heavy quarks happen earlier than those of strange quarks.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: SC (Armenia), BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES and BNSF (Bulgaria); CERN; CAS, MoST, and NSFC (China); MINCIENCIAS (Colombia); MSES and CSF (Croatia); RIF (Cyprus); SENESCYT (Ecuador); ERC PRG, 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 (In-

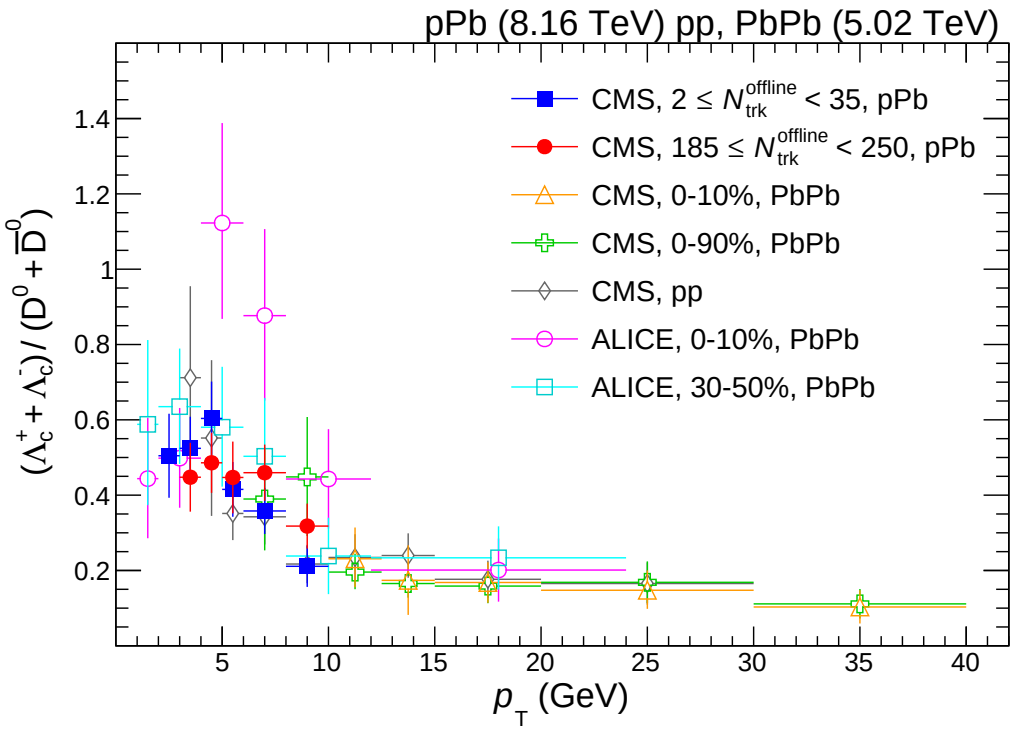

Figure 5: Comparison between the Λ_c^+-to-D^0 ratio as a function of p_T in pp, pPb, and PbPb (different centrality ranges) collisions at the nucleon-nucleon center-of-mass energies of 5.02, 8.16, and 5.02 TeV, respectively [52, 86]. The uncertainties are denoted by vertical bars. The ratio is measured with the rapidity ranges $-1.46 < y_{cm} < 0.54$ in pPb collisions and $|y_{cm}| < 1$ in pp and PbPb collisions by the CMS Collaboration [86] and $|y_{cm}| < 0.5$ by the ALICE Collaboration [52].

dia); 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, and TKP2021-NKTA-64 (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).

References

[1] ALICE Collaboration, "Elliptic flow of charged particles in Pb-Pb collisions at 2.76 TeV", *Phys. Rev. Lett.* **105** (2010) 252302, doi:10.1103/PhysRevLett.105.252302, arXiv:1011.3914.

[2] CMS Collaboration, "Measurement of the elliptic anisotropy of charged particles produced in PbPb collisions at nucleon-nucleon center-of-mass energy = 2.76 TeV", *Phys. Rev. C* **87** (2013) 014902, doi:10.1103/PhysRevC.87.014902, arXiv:1204.1409.

[3] CMS Collaboration, "Overview of high-density QCD studies with the CMS experiment at the LHC", 2024. arXiv:2405.10785. Submitted to Physics Reports.

[4] STAR Collaboration, "Elliptic flow in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 130\,\mathrm{GeV}$", *Phys. Rev. Lett.* **86** (2001) 402, doi:10.1103/PhysRevLett.86.402, arXiv:nucl-ex/0009011.

[5] PHENIX Collaboration, "Elliptic flow of identified hadrons in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **91** (2003) 182301, doi:10.1103/PhysRevLett.91.182301, arXiv:nucl-ex/0305013.

[6] STAR Collaboration, "Distributions of charged hadrons associated with high transverse momentum particles in pp and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **95** (2005) 152301, doi:10.1103/PhysRevLett.95.152301, arXiv:nucl-ex/0501016.

[7] PHOBOS Collaboration, "System size dependence of cluster properties from two-particle angular correlations in Cu+Cu and Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. C* **81** (2010) 024904, doi:10.1103/PhysRevC.81.024904, arXiv:0812.1172.

[8] PHOBOS Collaboration, "High transverse momentum triggered correlations over a large pseudorapidity acceptance in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$", *Phys. Rev. Lett.* **104** (2010) 062301, doi:10.1103/PhysRevLett.104.062301, arXiv:0903.2811.

[9] STAR Collaboration, "Long range rapidity correlations and jet production in high energy nuclear collisions", *Phys. Rev. C* **80** (2009) 064912, doi:10.1103/PhysRevC.80.064912, arXiv:0909.0191.

[10] CMS Collaboration, "Long-range and short-range dihadron angular correlations in central PbPb collisions at a nucleon-nucleon center of mass energy of 2.76 TeV", *JHEP* **07** (2011) 076, doi:10.1007/JHEP07(2011)076, arXiv:1105.2438.

[11] CMS Collaboration, "Centrality dependence of dihadron correlations and azimuthal anisotropy harmonics in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *Eur. Phys. J. C* **72** (2012) 2012, doi:10.1140/epjc/s10052-012-2012-3, arXiv:1201.3158.

[12] ATLAS Collaboration, "Measurement of the azimuthal anisotropy for charged particle production in $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$ lead-lead collisions with the ATLAS detector", *Phys. Rev. C* **86** (2012) 014907, doi:10.1103/PhysRevC.86.014907, arXiv:1203.3087.

[13] CMS Collaboration, "Studies of azimuthal dihadron correlations in ultra-central PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$", *JHEP* **02** (2014) 088, doi:10.1007/JHEP02(2014)088, arXiv:1312.1845.

[14] J.-Y. Ollitrault, "Anisotropy as a signature of transverse collective flow", *Phys. Rev. D* **46** (1992) 229, doi:10.1103/PhysRevD.46.229.

[15] U. Heinz and R. Snellings, "Collective flow and viscosity in relativistic heavy-ion collisions", *Ann. Rev. Nucl. Part. Sci.* **63** (2013) 123, doi:10.1146/annurev-nucl-102212-170540, arXiv:1301.2826.

[16] C. Gale, S. Jeon, and B. Schenke, "Hydrodynamic modeling of heavy-ion collisions", *Int. J. Mod. Phys. A* **28** (2013) 1340011, doi:10.1142/S0217751X13400113, arXiv:1301.5893.

[17] ALICE Collaboration, "D-meson azimuthal anisotropy in midcentral Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Rev. Lett.* **120** (2018) 102301, doi:10.1103/PhysRevLett.120.102301, arXiv:1707.01005.

[18] CMS Collaboration, "Elliptic flow of charm and strange hadrons in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$", *Phys. Rev. Lett.* **121** (2018) 082301, doi:10.1103/PhysRevLett.121.082301, arXiv:1804.09767.

[19] CMS Collaboration, "Measurement of prompt D^0 and $\overline{\mathrm{D}}^0$ meson azimuthal anisotropy and search for strong electric fields in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Lett. B* **816** (2021) 136253, doi:10.1016/j.physletb.2021.136253, arXiv:2009.12628.

[20] ALICE Collaboration, "Elliptic flow of electrons from beauty-hadron decays in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Rev. Lett.* **126** (2021) 162001, doi:10.1103/PhysRevLett.126.162001, arXiv:2005.11130.

[21] ATLAS Collaboration, "Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ with the ATLAS detector", *Phys. Lett. B* **807** (2020) 135595, doi:10.1016/j.physletb.2020.135595, arXiv:2003.03565.

[22] CMS Collaboration, "Measurements of azimuthal anisotropy of nonprompt D^0 mesons in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$", *Phys. Lett. B* **850** (2024) 138389, doi:10.1016/j.physletb.2023.138389, arXiv:2212.01636.

[23] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-proton collisions at the LHC", *JHEP* **09** (2010) 091, doi:10.1007/JHEP09(2010)091, arXiv:1009.4122.

[24] ATLAS Collaboration, "Observation of long-range elliptic azimuthal anisotropies in $\sqrt{s} = 13$ and 2.76 TeV pp collisions with the ATLAS detector", *Phys. Rev. Lett.* **116** (2016) 172301, doi:10.1103/PhysRevLett.116.172301, arXiv:1509.04776.

[25] CMS Collaboration, "Measurement of long-range near-side two-particle angular correlations in pp collisions at $\sqrt{s}$ =13 TeV", *Phys. Rev. Lett.* **116** (2016) 172302, doi:10.1103/PhysRevLett.116.172302, arXiv:1510.03068.

[26] CMS Collaboration, "Evidence for collectivity in pp collisions at the LHC", *Phys. Lett. B* **765** (2017) 193, doi:10.1016/j.physletb.2016.12.009, arXiv:1606.06198.

[27] CMS Collaboration, "Observation of long-range near-side angular correlations in proton-lead collisions at the LHC", *Phys. Lett. B* **718** (2013) 795, doi:10.1016/j.physletb.2012.11.025, arXiv:1210.5482.

[28] ALICE Collaboration, "Long-range angular correlations on the near and away side in pPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", *Phys. Lett. B* **719** (2013) 29, doi:10.1016/j.physletb.2013.01.012, arXiv:1212.2001.

[29] ATLAS Collaboration, "Observation of associated near-side and away-side long-range correlations in $\sqrt{s_{\rm NN}} = 5.02$ TeV proton-lead collisions with the ATLAS detector", *Phys. Rev. Lett.* **110** (2013) 182302, doi:10.1103/PhysRevLett.110.182302, arXiv:1212.5198.

[30] CMS Collaboration, "Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and PbPb collisions", *Phys. Lett. B* **724** (2013) 213, doi:10.1016/j.physletb.2013.06.028, arXiv:1305.0609.

[31] LHCb Collaboration, "Measurements of long-range near-side angular correlations in $\sqrt{s_{\rm NN}} = 5$ TeV proton-lead collisions in the forward region", *Phys. Lett. B* **762** (2016) 473, doi:10.1016/j.physletb.2016.09.064, arXiv:1512.00439.

[32] ALICE Collaboration, "Long-range angular correlations of π, K and p in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", *Phys. Lett. B* **726** (2013) 164, doi:10.1016/j.physletb.2013.08.024, arXiv:1307.3237.

[33] CMS Collaboration, "Long-range two-particle correlations of strange hadrons with charged particles in pPb and PbPb collisions at LHC energies", *Phys. Lett. B* **742** (2015) 200, doi:10.1016/j.physletb.2015.01.034, arXiv:1409.3392.

[34] CMS Collaboration, "Evidence for collective multi-particle correlations in pPb collisions", *Phys. Rev. Lett.* **115** (2015) 012301, doi:10.1103/PhysRevLett.115.012301, arXiv:1502.05382.

[35] ATLAS Collaboration, "Measurement of multi-particle azimuthal correlations in pp, p+Pb and low-multiplicity Pb+Pb collisions with the ATLAS detector", *Eur. Phys. J. C* **77** (2017) 428, doi:10.1140/epjc/s10052-017-4988-1, arXiv:1705.04176.

[36] ATLAS Collaboration, "Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and p+Pb collisions with the ATLAS detector at the CERN Large Hadron Collider", *Phys. Rev. C* **97** (2018) 024904, doi:10.1103/PhysRevC.97.024904, arXiv:1708.03559.

[37] PHENIX Collaboration, "Creation of quark-gluon plasma droplets with three distinct geometries", *Nature Phys.* **15** (2019) 214, doi:10.1038/s41567-018-0360-0, arXiv:1805.02973.

[38] CMS Collaboration, "Studies of charm and beauty hadron long-range correlations in pp and pPb collisions at LHC energies", *Phys. Lett. B* **813** (2021) 136036, doi:10.1016/j.physletb.2020.136036, arXiv:2009.07065.

[39] ALICE Collaboration, "Search for collectivity with azimuthal J/ψ-hadron correlations in high multiplicity p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ and 8.16 TeV", *Phys. Lett. B* **780** (2018) 7, doi:10.1016/j.physletb.2018.02.039, arXiv:1709.06807.

[40] CMS Collaboration, "Observation of prompt J/ψ meson elliptic flow in high-multiplicity pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV", *Phys. Lett. B* **791** (2019) 172, doi:10.1016/j.physletb.2019.02.018, arXiv:1810.01473.

[41] ATLAS Collaboration, "Measurement of azimuthal anisotropy of muons from charm and bottom hadrons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector", *Phys. Rev. Lett.* **124** (2020) 082301, doi:10.1103/PhysRevLett.124.082301, arXiv:1909.01650.

[42] K. Dusling, W. Li, and B. Schenke, "Novel collective phenomena in high-energy proton-proton and proton-nucleus collisions", *Int. J. Mod. Phys. E* **25** (2016) 1630002, doi:10.1142/S0218301316300022, arXiv:1509.07939.

[43] J. L. Nagle and W. A. Zajc, "Small system collectivity in relativistic hadronic and nuclear collisions", *Ann. Rev. Nucl. Part. Sci.* **68** (2018) 211, doi:10.1146/annurev-nucl-101916-123209, arXiv:1801.03477.

[44] X. Du and R. Rapp, "In-medium charmonium production in proton-nucleus collisions", *JHEP* **03** (2019) 015, doi:10.1007/JHEP03(2019)015, arXiv:1808.10014.

[45] C. Zhang et al., "Elliptic flow of heavy quarkonia in pA collisions", *Phys. Rev. Lett.* **122** (2019) 172302, doi:10.1103/PhysRevLett.122.172302, arXiv:1901.10320.

[46] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, "Hadronization in heavy ion collisions: recombination and fragmentation of partons", *Phys. Rev. Lett.* **90** (2003) 202303, doi:10.1103/PhysRevLett.90.202303, arXiv:nucl-th/0301087.

[47] R. J. Fries, B. Muller, C. Nonaka, and S. A. Bass, "Hadron production in heavy ion collisions: fragmentation and recombination from a dense parton phase", *Phys. Rev. C* **68** (2003) 044902, doi:10.1103/PhysRevC.68.044902, arXiv:nucl-th/0306027.

[48] S. Plumari et al., "Charmed hadrons from coalescence plus fragmentation in relativistic nucleus-nucleus collisions at RHIC and LHC", *Eur. Phys. J. C* **78** (2018) 348, doi:10.1140/epjc/s10052-018-5828-7, arXiv:1712.00730.

[49] M. He and R. Rapp, "Hadronization and charm-hadron ratios in heavy-ion collisions", *Phys. Rev. Lett.* **124** (2020) 042301, doi:10.1103/PhysRevLett.124.042301, arXiv:1905.09216.

[50] STAR Collaboration, "First measurement of Λ_c^+ baryon production in AuAu collisions at $\sqrt{s_{NN}} = 200\,\text{GeV}$", *Phys. Rev. Lett.* **124** (2020) 172301, doi:10.1103/PhysRevLett.124.172301, arXiv:1910.14628.

[51] CMS Collaboration, "Production of Λ_c^+ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *Phys. Lett. B* **803** (2020) 135328, doi:10.1016/j.physletb.2020.135328, arXiv:1906.03322.

[52] ALICE Collaboration, "Constraining hadronization mechanisms with Λ_c^+/D^0 production ratios in PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *Phys. Lett. B* **839** (2023) 137796, doi:10.1016/j.physletb.2023.137796, arXiv:2112.08156.

[53] CMS Collaboration, "Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC", *Phys. Lett. B* **768** (2017) 103, doi:10.1016/j.physletb.2017.01.075, arXiv:1605.06699.

[54] H.-H. Li, F.-L. Shao, J. Song, and R.-Q. Wang, "Production of single-charm hadrons by quark combination mechanism in pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *Phys. Rev. C* **97** (2018) 064915, doi:10.1103/PhysRevC.97.064915, arXiv:1712.08921.

[55] V. Minissale, S. Plumari, and V. Greco, "Charm hadrons in pp collisions at LHC energy within a coalescence plus fragmentation approach", *Phys. Lett. B* **821** (2021) 136622, doi:10.1016/j.physletb.2021.136622, arXiv:2012.12001.

[56] ALICE Collaboration, "Λ_c^+ production and baryon-to-meson ratios in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ at the LHC", *Phys. Rev. Lett.* **127** (2021) 202301, doi:10.1103/PhysRevLett.127.202301, arXiv:2011.06078.

[57] ALICE Collaboration, "Λ_c^+ production in pp and in pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *Phys. Rev. C* **104** (2021) 054905, doi:10.1103/PhysRevC.104.054905, arXiv:2011.06079.

[58] ALICE Collaboration, "First measurement of Λ_c^+ production down to $p_T = 0$ in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *Phys. Rev. C* **107** (2023) 064901, doi:10.1103/PhysRevC.107.064901, arXiv:2211.14032.

[59] ALICE Collaboration, "Observation of a multiplicity dependence in the p_T-differential charm baryon-to-meson ratios in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *Phys. Lett. B* **829** (2022) 137065, doi:10.1016/j.physletb.2022.137065, arXiv:2111.11948.

[60] M. He and R. Rapp, "Charm-baryon production in proton-proton collisions", *Phys. Lett. B* **795** (2019) 117, doi:10.1016/j.physletb.2019.06.004, arXiv:1902.08889.

[61] "HEPData record for this analysis", 2024. doi:10.17182/hepdata.141626.

[62] G. Bayatian et al., "Design, performance and calibration of the CMS forward calorimeter wedges", *Eur. Phys. J. C* **53** (2008) 139, doi:10.1140/epjc/s10052-007-0459-4.

[63] CMS Collaboration, "The CMS experiment at the CERN LHC", *JINST* **3** (2008) S08004, doi:10.1088/1748-0221/3/08/S08004.

[64] CMS Collaboration, "Description and performance of track and primary-vertex reconstruction with the CMS tracker", *JINST* **9** (2014) P10009, doi:10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.

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

[66] CMS Collaboration, "The CMS trigger system", *JINST* **12** (2017) P01020, doi:10.1088/1748-0221/12/01/P01020, arXiv:1609.02366.

[67] CMS Collaboration, "CMS luminosity measurement using 2016 proton-nucleus collisions at nucleon-nucleon center-of-mass energy of 8.16 TeV", Physics Analysis Summary CMS-PAS-LUM-17-002, 2018.

[68] CMS Collaboration, "Constraints on the chiral magnetic effect using charge-dependent azimuthal correlations in pPb and PbPb collisions at the CERN Large Hadron Collider", *Phys. Rev. C* **97** (2018) 044912, doi:10.1103/PhysRevC.97.044912, arXiv:1708.01602.

[69] CMS Collaboration, "Observation of correlated azimuthal anisotropy fourier harmonics in pp and p+Pb collisions at the LHC", *Phys. Rev. Lett.* **120** (2018) 092301, doi:10.1103/PhysRevLett.120.092301, arXiv:1709.09189.

[70] T. Sjöstrand et al., "An introduction to PYTHIA 8.2", *Comput. Phys. Commun.* **191** (2015) 159, doi:10.1016/j.cpc.2015.01.024, arXiv:1410.3012.

[71] CMS Collaboration, "Extraction and validation of a new set of CMS PYTHIA8 tunes from underlying-event measurements", *Eur. Phys. J. C* **80** (2020) 4, doi:10.1140/epjc/s10052-019-7499-4, arXiv:1903.12179.

[72] T. Pierog et al., "EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider", *Phys. Rev. C* **92** (2015) 034906, doi:10.1103/PhysRevC.92.034906, arXiv:1306.0121.

[73] Geant4 Collaboration, "GEANT4—a simulation toolkit", *Nucl. Instrum. and Meth. A* **506** (2003) 250, doi:10.1016/S0168-9002(03)01368-8.

[74] D. J. Lange, "The EVTGEN particle decay simulation package", *Nucl. Instrum. Meth. A* **462** (2001) 152, doi:10.1016/S0168-9002(01)00089-4.

[75] Particle Data Group Collaboration, "Review of Particle Physics", *PTEP* **2022** (2022) 083C01, doi:10.1093/ptep/ptac097.

[76] H. Voss, A. Höcker, J. Stelzer, and F. Tegenfeldt, "TMVA, the toolkit for multivariate data analysis with ROOT", in *XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT)*, p. 40. 2007. arXiv:physics/0703039. [PoS(ACAT)040]. doi:10.22323/1.050.0040.

[77] A. Giammanco, "Particle identification with energy loss in the CMS silicon strip tracker", CMS Note CERN-CMS-NOTE-2008-005, 2008.

[78] M. J. Oreglia, "A study of the reactions $\psi' \to \gamma\gamma\psi$". PhD thesis, Stanford University, 1980. SLAC Report SLAC-R-236.

[79] M. Cacciari et al., "Theoretical predictions for charm and bottom production at the LHC", *JHEP* **10** (2012) 137, doi:10.1007/JHEP10(2012)137, arXiv:1205.6344.

[80] LHCb Collaboration, "Measurement of b hadron fractions in 13 TeV pp collisions", *Phys. Rev. D* **100** (2019) 031102, doi:10.1103/PhysRevD.100.031102, arXiv:1902.06794.

[81] ALICE Collaboration, "Study of flavor dependence of the baryon-to-meson ratio in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$", *Phys. Rev. D* **108** (2023) 112003, doi:10.1103/PhysRevD.108.112003, arXiv:2308.04873.

[82] LHCb Collaboration, "Measurement of B^+, B^0 and Λ_b^0 production in pPb collisions at $\sqrt{s_{NN}} = 8.16\,\text{TeV}$", *Phys. Rev. D* **99** (2019) 052011, doi:10.1103/PhysRevD.99.052011, arXiv:1902.05599.

[83] CMS Collaboration, "Tracking POG results for pion efficiency with the D^* meson using data from 2016 and 2017", technical report, 2018.

[84] A. Beraudo et al., "In-medium hadronization of heavy quarks and its effect on charmed meson and baryon distributions in heavy-ion collisions", *Eur. Phys. J. C* **82** (2022) 607, doi:10.1140/epjc/s10052-022-10482-y, arXiv:2202.08732.

[85] C. Zhang et al., "Collectivity of heavy mesons in proton-nucleus collisions", *Phys. Rev. D* **102** (2020) 034010, doi:10.1103/PhysRevD.102.034010, arXiv:2002.09878.

[86] CMS Collaboration, "Study of charm hadronization with prompt Λ_c^+ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$", *JHEP* **01** (2024) 128, doi:10.1007/JHEP01(2024)128, arXiv:2307.11186.

A The CMS Collaboration

Yerevan Physics Institute, Yerevan, Armenia
A. Hayrapetyan, A. Tumasyan[1]

Institut für Hochenergiephysik, Vienna, Austria
W. Adam, J.W. Andrejkovic, 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, D. Schwarz, M. Sonawane, S. Templ, W. Waltenberger, C.-E. Wulz[2]

Universiteit Antwerpen, Antwerpen, Belgium
M.R. Darwish[3], T. Janssen, P. Van Mechelen

Vrije Universiteit Brussel, Brussel, Belgium
E.S. Bols, J. D'Hondt, S. Dansana, A. De Moor, M. Delcourt, H. El Faham, S. Lowette, I. Makarenko, D. Müller, A.R. Sahasransu, S. Tavernier, M. Tytgat[4], S. Van Putte, D. Vannerom

Université Libre de Bruxelles, Bruxelles, Belgium
B. Clerbaux, G. De Lentdecker, L. Favart, D. Hohov, J. Jaramillo, A. Khalilzadeh, K. Lee, M. Mahdavikhorrami, A. Malara, S. Paredes, L. Pétré, N. Postiau, L. Thomas, M. Vanden Bemden, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium
M. De Coen, D. Dobur, Y. Hong, J. Knolle, L. Lambrecht, G. Mestdach, C. Rendón, A. Samalan, K. Skovpen, N. Van Den Bossche, L. Wezenbeek

Université Catholique de Louvain, Louvain-la-Neuve, Belgium
A. Benecke, G. Bruno, C. Caputo, C. Delaere, I.S. Donertas, A. Giammanco, K. Jaffel, Sa. Jain, V. Lemaitre, J. Lidrych, P. Mastrapasqua, K. Mondal, T.T. Tran, S. Wertz

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
G.A. Alves, E. Coelho, C. Hensel, T. Menezes De Oliveira, A. Moraes, P. Rebello Teles, M. Soeiro

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil
W.L. Aldá Júnior, M. Alves Gallo Pereira, M. Barroso Ferreira Filho, H. Brandao Malbouisson, W. Carvalho, J. Chinellato[5], E.M. Da Costa, G.G. Da Silveira[6], D. De Jesus Damiao, S. Fonseca De Souza, J. Martins[7], C. Mora Herrera, K. Mota Amarilo, L. Mundim, H. Nogima, A. Santoro, A. Sznajder, M. Thiel, A. Vilela Pereira

Universidade Estadual Paulista, Universidade Federal do ABC, São Paulo, Brazil
C.A. Bernardes[6], L. Calligaris, T.R. Fernandez Perez Tomei, E.M. Gregores, P.G. Mercadante, S.F. Novaes, B. Orzari, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria
A. Aleksandrov, G. Antchev, R. Hadjiiska, P. Iaydjiev, M. Misheva, M. Shopova, G. Sultanov

University of Sofia, Sofia, Bulgaria
A. Dimitrov, L. Litov, B. Pavlov, P. Petkov, A. Petrov, E. Shumka

Instituto De Alta Investigación, Universidad de Tarapacá, Casilla 7 D, Arica, Chile
S. Keshri, S. Thakur

Beihang University, Beijing, China
T. Cheng, Q. Guo, T. Javaid, M. Mittal, L. Yuan

Department of Physics, Tsinghua University, Beijing, China
Z. Hu, J. Liu, K. Yi[8,9]

Institute of High Energy Physics, Beijing, China
G.M. Chen[10], H.S. Chen[10], M. Chen[10], F. Iemmi, C.H. Jiang, A. Kapoor[11], H. Liao, Z.-A. Liu[12], F. Monti, M.A. Shahzad[10], R. Sharma[13], J.N. Song[12], J. Tao, C. Wang[10], J. Wang, Z. Wang[10], H. Zhang

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China
A. Agapitos, Y. Ban, A. Levin, C. Li, Q. Li, Y. Mao, S.J. Qian, X. Sun, D. Wang, H. Yang, L. Zhang, C. Zhou

Sun Yat-Sen University, Guangzhou, China
Z. You

University of Science and Technology of China, Hefei, China
N. Lu

Nanjing Normal University, Nanjing, China
G. Bauer[14]

Institute of Modern Physics and Key Laboratory of Nuclear Physics and Ion-beam Application (MOE) - Fudan University, Shanghai, China
X. Gao[15], D. Leggat, H. Okawa, Y. Zhang

Zhejiang University, Hangzhou, Zhejiang, China
Z. Lin, C. Lu, M. Xiao

Universidad de Los Andes, Bogota, Colombia
C. Avila, D.A. Barbosa Trujillo, A. Cabrera, C. Florez, J. Fraga, J.A. Reyes Vega

Universidad de Antioquia, Medellin, Colombia
J. Mejia Guisao, F. Ramirez, M. Rodriguez, J.D. Ruiz Alvarez

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia
D. Giljanovic, N. Godinovic, D. Lelas, A. Sculac

University of Split, Faculty of Science, Split, Croatia
M. Kovac, T. Sculac[16]

Institute Rudjer Boskovic, Zagreb, Croatia
P. Bargassa, V. Brigljevic, B.K. Chitroda, D. Ferencek, S. Mishra, A. Starodumov[17], T. Susa

University of Cyprus, Nicosia, Cyprus
A. Attikis, K. Christoforou, S. Konstantinou, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski, H. Saka, A. Stepennov

Charles University, Prague, Czech Republic
M. Finger, M. Finger Jr., A. Kveton

Escuela Politecnica Nacional, Quito, Ecuador
E. Ayala

Universidad San Francisco de Quito, Quito, Ecuador
E. Carrera Jarrin

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt
S. Elgammal[18], A. Ellithi Kamel[19]

Center for High Energy Physics (CHEP-FU), Fayoum University, El-Fayoum, Egypt
M.A. Mahmoud, Y. Mohammed

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia
R.K. Dewanjee[20], K. Ehataht, M. Kadastik, T. Lange, S. Nandan, C. Nielsen, J. Pata, M. Raidal, L. Tani, C. Veelken

Department of Physics, University of Helsinki, Helsinki, Finland
H. Kirschenmann, K. Osterberg, M. Voutilainen

Helsinki Institute of Physics, Helsinki, Finland
S. Bharthuar, E. Brücken, F. Garcia, J. Havukainen, K.T.S. Kallonen, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, M. Lotti, L. Martikainen, M. Myllymäki, M.m. Rantanen, H. Siikonen, E. Tuominen, J. Tuominiemi

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland
P. Luukka, H. Petrow, T. Tuuva†

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, P. Gras, G. Hamel de Monchenault, V. Lohezic, J. Malcles, J. Rander, A. Rosowsky, M.Ö. Sahin, A. Savoy-Navarro[21], P. Simkina, M. Titov, M. Tornago

Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, Institut Polytechnique de Paris, Palaiseau, France
C. Baldenegro Barrera, F. Beaudette, A. Buchot Perraguin, P. Busson, A. Cappati, C. Charlot, F. Damas, O. Davignon, A. De Wit, G. Falmagne, B.A. Fontana Santos Alves, S. Ghosh, A. Gilbert, R. Granier de Cassagnac, A. Hakimi, B. Harikrishnan, L. Kalipoliti, G. Liu, J. Motta, M. Nguyen, C. Ochando, L. Portales, R. Salerno, U. Sarkar, J.B. Sauvan, Y. Sirois, A. Tarabini, E. Vernazza, A. Zabi, A. Zghiche

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France
J.-L. Agram[22], J. Andrea, D. Apparu, D. Bloch, J.-M. Brom, E.C. Chabert, C. Collard, S. Falke, U. Goerlach, C. Grimault, R. Haeberle, A.-C. Le Bihan, M. Meena, G. Saha, M.A. Sessini, P. Van Hove

Institut de Physique des 2 Infinis de Lyon (IP2I), Villeurbanne, France
S. Beauceron, B. Blancon, G. Boudoul, N. Chanon, J. Choi, D. Contardo, P. Depasse, C. Dozen[23], H. El Mamouni, J. Fay, S. Gascon, M. Gouzevitch, C. Greenberg, G. Grenier, B. Ille, I.B. Laktineh, M. Lethuillier, L. Mirabito, S. Perries, A. Purohit, M. Vander Donckt, P. Verdier, J. Xiao

Georgian Technical University, Tbilisi, Georgia
I. Lomidze, T. Toriashvili[24], Z. Tsamalaidze[17]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany
V. Botta, L. Feld, K. Klein, M. Lipinski, D. Meuser, A. Pauls, N. Röwert, M. Teroerde

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
S. Diekmann, A. Dodonova, N. Eich, D. Eliseev, F. Engelke, M. Erdmann, P. Fackeldey, B. Fischer, T. Hebbeker, K. Hoepfner, F. Ivone, A. Jung, M.y. Lee, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, S. Mukherjee, D. Noll, A. Novak, F. Nowotny, A. Pozdnyakov, Y. Rath, W. Redjeb, F. Rehm, H. Reithler, V. Sarkisovi, A. Schmidt, A. Sharma, J.L. Spah, A. Stein, F. Torres Da Silva De Araujo[25], L. Vigilante, S. Wiedenbeck, S. Zaleski

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany
C. Dziwok, G. Flügge, W. Haj Ahmad[26], T. Kress, A. Nowack, O. Pooth, A. Stahl, T. Ziemons, A. Zotz

Deutsches Elektronen-Synchrotron, Hamburg, Germany
H. Aarup Petersen, M. Aldaya Martin, J. Alimena, S. Amoroso, Y. An, S. Baxter, M. Bayatmakou, H. Becerril Gonzalez, O. Behnke, A. Belvedere, S. Bhattacharya, F. Blekman[27], K. Borras[28], D. Brunner, A. Campbell, A. Cardini, C. Cheng, F. Colombina, S. Consuegra Rodríguez, G. Correia Silva, M. De Silva, G. Eckerlin, D. Eckstein, L.I. Estevez Banos, O. Filatov, E. Gallo[27], A. Geiser, A. Giraldi, G. Greau, V. Guglielmi, M. Guthoff, A. Hinzmann, A. Jafari[29], L. Jeppe, N.Z. Jomhari, B. Kaech, M. Kasemann, H. Kaveh, C. Kleinwort, R. Kogler, M. Komm, D. Krücker, W. Lange, D. Leyva Pernia, K. Lipka[30], W. Lohmann[31], R. Mankel, I.-A. Melzer-Pellmann, M. Mendizabal Morentin, J. Metwally, A.B. Meyer, G. Milella, A. Mussgiller, L.P. Nair, A. Nürnberg, Y. Otarid, J. Park, D. Pérez Adán, E. Ranken, A. Raspereza, B. Ribeiro Lopes, J. Rübenach, A. Saggio, M. Scham[32,28], S. Schnake[28], P. Schütze, C. Schwanenberger[27], D. Selivanova, M. Shchedrolosiev, R.E. Sosa Ricardo, D. Stafford, F. Vazzoler, A. Ventura Barroso, R. Walsh, Q. Wang, Y. Wen, K. Wichmann, L. Wiens[28], C. Wissing, Y. Yang, A. Zimermmane Castro Santos

University of Hamburg, Hamburg, Germany
A. Albrecht, S. Albrecht, M. Antonello, S. Bein, L. Benato, M. Bonanomi, P. Connor, M. Eich, K. El Morabit, Y. Fischer, A. Fröhlich, C. Garbers, E. Garutti, A. Grohsjean, M. Hajheidari, J. Haller, H.R. Jabusch, G. Kasieczka, P. Keicher, R. Klanner, W. Korcari, T. Kramer, V. Kutzner, F. Labe, J. Lange, A. Lobanov, C. Matthies, A. Mehta, 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, M. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany
S. Brommer, M. Burkart, E. Butz, T. Chwalek, A. Dierlamm, A. Droll, N. Faltermann, M. Giffels, A. Gottmann, F. Hartmann[33], R. Hofsaess, M. Horzela, U. Husemann, J. Kieseler, M. Klute, R. Koppenhöfer, J.M. Lawhorn, M. Link, A. Lintuluoto, S. Maier, S. Mitra, M. Mormile, Th. Müller, M. Neukum, M. Oh, M. Presilla, G. Quast, K. Rabbertz, B. Regnery, N. Shadskiy, I. Shvetsov, H.J. Simonis, N. Trevisani, R. Ulrich, J. van der Linden, R.F. Von Cube, M. Wassmer, S. Wieland, F. Wittig, R. Wolf, S. Wunsch, X. Zuo

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece
G. Anagnostou, P. Assiouras, G. Daskalakis, A. Kyriakis, A. Papadopoulos[33], A. Stakia

National and Kapodistrian University of Athens, Athens, Greece
P. Kontaxakis, G. Melachroinos, A. Panagiotou, I. Papavergou, I. Paraskevas, N. Saoulidou, K. Theofilatos, E. Tziaferi, K. Vellidis, I. Zisopoulos

National Technical University of Athens, Athens, Greece
G. Bakas, T. Chatzistavrou, G. Karapostoli, K. Kousouris, I. Papakrivopoulos, E. Siamarkou, G. Tsipolitis, A. Zacharopoulou

University of Ioánnina, Ioánnina, Greece
K. Adamidis, I. Bestintzanos, I. Evangelou, C. Foudas, P. Gianneios, C. Kamtsikis, P. Katsoulis, P. Kokkas, P.G. Kosmoglou Kioseoglou, N. Manthos, I. Papadopoulos, J. Strologas

HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
M. Bartók[34], C. Hajdu, D. Horvath[35,36], F. Sikler, V. Veszpremi

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary
M. Csanád, K. Farkas, M.M.A. Gadallah[37], Á. Kadlecsik, P. Major, K. Mandal, G. Pásztor, A.J. Rádl[38], G.I. Veres

Faculty of Informatics, University of Debrecen, Debrecen, Hungary
P. Raics, B. Ujvari[39], G. Zilizi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary
G. Bencze, S. Czellar, J. Karancsi[34], J. Molnar, Z. Szillasi

Karoly Robert Campus, MATE Institute of Technology, Gyongyos, Hungary
T. Csorgo[38], F. Nemes[38], T. Novak

Panjab University, Chandigarh, India
J. Babbar, S. Bansal, S.B. Beri, V. Bhatnagar, G. Chaudhary, S. Chauhan, N. Dhingra[40], A. Kaur, A. Kaur, H. Kaur, M. Kaur, S. Kumar, K. Sandeep, T. Sheokand, J.B. Singh, A. Singla

University of Delhi, Delhi, India
A. Ahmed, A. Bhardwaj, A. Chhetri, B.C. Choudhary, A. Kumar, M. Naimuddin, K. Ranjan, S. Saumya

Saha Institute of Nuclear Physics, HBNI, Kolkata, India
S. Acharya[41], S. Baradia, S. Barman[42], S. Bhattacharya, D. Bhowmik, S. Dutta, S. Dutta, P. Palit, B. Sahu[41], S. Sarkar

Indian Institute of Technology Madras, Madras, India
M.M. Ameen, P.K. Behera, S.C. Behera, S. Chatterjee, P. Jana, P. Kalbhor, J.R. Komaragiri[43], D. Kumar[43], L. Panwar[43], R. Pradhan, P.R. Pujahari, N.R. Saha, A. Sharma, A.K. Sikdar, S. Verma

Tata Institute of Fundamental Research-A, Mumbai, India
T. Aziz, I. Das, S. Dugad, M. Kumar, G.B. Mohanty, P. Suryadevara

Tata Institute of Fundamental Research-B, Mumbai, India

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

National Institute of Science Education and Research, An OCC of Homi Bhabha National Institute, Bhubaneswar, Odisha, India
S. Bahinipati[44], A.K. Das, C. Kar, D. Maity[45], P. Mal, T. Mishra, V.K. Muraleedharan Nair Bindhu[45], K. Naskar[45], A. Nayak[45], P. Sadangi, P. Saha, S.K. Swain, S. Varghese[45], D. Vats[45]

Indian Institute of Science Education and Research (IISER), Pune, India
A. Alpana, S. Dube, B. Gomber[41], B. Kansal, A. Laha, S. Sharma

Isfahan University of Technology, Isfahan, Iran
H. Bakhshiansohi[46], E. Khazaie[47], M. Zeinali[48]

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran
S. Chenarani[49], S.M. Etesami, M. Khakzad, M. Mohammadi Najafabadi

University College Dublin, Dublin, Ireland
M. Grunewald

INFN Sezione di Bari[a], Università di Bari[b], Politecnico di Bari[c], Bari, Italy
M. Abbrescia[a,b], R. Aly[a,c,50], A. Colaleo[a,b], D. Creanza[a,c], B. D'Anzi[a,b], N. De Filippis[a,c], M. De Palma[a,b], A. Di Florio[a,c], W. Elmetenawee[a,b,50], L. Fiore[a], G. Iaselli[a,c], M. Louka[a,b], G. Maggi[a,c], M. Maggi[a], I. Margjeka[a,b], 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], G. Ramirez-Sanchez[a,c], D. Ramos[a], A. Ranieri[a], L. Silvestris[a], F.M. Simone[a,b], Ü. Sözbilir[a], A. Stamerra[a], R. Venditti[a], P. Verwilligen[a], A. Zaza[a,b]

INFN Sezione di Bologna[a], Università di Bologna[b], Bologna, Italy
G. Abbiendi[a], C. Battilana[a,b], D. Bonacorsi[a,b], L. Borgonovi[a], R. Campanini[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,b], P. Giacomelli[a], L. Giommi[a,b], C. Grandi[a], L. Guiducci[a,b], S. Lo Meo[a,51], L. Lunerti[a,b], G. Masetti[a], F.L. Navarria[a,b], A. Perrotta[a], F. Primavera[a,b], A.M. Rossi[a,b], T. Rovelli[a,b], G.P. Siroli[a,b]

INFN Sezione di Catania[a], Università di Catania[b], Catania, Italy
S. Costa[a,b,52], A. Di Mattia[a], R. Potenza[a,b], A. Tricomi[a,b,52], C. Tuve[a,b]

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

INFN Laboratori Nazionali di Frascati, Frascati, Italy
L. Benussi, S. Bianco, S. Meola[53], D. Piccolo

INFN Sezione di Genova[a], Università di Genova[b], Genova, Italy
P. Chatagnon[a], F. Ferro[a], E. Robutti[a], S. Tosi[a,b]

INFN Sezione di Milano-Bicocca[a], Università di Milano-Bicocca[b], Milano, Italy
A. Benaglia[a], G. Boldrini[a,b], F. Brivio[a], F. Cetorelli[a], 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], D. Pedrini[a], B.S. Pinolini[a], S. Ragazzi[a,b], T. Tabarelli de Fatis[a,b], D. Zuolo[a]

INFN Sezione di Napoli[a], Università di Napoli 'Federico II'[b], Napoli, Italy; Università della Basilicata[c], Potenza, Italy; Scuola Superiore Meridionale (SSM)[d], Napoli, Italy
S. Buontempo[a], A. Cagnotta[a,b], F. Carnevali[a,b], N. Cavallo[a,c], A. De Iorio[a,b], F. Fabozzi[a,c], A.O.M. Iorio[a,b], L. Lista[a,b,54], P. Paolucci[a,33], B. Rossi[a], C. Sciacca[a,b]

INFN Sezione di Padova[a], Università di Padova[b], Padova, Italy; Università di Trento[c], Trento, Italy
R. Ardino[a], P. Azzi[a], N. Bacchetta[a,55], M. Benettoni[a], D. Bisello[a,b], P. Bortignon[a], A. Bragagnolo[a,b], R. Carlin[a,b], T. Dorigo[a], F. Gasparini[a,b], U. Gasparini[a,b], G. Grosso[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], G. Strong[a], M. Tosi[a,b], A. Triossi[a,b], S. Ventura[a], H. Yarar[a,b], M. Zanetti[a,b], P. Zotto[a,b], A. Zucchetta[a,b], G. Zumerle[a,b]

INFN Sezione di Pavia[a], Università di Pavia[b], Pavia, Italy
S. Abu Zeid[a,56], C. Aimè[a,b], A. Braghieri[a], S. Calzaferri[a,b], D. Fiorina[a,b], P. Montagna[a,b], V. Re[a], C. Riccardi[a,b], P. Salvini[a], I. Vai[a,b], P. Vitulo[a,b]

INFN Sezione di Perugia[a], Università di Perugia[b], Perugia, Italy
S. Ajmal[a,b], P. Asenov[a,57], G.M. Bilei[a], D. Ciangottini[a,b], L. Fanò[a,b], M. Magherini[a,b], G. Mantovani[a,b], V. Mariani[a,b], M. Menichelli[a], F. Moscatelli[a,57], A. Rossi[a,b], A. Santocchia[a,b], D. Spiga[a], T. Tedeschi[a,b]

INFN Sezione di Pisa[a], Università di Pisa[b], Scuola Normale Superiore di Pisa[c], Pisa, Italy; Università di Siena[d], Siena, Italy
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], D. Matos Figueiredo[a], A. Messineo[a,b], M. Musich[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], A. Venturi[a], P.G. Verdini[a]

INFN Sezione di Roma[a], Sapienza Università di Roma[b], Roma, Italy
P. Barria[a], M. Campana[a,b], F. Cavallari[a], L. Cunqueiro Mendez[a,b], D. Del Re[a,b], E. Di Marco[a], M. Diemoz[a], F. Errico[a,b], E. Longo[a,b], P. Meridiani[a], 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]

INFN Sezione di Torino[a], Università di Torino[b], Torino, Italy; Università del Piemonte Orientale[c], Novara, 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], 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], S. Maselli[a], A. Mecca[a,b], 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], D. Soldi[a,b], A. Staiano[a], C. Tarricone[a,b], D. Trocino[a], G. Umoret[a,b], E. Vlasov[a,b]

INFN Sezione di Trieste[a], Università di Trieste[b], Trieste, Italy
S. Belforte[a], V. Candelise[a,b], M. Casarsa[a], F. Cossutti[a], K. De Leo[a,b], G. Della Ricca[a,b]

Kyungpook National University, Daegu, Korea
S. Dogra, J. Hong, C. Huh, B. Kim, D.H. Kim, J. Kim, H. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, M.S. Ryu, S. Sekmen, Y.C. Yang

Department of Mathematics and Physics - GWNU, Gangneung, Korea
M.S. Kim

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea
G. Bak, P. Gwak, H. Kim, D.H. Moon

Hanyang University, Seoul, Korea
E. Asilar, D. Kim, T.J. Kim, J.A. Merlin

Korea University, Seoul, Korea
S. Choi, S. Han, B. Hong, K. Lee, K.S. Lee, S. Lee, J. Park, S.K. Park, J. Yoo

Kyung Hee University, Department of Physics, Seoul, Korea
J. Goh, S. Yang

Sejong University, Seoul, Korea
H. S. Kim, Y. Kim, S. Lee

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

University of Seoul, 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

Yonsei University, Department of Physics, Seoul, Korea
S. Ha, H.D. Yoo

Sungkyunkwan University, Suwon, Korea
M. Choi, M.R. Kim, H. Lee, Y. Lee, I. Yu

College of Engineering and Technology, American University of the Middle East (AUM), Dasman, Kuwait
T. Beyrouthy, Y. Maghrbi

Riga Technical University, Riga, Latvia
K. Dreimanis, A. Gaile, G. Pikurs, A. Potrebko, M. Seidel, V. Veckalns[58]

University of Latvia (LU), Riga, Latvia
N.R. Strautnieks

Vilnius University, Vilnius, Lithuania
M. Ambrozas, A. Juodagalvis, A. Rinkevicius, G. Tamulaitis

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia
N. Bin Norjoharuddeen, I. Yusuff[59], Z. Zolkapli

Universidad de Sonora (UNISON), Hermosillo, Mexico

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

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico
G. Ayala, H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-De La Cruz[60], R. Lopez-Fernandez, C.A. Mondragon Herrera, A. Sánchez Hernández

Universidad Iberoamericana, Mexico City, Mexico
C. Oropeza Barrera, M. Ramírez García

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico
I. Bautista, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

University of Montenegro, Podgorica, Montenegro
I. Bubanja, N. Raicevic

University of Canterbury, Christchurch, New Zealand
P.H. Butler

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
A. Ahmad, M.I. Asghar, A. Awais, M.I.M. Awan, H.R. Hoorani, W.A. Khan

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland
V. Avati, L. Grzanka, M. Malawski

National Centre for Nuclear Research, Swierk, Poland
H. Bialkowska, M. Bluj, B. Boimska, M. Górski, M. Kazana, M. Szleper, P. Zalewski

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
K. Bunkowski, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, A. Muhammad

Warsaw University of Technology, Warsaw, Poland
K. Pozniak, W. Zabolotny

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
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, T. Niknejad, A. Petrilli, M. Pisano, J. Seixas, J. Varela, J.W. Wulff

Faculty of Physics, University of Belgrade, Belgrade, Serbia
P. Adzic, P. Milenovic

VINCA Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
M. Dordevic, J. Milosevic, V. Rekovic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
M. Aguilar-Benitez, J. Alcaraz Maestre, Cristina F. Bedoya, 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. León Holgado, D. Moran, C. M. Morcillo Perez, Á. Navarro Tobar, C. Perez Dengra, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, D.D. Redondo Ferrero, L. Romero, S. Sánchez Navas,

L. Urda Gómez, J. Vazquez Escobar, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain
J.F. de Trocóniz

Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
B. Alvarez Gonzalez, J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, C. Ramón Álvarez, V. Rodríguez Bouza, A. Soto Rodríguez, A. Trapote, C. Vico Villalba, P. Vischia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
S. Bhowmik, S. Blanco Fernández, J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, J. Duarte Campderros, M. Fernandez, C. Fernandez Madrazo, G. Gomez, C. Lasaosa García, 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

University of Colombo, Colombo, Sri Lanka
M.K. Jayananda, B. Kailasapathy[61], D.U.J. Sonnadara, D.D.C. Wickramarathna

University of Ruhuna, Department of Physics, Matara, Sri Lanka
W.G.D. Dharmaratna, K. Liyanage, N. Perera, N. Wickramage

CERN, European Organization for Nuclear Research, Geneva, Switzerland
D. Abbaneo, C. Amendola, E. Auffray, G. Auzinger, J. Baechler, D. Barney, A. Bermúdez Martínez, M. Bianco, B. Bilin, A.A. Bin Anuar, A. Bocci, E. Brondolin, C. Caillol, G. Cerminara, N. Chernyavskaya, D. d'Enterria, A. Dabrowski, A. David, A. De Roeck, M.M. Defranchis, M. Deile, M. Dobson, F. Fallavollita[62], L. Forthomme, G. Franzoni, W. Funk, S. Giani, D. Gigi, K. Gill, F. Glege, L. Gouskos, M. Haranko, J. Hegeman, B. Huber, V. Innocente, T. James, P. Janot, S. Laurila, P. Lecoq, E. Leutgeb, C. Lourenço, B. Maier, L. Malgeri, M. Mannelli, A.C. Marini, M. Matthewman, F. Meijers, S. Mersi, E. Meschi, V. Milosevic, F. Moortgat, M. Mulders, S. Orfanelli, F. Pantaleo, G. Petrucciani, A. Pfeiffer, M. Pierini, D. Piparo, H. Qu, D. Rabady, G. Reales Gutiérrez, M. Rovere, H. Sakulin, S. Scarfi, C. Schwick, M. Selvaggi, A. Sharma, K. Shchelina, P. Silva, P. Sphicas[63], A.G. Stahl Leiton, A. Steen, S. Summers, D. Treille, P. Tropea, A. Tsirou, D. Walter, J. Wanczyk[64], K.A. Wozniak[65], S. Wuchterl, P. Zehetner, P. Zejdl, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland
T. Bevilacqua[66], L. Caminada[66], A. Ebrahimi, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, C. Lange, M. Missiroli[66], L. Noehte[66], T. Rohe

ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
T.K. Aarrestad, K. Androsov[64], M. Backhaus, A. Calandri, C. Cazzaniga, K. Datta, A. De Cosa, G. Dissertori, M. Dittmar, M. Donegà, F. Eble, M. Galli, K. Gedia, F. Glessgen, C. Grab, D. Hits, W. Lustermann, A.-M. Lyon, R.A. Manzoni, M. Marchegiani, L. Marchese, C. Martin Perez, A. Mascellani[64], F. Nessi-Tedaldi, F. Pauss, V. Perovic, S. Pigazzini, M.G. Ratti, M. Reichmann, C. Reissel, T. Reitenspiess, B. Ristic, F. Riti, D. Ruini, D.A. Sanz Becerra, R. Seidita, J. Steggemann[64], D. Valsecchi, R. Wallny

Universität Zürich, Zurich, Switzerland
C. Amsler[67], P. Bärtschi, C. Botta, D. Brzhechko, M.F. Canelli, K. Cormier, R. Del Burgo, J.K. Heikkilä, M. Huwiler, W. Jin, A. Jofrehei, B. Kilminster, S. Leontsinis, S.P. Liechti, A. Macchiolo, P. Meiring, V.M. Mikuni, U. Molinatti, I. Neutelings, A. Reimers, P. Robmann, S. Sanchez Cruz, K. Schweiger, M. Senger, Y. Takahashi, R. Tramontano

National Central University, Chung-Li, Taiwan
C. Adloff[68], C.M. Kuo, W. Lin, P.K. Rout, P.C. Tiwari[43], S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan
L. Ceard, Y. Chao, K.F. Chen, P.s. Chen, Z.g. Chen, W.-S. Hou, T.h. Hsu, Y.w. Kao, R. Khurana, G. Kole, Y.y. Li, R.-S. Lu, E. Paganis, X.f. Su, J. Thomas-Wilsker, L.s. Tsai, H.y. Wu, E. Yazgan

High Energy Physics Research Unit, Department of Physics, Faculty of Science, Chulalongkorn University, Bangkok, Thailand
C. Asawatangtrakuldee, N. Srimanobhas, V. Wachirapusitanand

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
D. Agyel, F. Boran, Z.S. Demiroglu, F. Dolek, I. Dumanoglu[69], E. Eskut, Y. Guler[70], E. Gurpinar Guler[70], C. Isik, O. Kara, A. Kayis Topaksu, U. Kiminsu, G. Onengut, K. Ozdemir[71], A. Polatoz, B. Tali[72], U.G. Tok, S. Turkcapar, E. Uslan, I.S. Zorbakir

Middle East Technical University, Physics Department, Ankara, Turkey
M. Yalvac[73]

Bogazici University, Istanbul, Turkey
B. Akgun, I.O. Atakisi, E. Gülmez, M. Kaya[74], O. Kaya[75], S. Tekten[76]

Istanbul Technical University, Istanbul, Turkey
A. Cakir, K. Cankocak[69,77], Y. Komurcu, S. Sen[78]

Istanbul University, Istanbul, Turkey
O. Aydilek, S. Cerci[72], V. Epshteyn, B. Hacisahinoglu, I. Hos[79], B. Kaynak, S. Ozkorucuklu, O. Potok, H. Sert, C. Simsek, D. Sunar Cerci[72], C. Zorbilmez

Yildiz Technical University, Istanbul, Turkey
B. Isildak[80]

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkiv, Ukraine
A. Boyaryntsev, B. Grynyov

National Science Centre, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
L. Levchuk

University of Bristol, Bristol, United Kingdom
D. Anthony, J.J. Brooke, A. Bundock, F. Bury, E. Clement, D. Cussans, H. Flacher, M. Glowacki, J. Goldstein, H.F. Heath, L. Kreczko, B. Krikler, S. Paramesvaran, S. Seif El Nasr-Storey, V.J. Smith, N. Stylianou[81], K. Walkingshaw Pass, R. White

Rutherford Appleton Laboratory, Didcot, United Kingdom
A.H. Ball, K.W. Bell, A. Belyaev[82], C. Brew, R.M. Brown, D.J.A. Cockerill,

C. Cooke, K.V. Ellis, K. Harder, S. Harper, M.-L. Holmberg[83], J. Linacre, K. Manolopoulos, D.M. Newbold, E. Olaiya, D. Petyt, T. Reis, G. Salvi, T. Schuh, C.H. Shepherd-Themistocleous, I.R. Tomalin, T. Williams

Imperial College, London, United Kingdom
R. Bainbridge, P. Bloch, C.E. Brown, O. Buchmuller, V. Cacchio, C.A. Carrillo Montoya, G.S. Chahal[84], D. Colling, J.S. Dancu, P. Dauncey, G. Davies, J. Davies, M. Della Negra, S. Fayer, G. Fedi, G. Hall, M.H. Hassanshahi, A. Howard, G. Iles, M. Knight, J. Langford, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, M. Mieskolainen, J. Nash[85], M. Pesaresi, B.C. Radburn-Smith, A. Richards, A. Rose, C. Seez, R. Shukla, A. Tapper, K. Uchida, G.P. Uttley, L.H. Vage, T. Virdee[33], M. Vojinovic, N. Wardle, D. Winterbottom

Brunel University, Uxbridge, United Kingdom
K. Coldham, J.E. Cole, A. Khan, P. Kyberd, I.D. Reid

Baylor University, Waco, Texas, USA
S. Abdullin, A. Brinkerhoff, B. Caraway, J. Dittmann, K. Hatakeyama, J. Hiltbrand, A.R. Kanuganti, B. McMaster, M. Saunders, S. Sawant, C. Sutantawibul, M. Toms[86], J. Wilson

Catholic University of America, Washington, DC, USA
R. Bartek, A. Dominguez, C. Huerta Escamilla, A.E. Simsek, R. Uniyal, A.M. Vargas Hernandez

The University of Alabama, Tuscaloosa, Alabama, USA
R. Chudasama, S.I. Cooper, S.V. Gleyzer, C.U. Perez, P. Rumerio[87], E. Usai, R. Yi

Boston University, Boston, Massachusetts, USA
A. Akpinar, A. Albert, D. Arcaro, C. Cosby, Z. Demiragli, C. Erice, E. Fontanesi, D. Gastler, S. Jeon, J. Rohlf, K. Salyer, D. Sperka, D. Spitzbart, I. Suarez, A. Tsatsos, S. Yuan

Brown University, Providence, Rhode Island, USA
G. Benelli, X. Coubez[28], D. Cutts, M. Hadley, U. Heintz, J.M. Hogan[88], T. Kwon, G. Landsberg, K.T. Lau, D. Li, J. Luo, S. Mondal, M. Narain[†], N. Pervan, S. Sagir[89], F. Simpson, M. Stamenkovic, W.Y. Wong, X. Yan, W. Zhang

University of California, Davis, Davis, California, USA
S. Abbott, J. Bonilla, C. Brainerd, R. Breedon, 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, D. Pellett, W. Wei, Y. Yao, F. Zhang

University of California, Los Angeles, California, USA
M. Bachtis, R. Cousins, A. Datta, G. Flores Avila, J. Hauser, M. Ignatenko, M.A. Iqbal, T. Lam, E. Manca, A. Nunez Del Prado, D. Saltzberg, V. Valuev

University of California, Riverside, Riverside, California, USA
R. Clare, J.W. Gary, M. Gordon, G. Hanson, W. Si, S. Wimpenny[†]

University of California, San Diego, La Jolla, California, USA
J.G. Branson, S. Cittolin, S. Cooperstein, D. Diaz, J. Duarte, L. Giannini, J. Guiang, R. Kansal, V. Krutelyov, R. Lee, J. Letts, M. Masciovecchio, F. Mokhtar, M. Pieri, M. Quinnan, B.V. Sathia Narayanan, V. Sharma, M. Tadel,

E. Vourliotis, F. Würthwein, Y. Xiang, A. Yagil

University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
A. Barzdukas, L. Brennan, C. Campagnari, G. Collura, A. Dorsett, J. Incandela, M. Kilpatrick, J. Kim, A.J. Li, P. Masterson, H. Mei, M. Oshiro, J. Richman, U. Sarica, R. Schmitz, F. Setti, J. Sheplock, D. Stuart, S. Wang

California Institute of Technology, Pasadena, California, USA
A. Bornheim, O. Cerri, A. Latorre, J. Mao, H.B. Newman, M. Spiropulu, J.R. Vlimant, C. Wang, S. Xie, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
J. Alison, S. An, M.B. Andrews, P. Bryant, V. Dutta, T. Ferguson, A. Harilal, C. Liu, T. Mudholkar, S. Murthy, M. Paulini, A. Roberts, A. Sanchez, W. Terrill

University of Colorado Boulder, Boulder, Colorado, USA
J.P. Cumalat, W.T. Ford, A. Hassani, G. Karathanasis, E. MacDonald, N. Manganelli, F. Marini, A. Perloff, C. Savard, N. Schonbeck, K. Stenson, K.A. Ulmer, S.R. Wagner, N. Zipper

Cornell University, Ithaca, New York, USA
J. Alexander, S. Bright-Thonney, X. Chen, D.J. Cranshaw, J. Fan, X. Fan, D. Gadkari, S. Hogan, J. Monroy, J.R. Patterson, J. Reichert, M. Reid, A. Ryd, J. Thom, P. Wittich, R. Zou

Fermi National Accelerator Laboratory, Batavia, Illinois, 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, J. Dickinson, 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, R. Heller, T.C. Herwig, J. Hirschauer, L. Horyn, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, T. Klijnsma, B. Klima, K.H.M. Kwok, S. Lammel, 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, V. Papadimitriou, N. Pastika, K. Pedro, C. Pena[90], F. Ravera, A. Reinsvold Hall[91], L. Ristori, 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

University of Florida, Gainesville, Florida, USA
C. Aruta, P. Avery, D. Bourilkov, L. Cadamuro, P. Chang, V. Cherepanov, R.D. Field, E. Koenig, M. Kolosova, J. Konigsberg, A. Korytov, K.H. Lo, K. Matchev, N. Menendez, G. Mitselmakher, K. Mohrman, A. Muthirakalayil Madhu, N. Rawal, D. Rosenzweig, S. Rosenzweig, K. Shi, J. Wang

Florida State University, Tallahassee, Florida, USA
T. Adams, A. Al Kadhim, A. Askew, N. Bower, R. Habibullah, V. Hagopian, R. Hashmi, R.S. Kim, S. Kim, T. Kolberg, G. Martinez, H. Prosper, P.R. Prova, O. Viazlo, M. Wulansatiti, R. Yohay, J. Zhang

Florida Institute of Technology, Melbourne, Florida, USA
B. Alsufyani, M.M. Baarmand, S. Butalla, T. Elkafrawy[56], M. Hohlmann,

R. Kumar Verma, M. Rahmani

University of Illinois Chicago, Chicago, USA, Chicago, USA
M.R. Adams, C. Bennett, R. Cavanaugh, S. Dittmer, R. Escobar Franco, O. Evdokimov, C.E. Gerber, D.J. Hofman, J.h. Lee, D. S. Lemos, A.H. Merrit, C. Mills, S. Nanda, G. Oh, B. Ozek, D. Pilipovic, T. Roy, S. Rudrabhatla, M.B. Tonjes, N. Varelas, X. Wang, Z. Ye, J. Yoo

The University of Iowa, Iowa City, Iowa, USA
M. Alhusseini, D. Blend, K. Dilsiz[92], L. Emediato, G. Karaman, O.K. Köseyan, J.-P. Merlo, A. Mestvirishvili[93], J. Nachtman, O. Neogi, H. Ogul[94], Y. Onel, A. Penzo, C. Snyder, E. Tiras[95]

Johns Hopkins University, Baltimore, Maryland, USA
B. Blumenfeld, L. Corcodilos, J. Davis, A.V. Gritsan, L. Kang, S. Kyriacou, P. Maksimovic, M. Roguljic, J. Roskes, S. Sekhar, M. Swartz, T.Á. Vámi

The University of Kansas, Lawrence, Kansas, USA
A. Abreu, L.F. Alcerro Alcerro, J. Anguiano, P. Baringer, A. Bean, Z. Flowers, D. Grove, J. King, G. Krintiras, M. Lazarovits, C. Le Mahieu, C. Lindsey, J. Marquez, N. Minafra, M. Murray, M. Nickel, M. Pitt, S. Popescu[96], C. Rogan, C. Royon, R. Salvatico, S. Sanders, C. Smith, Q. Wang, G. Wilson

Kansas State University, Manhattan, Kansas, USA
B. Allmond, A. Ivanov, K. Kaadze, A. Kalogeropoulos, D. Kim, Y. Maravin, K. Nam, J. Natoli, D. Roy, G. Sorrentino

Lawrence Livermore National Laboratory, Livermore, California, USA
F. Rebassoo, D. Wright

University of Maryland, College Park, Maryland, USA
A. Baden, A. Belloni, A. Bethani, Y.M. Chen, S.C. Eno, N.J. Hadley, S. Jabeen, R.G. Kellogg, T. Koeth, Y. Lai, S. Lascio, A.C. Mignerey, S. Nabili, C. Palmer, C. Papageorgakis, M.M. Paranjpe, L. Wang

Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
J. Bendavid, W. Busza, I.A. Cali, Y. Chen, M. D'Alfonso, J. Eysermans, C. Freer, G. Gomez-Ceballos, M. Goncharov, P. Harris, D. Hoang, D. Kovalskyi, J. Krupa, L. Lavezzo, Y.-J. Lee, K. Long, C. Mironov, C. Paus, D. Rankin, C. Roland, G. Roland, S. Rothman, Z. Shi, G.S.F. Stephans, J. Wang, Z. Wang, B. Wyslouch, T. J. Yang

University of Minnesota, Minneapolis, Minnesota, USA
B. Crossman, B.M. Joshi, C. Kapsiak, M. Krohn, D. Mahon, J. Mans, B. Marzocchi, S. Pandey, M. Revering, R. Rusack, R. Saradhy, N. Schroeder, N. Strobbe, M.A. Wadud

University of Mississippi, Oxford, Mississippi, USA
L.M. Cremaldi

University of Nebraska-Lincoln, Lincoln, Nebraska, USA
K. Bloom, M. Bryson, D.R. Claes, C. Fangmeier, F. Golf, G. Haza, J. Hossain, C. Joo, I. Kravchenko, I. Reed, J.E. Siado, W. Tabb, A. Vagnerini, A. Wightman, F. Yan, D. Yu, A.G. Zecchinelli

State University of New York at Buffalo, Buffalo, New York, USA
G. Agarwal, H. Bandyopadhyay, L. Hay, I. Iashvili, A. Kharchilava, M. Morris, D. Nguyen, S. Rappoccio, H. Rejeb Sfar, A. Williams

Northeastern University, Boston, Massachusetts, USA
E. Barberis, J. Dervan, Y. Haddad, Y. Han, A. Krishna, J. Li, M. Lu, G. Madigan, R. Mccarthy, D.M. Morse, V. Nguyen, T. Orimoto, A. Parker, L. Skinnari, A. Tishelman-Charny, B. Wang, D. Wood

Northwestern University, Evanston, Illinois, USA
S. Bhattacharya, J. Bueghly, Z. Chen, K.A. Hahn, Y. Liu, Y. Miao, D.G. Monk, M.H. Schmitt, A. Taliercio, M. Velasco

University of Notre Dame, Notre Dame, Indiana, USA
R. Band, R. Bucci, S. Castells, M. Cremonesi, A. Das, R. Goldouzian, M. Hildreth, K.W. Ho, 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[17], H. Nelson, M. Osherson, A. Piccinelli, R. Ruchti, A. Townsend, Y. Wan, M. Wayne, H. Yockey, M. Zarucki, L. Zygala

The Ohio State University, Columbus, Ohio, USA
A. Basnet, B. Bylsma, M. Carrigan, L.S. Durkin, C. Hill, M. Joyce, A. Lesauvage, M. Nunez Ornelas, K. Wei, B.L. Winer, B. R. Yates

Princeton University, Princeton, New Jersey, USA
F.M. Addesa, H. Bouchamaoui, P. Das, G. Dezoort, P. Elmer, A. Frankenthal, B. Greenberg, N. Haubrich, S. Higginbotham, G. Kopp, S. Kwan, D. Lange, A. Loeliger, D. Marlow, I. Ojalvo, J. Olsen, A. Shevelev, D. Stickland, C. Tully

University of Puerto Rico, Mayaguez, Puerto Rico, USA
S. Malik

Purdue University, West Lafayette, Indiana, USA
A.S. Bakshi, V.E. Barnes, S. Chandra, R. Chawla, S. Das, A. Gu, L. Gutay, M. Jones, A.W. Jung, D. Kondratyev, 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, W. Xie

Purdue University Northwest, Hammond, Indiana, USA
J. Dolen, N. Parashar, A. Pathak

Rice University, Houston, Texas, USA
D. Acosta, A. Baty, T. Carnahan, K.M. Ecklund, P.J. Fernández Manteca, S. Freed, P. Gardner, F.J.M. Geurts, A. Kumar, W. Li, O. Miguel Colin, B.P. Padley, R. Redjimi, J. Rotter, E. Yigitbasi, Y. Zhang

University of Rochester, Rochester, New York, USA
A. Bodek, P. de Barbaro, R. Demina, J.L. Dulemba, C. Fallon, A. Garcia-Bellido, O. Hindrichs, A. Khukhunaishvili, P. Parygin[86], E. Popova[86], R. Taus, G.P. Van Onsem

The Rockefeller University, New York, New York, USA
K. Goulianos

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

B. Chiarito, J.P. Chou, Y. Gershtein, E. Halkiadakis, A. Hart, M. Heindl, D. Jaroslawski, O. Karacheban[31], I. Laflotte, A. Lath, R. Montalvo, K. Nash, H. Routray, S. Salur, S. Schnetzer, S. Somalwar, R. Stone, S.A. Thayil, S. Thomas, J. Vora, H. Wang

University of Tennessee, Knoxville, Tennessee, USA
H. Acharya, D. Ally, A.G. Delannoy, S. Fiorendi, T. Holmes, N. Karunarathna, L. Lee, E. Nibigira, S. Spanier

Texas A&M University, College Station, Texas, USA
D. Aebi, M. Ahmad, O. Bouhali[97], M. Dalchenko, R. Eusebi, J. Gilmore, T. Huang, T. Kamon[98], H. Kim, S. Luo, S. Malhotra, R. Mueller, D. Overton, D. Rathjens, A. Safonov

Texas Tech University, Lubbock, Texas, USA
N. Akchurin, J. Damgov, V. Hegde, A. Hussain, Y. Kazhykarim, K. Lamichhane, S.W. Lee, A. Mankel, T. Peltola, I. Volobouev, A. Whitbeck

Vanderbilt University, Nashville, Tennessee, USA
E. Appelt, S. Greene, A. Gurrola, W. Johns, R. Kunnawalkam Elayavalli, A. Melo, F. Romeo, P. Sheldon, S. Tuo, J. Velkovska, J. Viinikainen

University of Virginia, Charlottesville, Virginia, USA
B. Cardwell, B. Cox, J. Hakala, R. Hirosky, A. Ledovskoy, C. Neu, C.E. Perez Lara

Wayne State University, Detroit, Michigan, USA
P.E. Karchin

University of Wisconsin - Madison, Madison, Wisconsin, USA
A. Aravind, S. Banerjee, K. Black, T. Bose, S. Dasu, I. De Bruyn, 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, D. Pinna, A. Savin, V. Shang, V. Sharma, W.H. Smith, D. Teague, H.F. Tsoi, W. Vetens, A. Warden

Authors affiliated with an institute or an international laboratory covered by a cooperation agreement with CERN
S. Afanasiev, D. Budkouski, I. Golutvin, I. Gorbunov, V. Karjavine, V. Korenkov, A. Lanev, A. Malakhov, V. Matveev[99], V. Palichik, V. Perelygin, M. Savina, V. Shalaev, S. Shmatov, S. Shulha, V. Smirnov, O. Teryaev, N. Voytishin, B.S. Yuldashev[100], A. Zarubin, I. Zhizhin, G. Gavrilov, V. Golovtcov, Y. Ivanov, V. Kim[99], P. Levchenko[101], V. Murzin, V. Oreshkin, D. Sosnov, V. Sulimov, L. Uvarov, A. Vorobyev[†], Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, I. Tlisova, A. Toropin, T. Aushev, V. Gavrilov, N. Lychkovskaya, A. Nikitenko[102,103], V. Popov, A. Zhokin, R. Chistov[99], M. Danilov[99], S. Polikarpov[99], V. Andreev, M. Azarkin, M. Kirakosyan, A. Terkulov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, L. Khein, O. Kodolova[103], V. Korotkikh, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan, V. Blinov[99], T. Dimova[99], L. Kardapoltsev[99], A. Kozyrev[99], O. Radchenko[99], Y. Skovpen[99], V. Kachanov, D. Konstantinov, S. Slabospitskii, A. Uzunian, A. Babaev, V. Borshch, D. Druzhkin[104], E. Tcherniaev

Authors affiliated with an institute formerly covered by a cooperation agreement with CERN
V. Chekhovsky, V. Makarenko

†: Deceased
[1]Also at Yerevan State University, Yerevan, Armenia
[2]Also at TU Wien, Vienna, Austria
[3]Also at Institute of Basic and Applied Sciences, Faculty of Engineering, Arab Academy for Science, Technology and Maritime Transport, Alexandria, Egypt
[4]Also at Ghent University, Ghent, Belgium
[5]Also at Universidade Estadual de Campinas, Campinas, Brazil
[6]Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil
[7]Also at UFMS, Nova Andradina, Brazil
[8]Also at Nanjing Normal University, Nanjing, China
[9]Now at The University of Iowa, Iowa City, Iowa, USA
[10]Also at University of Chinese Academy of Sciences, Beijing, China
[11]Also at China Center of Advanced Science and Technology, Beijing, China
[12]Also at University of Chinese Academy of Sciences, Beijing, China
[13]Also at China Spallation Neutron Source, Guangdong, China
[14]Now at Henan Normal University, Xinxiang, China
[15]Also at Université Libre de Bruxelles, Bruxelles, Belgium
[16]Also at University of Latvia (LU), Riga, Latvia
[17]Also at an institute or an international laboratory covered by a cooperation agreement with CERN
[18]Now at British University in Egypt, Cairo, Egypt
[19]Now at Cairo University, Cairo, Egypt
[20]Also at Birla Institute of Technology, Mesra, Mesra, India
[21]Also at Purdue University, West Lafayette, Indiana, USA
[22]Also at Université de Haute Alsace, Mulhouse, France
[23]Also at Istinye University, Istanbul, Turkey
[24]Also at Tbilisi State University, Tbilisi, Georgia
[25]Also at The University of the State of Amazonas, Manaus, Brazil
[26]Also at Erzincan Binali Yildirim University, Erzincan, Turkey
[27]Also at University of Hamburg, Hamburg, Germany
[28]Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany
[29]Also at Isfahan University of Technology, Isfahan, Iran
[30]Also at Bergische University Wuppertal (BUW), Wuppertal, Germany
[31]Also at Brandenburg University of Technology, Cottbus, Germany
[32]Also at Forschungszentrum Jülich, Juelich, Germany
[33]Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland
[34]Also at Institute of Physics, University of Debrecen, Debrecen, Hungary
[35]Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary
[36]Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania
[37]Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt
[38]Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary
[39]Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary
[40]Also at Punjab Agricultural University, Ludhiana, India
[41]Also at University of Hyderabad, Hyderabad, India
[42]Also at University of Visva-Bharati, Santiniketan, India
[43]Also at Indian Institute of Science (IISc), Bangalore, India
[44]Also at IIT Bhubaneswar, Bhubaneswar, India

[45]Also at Institute of Physics, Bhubaneswar, India
[46]Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany
[47]Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran
[48]Also at Sharif University of Technology, Tehran, Iran
[49]Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran
[50]Also at Helwan University, Cairo, Egypt
[51]Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy
[52]Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy
[53]Also at Università degli Studi Guglielmo Marconi, Roma, Italy
[54]Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy
[55]Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[56]Also at Ain Shams University, Cairo, Egypt
[57]Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy
[58]Also at Riga Technical University, Riga, Latvia
[59]Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia
[60]Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico
[61]Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka
[62]Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy
[63]Also at National and Kapodistrian University of Athens, Athens, Greece
[64]Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland
[65]Also at University of Vienna, Vienna, Austria
[66]Also at Universität Zürich, Zurich, Switzerland
[67]Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria
[68]Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France
[69]Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey
[70]Also at Konya Technical University, Konya, Turkey
[71]Also at Izmir Bakircay University, Izmir, Turkey
[72]Also at Adiyaman University, Adiyaman, Turkey
[73]Also at Bozok Universitetesi Rektörlügü, Yozgat, Turkey
[74]Also at Marmara University, Istanbul, Turkey
[75]Also at Milli Savunma University, Istanbul, Turkey
[76]Also at Kafkas University, Kars, Turkey
[77]Now at Istanbul Okan University, Istanbul, Turkey
[78]Also at Hacettepe University, Ankara, Turkey
[79]Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey
[80]Also at Yildiz Technical University, Istanbul, Turkey
[81]Also at Vrije Universiteit Brussel, Brussel, Belgium
[82]Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
[83]Also at University of Bristol, Bristol, United Kingdom
[84]Also at IPPP Durham University, Durham, United Kingdom
[85]Also at Monash University, Faculty of Science, Clayton, Australia
[86]Now at another institute or international laboratory covered by a cooperation agreement with CERN

[87]Also at Università di Torino, Torino, Italy
[88]Also at Bethel University, St. Paul, Minnesota, USA
[89]Also at Karamanoğlu Mehmetbey University, Karaman, Turkey
[90]Also at California Institute of Technology, Pasadena, California, USA
[91]Also at United States Naval Academy, Annapolis, Maryland, USA
[92]Also at Bingol University, Bingol, Turkey
[93]Also at Georgian Technical University, Tbilisi, Georgia
[94]Also at Sinop University, Sinop, Turkey
[95]Also at Erciyes University, Kayseri, Turkey
[96]Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania
[97]Also at Texas A&M University at Qatar, Doha, Qatar
[98]Also at Kyungpook National University, Daegu, Korea
[99]Also at another institute or international laboratory covered by a cooperation agreement with CERN
[100]Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan
[101]Also at Northeastern University, Boston, Massachusetts, USA
[102]Also at Imperial College, London, United Kingdom
[103]Now at Yerevan Physics Institute, Yerevan, Armenia
[104]Also at Universiteit Antwerpen, Antwerpen, Belgium