



Letter

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

The CMS Collaboration^{*}

CERN, Geneva, Switzerland

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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 $\Lambda_c^+ \rightarrow K_S^0 p$, while the D^0 meson is reconstructed via $D^0 \rightarrow K^- \pi^+$. 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 $\Lambda/\bar{\Lambda}$ 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.

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 [1–4] and the BNL RHIC [5–8]. The observed azimuthal anisotropies of the particles emitted [9–14], 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 [15–17]. Similar observations of a common collective signature for charm mesons [18–20] and bottom mesons [21–23] 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) [24–27] and proton-lead (pPb) [28–38] collisions. The elliptic flow for prompt D^0 [19,39] and J/ψ [40,41] 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 [39,42]. Although effects of final-state partonic rescatterings in a dense medium can successfully explain a large variety of measure-

ments for light quarks (see reviews in Refs. [43,44]), they alone cannot describe the large flow for charm quarks [45]. Meanwhile, calculations based on initial-state effects, such as gluon saturation models, can successfully describe experimental measurements for several charm and bottom mesons [46].

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 [47,48]. 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) [49,50]. 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 [51–53]. 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 [54],

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

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 [55,56] are in agreement with measurements of Λ_c^+ baryon yields [57–59] 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 [60,61].

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 $\sqrt{s_{NN}} = 8.16$ TeV, for the first time in different multiplicity intervals. Tabulated results are provided in the HEPData record for this analysis [62].

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 [63], 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. [64].

The silicon tracker measures charged particles within the range $|\eta_{lab}| < 2.5$ 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 pixels and 15 148 silicon strip detector modules. For particles of $1 < p_T < 10$ GeV and $|\eta_{lab}| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [65].

The event samples are collected by the CMS experiment with a two-level trigger system [66,67]. 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 $\sqrt{s_{NN}} = 8.16$ TeV and correspond to an integrated luminosity of $186.0 \pm 6.5 \text{ nb}^{-1}$ [68]. 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 $|y_{lab}| < 1$, which is used for particle selections, corresponds to the rapidity range $-1.46 < y_{cm} < 0.54$ 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. [27,69,70]. 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 $p_T > 0.4$ 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 [65]. 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 $|\eta| < 2.4$, $p_T > 0.4$ 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

Table 1

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

Multiplicity interval ($N_{\text{trk}}^{\text{offline}}$)	$\langle N_{\text{trk}}^{\text{offline}} \rangle$	$\langle N_{\text{trk}}^{\text{corrected}} \rangle$
[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

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 $4.22 (97.8) \text{ nb}^{-1}$.

3. Data analysis

Similar to previous measurements [28,31,34,35], 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 according to the number of selected offline tracks ($N_{\text{trk}}^{\text{offline}}$) with $|\eta_{lab}| < 2.4$ and $p_T > 0.4$ GeV that originate from the PV [27,65]. 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. During the data taking, the average number of collisions per bunch crossing (pileup) varied from 0.10 to 0.25. The average number of tracks in each $N_{\text{trk}}^{\text{offline}}$ range before and after correcting for inefficiencies and misidentification rates in the tracking system is denoted as $\langle N_{\text{trk}}^{\text{offline}} \rangle$ and $\langle N_{\text{trk}}^{\text{corrected}} \rangle$, respectively. The statistical uncertainty in $\langle N_{\text{trk}}^{\text{corrected}} \rangle$ 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 $\langle N_{\text{trk}}^{\text{offline}} \rangle$ and $\langle N_{\text{trk}}^{\text{corrected}} \rangle$ values in each $N_{\text{trk}}^{\text{offline}}$ range are summarized in Table 1; for minimum bias pPb events, these values are 50 and 59.5 ± 0.5 , respectively. To optimize the signal significance and efficiency, a sample of simulated signal events is generated using hard processes in PYTHIA 8.209 [71], using the CUETP8M1 tune [72]. These signal events are embedded into pPb events generated with the EPOS LHC model [73]. The response of the CMS detector for generated events is simulated using the GEANT4 [74] toolkit. The decay kinematics for Λ_c^+ and D^0 particles are simulated using EVTGEN [75].

The Λ_c^+ baryons are reconstructed using the decay channel $\Lambda_c^+ \rightarrow K_S^0 p$ with the branching fraction of $(1.59 \pm 0.07)\%$ [76], where K_S^0 mesons are reconstructed via the $K_S^0 \rightarrow \pi^+ \pi^-$ decays with the branching fraction of $(69.20 \pm 0.05)\%$ [76]. Throughout this Letter, charge-conjugate modes are implied unless explicitly noted otherwise. The decay vertex for each K_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 K_S^0 signal yield significance (over the non-signal hypothesis) of these signals, following the same procedures as Ref. [19]. The invariant mass of each K_S^0 candidate ($M_{\pi^+ \pi^-}$) is required to be within $|M_{\pi^+ \pi^-} - M_{K_S^0}| < 0.02$ GeV, where $M_{K_S^0}$ is the K_S^0 meson mass [76]. The secondary decay vertices of the Λ_c^+ baryon are reconstructed by combining a K_S^0 candidate with another charged track in the event. For the Λ_c^+ reconstruction, each K_S^0 candidate is treated as a particle with its kinematic parameters and covariance matrix taken from the K_S^0 vertex fit. In this step, the K_S^0 mass is fixed to the nominal PDG value [76], rather than using the reconstructed $\pi^+ \pi^-$ invariant mass. This improves the mass resolution of the Λ_c^+ candidate. The Λ_c^+ candi-

dates (including signals and backgrounds) with invariant mass falling within $|M_{K_S^0 p} - M_{\Lambda_c^+}| < 0.2$ GeV, are considered in this analysis, where $M_{\Lambda_c^+}$ is the mass of the Λ_c^+ baryon [76]. A multilayer perceptron (MLP) is trained with the Toolkit for Multivariate Data Analysis (TMVA) package [77] 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. [78].

Events populating the sideband region, defined as $0.06 < |M_{K_S^0 p} - M_{\Lambda_c^+}| < 0.11$ 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 $D^0 \rightarrow K^- \pi^+$ with the branching fraction of $(3.947 \pm 0.030)\%$ [76]. 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. [39].

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. Fig. 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 [79] to describe the processes $D^0 \rightarrow \pi^+ \pi^-$ and $D^0 \rightarrow K^+ K^-$; and a third-order polynomial to model the combinatorial background. Examples of fits to the D^0 invariant mass are shown in Ref. [39].

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

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

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, 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. [57]. 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., $\Lambda_b^0 \rightarrow \Lambda_c^+ X$ and $B \rightarrow \Lambda_c^+ X$. 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 calcula-

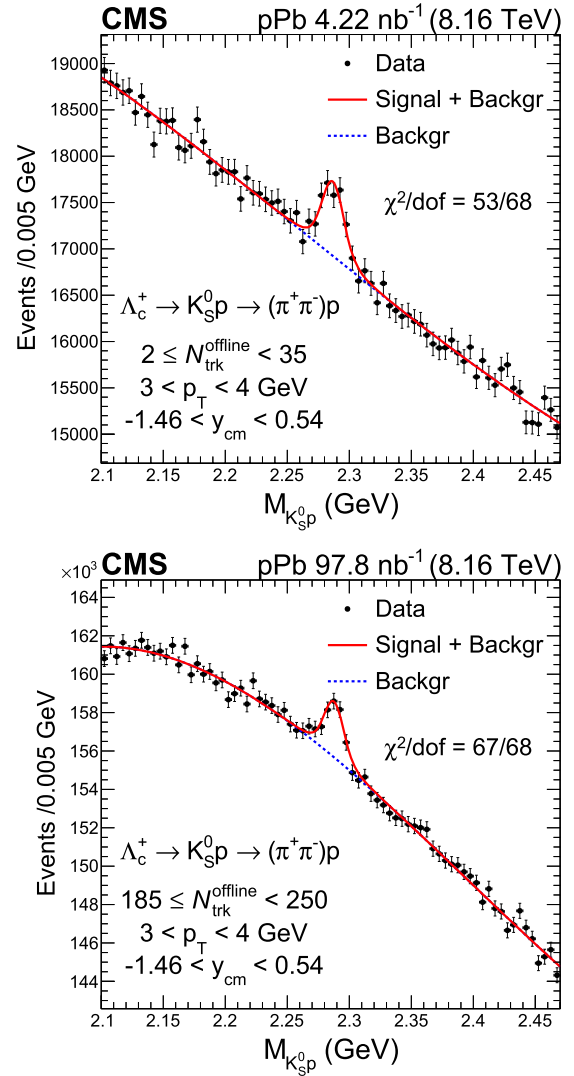


Fig. 1. The fitted mass spectra, along with the goodness-of-fit values, for Λ_c^+ candidates with $3 < p_T < 4$ GeV and $-1.46 < y_{\text{cm}} < 0.54$. The spectrum for the multiplicity class with $2 \leq N_{\text{trk}}^{\text{offline}} < 35$ is shown in the upper plot, and the spectrum for $185 \leq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

tion [80] and rescaled according to the fragmentation fractions measured by the LHCb Collaboration [81]. 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 $B(\Lambda_b^0 \rightarrow \Lambda_c^+ X)$ value is set to 83%, as in the EVTGEN package, and it includes the contributions from unobserved decay channels [82]. The corresponding branching fractions for the B mesons are set to 5% by summing over all channels reported in Ref. [76]. 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 ($1 - f^{\text{prompt}}$), which has little dependence on p_T and $N_{\text{trk}}^{\text{offline}}$ within uncertainties, is given in Table 2.

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 tem-

Table 2

Summary table for the fraction of nonprompt Λ_c^+ baryons ($1 - f^{\text{prompt}}$) 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	$6.8^{+11}_{-5.8}$	—
3–4	$4.1^{+4.1}_{-3.5}$	$4.3^{+6.0}_{-4.3}$
4–5	$3.3^{+3.5}_{-2.9}$	$3.4^{+3.7}_{-3.0}$
5–6	$3.6^{+3.9}_{-2.9}$	$3.6^{+3.0}_{-2.9}$
6–8	$3.5^{+3.8}_{-3.5}$	$3.1^{+3.4}_{-3.1}$
8–10	$3.9^{+3.3}_{-3.9}$	$4.3^{+6.1}_{-4.3}$

plates 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. [39].

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 $N_{\text{trk}}^{\text{offline}}$ 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 [80]. 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 $\pm 25\%$ [83]. The uncertainty from the LHCb fragmentation fraction measurements is also considered [81]. 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 [84], 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 efficiency 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. 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 $N_{\text{trk}}^{\text{offline}}$) 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,

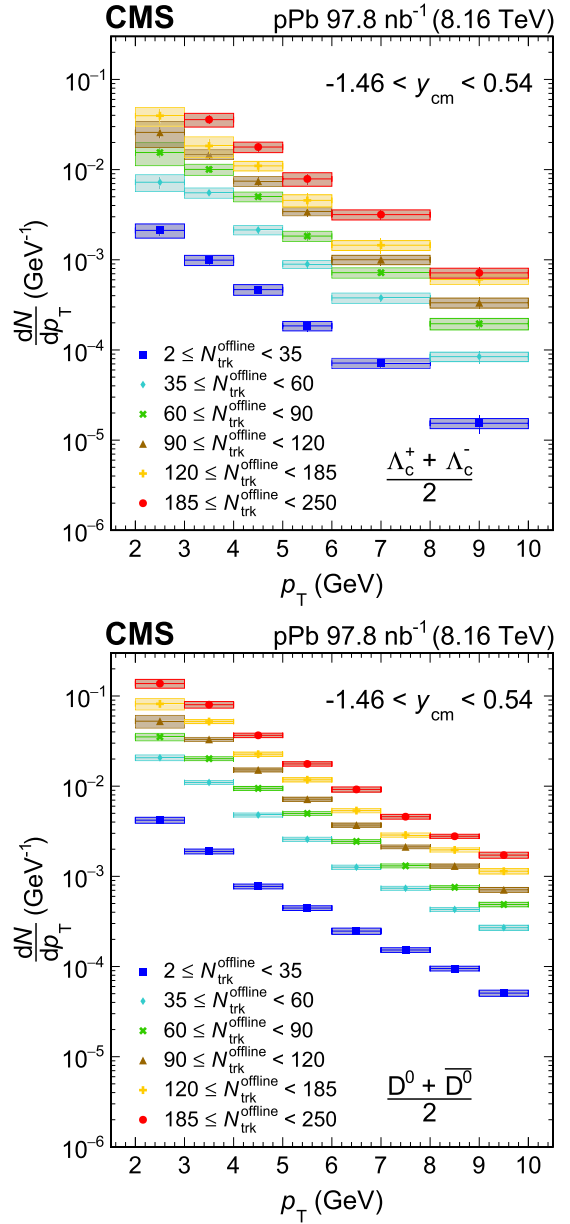


Fig. 2. Transverse momentum spectra for Λ_c^+ baryons (upper) and D^0 mesons (lower) with $-1.46 < y_{\text{cm}} < 0.54$ in different multiplicity classes. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties.

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.

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 for three multiplicity classes. 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 $\sqrt{s_{\text{NN}}} = 5.02$ TeV

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

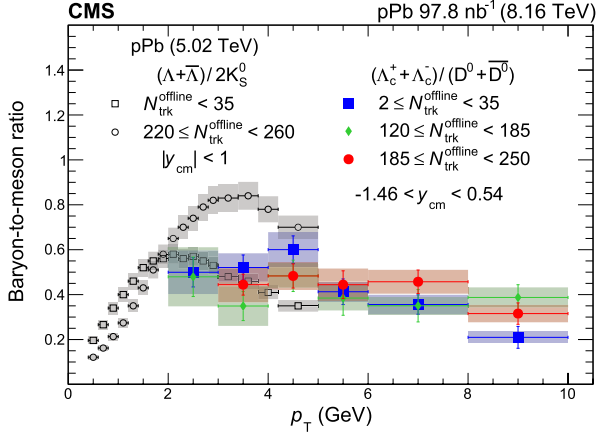


Fig. 3. Ratio of Λ_c^+ baryons to D^0 mesons production in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with $2 \leq N_{trk}^{offline} < 35$, $120 \leq N_{trk}^{offline} < 185$ and $185 \leq N_{trk}^{offline} < 250$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The gray markers are for Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV from Ref. [54].

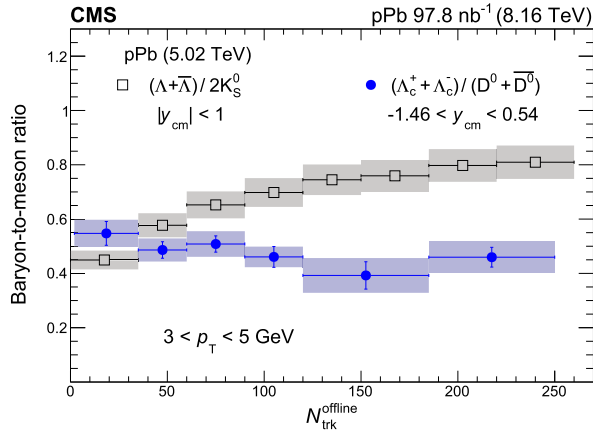


Fig. 4. Ratio of Λ_c^+ baryon to D^0 meson production with $-1.46 < y_{cm} < 0.54$ in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV as a function of $N_{trk}^{offline}$. The vertical bars show the statistical uncertainties while the shaded areas represent the systematic uncertainties. The ratio of Λ baryon to (two times) K_S^0 meson production at $\sqrt{s_{NN}} = 5.02$ TeV obtained from data in Ref. [54] is also shown for comparisons, denoted by gray markers.

reported in Refs. [57,59]. 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 [54].

To further investigate the system size dependence, the charm baryon-to-meson ratio is also plotted as a function of $N_{trk}^{offline}$ 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 hadroniza-

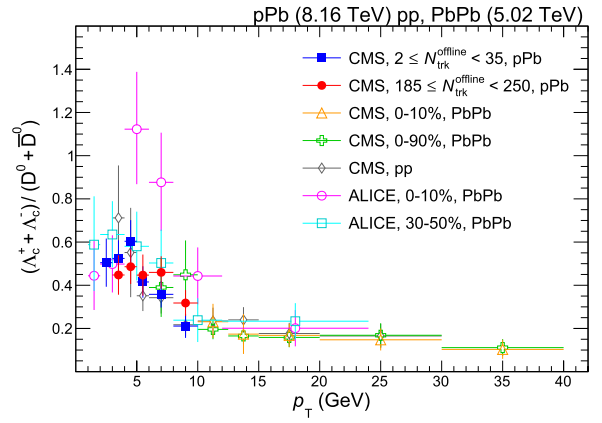


Fig. 5. Comparison between the Λ_c^+ -to- D^0 ratio as a function of p_T in pp, pPb, and PbPb (different centrality ranges) collisions at the nucleon-nucleon center-of-mass energies of 5.02, 8.16, and 5.02 TeV, respectively [53,87]. The ratio is measured with the rapidity ranges $-1.46 < y_{cm} < 0.54$ in pPb collisions and $|y_{cm}| < 1$ in pp and PbPb collisions by the CMS Collaboration [87] and $|y_{cm}| < 0.5$ by the ALICE Collaboration [53]. The vertical bars indicate the uncertainties. For pPb, the uncertainty is the quadratic sum of statistical and systematic uncertainties; for pp and PbPb, the uncertainties are as reported in Ref. [53] and [87], respectively.

tion 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 [19,41]. In models of QGP formation, charm quarks are expected to experience kinetic propagation inside the liquid QGP [50,85], 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 [46,86].

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 [53,87] 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 $\Lambda_c^+ \rightarrow K_S^0 p$, while the D^0 meson is reconstructed from $D^0 \rightarrow K^- \pi^+$. 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 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.

Declaration of competing interest

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Data availability

Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the [CMS data preservation, re-use and open access policy](#).

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The CMS collaboration

A. Hayrapetyan, A. Tumasyan ¹

Yerevan Physics Institute, Yerevan, Armenia

W. Adam ¹, J.W. Andrejkovic, T. Bergauer ¹, S. Chatterjee ¹, K. Damanakis ¹, M. Dragicevic ¹, P.S. Hussain ¹, M. Jeitler ^{1,2}, N. Krammer ¹, A. Li ¹, D. Liko ¹, I. Mikulec ¹, J. Schieck ^{1,2}, R. Schöfbeck ¹, D. Schwarz ¹, M. Sonawane ¹, S. Templ ¹, W. Waltenberger ¹, C.-E. Wulz ^{1,2}

Institut für Hochenergiephysik, Vienna, Austria

M.R. Darwish ^{1,3}, T. Janssen ¹, P. Van Mechelen ¹

Universiteit Antwerpen, Antwerpen, Belgium

E.S. Bols ¹, J. D'Hondt ¹, S. Dansana ¹, A. De Moor ¹, M. Delcourt ¹, H. El Faham ¹, S. Lowette ¹, I. Makarenko ¹, D. Müller ¹, A.R. Sahasransu ¹, S. Tavernier ¹, M. Tytgat ^{1,4}, S. Van Putte ¹, D. Vannerom ¹

Vrije Universiteit Brussel, Brussel, Belgium

B. Clerbaux ¹, G. De Lentdecker ¹, L. Favart ¹, D. Hohov ¹, J. Jaramillo ¹, A. Khalilzadeh, K. Lee ¹, M. Mahdavihorrani ¹, A. Malara ¹, S. Paredes ¹, L. Pétré ¹, N. Postiau, L. Thomas ¹, M. Vanden Bemden ¹, C. Vander Velde ¹, P. Vanlaer ¹

Université Libre de Bruxelles, Bruxelles, Belgium

M. De Coen ¹, D. Dobur ¹, Y. Hong ¹, J. Knolle ¹, L. Lambrecht ¹, G. Mestdach, C. Rendón ¹, A. Samalan, K. Skovpen ¹, N. Van Den Bossche ¹, L. Wezenbeek ¹

Ghent University, Ghent, Belgium

A. Benecke ¹, G. Bruno ¹, C. Caputo ¹, C. Delaere ¹, I.S. Donertas ¹, A. Giammanco ¹, K. Jaffel ¹, Sa. Jain ¹, V. Lemaître, J. Lidrych ¹, P. Mastrapasqua ¹, K. Mondal ¹, T.T. Tran ¹, S. Wertz ¹

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

G.A. Alves ¹, E. Coelho ¹, C. Hensel ¹, T. Menezes De Oliveira ¹, A. Moraes ¹, P. Rebello Teles ¹, M. Soeiro

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil

W.L. Aldá Júnior^{}, M. Alves Gallo Pereira^{}, M. Barroso Ferreira Filho^{}, H. Brandao Malbouisson^{},
W. Carvalho^{}, J. Chinellato^{}, E.M. Da Costa^{}, G.G. Da Silva^{}, D. De Jesus Damiao^{},
S. Fonseca De Souza^{}, J. Martins^{}, C. Mora Herrera^{}, K. Mota Amarilo^{}, L. Mundim^{}, H. Nogima^{},
A. Santoro^{}, A. Sznajder^{}, M. Thiel^{}, A. Vilela Pereira^{}

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

C.A. Bernardes^{}, L. Calligaris^{}, T.R. Fernandez Perez Tomei^{}, E.M. Gregores^{}, P.G. Mercadante^{},
S.F. Novaes^{}, B. Orzari^{}, Sandra S. Padula^{}

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

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

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

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

University of Sofia, Sofia, Bulgaria

S. Keshri^{}, S. Thakur^{}

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

T. Cheng^{}, Q. Guo, T. Javaid^{}, M. Mittal^{}, L. Yuan^{}

Beihang University, Beijing, China

Z. Hu^{}, J. Liu, K. Yi^{},^{},^{}

Department of Physics, Tsinghua University, Beijing, China

G.M. Chen^{},^{}, H.S. Chen^{},^{}, M. Chen^{},^{}, F. Iemmi^{}, C.H. Jiang, A. Kapoor^{},^{}, H. Liao^{}, Z.-A. Liu^{},^{},
F. Monti^{}, M.A. Shahzad^{}, R. Sharma^{},^{}, J.N. Song^{}, J. Tao^{}, C. Wang^{}, J. Wang^{}, Z. Wang^{},
H. Zhang^{}

Institute of High Energy Physics, 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^{}

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

Z. You^{}

Sun Yat-Sen University, Guangzhou, China

N. Lu^{}

University of Science and Technology of China, Hefei, China

G. Bauer^{}

Nanjing Normal University, Nanjing, China

X. Gao^{},^{}, D. Leggat, H. Okawa^{}, Y. Zhang^{}

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

Z. Lin^{}, C. Lu^{}, M. Xiao^{}

Zhejiang University, Hangzhou, Zhejiang, China

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

Universidad de Los Andes, Bogota, Colombia

J. Mejia Guisao^{}, F. Ramirez^{}, M. Rodriguez^{}, J.D. Ruiz Alvarez^{}

Universidad de Antioquia, Medellin, Colombia

D. Giljanovic^{ID}, N. Godinovic^{ID}, D. Lelas^{ID}, A. Sculac^{ID}

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

M. Kovac^{ID}, T. Sculac^{ID},¹⁶

University of Split, Faculty of Science, Split, Croatia

P. Bargassa^{ID}, V. Brigljevic^{ID}, B.K. Chitroda^{ID}, D. Ferencek^{ID}, S. Mishra^{ID}, A. Starodumov^{ID},¹⁷, T. Susa^{ID}

Institute Rudjer Boskovic, Zagreb, Croatia

A. Attikis^{ID}, K. Christoforou^{ID}, S. Konstantinou^{ID}, J. Mousa^{ID}, C. Nicolaou, F. Ptochos^{ID}, P.A. Razis^{ID},
H. Rykaczewski, H. Saka^{ID}, A. Stepennov^{ID}

University of Cyprus, Nicosia, Cyprus

M. Finger^{ID}, M. Finger Jr.^{ID}, A. Kveton^{ID}

Charles University, Prague, Czech Republic

E. Ayala^{ID}

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin^{ID}

Universidad San Francisco de Quito, Quito, Ecuador

S. Elgammal¹⁸, A. Ellithi Kamel¹⁹

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

M.A. Mahmoud^{ID}, Y. Mohammed^{ID}

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

R.K. Dewanjee^{ID},²⁰ K. Ehataht^{ID}, M. Kadastik, T. Lange^{ID}, S. Nandan^{ID}, C. Nielsen^{ID}, J. Pata^{ID}, M. Raidal^{ID},
L. Tani^{ID}, C. Veelken^{ID}

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

H. Kirschenmann^{ID}, K. Osterberg^{ID}, M. Voutilainen^{ID}

Department of Physics, University of Helsinki, Helsinki, Finland

S. Bharthuar^{ID}, E. Brücken^{ID}, F. Garcia^{ID}, J. Havukainen^{ID}, K.T.S. Kallonen^{ID}, R. Kinnunen, T. Lampén^{ID},
K. Lassila-Perini^{ID}, S. Lehti^{ID}, T. Lindén^{ID}, M. Lotti, L. Martikainen^{ID}, M. Myllymäki^{ID}, M.m. Rantanen^{ID},
H. Siikonen^{ID}, E. Tuominen^{ID}, J. Tuominiemi^{ID}

Helsinki Institute of Physics, Helsinki, Finland

P. Luukka^{ID}, H. Petrow^{ID}, T. Tuuva[†]

Lappeenranta-Lahti University of Technology, Lappeenranta, Finland

M. Besancon^{ID}, F. Couderc^{ID}, M. Dejardin^{ID}, D. Denegri, J.L. Faure, F. Ferri^{ID}, S. Ganjour^{ID}, P. Gras^{ID},
G. Hamel de Monchenault^{ID}, V. Lohezic^{ID}, J. Malcles^{ID}, J. Rander, A. Rosowsky^{ID}, M.Ö. Sahin^{ID},
A. Savoy-Navarro^{ID},²¹ P. Simkina^{ID}, M. Titov^{ID}, M. Tornago^{ID}

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

C. Baldenegro Barrera^{ID}, F. Beaudette^{ID}, A. Buchot Perraguin^{ID}, P. Busson^{ID}, A. Cappati^{ID}, C. Charlot^{ID},
F. Damas^{ID}, O. Davignon^{ID}, A. De Wit^{ID}, G. Falmagne^{ID}, B.A. Fontana Santos Alves^{ID}, S. Ghosh^{ID},
A. Gilbert^{ID}, R. Granier de Cassagnac^{ID}, A. Hakimi^{ID}, B. Harikrishnan^{ID}, L. Kalipoliti^{ID}, G. Liu^{ID}, J. Motta^{ID},

M. Nguyen^{1b}, C. Ochando^{1b}, L. Portales^{1b}, R. Salerno^{1b}, U. Sarkar^{1b}, J.B. Sauvan^{1b}, Y. Sirois^{1b},
A. Tarabini^{1b}, E. Vernazza^{1b}, A. Zabi^{1b}, A. Zghiche^{1b}

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

J.-L. Agram^{1b,22}, J. Andrea^{1b}, D. Apparu^{1b}, D. Bloch^{1b}, J.-M. Brom^{1b}, E.C. Chabert^{1b}, C. Collard^{1b},
S. Falke^{1b}, U. Goerlach^{1b}, C. Grimault, R. Haeberle^{1b}, A.-C. Le Bihan^{1b}, M. Meena^{1b}, G. Saha^{1b},
M.A. Sessini^{1b}, P. Van Hove^{1b}

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

S. Beauceron^{1b}, B. Blancon^{1b}, G. Boudoul^{1b}, N. Chanon^{1b}, J. Choi^{1b}, D. Contardo^{1b}, P. Depasse^{1b},
C. Dozen^{1b,23}, H. El Mamouni, J. Fay^{1b}, S. Gascon^{1b}, M. Gouzevitch^{1b}, C. Greenberg^{1b}, G. Grenier^{1b},
B. Ille^{1b}, I.B. Laktineh, M. Lethuillier^{1b}, L. Mirabito, S. Perries, A. Purohit^{1b}, M. Vander Donckt^{1b},
P. Verdier^{1b}, J. Xiao^{1b}

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

I. Lomidze^{1b}, T. Toriashvili^{1b,24}, Z. Tsamalaidze^{1b,25}

Georgian Technical University, Tbilisi, Georgia

V. Botta^{1b}, L. Feld^{1b}, K. Klein^{1b}, M. Lipinski^{1b}, D. Meuser^{1b}, A. Pauls^{1b}, N. Röwert^{1b}, M. Teroerde^{1b}

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

S. Diekmann^{1b}, A. Dodonova^{1b}, N. Eich^{1b}, D. Eliseev^{1b}, F. Engelke^{1b}, M. Erdmann^{1b}, P. Fackeldey^{1b},
B. Fischer^{1b}, T. Hebbeker^{1b}, K. Hoepfner^{1b}, F. Ivone^{1b}, A. Jung^{1b}, M.y. Lee^{1b}, L. Mastrolorenzo,
M. Merschmeyer^{1b}, A. Meyer^{1b}, S. Mukherjee^{1b}, D. Noll^{1b}, A. Novak^{1b}, F. Nowotny, A. Pozdnyakov^{1b},
Y. Rath, W. Redjeb^{1b}, F. Rehm, H. Reithler^{1b}, V. Sarkisovi^{1b}, A. Schmidt^{1b}, A. Sharma^{1b}, J.L. Spah^{1b},
A. Stein^{1b}, F. Torres Da Silva De Araujo^{1b,26}, L. Vigilante, S. Wiedenbeck^{1b}, S. Zaleski

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

C. Dziwok^{1b}, G. Flügge^{1b}, W. Haj Ahmad²⁷, T. Kress^{1b}, A. Nowack^{1b}, O. Pooth^{1b}, A. Stahl^{1b}, T. Ziemons^{1b},
A. Zotz^{1b}

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

H. Aarup Petersen^{1b}, M. Aldaya Martin^{1b}, J. Alimena^{1b}, S. Amoroso, Y. An^{1b}, S. Baxter^{1b}, M. Bayatmakou^{1b},
H. Becerril Gonzalez^{1b}, O. Behnke^{1b}, A. Belvedere^{1b}, S. Bhattacharya^{1b}, F. Blekman^{1b,28}, K. Borras^{1b,29},
D. Brunner^{1b}, A. Campbell^{1b}, A. Cardini^{1b}, C. Cheng^{1b}, F. Colombina^{1b}, S. Consuegra Rodríguez^{1b},
G. Correia Silva^{1b}, M. De Silva^{1b}, G. Eckerlin, D. Eckstein^{1b}, L.I. Estevez Banos^{1b}, O. Filatov^{1b}, E. Gallo^{1b,28},
A. Geiser^{1b}, A. Giraldi^{1b}, G. Greau, V. Guglielmi^{1b}, M. Guthoff^{1b}, A. Hinzmann^{1b}, A. Jafari^{1b,30}, L. Jeppe^{1b},
N.Z. Jomhari^{1b}, B. Kaech^{1b}, M. Kasemann^{1b}, H. Kaveh^{1b}, C. Kleinwort^{1b}, R. Kogler^{1b}, M. Komm^{1b},
D. Krücker^{1b}, W. Lange, D. Leyva Pernia^{1b}, K. Lipka^{1b,31}, W. Lohmann^{1b,32}, R. Mankel^{1b},
I.-A. Melzer-Pellmann^{1b}, M. Mendizabal Morentin^{1b}, J. Metwally, A.B. Meyer^{1b}, G. Milella^{1b}, A. Mussgiller^{1b},
L.P. Nair^{1b}, A. Nürnberg^{1b}, Y. Otari, J. Park^{1b}, D. Pérez Adán^{1b}, E. Ranken^{1b}, A. Raspereza^{1b},
B. Ribeiro Lopes^{1b}, J. Rübenach, A. Saggio^{1b}, M. Scham^{1b,33,29}, S. Schnake^{1b,29}, P. Schütze^{1b},
C. Schwanenberger^{1b,28}, D. Selivanova^{1b}, M. Shchedrolosiev^{1b}, R.E. Sosa Ricardo^{1b}, D. Stafford^{1b},
F. Vazzoler^{1b}, A. Ventura Barroso^{1b}, R. Walsh^{1b}, Q. Wang^{1b}, Y. Wen^{1b}, K. Wichmann, L. Wiens^{1b,29},
C. Wissing^{1b}, Y. Yang^{1b}, A. Zimmermann Castro Santos^{1b}

Deutsches Elektronen-Synchrotron, Hamburg, Germany

A. Albrecht^{1b}, S. Albrecht^{1b}, M. Antonello^{1b}, S. Bein^{1b}, L. Benato^{1b}, M. Bonanomi^{1b}, P. Connor^{1b}, M. Eich,
K. El Morabit^{1b}, Y. Fischer^{1b}, A. Fröhlich, C. Garbers^{1b}, E. Garutti^{1b}, A. Grohsjean^{1b}, M. Hajheidari,

J. Haller^{ID}, H.R. Jabusch^{ID}, G. Kasieczka^{ID}, P. Keicher^{ID}, R. Klanner^{ID}, W. Korcari^{ID}, T. Kramer^{ID},
 V. Kutzner^{ID}, F. Labe^{ID}, J. Lange^{ID}, A. Lobanov^{ID}, C. Matthies^{ID}, A. Mehta^{ID}, L. Moureaux^{ID}, M. Mrowietz,
 A. Nigamova^{ID}, Y. Nissan, A. Paasch^{ID}, K.J. Pena Rodriguez^{ID}, T. Quadfasel^{ID}, B. Raciti^{ID}, M. Rieger^{ID},
 D. Savoie^{ID}, J. Schindler^{ID}, P. Schleper^{ID}, M. Schröder^{ID}, J. Schwandt^{ID}, M. Sommerhalder^{ID}, H. Stadie^{ID},
 G. Steinbrück^{ID}, A. Tews, M. Wolf^{ID}

University of Hamburg, Hamburg, Germany

S. Brommer^{ID}, M. Burkart, E. Butz^{ID}, T. Chwalek^{ID}, A. Dierlamm^{ID}, A. Droll, N. Faltermann^{ID}, M. Giffels^{ID},
 A. Gottmann^{ID}, F. Hartmann^{ID,34}, R. Hofsaess^{ID}, M. Horzela^{ID}, U. Husemann^{ID}, J. Kieseler^{ID}, M. Klute^{ID},
 R. Koppenhöfer^{ID}, J.M. Lawhorn^{ID}, M. Link, A. Lintuluoto^{ID}, S. Maier^{ID}, S. Mitra^{ID}, M. Mormile^{ID},
 Th. Müller^{ID}, M. Neukum, M. Oh^{ID}, M. Presilla^{ID}, G. Quast^{ID}, K. Rabbertz^{ID}, B. Regnery^{ID}, N. Shadskiy^{ID},
 I. Shvetsov^{ID}, H.J. Simonis^{ID}, N. Trevisani^{ID}, R. Ulrich^{ID}, J. van der Linden^{ID}, R.F. Von Cube^{ID},
 M. Wassmer^{ID}, S. Wieland^{ID}, F. Wittig, R. Wolf^{ID}, S. Wunsch, X. Zuo^{ID}

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, P. Assiouras^{ID}, G. Daskalakis^{ID}, A. Kyriakis^{ID}, A. Papadopoulos³⁴, A. Stakia^{ID}

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

P. Kontaxakis^{ID}, G. Melachroinos, A. Panagiotou, I. Papavergou^{ID}, I. Paraskevas^{ID}, N. Saoulidou^{ID},
 K. Theofilatos^{ID}, E. Tziaferi^{ID}, K. Vellidis^{ID}, I. Zisopoulos^{ID}

National and Kapodistrian University of Athens, Athens, Greece

G. Bakas^{ID}, T. Chatzistavrou, G. Karapostoli^{ID}, K. Kousouris^{ID}, I. Papakrivopoulos^{ID}, E. Siamarkou,
 G. Tsiopolitis^{ID}, A. Zacharopoulou

National Technical University of Athens, Athens, Greece

K. Adamidis, I. Bestintzanos, I. Evangelou^{ID}, C. Foudas, P. Gianneios^{ID}, C. Kamtsikis, P. Katsoulis,
 P. Kokkas^{ID}, P.G. Kosmoglou Kioseoglou^{ID}, N. Manthos^{ID}, I. Papadopoulos^{ID}, J. Strologas^{ID}

University of Ioánnina, Ioánnina, Greece

M. Bartók^{ID,35}, C. Hajdu^{ID}, D. Horvath^{ID,36,37}, F. Sikler^{ID}, V. Veszpremi^{ID}

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

M. Csanád^{ID}, K. Farkas^{ID}, M.M.A. Gadallah^{ID,38}, Á. Kadlecik^{ID}, P. Major^{ID}, K. Mandal^{ID}, G. Pásztor^{ID},
 A.J. Rádl^{ID,39}, G.I. Veres^{ID}

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

P. Raics, B. Ujvari^{ID,40}, G. Zilizi^{ID}

Faculty of Informatics, University of Debrecen, Debrecen, Hungary

G. Bencze, S. Czellar, J. Karancsi^{ID,35}, J. Molnar, Z. Szillasi

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

T. Csorgo^{ID,39}, F. Nemes^{ID,39}, T. Novak^{ID}

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

J. Babbar^{ID}, S. Bansal^{ID}, S.B. Beri, V. Bhatnagar^{ID}, G. Chaudhary^{ID}, S. Chauhan^{ID}, N. Dhingra^{ID,41},
 A. Kaur^{ID}, A. Kaur^{ID}, H. Kaur^{ID}, M. Kaur^{ID}, S. Kumar^{ID}, K. Sandeep^{ID}, T. Sheokand, J.B. Singh^{ID}, A. Singla^{ID}

Panjab University, Chandigarh, India

A. Ahmed^{ID}, A. Bhardwaj^{ID}, A. Chhetri^{ID}, B.C. Choudhary^{ID}, A. Kumar^{ID}, M. Naimuddin^{ID}, K. Ranjan^{ID},
 S. Saumya^{ID}

University of Delhi, Delhi, India

S. Acharya^{ID,42}, S. Baradia^{ID}, S. Barman^{ID,43}, S. Bhattacharya^{ID}, D. Bhowmik, S. Dutta^{ID}, S. Dutta, P. Palit^{ID}, B. Sahu^{ID,42}, S. Sarkar

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

M.M. Ameen^{ID}, P.K. Behera^{ID}, S.C. Behera^{ID}, S. Chatterjee^{ID}, P. Jana^{ID}, P. Kalbhor^{ID}, J.R. Komaragiri^{ID,44}, D. Kumar^{ID,44}, L. Panwar^{ID,44}, R. Pradhan^{ID}, P.R. Pujahari^{ID}, N.R. Saha^{ID}, A. Sharma^{ID}, A.K. Sikdar^{ID}, S. Verma^{ID}

Indian Institute of Technology Madras, Madras, India

T. Aziz, I. Das^{ID}, S. Dugad, M. Kumar^{ID}, G.B. Mohanty^{ID}, P. Suryadevara

Tata Institute of Fundamental Research-A, Mumbai, India

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

Tata Institute of Fundamental Research-B, Mumbai, India

S. Bahinipati^{ID,45}, A.K. Das, C. Kar^{ID}, D. Maity^{ID,46}, P. Mal^{ID}, T. Mishra^{ID}, V.K. Muraleedharan Nair Bindhu^{ID,46}, K. Naskar^{ID,46}, A. Nayak^{ID,46}, P. Sadangi, P. Saha^{ID}, S.K. Swain^{ID}, S. Varghese^{ID,46}, D. Vats^{ID,46}

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

A. Alpana^{ID}, S. Dube^{ID}, B. Gomber^{ID,42}, B. Kansal^{ID}, A. Laha^{ID}, S. Sharma^{ID}

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

H. Bakhshiansohi^{ID,47}, E. Khazaie^{ID,48}, M. Zeinali^{ID,49}

Isfahan University of Technology, Isfahan, Iran

S. Chenarani^{ID,50}, S.M. Etesami^{ID}, M. Khakzad^{ID}, M. Mohammadi Najafabadi^{ID}

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

M. Grunewald^{ID}

University College Dublin, Dublin, Ireland

M. Abbrescia^{a,b,ID}, R. Aly^{a,c,ID,51}, A. Colaleo^{a,b,ID}, D. Creanza^{a,c,ID}, B. D'Anzi^{a,b,ID}, N. De Filippis^{a,c,ID}, M. De Palma^{a,b,ID}, A. Di Florio^{a,c,ID}, W. Elmetenawee^{a,b,ID,51}, L. Fiore^{a,ID}, G. Iaselli^{a,c,ID}, M. Louka^{a,b}, G. Maggi^{a,c,ID}, M. Maggi^{a,ID}, I. Margjeka^{a,b,ID}, V. Mastrapasqua^{a,b,ID}, S. My^{a,b,ID}, S. Nuzzo^{a,b,ID}, A. Pellecchia^{a,b,ID}, A. Pompili^{a,b,ID}, G. Pugliese^{a,c,ID}, R. Radogna^{a,ID}, G. Ramirez-Sanchez^{a,c,ID}, D. Ramos^{a,ID}, A. Ranieri^{a,ID}, L. Silvestris^{a,ID}, F.M. Simone^{a,b,ID}, Ü. Sözbilir^{a,ID}, A. Stamerra^{a,ID}, R. Venditti^{a,ID}, P. Verwilligen^{a,ID}, A. Zaza^{a,b,ID}

^a INFN Sezione di Bari, Bari, Italy

^b Università di Bari, Bari, Italy

^c Politecnico di Bari, Bari, Italy

G. Abbiendi^{a,ID}, C. Battilana^{a,b,ID}, D. Bonacorsi^{a,b,ID}, L. Borgonovi^{a,ID}, R. Campanini^{a,b,ID}, P. Capiluppi^{a,b,ID}, A. Castro^{a,b,ID}, F.R. Cavallo^{a,ID}, M. Cuffiani^{a,b,ID}, G.M. Dallavalle^{a,ID}, T. Diotallevi^{a,b,ID}, F. Fabbri^{a,ID}, A. Fanfani^{a,b,ID}, D. Fasanella^{a,b,ID}, P. Giacomelli^{a,ID}, L. Giommi^{a,b,ID}, C. Grandi^{a,ID}, L. Guiducci^{a,b,ID}, S. Lo Meo^{a,ID,52}, L. Lunerti^{a,b,ID}, G. Masetti^{a,ID}, F.L. Navarria^{a,b,ID}, A. Perrotta^{a,ID}, F. Primavera^{a,b,ID}, A.M. Rossi^{a,b,ID}, T. Rovelli^{a,b,ID}, G.P. Siroli^{a,b,ID}

^a INFN Sezione di Bologna, Bologna, Italy

^b Università di Bologna, Bologna, Italy

S. Costa ^{a,b, , 53}, A. Di Mattia ^{a, }, R. Potenza ^{a,b}, A. Tricomi ^{a,b, , 53}, C. Tuve ^{a,b, }

^a INFN Sezione di Catania, Catania, Italy

^b Università di Catania, Catania, 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, }

^a INFN Sezione di Firenze, Firenze, Italy

^b Università di Firenze, Firenze, Italy

L. Benussi ^{}, S. Bianco ^{}, S. Meola ^{, 54}, D. Piccolo ^{}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

P. Chatagnon ^{a, }, F. Ferro ^{a, }, E. Robutti ^{a, }, S. Tosi ^{a,b, }

^a INFN Sezione di Genova, Genova, Italy

^b Università di Genova, Genova, Italy

A. Benaglia ^{a, }, 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, }

^a INFN Sezione di Milano-Bicocca, Milano, Italy

^b Università di Milano-Bicocca, Milano, Italy

S. Buontempo ^{a, }, A. Cagnotta ^{a,b, }, F. Carnevali ^{a,b}, N. Cavallo ^{a,c, }, A. De Iorio ^{a,b, }, F. Fabozzi ^{a,c, },
A.O.M. Iorio ^{a,b, }, L. Lista ^{a,b, , 55}, P. Paolucci ^{a, , 34}, B. Rossi ^{a, }, C. Sciacca ^{a,b, }

^a INFN Sezione di Napoli, Napoli, Italy

^b Università di Napoli 'Federico II', Napoli, Italy

^c Università della Basilicata, Potenza, Italy

^d Scuola Superiore Meridionale (SSM), Napoli, Italy

R. Ardino ^{a, }, P. Azzi ^{a, }, N. Bacchetta ^{a, , 56}, 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, }

^a INFN Sezione di Padova, Padova, Italy

^b Università di Padova, Padova, Italy

^c Università di Trento, Trento, Italy

S. Abu Zeid ^{a, , 57}, 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, }

^a INFN Sezione di Pavia, Pavia, Italy

^b Università di Pavia, Pavia, Italy

S. Ajmal ^{a,b, }, P. Asenov ^{a, , 58}, 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, , 58}, A. Rossi ^{a,b, }, A. Santocchia ^{a,b, },
D. Spiga ^{a, }, T. Tedeschi ^{a,b, }

^a INFN Sezione di Perugia, Perugia, Italy

^b Università di Perugia, Perugia, Italy

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, ID}, A. Rizzi^{a,b, ID}, G. Rolandi^{a,c, ID}, S. Roy Chowdhury^{a, ID}, T. Sarkar^{a, ID}, A. Scribano^{a, ID},
P. Spagnolo^{a, ID}, R. Tenchini^{a, ID}, G. Tonelli^{a,b, ID}, N. Turini^{a,d, ID}, A. Venturi^{a, ID}, P.G. Verdini^{a, ID}

^a INFN Sezione di Pisa, Pisa, Italy

^b Università di Pisa, Pisa, Italy

^c Scuola Normale Superiore di Pisa, Pisa, Italy

^d Università di Siena, Siena, Italy

P. Barria^{a, ID}, M. Campana^{a,b, ID}, F. Cavallari^{a, ID}, L. Cunqueiro Mendez^{a,b, ID}, D. Del Re^{a,b, ID}, E. Di Marco^{a, ID},
M. Diemoz^{a, ID}, F. Errico^{a,b, ID}, E. Longo^{a,b, ID}, P. Meridiani^{a, ID}, J. Mijuskovic^{a,b, ID}, G. Organtini^{a,b, ID},
F. Pandolfi^{a, ID}, R. Paramatti^{a,b, ID}, C. Quaranta^{a,b, ID}, S. Rahatlou^{a,b, ID}, C. Rovelli^{a, ID}, F. Santanastasio^{a,b, ID},
L. Soffi^{a, ID}

^a INFN Sezione di Roma, Roma, Italy

^b Sapienza Università di Roma, Roma, Italy

N. Amapane^{a,b, ID}, R. Arcidiacono^{a,c, ID}, S. Argiro^{a,b, ID}, M. Arneodo^{a,c, ID}, N. Bartosik^{a, ID}, R. Bellan^{a,b, ID},
A. Bellora^{a,b, ID}, C. Biino^{a, ID}, N. Cartiglia^{a, ID}, M. Costa^{a,b, ID}, R. Covarelli^{a,b, ID}, N. Demaria^{a, ID}, L. Finco^{a, ID},
M. Grippo^{a,b, ID}, B. Kiani^{a,b, ID}, F. Legger^{a, ID}, F. Luongo^{a,b, ID}, C. Mariotti^{a, ID}, S. Maselli^{a, ID}, A. Mecca^{a,b, ID},
E. Migliore^{a,b, ID}, M. Monteno^{a, ID}, R. Mulargia^{a, ID}, M.M. Obertino^{a,b, ID}, G. Ortona^{a, ID}, L. Pacher^{a,b, ID},
N. Pastrone^{a, ID}, M. Pelliccioni^{a, ID}, M. Ruspa^{a,c, ID}, F. Siviero^{a,b, ID}, V. Sola^{a,b, ID}, A. Solano^{a,b, ID}, D. Soldi^{a,b, ID},
A. Staiano^{a, ID}, C. Tarricone^{a,b, ID}, D. Trocino^{a, ID}, G. Umoret^{a,b, ID}, E. Vlasov^{a,b, ID}

^a INFN Sezione di Torino, Torino, Italy

^b Università di Torino, Torino, Italy

^c Università del Piemonte Orientale, Novara, Italy

S. Belforte^{a, ID}, V. Candelise^{a,b, ID}, M. Casarsa^{a, ID}, F. Cossutti^{a, ID}, K. De Leo^{a,b, ID}, G. Della Ricca^{a,b, ID}

^a INFN Sezione di Trieste, Trieste, Italy

^b Università di Trieste, Trieste, Italy

S. Dogra^{ID}, J. Hong^{ID}, C. Huh^{ID}, B. Kim^{ID}, D.H. Kim^{ID}, J. Kim, H. Lee, S.W. Lee^{ID}, C.S. Moon^{ID}, Y.D. Oh^{ID},
M.S. Ryu^{ID}, S. Sekmen^{ID}, Y.C. Yang^{ID}

Kyungpook National University, Daegu, Korea

M.S. Kim^{ID}

Department of Mathematics and Physics - GWNu, Gangneung, Korea

G. Bak^{ID}, P. Gwak^{ID}, H. Kim^{ID}, D.H. Moon^{ID}

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

E. Asilar^{ID}, D. Kim^{ID}, T.J. Kim^{ID}, J.A. Merlin

Hanyang University, Seoul, Korea

S. Choi^{ID}, S. Han, B. Hong^{ID}, K. Lee, K.S. Lee^{ID}, S. Lee^{ID}, J. Park, S.K. Park, J. Yoo^{ID}

Korea University, Seoul, Korea

J. Goh^{ID}, S. Yang^{ID}

Kyung Hee University, Department of Physics, Seoul, Korea

H.S. Kim^{ID}, Y. Kim, S. Lee

Sejong University, Seoul, Korea

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

Seoul National University, Seoul, Korea

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

University of Seoul, Seoul, Korea

S. Ha , H.D. Yoo 

Yonsei University, Department of Physics, Seoul, Korea

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

Sungkyunkwan University, Suwon, Korea

T. Beyrouthy , Y. Maghrbi 

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

K. Dreimanis , A. Gaile , G. Pikurs, A. Potrebko , M. Seidel , V. Veckalns ,⁵⁹

Riga Technical University, Riga, Latvia

N.R. Strautnieks 

University of Latvia (LU), Riga, Latvia

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

Vilnius University, Vilnius, Lithuania

N. Bin Norjoharuddeen , I. Yusuff ,⁶⁰ Z. Zolkapli

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

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

Universidad de Sonora (UNISON), Hermosillo, Mexico

G. Ayala , H. Castilla-Valdez , E. De La Cruz-Burelo , I. Heredia-De La Cruz ,⁶¹ R. Lopez-Fernandez ,
C.A. Mondragon Herrera, A. Sánchez Hernández 

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

C. Oropeza Barrera , M. Ramírez García 

Universidad Iberoamericana, Mexico City, Mexico

I. Bautista , I. Pedraza , H.A. Salazar Ibarguen , C. Uribe Estrada 

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

I. Bubanja , N. Raicevic 

University of Montenegro, Podgorica, Montenegro

P.H. Butler 

University of Canterbury, Christchurch, New Zealand

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

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

V. Avati, L. Grzanka , M. Malawski 

AGH University of Krakow, Faculty of Computer Science, Electronics and Telecommunications, Krakow, Poland

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

National Centre for Nuclear Research, Swierk, Poland

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

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

K. Pozniak , W. Zabolotny 

Warsaw University of Technology, Warsaw, Poland

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

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

P. Adzic^{ID}, P. Milenovic^{ID}

Faculty of Physics, University of Belgrade, Belgrade, Serbia

M. Dordevic^{ID}, J. Milosevic^{ID}, V. Rekovic

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

M. Aguilar-Benitez, J. Alcaraz Maestre^{ID}, Cristina F. Bedoya^{ID}, M. Cepeda^{ID}, M. Cerrada^{ID}, N. Colino^{ID},
B. De La Cruz^{ID}, A. Delgado Peris^{ID}, A. Escalante Del Valle^{ID}, D. Fernández Del Val^{ID},
J.P. Fernández Ramos^{ID}, J. Flix^{ID}, M.C. Fouz^{ID}, O. Gonzalez Lopez^{ID}, S. Goy Lopez^{ID}, J.M. Hernandez^{ID},
M.I. Josa^{ID}, J. León Holgado^{ID}, D. Moran^{ID}, C.M. Morcillo Perez^{ID}, Á. Navarro Tobar^{ID}, C. Perez Dengra^{ID},
A. Pérez-Calero Yzquierdo^{ID}, J. Puerta Pelayo^{ID}, I. Redondo^{ID}, D.D. Redondo Ferrero^{ID}, L. Romero,
S. Sánchez Navas^{ID}, L. Urda Gómez^{ID}, J. Vazquez Escobar^{ID}, C. Willmott

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

J.F. de Trocóniz^{ID}

Universidad Autónoma de Madrid, Madrid, Spain

B. Alvarez Gonzalez^{ID}, J. Cuevas^{ID}, J. Fernandez Menendez^{ID}, S. Folgueras^{ID}, I. Gonzalez Caballero^{ID},
J.R. González Fernández^{ID}, E. Palencia Cortezon^{ID}, C. Ramón Álvarez^{ID}, V. Rodríguez Bouza^{ID},
A. Soto Rodríguez^{ID}, A. Trapote^{ID}, C. Vico Villalba^{ID}, P. Vischia^{ID}

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

S. Bhowmik^{ID}, S. Blanco Fernández^{ID}, J.A. Brochero Cifuentes^{ID}, I.J. Cabrillo^{ID}, A. Calderon^{ID},
J. Duarte Campderros^{ID}, M. Fernandez^{ID}, C. Fernandez Madrazo^{ID}, G. Gomez^{ID}, C. Lasasosa García^{ID},
C. Martinez Rivero^{ID}, P. Martinez Ruiz del Arbol^{ID}, F. Matorras^{ID}, P. Matorras Cuevas^{ID},
E. Navarrete Ramos^{ID}, J. Piedra Gomez^{ID}, L. Scodellaro^{ID}, I. Vila^{ID}, J.M. Vizan Garcia^{ID}

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

M.K. Jayananda^{ID}, B. Kailasapathy^{ID,62}, D.U.J. Sonnadara^{ID}, D.D.C. Wickramaratna^{ID}

University of Colombo, Colombo, Sri Lanka

W.G.D. Dharmaratna^{ID}, K. Liyanage^{ID}, N. Perera^{ID}, N. Wickramage^{ID}

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

D. Abbaneo^{ID}, C. Amendola^{ID}, E. Auffray^{ID}, G. Auzinger^{ID}, J. Baechler, D. Barney^{ID},
A. Bermúdez Martínez^{ID}, M. Bianco^{ID}, B. Bilin^{ID}, A.A. Bin Anuar^{ID}, A. Bocci^{ID}, E. Brondolin^{ID}, C. Caillol^{ID},
G. Cerminara^{ID}, N. Chernyavskaya^{ID}, D. d'Enterria^{ID}, A. Dabrowski^{ID}, A. David^{ID}, A. De Roeck^{ID},
M.M. Defranchis^{ID}, M. Deile^{ID}, M. Dobson^{ID}, F. Fallavollita⁶³, L. Forthomme^{ID}, G. Franzoni^{ID}, W. Funk^{ID},
S. Giani, D. Gigi, K. Gill^{ID}, F. Glege^{ID}, L. Gouskos^{ID}, M. Haranko^{ID}, J. Hegeman^{ID}, B. Huber^{ID},
V. Innocente^{ID}, T. James^{ID}, P. Janot^{ID}, S. Laurila^{ID}, P. Lecoq^{ID}, E. Leutgeb^{ID}, C. Lourenço^{ID}, B. Maier^{ID},
L. Malgeri^{ID}, M. Mannelli^{ID}, A.C. Marini^{ID}, M. Matthewman, F. Meijers^{ID}, S. Mersi^{ID}, E. Meschi^{ID},
V. Milosevic^{ID}, F. Moortgat^{ID}, M. Mulders^{ID}, S. Orfanelli, F. Pantaleo^{ID}, G. Petrucciani^{ID}, A. Pfeiffer^{ID},
M. Pierini^{ID}, D. Piparo^{ID}, H. Qu^{ID}, D. Rabady^{ID}, G. Reales Gutiérrez, M. Rovere^{ID}, H. Sakulin^{ID}, S. Scarfi^{ID},

C. Schwick^{ID}, M. Selvaggi^{ID}, A. Sharma^{ID}, K. Shchelina^{ID}, P. Silva^{ID}, P. Sphicas^{ID,64}, A.G. Stahl Leiton^{ID},
 A. Steen^{ID}, S. Summers^{ID}, D. Treille^{ID}, P. Tropea^{ID}, A. Tsirou, D. Walter^{ID}, J. Wanczyk^{ID,65},
 K.A. Wozniak^{ID,66}, S. Wuchterl^{ID}, P. Zehetner^{ID}, P. Zejdl^{ID}, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

T. Bevilacqua^{ID,67}, L. Caminada^{ID,67}, A. Ebrahimi^{ID}, W. Erdmann^{ID}, R. Horisberger^{ID}, Q. Ingram^{ID},
 H.C. Kaestli^{ID}, D. Kotlinski^{ID}, C. Lange^{ID}, M. Missiroli^{ID,67}, L. Noehte^{ID,67}, T. Rohe^{ID}

PSI Center for Neutron and Muon Sciences, Villigen, Switzerland

T.K. Aarrestad^{ID}, K. Androsov^{ID,65}, M. Backhaus^{ID}, A. Calandri^{ID}, C. Cazzaniga^{ID}, K. Datta^{ID}, A. De Cosa^{ID},
 G. Dissertori^{ID}, M. Dittmar, M. Donegà^{ID}, F. Eble^{ID}, M. Galli^{ID}, K. Gedia^{ID}, F. Glessgen^{ID}, C. Grab^{ID},
 D. Hits^{ID}, W. Lustermann^{ID}, A.-M. Lyon^{ID}, R.A. Manzoni^{ID}, M. Marchegiani^{ID}, L. Marchese^{ID},
 C. Martin Perez^{ID}, A. Mascellani^{ID,65}, F. Nessi-Tedaldi^{ID}, F. Pauss^{ID}, V. Perovic^{ID}, S. Pigazzini^{ID},
 M.G. Ratti^{ID}, M. Reichmann^{ID}, C. Reissel^{ID}, T. Reitspiess^{ID}, B. Ristic^{ID}, F. Riti^{ID}, D. Ruini,
 D.A. Sanz Becerra^{ID}, R. Seidita^{ID}, J. Steggemann^{ID,65}, D. Valsecchi^{ID}, R. Wallny^{ID}

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

C. Amsler^{ID,68}, P. Bäertschi^{ID}, C. Botta^{ID}, D. Brzhechko, M.F. Canelli^{ID}, K. Cormier^{ID}, R. Del Burgo,
 J.K. Heikkilä^{ID}, M. Huwiler^{ID}, W. Jin^{ID}, A. Jofrehei^{ID}, B. Kilminster^{ID}, S. Leontsinis^{ID}, S.P. Liechti^{ID},
 A. Macchiolo^{ID}, P. Meiring^{ID}, V.M. Mikuni^{ID}, U. Molinatti^{ID}, I. Neutelings^{ID}, A. Reimers^{ID}, P. Robmann,
 S. Sanchez Cruz^{ID}, K. Schweiger^{ID}, M. Senger^{ID}, Y. Takahashi^{ID}, R. Tramontano^{ID}

Universität Zürich, Zurich, Switzerland

C. Adloff⁶⁹, C.M. Kuo, W. Lin, P.K. Rout^{ID}, P.C. Tiwari^{ID,44}, S.S. Yu^{ID}

National Central University, Chung-Li, Taiwan

L. Ceard, Y. Chao^{ID}, K.F. Chen^{ID}, P.s. Chen, Z.g. Chen, W.-S. Hou^{ID}, T.h. Hsu, Y.w. Kao, R. Khurana,
 G. Kole^{ID}, Y.y. Li^{ID}, R.-S. Lu^{ID}, E. Paganis^{ID}, X.f. Su^{ID}, J. Thomas-Wilsker^{ID}, L.s. Tsai, H.y. Wu, E. Yazgan^{ID}

National Taiwan University (NTU), Taipei, Taiwan

C. Asawatangtrakuldee^{ID}, N. Srimanobhas^{ID}, V. Wachirapusanand^{ID}

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

D. Agyel^{ID}, F. Boran^{ID}, Z.S. Demiroglu^{ID}, F. Dolek^{ID}, I. Dumanoglu^{ID,70}, E. Eskut^{ID}, Y. Guler^{ID,71},
 E. Gurpınar Guler^{ID,71}, C. Isik^{ID}, O. Kara, A. Kayis Topaksu^{ID}, U. Kiminsu^{ID}, G. Onengut^{ID}, K. Ozdemir^{ID,72},
 A. Polatoz^{ID}, B. Tali^{ID,73}, U.G. Tok^{ID}, S. Turkcapar^{ID}, E. Usan^{ID}, I.S. Zorbakir^{ID}

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

M. Yalvac^{ID,74}

Middle East Technical University, Physics Department, Ankara, Turkey

B. Akgun^{ID}, I.O. Atakisi^{ID}, E. Gülmez^{ID}, M. Kaya^{ID,75}, O. Kaya^{ID,76}, S. Tekten^{ID,77}

Bogazici University, Istanbul, Turkey

A. Cakir^{ID}, K. Cankocak^{ID,70,78}, Y. Komurcu^{ID}, S. Sen^{ID,79}

Istanbul Technical University, Istanbul, Turkey

O. Aydılek^{ID}, S. Cerci^{ID,73}, V. Epshteyn^{ID}, B. Hacisahinoglu^{ID}, I. Hos^{ID,80}, B. Kaynak^{ID}, S. Ozkorucuklu^{ID},
 O. Potok^{ID}, H. Sert^{ID}, C. Simsek^{ID}, D. Sunar Cerci^{ID,73}, C. Zorbilmez^{ID}

Istanbul University, Istanbul, Turkey

B. Isildak^{ID,81}

Yildiz Technical University, Istanbul, Turkey

A. Boyaryntsev^{ID}, B. Grynyov^{ID}

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

L. Levchuk^{ID}

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

D. Anthony^{ID}, J.J. Brooke^{ID}, A. Bundock^{ID}, F. Bury^{ID}, E. Clement^{ID}, D. Cussans^{ID}, H. Flacher^{ID},
M. Glowacki^{ID}, J. Goldstein^{ID}, H.F. Heath^{ID}, L. Kreczko^{ID}, B. Krikler^{ID}, S. Paramesvaran^{ID},
S. Seif El Nasr-Storey^{ID}, V.J. Smith^{ID}, N. Stylianou^{ID},⁸², K. Walkingshaw^{ID}, R. White^{ID}

University of Bristol, Bristol, United Kingdom

A.H. Ball^{ID}, K.W. Bell^{ID}, A. Belyaev^{ID},⁸³, C. Brew^{ID}, R.M. Brown^{ID}, D.J.A. Cockerill^{ID}, C. Cooke^{ID}, K.V. Ellis,
K. Harder^{ID}, S. Harper^{ID}, M.-L. Holmberg^{ID},⁸⁴, J. Linacre^{ID}, K. Manolopoulos^{ID}, D.M. Newbold^{ID}, E. Olaiya,
D. Petyt^{ID}, T. Reis^{ID}, G. Salvi^{ID}, T. Schuh^{ID}, C.H. Shepherd-Themistocleous^{ID}, I.R. Tomalin^{ID}, T. Williams^{ID}

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge^{ID}, P. Bloch^{ID}, C.E. Brown^{ID}, O. Buchmuller^{ID}, V. Cacchio^{ID}, C.A. Carrillo Montoya^{ID},
G.S. Chahal^{ID},⁸⁵, D. Colling^{ID}, J.S. Dancu^{ID}, P. Dauncey^{ID}, G. Davies^{ID}, J. Davies^{ID}, M. Della Negra^{ID}, S. Fayer,
G. Fedi^{ID}, G. Hall^{ID}, M.H. Hassanshahi^{ID}, A. Howard^{ID}, G. Iles^{ID}, M. Knight^{ID}, J. Langford^{ID}, L. Lyons^{ID},
A.-M. Magnan^{ID}, S. Malik^{ID}, A. Martelli^{ID}, M. Mieskolainen^{ID}, J. Nash^{ID},⁸⁶, M. Pesaresi^{ID},
B.C. Radburn-Smith^{ID}, A. Richards^{ID}, A. Rose^{ID}, C. Seez^{ID}, R. Shukla^{ID}, A. Tapper^{ID}, K. Uchida^{ID},
G.P. Uttley^{ID}, L.H. Vage^{ID}, T. Virdee^{ID},³⁴, M. Vojinovic^{ID}, N. Wardle^{ID}, D. Winterbottom^{ID}

Imperial College, London, United Kingdom

K. Coldham^{ID}, J.E. Cole^{ID}, A. Khan^{ID}, P. Kyberd^{ID}, I.D. Reid^{ID}

Brunel University, Uxbridge, United Kingdom

S. Abdullin^{ID}, A. Brinkerhoff^{ID}, B. Caraway^{ID}, J. Dittmann^{ID}, K. Hatakeyama^{ID}, J. Hiltbrand^{ID},
A.R. Kanuganti^{ID}, B. McMaster^{ID}, M. Saunders^{ID}, S. Sawant^{ID}, C. Sutantawibul^{ID}, M. Toms^{ID},⁸⁷, J. Wilson^{ID}

Baylor University, Waco, TX, USA

R. Bartek^{ID}, A. Dominguez^{ID}, C. Huerta Escamilla^{ID}, A.E. Simsek^{ID}, R. Uniyal^{ID}, A.M. Vargas Hernandez^{ID}

Catholic University of America, Washington, DC, USA

R. Chudasama^{ID}, S.I. Cooper^{ID}, S.V. Gleyzer^{ID}, C.U. Perez^{ID}, P. Rumerio^{ID},⁸⁸, E. Usai^{ID}, R. Yi^{ID}

The University of Alabama, Tuscaloosa, AL, USA

A. Akpinar^{ID}, A. Albert^{ID}, D. Arcaro^{ID}, C. Cosby^{ID}, Z. Demiragli^{ID}, C. Erice^{ID}, E. Fontanesi^{ID}, D. Gastler^{ID},
S. Jeon^{ID}, J. Rohlf^{ID}, K. Salyer^{ID}, D. Sperka^{ID}, D. Spitzbart^{ID}, I. Suarez^{ID}, A. Tsatsos^{ID}, S. Yuan^{ID}

Boston University, Boston, MA, USA

G. Benelli^{ID}, X. Coubez^{ID},²⁹, D. Cutts^{ID}, M. Hadley^{ID}, U. Heintz^{ID}, J.M. Hogan^{ID},⁸⁹, T. Kwon^{ID}, G. Landsberg^{ID},
K.T. Lau^{ID}, D. Li^{ID}, J. Luo^{ID}, S. Mondal^{ID}, M. Narain^{ID},[†], N. Pervan^{ID}, S. Sagir^{ID},⁹⁰, F. Simpson^{ID},
M. Stamenkovic^{ID}, W.Y. Wong^{ID}, X. Yan^{ID}, W. Zhang^{ID}

Brown University, Providence, RI, USA

S. Abbott^{ID}, J. Bonilla^{ID}, C. Brainerd^{ID}, R. Breedon^{ID}, M. Calderon De La Barca Sanchez^{ID}, M. Chertok^{ID},
M. Citron^{ID}, J. Conway^{ID}, P.T. Cox^{ID}, R. Erbacher^{ID}, F. Jensen^{ID}, O. Kukral^{ID}, G. Mocellin^{ID},
M. Mulhearn^{ID}, D. Pellett^{ID}, W. Wei^{ID}, Y. Yao^{ID}, F. Zhang^{ID}

University of California, Davis, Davis, CA, USA

M. Bachtis^{ID}, R. Cousins^{ID}, A. Datta^{ID}, G. Flores Avila^{ID}, J. Hauser^{ID}, M. Ignatenko^{ID}, M.A. Iqbal^{ID},
T. Lam^{ID}, E. Manca^{ID}, A. Nunez Del Prado, D. Saltzberg^{ID}, V. Valuev^{ID}

University of California, Los Angeles, CA, USA

R. Clare^{ID}, J.W. Gary^{ID}, M. Gordon, G. Hanson^{ID}, W. Si^{ID}, S. Wimpenny^{ID,†}

University of California, Riverside, Riverside, CA, USA

J.G. Branson^{ID}, S. Cittolin^{ID}, S. Cooperstein^{ID}, D. Diaz^{ID}, J. Duarte^{ID}, L. Giannini^{ID}, J. Guiang^{ID},
R. Kansal^{ID}, V. Krutelyov^{ID}, R. Lee^{ID}, J. Letts^{ID}, M. Masciovecchio^{ID}, F. Mokhtar^{ID}, M. Pieri^{ID},
M. Quinnan^{ID}, B.V. Sathia Narayanan^{ID}, V. Sharma^{ID}, M. Tadel^{ID}, E. Vourliotis^{ID}, F. Würthwein^{ID},
Y. Xiang^{ID}, A. Yagil^{ID}

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

A. Barzdukas^{ID}, L. Brennan^{ID}, C. Campagnari^{ID}, G. Collura^{ID}, A. Dorsett^{ID}, J. Incandela^{ID}, M. Kilpatrick^{ID},
J. Kim^{ID}, A.J. Li^{ID}, P. Masterson^{ID}, H. Mei^{ID}, M. Oshiro^{ID}, J. Richman^{ID}, U. Sarica^{ID}, R. Schmitz^{ID},
F. Setti^{ID}, J. Sheplock^{ID}, D. Stuart^{ID}, S. Wang^{ID}

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

A. Bornheim^{ID}, O. Cerri, A. Latorre, J. Mao^{ID}, H.B. Newman^{ID}, M. Spiropulu^{ID}, J.R. Vlimant^{ID}, C. Wang^{ID},
S. Xie^{ID}, R.Y. Zhu^{ID}

California Institute of Technology, Pasadena, CA, USA

J. Alison^{ID}, S. An^{ID}, M.B. Andrews^{ID}, P. Bryant^{ID}, V. Dutta^{ID}, T. Ferguson^{ID}, A. Harilal^{ID}, C. Liu^{ID},
T. Mudholkar^{ID}, S. Murthy^{ID}, M. Paulini^{ID}, A. Roberts^{ID}, A. Sanchez^{ID}, W. Terrill^{ID}

Carnegie Mellon University, Pittsburgh, PA, USA

J.P. Cumalat^{ID}, W.T. Ford^{ID}, A. Hassani^{ID}, G. Karathanasis^{ID}, E. MacDonald, N. Manganelli^{ID}, F. Marini^{ID},
A. Perloff^{ID}, C. Savard^{ID}, N. Schonbeck^{ID}, K. Stenson^{ID}, K.A. Ulmer^{ID}, S.R. Wagner^{ID}, N. Zipper^{ID}

University of Colorado Boulder, Boulder, CO, USA

J. Alexander^{ID}, S. Bright-Thonney^{ID}, X. Chen^{ID}, D.J. Cranshaw^{ID}, J. Fan^{ID}, X. Fan^{ID}, D. Gadkari^{ID},
S. Hogan^{ID}, J. Monroy^{ID}, J.R. Patterson^{ID}, J. Reichert^{ID}, M. Reid^{ID}, A. Ryd^{ID}, J. Thom^{ID}, P. Wittich^{ID},
R. Zou^{ID}

Cornell University, Ithaca, NY, USA

M. Albrow^{ID}, M. Alyari^{ID}, O. Amram^{ID}, G. Apollinari^{ID}, A. Apresyan^{ID}, L.A.T. Bauerdick^{ID}, D. Berry^{ID},
J. Berryhill^{ID}, P.C. Bhat^{ID}, K. Burkett^{ID}, J.N. Butler^{ID}, A. Canepa^{ID}, G.B. Cerati^{ID}, H.W.K. Cheung^{ID},
F. Chlebana^{ID}, G. Cummings^{ID}, J. Dickinson^{ID}, I. Dutta^{ID}, V.D. Elvira^{ID}, Y. Feng^{ID}, J. Freeman^{ID},
A. Gandrakota^{ID}, Z. Gece^{ID}, L. Gray^{ID}, D. Green, A. Grummer^{ID}, S. Grünendahl^{ID}, D. Guerrero^{ID},
O. Gutsche^{ID}, R.M. Harris^{ID}, R. Heller^{ID}, T.C. Herwig^{ID}, J. Hirschauer^{ID}, L. Horyn^{ID}, B. Jayatilaka^{ID},
S. Jindariani^{ID}, M. Johnson^{ID}, U. Joshi^{ID}, T. Klijnsma^{ID}, B. Klima^{ID}, K.H.M. Kwok^{ID}, S. Lammel^{ID},
D. Lincoln^{ID}, R. Lipton^{ID}, T. Liu^{ID}, C. Madrid^{ID}, K. Maeshima^{ID}, C. Mantilla^{ID}, D. Mason^{ID}, P. McBride^{ID},
P. Merkel^{ID}, S. Mrenna^{ID}, S. Nahn^{ID}, J. Ngadiuba^{ID}, D. Noonan^{ID}, V. Papadimitriou^{ID}, N. Pastika^{ID},
K. Pedro^{ID}, C. Pena^{ID,91}, F. Ravera^{ID}, A. Reinsvold Hall^{ID,92}, L. Ristori^{ID}, E. Sexton-Kennedy^{ID}, N. Smith^{ID},
A. Soha^{ID}, L. Spiegel^{ID}, S. Stoynev^{ID}, J. Strait^{ID}, L. Taylor^{ID}, S. Tkaczyk^{ID}, N.V. Tran^{ID}, L. Uplegger^{ID},
E.W. Vaandering^{ID}, I. Zoi^{ID}

Fermi National Accelerator Laboratory, Batavia, IL, USA

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

University of Florida, Gainesville, FL, USA

T. Adams^{ID}, A. Al Kadhim^{ID}, A. Askew^{ID}, N. Bower^{ID}, R. Habibullah^{ID}, V. Hagopian^{ID}, R. Hashmi^{ID},
R.S. Kim^{ID}, S. Kim^{ID}, T. Kolberg^{ID}, G. Martinez, H. Prosper^{ID}, P.R. Prova, O. Viazlo^{ID}, M. Wulansatiti^{ID},
R. Yohay^{ID}, J. Zhang

Florida State University, Tallahassee, FL, USA

B. Alsufyani^{ID}, M.M. Baarmand^{ID}, S. Butalla^{ID}, T. Elkafrawy^{ID},⁵⁷ M. Hohlmann^{ID}, R. Kumar Verma^{ID},
M. Rahmani

Florida Institute of Technology, Melbourne, FL, USA

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

University of Illinois Chicago, Chicago, IL, USA

M. Alhusseini^{ID}, D. Blend, K. Dilsiz^{ID},⁹³ L. Emediato^{ID}, G. Karaman^{ID}, O.K. Köseyan^{ID}, J.-P. Merlo,
A. Mestvirishvili^{ID},⁹⁴ J. Nachtman^{ID}, O. Neogi, H. Ogul^{ID},⁹⁵ Y. Onel^{ID}, A. Penzo^{ID}, C. Snyder, E. Tiras^{ID},⁹⁶

The University of Iowa, Iowa City, IA, USA

B. Blumenfeld^{ID}, L. Corcodilos^{ID}, J. Davis^{ID}, A.V. Gritsan^{ID}, L. Kang^{ID}, S. Kyriacou^{ID}, P. Maksimovic^{ID},
M. Roguljic^{ID}, J. Roskes^{ID}, S. Sekhar^{ID}, M. Swartz^{ID}, T.Á. Vámi^{ID}

Johns Hopkins University, Baltimore, MD, USA

A. Abreu^{ID}, L.F. Alcerro Alcerro^{ID}, J. Anguiano^{ID}, P. Baringer^{ID}, A. Bean^{ID}, Z. Flowers^{ID}, D. Grove^{ID},
J. King^{ID}, G. Krintiras^{ID}, M. Lazarovits^{ID}, C. Le Mahieu^{ID}, C. Lindsey, J. Marquez^{ID}, N. Minafra^{ID},
M. Murray^{ID}, M. Nickel^{ID}, M. Pitt^{ID}, S. Popescu^{ID},⁹⁷ C. Rogan^{ID}, C. Royon^{ID}, R. Salvatico^{ID}, S. Sanders^{ID},
C. Smith^{ID}, Q. Wang^{ID}, G. Wilson^{ID}

The University of Kansas, Lawrence, KS, USA

B. Allmond^{ID}, A. Ivanov^{ID}, K. Kaadze^{ID}, A. Kalogeropoulos^{ID}, D. Kim, Y. Maravin^{ID}, K. Nam, J. Natoli^{ID},
D. Roy^{ID}, G. Sorrentino^{ID}

Kansas State University, Manhattan, KS, USA

F. Rebassoo^{ID}, D. Wright^{ID}

Lawrence Livermore National Laboratory, Livermore, CA, USA

A. Baden^{ID}, A. Belloni^{ID}, A. Bethani^{ID}, Y.M. Chen^{ID}, S.C. Eno^{ID}, N.J. Hadley^{ID}, S. Jabeen^{ID}, R.G. Kellogg^{ID},
T. Koeth^{ID}, Y. Lai^{ID}, S. Lascio^{ID}, A.C. Mignerey^{ID}, S. Nabili^{ID}, C. Palmer^{ID}, C. Papageorgakis^{ID},
M.M. Paranjpe, L. Wang^{ID}

University of Maryland, College Park, MD, USA

J. Bendavid^{ID}, W. Busza^{ID}, I.A. Cali^{ID}, Y. Chen^{ID}, M. D'Alfonso^{ID}, J. Eysermans^{ID}, C. Freer^{ID},
G. Gomez-Ceballos^{ID}, M. Goncharov, P. Harris, D. Hoang, D. Kovalskyi^{ID}, J. Krupa^{ID}, L. Lavezzo^{ID},

Y.-J. Lee^{ID}, K. Long^{ID}, C. Mironov^{ID}, C. Paus^{ID}, D. Rankin^{ID}, C. Roland^{ID}, G. Roland^{ID}, S. Rothman^{ID},
Z. Shi^{ID}, G.S.F. Stephans^{ID}, J. Wang, Z. Wang^{ID}, B. Wyslouch^{ID}, T.J. Yang^{ID}

Massachusetts Institute of Technology, Cambridge, MA, USA

B. Crossman^{ID}, B.M. Joshi^{ID}, C. Kapsiak^{ID}, M. Krohn^{ID}, D. Mahon^{ID}, J. Mans^{ID}, B. Marzocchi^{ID},
S. Pandey^{ID}, M. Revering^{ID}, R. Rusack^{ID}, R. Saradhy^{ID}, N. Schroeder^{ID}, N. Strobbe^{ID}, M.A. Wadud^{ID}

University of Minnesota, Minneapolis, MN, USA

L.M. Cremaldi^{ID}

University of Mississippi, Oxford, MS, USA

K. Bloom^{ID}, M. Bryson, D.R. Claes^{ID}, C. Fangmeier^{ID}, F. Golf^{ID}, G. Haza^{ID}, J. Hossain^{ID}, C. Joo^{ID},
I. Kravchenko^{ID}, I. Reed^{ID}, J.E. Siado^{ID}, W. Tabb^{ID}, A. Vagnerini^{ID}, A. Wightman^{ID}, F. Yan^{ID}, D. Yu^{ID},
A.G. Zecchinelli^{ID}

University of Nebraska-Lincoln, Lincoln, NE, USA

G. Agarwal^{ID}, H. Bandyopadhyay^{ID}, L. Hay^{ID}, I. Iashvili^{ID}, A. Kharchilava^{ID}, M. Morris^{ID}, D. Nguyen^{ID},
S. Rappoccio^{ID}, H. Rejeb Sfar, A. Williams^{ID}

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

E. Barberis^{ID}, J. Dervan^{ID}, Y. Haddad^{ID}, Y. Han^{ID}, A. Krishna^{ID}, J. Li^{ID}, M. Lu^{ID}, G. Madigan^{ID},
R. McCarthy^{ID}, D.M. Morse^{ID}, V. Nguyen^{ID}, T. Orimoto^{ID}, A. Parker^{ID}, L. Skinnari^{ID},
A. Tishelman-Charny^{ID}, B. Wang^{ID}, D. Wood^{ID}

Northeastern University, Boston, MA, USA

S. Bhattacharya^{ID}, J. Bueghly, Z. Chen^{ID}, K.A. Hahn^{ID}, Y. Liu^{ID}, Y. Miao^{ID}, D.G. Monk^{ID}, M.H. Schmitt^{ID},
A. Taliencio^{ID}, M. Velasco

Northwestern University, Evanston, IL, USA

R. Band^{ID}, R. Bucci, S. Castells^{ID}, M. Cremonesi, A. Das^{ID}, R. Goldouzian^{ID}, M. Hildreth^{ID}, K.W. Ho^{ID},
K. Hurtado Anampa^{ID}, T. Ivanov^{ID}, C. Jessop^{ID}, K. Lannon^{ID}, J. Lawrence^{ID}, N. Loukas^{ID}, L. Lutton^{ID},
J. Mariano, N. Marinelli, I. Mcalister, T. McCauley^{ID}, C. Mcgrady^{ID}, C. Moore^{ID}, Y. Musienko^{ID,17},
H. Nelson^{ID}, M. Osherson^{ID}, A. Piccinelli^{ID}, R. Ruchti^{ID}, A. Townsend^{ID}, Y. Wan, M. Wayne^{ID}, H. Yockey,
M. Zarucki^{ID}, L. Zygala^{ID}

University of Notre Dame, Notre Dame, IN, USA

A. Basnet^{ID}, B. Bylsma, M. Carrigan^{ID}, L.S. Durkin^{ID}, C. Hill^{ID}, M. Joyce^{ID}, A. Lesauvage^{ID},
M. Nunez Ornelas^{ID}, K. Wei, B.L. Winer^{ID}, B.R. Yates^{ID}

The Ohio State University, Columbus, OH, USA

F.M. Addesa^{ID}, H. Bouchamaoui^{ID}, P. Das^{ID}, G. Dezoort^{ID}, P. Elmer^{ID}, A. Frankenthal^{ID}, B. Greenberg^{ID},
N. Haubrich^{ID}, S. Higginbotham^{ID}, G. Kopp^{ID}, S. Kwan^{ID}, D. Lange^{ID}, A. Loeliger^{ID}, D. Marlow^{ID},
I. Ojalvo^{ID}, J. Olsen^{ID}, A. Shevelev^{ID}, D. Stickland^{ID}, C. Tully^{ID}

Princeton University, Princeton, NJ, USA

S. Malik^{ID}

University of Puerto Rico, Mayaguez, PR, USA

A.S. Bakshi^{ID}, V.E. Barnes^{ID}, S. Chandra^{ID}, R. Chawla^{ID}, S. Das^{ID}, A. Gu^{ID}, L. Gutay, M. Jones^{ID},
A.W. Jung^{ID}, D. Kondratyev^{ID}, A.M. Koshy, M. Liu^{ID}, G. Negro^{ID}, N. Neumeister^{ID}, G. Paspalaki^{ID},
S. Piperov^{ID}, V. Scheurer, J.F. Schulte^{ID}, M. Stojanovic^{ID}, J. Thieman^{ID}, A.K. Viridi^{ID}, F. Wang^{ID}, W. Xie^{ID}

Purdue University, West Lafayette, IN, USA

J. Dolen^{ID}, N. Parashar^{ID}, A. Pathak^{ID}

Purdue University Northwest, Hammond, IN, USA

D. Acosta^{ID}, A. Baty^{ID}, T. Carnahan^{ID}, K.M. Ecklund^{ID}, P.J. Fernández Manteca^{ID}, S. Freed, P. Gardner, F.J.M. Geurts^{ID}, A. Kumar^{ID}, W. Li^{ID}, O. Miguel Colin^{ID}, B.P. Padley^{ID}, R. Redjimi, J. Rotter^{ID}, E. Yigitbasi^{ID}, Y. Zhang^{ID}

Rice University, Houston, TX, USA

A. Bodek^{ID}, P. de Barbaro^{ID}, R. Demina^{ID}, J.L. Dulemba^{ID}, C. Fallon, A. Garcia-Bellido^{ID}, O. Hindrichs^{ID}, A. Khukhunaishvili^{ID}, P. Parygin^{ID,98}, E. Popova^{ID,98}, R. Taus^{ID}, G.P. Van Onsem^{ID}

University of Rochester, Rochester, NY, USA

K. Goulios^{ID}

The Rockefeller University, New York, NY, USA

B. Chiarito, J.P. Chou^{ID}, Y. Gershtein^{ID}, E. Halkiadakis^{ID}, A. Hart^{ID}, M. Heindl^{ID}, D. Jaroslawski^{ID}, O. Karacheban^{ID,32}, I. Laflotte^{ID}, A. Lath^{ID}, R. Montalvo, K. Nash, H. Routray^{ID}, S. Salur^{ID}, S. Schnetzer, S. Somalwar^{ID}, R. Stone^{ID}, S.A. Thayil^{ID}, S. Thomas, J. Vora^{ID}, H. Wang^{ID}

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

H. Acharya, D. Ally^{ID}, A.G. Delannoy^{ID}, S. Fiorendi^{ID}, T. Holmes^{ID}, N. Karunaratna^{ID}, L. Lee^{ID}, E. Nibigira^{ID}, S. Spanier^{ID}

University of Tennessee, Knoxville, TN, USA

D. Aebi^{ID}, M. Ahmad^{ID}, O. Bouhali^{ID,99}, M. Dalchenko^{ID}, R. Eusebi^{ID}, J. Gilmore^{ID}, T. Huang^{ID}, T. Kamon^{ID,100}, H. Kim^{ID}, S. Luo^{ID}, S. Malhotra, R. Mueller^{ID}, D. Overton^{ID}, D. Rathjens^{ID}, A. Safonov^{ID}

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

N. Akchurin^{ID}, J. Damgov^{ID}, V. Hegde^{ID}, A. Hussain^{ID}, Y. Kazhykarim, K. Lamichhane^{ID}, S.W. Lee^{ID}, A. Mankel^{ID}, T. Peltola^{ID}, I. Volobouev^{ID}, A. Whitbeck^{ID}

Texas Tech University, Lubbock, TX, USA

E. Appelt^{ID}, S. Greene, A. Gurrola^{ID}, W. Johns^{ID}, R. Kunnawalkam Elayavalli^{ID}, A. Melo^{ID}, F. Romeo^{ID}, P. Sheldon^{ID}, S. Tuo^{ID}, J. Velkovska^{ID}, J. Viinikainen^{ID}

Vanderbilt University, Nashville, TN, USA

B. Cardwell^{ID}, B. Cox^{ID}, J. Hakala^{ID}, R. Hirosky^{ID}, A. Ledovskoy^{ID}, C. Neu^{ID}, C.E. Perez Lara^{ID}

University of Virginia, Charlottesville, VA, USA

P.E. Karchin^{ID}

Wayne State University, Detroit, MI, USA

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

University of Wisconsin - Madison, Madison, WI, USA

Yu. Andreev^{ID}, A. Dermenev^{ID}, S. Gninenko^{ID}, N. Golubev^{ID}, A. Karneyeu^{ID}, D. Kirpichnikov^{ID},
 M. Kirsanov^{ID}, N. Krasnikov^{ID}, I. Tlisova^{ID}, A. Toropin^{ID}, V. Gavrilov^{ID}, N. Lychkovskaya^{ID},
 A. Nikitenko^{ID,101,102}, V. Popov^{ID}, A. Zhokin^{ID}

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

S. Afanasiev^{ID}, D. Budkouski^{ID}, I. Golutvin^{ID}, I. Gorbunov^{ID}, V. Karjavine^{ID}, V. Korenkov^{ID}, A. Lanev^{ID},
 A. Malakhov^{ID}, V. Matveev^{ID,103}, V. Palichik^{ID}, V. Perelygin^{ID}, M. Savina^{ID}, V. Shalaev^{ID}, S. Shmatov^{ID},
 S. Shulha^{ID}, V. Smirnov^{ID}, O. Teryaev^{ID}, N. Voytishin^{ID}, B.S. Yuldashev¹⁰⁴, A. Zarubin^{ID}, I. Zhizhin^{ID},
 G. Gavrilov^{ID}, V. Golovtcov^{ID}, Y. Ivanov^{ID}, V. Kim^{ID,105}, P. Levchenko^{ID,106}, V. Murzin^{ID}, V. Oreshkin^{ID},
 D. Sosnov^{ID}, V. Sulimov^{ID}, L. Uvarov^{ID}, A. Vorobyev[†], T. Aushev^{ID}, R. Chistov^{ID,105}, M. Danilov^{ID,105},
 S. Polikarpov^{ID,105}, V. Andreev^{ID}, M. Azarkin^{ID}, M. Kirakosyan, A. Terkulov^{ID}, A. Belyaev^{ID}, E. Boos^{ID},
 A. Demiyanov^{ID}, A. Ershov^{ID}, A. Gribushin^{ID}, L. Khein^{ID}, O. Kodolova^{ID,102}, V. Korotkikh, S. Obraztsov^{ID},
 S. Petrushanko^{ID}, V. Savrin^{ID}, A. Snigirev^{ID}, I. Vardanyan^{ID}, V. Blinov¹⁰⁵, T. Dimova^{ID,105},
 L. Kardapoltsev^{ID,105}, A. Kozyrev^{ID,105}, O. Radchenko^{ID,105}, Y. Skovpen^{ID,105}, V. Kachanov^{ID},
 D. Konstantinov^{ID}, S. Slabospitskii^{ID}, A. Uzunian^{ID}, A. Babaev^{ID}, V. Borshch^{ID}, D. Druzhkin^{ID,107},
 E. Tcherniaev^{ID}, V. Chekhovsky, V. Makarenko^{ID}

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

[†] Deceased.

¹ Also at Yerevan State University, Yerevan, Armenia.

² Also at TU Wien, Vienna, Austria.

³ Also at 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 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 an institute formerly covered by a cooperation agreement with CERN.

²⁶ Also at The University of the State of Amazonas, Manaus, Brazil.

²⁷ Also at Erzincan Binali Yildirim University, Erzincan, Turkey.

²⁸ Also at University of Hamburg, Hamburg, Germany.

²⁹ Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.

³⁰ Also at Isfahan University of Technology, Isfahan, Iran.

³¹ Also at Bergische University Wuppertal (BUW), Wuppertal, Germany.

³² Also at Brandenburg University of Technology, Cottbus, Germany.

³³ Also at Forschungszentrum Jülich, Jülich, Germany.

³⁴ Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

³⁵ Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.

³⁶ Also at HUN-REN ATOMKI - Institute of Nuclear Research, Debrecen, Hungary.

³⁷ Now at Universitatea Babes-Bolyai - Facultatea de Fizica, Cluj-Napoca, Romania.

³⁸ Also at Physics Department, Faculty of Science, Assiut University, Assiut, Egypt.

³⁹ Also at HUN-REN Wigner Research Centre for Physics, Budapest, Hungary.

⁴⁰ Also at Faculty of Informatics, University of Debrecen, Debrecen, Hungary.

⁴¹ Also at Punjab Agricultural University, Ludhiana, India.

⁴² Also at University of Hyderabad, Hyderabad, India.

⁴³ Also at University of Visva-Bharati, Santiniketan, India.

⁴⁴ Also at Indian Institute of Science (IISc), Bangalore, India.

⁴⁵ Also at IIT Bhubaneswar, Bhubaneswar, India.

⁴⁶ Also at Institute of Physics, Bhubaneswar, India.

⁴⁷ Also at Deutsches Elektronen-Synchrotron, Hamburg, Germany.

- ⁴⁸ Also at Department of Physics, Isfahan University of Technology, Isfahan, Iran.
- ⁴⁹ Also at Sharif University of Technology, Tehran, Iran.
- ⁵⁰ Also at Department of Physics, University of Science and Technology of Mazandaran, Behshahr, Iran.
- ⁵¹ Also at Helwan University, Cairo, Egypt.
- ⁵² Also at Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Bologna, Italy.
- ⁵³ Also at Centro Siciliano di Fisica Nucleare e di Struttura Della Materia, Catania, Italy.
- ⁵⁴ Also at Università degli Studi Guglielmo Marconi, Roma, Italy.
- ⁵⁵ Also at Scuola Superiore Meridionale, Università di Napoli 'Federico II', Napoli, Italy.
- ⁵⁶ Also at Fermi National Accelerator Laboratory, Batavia, Illinois, USA.
- ⁵⁷ Also at Ain Shams University, Cairo, Egypt.
- ⁵⁸ Also at Consiglio Nazionale delle Ricerche - Istituto Officina dei Materiali, Perugia, Italy.
- ⁵⁹ Also at Riga Technical University, Riga, Latvia.
- ⁶⁰ Also at Department of Applied Physics, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, Bangi, Malaysia.
- ⁶¹ Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ⁶² Also at Trincomalee Campus, Eastern University, Sri Lanka, Nilaveli, Sri Lanka.
- ⁶³ Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ⁶⁴ Also at National and Kapodistrian University of Athens, Athens, Greece.
- ⁶⁵ Also at Ecole Polytechnique Fédérale Lausanne, Lausanne, Switzerland.
- ⁶⁶ Also at University of Vienna, Vienna, Austria.
- ⁶⁷ Also at Universität Zürich, Zurich, Switzerland.
- ⁶⁸ Also at Stefan Meyer Institute for Subatomic Physics, Vienna, Austria.
- ⁶⁹ Also at Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France.
- ⁷⁰ Also at Near East University, Research Center of Experimental Health Science, Mersin, Turkey.
- ⁷¹ Also at Konya Technical University, Konya, Turkey.
- ⁷² Also at Izmir Bakircay University, Izmir, Turkey.
- ⁷³ Also at Adiyaman University, Adiyaman, Turkey.
- ⁷⁴ Also at Bozok Universitetesi Rektörlüğü, Yozgat, Turkey.
- ⁷⁵ Also at Marmara University, Istanbul, Turkey.
- ⁷⁶ Also at Milli Savunma University, Istanbul, Turkey.
- ⁷⁷ Also at Kafkas University, Kars, Turkey.
- ⁷⁸ Now at Istanbul Okan University, Istanbul, Turkey.
- ⁷⁹ Also at Hacettepe University, Ankara, Turkey.
- ⁸⁰ Also at Istanbul University - Cerrahpasa, Faculty of Engineering, Istanbul, Turkey.
- ⁸¹ Also at Yildiz Technical University, Istanbul, Turkey.
- ⁸² Also at Vrije Universiteit Brussel, Brussel, Belgium.
- ⁸³ Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ⁸⁴ Also at University of Bristol, Bristol, United Kingdom.
- ⁸⁵ Also at IPPP Durham University, Durham, United Kingdom.
- ⁸⁶ Also at Monash University, Faculty of Science, Clayton, Australia.
- ⁸⁷ Now at another international laboratory covered by a cooperation agreement with CERN.
- ⁸⁸ Also at Università di Torino, Torino, Italy.
- ⁸⁹ Also at Bethel University, St. Paul, Minnesota, USA.
- ⁹⁰ Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ⁹¹ Also at California Institute of Technology, Pasadena, California, USA.
- ⁹² Also at United States Naval Academy, Annapolis, Maryland, USA.
- ⁹³ Also at Bingöl University, Bingöl, Turkey.
- ⁹⁴ Also at Georgian Technical University, Tbilisi, Georgia.
- ⁹⁵ Also at Sinop University, Sinop, Turkey.
- ⁹⁶ Also at Erciyes University, Kayseri, Turkey.
- ⁹⁷ Also at Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH), Bucharest, Romania.
- ⁹⁸ Now at another institute formerly covered by a cooperation agreement with CERN.
- ⁹⁹ Also at Texas A&M University at Qatar, Doha, Qatar.
- ¹⁰⁰ Also at Kyungpook National University, Daegu, Korea.
- ¹⁰¹ Also at Imperial College, London, United Kingdom.
- ¹⁰² Now at Yerevan Physics Institute, Yerevan, Armenia.
- ¹⁰³ Also at another international laboratory covered by a cooperation agreement with CERN.
- ¹⁰⁴ Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- ¹⁰⁵ Also at another institute formerly covered by a cooperation agreement with CERN.
- ¹⁰⁶ Also at Northeastern University, Boston, Massachusetts, USA.
- ¹⁰⁷ Also at Universiteit Antwerpen, Antwerpen, Belgium.