

Strange hadron production in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

A. M. Sirunyan *et al.**
(CMS Collaboration)[†]



(Received 10 October 2019; accepted 6 April 2020; published 22 June 2020)

The transverse momentum (p_T) distributions of Λ , Ξ^- , and Ω^- baryons, their antiparticles, and K_S^0 mesons are measured in proton-proton (pp) and proton-lead (pPb) collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV over a broad rapidity range. The data, corresponding to integrated luminosities of 40.2 nb^{-1} and $15.6 \mu\text{b}^{-1}$ for pp and pPb collisions, respectively, were collected by the CMS experiment. The nuclear modification factor R_{pPb} , which is defined as the ratio of the particle yield in pPb collisions and a scaled pp reference, is measured for each particle. A strong dependence on particle species is observed in the p_T range from 2 to 7 GeV, where R_{pPb} for K_S^0 is consistent with unity, while an enhancement ordered by strangeness content and/or particle mass is observed for the three baryons. In pPb collisions, the strange hadron production is asymmetric about the nucleon-nucleon center-of-mass rapidity. Enhancements, which depend on the particle type, are observed in the direction of the Pb beam. The results are compared with predictions from EPOS LHC, which includes parametrized radial flow. The model is in qualitative agreement with the R_{pPb} data, but fails to describe the dependence on particle species in the yield asymmetries measured away from midrapidity in pPb collisions.

DOI: [10.1103/PhysRevC.101.064906](https://doi.org/10.1103/PhysRevC.101.064906)

I. INTRODUCTION

The transverse momentum (p_T) distributions of the particles produced in high-energy nuclear collisions can provide insights into the nature of the produced hot and dense matter, known as the quark-gluon plasma (QGP), and its dynamical evolution. Comparisons of the p_T spectra of hadrons produced in proton-proton (pp), proton-nucleus (pA), and nucleus-nucleus (AB) collisions are often used to elucidate the QGP properties. The many physical processes that contribute to hadron production involve distinct energy scales and therefore dominate different ranges in the p_T distributions in various collision systems. In heavy-ion collisions, hadrons with $p_T \lesssim 2$ GeV typically reflect the properties of the bulk system, such as the temperature at freeze-out, hadro-chemical composition, and collective expansion velocity. Measurements of identified hadrons at low p_T can be used to extract these properties [1–6].

At high $p_T (\gtrsim 8 \text{ GeV})$, particles are primarily produced through fragmentation of partons that have participated in a hard scattering involving a large momentum transfer. In AB collisions that create a QGP, these partons might lose energy traversing the medium, which would result in suppression

of high- p_T hadron production. The suppression is quantified by the nuclear modification factor R_{AB} , which is defined as the ratio of particle yields in AB collisions to those in pp collisions, scaled by the average number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, in the AB collisions:

$$R_{AB}(p_T) = \frac{dN^{AB}/dp_T}{\langle N_{\text{coll}} \rangle dN^{pp}/dp_T} = \frac{dN^{AB}/dp_T}{\langle T_{AB} \rangle d\sigma^{pp}/dp_T}. \quad (1)$$

The ratio of $\langle N_{\text{coll}} \rangle$ with the total inelastic pp cross section σ^{pp} , defined as $\langle T_{AB} \rangle = \langle N_{\text{coll}} \rangle / \sigma^{pp}$, is known as the nuclear overlap function. Both $\langle N_{\text{coll}} \rangle$ and $\langle T_{AB} \rangle$ can be calculated from a Glauber model of the nuclear collision geometry [7].

In the intermediate p_T region ($2 \lesssim p_T \lesssim 8 \text{ GeV}$), the dominant particle production mechanism switches from soft processes to hard scattering. For a given particle species, this transition may happen in a momentum range that depends on the mass of the particle and on its quark composition. Particles of greater mass are boosted to larger transverse momentum because of radial flow (common velocity field for all particles) [8], and baryon production may be enhanced ($R_{AB} > 1$) as a result of hadronization by recombination [9–11]. In addition, there are several initial-state effects that can result in $R_{AB} \neq 1$. Momentum broadening from multiple scattering of projectile partons by the target nucleus before undergoing a hard scattering [12,13] can cause an enhancement. Alternatively, nuclear shadowing [14], i.e., suppression of the parton distribution functions in the nucleus relative to those in the proton in the small parton fractional momentum range ($x < 0.01$), can lead to suppression in hadron production. The study of nuclear modification factors over a broad momentum range and for multiple particle species is

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

[†]cms-publication-committee-chair@cern.ch

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

a valuable tool for disentangling different effects and for constraining theoretical models.

Traditionally, pA and deuteron-nucleus (dA) collisions have been considered as reference systems that do not produce a hot QCD medium [15–18] and therefore would only carry information about cold nuclear matter initial-state effects. However, in the last few years there have been extensive studies of two- and multiparticle azimuthal correlations in high-multiplicity pp and pPb collisions at the LHC [19–22], which indicate collective behavior similar to that observed in heavy-ion collisions, where it is attributed to collective flow in the QGP. Recent measurements from the BNL Relativistic Heavy Ion Collider (RHIC) use high-multiplicity pAu [23], dAu [24], and 3HeAu collisions [25] to study the effects of the initial geometry on the final-state particle correlations. They find that hydrodynamic models that include short-lived QGP droplets provide simultaneous quantitative description of the measurements [26]. Additionally, measurements of strange-particle production by the ALICE Collaboration [27,28] indicate strangeness enhancement in pPb and high-multiplicity pp collisions—a signature that has long been considered an important indication of QGP formation [29]. Measurements of low- p_T spectra of strange particles produced in high multiplicity small-system collisions [27,30] are consistent with the presence of radial flow [31]. On the other hand, jet quenching is not observed at high p_T in pPb collisions [32–36]. Thus, further studies of the rapidity and p_T dependence of strange-particle production from low to high p_T can provide significant information on the nature of the QCD medium produced in small systems.

In pPb collisions, radial flow, nuclear shadowing, and multiple scattering are all expected to have different effects on particle production in the forward (p -going) and backward (Pb-going) rapidity regions. Radial flow is expected to be greater in the Pb-going than the p -going direction and therefore to produce a stronger mass dependence on the Pb-going side [37,38]. The effect of nuclear shadowing is expected to be more prominent in the p -going direction, where smaller x fractions are accessed in the nucleus. This should result in larger R_{pPb} values in the Pb-going as compared with the p -going direction.

The effect of parton multiple scattering is not completely understood and has been shown to depend on multiple factors, e.g., whether the scatterings are elastic, inelastic, coherent or incoherent [12,39]. These predictions can be tested with measurements of R_{pPb} in the p - and Pb-going directions separately, and of the particle yield rapidity asymmetry Y_{asym} in pPb collisions, where

$$Y_{\text{asym}}(p_T) = \frac{d^2N(p_T)/dy_{\text{CM}}dp_T|_{y_{\text{CM}} \in [-b, -a]}}{d^2N(p_T)/dy_{\text{CM}}dp_T|_{y_{\text{CM}} \in [a, b]}}. \quad (2)$$

Here, y_{CM} is the rapidity computed in the center-of-mass frame of the colliding nucleons, a and b are always non-negative and, by definition, refer to the proton beam direction.

This paper presents measurements of strange hadron p_T spectra at $|y_{\text{CM}}| < 1.8$, $-1.8 < y_{\text{CM}} < 0$, and $0 < y_{\text{CM}} < 1.8$ in pp and pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. These measurements are shown for the K_S^0 and the sum of $\Lambda + \bar{\Lambda}$, $\Xi^- +$

Ξ^+ , and $\Omega^- + \bar{\Omega}^+$ (hereafter referred to as Λ , Ξ^- , and Ω^- , respectively). Based on these spectra, R_{pPb} for each particle species is studied as a function of p_T in the three rapidity ranges above. Because of limitations in the size of the data sample, the R_{pPb} of the Ω^- baryon is studied in the range $|y_{\text{CM}}| < 1.8$. To study the rapidity dependence in strange hadron production in pPb collisions, the K_S^0 and Λ spectra are measured in several additional rapidity ranges. The Y_{asym} is evaluated for $0.3 < |y_{\text{CM}}| < 0.8$, $0.8 < |y_{\text{CM}}| < 1.3$, and $1.3 < |y_{\text{CM}}| < 1.8$. The results are compared with predictions from the EPOS LHC model, which includes collective flow in pp and pPb collisions.

II. THE COMPACT MUON SOLENOID DETECTOR

The central feature of the Compact Muon Solenoid (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, and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. The silicon tracker measures charged particles within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules. The pixel detector comprises three barrel layers and two forward disks on each side of the interaction point. For nonisolated particles of $1 < p_T < 10$ GeV and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [40]. The forward hadron (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m from the interaction region, one on each end, and together they provide coverage in the range $3.0 < |\eta| < 5.2$. 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. [41]. The Monte Carlo (MC) simulation of the particle propagation and detector response is based on the GEANT4 [42] program.

III. DATA SAMPLES AND EVENT SELECTION

Minimum bias (MB) pp and pPb data used in this analysis were collected in 2015 and 2013 at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, corresponding to integrated luminosities of 40.2 nb^{-1} and $15.6 \mu\text{b}^{-1}$, respectively. In pPb collisions, the beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei. The data were collected in two different run conditions: one with the protons circulating in the clockwise direction in the LHC ring, and one with them circulating in the counterclockwise direction. By convention, the proton beam rapidity is taken to be positive when combining the data from the two run configurations. Because of the asymmetric beam conditions, the nucleon-nucleon center of mass in the pPb collisions moves with speed $\beta = 0.434$ in the laboratory frame. As a consequence, a massless particle emitted at $y_{\text{CM}} = 0$ will be detected at a rapidity of 0.465 in the laboratory frame.

The triggers and event selections are the same as those discussed for pp collisions in Refs. [43,44], requiring one energy deposit above the readout threshold of 3 GeV on either side of the HF calorimeters. The MB pPb events are triggered by requiring at least one reconstructed track with $p_T > 0.4$ GeV in the pixel detector.

In the subsequent analysis of both collision systems, events are selected by requiring at least one reconstructed collision vertex with two or more associated tracks. All vertices are required to be within 15 cm of the nominal interaction point along the beam axis and 0.15 cm transverse to the beam axis direction. Beam-related background is suppressed by rejecting events in which less than 25% of all reconstructed tracks satisfy the high-purity selection defined in Ref. [40]. In addition, having at least one HF calorimeter tower on each side of the HF with more than 3 GeV of total energy is required for pPb collisions to further remove background events. There is a 3% probability to have at least one additional interaction in the same bunch crossing (pileup) in the pPb data sample. The procedure used to reject pileup events in pPb collisions is described in Ref. [20]. It is based on the number of tracks associated with each reconstructed vertex and the distance between different vertices. The pileup-rejection efficiency is found to be $92\% \pm 2\%$, which is confirmed by using a low pileup data sample. The average pileup (the mean of the Poisson distribution of the number of collisions per bunch crossing) is approximately 0.9 in pp collisions. Following the same procedure as in Ref. [43], all the reconstructed vertices are selected to extract the pp strange-particle spectra. The pp integrated luminosity [45] is used to normalize the spectrum in pp collisions.

The PYTHIA 8.209 generator [46] with the underlying event tune CUETP8M1 [47] is used to simulate the selection efficiency in pp collisions. The efficiency to identify inelastic events is 95%. For pPb collisions, the selection efficiency is estimated with respect to a detector-independent class of collisions termed “double-sided” (DS) events, which are very similar to those that pass the HF selection criteria described above. A DS event is defined as a collision producing at least one particle of lifetime $c\tau > 10^{-18}$ m with energy $E > 3$ GeV in the region $3 < \eta < 5$, and another such particle in the region $-5 < \eta < -3$. In a simulated sample of pPb DS events produced using version 1.383 [48] of the HIJING MC generator [49], the above selection has a 99% selection efficiency. A similar study using the EPOS LHC generator shows less than 1% difference. In MC samples produced by EPOS LHC and HIJING, DS events correspond to 94%–97% of the hadronic inelastic pPb collisions. A procedure similar to that in Refs. [36,43] is used to correct the strange-particle spectra in pp and pPb collisions to spectra for inelastic collisions and DS events, respectively, with multiplicity-dependent correction factors. The values of R_{pPb} will decrease by 3%–6% if the normalization of the pPb spectra are corrected for the efficiency of detecting inelastic collisions instead of DS events.

IV. PARTICLE RECONSTRUCTION AND YIELDS

The K_S^0 , Λ , Ξ^- , and Ω^- candidates in this paper are identified and analyzed following the procedure used in previous

analyses [30,50]. The K_S^0 and Λ (generally referred to as V^0) candidates are reconstructed via their decay topology by combining pairs of oppositely charged tracks that are displaced from the primary vertex to define a secondary vertex. The mass ranges are indicated by the horizontal axes of Fig. 1. In the K_S^0 reconstruction, the two tracks are assumed to be pions. For Λ reconstruction, the track with lower momentum is assumed to be a pion, while the one with higher momentum is assumed to be a proton. To optimize the reconstruction of V^0 particles, requirements are applied to the three-dimensional (3D) distance of closest approach (DCA) significance of the V^0 decay products with respect to the primary vertex. This significance, defined as the 3D DCA between the decay products and the primary vertex divided by its uncertainty, must be larger than two for both daughter tracks. To further reduce the background from random combinations of tracks, the 3D DCA significance of the V^0 candidates with respect to the primary vertex cannot exceed 2.5. Because of the long lifetime of the V^0 particles, the 3D decay length significance, which is the 3D distance between the primary and V^0 vertices divided by its uncertainty, must be larger than three. To remove K_S^0 candidates misidentified as Λ particles, the Λ candidate mass assuming both tracks to be pions must differ from the nominal K_S^0 mass value [51] by more than 20 MeV. A similar procedure is done to remove Λ candidates misidentified as K_S^0 particles. To remove photon conversions to an electron-positron pair, the V^0 candidate mass must exceed 15 MeV if the tracks are both assumed to have the electron mass.

For the Ξ^- and Ω^- baryon reconstruction, a previously reconstructed Λ candidate is combined with an additional charged track carrying the correct charge sign, to define a common secondary vertex. This track is assumed to be a pion (kaon) in Ξ^- (Ω^-) reconstruction. Since the Λ candidate in the reconstruction of Ξ^- and Ω^- is a secondary particle, the 3D separation significance between the Λ candidate vertex and the primary vertex is required to be larger than 10. Additionally, the 3D DCA significance requirement for the pion track from the Λ candidate is increased from two to three, and this has the effect of reducing the background in the reconstruction of Ξ^- and Ω^- . The 3D DCA significance of a pion (kaon) track from the Ξ^- (Ω^-) baryon decay with respect to the primary vertex is required to be larger than four. To ensure that the reconstructed Ξ^- and Ω^- candidates are primary particles, their 3D DCA significance with respect to the primary vertex is required to be less than three.

The invariant-mass distributions of reconstructed K_S^0 , Λ , Ξ^- , and Ω^- candidates in the range $|y_{CM}| < 1.8$ are shown in Fig. 1 for pPb events. Prominent mass peaks are visible, with little background. The solid lines show the results of a maximum likelihood fit. In this fit, each strange-particle mass peak is modeled using a sum of two Gaussian functions with a common mean. The “average σ ” values in Fig. 1 are the square root of the weighted average of the variances of the two Gaussian functions. The background is modeled by using a quadratic function for the K_S^0 mesons, and with the analytic form Cq^D for the baryons to mimic the available phase-space volume, where q is the difference between the mass of the

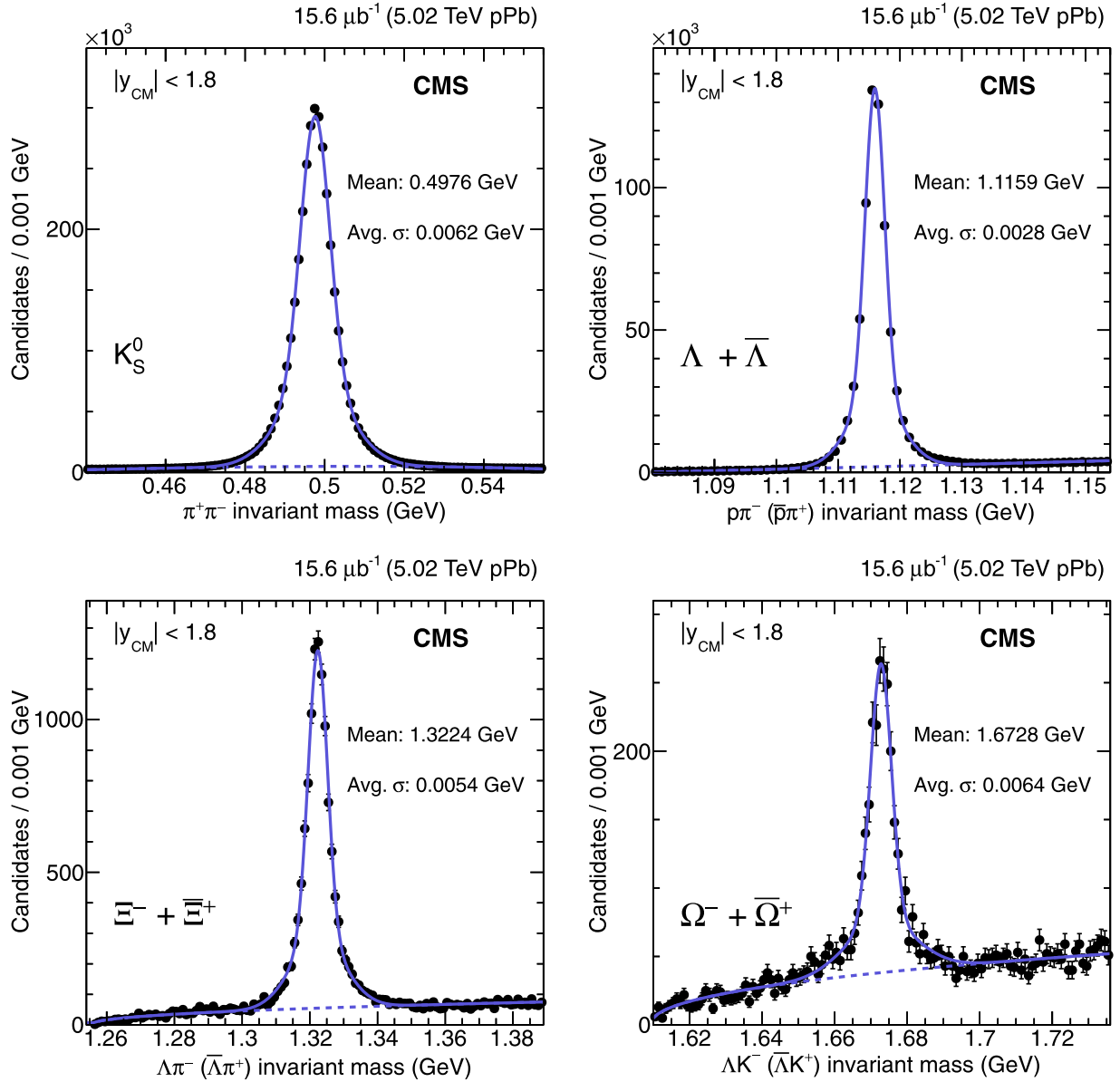


FIG. 1. Invariant-mass distribution of K_S^0 (upper left), $\Lambda + \bar{\Lambda}$ (upper right), $\Xi^- + \bar{\Xi}^+$ (lower left), and $\Omega^- + \bar{\Omega}^+$ (lower right) candidates within $|y_{\text{CM}}| < 1.8$ in pPb collisions. The solid lines show the results of fits described in the text. The dashed lines indicate the fitted background component.

mother candidate and the sum of the assumed two daughter track masses, and C and D are free parameters. These fit functions are found to provide a reasonable description of the signal and background with relatively few free parameters. The fits are performed over the mass ranges indicated by the limits of the horizontal axes in each panel of Fig. 1 to obtain the raw strange-particle yields $N_{K_S^0}^{\text{raw}}$, N_{Λ}^{raw} , $N_{\Xi^-}^{\text{raw}}$, and $N_{\Omega^-}^{\text{raw}}$.

The raw strange-particle yield is corrected for the branching fraction (B), acceptance (α), and reconstruction efficiency (ϵ), using simulations based on the EPOS LHC event generator [38] and a GEANT4 model of the CMS detector. The corrected

yield, $N_{K_S^0}^{\text{corr}}$, $N_{\Lambda}^{\text{corr}}$, $N_{\Xi^-}^{\text{corr}}$, $N_{\Omega^-}^{\text{corr}}$ is given by

$$\begin{aligned}
 N_{K_S^0}^{\text{corr}} &= \frac{N_{K_S^0}^{\text{raw}}}{B\alpha\epsilon}, \\
 N_{\Lambda}^{\text{corr}} &= \frac{N_{\Lambda}^{\text{raw}}}{B\alpha\epsilon}, \\
 N_{\Xi^-}^{\text{corr}} &= \frac{N_{\Xi^-}^{\text{raw}}}{B\alpha\epsilon}, \\
 N_{\Omega^-}^{\text{corr}} &= \frac{N_{\Omega^-}^{\text{raw}}}{B\alpha\epsilon},
 \end{aligned} \tag{3}$$

where $B\alpha\epsilon$ is obtained by the ratio of reconstructed yield to generated yield of prompt strange particles in MC simulations. The corrections are obtained separately in each rapidity range under study.

The raw Λ particle yield also contains a contribution from decays of Ξ^- and Ω^- particles. This ‘‘nonprompt’’ contribution is largely determined by the relative ratio of Ξ^- to Λ yield since the contribution from Ω^- particles is negligible. While stringent requirements on the significance of the 3D DCA for the Λ candidates with respect to the primary vertex remove a large fraction of nonprompt Λ candidates, up to 4% of the Λ candidates from simulations are found to be nonprompt at intermediate p_T . The method used to account for the nonprompt Λ contribution is the same as in the previous analysis [30]. If the ratio of Ξ^- to Λ yield is modeled precisely in MC generators, contamination of nonprompt Λ particles will be eliminated in the correction procedure using Eq. (3). Otherwise, an additional correction for the residual effect is necessary. As the Ξ^- particle yields are explicitly measured in this analysis, this residual correction factor can be derived from data as

$$f_{\Lambda, np}^{\text{residual}} = 1 + f_{\Lambda, np}^{\text{raw, MC}} \left(\frac{N_{\Xi^-}^{\text{corr}}/N_{\Lambda}^{\text{corr}}}{N_{\Xi^-}^{\text{MC}}/N_{\Lambda}^{\text{MC}}} - 1 \right), \quad (4)$$

where $f_{\Lambda, np}^{\text{raw, MC}}$ denotes the fraction of nonprompt Λ candidates in the reconstructed sample, and is obtained from MC simulation. The $N_{\Xi^-}^{\text{corr}}/N_{\Lambda}^{\text{corr}}$ and $N_{\Xi^-}^{\text{MC}}/N_{\Lambda}^{\text{MC}}$ terms are the Ξ^- -to- Λ ratios from the data after applying corrections in Eq. (3), and from generator-level MC simulations, respectively. The final measured Λ particle yield is given by $N_{\Lambda}^{\text{corr}}/f_{\Lambda, np}^{\text{residual}}$. Based on studies using EPOS LHC, which has a similar Ξ^- -to- Λ ratio as the data, the residual nonprompt contributions to Λ yields are found to be negligible. Note that $N_{\Lambda}^{\text{corr}}$ used in Eq. (4) is first derived by using Eq. (3), which in principle contains the residual nonprompt Λ contributions. Therefore, by applying Eq. (4) in an iterative fashion, $N_{\Lambda}^{\text{corr}}$ will approach a result corresponding to prompt Λ particles. A second iteration of the correction procedure was found to have an effect of less than 0.1% of the Λ baryon yield, and hence was not pursued. The nonprompt contributions to Ξ^- and Ω^- baryon yields are found to be negligible, since the absolute yields and branching ratios of the hadrons that feed into them are much smaller than those for Λ baryons.

V. SYSTEMATIC UNCERTAINTIES

The dominant sources of systematic uncertainty are associated with the strange-particle reconstruction, especially the efficiency determination. Tables I and II summarize the sources of systematic uncertainties in the K_S^0 , Λ , Ξ^- , and Ω^- p_T spectra, R_{pPb} , and Y_{asym} for different y_{CM} ranges in both pp and pPb collisions.

The systematic uncertainty from the yield extraction is evaluated with different background fit functions and methods for extracting the yields. The background fit function is varied to a third-order polynomial for the systematic studies. The yields are compared between integrating over the signal functions and counting the yield from the signal region of

TABLE I. Summary of different sources of systematic uncertainties in K_S^0 , Λ , Ξ^- , and Ω^- p_T spectra and R_{pPb} measurements for different y_{CM} ranges in both pp and pPb collisions. The ranges quoted cover both the p_T and the rapidity dependence of the uncertainties.

Source	K_S^0 (%)	Λ (%)	Ξ^- (%)	Ω^- (%)
Yield extraction	0–2	0–4	2	3
Selection criteria	1–4	1–5	3	6
Momentum resolution	1	1	1	1
Tracking efficiency	8	8	12	12
Feed-down correction		2–3		
Pileup effect (pp only)	1–2.3	1–2	3	3
Beam direction (pPb only)	1–4	1–5	3	4
Integrated lum. (pp only)	2.3	2.3	2.3	2.3
$\langle T_{pPb} \rangle$ (for R_{pPb})	4.8	4.8	4.8	4.8
Total (yields in pp coll.)	8.6–9.3	8.9–10.6	13.1	14.3
Total (yields in pPb coll.)	8.2–10.1	8.6–12.3	13.8	15.1
Total (R_{pPb})	3.1–5.6	4.3–10.4	6.8	10.8

the histograms. On the basis of these studies, systematic uncertainties of 0%–4% are assigned to the yields. Systematic effects related to the selection of the strange-particle candidates are evaluated by varying the selection criteria, resulting in an uncertainty of 1%–6%. The impact of finite momentum resolution on the spectra is estimated using the EPOS LHC event generator. Specifically, the generator-level p_T spectra of the strange particles are smeared by the momentum resolution, which is determined from the momentum difference between the generator-level and the matched reconstructed-level particles. The difference between the smeared and original spectra is less than 1%. The systematic uncertainty in determining the efficiency of a single track is 4% [52]. The tracking efficiency is strongly correlated with the lifetime of a particle, because when and where a particle decays determine how efficiently the detector captures its decay products. We observe agreement of the strange particle lifetime distribution ($c\tau$) between data and simulation, which provides a cross-check. This translates into a systematic uncertainty in the reconstruction efficiency of 8% for the K_S^0 and Λ particles, and 12% for the Ξ^- and Ω^- particles. The systematic uncertainty associated with a feed-down effect for the Λ candidate spectra is evaluated through propagation of the systematic

TABLE II. Summary of systematic uncertainties in the Y_{asym} measurements in pPb collisions. The ranges quoted cover both the p_T and the rapidity dependence of the uncertainties. Because of limitations in the size of the data sample, the Y_{asym} of Ξ^- and Ω^- are not presented.

Source	K_S^0 (%)	Λ (%)
Yield extraction		0–3
Selection criteria	1–5	1–6
Momentum resolution	1	1
Feed-down correction		2–3
Beam direction	2–4	2–6
Total (Y_{asym})	2.4–6.5	3.2–9.3

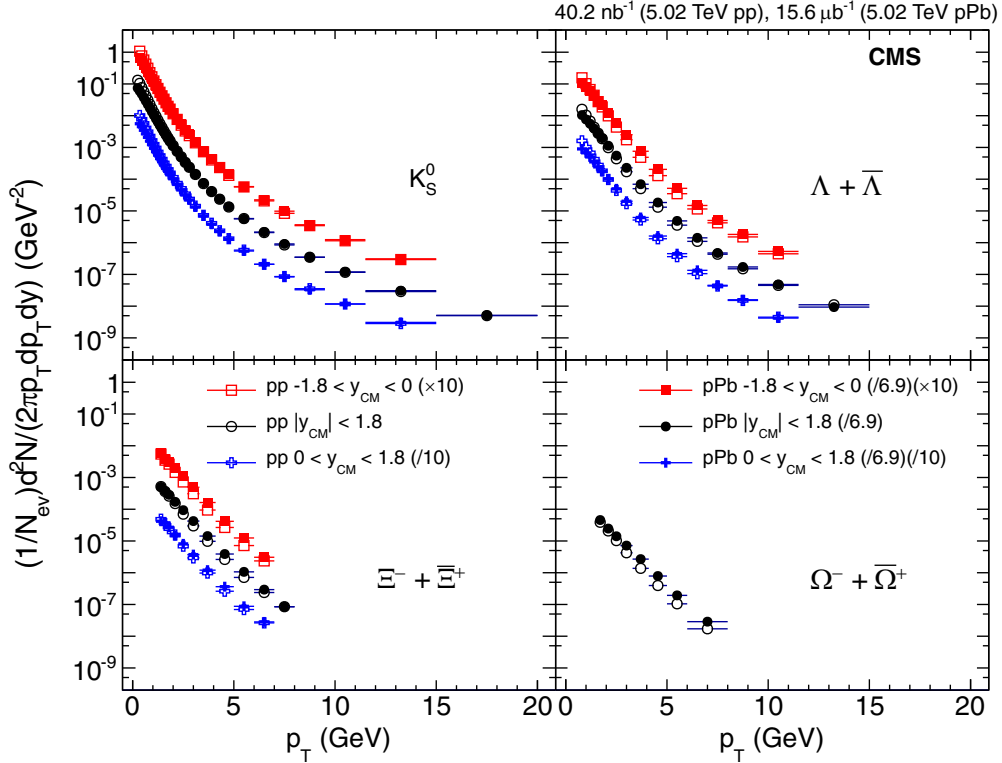


FIG. 2. The invariant p_T -differential spectra of K_S^0 (upper left), $\Lambda + \bar{\Lambda}$ (upper right), $\Xi^- + \bar{\Xi}^+$ (lower left), and $\Omega^- + \bar{\Omega}^+$ (lower right) for $|y_{CM}| < 1.8$, $-1.8 < y_{CM} < 0$, and $0 < y_{CM} < 1.8$ in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Spectra for different y_{CM} ranges are scaled by factors of powers of 10, with $|y_{CM}| < 1.8$ not scaled. To compare the strange-particle spectra in pp and pPb collisions directly, the spectra in pPb collisions are divided by 6.9, which is the average number of binary nucleon-nucleon collisions. The vertical bars correspond to statistical uncertainties, which are usually smaller than the marker size, while the horizontal bars represent the bin width.

uncertainty in the $N_{\Xi^-}^{\text{corr}}/N_{\Lambda}^{\text{corr}}$ ratio in Eq. (4) to the $f_{\Lambda, np}^{\text{residual}}$ factor, and is found to be 2%–3%. Systematic uncertainty introduced by pileup effects for pp data is estimated to be 1%–3%. This uncertainty is evaluated through the comparison of strange-particle spectra between data with low and high pileup. The uncertainty associated with pileup is negligible for the pPb data. In pPb collisions, the direction of the p and Pb beams were reversed during the course of the data collection. A comparison of the particle p_T spectra in both data periods yields an uncertainty of 1%–5%. The uncertainty in the integrated luminosity for pp collisions is 2.3% [45]. As in Ref. [36], the uncertainty in $\langle T_{pPb} \rangle$ is 4.8%.

Since the same tracking algorithm is used in the pp and pPb data reconstruction, the uncertainties in the tracking efficiency largely cancel in the R_{pPb} ratio and are negligible compared with other sources of systematic uncertainty, which are uncorrelated between the two collision systems and are summed in quadrature. The overall uncertainty in R_{pPb} for the different particle species are listed in the bottom row of Table I. These numbers exclude the luminosity and $\langle T_{pPb} \rangle$ uncertainties, which are common to all data points.

The uncertainties in Y_{asym} are evaluated in a similar way as for the particle spectra, but the effects of the different sources of uncertainty are considered directly in the values of Y_{asym} . The tracking efficiency largely cancels in the ratio, while the effects from the detector acceptance are accounted for by comparing the data sets taken with different beam directions.

The remaining uncertainties are uncorrelated and are summed up in quadrature, as detailed in Table II.

VI. RESULTS

A. Transverse momentum spectra and nuclear modification factor

The invariant p_T -differential spectra of K_S^0 , Λ , Ξ^- , and Ω^- particles with $|y_{CM}| < 1.8$, $-1.8 < y_{CM} < 0$, and $0 < y_{CM} < 1.8$ in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented in Fig. 2. For R_{pPb} calculations, the pp spectrum is measured as a differential cross section with normalization determined from the integrated luminosity. To convert the cross section to a per-event yield for comparison on the same figure, it is divided by 70 ± 5 mb [43,51], which corresponds to the total inelastic pp cross section. To compare the strange-particle spectra in pp and pPb collisions directly, the spectra in pPb collisions are divided by the average number of binary nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle = 6.9 \pm 0.5$, which is obtained from a Glauber MC simulation [7]. The nuclear radius and skin depth utilized are 6.62 ± 0.06 fm and 0.546 ± 0.010 fm, respectively, and a minimal distance between the nucleons of 0.04 ± 0.04 fm is imposed [43].

With the efficiency-corrected strange-particle spectra, the R_{pPb} values of K_S^0 , Λ , Ξ^- , and Ω^- particles are calculated in different y_{CM} ranges. Figure 3 shows the R_{pPb} of each particle

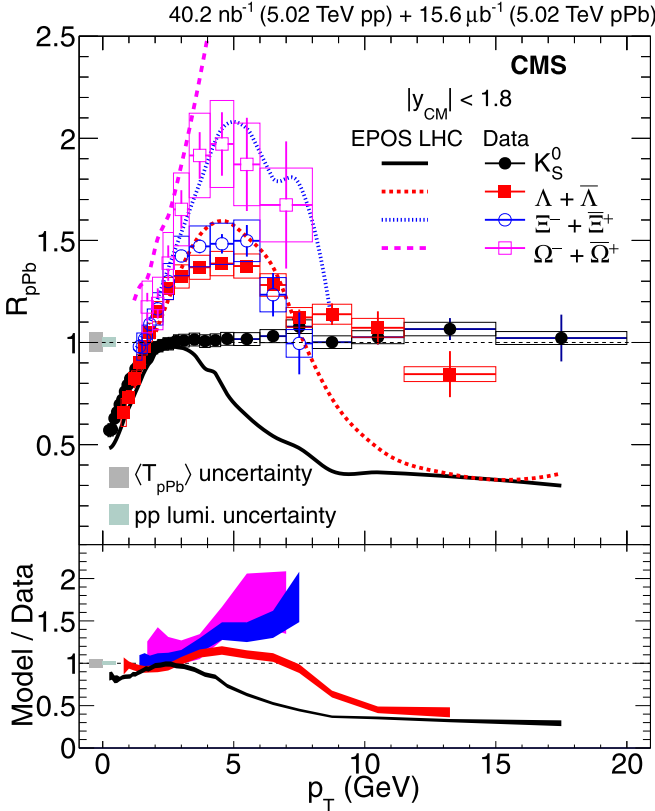


FIG. 3. (Upper) Nuclear modification factors for K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), $\Xi^- + \bar{\Xi}^+$ (blue open circles), and $\Omega^- + \bar{\Omega}^+$ (purple open squares) for $|y_{CM}| < 1.8$ in pPb collisions are presented. The vertical bars correspond to statistical uncertainties, and the horizontal bars represent the bin width, while the open boxes around the markers denote the systematic uncertainties. The $\langle T_{pPb} \rangle$ and pp integrated luminosity uncertainties are represented by the shaded boxes around unity. The results are compared with the EPOS LHC predictions, which include collective flow in pp and pPb collisions. The data and predictions share the same color for each particle species. (Lower) The ratios of nuclear modification factors for K_S^0 , $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$, and $\Omega^- + \bar{\Omega}^+$ of the EPOS LHC predictions to the measurements are shown. The bands represent the combination of statistical and systematic uncertainties.

species at $|y_{CM}| < 1.8$. The R_{pPb} values of K_S^0 are consistent with unity for $p_T > 2$ GeV. For baryons, the R_{pPb} of both Λ and Ξ^- reach unity for p_T somewhere between 7 and 8 GeV. This is consistent with the charged-particle R_{pPb} [36], which also shows no modification in the p_T range from 7 to 20 GeV. In the intermediate p_T range from 2 to 7 GeV, an enhancement with clear mass and strangeness-content ordering is observed for baryons with the greater mass and strangeness corresponding to larger R_{pPb} . The observed mass ordering is consistent with expectations from the radial-flow effect in hydrodynamic models [38]. The predictions from EPOS LHC, including collective flow in pp and pPb collisions, are compared with data in Fig. 3. The calculations indeed predict clear mass ordering for baryon R_{pPb} in this p_T range, with even stronger mass dependence than observed in data. At higher p_T , R_{pPb} of K_S^0 and Λ calculated from the EPOS LHC model is

markedly smaller than the data because of the strong screening in nuclear collisions in EPOS LHC. This screening is needed to reduce the number of binary collisions in the initial state in order to produce the correct multiplicity [38]. It is not clear from current measurements whether effects from recombination play a role. This can be addressed by studies that include identified baryons and mesons with similar masses, such as the measurements of proton and ϕ meson R_{dAu} at RHIC [53]. To fully understand particle production in this p_T range, more theoretical calculations including the recombination models are needed. For p_T values less than 2 GeV, the predicted R_{pPb} values from the EPOS LHC model qualitatively agree with the experimental results for each of the particle species. In this p_T range, R_{pPb} for K_S^0 and Λ become less than unity, as expected for soft particle production.

The R_{pPb} values of K_S^0 , Λ , and Ξ^- particles for $-1.8 < y_{CM} < 0$ and $0 < y_{CM} < 1.8$ are presented as functions of p_T in Fig. 4. Because of the limitations in the size of the data sample, the R_{pPb} of the Ω^- baryon is not shown in the p - and Pb -going direction separately. Above $p_T > 2$ GeV, R_{pPb} of all three species are found to be larger in the Pb -going direction than the p -going direction, with a stronger splitting between K_S^0 and baryons in the Pb -going direction. This trend is consistent with expectations from the radial-flow effect in hydrodynamic models [37,38]. The predicted values of R_{pPb} for Ξ^- particles from the EPOS LHC model are larger than those from data in both p -going and Pb -going directions. Momentum broadening from parton multiple scattering as implemented in Ref. [12] predicts a stronger enhancement in the p -going direction, which is inconsistent with the results in Fig. 4. However, this could be explained by the prediction that this effect is small compared with the nuclear shadowing effect [54] at the LHC energies. The probed parton momentum fraction x in the nucleus is less than 0.02 for the p_T and rapidity considered in this analysis. Therefore, these measurements are sensitive to the shadowing effect, and R_{pPb} should be smaller in the p -going direction because the probed x fractions in the nucleus are smaller. The combined treatment of initial and final-state scatterings described in Ref. [39] is in qualitative agreement with the data.

B. The asymmetry of particle-yield rapidity

The invariant p_T -differential spectra of K_S^0 and Λ for five different y_{CM} ranges in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are presented in Fig. 5. Figure 6 shows the Y_{asym} (Pb -going direction in the numerator) as functions of p_T for K_S^0 , Λ and charged particles [36] for different rapidity (pseudorapidity) ranges. The observed Y_{asym} values depend both on p_T and particle species, and these dependencies are more pronounced in the forward (larger) y_{CM} ranges. The Y_{asym} are larger in the forward region, consistent with expectations from nuclear shadowing, and overall larger than unity in all measured $|y_{CM}|$ ranges. Significant departures from unity, and particle-species dependencies are seen away from midrapidity in the region $1.3 < y_{CM} < 1.8$. As a function of p_T for all particle species, the Y_{asym} values first rise and then fall, approaching unity at higher p_T . The peak values for Λ are shifted to higher p_T compared with the those of K_S^0 and charged

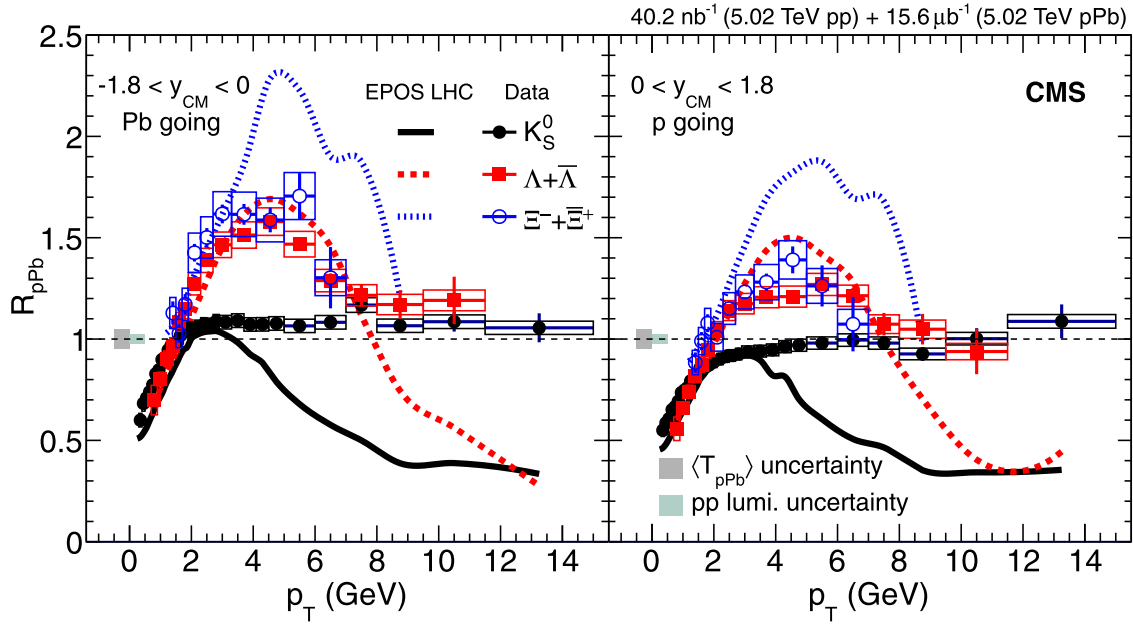


FIG. 4. Nuclear modification factors of K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), and $\Xi^- + \bar{\Xi}^+$ (blue open circles) particles for $-1.8 < y_{\text{CM}} < 0$ (Pb-going, left) and $0 < y_{\text{CM}} < 1.8$ (p -going, right) in $p\text{Pb}$ collisions are presented. The vertical bars correspond to statistical uncertainties, and the horizontal bars represent the bin width, while the open boxes around the markers denote the systematic uncertainties. The $\langle T_{p\text{Pb}} \rangle$ and pp integrated luminosity uncertainties are represented by the shaded boxes around unity. The results are compared with the EPOS LHC predictions, which include collective flow in pp and $p\text{Pb}$ collisions [38]. The data and predictions share the same color for each particle species.

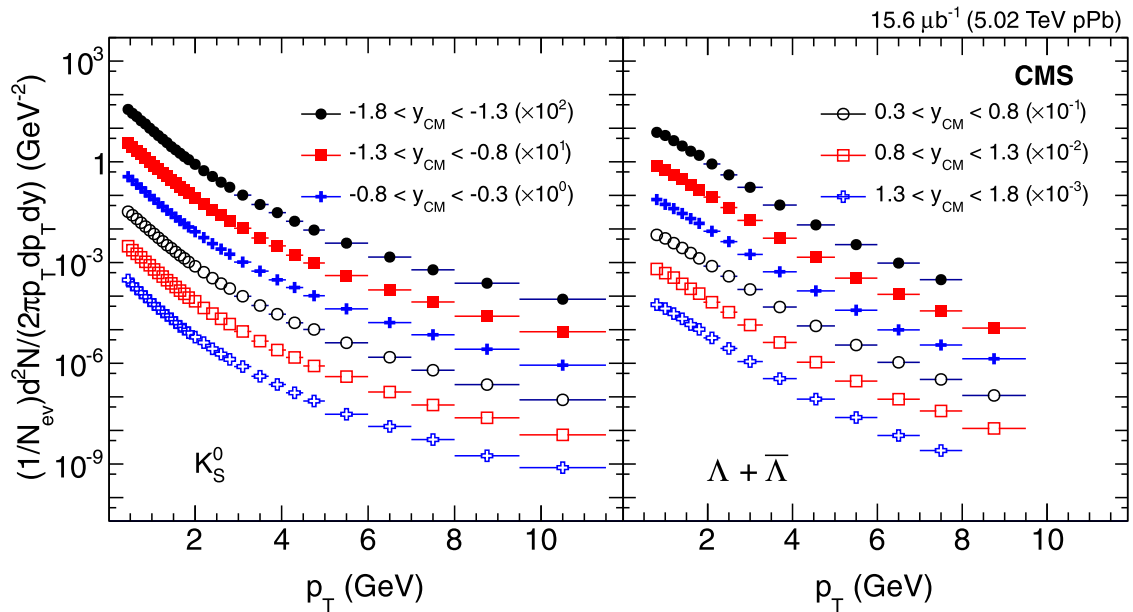


FIG. 5. The invariant p_T -differential spectra of K_S^0 (left) and $\Lambda + \bar{\Lambda}$ (right) particles for $-1.8 < y_{\text{CM}} < -1.3$, $-1.3 < y_{\text{CM}} < -0.8$, $-0.8 < y_{\text{CM}} < -0.3$, $0.3 < y_{\text{CM}} < 0.8$, $0.8 < y_{\text{CM}} < 1.3$, and $1.3 < y_{\text{CM}} < 1.8$ in $p\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Spectra in different y_{CM} ranges are scaled by factors of powers of 10, with $-0.8 < y_{\text{CM}} < -0.3$ not scaled. The vertical bars correspond to statistical uncertainties, which are usually smaller than the marker size, while the horizontal bars represent the bin width.

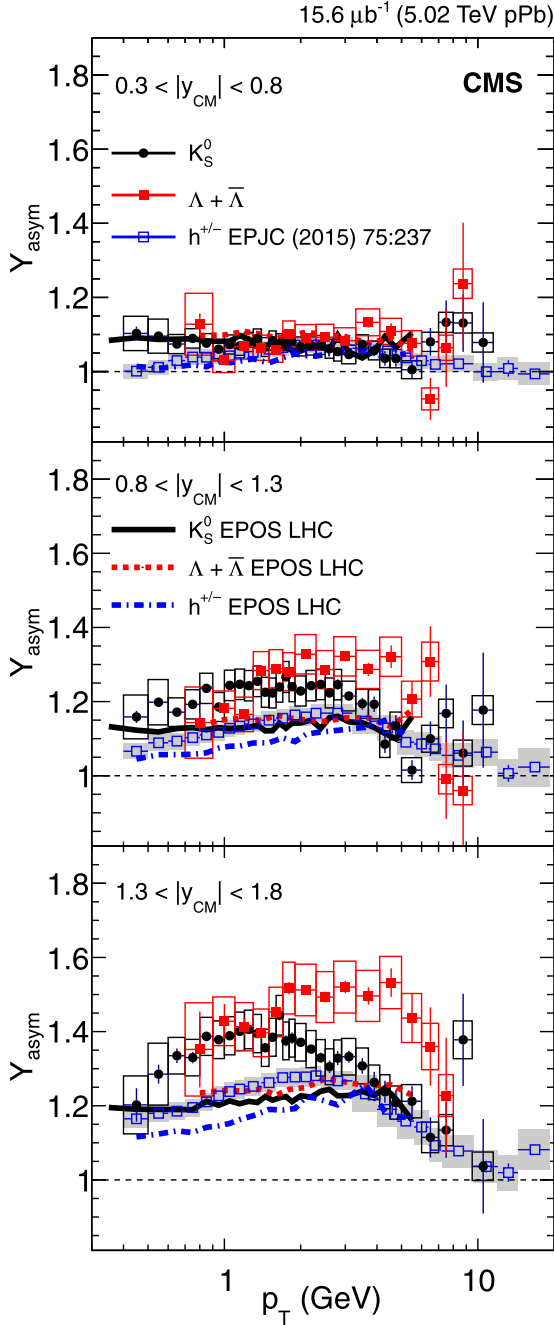


FIG. 6. The Y_{asym} of K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), and charged particles (blue open squares) at $0.3 < |y_{\text{CM}}| < 0.8$, $0.8 < |y_{\text{CM}}| < 1.3$, and $1.3 < |y_{\text{CM}}| < 1.8$ ($|\eta_{\text{CM}}|$ ranges for charged particles) in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The vertical bars correspond to statistical uncertainties, and the horizontal bars represent the bin width, while the boxes around the markers denote the systematic uncertainties. The results are compared with the EPOS LHC predictions, which include collective flow in pp and pPb collisions [38]. The data and predictions share the same color for each particle species.

particles, which include a p_T -dependent mixture of charged hadrons. The Y_{asym} of K_S^0 and Λ are larger than those of charged particles. These detailed structures, with mass dependence and meson-baryon differences, will provide strong

constraints on hydrodynamic and recombination models in which particle species dependencies arise from the differences in mass or number of constituent quarks, respectively. The results of Y_{asym} are compared with the EPOS LHC predictions for K_S^0 , Λ , and inclusive charged particles produced in the three y_{CM} ranges. The Y_{asym} from EPOS LHC increases from mid- y_{CM} to forward y_{CM} , consistent with the trend of the data, but fails to describe the particle-species dependence at forward y_{CM} .

VII. SUMMARY

The transverse momentum (p_T) spectra of K_S^0 mesons, and Λ , Ξ^- , and Ω^- baryons (each summed with its antiparticle) have been measured in proton-proton and proton-lead collisions in several nucleon-nucleon center-of-mass rapidity (y_{CM}) ranges. The nuclear modification factors of K_S^0 , Λ , and Ξ^- in $|y_{\text{CM}}| < 1.8$, $-1.8 < y_{\text{CM}} < 0$, and $0 < y_{\text{CM}} < 1.8$ ranges are measured. In the p_T range from 2 to 7 GeV, enhancements are visible and a clear mass ordering is observed, which is consistent with expectations from radial-flow effects in hydrodynamic models. For each particle species, the nuclear modification factor R_{pPb} in the Pb-going side is higher than in the p -going side. This trend is also consistent with expectations from radial flow. The rapidity asymmetries Y_{asym} in K_S^0 and Λ yields between equivalent positive and negative y_{CM} are presented as functions of p_T in $0.3 < |y_{\text{CM}}| < 0.8$, $0.8 < |y_{\text{CM}}| < 1.3$, and $1.3 < |y_{\text{CM}}| < 1.8$, and compared with those for charged particles. The Y_{asym} values are larger than unity in all three y_{CM} ranges with greater enhancements observed at more forward regions. The mass dependence of R_{pPb} in the EPOS LHC model, which includes collective flow, is stronger than that observed in the data. The model also describes the increasing trend of Y_{asym} from midrapidity to forward rapidity, but fails to describe the dependence on particle species at forward rapidity. The results presented in this paper provide new insights into particle production in pPb collisions at high energies.

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 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 and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKIFIA

(Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (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 Grants, Contracts No. 675440, No. 752730, and No. 765710 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science—EOS"—be.h project No. 30820817; the Beijing Municipal Science & Technology Commission, No. Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Mo-

mentum") Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKfIA research Grants No. 123842, No. 123959, No. 124845, No. 124850, No. 125105, No. 128713, No. 128786, and No. 129058 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, co-financed from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Ministry of Science and Education, Grant No. 3.2989.2017 (Russia); the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, Grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalís and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Nvidia Corporation; the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

-
- [1] I. G. Bearden *et al.* (NA44 Collaboration), Collective Expansion in High Energy Heavy Ion Collisions, *Phys. Rev. Lett.* **78**, 2080 (1997).
- [2] H. Appelshäuser *et al.* (NA49 Collaboration), Baryon Stopping and Charged Particle Distributions in Central Pb + Pb Collisions at 158 GeV per Nucleon, *Phys. Rev. Lett.* **82**, 2471 (1999).
- [3] C. Adler *et al.* (STAR Collaboration), Measurement of Inclusive Antiprotons from Au + Au Collisions at $\sqrt{s_{NN}} = 130$ GeV, *Phys. Rev. Lett.* **87**, 262302 (2001).
- [4] K. Adcox *et al.* (PHENIX Collaboration), Single identified hadron spectra from $\sqrt{s_{NN}} = 130$ GeV Au + Au collisions, *Phys. Rev. C* **69**, 024904 (2004).
- [5] S. S. Adler *et al.* (PHENIX Collaboration), Identified charged particle spectra and yields in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* **69**, 034909 (2004).
- [6] ALICE Collaboration, Centrality dependence of π , K , p production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, *Phys. Rev. C* **88**, 044910 (2013).
- [7] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Glauber modeling in high energy nuclear collisions, *Annu. Rev. Nucl. Part. Sci.* **57**, 205 (2007).
- [8] E. Schnedermann, J. Sollfrank, and U. W. Heinz, Thermal phenomenology of hadrons from 200A GeV S + S collisions, *Phys. Rev. C* **48**, 2462 (1993).
- [9] R. C. Hwa and C. B. Yang, Scaling distributions of quarks, mesons and proton for all p_T , energy and centrality, *Phys. Rev. C* **67**, 064902 (2003).
- [10] R. J. Fries, B. Müller, C. Nonaka, and S. A. Bass, Hadronization in Heavy-Ion Collisions: Recombination and Fragmentation of Partons, *Phys. Rev. Lett.* **90**, 202303 (2003).
- [11] V. Greco, C. M. Ko, and P. Levai, Parton Coalescence and Antiproton/Pion Anomaly at RHIC, *Phys. Rev. Lett.* **90**, 202302 (2003).
- [12] X.-N. Wang, Rapidity asymmetry in high-energy $d + A$ collisions, *Phys. Lett. B* **565**, 116 (2003).
- [13] Z.-B. Kang, I. Vitev, and H. Xing, Nuclear modification of high transverse momentum particle production in $p + A$ collisions at RHIC and LHC, *Phys. Lett. B* **718**, 482 (2012).
- [14] M. Arneodo, Nuclear effects in structure functions, *Phys. Rep.* **240**, 301 (1994).
- [15] S. S. Adler *et al.* (PHENIX Collaboration), Absence of Suppression in Particle Production at Large Transverse Momentum in $\sqrt{s_{NN}} = 200$ GeV $d + A$ Collisions, *Phys. Rev. Lett.* **91**, 072303 (2003).
- [16] B. B. Back *et al.* (PHOBOS Collaboration), Centrality Dependence of Charged Hadron Transverse Momentum Spectra in $d + A$ Collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. Lett.* **91**, 072302 (2003).
- [17] J. Adams *et al.* (STAR Collaboration), Evidence from $d + A$ Measurements for Final-State Suppression of High- p_T Hadrons in Au + Au Collisions at RHIC, *Phys. Rev. Lett.* **91**, 072304 (2003).
- [18] I. Arsene *et al.* (BRAHMS Collaboration), Transverse Momentum Spectra in Au + Au and $d + A$ Collisions at $\sqrt{s_{NN}} = 200$ GeV and the Pseudorapidity Dependence of High- p_T Suppression, *Phys. Rev. Lett.* **91**, 072305 (2003).
- [19] CMS Collaboration, Observation of long-range near-side angular correlations in proton-lead collisions at the LHC, *Phys. Lett. B* **718**, 795 (2013).
- [20] CMS Collaboration, Multiplicity and transverse momentum dependence of two- and four-particle correlations in pPb and $PbPb$ collisions, *Phys. Lett. B* **724**, 213 (2013).

- [21] CMS Collaboration, Evidence for Collective Multiparticle Correlations in p -Pb Collisions, *Phys. Rev. Lett.* **115**, 012301 (2015).
- [22] CMS Collaboration, Evidence for collectivity in pp collisions at the LHC, *Phys. Lett. B* **765**, 193 (2017).
- [23] C. Aidala *et al.* (PHENIX Collaboration), Measurement of long-range angular correlations and azimuthal anisotropies in high-multiplicity $p + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* **95**, 034910 (2017).
- [24] A. Adare *et al.* (PHENIX Collaboration), Measurement of Long-Range Angular Correlation and Quadrupole Anisotropy of Pions and (Anti)Protons in Central $d + Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. Lett.* **114**, 192301 (2015).
- [25] A. Adare *et al.* (PHENIX Collaboration), Measurements of Elliptic and Triangular Flow in High-Multiplicity $^3He + Au$ Collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. Lett.* **115**, 142301 (2015).
- [26] C. Aidala *et al.* (PHENIX Collaboration), Creation of quark-gluon plasma droplets with three distinct geometries, *Nat. Phys.* **15**, 214 (2019).
- [27] ALICE Collaboration, Multi-strange baryon production in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Lett. B* **758**, 389 (2016).
- [28] ALICE Collaboration, Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, *Nat. Phys.* **13**, 535 (2017).
- [29] J. Rafelski and B. Muller, Strangeness Production in the Quark-Gluon Plasma, *Phys. Rev. Lett.* **48**, 1066 (1982).
- [30] CMS Collaboration, Multiplicity and rapidity dependence of strange hadron production in pp , pPb , and $PbPb$ collisions at the LHC, *Phys. Lett. B* **768**, 103 (2017).
- [31] CMS Collaboration, Study of the production of charged pions, kaons, and protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Eur. Phys. J. C* **74**, 2847 (2014).
- [32] CMS Collaboration, Measurement of inclusive jet production and nuclear modifications in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Eur. Phys. J. C* **76**, 372 (2016).
- [33] ALICE Collaboration, Measurement of charged jet production cross sections and nuclear modification in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Lett. B* **749**, 68 (2015).
- [34] ALICE Collaboration, Transverse momentum dependence of inclusive primary charged-particle production in p -Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Eur. Phys. J. C* **74**, 3054 (2014).
- [35] ATLAS Collaboration, Transverse momentum, rapidity, and centrality dependence of inclusive charged-particle production in $\sqrt{s_{NN}} = 5.02$ TeV $p + Pb$ collisions measured by the ATLAS experiment, *Phys. Lett. B* **763**, 313 (2016).
- [36] CMS Collaboration, Nuclear effects on the transverse momentum spectra of charged particles in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Eur. Phys. J. C* **75**, 237 (2015).
- [37] P. Bozek, A. Bzdak, and V. Skokov, The rapidity dependence of the average transverse momentum in $p + Pb$ collisions at the LHC: The color glass condensate versus hydrodynamics, *Phys. Lett. B* **728**, 662 (2014).
- [38] T. Pierog, I. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner, EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider, *Phys. Rev. C* **92**, 034906 (2015).
- [39] Z.-B. Kang, I. Vitev, and H. Xing, Multiple scattering effects on inclusive particle production in the large- x regime, *Phys. Rev. D* **88**, 054010 (2013).
- [40] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, *J. Instrum.* **9**, P10009 (2014).
- [41] CMS Collaboration, The CMS experiment at the CERN LHC, *J. Instrum.* **3**, S08004 (2008).
- [42] S. Agostinelli *et al.* (GEANT4 Collaboration), GEANT4—A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [43] CMS Collaboration, Charged-particle nuclear modification factors in $PbPb$ and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *J. High Energy Phys.* **04** (2017) 039.
- [44] CMS Collaboration, The CMS trigger system, *J. Instrum.* **12**, P01020 (2017).
- [45] CMS Collaboration, CMS Luminosity Calibration for the pp Reference Run at $\sqrt{s} = 5.02$ TeV, CMS Physics Analysis Summary, Report No. CMS-PAS-LUM-16-001 (2016), <http://cdsweb.cern.ch/record/2235781>.
- [46] T. Sjöstrand, S. Ask, J. R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C. O. Rasmussen, and P. Z. Skands, An introduction to PYTHIA 8.2, *Comput. Phys. Commun.* **191**, 159 (2015).
- [47] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, *Eur. Phys. J. C* **76**, 155 (2016).
- [48] M. Gyulassy and X.-N. Wang, HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, *Comput. Phys. Commun.* **83**, 307 (1994).
- [49] X.-N. Wang and M. Gyulassy, HIJING: A Monte Carlo model for multiple jet production in pp , pA , and AA collisions, *Phys. Rev. D* **44**, 3501 (1991).
- [50] CMS Collaboration, Strange particle production in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV, *J. High Energy Phys.* **05** (2011) 064.
- [51] C. Patrignani *et al.* (Particle Data Group), Review of particle physics, *Chin. Phys. C* **40**, 100001 (2016).
- [52] CMS Collaboration, Measurement of Tracking Efficiency, CMS Physics Analysis Summary, Report No. CMS-PAS-TRK-10-002 (2010), <http://cdsweb.cern.ch/record/1279139>.
- [53] A. Adare *et al.* (PHENIX Collaboration), Spectra and ratios of identified particles in $Au + Au$ and $d + Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV, *Phys. Rev. C* **88**, 024906 (2013).
- [54] J. L. Albacete *et al.*, Predictions for $p + Pb$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Int. J. Mod. Phys. E* **22**, 1330007 (2013).

A. M. Sirunyan,¹ A. Tumasyan,¹ W. Adam,² F. Ambrogio,² E. Asilar,² T. Bergauer,² J. Brandstetter,² M. Dragicevic,² J. Erö,² A. Escalante Del Valle,² M. Flechl,² R. Frühwirth,^{2,a} V. M. Ghete,² J. Hrubec,² M. Jeitler,^{2,a} N. Krammer,² I. Krätschmer,² D. Liko,² T. Madlener,² I. Mikulec,² N. Rad,² H. Rohringer,² J. Schieck,^{2,a} R. Schöfbeck,² M. Spanring,² D. Spitzbart,² A. Taurok,² W. Waltenberger,² J. Wittmann,² C.-E. Wulz,^{2,a} M. Zarucki,² V. Chekhovsky,³ V. Mossolov,³ J. Suarez Gonzalez,³

E. A. De Wolf,⁴ D. Di Croce,⁴ X. Janssen,⁴ J. Lauwers,⁴ M. Pieters,⁴ M. Van De Klundert,⁴ H. Van Haevermaet,⁴ P. Van Mechelen,⁴ N. Van Remortel,⁴ S. Abu Zeid,⁵ F. Blekman,⁵ J. D'Hondt,⁵ I. De Bruyn,⁵ J. De Clercq,⁵ K. Deroover,⁵ G. Flouris,⁵ D. Lontkovskiy,⁵ S. Lowette,⁵ I. Marchesini,⁵ S. Moortgat,⁵ L. Moreels,⁵ Q. Python,⁵ K. Skovpen,⁵ S. Tavernier,⁵ W. Van Doninck,⁵ P. Van Mulders,⁵ I. Van Parijs,⁵ D. Beghin,⁶ B. Bilin,⁶ H. Brun,⁶ B. Clerbaux,⁶ G. De Lentdecker,⁶ H. Delannoy,⁶ B. Dorney,⁶ G. Fasanella,⁶ L. Favart,⁶ R. Goldouzian,⁶ A. Grebenyuk,⁶ A. K. Kalsi,⁶ T. Lenzi,⁶ J. Luetic,⁶ N. Postiau,⁶ E. Starling,⁶ L. Thomas,⁶ C. Vander Velde,⁶ P. Vanlaer,⁶ D. Vannerom,⁶ Q. Wang,⁶ T. Cornelis,⁷ D. Dobur,⁷ A. Fagot,⁷ M. Gul,⁷ I. Khvastunov,^{7,b} D. Poyraz,⁷ C. Roskas,⁷ D. Trocino,⁷ M. Tytgat,⁷ W. Verbeke,⁷ B. Vermassen,⁷ M. Vit,⁷ N. Zaganidis,⁷ H. Bakhshiansohi,⁸ O. Bondu,⁸ S. Brochet,⁸ G. Bruno,⁸ C. Caputo,⁸ P. David,⁸ C. Delaere,⁸ M. Delcourt,⁸ B. Francois,⁸ A. Giammanco,⁸ G. Krintiras,⁸ V. Lemaître,⁸ A. Magitteri,⁸ A. Mertens,⁸ M. Musich,⁸ K. Piotrkowski,⁸ A. Saggio,⁸ M. Vidal Marono,⁸ S. Wertz,⁸ J. Zobec,⁸ F. L. Alves,⁹ G. A. Alves,⁹ L. Brito,⁹ M. Correa Martins Junior,⁹ G. Correia Silva,⁹ C. Hensel,⁹ A. Moraes,⁹ M. E. Pol,⁹ P. Rebello Teles,⁹ E. Belchior Batista Das Chagas,¹⁰ W. Carvalho,¹⁰ J. Chinellato,^{10,c} E. Coelho,¹⁰ E. M. Da Costa,¹⁰ G. G. Da Silveira,^{10,d} D. De Jesus Damiao,¹⁰ C. De Oliveira Martins,¹⁰ S. Fonseca De Souza,¹⁰ H. Malbouisson,¹⁰ D. Matos Figueiredo,¹⁰ M. Melo De Almeida,¹⁰ C. Mora Herrera,¹⁰ L. Mundim,¹⁰ H. Nogima,¹⁰ W. L. Prado Da Silva,¹⁰ L. J. Sanchez Rosas,¹⁰ A. Santoro,¹⁰ A. Sznajder,¹⁰ M. Thiel,¹⁰ E. J. Tonelli Manganote,^{10,c} F. Torres Da Silva De Araujo,¹⁰ A. Vilela Pereira,¹⁰ S. Ahuja,^{11,12} C. A. Bernardes,^{11,12} L. Calligaris,^{11,12} T. R. Fernandez Perez Tomei,^{11,12} E. M. Gregores,^{11,12} P. G. Mercadante,^{11,12} S. F. Novaes,^{11,12} Sandra S. Padula,^{11,12} D. Romero Abad,^{11,12} A. Aleksandrov,¹³ R. Hadjiiska,¹³ P. Iaydjiev,¹³ A. Marinov,¹³ M. Misheva,¹³ M. Rodozov,¹³ M. Shopova,¹³ G. Sultanov,¹³ A. Dimitrov,¹⁴ L. Litov,¹⁴ B. Pavlov,¹⁴ P. Petkov,¹⁴ W. Fang,^{15,e} X. Gao,^{15,e} L. Yuan,¹⁵ M. Ahmad,¹⁶ J. G. Bian,¹⁶ G. M. Chen,¹⁶ H. S. Chen,¹⁶ M. Chen,¹⁶ Y. Chen,¹⁶ C. H. Jiang,¹⁶ D. Leggat,¹⁶ H. Liao,¹⁶ Z. Liu,¹⁶ F. Romeo,¹⁶ S. M. Shaheen,^{16,f} A. Spiezia,¹⁶ J. Tao,¹⁶ C. Wang,¹⁶ Z. Wang,¹⁶ E. Yazgan,¹⁶ H. Zhang,¹⁶ J. Zhao,¹⁶ Y. Ban,¹⁷ G. Chen,¹⁷ A. Levin,¹⁷ J. Li,¹⁷ L. Li,¹⁷ Q. Li,¹⁷ Y. Mao,¹⁷ S. J. Qian,¹⁷ D. Wang,¹⁷ Z. Xu,¹⁷ Y. Wang,¹⁸ C. Avila,¹⁹ A. Cabrera,¹⁹ C. A. Carrillo Montoya,¹⁹ L. F. Chaparro Sierra,¹⁹ C. Florez,¹⁹ C. F. González Hernández,¹⁹ M. A. Segura Delgado,¹⁹ B. Courbon,²⁰ N. Godinovic,²⁰ D. Lelas,²⁰ I. Puljak,²⁰ T. Sculac,²⁰ Z. Antunovic,²¹ M. Kovac,²¹ V. Brigljevic,²² D. Ferencek,²² K. Kadija,²² B. Mesic,²² A. Starodumov,^{22,g} T. Susa,²² M. W. Ather,²³ A. Attikis,²³ M. Kolosova,²³ G. Mavromanolakis,²³ J. Mousa,²³ C. Nicolaou,²³ F. Ptochos,²³ P. A. Razis,²³ H. Rykaczewski,²³ M. Finger,^{24,h} M. Finger, Jr.,^{24,h} E. Ayala,²⁵ E. Carrera Jarrin,²⁶ A. Ellithi Kamel,^{27,i} M. A. Mahmoud,^{27,j} E. Salama,^{27,k} S. Bhowmik,²⁸ A. Carvalho Antunes De Oliveira,²⁸ R. K. Dewanjee,²⁸ K. Ehattat,²⁸ M. Kadastik,²⁸ M. Raidal,²⁸ C. Veelken,²⁸ P. Eerola,²⁹ H. Kirschenmann,²⁹ J. Pekkanen,²⁹ M. Voutilainen,²⁹ J. Havukainen,³⁰ J. K. Heikkilä,³⁰ T. Järvinen,³⁰ V. Karimäki,³⁰ R. Kinnunen,³⁰ T. Lampén,³⁰ K. Lassila-Perini,³⁰ S. Laurila,³⁰ S. Lehti,³⁰ T. Lindén,³⁰ P. Luukka,³⁰ T. Mäenpää,³⁰ H. Siikonen,³⁰ E. Tuominen,³⁰ J. Tuominiemi,³⁰ T. Tuuva,³¹ M. Besancon,³² F. Couderc,³² M. Dejardin,³² D. Denegri,³² J. L. Faure,³² F. Ferri,³² S. Ganjour,³² A. Givernaud,³² P. Gras,³² G. Hamel de Monchenault,³² P. Jarry,³² C. Leloup,³² E. Locci,³² J. Malcles,³² G. Negro,³² J. Rander,³² A. Rosowsky,³² M. Ö. Sahin,³² M. Titov,³² A. Abdulsalam,^{33,1} C. Amendola,³³ I. Antropov,³³ F. Beaudette,³³ P. Busson,³³ C. Charlot,³³ R. Granier de Cassagnac,³³ I. Kucher,³³ S. Lisniak,³³ A. Lobanov,³³ J. Martin Blanco,³³ M. Nguyen,³³ C. Ochando,³³ G. Ortona,³³ P. Paganini,³³ P. Pigard,³³ R. Salerno,³³ J. B. Sauvan,³³ Y. Sirois,³³ A. G. Stahl Leiton,³³ A. Zabi,³³ A. Zghiche,³³ J.-L. Agram,^{34,m} J. Andrea,³⁴ D. Bloch,³⁴ J.-M. Brom,³⁴ E. C. Chabert,³⁴ V. Cherepanov,³⁴ C. Collard,³⁴ E. Conte,^{34,m} J.-C. Fontaine,^{34,m} D. Gelé,³⁴ U. Goerlach,³⁴ M. Jansová,³⁴ A.-C. Le Bihan,³⁴ N. Tonon,³⁴ P. Van Hove,³⁴ S. Gadrat,³⁵ S. Beauceron,³⁶ C. Bernet,³⁶ G. Boudoul,³⁶ N. Chanon,³⁶ R. Chierici,³⁶ D. Contardo,³⁶ P. Depasse,³⁶ H. El Mamouni,³⁶ J. Fay,³⁶ L. Finco,³⁶ S. Gascon,³⁶ M. Gouzevitch,³⁶ G. Grenier,³⁶ B. Ille,³⁶ F. Lagarde,³⁶ I. B. Laktineh,³⁶ H. Lattaud,³⁶ M. Lethuillier,³⁶ L. Mirabito,³⁶ A. L. Pequegnot,³⁶ S. Perries,³⁶ A. Popov,^{36,n} V. Sordini,³⁶ M. Vander Donckt,³⁶ S. Viret,³⁶ S. Zhang,³⁶ A. Khvedelidze,^{37,h} Z. Tsamalaidze,^{38,h} C. Autermann,³⁹ L. Feld,³⁹ M. K. Kiesel,³⁹ K. Klein,³⁹ M. Lipinski,³⁹ M. Preuten,³⁹ M. P. Rauch,³⁹ C. Schomakers,³⁹ J. Schulz,³⁹ M. Teroerde,³⁹ B. Wittmer,³⁹ V. Zhukov,^{39,n} A. Albert,⁴⁰ D. Duchardt,⁴⁰ M. Endres,⁴⁰ M. Erdmann,⁴⁰ T. Esch,⁴⁰ R. Fischer,⁴⁰ S. Ghosh,⁴⁰ A. Güth,⁴⁰ T. Hebbeker,⁴⁰ C. Heidemann,⁴⁰ K. Hoepfner,⁴⁰ H. Keller,⁴⁰ S. Knutzen,⁴⁰ L. Mastrolorenzo,⁴⁰ M. Merschmeyer,⁴⁰ A. Meyer,⁴⁰ P. Millet,⁴⁰ S. Mukherjee,⁴⁰ T. Pook,⁴⁰ M. Radziej,⁴⁰ H. Reithler,⁴⁰ M. Rieger,⁴⁰ F. Scheuch,⁴⁰ A. Schmidt,⁴⁰ D. Teyssier,⁴⁰ G. Flügge,⁴¹ O. Hlushchenko,⁴¹ B. Kargoll,⁴¹ T. Kress,⁴¹ A. Künsken,⁴¹ T. Müller,⁴¹ A. Nehrhorn,⁴¹ A. Nowack,⁴¹ C. Pistone,⁴¹ O. Pooth,⁴¹ H. Sert,⁴¹ A. Stahl,^{41,o} M. Aldaya Martin,⁴² T. Arndt,⁴² C. Asawatangtrakuldee,⁴² I. Babounikau,⁴² K. Beernaert,⁴² O. Behnke,⁴² U. Behrens,⁴² A. Bermúdez Martínez,⁴² D. Bertsche,⁴² A. A. Bin Anuar,⁴² K. Borras,^{42,p} V. Botta,⁴² A. Campbell,⁴² P. Connor,⁴² C. Contreras-Campana,⁴² F. Costanza,⁴² V. Danilov,⁴² A. De Wit,⁴² M. M. Defranchis,⁴² C. Diez Pardos,⁴² D. Domínguez Damiani,⁴² G. Eckerlin,⁴² T. Eichhorn,⁴² A. Elwood,⁴² E. Eren,⁴² E. Gallo,^{42,q} A. Geiser,⁴² J. M. Grados Luyando,⁴² A. Grohsjean,⁴² P. Gunnellini,⁴² M. Guthoff,⁴² M. Haranko,⁴² A. Harb,⁴² J. Hauk,⁴² H. Jung,⁴² M. Kasemann,⁴² J. Keaveney,⁴² C. Kleinwort,⁴² J. Knolle,⁴² D. Krücker,⁴² W. Lange,⁴² A. Lelek,⁴² T. Lenz,⁴² K. Lipka,⁴² W. Lohmann,^{42,r} R. Mankel,⁴² I.-A. Melzer-Pellmann,⁴² A. B. Meyer,⁴² M. Meyer,⁴² M. Missiroli,⁴² G. Mittag,⁴² J. Mnich,⁴² V. Myronenko,⁴² S. K. Pflitsch,⁴² D. Pitzl,⁴² A. Raspereza,⁴² M. Savitskiy,⁴² P. Saxena,⁴² P. Schütze,⁴² C. Schwanenberger,⁴² R. Shevchenko,⁴² A. Singh,⁴² N. Stefaniuk,⁴² H. Tholen,⁴² O. Turkot,⁴² A. Vagnerini,⁴² G. P. Van Onsem,⁴² R. Walsh,⁴² Y. Wen,⁴² K. Wichmann,⁴² C. Wissing,⁴² O. Zenaiev,⁴² R. Aggleton,⁴³ S. Bein,⁴³ L. Benato,⁴³ A. Benecke,⁴³ V. Blobel,⁴³ M. Centis Vignali,⁴³ T. Dreyer,⁴³ E. Garutti,⁴³ D. Gonzalez,⁴³ J. Haller,⁴³ A. Hinemann,⁴³ A. Karavdina,⁴³ G. Kasieczka,⁴³ R. Klanner,⁴³ R. Kogler,⁴³ N. Kovalchuk,⁴³ S. Kurz,⁴³ V. Kutzner,⁴³ J. Lange,⁴³ D. Marconi,⁴³ J. Multhaup,⁴³ M. Niedziela,⁴³ D. Nowatschin,⁴³ A. Perieanu,⁴³

A. Reimers,⁴³ O. Rieger,⁴³ C. Scharf,⁴³ P. Schleper,⁴³ S. Schumann,⁴³ J. Schwandt,⁴³ J. Sonneveld,⁴³ H. Stadie,⁴³ G. Steinbrück,⁴³ F. M. Stober,⁴³ M. Stöver,⁴³ D. Troendle,⁴³ A. Vanhoefer,⁴³ B. Vormwald,⁴³ M. Akbiyik,⁴⁴ C. Barth,⁴⁴ M. Baselga,⁴⁴ S. Baur,⁴⁴ E. Butz,⁴⁴ R. Caspart,⁴⁴ T. Chwalek,⁴⁴ F. Colombo,⁴⁴ W. De Boer,⁴⁴ A. Dierlamm,⁴⁴ N. Faltermann,⁴⁴ B. Freund,⁴⁴ M. Giffels,⁴⁴ M. A. Harrendorf,⁴⁴ F. Hartmann,^{44,o} S. M. Heindl,⁴⁴ U. Husemann,⁴⁴ F. Kassel,^{44,o} I. Katkov,^{44,n} S. Kudella,⁴⁴ H. Mildner,⁴⁴ S. Mitra,⁴⁴ M. U. Mozer,⁴⁴ Th. Müller,⁴⁴ M. Plagge,⁴⁴ G. Quast,⁴⁴ K. Rabbertz,⁴⁴ M. Schröder,⁴⁴ I. Shvetsov,⁴⁴ G. Sieber,⁴⁴ H. J. Simonis,⁴⁴ R. Ulrich,⁴⁴ S. Wayand,⁴⁴ M. Weber,⁴⁴ T. Weiler,⁴⁴ S. Williamson,⁴⁴ C. Wöhrmann,⁴⁴ R. Wolf,⁴⁴ G. Anagnostou,⁴⁵ G. Daskalakis,⁴⁵ T. Geralis,⁴⁵ A. Kyriakis,⁴⁵ D. Loukas,⁴⁵ G. Paspalaki,⁴⁵ I. Topsis-Giotis,⁴⁵ G. Karathanasis,⁴⁶ S. Kesisoglou,⁴⁶ P. Kontaxakis,⁴⁶ A. Panagiotou,⁴⁶ N. Saoulidou,⁴⁶ E. Tziaferi,⁴⁶ K. Vellidis,⁴⁶ K. Kousouris,⁴⁷ I. Papakrivopoulos,⁴⁷ G. Tsiolitis,⁴⁷ I. Evangelou,⁴⁸ C. Foudas,⁴⁸ P. Gianneios,⁴⁸ P. Katsoulis,⁴⁸ P. Kokkas,⁴⁸ S. Mallios,⁴⁸ N. Manthos,⁴⁸ I. Papadopoulos,⁴⁸ E. Paradas,⁴⁸ J. Strologas,⁴⁸ F. A. Triantis,⁴⁸ D. Tsitsonis,⁴⁸ M. Bartók,^{49,s} M. Csanad,⁴⁹ N. Filipovic,⁴⁹ P. Major,⁴⁹ M. I. Nagy,⁴⁹ G. Pasztor,⁴⁹ O. Surányi,⁴⁹ G. I. Veres,⁴⁹ G. Bencze,⁵⁰ C. Hajdu,⁵⁰ D. Horvath,^{50,t} Á. Hunyadi,⁵⁰ F. Sikler,⁵⁰ T. Á. Vámi,⁵⁰ V. Veszpremi,⁵⁰ G. Vesztergombi,^{50,u} N. Beni,⁵¹ S. Czellar,⁵¹ J. Karancsi,^{51,v} A. Makovec,⁵¹ J. Molnar,⁵¹ Z. Szillasi,⁵¹ P. Raics,⁵² Z. L. Trocsanyi,⁵² B. Ujvari,⁵² S. Choudhury,⁵³ J. R. Komaragiri,⁵³ P. C. Tiwari,⁵³ S. Bahinipati,^{54,w} C. Kar,⁵⁴ P. Mal,⁵⁴ K. Mandal,⁵⁴ A. Nayak,^{54,x} D. K. Sahoo,^{54,w} S. K. Swain,⁵⁴ S. Bansal,⁵⁵ S. B. Beri,⁵⁵ V. Bhatnagar,⁵⁵ S. Chauhan,⁵⁵ R. Chawla,⁵⁵ N. Dhingra,⁵⁵ R. Gupta,⁵⁵ A. Kaur,⁵⁵ A. Kaur,⁵⁵ M. Kaur,⁵⁵ S. Kaur,⁵⁵ R. Kumar,⁵⁵ P. Kumari,⁵⁵ M. Lohan,⁵⁵ A. Mehta,⁵⁵ K. Sandeep,⁵⁵ S. Sharma,⁵⁵ J. B. Singh,⁵⁵ G. Walia,⁵⁵ A. Bhardwaj,⁵⁶ B. C. Choudhary,⁵⁶ R. B. Garg,⁵⁶ M. Gola,⁵⁶ S. Keshri,⁵⁶ Ashok Kumar,⁵⁶ S. Malhotra,⁵⁶ M. Naimuddin,⁵⁶ P. Priyanka,⁵⁶ K. Ranjan,⁵⁶ Aashaq Shah,⁵⁶ R. Sharma,⁵⁶ R. Bhardwaj,^{57,y} M. Bharti,⁵⁷ R. Bhattacharya,⁵⁷ S. Bhattacharya,⁵⁷ U. Bhawandeep,^{57,y} D. Bhowmik,⁵⁷ S. Dey,⁵⁷ S. Dutt,^{57,y} S. Dutta,⁵⁷ S. Ghosh,⁵⁷ K. Mondal,⁵⁷ S. Nandan,⁵⁷ A. Purohit,⁵⁷ P. K. Rout,⁵⁷ A. Roy,⁵⁷ S. Roy Chowdhury,⁵⁷ S. Sarkar,⁵⁷ M. Sharan,⁵⁷ B. Singh,⁵⁷ S. Thakur,^{57,y} P. K. Behera,⁵⁸ R. Chudasama,⁵⁹ D. Dutta,⁵⁹ V. Jha,⁵⁹ V. Kumar,⁵⁹ P. K. Netrakanti,⁵⁹ L. M. Pant,⁵⁹ P. Shukla,⁵⁹ T. Aziz,⁶⁰ M. A. Bhat,⁶⁰ S. Dugad,⁶⁰ G. B. Mohanty,⁶⁰ N. Sur,⁶⁰ B. Sutar,⁶⁰ Ravindra Kumar Verma,⁶⁰ S. Banerjee,⁶¹ S. Bhattacharya,⁶¹ S. Chatterjee,⁶¹ P. Das,⁶¹ M. Guchait,⁶¹ Sa. Jain,⁶¹ S. Karmakar,⁶¹ S. Kumar,⁶¹ M. Maity,^{61,z} G. Majumder,⁶¹ K. Mazumdar,⁶¹ N. Sahoo,⁶¹ T. Sarkar,^{61,z} S. Chauhan,⁶² S. Dube,⁶² V. Hegde,⁶² A. Kapoor,⁶² K. Kotheekar,⁶² S. Pandey,⁶² A. Rane,⁶² S. Sharma,⁶² S. Chenarani,^{63,aa} E. Eskandari Tadavani,⁶³ S. M. Etesami,^{63,aa} M. Khakzad,⁶³ M. Mohammadi Najafabadi,⁶³ M. Naseri,⁶³ F. Rezaei Hosseinabadi,⁶³ B. Safarzadeh,^{63,ab} M. Zeinali,⁶³ M. Felcini,⁶⁴ M. Grunewald,⁶⁴ M. Abbrescia,^{65,66,67} C. Calabria,^{65,66,67} A. Colaleo,^{65,66,67} D. Creanza,^{65,66,67} L. Cristella,^{65,66,67} N. De Filippis,^{65,66,67} M. De Palma,^{65,66,67} A. Di Florio,^{65,66,67} F. Errico,^{65,66,67} L. Fiore,^{65,66,67} A. Gelmi,^{65,66,67} G. Iaselli,^{65,66,67} M. Ince,^{65,66,67} S. Lezki,^{65,66,67} G. Maggi,^{65,66,67} M. Maggi,^{65,66,67} G. Miniello,^{65,66,67} S. My,^{65,66,67} S. Nuzzo,^{65,66,67} A. Pompili,^{65,66,67} G. Pugliese,^{65,66,67} R. Radogna,^{65,66,67} A. Ranieri,^{65,66,67} G. Selvaggi,^{65,66,67} A. Sharma,^{65,66,67} L. Silvestris,^{65,66,67} R. Venditti,^{65,66,67} P. Verwilligen,^{65,66,67} G. Zito,^{65,66,67} G. Abbiendi,^{68,69} C. Battilana,^{68,69} D. Bonacorsi,^{68,69} L. Borghonovi,^{68,69} S. Braibant-Giacomelli,^{68,69} R. Campanini,^{68,69} P. Capiluppi,^{68,69} A. Castro,^{68,69} F. R. Cavallo,^{68,69} S. S. Chhibra,^{68,69} C. Ciocca,^{68,69} G. Codispoti,^{68,69} M. Cuffiani,^{68,69} G. M. Dallavalle,^{68,69} F. Fabbri,^{68,69} A. Fanfani,^{68,69} P. Giacomelli,^{68,69} C. Grandi,^{68,69} L. Guiducci,^{68,69} F. Iemmi,^{68,69} S. Marcellini,^{68,69} G. Masetti,^{68,69} A. Montanari,^{68,69} F. L. Navarria,^{68,69} A. Perrotta,^{68,69} F. Primavera,^{68,69,o} A. M. Rossi,^{68,69} T. Rovelli,^{68,69} G. P. Siroli,^{68,69} N. Tosi,^{68,69} S. Albergo,^{70,71} A. Di Mattia,^{70,71} R. Potenza,^{70,71} A. Tricoli,^{70,71} C. Tuve,^{70,71} G. Barbagli,^{72,73} K. Chatterjee,^{72,73} V. Ciulli,^{72,73} C. Civinini,^{72,73} R. D'Alessandro,^{72,73} E. Focardi,^{72,73} G. Latino,^{72,73} P. Lenzi,^{72,73} M. Meschini,^{72,73} S. Paoletti,^{72,73} L. Russo,^{72,73,ac} G. Sguazzoni,^{72,73} D. Strom,^{72,73} L. Viliani,^{72,73} L. Benussi,⁷⁴ S. Bianco,⁷⁴ F. Fabbri,⁷⁴ D. Piccolo,⁷⁴ F. Ferro,^{75,76} F. Ravera,^{75,76} E. Robutti,^{75,76} S. Tosi,^{75,76} A. Benaglia,^{77,78} A. Beschi,^{77,78} L. Brianza,^{77,78} F. Brivio,^{77,78} V. Ciriolo,^{77,78,o} S. Di Guida,^{77,78,o} M. E. Dinardo,^{77,78} S. Fiorendi,^{77,78} S. Gennai,^{77,78} A. Ghezzi,^{77,78} P. Govoni,^{77,78} M. Malberti,^{77,78} S. Malvezzi,^{77,78} A. Massironi,^{77,78} D. Menasce,^{77,78} L. Moroni,^{77,78} M. Paganoni,^{77,78} D. Pedrini,^{77,78} S. Ragazzi,^{77,78} T. Tabarelli de Fatis,^{77,78} S. Buontempo,^{79,80,81,82} N. Cavallo,^{79,80,81,82} A. Di Crescenzo,^{79,80,81,82} F. Fabozzi,^{79,80,81,82} F. Fienga,^{79,80,81,82} G. Galati,^{79,80,81,82} A. O. M. Iorio,^{79,80,81,82} W. A. Khan,^{79,80,81,82} L. Lista,^{79,80,81,82} S. Meola,^{79,80,81,82,o} P. Paolucci,^{79,80,81,82,o} C. Sciacca,^{79,80,81,82} E. Voevodina,^{79,80,81,82} P. Azzi,^{83,84,85} N. Bacchetta,^{83,84,85} D. Bisello,^{83,84,85} A. Boletti,^{83,84,85} A. Bragagnolo,^{83,84,85} R. Carlin,^{83,84,85} P. Checchia,^{83,84,85} M. Dall'Osso,^{83,84,85} P. De Castro Manzano,^{83,84,85} T. Dorigo,^{83,84,85} U. Dosselli,^{83,84,85} F. Gasparini,^{83,84,85} U. Gasparini,^{83,84,85} A. Gozzelino,^{83,84,85} S. Lacapra,^{83,84,85} P. Lujan,^{83,84,85} M. Margoni,^{83,84,85} A. T. Meneguzzo,^{83,84,85} J. Pazzini,^{83,84,85} P. Ronchese,^{83,84,85} R. Rossin,^{83,84,85} F. Simonetto,^{83,84,85} A. Tiko,^{83,84,85} E. Torassa,^{83,84,85} M. Zanetti,^{83,84,85} P. Zotto,^{83,84,85} G. Zumerle,^{83,84,85} A. Braghieri,^{86,87} A. Magnani,^{86,87} P. Montagna,^{86,87} S. P. Ratti,^{86,87} V. Re,^{86,87} M. Ressegotti,^{86,87} C. Riccardi,^{86,87} P. Salvini,^{86,87} I. Vai,^{86,87} P. Vitulo,^{86,87} L. Alunni Soletizi,^{88,89} M. Biasini,^{88,89} G. M. Bilei,^{88,89} C. Cecchi,^{88,89} D. Ciangottini,^{88,89} L. Fanò,^{88,89} P. Lariccia,^{88,89} R. Leonardi,^{88,89} E. Manoni,^{88,89} G. Mantovani,^{88,89} V. Mariani,^{88,89} M. Menichelli,^{88,89} A. Rossi,^{88,89} A. Santocchia,^{88,89} D. Spiga,^{88,89} K. Androsov,^{90,91,92} P. Azzurri,^{90,91,92} G. Bagliesi,^{90,91,92} L. Bianchini,^{90,91,92} T. Boccali,^{90,91,92} L. Borrello,^{90,91,92} R. Castaldi,^{90,91,92} M. A. Ciocci,^{90,91,92} R. Dell'Orso,^{90,91,92} G. Fedi,^{90,91,92} F. Fiori,^{90,91,92} L. Giannini,^{90,91,92} A. Giassi,^{90,91,92} M. T. Grippo,^{90,91,92} F. Ligabue,^{90,91,92} E. Manca,^{90,91,92} G. Mandorli,^{90,91,92} A. Messineo,^{90,91,92} F. Palla,^{90,91,92} A. Rizzi,^{90,91,92} P. Spagnolo,^{90,91,92} R. Tenchini,^{90,91,92} G. Tonelli,^{90,91,92} A. Venturi,^{90,91,92} P. G. Verdini,^{90,91,92} L. Barone,^{93,94} F. Cavallari,^{93,94} M. Cipriani,^{93,94} N. Daci,^{93,94} D. Del Re,^{93,94} E. Di Marco,^{93,94} M. Diemoz,^{93,94} S. Gelli,^{93,94} E. Longo,^{93,94} B. Marzocchi,^{93,94} P. Meridiani,^{93,94} G. Organtini,^{93,94} F. Pandolfi,^{93,94} R. Paramatti,^{93,94} F. Preiato,^{93,94} S. Rahatlou,^{93,94} C. Rovelli,^{93,94}

- F. Santanastasio,^{93,94} N. Amapane,^{95,96,97} R. Arcidiacono,^{95,96,97} S. Argiro,^{95,96,97} M. Arneodo,^{95,96,97} N. Bartosik,^{95,96,97} R. Bellan,^{95,96,97} C. Biino,^{95,96,97} N. Cartiglia,^{95,96,97} F. Cenna,^{95,96,97} S. Cometti,^{95,96,97} M. Costa,^{95,96,97} R. Covarelli,^{95,96,97} N. Demaria,^{95,96,97} B. Kiani,^{95,96,97} C. Mariotti,^{95,96,97} S. Maselli,^{95,96,97} E. Migliore,^{95,96,97} V. Monaco,^{95,96,97} E. Monteil,^{95,96,97} M. Monteno,^{95,96,97} M. M. Obertino,^{95,96,97} L. Pacher,^{95,96,97} N. Pastrone,^{95,96,97} M. Pelliccioni,^{95,96,97} G. L. Pinna Angioni,^{95,96,97} A. Romero,^{95,96,97} M. Ruspa,^{95,96,97} R. Sacchi,^{95,96,97} K. Shchelina,^{95,96,97} V. Sola,^{95,96,97} A. Solano,^{95,96,97} D. Soldi,^{95,96,97} A. Staiano,^{95,96,97} S. Belforte,^{98,99} V. Candelise,^{98,99} M. Casarsa,^{98,99} F. Cossutti,^{98,99} G. Della Ricca,^{98,99} F. Vazzoler,^{98,99} A. Zanetti,^{98,99} D. H. Kim,¹⁰⁰ G. N. Kim,¹⁰⁰ M. S. Kim,¹⁰⁰ J. Lee,¹⁰⁰ S. Lee,¹⁰⁰ S. W. Lee,¹⁰⁰ C. S. Moon,¹⁰⁰ Y. D. Oh,¹⁰⁰ S. Sekmen,¹⁰⁰ D. C. Son,¹⁰⁰ Y. C. Yang,¹⁰⁰ H. Kim,¹⁰¹ D. H. Moon,¹⁰¹ G. Oh,¹⁰¹ J. Goh,^{102,ad} T. J. Kim,¹⁰² S. Cho,¹⁰³ S. Choi,¹⁰³ Y. Go,¹⁰³ D. Gyun,¹⁰³ S. Ha,¹⁰³ B. Hong,¹⁰³ Y. Jo,¹⁰³ K. Lee,¹⁰³ K. S. Lee,¹⁰³ S. Lee,¹⁰³ J. Lim,¹⁰³ S. K. Park,¹⁰³ Y. Roh,¹⁰³ H. S. Kim,¹⁰⁴ J. Almond,¹⁰⁵ J. Kim,¹⁰⁵ J. S. Kim,¹⁰⁵ H. Lee,¹⁰⁵ K. Lee,¹⁰⁵ K. Nam,¹⁰⁵ S. B. Oh,¹⁰⁵ B. C. Radburn-Smith,¹⁰⁵ S. h. Seo,¹⁰⁵ U. K. Yang,¹⁰⁵ H. D. Yoo,¹⁰⁵ G. B. Yu,¹⁰⁵ D. Jeon,¹⁰⁶ H. Kim,¹⁰⁶ J. H. Kim,¹⁰⁶ J. S. H. Lee,¹⁰⁶ I. C. Park,¹⁰⁶ Y. Choi,¹⁰⁷ C. Hwang,¹⁰⁷ J. Lee,¹⁰⁷ I. Yu,¹⁰⁷ V. Dudenias,¹⁰⁸ A. Juodagalvis,¹⁰⁸ J. Vaitkus,¹⁰⁸ I. Ahmed,¹⁰⁹ Z. A. Ibrahim,¹⁰⁹ M. A. B. Md Ali,^{109,ae} F. Mohamad Idris,^{109,af} W. A. T. Wan Abdullah,¹⁰⁹ M. N. Yusli,¹⁰⁹ Z. Zolkapli,¹⁰⁹ A. Castaneda Hernandez,¹¹⁰ J. A. Murillo Quijada,¹¹⁰ H. Castilla-Valdez,¹¹¹ E. De La Cruz-Burelo,¹¹¹ M. C. Duran-Osuna,¹¹¹ I. Heredia-De La Cruz,^{111,ag} R. Lopez-Fernandez,¹¹¹ J. Mejia Guisao,¹¹¹ R. I. Rabadan-Trejo,¹¹¹ G. Ramirez-Sanchez,¹¹¹ R. Reyes-Almanza,¹¹¹ A. Sanchez-Hernandez,¹¹¹ S. Carrillo Moreno,¹¹² C. Oropeza Barrera,¹¹² F. Vazquez Valencia,¹¹² J. Eysermans,¹¹³ I. Pedraza,¹¹³ H. A. Salazar Ibarguen,¹¹³ C. Uribe Estrada,¹¹³ A. Morelos Pineda,¹¹⁴ D. Krofcheck,¹¹⁵ S. Bheesette,¹¹⁶ P. H. Butler,¹¹⁶ A. Ahmad,¹¹⁷ M. Ahmad,¹¹⁷ M. I. Asghar,¹¹⁷ Q. Hassan,¹¹⁷ H. R. Hoorani,¹¹⁷ A. Saddique,¹¹⁷ M. A. Shah,¹¹⁷ M. Shoaib,¹¹⁷ M. Waqas,¹¹⁷ H. Bialkowska,¹¹⁸ M. Bluj,¹¹⁸ B. Boimska,¹¹⁸ T. Frueboes,¹¹⁸ M. Górski,¹¹⁸ M. Kazana,¹¹⁸ K. Nawrocki,¹¹⁸ M. Szleper,¹¹⁸ P. Traczyk,¹¹⁸ P. Zalewski,¹¹⁸ K. Bunkowski,¹¹⁹ A. Byszuk,^{119,ah} K. Doroba,¹¹⁹ A. Kalinowski,¹¹⁹ M. Konecki,¹¹⁹ J. Krolikowski,¹¹⁹ M. Misiura,¹¹⁹ M. Olszewski,¹¹⁹ A. Pyskir,¹¹⁹ M. Walczak,¹¹⁹ P. Bargassa,¹²⁰ C. Beirão Da Cruz E Silva,¹²⁰ A. Di Francesco,¹²⁰ P. Faccioli,¹²⁰ B. Galinhas,¹²⁰ M. Gallinaro,¹²⁰ J. Hollar,¹²⁰ N. Leonardo,¹²⁰ L. Lloret Iglesias,¹²⁰ M. V. Nemallapudi,¹²⁰ J. Seixas,¹²⁰ G. Strong,¹²⁰ O. Toldaiev,¹²⁰ D. Vadrucchio,¹²⁰ J. Varela,¹²⁰ A. Baginyan,¹²¹ A. Golunov,¹²¹ I. Golutvin,¹²¹ V. Karjavin,¹²¹ I. Kashunin,¹²¹ V. Korenkov,¹²¹ G. Kozlov,¹²¹ A. Lanev,¹²¹ A. Malakhov,¹²¹ V. Matveev,^{121,ai} P. Moisenz,¹²¹ V. Palichik,¹²¹ V. Perelygin,¹²¹ S. Shmatov,¹²¹ N. Skatchkov,¹²¹ V. Smirnov,¹²¹ B. S. Yuldashev,^{121,aj} A. Zarubin,¹²¹ V. Zhiltsov,¹²¹ V. Golovtsov,¹²² Y. Ivanov,¹²² V. Kim,^{122,ak} E. Kuznetsova,^{122,al} P. Levchenko,¹²² V. Murzin,¹²² V. Oreshkin,¹²² I. Smirnov,¹²² D. Sosnov,¹²² V. Sulimov,¹²² L. Uvarov,¹²² S. Vavilov,¹²² A. Vorobyev,¹²² Yu. Andreev,¹²³ A. Dermenev,¹²³ S. Gninenko,¹²³ N. Golubev,¹²³ A. Karneyeu,¹²³ M. Kirsanov,¹²³ N. Krasnikov,¹²³ A. Pashenkov,¹²³ D. Tlisov,¹²³ A. Toropin,¹²³ V. Epshteyn,¹²⁴ V. Gavrilov,¹²⁴ N. Lychkovskaya,¹²⁴ V. Popov,¹²⁴ I. Pozdnyakov,¹²⁴ G. Safronov,¹²⁴ A. Spiridonov,¹²⁴ A. Stepanov,¹²⁴ V. Stolin,¹²⁴ M. Toms,¹²⁴ E. Vlasov,¹²⁴ A. Zhokin,¹²⁴ T. Aushev,¹²⁵ M. Chadeeva,^{126,am} P. Parygin,¹²⁶ D. Philippov,¹²⁶ S. Polikarpov,^{126,am} E. Popova,¹²⁶ V. Rusinov,¹²⁶ V. Andreev,¹²⁷ M. Azarkin,^{127,an} I. Dremin,^{127,an} M. Kirakosyan,^{127,an} S. V. Rusakov,¹²⁷ A. Terkulov,¹²⁷ A. Baskakov,¹²⁸ A. Belyaev,¹²⁸ E. Boos,¹²⁸ A. Demiyarov,¹²⁸ A. Ershov,¹²⁸ A. Gribushin,¹²⁸ O. Kodolova,¹²⁸ V. Korotkikh,¹²⁸ I. Lokhtin,¹²⁸ I. Miagkov,¹²⁸ S. Obraztsov,¹²⁸ S. Petrushanko,¹²⁸ V. Savrin,¹²⁸ A. Snigirev,¹²⁸ I. Vardanyan,¹²⁸ V. Blinov,^{129,ao} T. Dimova,^{129,ao} L. Kardapoltsev,^{129,ao} D. Shtol,^{129,ao} Y. Skovpen,^{129,ao} I. Azhgirey,¹³⁰ I. Bayshev,¹³⁰ S. Bitioukov,¹³⁰ D. Elumakhov,¹³⁰ A. Godizov,¹³⁰ V. Kachanov,¹³⁰ A. Kalinin,¹³⁰ D. Konstantinov,¹³⁰ P. Mandrik,¹³⁰ V. Petrov,¹³⁰ R. Ryutin,¹³⁰ S. Slabospitskii,¹³⁰ A. Sobol,¹³⁰ S. Troshin,¹³⁰ N. Tyurin,¹³⁰ A. Uzunian,¹³⁰ A. Volkov,¹³⁰ A. Babaev,¹³¹ S. Baidali,¹³¹ P. Adzic,^{132,ap} P. Cirkovic,¹³² D. Devetak,¹³² M. Dordevic,¹³² J. Milosevic,¹³² J. Alcaraz Maestre,¹³³ A. Álvarez Fernández,¹³³ I. Bachiller,¹³³ M. Barrio Luna,¹³³ J. A. Brochero Cifuentes,¹³³ M. Cerrada,¹³³ N. Colino,¹³³ B. De La Cruz,¹³³ A. Delgado Peris,¹³³ C. Fernandez Bedoya,¹³³ J. P. Fernández Ramos,¹³³ J. Flix,¹³³ M. C. Fouz,¹³³ O. Gonzalez Lopez,¹³³ S. Goy Lopez,¹³³ J. M. Hernandez,¹³³ M. I. Josa,¹³³ D. Moran,¹³³ A. Pérez-Calero Yzquierdo,¹³³ J. Puerta Pelayo,¹³³ I. Redondo,¹³³ L. Romero,¹³³ M. S. Soares,¹³³ A. Triossi,¹³³ C. Albajar,¹³⁴ J. F. de Trocóniz,¹³⁴ J. Cuevas,¹³⁵ C. Erice,¹³⁵ J. Fernandez Menendez,¹³⁵ S. Folgueras,¹³⁵ I. Gonzalez Caballero,¹³⁵ J. R. González Fernández,¹³⁵ E. Palencia Cortezon,¹³⁵ V. Rodríguez Bouza,¹³⁵ S. Sanchez Cruz,¹³⁵ P. Vischia,¹³⁵ J. M. Vizan Garcia,¹³⁵ I. J. Cabrillo,¹³⁶ A. Calderon,¹³⁶ B. Chazin Quero,¹³⁶ J. Duarte Campderros,¹³⁶ M. Fernandez,¹³⁶ P. J. Fernández Manteca,¹³⁶ A. García Alonso,¹³⁶ J. Garcia-Ferrero,¹³⁶ G. Gomez,¹³⁶ A. Lopez Virto,¹³⁶ J. Marco,¹³⁶ C. Martinez Rivero,¹³⁶ P. Martinez Ruiz del Arbol,¹³⁶ F. Matorras,¹³⁶ J. Piedra Gomez,¹³⁶ C. Prieels,¹³⁶ T. Rodrigo,¹³⁶ A. Ruiz-Jimeno,¹³⁶ L. Scodellaro,¹³⁶ N. Trevisani,¹³⁶ I. Vila,¹³⁶ R. Vilar Cortabitarte,¹³⁶ D. Abbaneo,¹³⁷ B. Akgun,¹³⁷ E. Auffray,¹³⁷ P. Baillon,¹³⁷ A. H. Ball,¹³⁷ D. Barney,¹³⁷ J. Bendavid,¹³⁷ M. Bianco,¹³⁷ A. Bocci,¹³⁷ C. Botta,¹³⁷ E. Brondolin,¹³⁷ T. Camporesi,¹³⁷ M. Cepeda,¹³⁷ G. Cerminara,¹³⁷ E. Chapon,¹³⁷ Y. Chen,¹³⁷ G. Cucciati,¹³⁷ D. d'Enterria,¹³⁷ A. Dabrowski,¹³⁷ V. Daponte,¹³⁷ A. David,¹³⁷ A. De Roeck,¹³⁷ N. Deelen,¹³⁷ M. Dobson,¹³⁷ T. du Pree,¹³⁷ M. Dünser,¹³⁷ N. Dupont,¹³⁷ A. Elliott-Peisert,¹³⁷ P. Everaerts,¹³⁷ F. Fallavollita,^{137,aq} D. Fasanella,¹³⁷ G. Franzoni,¹³⁷ J. Fulcher,¹³⁷ W. Funk,¹³⁷ D. Gigi,¹³⁷ A. Gilbert,¹³⁷ K. Gill,¹³⁷ F. Glege,¹³⁷ M. Guilbaud,¹³⁷ D. Gulhan,¹³⁷ J. Hegeman,¹³⁷ V. Innocente,¹³⁷ A. Jafari,¹³⁷ P. Janot,¹³⁷ O. Karacheban,^{137,r} J. Kieseler,¹³⁷ A. Kornmayer,¹³⁷ M. Krammer,^{137,a} C. Lange,¹³⁷ P. Lecoq,¹³⁷ C. Lourenço,¹³⁷ L. Malgeri,¹³⁷ M. Mannelli,¹³⁷ F. Meijers,¹³⁷ J. A. Merlin,¹³⁷ S. Mersi,¹³⁷ E. Meschi,¹³⁷ P. Milenovic,^{137,ar} F. Moortgat,¹³⁷ M. Mulders,¹³⁷ J. Ngadiuba,¹³⁷ S. Orfanelli,¹³⁷ L. Orsini,¹³⁷ F. Pantaleo,^{137,o} L. Pape,¹³⁷ E. Perez,¹³⁷ M. Peruzzi,¹³⁷ A. Petrilli,¹³⁷ G. Petrucciani,¹³⁷ A. Pfeiffer,¹³⁷ M. Pierini,¹³⁷ F. M. Pitters,¹³⁷ D. Rabady,¹³⁷ A. Racz,¹³⁷ T. Reis,¹³⁷ G. Rolandi,^{137,as} M. Rovere,¹³⁷ H. Sakulin,¹³⁷ C. Schäfer,¹³⁷ C. Schwick,¹³⁷ M. Seidel,¹³⁷ M. Selvaggi,¹³⁷

A. Sharma,¹³⁷ P. Silva,¹³⁷ P. Sphicas,^{137,at} A. Stakia,¹³⁷ J. Steggemann,¹³⁷ M. Tosi,¹³⁷ D. Treille,¹³⁷ A. Tsirou,¹³⁷ V. Veckalns,^{137,au} W. D. Zeuner,¹³⁷ L. Caminada,^{138,av} K. Deiters,¹³⁸ W. Erdmann,¹³⁸ R. Horisberger,¹³⁸ Q. Ingram,¹³⁸ H. C. Kaestli,¹³⁸ D. Kotlinski,¹³⁸ U. Langenegger,¹³⁸ T. Rohe,¹³⁸ S. A. Wiederkehr,¹³⁸ M. Backhaus,¹³⁹ L. Bäni,¹³⁹ P. Berger,¹³⁹ N. Chernyavskaya,¹³⁹ G. Dissertori,¹³⁹ M. Dittmar,¹³⁹ M. Donegà,¹³⁹ C. Dorfer,¹³⁹ C. Grab,¹³⁹ C. Heidegger,¹³⁹ D. Hits,¹³⁹ J. Hoss,¹³⁹ T. Klijnsma,¹³⁹ W. Lustermann,¹³⁹ R. A. Manzoni,¹³⁹ M. Marionneau,¹³⁹ M. T. Meinhard,¹³⁹ F. Micheli,¹³⁹ P. Musella,¹³⁹ F. Nessi-Tedaldi,¹³⁹ J. Pata,¹³⁹ F. Pauss,¹³⁹ G. Perrin,¹³⁹ L. Perrozzi,¹³⁹ S. Pigazzini,¹³⁹ M. Quittnat,¹³⁹ D. Ruini,¹³⁹ D. A. Sanz Becerra,¹³⁹ M. Schönenberger,¹³⁹ L. Shchutska,¹³⁹ V. R. Tavolaro,¹³⁹ K. Theofilatos,¹³⁹ M. L. Vesterbacka Olsson,¹³⁹ R. Wallny,¹³⁹ D. H. Zhu,¹³⁹ T. K. Aarrestad,¹⁴⁰ C. Amsler,^{140,aw} D. Brzhechko,¹⁴⁰ M. F. Canelli,¹⁴⁰ A. De Cosa,¹⁴⁰ R. Del Burgo,¹⁴⁰ S. Donato,¹⁴⁰ C. Galloni,¹⁴⁰ T. Hreus,¹⁴⁰ B. Kilminster,¹⁴⁰ I. Neutelings,¹⁴⁰ D. Pinna,¹⁴⁰ G. Rauco,¹⁴⁰ P. Robmann,¹⁴⁰ D. Salerno,¹⁴⁰ K. Schweiger,¹⁴⁰ C. Seitz,¹⁴⁰ Y. Takahashi,¹⁴⁰ A. Zucchetta,¹⁴⁰ Y. H. Chang,¹⁴¹ K. y. Cheng,¹⁴¹ T. H. Doan,¹⁴¹ Sh. Jain,¹⁴¹ R. Khurana,¹⁴¹ C. M. Kuo,¹⁴¹ W. Lin,¹⁴¹ A. Pozdnyakov,¹⁴¹ S. S. Yu,¹⁴¹ P. Chang,¹⁴² Y. Chao,¹⁴² K. F. Chen,¹⁴² P. H. Chen,¹⁴² W.-S. Hou,¹⁴² Arun Kumar,¹⁴² Y. y. Li,¹⁴² Y. F. Liu,¹⁴² R.-S. Lu,¹⁴² E. Paganis,¹⁴² A. Psallidas,¹⁴² A. Steen,¹⁴² J. f. Tsai,¹⁴² B. Asavapibhop,¹⁴³ N. Srimanobhas,¹⁴³ N. Suwonjandee,¹⁴³ M. N. Bakirci,^{144,ax} A. Bat,¹⁴⁴ F. Boran,¹⁴⁴ S. Cerci,^{144,ay} S. Damarseekin,¹⁴⁴ Z. S. Demiroglu,¹⁴⁴ F. Dolek,¹⁴⁴ C. Dozen,¹⁴⁴ I. Dumanoglu,¹⁴⁴ E. Eskut,¹⁴⁴ S. Girgis,¹⁴⁴ G. Gokbulut,¹⁴⁴ Y. Guler,¹⁴⁴ E. Gurpinar,¹⁴⁴ I. Hos,^{144,az} C. Isik,¹⁴⁴ E. E. Kangal,^{144,ba} O. Kara,¹⁴⁴ A. Kayis Topaksu,¹⁴⁴ U. Kiminsu,¹⁴⁴ M. Oglakci,¹⁴⁴ G. Onengut,¹⁴⁴ K. Ozdemir,^{144,bb} A. Polatoz,¹⁴⁴ U. G. Tok,¹⁴⁴ S. Turkcapar,¹⁴⁴ I. S. Zorbakir,¹⁴⁴ C. Zorbilmez,¹⁴⁴ B. Ilidak,^{145,bc} G. Karapinar,^{145,bd} M. Yalvac,¹⁴⁵ M. Zeyrek,¹⁴⁵ I. O. Atakisi,¹⁴⁶ E. Gülmez,¹⁴⁶ M. Kaya,^{146,be} O. Kaya,^{146,bf} S. Ozkorucuklu,^{146,bg} S. Tekten,¹⁴⁶ E. A. Yetkin,^{146,bh} M. N. Agaras,¹⁴⁷ S. Atay,¹⁴⁷ A. Cakir,¹⁴⁷ K. Cankocak,¹⁴⁷ Y. Komurcu,¹⁴⁷ S. Sen,^{147,bi} B. Grynyov,¹⁴⁸ L. Levchuk,¹⁴⁹ F. Ball,¹⁵⁰ L. Beck,¹⁵⁰ J. J. Brooke,¹⁵⁰ D. Burns,¹⁵⁰ E. Clement,¹⁵⁰ D. Cussans,¹⁵⁰ O. Davignon,¹⁵⁰ H. Flacher,¹⁵⁰ J. Goldstein,¹⁵⁰ G. P. Heath,¹⁵⁰ H. F. Heath,¹⁵⁰ L. Kreczko,¹⁵⁰ D. M. Newbold,^{150,bj} S. Paramesvaran,¹⁵⁰ B. Penning,¹⁵⁰ T. Sakuma,¹⁵⁰ D. Smith,¹⁵⁰ V. J. Smith,¹⁵⁰ J. Taylor,¹⁵⁰ A. Titterton,¹⁵⁰ A. Belyaev,^{151,bk} C. Brew,¹⁵¹ R. M. Brown,¹⁵¹ D. Cieri,¹⁵¹ D. J. A. Cockerill,¹⁵¹ J. A. Coughlan,¹⁵¹ K. Harder,¹⁵¹ S. Harper,¹⁵¹ J. Linacre,¹⁵¹ E. Olaiya,¹⁵¹ D. Petyt,¹⁵¹ C. H. Shepherd-Themistocleous,¹⁵¹ A. Thea,¹⁵¹ I. R. Tomalin,¹⁵¹ T. Williams,¹⁵¹ W. J. Womersley,¹⁵¹ G. Auzinger,¹⁵² R. Bainbridge,¹⁵² P. Bloch,¹⁵² J. Borg,¹⁵² S. Breeze,¹⁵² O. Buchmuller,¹⁵² A. Bundock,¹⁵² S. Casasso,¹⁵² D. Colling,¹⁵² L. Corpe,¹⁵² P. Dauncey,¹⁵² G. Davies,¹⁵² M. Della Negra,¹⁵² R. Di Maria,¹⁵² Y. Haddad,¹⁵² G. Hall,¹⁵² G. Iles,¹⁵² T. James,¹⁵² M. Komm,¹⁵² C. Laner,¹⁵² L. Lyons,¹⁵² A.-M. Magnan,¹⁵² S. Malik,¹⁵² A. Martelli,¹⁵² J. Nash,^{152,bl} A. Nikitenko,^{152,g} V. Palladino,¹⁵² M. Pesaresi,¹⁵² A. Richards,¹⁵² A. Rose,¹⁵² E. Scott,¹⁵² C. Seez,¹⁵² A. Shtipliyki,¹⁵² G. Singh,¹⁵² M. Stoye,¹⁵² T. Strebler,¹⁵² S. Summers,¹⁵² A. Tapper,¹⁵² K. Uchida,¹⁵² T. Virdee,^{152,o} N. Wardle,¹⁵² D. Winterbottom,¹⁵² J. Wright,¹⁵² S. C. Zenz,¹⁵² J. E. Cole,¹⁵³ P. R. Hobson,¹⁵³ A. Khan,¹⁵³ P. Kyberd,¹⁵³ C. K. Mackay,¹⁵³ A. Morton,¹⁵³ I. D. Reid,¹⁵³ L. Teodorescu,¹⁵³ S. Zahid,¹⁵³ K. Call,¹⁵⁴ J. Dittmann,¹⁵⁴ K. Hatakeyama,¹⁵⁴ H. Liu,¹⁵⁴ C. Madrid,¹⁵⁴ B. McMaster,¹⁵⁴ N. Pastika,¹⁵⁴ C. Smith,¹⁵⁴ R. Bartek,¹⁵⁵ A. Dominguez,¹⁵⁵ A. Buccilli,¹⁵⁶ S. I. Cooper,¹⁵⁶ C. Henderson,¹⁵⁶ P. Rumerio,¹⁵⁶ C. West,¹⁵⁶ D. Arcaro,¹⁵⁷ T. Bose,¹⁵⁷ D. Gastler,¹⁵⁷ D. Rankin,¹⁵⁷ C. Richardson,¹⁵⁷ J. Rohlf,¹⁵⁷ L. Sulak,¹⁵⁷ D. Zou,¹⁵⁷ G. Benelli,¹⁵⁸ X. Coubez,¹⁵⁸ D. Cutts,¹⁵⁸ M. Hadley,¹⁵⁸ J. Hakala,¹⁵⁸ U. Heintz,¹⁵⁸ J. M. Hogan,^{158,bm} K. H. M. Kwok,¹⁵⁸ E. Laird,¹⁵⁸ G. Landsberg,¹⁵⁸ J. Lee,¹⁵⁸ Z. Mao,¹⁵⁸ M. Narain,¹⁵⁸ S. Piperov,¹⁵⁸ S. Sagir,^{158,bn} R. Syarif,¹⁵⁸ E. Usai,¹⁵⁸ D. Yu,¹⁵⁸ R. Band,¹⁵⁹ C. Brainerd,¹⁵⁹ R. Breedon,¹⁵⁹ D. Burns,¹⁵⁹ M. Calderon De La Barca Sanchez,¹⁵⁹ M. Chertok,¹⁵⁹ J. Conway,¹⁵⁹ R. Conway,¹⁵⁹ P. T. Cox,¹⁵⁹ R. Erbacher,¹⁵⁹ C. Flores,¹⁵⁹ G. Funk,¹⁵⁹ W. Ko,¹⁵⁹ O. Kukral,¹⁵⁹ R. Lander,¹⁵⁹ C. Mclean,¹⁵⁹ M. Mulhearn,¹⁵⁹ D. Pellett,¹⁵⁹ J. Pilot,¹⁵⁹ S. Shalhout,¹⁵⁹ M. Shi,¹⁵⁹ D. Stolp,¹⁵⁹ D. Taylor,¹⁵⁹ K. Tos,¹⁵⁹ M. Tripathi,¹⁵⁹ Z. Wang,¹⁵⁹ M. Bachtis,¹⁶⁰ C. Bravo,¹⁶⁰ R. Cousins,¹⁶⁰ A. Dasgupta,¹⁶⁰ A. Florent,¹⁶⁰ J. Hauser,¹⁶⁰ M. Ignatenko,¹⁶⁰ N. Mccoll,¹⁶⁰ S. Regnard,¹⁶⁰ D. Saltzberg,¹⁶⁰ C. Schnaible,¹⁶⁰ V. Valuev,¹⁶⁰ E. Bouvier,¹⁶¹ K. Burt,¹⁶¹ R. Clare,¹⁶¹ J. W. Gary,¹⁶¹ S. M. A. Ghiasi Shirazi,¹⁶¹ G. Hanson,¹⁶¹ G. Karapostoli,¹⁶¹ E. Kennedy,¹⁶¹ F. Lacroix,¹⁶¹ O. R. Long,¹⁶¹ M. Olmedo Negrete,¹⁶¹ M. I. Paneva,¹⁶¹ W. Si,¹⁶¹ L. Wang,¹⁶¹ H. Wei,¹⁶¹ S. Wimpenny,¹⁶¹ B. R. Yates,¹⁶¹ J. G. Branson,¹⁶² S. Cittolin,¹⁶² M. Derdzinski,¹⁶² R. Gerosa,¹⁶² D. Gilbert,¹⁶² B. Hashemi,¹⁶² A. Holzner,¹⁶² D. Klein,¹⁶² G. Kole,¹⁶² V. Krutelyov,¹⁶² J. Letts,¹⁶² M. Masciovecchio,¹⁶² D. Olivito,¹⁶² S. Padhi,¹⁶² M. Pieri,¹⁶² M. Sani,¹⁶² V. Sharma,¹⁶² S. Simon,¹⁶² M. Tadel,¹⁶² A. Vartak,¹⁶² S. Wasserbaech,^{162,bo} J. Wood,¹⁶² F. Würthwein,¹⁶² A. Yagil,¹⁶² G. Zevi Della Porta,¹⁶² N. Amin,¹⁶³ R. Bhandari,¹⁶³ J. Bradmiller-Feld,¹⁶³ C. Campagnari,¹⁶³ M. Citron,¹⁶³ A. Dishaw,¹⁶³ V. Dutta,¹⁶³ M. Franco Sevilla,¹⁶³ L. Gouskos,¹⁶³ R. Heller,¹⁶³ J. Incandela,¹⁶³ A. Ovcharova,¹⁶³ H. Qu,¹⁶³ J. Richman,¹⁶³ D. Stuart,¹⁶³ I. Suarez,¹⁶³ S. Wang,¹⁶³ J. Yoo,¹⁶³ D. Anderson,¹⁶⁴ A. Bornheim,¹⁶⁴ J. M. Lawhorn,¹⁶⁴ H. B. Newman,¹⁶⁴ T. Q. Nguyen,¹⁶⁴ M. Spiropulu,¹⁶⁴ J. R. Vlimant,¹⁶⁴ R. Wilkinson,¹⁶⁴ S. Xie,¹⁶⁴ Z. Zhang,¹⁶⁴ R. Y. Zhu,¹⁶⁴ M. B. Andrews,¹⁶⁵ T. Ferguson,¹⁶⁵ T. Mudholkar,¹⁶⁵ M. Paulini,¹⁶⁵ M. Sun,¹⁶⁵ I. Vorobiev,¹⁶⁵ M. Weinberg,¹⁶⁵ J. P. Cumalat,¹⁶⁶ W. T. Ford,¹⁶⁶ F. Jensen,¹⁶⁶ A. Johnson,¹⁶⁶ M. Krohn,¹⁶⁶ S. Leontsinis,¹⁶⁶ E. MacDonald,¹⁶⁶ T. Mulholland,¹⁶⁶ K. Stenson,¹⁶⁶ K. A. Ulmer,¹⁶⁶ S. R. Wagner,¹⁶⁶ J. Alexander,¹⁶⁷ J. Chaves,¹⁶⁷ Y. Cheng,¹⁶⁷ J. Chu,¹⁶⁷ A. Datta,¹⁶⁷ K. Mcdermott,¹⁶⁷ N. Mirman,¹⁶⁷ J. R. Patterson,¹⁶⁷ D. Quach,¹⁶⁷ A. Rinkevicius,¹⁶⁷ A. Ryd,¹⁶⁷ L. Skinnari,¹⁶⁷ L. Soffi,¹⁶⁷ S. M. Tan,¹⁶⁷ Z. Tao,¹⁶⁷ J. Thom,¹⁶⁷ J. Tucker,¹⁶⁷ P. Wittich,¹⁶⁷ M. Zientek,¹⁶⁷ S. Abdullin,¹⁶⁸ M. Albrow,¹⁶⁸ M. Alyari,¹⁶⁸ G. Apollinari,¹⁶⁸ A. Apresyan,¹⁶⁸ A. Apyan,¹⁶⁸ S. Banerjee,¹⁶⁸ L. A. T. Bauerdick,¹⁶⁸ A. Beretvas,¹⁶⁸ J. Berryhill,¹⁶⁸ P. C. Bhat,¹⁶⁸ G. Bolla,^{168,bp} K. Burkett,¹⁶⁸ J. N. Butler,¹⁶⁸ A. Canepa,¹⁶⁸ G. B. Cerati,¹⁶⁸ H. W. K. Cheung,¹⁶⁸ F. Chlebana,¹⁶⁸ M. Cremonesi,¹⁶⁸ J. Duarte,¹⁶⁸ V. D. Elvira,¹⁶⁸ J. Freeman,¹⁶⁸ Z. Gecse,¹⁶⁸ E. Gottschalk,¹⁶⁸ L. Gray,¹⁶⁸ D. Green,¹⁶⁸ S. Grünendahl,¹⁶⁸ O. Gutsche,¹⁶⁸ J. Hanlon,¹⁶⁸ R. M. Harris,¹⁶⁸ S. Hasegawa,¹⁶⁸ J. Hirschauer,¹⁶⁸ Z. Hu,¹⁶⁸ B. Jayatilaka,¹⁶⁸ S. Jindariani,¹⁶⁸ M. Johnson,¹⁶⁸

U. Joshi,¹⁶⁸ B. Klima,¹⁶⁸ M. J. Kortelainen,¹⁶⁸ B. Kreis,¹⁶⁸ S. Lammel,¹⁶⁸ D. Lincoln,¹⁶⁸ R. Lipton,¹⁶⁸ M. Liu,¹⁶⁸ T. Liu,¹⁶⁸ J. Lykken,¹⁶⁸ K. Maeshima,¹⁶⁸ J. M. Marraffino,¹⁶⁸ D. Mason,¹⁶⁸ P. McBride,¹⁶⁸ P. Merkel,¹⁶⁸ S. Mrenna,¹⁶⁸ S. Nahn,¹⁶⁸ V. O'Dell,¹⁶⁸ K. Pedro,¹⁶⁸ C. Pena,¹⁶⁸ O. Prokofyev,¹⁶⁸ G. Rakness,¹⁶⁸ L. Ristori,¹⁶⁸ A. Savoy-Navarro,^{168,bq} B. Schneider,¹⁶⁸ E. Sexton-Kennedy,¹⁶⁸ A. Soha,¹⁶⁸ W. J. Spalding,¹⁶⁸ L. Spiegel,¹⁶⁸ S. Stoynev,¹⁶⁸ J. Strait,¹⁶⁸ N. Strobbe,¹⁶⁸ L. Taylor,¹⁶⁸ S. Tkaczyk,¹⁶⁸ N. V. Tran,¹⁶⁸ L. Uplegger,¹⁶⁸ E. W. Vaandering,¹⁶⁸ C. Vernieri,¹⁶⁸ M. Verzocchi,¹⁶⁸ R. Vidal,¹⁶⁸ M. Wang,¹⁶⁸ H. A. Weber,¹⁶⁸ A. Whitbeck,¹⁶⁸ D. Acosta,¹⁶⁹ P. Avery,¹⁶⁹ P. Bortignon,¹⁶⁹ D. Bourilkov,¹⁶⁹ A. Brinkerhoff,¹⁶⁹ L. Cadamuro,¹⁶⁹ A. Carnes,¹⁶⁹ M. Carver,¹⁶⁹ D. Curry,¹⁶⁹ R. D. Field,¹⁶⁹ S. V. Gleyzer,¹⁶⁹ B. M. Joshi,¹⁶⁹ J. Konigsberg,¹⁶⁹ A. Korytov,¹⁶⁹ P. Ma,¹⁶⁹ K. Matchev,¹⁶⁹ H. Mei,¹⁶⁹ G. Mitselmakher,¹⁶⁹ K. Shi,¹⁶⁹ D. Sperka,¹⁶⁹ J. Wang,¹⁶⁹ S. Wang,¹⁶⁹ Y. R. Joshi,¹⁷⁰ S. Linn,¹⁷⁰ A. Ackert,¹⁷¹ T. Adams,¹⁷¹ A. Askew,¹⁷¹ S. Hagopian,¹⁷¹ V. Hagopian,¹⁷¹ K. F. Johnson,¹⁷¹ T. Kolberg,¹⁷¹ G. Martinez,¹⁷¹ T. Perry,¹⁷¹ H. Prosper,¹⁷¹ A. Saha,¹⁷¹ V. Sharma,¹⁷¹ R. Yohay,¹⁷¹ M. M. Baarmand,¹⁷² V. Bhopatkar,¹⁷² S. Colafranceschi,¹⁷² M. Hohmann,¹⁷² D. Noonan,¹⁷² M. Rahmani,¹⁷² T. Roy,¹⁷² F. Yumiceva,¹⁷² M. R. Adams,¹⁷³ L. Apanasevich,¹⁷³ D. Berry,¹⁷³ R. R. Betts,¹⁷³ R. Cavanaugh,¹⁷³ X. Chen,¹⁷³ S. Dittmer,¹⁷³ O. Evdokimov,¹⁷³ C. E. Gerber,¹⁷³ D. A. Hangal,¹⁷³ D. J. Hofman,¹⁷³ K. Jung,¹⁷³ J. Kamin,¹⁷³ C. Mills,¹⁷³ I. D. Sandoval Gonzalez,¹⁷³ M. B. Tonjes,¹⁷³ N. Varelas,¹⁷³ H. Wang,¹⁷³ X. Wang,¹⁷³ Z. Wu,¹⁷³ J. Zhang,¹⁷³ M. Alhusseini,¹⁷⁴ B. Bilki,^{174,br} W. Clarida,¹⁷⁴ K. Dilsiz,^{174,bs} S. Durgut,¹⁷⁴ R. P. Gandrajula,¹⁷⁴ M. Haytmyradov,¹⁷⁴ V. Khristenko,¹⁷⁴ J.-P. Merlo,¹⁷⁴ A. Mestvirishvili,¹⁷⁴ A. Moeller,¹⁷⁴ J. Nachtman,¹⁷⁴ H. Ogul,^{174,bt} Y. Onel,¹⁷⁴ F. Ozok,^{174,bu} A. Penzo,¹⁷⁴ C. Snyder,¹⁷⁴ E. Tiras,¹⁷⁴ J. Wetzel,¹⁷⁴ B. Blumenfeld,¹⁷⁵ A. Cocoros,¹⁷⁵ N. Eminizer,¹⁷⁵ D. Fehling,¹⁷⁵ L. Feng,¹⁷⁵ A. V. Gritsan,¹⁷⁵ W. T. Hung,¹⁷⁵ P. Maksimovic,¹⁷⁵ J. Roskes,¹⁷⁵ U. Sarica,¹⁷⁵ M. Swartz,¹⁷⁵ M. Xiao,¹⁷⁵ C. You,¹⁷⁵ A. Al-bataineh,¹⁷⁶ P. Baringer,¹⁷⁶ A. Bean,¹⁷⁶ S. Boren,¹⁷⁶ J. Bowen,¹⁷⁶ A. Bylinkin,¹⁷⁶ J. Castle,¹⁷⁶ S. Khalil,¹⁷⁶ A. Kropivnitskaya,¹⁷⁶ D. Majumder,¹⁷⁶ W. Mcbrayer,¹⁷⁶ M. Murray,¹⁷⁶ C. Rogan,¹⁷⁶ S. Sanders,¹⁷⁶ E. Schmitz,¹⁷⁶ J. D. Tapia Takaki,¹⁷⁶ Q. Wang,¹⁷⁶ S. Duric,¹⁷⁷ A. Ivanov,¹⁷⁷ K. Kaadze,¹⁷⁷ D. Kim,¹⁷⁷ Y. Maravin,¹⁷⁷ D. R. Mendis,¹⁷⁷ T. Mitchell,¹⁷⁷ A. Modak,¹⁷⁷ A. Mohammadi,¹⁷⁷ L. K. Saini,¹⁷⁷ N. Skhirtladze,¹⁷⁷ F. Rebassoo,¹⁷⁸ D. Wright,¹⁷⁸ A. Baden,¹⁷⁹ O. Baron,¹⁷⁹ A. Belloni,¹⁷⁹ S. C. Eno,¹⁷⁹ Y. Feng,¹⁷⁹ C. Ferraioli,¹⁷⁹ N. J. Hadley,¹⁷⁹ S. Jabeen,¹⁷⁹ G. Y. Jeng,¹⁷⁹ R. G. Kellogg,¹⁷⁹ J. Kunkle,¹⁷⁹ A. C. Mignerey,¹⁷⁹ F. Ricci-Tam,¹⁷⁹ Y. H. Shin,¹⁷⁹ A. Skuja,¹⁷⁹ S. C. Tonwar,¹⁷⁹ K. Wong,¹⁷⁹ D. Abercrombie,¹⁸⁰ B. Allen,¹⁸⁰ V. Azzolini,¹⁸⁰ A. Baty,¹⁸⁰ G. Bauer,¹⁸⁰ R. Bi,¹⁸⁰ S. Brandt,¹⁸⁰ W. Busza,¹⁸⁰ I. A. Cali,¹⁸⁰ M. D'Alfonso,¹⁸⁰ Z. Demiragli,¹⁸⁰ G. Gomez Ceballos,¹⁸⁰ M. Goncharov,¹⁸⁰ P. Harris,¹⁸⁰ D. Hsu,¹⁸⁰ M. Hu,¹⁸⁰ Y. Iiyama,¹⁸⁰ G. M. Innocenti,¹⁸⁰ M. Klute,¹⁸⁰ D. Kovalskyi,¹⁸⁰ Y.-J. Lee,¹⁸⁰ P. D. Luckey,¹⁸⁰ B. Maier,¹⁸⁰ A. C. Marini,¹⁸⁰ C. Mcginn,¹⁸⁰ C. Mironov,¹⁸⁰ S. Narayanan,¹⁸⁰ X. Niu,¹⁸⁰ C. Paus,¹⁸⁰ C. Roland,¹⁸⁰ G. Roland,¹⁸⁰ G. S. F. Stephans,¹⁸⁰ K. Sumorok,¹⁸⁰ K. Tatar,¹⁸⁰ D. Velicanu,¹⁸⁰ J. Wang,¹⁸⁰ T. W. Wang,¹⁸⁰ B. Wyslouch,¹⁸⁰ S. Zhaozhong,¹⁸⁰ A. C. Benvenuti,¹⁸¹ R. M. Chatterjee,¹⁸¹ A. Evans,¹⁸¹ P. Hansen,¹⁸¹ S. Kalafut,¹⁸¹ Y. Kubota,¹⁸¹ Z. Lesko,¹⁸¹ J. Mans,¹⁸¹ S. Nourbakhsh,¹⁸¹ N. Ruckstuhl,¹⁸¹ R. Rusack,¹⁸¹ J. Turkewitz,¹⁸¹ M. A. Wadud,¹⁸¹ J. G. Acosta,¹⁸² S. Oliveros,¹⁸² E. Avdeeva,¹⁸³ K. Bloom,¹⁸³ D. R. Claes,¹⁸³ C. Fangmeier,¹⁸³ F. Golf,¹⁸³ R. Gonzalez Suarez,¹⁸³ R. Kamalieddin,¹⁸³ I. Kravchenko,¹⁸³ J. Monroy,¹⁸³ J. E. Siado,¹⁸³ G. R. Snow,¹⁸³ B. Stieger,¹⁸³ A. Godshalk,¹⁸⁴ C. Harrington,¹⁸⁴ I. Iashvili,¹⁸⁴ A. Kharchilava,¹⁸⁴ D. Nguyen,¹⁸⁴ A. Parker,¹⁸⁴ S. Rappoccio,¹⁸⁴ B. Roozbahani,¹⁸⁴ G. Alverson,¹⁸⁵ E. Barberis,¹⁸⁵ C. Freer,¹⁸⁵ A. Hortiangtham,¹⁸⁵ D. M. Morse,¹⁸⁵ T. Orimoto,¹⁸⁵ R. Teixeira De Lima,¹⁸⁵ T. Wamorkar,¹⁸⁵ B. Wang,¹⁸⁵ A. Wisecarver,¹⁸⁵ D. Wood,¹⁸⁵ S. Bhattacharya,¹⁸⁶ O. Charaf,¹⁸⁶ K. A. Hahn,¹⁸⁶ N. Mucia,¹⁸⁶ N. Odell,¹⁸⁶ M. H. Schmitt,¹⁸⁶ K. Sung,¹⁸⁶ M. Trovato,¹⁸⁶ M. Velasco,¹⁸⁶ R. Bucci,¹⁸⁷ N. Dev,¹⁸⁷ M. Hildreth,¹⁸⁷ K. Hurtado Anampa,¹⁸⁷ C. Jessop,¹⁸⁷ D. J. Karmgard,¹⁸⁷ N. Kellams,¹⁸⁷ K. Lannon,¹⁸⁷ W. Li,¹⁸⁷ N. Loukas,¹⁸⁷ N. Marinelli,¹⁸⁷ F. Meng,¹⁸⁷ C. Mueller,¹⁸⁷ Y. Musienko,^{187,bv} M. Planer,¹⁸⁷ A. Reinsvold,¹⁸⁷ R. Ruchti,¹⁸⁷ P. Siddireddy,¹⁸⁷ G. Smith,¹⁸⁷ S. Taroni,¹⁸⁷ M. Wayne,¹⁸⁷ A. Wightman,¹⁸⁷ M. Wolf,¹⁸⁷ A. Woodard,¹⁸⁷ J. Alimena,¹⁸⁸ L. Antonelli,¹⁸⁸ B. Bylsma,¹⁸⁸ L. S. Durkin,¹⁸⁸ S. Flowers,¹⁸⁸ B. Francis,¹⁸⁸ A. Hart,¹⁸⁸ C. Hill,¹⁸⁸ W. Ji,¹⁸⁸ T. Y. Ling,¹⁸⁸ W. Luo,¹⁸⁸ B. L. Winer,¹⁸⁸ H. W. Wulsin,¹⁸⁸ S. Cooperstein,¹⁸⁹ P. Elmer,¹⁸⁹ J. Hardenbrook,¹⁸⁹ P. Hebda,¹⁸⁹ S. Higginbotham,¹⁸⁹ A. Kalogeropoulos,¹⁸⁹ D. Lange,¹⁸⁹ M. T. Lucchini,¹⁸⁹ J. Luo,¹⁸⁹ D. Marlow,¹⁸⁹ K. Mei,¹⁸⁹ I. Ojalvo,¹⁸⁹ J. Olsen,¹⁸⁹ C. Palmer,¹⁸⁹ P. Piroué,¹⁸⁹ J. Salfeld-Nebgen,¹⁸⁹ D. Stickland,¹⁸⁹ C. Tully,¹⁸⁹ S. Malik,¹⁹⁰ S. Norberg,¹⁹⁰ A. Barker,¹⁹¹ V. E. Barnes,¹⁹¹ S. Das,¹⁹¹ L. Gutay,¹⁹¹ M. Jones,¹⁹¹ A. W. Jung,¹⁹¹ A. Khatiwada,¹⁹¹ B. Mahakud,¹⁹¹ D. H. Miller,¹⁹¹ N. Neumeister,¹⁹¹ C. C. Peng,¹⁹¹ H. Qiu,¹⁹¹ J. F. Schulte,¹⁹¹ J. Sun,¹⁹¹ F. Wang,¹⁹¹ R. Xiao,¹⁹¹ W. Xie,¹⁹¹ T. Cheng,¹⁹² J. Dolen,¹⁹² N. Parashar,¹⁹² Z. Chen,¹⁹³ K. M. Ecklund,¹⁹³ S. Freed,¹⁹³ F. J. M. Geurts,¹⁹³ M. Kilpatrick,¹⁹³ W. Li,¹⁹³ B. Michlin,¹⁹³ B. P. Padley,¹⁹³ J. Roberts,¹⁹³ J. Rorie,¹⁹³ W. Shi,¹⁹³ Z. Tu,¹⁹³ J. Zabel,¹⁹³ A. Zhang,¹⁹³ A. Bodek,¹⁹⁴ P. de Barbaro,¹⁹⁴ R. Demina,¹⁹⁴ Y. t. Duh,¹⁹⁴ J. L. Dulemba,¹⁹⁴ C. Fallon,¹⁹⁴ T. Ferbel,¹⁹⁴ M. Galanti,¹⁹⁴ A. Garcia-Bellido,¹⁹⁴ J. Han,¹⁹⁴ O. Hindrichs,¹⁹⁴ A. Khukhunaishvili,¹⁹⁴ K. H. Lo,¹⁹⁴ P. Tan,¹⁹⁴ R. Taus,¹⁹⁴ M. Verzetti,¹⁹⁴ A. Agapitos,¹⁹⁵ J. P. Chou,¹⁹⁵ Y. Gershtein,¹⁹⁵ T. A. Gómez Espinosa,¹⁹⁵ E. Halkiadakis,¹⁹⁵ M. Heindl,¹⁹⁵ E. Hughes,¹⁹⁵ S. Kaplan,¹⁹⁵ R. Kunnawalkam Elayavalli,¹⁹⁵ S. Kyriacou,¹⁹⁵ A. Lath,¹⁹⁵ R. Montalvo,¹⁹⁵ K. Nash,¹⁹⁵ M. Osherson,¹⁹⁵ H. Saka,¹⁹⁵ S. Salur,¹⁹⁵ S. Schnetzer,¹⁹⁵ D. Sheffield,¹⁹⁵ S. Somalwar,¹⁹⁵ R. Stone,¹⁹⁵ S. Thomas,¹⁹⁵ P. Thomassen,¹⁹⁵ M. Walker,¹⁹⁵ A. G. Delannoy,¹⁹⁶ J. Heideman,¹⁹⁶ G. Riley,¹⁹⁶ K. Rose,¹⁹⁶ S. Spanier,¹⁹⁶ K. Thapa,¹⁹⁶ O. Bouhali,^{197,bw} A. Celik,¹⁹⁷ M. Dalchenko,¹⁹⁷ M. De Mattia,¹⁹⁷ A. Delgado,¹⁹⁷ S. Dildick,¹⁹⁷ R. Eusebi,¹⁹⁷ J. Gilmore,¹⁹⁷ T. Huang,¹⁹⁷ T. Kamon,^{197,bx} S. Luo,¹⁹⁷ R. Mueller,¹⁹⁷ Y. Pakhotin,¹⁹⁷ R. Patel,¹⁹⁷ A. Perloff,¹⁹⁷ L. Perniè,¹⁹⁷ D. Rathjens,¹⁹⁷ A. Safonov,¹⁹⁷ A. Tatarinov,¹⁹⁷ N. Akchurin,¹⁹⁸ J. Damgov,¹⁹⁸ F. De Guio,¹⁹⁸ P. R. Duerdo,¹⁹⁸ S. Kunori,¹⁹⁸ K. Lamichhane,¹⁹⁸ S. W. Lee,¹⁹⁸ T. Mengke,¹⁹⁸ S. Muthumuni,¹⁹⁸ T. Peltola,¹⁹⁸ S. Undleeb,¹⁹⁸ I. Volobouev,¹⁹⁸ Z. Wang,¹⁹⁸ S. Greene,¹⁹⁹ A. Gurrola,¹⁹⁹ R. Janjam,¹⁹⁹ W. Johns,¹⁹⁹ C. Maguire,¹⁹⁹ A. Melo,¹⁹⁹ H. Ni,¹⁹⁹ K. Padeken,¹⁹⁹ J. D. Ruiz Alvarez,¹⁹⁹ P. Sheldon,¹⁹⁹ S. Tuo,¹⁹⁹ J. Velkovska,¹⁹⁹ M. Verweij,¹⁹⁹ Q. Xu,¹⁹⁹ M. W. Arenton,²⁰⁰ P. Barria,²⁰⁰ B. Cox,²⁰⁰ R. Hirosky,²⁰⁰

M. Joyce,²⁰⁰ A. Ledovskoy,²⁰⁰ H. Li,²⁰⁰ C. Neu,²⁰⁰ T. Sinthuprasith,²⁰⁰ Y. Wang,²⁰⁰ E. Wolfe,²⁰⁰ F. Xia,²⁰⁰ R. Harr,²⁰¹ P. E. Karchin,²⁰¹ N. Poudyal,²⁰¹ J. Sturdy,²⁰¹ P. Thapa,²⁰¹ S. Zaleski,²⁰¹ M. Brodski,²⁰² J. Buchanan,²⁰² C. Caillol,²⁰² D. Carlsmith,²⁰² S. Dasu,²⁰² L. Dodd,²⁰² B. Gomber,²⁰² M. Grothe,²⁰² M. Herndon,²⁰² A. Hervé,²⁰² U. Hussain,²⁰² P. Klabbers,²⁰² A. Lanaro,²⁰² A. Levine,²⁰² K. Long,²⁰² R. Loveless,²⁰² T. Ruggles,²⁰² A. Savin,²⁰² N. Smith,²⁰² W. H. Smith,²⁰² and N. Woods²⁰²

(CMS Collaboration)

¹*Yerevan Physics Institute, Yerevan, Armenia*

²*Institut für Hochenergiephysik, Wien, Austria*

³*Institute for Nuclear Problems, Minsk, Belarus*

⁴*Universiteit Antwerpen, Antwerpen, Belgium*

⁵*Vrije Universiteit Brussel, Brussel, Belgium*

⁶*Université Libre de Bruxelles, Bruxelles, Belgium*

⁷*Ghent University, Ghent, Belgium*

⁸*Université Catholique de Louvain, Louvain-la-Neuve, Belgium*

⁹*Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil*

¹⁰*Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil*

¹¹*Universidade Estadual Paulista, São Paulo, Brazil*

¹²*Universidade Federal do ABC, São Paulo, Brazil*

¹³*Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria*

¹⁴*University of Sofia, Sofia, Bulgaria*

¹⁵*Beihang University, Beijing, China*

¹⁶*Institute of High Energy Physics, Beijing, China*

¹⁷*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China*

¹⁸*Tsinghua University, Beijing, China*

¹⁹*Universidad de Los Andes, Bogota, Colombia*

²⁰*University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia*

²¹*University of Split, Faculty of Science, Split, Croatia*

²²*Institute Rudjer Boskovic, Zagreb, Croatia*

²³*University of Cyprus, Nicosia, Cyprus*

²⁴*Charles University, Prague, Czech Republic*

²⁵*Escuela Politecnica Nacional, Quito, Ecuador*

²⁶*Universidad San Francisco de Quito, Quito, Ecuador*

²⁷*Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt*

²⁸*National Institute of Chemical Physics and Biophysics, Tallinn, Estonia*

²⁹*Department of Physics, University of Helsinki, Helsinki, Finland*

³⁰*Helsinki Institute of Physics, Helsinki, Finland*

³¹*Lappeenranta University of Technology, Lappeenranta, Finland*

³²*IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*

³³*Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France*

³⁴*Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France*

³⁵*Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France*

³⁶*Université de Lyon, Université Claude Bernard Lyon I, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France*

³⁷*Georgian Technical University, Tbilisi, Georgia*

³⁸*Tbilisi State University, Tbilisi, Georgia*

³⁹*RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany*

⁴⁰*RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany*

⁴¹*RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany*

⁴²*Deutsches Elektronen-Synchrotron, Hamburg, Germany*

⁴³*University of Hamburg, Hamburg, Germany*

⁴⁴*Karlsruher Institut fuer Technologie, Karlsruhe, Germany*

⁴⁵*Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece*

⁴⁶*National and Kapodistrian University of Athens, Athens, Greece*

⁴⁷*National Technical University of Athens, Athens, Greece*

⁴⁸*University of Ioánnina, Ioánnina, Greece*

⁴⁹*MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary*

⁵⁰*Wigner Research Centre for Physics, Budapest, Hungary*

- ⁵¹*Institute of Nuclear Research ATOMKI, Debrecen, Hungary*
- ⁵²*Institute of Physics, University of Debrecen, Debrecen, Hungary*
- ⁵³*Indian Institute of Science (IISc), Bangalore, India*
- ⁵⁴*National Institute of Science Education and Research, HBNI, Bhubaneswar, India*
- ⁵⁵*Panjab University, Chandigarh, India*
- ⁵⁶*University of Delhi, Delhi, India*
- ⁵⁷*Saha Institute of Nuclear Physics, HBNI, Kolkata, India*
- ⁵⁸*Indian Institute of Technology Madras, Madras, India*
- ⁵⁹*Bhabha Atomic Research Centre, Mumbai, India*
- ⁶⁰*Tata Institute of Fundamental Research-A, Mumbai, India*
- ⁶¹*Tata Institute of Fundamental Research-B, Mumbai, India*
- ⁶²*Indian Institute of Science Education and Research (IISER), Pune, India*
- ⁶³*Institute for Research in Fundamental Sciences (IPM), Tehran, Iran*
- ⁶⁴*University College Dublin, Dublin, Ireland*
- ⁶⁵*INFN Sezione di Bari, Bari, Italy*
- ⁶⁶*Università di Bari, Bari, Italy*
- ⁶⁷*Politecnico di Bari, Bari, Italy*
- ⁶⁸*INFN Sezione di Bologna, Bologna, Italy*
- ⁶⁹*Università di Bologna, Bologna, Italy*
- ⁷⁰*INFN Sezione di Catania, Catania, Italy*
- ⁷¹*Università di Catania, Catania, Italy*
- ⁷²*INFN Sezione di Firenze, Firenze, Italy*
- ⁷³*Università di Firenze, Firenze, Italy*
- ⁷⁴*INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- ⁷⁵*INFN Sezione di Genova, Genova, Italy*
- ⁷⁶*Università di Genova, Genova, Italy*
- ⁷⁷*INFN Sezione di Milano-Bicocca, Milano, Italy*
- ⁷⁸*Università di Milano-Bicocca, Milano, Italy*
- ⁷⁹*INFN Sezione di Napoli, Napoli, Italy*
- ⁸⁰*Università di Napoli "Federico II," Napoli, Italy*
- ⁸¹*Università della Basilicata, Potenza, Italy*
- ⁸²*Università G. Marconi, Roma, Italy*
- ⁸³*INFN Sezione di Padova, Padova, Italy*
- ⁸⁴*Università di Padova, Padova, Italy*
- ⁸⁵*Università di Trento, Trento, Italy*
- ⁸⁶*INFN Sezione di Pavia, Pavia, Italy*
- ⁸⁷*Università di Pavia, Pavia, Italy*
- ⁸⁸*INFN Sezione di Perugia, Perugia, Italy*
- ⁸⁹*Università di Perugia, Perugia, Italy*
- ⁹⁰*INFN Sezione di Pisa, Pisa, Italy*
- ⁹¹*Università di Pisa, Pisa, Italy*
- ⁹²*Scuola Normale Superiore di Pisa, Pisa, Italy*
- ⁹³*INFN Sezione di Roma, Rome, Italy*
- ⁹⁴*Sapienza Università di Roma, Rome, Italy*
- ⁹⁵*INFN Sezione di Torino, Torino, Italy*
- ⁹⁶*Università di Torino, Torino, Italy*
- ⁹⁷*Università del Piemonte Orientale, Novara, Italy*
- ⁹⁸*INFN Sezione di Trieste, Trieste, Italy*
- ⁹⁹*Università di Trieste, Trieste, Italy*
- ¹⁰⁰*Kyungpook National University, Daegu, Korea*
- ¹⁰¹*Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea*
- ¹⁰²*Hanyang University, Seoul, Korea*
- ¹⁰³*Korea University, Seoul, Korea*
- ¹⁰⁴*Sejong University, Seoul, Korea*
- ¹⁰⁵*Seoul National University, Seoul, Korea*
- ¹⁰⁶*University of Seoul, Seoul, Korea*
- ¹⁰⁷*Sungkyunkwan University, Suwon, Korea*
- ¹⁰⁸*Vilnius University, Vilnius, Lithuania*
- ¹⁰⁹*National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia*

- ¹¹⁰Universidad de Sonora (UNISON), Hermosillo, Mexico
- ¹¹¹Centro de Investigación y de Estudios Avanzados del IPN, Mexico City, Mexico
- ¹¹²Universidad Iberoamericana, Mexico City, Mexico
- ¹¹³Benemerita Universidad Autónoma de Puebla, Puebla, Mexico
- ¹¹⁴Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico
- ¹¹⁵University of Auckland, Auckland, New Zealand
- ¹¹⁶University of Canterbury, Christchurch, New Zealand
- ¹¹⁷National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan
- ¹¹⁸National Centre for Nuclear Research, Swierk, Poland
- ¹¹⁹Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland
- ¹²⁰Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal
- ¹²¹Joint Institute for Nuclear Research, Dubna, Russia
- ¹²²Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia
- ¹²³Institute for Nuclear Research, Moscow, Russia
- ¹²⁴Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC “Kurchatov Institute,” Moscow, Russia
- ¹²⁵Moscow Institute of Physics and Technology, Moscow, Russia
- ¹²⁶National Research Nuclear University “Moscow Engineering Physics Institute” (MEPhI), Moscow, Russia
- ¹²⁷P.N. Lebedev Physical Institute, Moscow, Russia
- ¹²⁸Skobel'syn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
- ¹²⁹Novosibirsk State University (NSU), Novosibirsk, Russia
- ¹³⁰Institute for High Energy Physics of National Research Centre “Kurchatov Institute,” Protvino, Russia
- ¹³¹National Research Tomsk Polytechnic University, Tomsk, Russia
- ¹³²University of Belgrade: Faculty of Physics and VINCA Institute of Nuclear Sciences, Serbia
- ¹³³Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
- ¹³⁴Universidad Autónoma de Madrid, Madrid, Spain
- ¹³⁵Universidad de Oviedo, Instituto Universitario de Ciencias y Tecnologías Espaciales de Asturias (ICTEA), Oviedo, Spain
- ¹³⁶Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain
- ¹³⁷CERN, European Organization for Nuclear Research, Geneva, Switzerland
- ¹³⁸Paul Scherrer Institut, Villigen, Switzerland
- ¹³⁹ETH Zurich - Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland
- ¹⁴⁰Universität Zürich, Zurich, Switzerland
- ¹⁴¹National Central University, Chung-Li, Taiwan
- ¹⁴²National Taiwan University (NTU), Taipei, Taiwan
- ¹⁴³Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand
- ¹⁴⁴Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey
- ¹⁴⁵Middle East Technical University, Physics Department, Ankara, Turkey
- ¹⁴⁶Bogazici University, Istanbul, Turkey
- ¹⁴⁷Istanbul Technical University, Istanbul, Turkey
- ¹⁴⁸Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine
- ¹⁴⁹National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine
- ¹⁵⁰University of Bristol, Bristol, United Kingdom
- ¹⁵¹Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹⁵²Imperial College, London, United Kingdom
- ¹⁵³Brunel University, Uxbridge, United Kingdom
- ¹⁵⁴Baylor University, Waco, Texas, USA
- ¹⁵⁵Catholic University of America, Washington, DC, USA
- ¹⁵⁶The University of Alabama, Tuscaloosa, Alabama, USA
- ¹⁵⁷Boston University, Boston, Massachusetts, USA
- ¹⁵⁸Brown University, Providence, Rhode Island, USA
- ¹⁵⁹University of California, Davis, Davis, California, USA
- ¹⁶⁰University of California, Los Angeles, California, USA
- ¹⁶¹University of California, Riverside, Riverside, California, USA
- ¹⁶²University of California, San Diego, La Jolla, California, USA
- ¹⁶³University of California, Santa Barbara - Department of Physics, Santa Barbara, California, USA
- ¹⁶⁴California Institute of Technology, Pasadena, California, USA
- ¹⁶⁵Carnegie Mellon University, Pittsburgh, Pennsylvania, USA
- ¹⁶⁶University of Colorado Boulder, Boulder, Colorado, USA
- ¹⁶⁷Cornell University, Ithaca, New York, USA
- ¹⁶⁸Fermi National Accelerator Laboratory, Batavia, Illinois, USA

- ¹⁶⁹University of Florida, Gainesville, Florida, USA
¹⁷⁰Florida International University, Miami, Florida, USA
¹⁷¹Florida State University, Tallahassee, Florida, USA
¹⁷²Florida Institute of Technology, Melbourne, Florida, USA
¹⁷³University of Illinois at Chicago (UIC), Chicago, Illinois, USA
¹⁷⁴The University of Iowa, Iowa City, Iowa, USA
¹⁷⁵Johns Hopkins University, Baltimore, Maryland, USA
¹⁷⁶The University of Kansas, Lawrence, Kansas, USA
¹⁷⁷Kansas State University, Manhattan, Kansas, USA
¹⁷⁸Lawrence Livermore National Laboratory, Livermore, California, USA
¹⁷⁹University of Maryland, College Park, Maryland, USA
¹⁸⁰Massachusetts Institute of Technology, Cambridge, Massachusetts, USA
¹⁸¹University of Minnesota, Minneapolis, Minnesota, USA
¹⁸²University of Mississippi, Oxford, Mississippi, USA
¹⁸³University of Nebraska-Lincoln, Lincoln, Nebraska, USA
¹⁸⁴State University of New York at Buffalo, Buffalo, New York, USA
¹⁸⁵Northeastern University, Boston, Massachusetts, USA
¹⁸⁶Northwestern University, Evanston, Illinois, USA
¹⁸⁷University of Notre Dame, Notre Dame, Indiana, USA
¹⁸⁸The Ohio State University, Columbus, Ohio, USA
¹⁸⁹Princeton University, Princeton, New Jersey, USA
¹⁹⁰University of Puerto Rico, Mayaguez, Puerto Rico, USA
¹⁹¹Purdue University, West Lafayette, Indiana, USA
¹⁹²Purdue University Northwest, Hammond, Indiana, USA
¹⁹³Rice University, Houston, Texas, USA
¹⁹⁴University of Rochester, Rochester, New York, USA
¹⁹⁵Rutgers, The State University of New Jersey, Piscataway, New Jersey, USA
¹⁹⁶University of Tennessee, Knoxville, Tennessee, USA
¹⁹⁷Texas A&M University, College Station, Texas, USA
¹⁹⁸Texas Tech University, Lubbock, Texas, USA
¹⁹⁹Vanderbilt University, Nashville, Tennessee, USA
²⁰⁰University of Virginia, Charlottesville, Virginia, USA
²⁰¹Wayne State University, Detroit, Michigan, USA
²⁰²University of Wisconsin-Madison, Madison, Wisconsin, USA

^aAlso at Vienna University of Technology, Vienna, Austria.

^bAlso at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.

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

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

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

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

^gAlso at Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of NRC “Kurchatov Institute,” Moscow, Russia.

^hAlso at Joint Institute for Nuclear Research, Dubna, Russia.

ⁱAlso at Cairo University, Cairo, Egypt.

^jAlso at Fayoum University, El-Fayoum, Egypt; British University in Egypt, Cairo, Egypt.

^kAlso at British University in Egypt, Cairo, Egypt; Ain Shams University, Cairo, Egypt.

^lAlso at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.

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

ⁿAlso at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.

^oAlso at CERN, European Organization for Nuclear Research, Geneva, Switzerland.

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

^qAlso at University of Hamburg, Hamburg, Germany.

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

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

^tAlso at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.

^uAlso at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary; Deceased.

^vAlso at Institute of Physics, University of Debrecen, Debrecen, Hungary.

^wAlso at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.

^xAlso at Institute of Physics, Bhubaneswar, India.

^yAlso at Shoolini University, Solan, India.

- ^zAlso at University of Visva-Bharati, Santiniketan, India.
- ^{aa}Also at Isfahan University of Technology, Isfahan, Iran.
- ^{ab}Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
- ^{ac}Also at Università degli Studi di Siena, Siena, Italy.
- ^{ad}Also at Kyung Hee University, Department of Physics, Seoul, Korea.
- ^{ae}Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
- ^{af}Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
- ^{ag}Also at Consejo Nacional de Ciencia y Tecnología, Mexico City, Mexico.
- ^{ah}Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
- ^{ai}Also at Institute for Nuclear Research, Moscow, Russia; National Research Nuclear University “Moscow Engineering Physics Institute” (MEPhI), Moscow, Russia.
- ^{aj}Also at Institute of Nuclear Physics of the Uzbekistan Academy of Sciences, Tashkent, Uzbekistan.
- ^{ak}Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
- ^{al}Also at University of Florida, Gainesville, Florida, USA.
- ^{am}Also at P.N. Lebedev Physical Institute, Moscow, Russia.
- ^{an}Also at National Research Nuclear University “Moscow Engineering Physics Institute” (MEPhI), Moscow, Russia.
- ^{ao}Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
- ^{ap}Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
- ^{aq}Also at INFN Sezione di Pavia, Università di Pavia, Pavia, Italy.
- ^{ar}Also at University of Belgrade, Belgrade, Serbia.
- ^{as}Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
- ^{at}Also at National and Kapodistrian University of Athens, Athens, Greece.
- ^{au}Also at Riga Technical University, Riga, Latvia.
- ^{av}Also at Universität Zürich, Zurich, Switzerland.
- ^{aw}Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
- ^{ax}Also at Gaziosmanpasa University, Tokat, Turkey.
- ^{ay}Also at Adiyaman University, Adiyaman, Turkey.
- ^{az}Also at Istanbul Aydin University, Istanbul, Turkey.
- ^{ba}Also at Mersin University, Mersin, Turkey.
- ^{bb}Also at Piri Reis University, Istanbul, Turkey.
- ^{bc}Also at Ozyegin University, Istanbul, Turkey.
- ^{bd}Also at Izmir Institute of Technology, Izmir, Turkey.
- ^{be}Also at Marmara University, Istanbul, Turkey.
- ^{bf}Also at Kafkas University, Kars, Turkey.
- ^{bg}Also at Istanbul University, Istanbul, Turkey.
- ^{bh}Also at Istanbul Bilgi University, Istanbul, Turkey.
- ^{bi}Also at Hacettepe University, Ankara, Turkey.
- ^{bj}Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
- ^{bk}Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
- ^{bl}Also at Monash University, Faculty of Science, Clayton, Australia.
- ^{bm}Also at Bethel University, St. Paul, Minnesota, USA.
- ^{bn}Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
- ^{bo}Also at Utah Valley University, Orem, Utah, USA.
- ^{bp}Deceased.
- ^{bq}Also at Purdue University, West Lafayette, Indiana, USA.
- ^{br}Also at Beykent University, Istanbul, Turkey.
- ^{bs}Also at Bingol University, Bingol, Turkey.
- ^{bt}Also at Sinop University, Sinop, Turkey.
- ^{bu}Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
- ^{bv}Also at Institute for Nuclear Research, Moscow, Russia.
- ^{bw}Also at Texas A&M University at Qatar, Doha, Qatar.
- ^{bx}Also at Kyungpook National University, Daegu, Korea.