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The CMS collaboration

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

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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 μb^{-1} for pp and pPb collisions, respectively, were collected by the CMS experiment. The nuclear modification factor $R_{p\text{Pb}}$, 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 $R_{p\text{Pb}}$ 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 $R_{p\text{Pb}}$ data, but fails to describe the dependence on particle species in the yield asymmetries measured away from midrapidity in pPb collisions.

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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 $p_T (\gtrsim 8$ 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:

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

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

In the intermediate p_T region ($2 \lesssim p_T \lesssim 8$ 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

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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 ^{3}HeAu 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 $R_{p\mathrm{Pb}}$ 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 $R_{p\mathrm{Pb}}$ in the p- and Pb-going directions separately, and of the particle yield rapidity asymmetry Y_{asym} in pPb collisions, where

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

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 $|y_{\mathrm{CM}}| < 1.8$, $-1.8 < y_{\mathrm{CM}} < 0$, and $0 < y_{\mathrm{CM}} < 1.8$ in pp and pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. These measurements are shown for the K_S^0 and the sum of $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$, and $\Omega^- + \bar{\Omega}^+$(hereafter referred to as Λ, Ξ^-, and Ω^-, respectively). Based on these spectra, $R_{p\mathrm{Pb}}$ 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 $R_{p\mathrm{Pb}}$ of the Ω^- baryon is studied in the range $|y_{\mathrm{CM}}| < 1.8$. 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 $0.3 < |y_{\mathrm{CM}}| < 0.8$, $0.8 < |y_{\mathrm{CM}}| < 1.3$, and $1.3 < |y_{\mathrm{CM}}| < 1.8$. 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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, corresponding to integrated luminosities of 40.2 nb^{-1} and 15.6 μb^{-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 $y_{\mathrm{CM}} = 0$ 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 *p*Pb 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 *p*Pb 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 *p*Pb data sample. The procedure used to reject pileup events in *p*Pb 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 *p*Pb 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 *p*Pb 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 *p*Pb collisions. A procedure similar to that in Refs. [36,43] is used to correct the strange-particle spectra in *pp* and *p*Pb collisions to spectra for inelastic collisions and DS events, respectively, with multiplicity-dependent correction factors. The values of $R_{p\text{Pb}}$ will decrease by 3%–6% if the normalization of the *p*Pb 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 $|y_{\text{CM}}| < 1.8$ are shown in Fig. 1 for *p*Pb 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

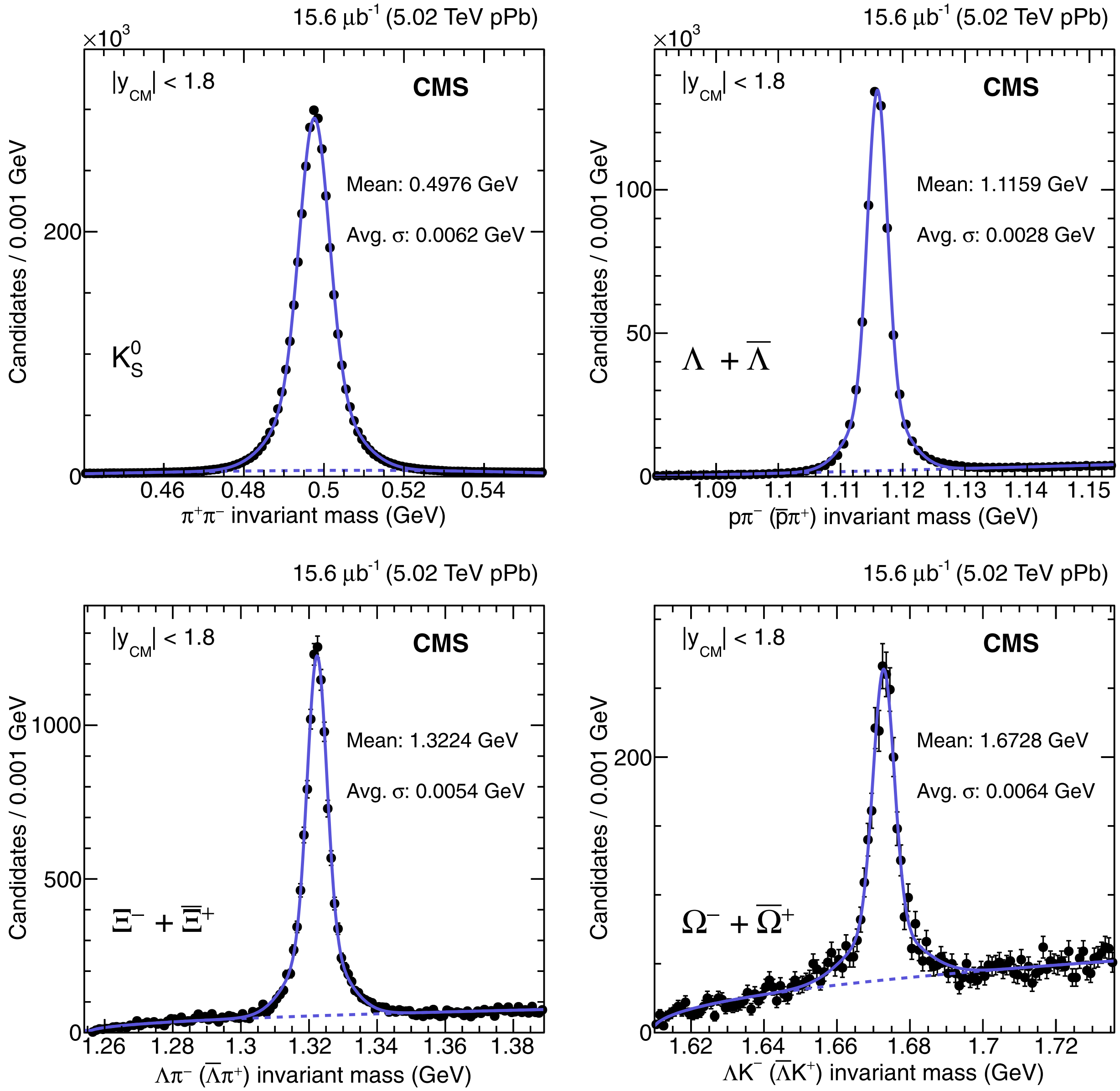

FIG. 1. Invariant-mass distribution of K^0_S (upper left), $\Lambda + \bar{\Lambda}$ (upper right), $\Xi^- + \bar{\Xi}^+$ (lower left), and $\Omega^- + \bar{\Omega}^+$ (lower right) candidates within $|y_{\mathrm{CM}}| < 1.8$ in pPb collisions. The solid lines show the results of fits described in the 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 $N^{\mathrm{raw}}_{K^0_S}$, $N^{\mathrm{raw}}_{\Lambda}$, $N^{\mathrm{raw}}_{\Xi^-}$, and $N^{\mathrm{raw}}_{\Omega^-}$.

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, $N^{\mathrm{corr}}_{K^0_S}$, $N^{\mathrm{corr}}_{\Lambda}$, $N^{\mathrm{corr}}_{\Xi^-}$, $N^{\mathrm{corr}}_{\Omega^-}$ is given by

$$N^{\mathrm{corr}}_{K^0_S} = \frac{N^{\mathrm{raw}}_{K^0_S}}{B\alpha\epsilon},\quad N^{\mathrm{corr}}_{\Lambda} = \frac{N^{\mathrm{raw}}_{\Lambda}}{B\alpha\epsilon},\quad N^{\mathrm{corr}}_{\Xi^-} = \frac{N^{\mathrm{raw}}_{\Xi^-}}{B\alpha\epsilon},\quad N^{\mathrm{corr}}_{\Omega^-} = \frac{N^{\mathrm{raw}}_{\Omega^-}}{B\alpha\epsilon}, \tag{3}$$

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

$$f^{\rm residual}_{\Lambda,\,\rm np} = 1 + f^{\rm raw,\,MC}_{\Lambda,\,\rm np}\left(\frac{N^{\rm corr}_{\Xi^-}/N^{\rm corr}_{\Lambda}}{N^{\rm MC}_{\Xi^-}/N^{\rm MC}_{\Lambda}} - 1\right), \tag{4}$$

where $f^{\rm raw,\,MC}_{\Lambda,\,\rm np}$ denotes the fraction of nonprompt Λ candidates in the reconstructed sample, and is obtained from MC simulation. The $N^{\rm corr}_{\Xi^-}/N^{\rm corr}_{\Lambda}$ and $N^{\rm MC}_{\Xi^-}/N^{\rm MC}_{\Lambda}$ 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 $N^{\rm corr}_{\Lambda}/f^{\rm residual}_{\Lambda,\,\rm np}$. 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 $N^{\rm corr}_{\Lambda}$ 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, $N^{\rm corr}_{\Lambda}$ 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^0_S, Λ, Ξ^-, and Ω^- p_T spectra, $R_{p\rm Pb}$, and $Y_{\rm asym}$ for different $y_{\rm CM}$ ranges in both *pp* and *p*Pb 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 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^0_S 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 I. Summary of different sources of systematic uncertainties in K^0_S, Λ, Ξ^-, and Ω^- p_T spectra and $R_{p\rm Pb}$ measurements for different $y_{\rm CM}$ ranges in both *pp* and *p*Pb collisions. The ranges quoted cover both the p_T and the rapidity dependence of the uncertainties.

Source	K^0_S (%)	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 (*p*Pb only)	1–4	1–5	3	4
Integrated lum. (*pp* only)	2.3	2.3	2.3	2.3
$\langle T_{p\rm Pb}\rangle$ (for $R_{p\rm Pb}$)	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 *p*Pb coll.)	8.2–10.1	8.6–12.3	13.8	15.1
Total ($R_{p\rm Pb}$)	3.1–5.6	4.3–10.4	6.8	10.8

TABLE II. Summary of systematic uncertainties in the $Y_{\rm asym}$ measurements in *p*Pb 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 $Y_{\rm asym}$ of Ξ^- and Ω^- are not presented.

Source	K^0_S (%)	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 ($Y_{\rm asym}$)	2.4–6.5	3.2–9.3

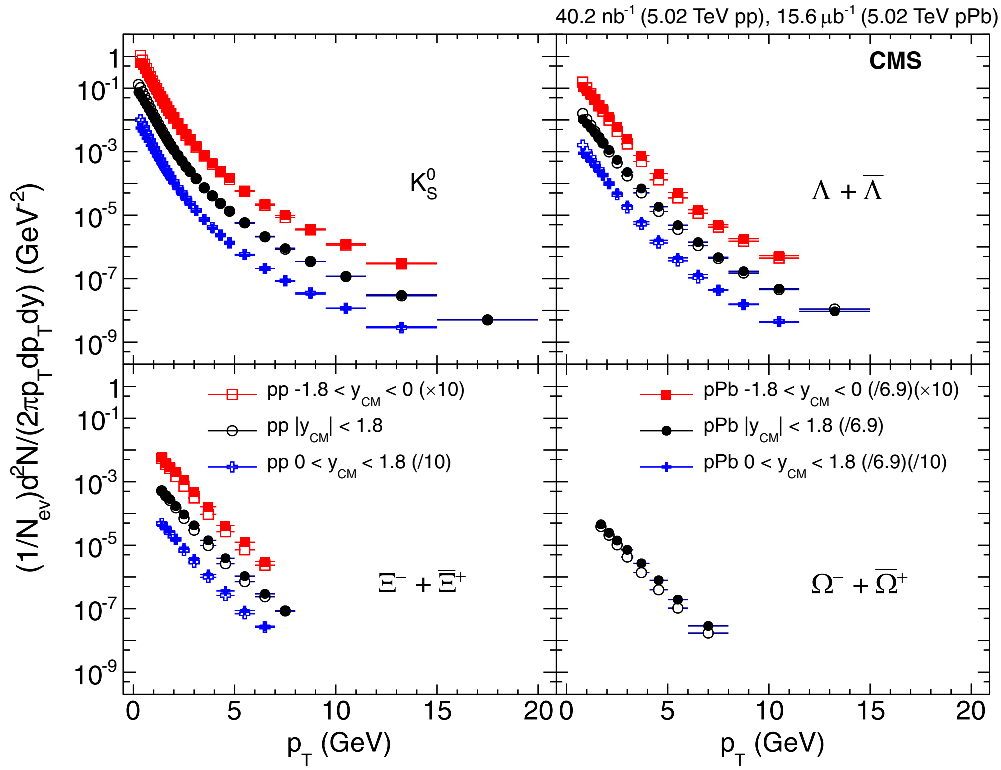

FIG. 2. The invariant p_T-differential spectra of K^0_S (upper left), $\Lambda + \bar{\Lambda}$ (upper right), $\Xi^- + \bar{\Xi}^+$ (lower left), and $\Omega^- + \bar{\Omega}^+$ (lower right) for $|y_{CM}| < 1.8$, $-1.8 < y_{CM} < 0$, and $0 < y_{CM} < 1.8$ in *pp* and *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ 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 *p*Pb collisions directly, the spectra in *p*Pb 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 $N^{corr}_{\Xi^-}/N^{corr}_{\Lambda}$ ratio in Eq. (4) to the $f^{residual}_{\Lambda,\,np}$ 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 *p*Pb data. In *p*Pb 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 *p*Pb 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^0_S, Λ, Ξ^-, and Ω^- particles with $|y_{CM}| < 1.8$, $-1.8 < y_{CM} < 0$, and $0 < y_{CM} < 1.8$ in *pp* and *p*Pb 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 *p*Pb collisions directly, the spectra in *p*Pb collisions are divided by the average number of binary nucleon-nucleon collisions, $\langle N_{coll}\rangle = 6.9 \pm 0.5$, 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^0_S, Λ, Ξ^-, and Ω^- particles are calculated in different y_{CM} ranges. Figure 3 shows the R_{pPb} of each particle

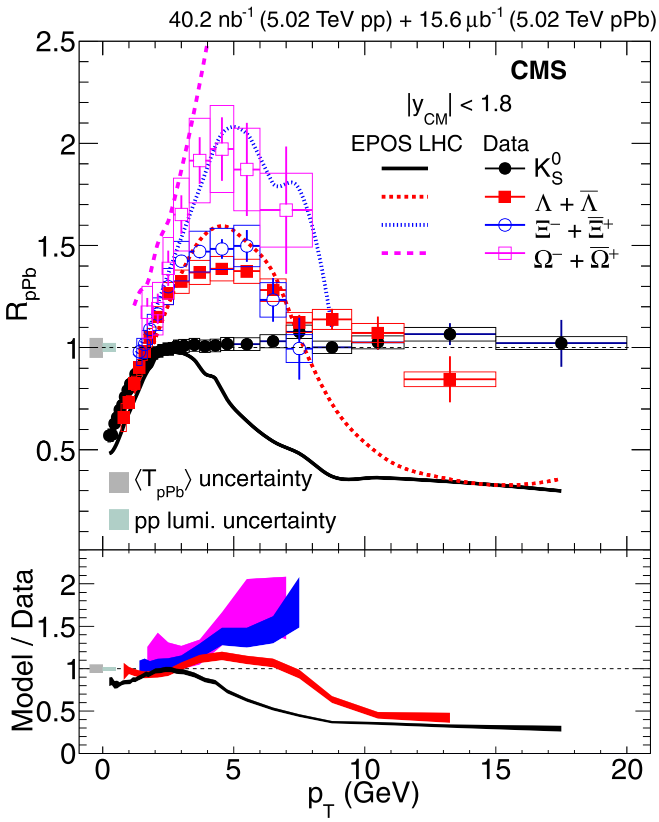

FIG. 3. (Upper) Nuclear modification factors for K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), $\Xi^- + \bar{\Xi}^+$ (blue open circles), and $\Omega^- + \bar{\Omega}^+$ (purple open squares) for $|y_{\rm CM}| < 1.8$ in *p*Pb collisions are presented. The vertical bars correspond to statistical uncertainties, and the horizontal bars represent the bin width, while the open boxes around the markers denote the systematic uncertainties. The $\langle T_{p\rm Pb}\rangle$ 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*Pb 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 $|y_{\rm CM}| < 1.8$. The $R_{p\rm Pb}$ values of K_S^0 are consistent with unity for $p_{\rm T} > 2$ GeV. For baryons, the $R_{p\rm Pb}$ of both Λ and Ξ^- reach unity for $p_{\rm T}$ somewhere between 7 and 8 GeV. This is consistent with the charged-particle $R_{p\rm Pb}$ [36], which also shows no modification in the $p_{\rm T}$ range from 7 to 20 GeV. In the intermediate $p_{\rm T}$ 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 $R_{p\rm Pb}$. 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 *p*Pb collisions, are compared with data in Fig. 3. The calculations indeed predict clear mass ordering for baryon $R_{p\rm Pb}$ in this $p_{\rm T}$ range, with even stronger mass dependence than observed in data. At higher $p_{\rm T}$, $R_{p\rm Pb}$ 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 $R_{d\rm Au}$ at RHIC [53]. To fully understand particle production in this $p_{\rm T}$ range, more theoretical calculations including the recombination models are needed. For $p_{\rm T}$ values less than 2 GeV, the predicted $R_{p\rm Pb}$ values from the EPOS LHC model qualitatively agree with the experimental results for each of the particle species. In this $p_{\rm T}$ range, $R_{p\rm Pb}$ for K_S^0 and Λ become less than unity, as expected for soft particle production.

The $R_{p\rm Pb}$ values of K_S^0, Λ, and Ξ^- particles for $-1.8 < y_{\rm CM} < 0$ and $0 < y_{\rm CM} < 1.8$ are presented as functions of $p_{\rm T}$ in Fig. 4. Because of the limitations in the size of the data sample, the $R_{p\rm Pb}$ of the Ω^- baryon is not shown in the *p*- and Pb-going direction separately. Above $p_{\rm T}{>}2$ GeV, $R_{p\rm Pb}$ 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 $R_{p\rm Pb}$ 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 $p_{\rm T}$ and rapidity considered in this analysis. Therefore, these measurements are sensitive to the shadowing effect, and $R_{p\rm Pb}$ 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 $p_{\rm T}$-differential spectra of K_S^0 and Λ for five different $y_{\rm CM}$ ranges in *p*Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV are presented in Fig. 5. Figure 6 shows the $Y_{\rm asym}$ (Pb-going direction in the numerator) as functions of $p_{\rm T}$ for K_S^0, Λ and charged particles [36] for different rapidity (pseudorapidity) ranges. The observed $Y_{\rm asym}$ values depend both on $p_{\rm T}$ and particle species, and these dependencies are more pronounced in the forward (larger) $y_{\rm CM}$ ranges. The $Y_{\rm asym}$ are larger in the forward region, consistent with expectations from nuclear shadowing, and overall larger than unity in all measured $|y_{\rm CM}|$ ranges. Significant departures from unity, and particle-species dependencies are seen away from midrapidity in the region $1.3 < y_{\rm CM} < 1.8$. As a function of $p_{\rm T}$ for all particle species, the $Y_{\rm asym}$ values first rise and then fall, approaching unity at higher $p_{\rm T}$. The peak values for Λ are shifted to higher $p_{\rm T}$ compared with the those of K_S^0 and charged

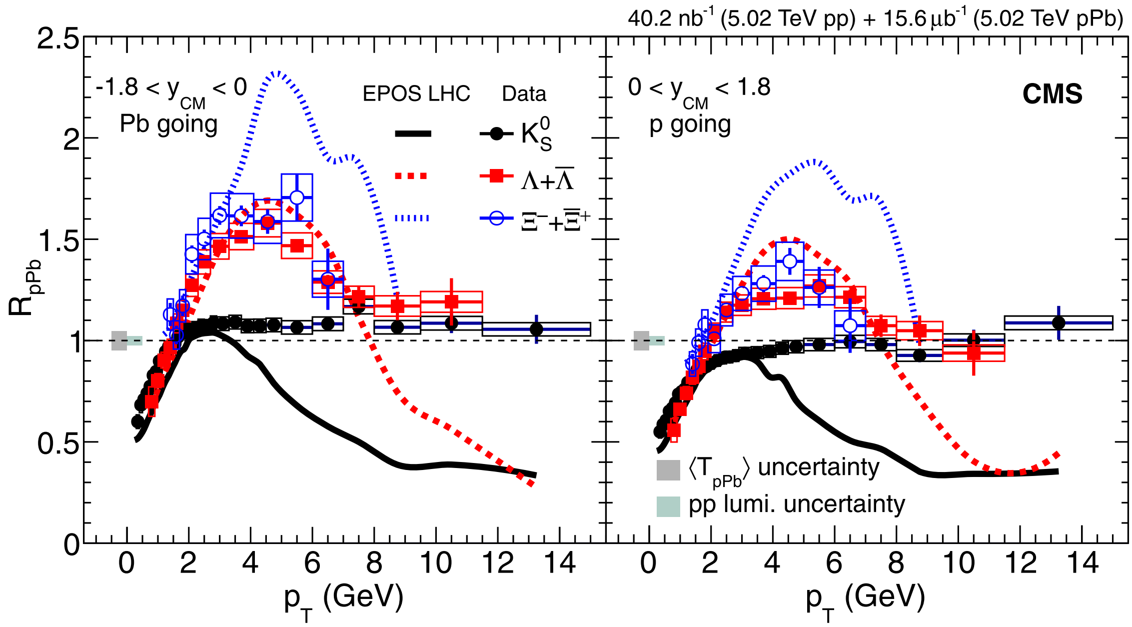

FIG. 4. Nuclear modification factors of K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), and $\Xi^- + \bar{\Xi}^+$ (blue open circles) particles for $-1.8 < y_{\mathrm{CM}} < 0$ (Pb-going, left) and $0 < y_{\mathrm{CM}} < 1.8$ (p-going, right) in pPb collisions are presented. 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 $\langle T_{p\mathrm{Pb}}\rangle$ 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 pPb collisions [38]. The data and predictions share the same color for each particle species.

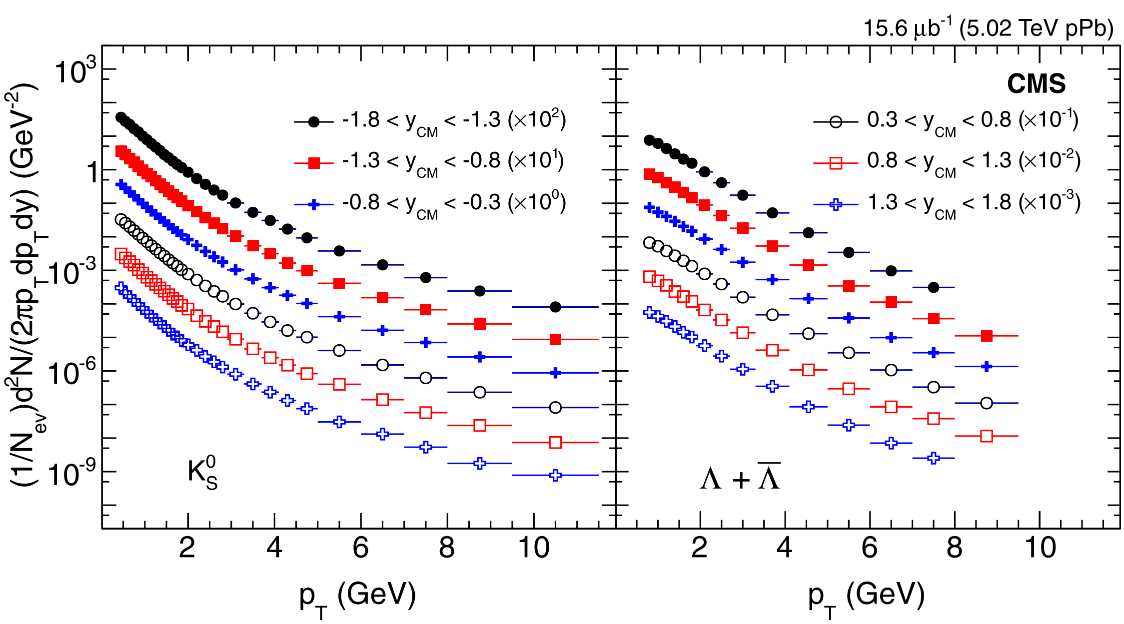

FIG. 5. The invariant p_{T}-differential spectra of K_S^0 (left) and $\Lambda + \bar{\Lambda}$ (right) particles for $-1.8 < y_{\mathrm{CM}} < -1.3$, $-1.3 < y_{\mathrm{CM}} < -0.8$, $-0.8 < y_{\mathrm{CM}} < -0.3$, $0.3 < y_{\mathrm{CM}} < 0.8$, $0.8 < y_{\mathrm{CM}} < 1.3$, and $1.3 < y_{\mathrm{CM}} < 1.8$ in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV. Spectra in different y_{CM} ranges are scaled by factors of powers of 10, with $-0.8 < y_{\mathrm{CM}} < -0.3$ 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.

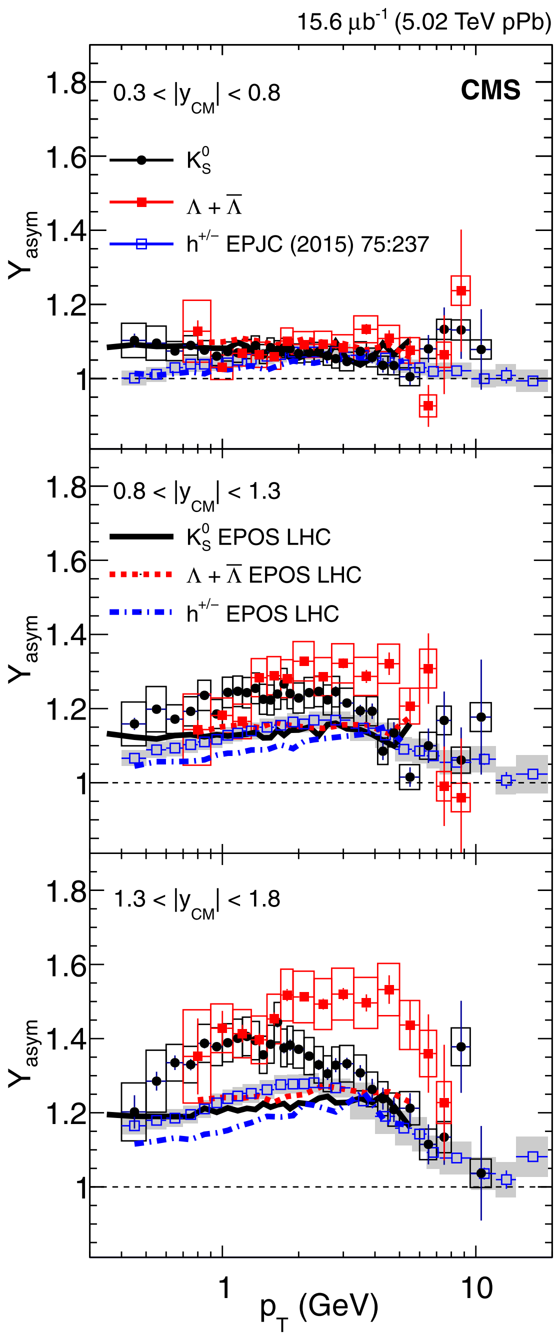

FIG. 6. The $Y_{\rm asym}$ of K_S^0 (black filled circles), $\Lambda + \bar{\Lambda}$ (red filled squares), and charged particles (blue open squares) at $0.3 < |y_{\rm CM}| < 0.8$, $0.8 < |y_{\rm CM}| < 1.3$, and $1.3 < |y_{\rm CM}| < 1.8$ ($|\eta_{\rm CM}|$ ranges for charged particles) in *p*Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ 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 *p*Pb collisions [38]. The data and predictions share the same color for each particle species.

particles, which include a $p_{\rm T}$-dependent mixture of charged hadrons. The $Y_{\rm asym}$ 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 $Y_{\rm asym}$ are compared with the EPOS LHC predictions for K_S^0, Λ, and inclusive charged particles produced in the three $y_{\rm CM}$ ranges. The $Y_{\rm asym}$ from EPOS LHC increases from mid-$y_{\rm CM}$ to forward $y_{\rm CM}$, consistent with the trend of the data, but fails to describe the particle-species dependence at forward $y_{\rm CM}$.

VII. SUMMARY

The transverse momentum ($p_{\rm T}$) 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 ($y_{\rm CM}$) ranges. The nuclear modification factors of K_S^0, Λ, and Ξ^- in $|y_{\rm CM}| < 1.8$, $-1.8 < y_{\rm CM} < 0$, and $0 < y_{\rm CM} < 1.8$ ranges are measured. In the $p_{\rm T}$ 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 $R_{p\rm Pb}$ 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 $Y_{\rm asym}$ in K_S^0 and Λ yields between equivalent positive and negative $y_{\rm CM}$ are presented as functions of $p_{\rm T}$ in $0.3 < |y_{\rm CM}| < 0.8$, $0.8 < |y_{\rm CM}| < 1.3$, and $1.3 < |y_{\rm CM}| < 1.8$, and compared with those for charged particles. The $Y_{\rm asym}$ values are larger than unity in all three $y_{\rm CM}$ ranges with greater enhancements observed at more forward regions. The mass dependence of $R_{p\rm Pb}$ 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 $Y_{\rm asym}$ 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 *p*Pb collisions at high energies.

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