Measurement of the nuclear modification factor of identified strange and multi-strange particles in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with CMS experiment

The CMS Collaboration

Abstract

Measurements of strange hadron ($K^0_S$, $\Lambda + \bar{\Lambda}$, $\Xi^- + \Xi^+$, and $\Omega^- + \Omega^+$) transverse momentum spectra in pp and pPb collisions are presented in several center-of-mass rapidity ($y_{\text{CM}}$) intervals. The data, corresponding to integrated luminosities of approximately 40.2 nb$^{-1}$ and 15.6 $\mu$b$^{-1}$ for pp and pPb respectively, were collected at $\sqrt{s_{NN}} = 5.02$ TeV by the CMS experiment. The nuclear modification factor, $R_{p\text{Pb}}$, is measured for each particle species. For $K^0_S$ mesons, $R_{p\text{Pb}}$ increases from $p_T = 0.5$ to 3.0 GeV, but is consistent with unity for $p_T > 3.0$ GeV. In the $p_T$ range from 3.0 to 6.0 GeV, $R_{p\text{Pb}}$ is above unity for the three baryons with $R_{p\text{Pb}}(\Omega^- + \Omega^+) > R_{p\text{Pb}}(\Xi^- + \Xi^+) > R_{p\text{Pb}}(\Lambda + \bar{\Lambda})$. In addition, the asymmetries in the $K^0_S$ and $\Lambda + \bar{\Lambda}$ yields between equivalent positive and negative $y_{\text{CM}}$ are presented as functions of $p_T$. The asymmetries increase away from mid-rapidity and for up to 2.0 GeV are found to be larger for $K^0_S$ and $\Lambda + \bar{\Lambda}$ than for charged hadrons. For $p_T > 2.0$ GeV the asymmetries are greater for $\Lambda + \bar{\Lambda}$ than for $K^0_S$. The results are compared to calculations from the EPOS LHC model with collective flow.
1 Introduction

The abundance of strange and multi-strange particles has long been considered as a useful probe for the formation of the quark-gluon plasma (QGP) [1]. Studies of relativistic heavy-ion collisions at the AGS, SPS, RHIC, and LHC show an enhancement of strangeness production [2–6]. Proton-nucleus (pA) and deuteron-nucleus (dA) collisions were originally considered as control experiments where QGP formation was not expected to occur. Measurements of strange particle production in pPb collisions from ALICE [7] indicate that strangeness enhancement is also observed in pPb collisions. There have been extensive studies of two- and multi-particle azimuthal correlations in high-multiplicity pp, pPb, and peripheral PbPb collisions [8–11], which may indicate collectivity in small systems. However, jet quenching [12, 13] is not observed in pPb collisions.

The measurements of strange particle production in these small systems from CMS [14] and ALICE [7], suggest that in a high-multiplicity environment, the results are consistent with predictions from hydrodynamic models with the radial-flow effect [15] for the low \( p_T \) region and the recombination models for \( p_T > 2 \) GeV, similar to those found in AA collisions. However, it is still unclear whether collectivity can extend to the low multiplicity region.

Particle production in pA and dA as compared to pp collisions has been extensively studied at both RHIC [16–19] and the LHC [20–22] using the nuclear modification factor. For collisions between two nuclei, A and B, the nuclear modification factor, \( R_{AB} \), is defined as the ratio of particle yield in AB collisions to those in pp collisions scaled by the average number of binary nucleon-nucleon collisions, \( \langle N_{\text{coll}} \rangle \), in AB collisions. It is given by

\[
R_{AB}(p_T) = \frac{d^2N_{AB}/dp_Tdy_{\text{CM}}}{\langle N_{\text{coll}} \rangle d^2N_{pp}/dp_Tdy_{\text{CM}}} = \frac{d^2N_{AB}/dp_Tdy_{\text{CM}}}{\langle T_{AB} \rangle d^2\sigma_{pp}/dp_Tdy_{\text{CM}}},
\]

where \( y_{\text{CM}} \) is the rapidity computed in the center-of-mass frame of the colliding nucleons, and \( \langle T_{AB} \rangle \), the nuclear overlap function, accounts for the nuclear collision geometry and is calculated from a Glauber model [23, 24]. If nuclear collisions behave as incoherent superpositions of nucleon-nucleon collisions, \( R_{AB} \) is expected to be unity.

Detailed studies of identified particle production and \( R_{dAu} \) at RHIC [25, 26] indicate that final state effects, such as those from the recombination models [27–29], play an important role in understanding the results in dAu collisions. The calculations from EPOS LHC [30], including parametrized collective flow dependent on the local energy density in the system in pp and pPb collisions, reproduced the charged-particle \( R_{pPb} \) for \( p_T < 5 \) GeV. The model predicted that particles with larger mass will have stronger radial flow and larger \( R_{pPb} \) for \( p_T \) between 2.5 and 5 GeV, especially for multi-strange baryons. Thus the strange particle \( R_{pPb} \) can provide critical information to further the understanding of collective dynamics in small systems.

In addition, measurements of strange particle \( R_{pPb} \) can provide information about Cronin [31, 32] and nuclear shadowing [33] effects. The Cronin effect, discovered in the 1970s, features an enhancement of hadron spectra at intermediate \( p_T \) in pA (scaled by \( \langle N_{\text{coll}} \rangle \)) relative to pp collisions. The enhancement has been attributed to multiple scattering of projectile partons by the target nucleus before the hard scattering. This multiple-scattering mechanism, which is an initial-state effect, was predicted to produce small modifications at LHC energies compared to other effects [34]. Another explanation of the Cronin enhancement is the parton recombination as a final-state effect [28], which was predicted to increase in magnitude when going from RHIC to LHC energies [35]. Nuclear shadowing refers to the phenomenon that the nuclear parton distribution functions are suppressed relative to the proton parton distribution functions in...
the small parton fractional momentum regime ($x < 0.01$). Therefore, considering only the shadowing effect, $R_{pPb}$ is expected to be less than unity at low $p_T$ [36].

All three effects, radial flow, Cronin enhancement, and nuclear shadowing are expected to have different characteristic particle production in the forward (p-going) and backward (Pb-going) rapidity regions. The radial flow is expected to be greater, and therefore to produce a stronger mass ordering, in the Pb-going direction than the p-going direction [30, 37]. The Cronin effect with the parton multiple scattering interpretation would result in a stronger enhancement in the p-going direction because of the transverse momentum broadening of the initial partons inside the projectile [36]. 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 would result in a larger $R_{pPb}$ in the Pb-going direction than the p-going direction. 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 $Y_{\text{asym}}$ in pPb collisions. The definition of $Y_{\text{asym}}$ is:

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

(2)

where $a$ and $b$ are always positive and refer to the proton beam direction.

This analysis presents measurements of strange and multi-strange particles: $K^0_S$, $\Lambda+\bar{\Lambda}$ (hereafter referred to as $\Lambda$), $\Xi^-+\bar{\Xi}^+$ (hereafter referred to as $\Xi^-$), and $\Omega^-+\bar{\Omega}^+$ (hereafter referred to as $\Omega^-$) $p_T$ spectra at $-1.8 < y_{\text{CM}} < 1.8$, $-1.8 < y_{\text{CM}} < 0$, and $0 < y_{\text{CM}} < 1.8$ in pp and pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Based on these spectra, $R_{pPb}$ for each particle species is studied as a function of $p_T$ in the three rapidity ranges. The $R_{pPb}$ of $\Omega^-$ is studied only in the large $-1.8 < y_{\text{CM}} < 1.8$ range because of the limited statistical precision. The $Y_{\text{asym}}$ of $K^0_S$ and $\Lambda$ as functions of $p_T$ for rapidity ranges $0.3 < |y_{\text{CM}}| < 0.8$, $0.8 < |y_{\text{CM}}| < 1.3$, and $1.3 < |y_{\text{CM}}| < 1.8$ are presented in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are compared to calculations from the EPOS LHC model including collective flow in pp and pPb collisions.

2 The CMS Detector

The CMS detector comprises a number of subsystems. These include a silicon tracker, a lead-tungstate crystal electromagnetic calorimeter, and a brass-scintillator hadron calorimeter all immersed in a 3.8 T axial magnetic field, while muon detectors are interspersed with the flux-return steel outside of the 6 m diameter superconducting solenoid. The silicon tracker consists of 1440 silicon pixel and 15148 silicon strip detector modules. It measures charged particles within the pseudorapidity range $|\eta| < 2.5$. 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) $\mu$m in the transverse (longitudinal) impact parameter [38]. Iron hadron-forward (HF) calorimeters, with quartz fibers read out by photomultipliers, cover a pseudorapidity range of 2.9 $< |\eta| < 5.2$ on either side of the interaction region. A detailed description of the CMS detector can be found in Ref. [39]. The Monte Carlo (MC) simulation of the particle propagation and detector response is based on the Geant4 [40] program.

3 Data samples and event selections

The 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, with integrated luminosities of 40.2 nb$^{-1}$ and 15.6 $\mu$b$^{-1}$, respectively. The
same triggers and event selections were used as in Refs. [22, 41]. MB pp collisions are triggered by requiring at least one side of HF to have a calorimeter tower energy signal. The MB pPb events are triggered by requiring at least one reconstructed track with $p_T > 0.4$ GeV in the pixel tracker.

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 the vertices are required to be within 15 cm of the nominal interaction point along the beam axis and 0.15 cm in the transverse 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. [38]. In addition, having at least one HF calorimeter tower on both the positive and negative sides 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. [9]. It is based on the number of tracks associated with each reconstructed vertex and the distance between different vertices. A purity of more than 99.9% for single pPb collision events is achieved for the MB data studied in this analysis. The average pileup is approximately 0.9 in pp collisions. Following the same procedure as in [41], all the reconstructed vertices are selected to extract the pp strange-particle spectra. The pp integrated luminosity [42] is used to normalize the spectrum in pp collisions.

From the PYTHIA8 Tune 4C [43] generator, the efficiency with respect to the inelastic events for the selections described in the paragraph above in pp collisions is 95%. For pPb collisions, the fraction of selected events is estimated with respect to a detector-independent class of collisions termed as “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 $-5 < \eta < -3$. About 99% of pPb DS events are selected from simulations using the HIJING MC generator [44]. Based on the estimate using EPOS LHC [30] and HIJING [44] event generators, the double-sided events correspond to 94-97% of inelastic pPb collisions. Similar to the correction procedure in [22, 41], the strange-particle spectra in pp and pPb collisions are corrected to inelastic collisions and DS events, respectively, as functions of the event multiplicity. The values of $R_{pPb}$ will decrease by 3-6% if pPb spectra are corrected to inelastic collisions.

4 The $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ candidate reconstruction and yields

The $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ candidates in this analysis are identified and analyzed following the procedure in previous analyses [14, 45]. The $K^0_S$ and $\Lambda$ candidates (generally referred to as $V^0$ candidates) are reconstructed via their decay topology by combining pairs of oppositely charged tracks that are detached from the primary vertex to form a good secondary vertex with an appropriate invariant mass. In $K^0_S$ reconstruction, the two tracks are assumed to be pions, and the pion PDG mass is assigned to each track. For $\Lambda$ reconstruction, the track with lower momentum is assumed to be a pion track, while the one with higher momentum is assumed to be a proton track. To optimize the reconstruction of $V^0$ particles, requirements on the three-dimensional (3D) distance of closest approach (DCA) significance of its decay products with respect to the primary vertex are applied. This significance, the 3D DCA between the decay products and the primary vertex divided by its uncertainty, must be larger than 2 for both daughter tracks. To further reduce the background from random combinations of tracks, the 3D DCA significance of $V^0$ candidates cannot exceed 2.5. Because of the long lifetime of
the \(\psi^0\) particles, the 3D decay length significance with respect to the primary vertex of the \(\psi^0\) candidates must be larger than 3. To remove \(K_0^\pm\) candidates misidentified as \(\Lambda\) particles, the \(\Lambda\) candidate mass assuming both tracks to be pions must differ from the nominal \(K_0^\pm\) mass value [46] by more than 20 MeV. A similar procedure is done to avoid \(\Lambda\) candidates misidentified as \(K_0^0\) particles. To remove photon conversions to an electron-positron pair, the mass of a \(K_0^0\) or \(\Lambda\) candidate, assuming both tracks to have the electron mass, must exceed 15 MeV.

For \(\Xi^-\) and \(\Omega^-\) reconstruction, a previously reconstructed \(\Lambda\) candidate is combined with an additional charged track carrying the correct sign, to define a common secondary vertex. This track is assumed to be a pion and kaon track in \(\Xi^-\), \(\Omega^-\) reconstruction, respectively. To reduce background and optimize the reconstruction of \(\Xi^-\) and \(\Omega^-\), the 3D DCA significance of a proton (pion) track from \(\Lambda\) decay with respect to the primary vertex must exceed 2. Similarly, the 3D DCA significance of a pion (kaon) track from the \(\Xi^-\) \((\Omega^-)\) decay with respect to the primary vertex is required to be larger than 4. The 3D DCA significance of the \(\Xi^-\) and \(\Omega^-\) candidates with respect to the primary vertex cannot exceed 3. The 3D decay length significance between the \(\Xi^-\) and \(\Omega^-\) vertices, and the primary vertex must exceed 2. The 3D separation significance between the associated \(\Lambda\) vertex and the primary vertex must be larger than 10.

The invariant mass distributions of reconstructed \(K_0^0\), \(\Lambda\), \(\Xi^-\), and \(\Omega^-\) candidates in the range \(-1.8 < y_{\text{CM}} < 1.8\) 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, the strange-particle peaks are modeled as the sum of two Gaussian functions with a common mean. The “average \(\sigma\)” values in Fig. 1 are the square root of the weighted average of the variances of the two Gaussian functions. The background is modeled with a quadratic function for the \(K_0^0\) results, and with the analytic form \(Aq^0\) for the baryons to mimic the available phase space volume, where \(q\) is the mass difference between the mother candidate and the sum of two daughter tracks. 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 ranges of strange-particle invariant masses indicated in Fig. 1 to obtain the raw strange-particle yields \(N_{\text{raw}}^{K_0^0/\Lambda/\Xi^-/\Omega^-}\).

The raw strange-particle yield is corrected for branching ratio (BR), acceptance (\(\alpha\)), and reconstruction (\(\epsilon\)) efficiency using simulations based on the EPOS LHC event generator [30] and a GEANT4 model of the detector. The corrected yield, \(N_{\text{corr}}^{K_0^0/\Lambda/\Xi^-/\Omega^-}\), is calculated from

\[
N_{\text{corr}}^{K_0^0/\Lambda/\Xi^-/\Omega^-} = \frac{N_{\text{raw}}^{K_0^0/\Lambda/\Xi^-/\Omega^-}}{\text{BR} \times \alpha \times \epsilon},
\]

where \(\text{BR} \times \alpha \times \epsilon\) is obtained by the ratio of reconstructed yield to generated yield of strange particles in MC simulations.

The raw \(\Lambda\) particle yield also contains a contribution from decays of \(\Xi^-\) and \(\Omega^-\) particles. This “nonprompt” contribution is largely determined by the relative ratio of \(\Xi^-\) to \(\Lambda\) yield (because the contribution from \(\Omega^-\) particles is negligible). Stringent requirements on the significance of the 3D distance of closest approach for \(\Lambda\) candidates with respect to the primary vertex remove a large fraction of nonprompt \(\Lambda\) candidates, while up to 4% of the \(\Lambda\) candidates are found to be nonprompt at intermediate \(p_T\) from simulations. The method used to account for the nonprompt \(\Lambda\) contribution is the same as in the previous analysis [14]. If the ratio of \(\Xi^-\) to \(\Lambda\) yield is modeled precisely in MC generators, contamination of nonprompt \(\Lambda\) particles will be eliminated in the correction procedure using Eq. (3). Otherwise, an additional correction for the
4. The $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ candidate reconstruction and yields

Figure 1: Invariant mass distribution of $K^0_S$ (top left), $\Lambda$ (top right), $\Xi^-$ (bottom left), and $\Omega^-$ (bottom right) candidates in $|y_{CM}| < 1.8$ in pPb collisions. The inclusion of the charge-conjugate states is implied for $\Lambda$, $\Xi^-$, and $\Omega^-$ particles. The solid lines show the results of fits described in the text. The dashed lines indicate the fitted background component.

residual effect is necessary. As the $\Xi^-$ particle yields are explicitly measured in this analysis, this residual correction factor can be derived in a data-driven way as,

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

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

5 Systematic uncertainties

Tables 1 and 2 summarize the sources of systematic uncertainties in $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ $p_T$ spectra, $R_{ppb}$, and $Y_{asym}$ at different $y_{CM}$ ranges in both pp and pPb collisions. The dominant sources of systematic uncertainty are associated with the strange-particle reconstruction, especially the efficiency determination.

Table 1: Summary of different sources of systematic uncertainties of $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ $p_T$ spectra and $R_{ppb}$ at 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.

<table>
<thead>
<tr>
<th>Source</th>
<th>$K^0_S$ (%)</th>
<th>$\Lambda$ (%)</th>
<th>$\Xi^-$ (%)</th>
<th>$\Omega^-$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extraction</td>
<td>0-2.0</td>
<td>0-4.0</td>
<td>2.0</td>
<td>3.0</td>
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<td>Selection criteria</td>
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<td>1.0-5.0</td>
<td>3.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Momentum resolution</td>
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<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Tracking efficiency</td>
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<td>8.0</td>
<td>12.0</td>
<td>12.0</td>
</tr>
<tr>
<td>Feed-down correction</td>
<td>-</td>
<td>2.0-3.0</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pileup effect (pp only)</td>
<td>1.0-2.3</td>
<td>1.0-2.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Beam direction (pPb only)</td>
<td>1.0-4.0</td>
<td>1.0-5.0</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Luminosity (pp only)</td>
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<td>2.3</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$\langle T_{ppb} \rangle$ (for $R_{ppb}$)</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Total (yields in pp)</td>
<td>8.6-9.3</td>
<td>8.9-10.6</td>
<td>13.1</td>
<td>14.3</td>
</tr>
<tr>
<td>Total (yields in pPb)</td>
<td>8.2-10.1</td>
<td>8.6-12.3</td>
<td>13.8</td>
<td>15.1</td>
</tr>
<tr>
<td>Total ($R_{ppb}$)</td>
<td>3.1-5.6</td>
<td>4.3-10.4</td>
<td>6.8</td>
<td>10.8</td>
</tr>
</tbody>
</table>

Table 2: Summary of systematic uncertainties on $Y_{asym}$ in pPb collisions. The ranges quoted cover both the $p_T$ and the rapidity dependence of the uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$K^0_S$ (%)</th>
<th>$\Lambda$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield extraction</td>
<td>-</td>
<td>0-3.0</td>
</tr>
<tr>
<td>Selection criteria</td>
<td>1.0-5.0</td>
<td>1.0-6.0</td>
</tr>
<tr>
<td>Momentum resolution</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Feed-down correction</td>
<td>-</td>
<td>2.0-3.0</td>
</tr>
<tr>
<td>Beam direction</td>
<td>2.0-4.0</td>
<td>2.0-6.0</td>
</tr>
<tr>
<td>Total ($Y_{asym}$)</td>
<td>2.4-6.5</td>
<td>3.2-9.3</td>
</tr>
</tbody>
</table>

The systematic uncertainty from 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 0-4.0% 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 1.0-6.0%. 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 1.0%. The systematic uncertainty in determining the efficiency of a single track is 4.0% [47]. This translates into a systematic uncertainty in the reconstruction efficiency of 8.0% for the $K_S^0$ and $\Lambda$ particles, and 12.0% for the $\Xi^-$ and $\Omega^-$ particles. The systematic uncertainty associated with a feed-down effect for $\Lambda$ spectra is evaluated through propagation of the systematic uncertainty in the $N_{\Xi^-}^{\text{corr}}/N_{\Lambda}^{\text{corr}}$ ratio in Eq. (4) to the $f_{\Lambda,Np}$ factor, and is found to be 2.0-3.0%. Systematic uncertainty introduced by pileup effects for pp data is estimated to be 1.0-3.0%. This uncertainty is evaluated through the comparison of strange-particle spectra between data with low and high pileup events. 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, with and without the beam reversal, yields an uncertainty of 1.0-5.0%. The uncertainty in the integrated luminosity for pp collisions is 2.3% [42]. As in [22], the uncertainty of $\langle T_{pPb} \rangle$ is 4.8%.

The uncertainty from the tracking efficiency cancels fully for the value of the $R_{pPb}$ and the $Y_{\text{asym}}$ because they have the same tracking reconstruction condition. All other sources of systematic uncertainty are uncorrelated and summed in quadrature to get the total systematic uncertainties for each strange particle.

6 Results

6.1 Nuclear modification factor of $K_S^0$, $\Lambda$, $\Xi^-$, and $\Omega^-$

The invariant $p_T$-differential spectra of $K_S^0$, $\Lambda$, $\Xi^-$, and $\Omega^-$ particles at $-1.8 < y_{\text{CM}} < 1.8$, $-1.8 < y_{\text{CM}} < 0$, and $0 < y_{\text{CM}} < 1.8$ in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02\text{ TeV}$ are presented in Fig. 2. Invariant differential yield is defined as the average number of particles per event weighted by $1/2\pi p_T$, for each $p_T$ and $y_{\text{CM}}$ range. The pp spectrum, for the purposes of measuring the $R_{pPb}$, is measured as a differential cross section with normalization determined from the integrated luminosity. In order to convert this quantity to a per-event yield for comparison on the same figure, a scaling factor of 70 mb [41], corresponding approximately to the total inelastic pp cross section, is applied. 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, $\langle N_{\text{coll}} \rangle = 6.9$, which is obtained from a Glauber MC simulation [23, 24]. For purpose of better visibility, spectra for different $y_{\text{CM}}$ ranges are scaled by factors of $10^6$, with $-1.8 < y_{\text{CM}} < 1.8$ not scaled.

With the efficiency-corrected strange-particle spectra, the $R_{pPb}$ of $K_S^0$, $\Lambda$, $\Xi^-$, and $\Omega^-$ are calculated in different $y_{\text{CM}}$ ranges. Figure 3 shows the $R_{pPb}$ of each particle species at $-1.8 < y_{\text{CM}} < 1.8$. The $R_{pPb}$ values of $K_S^0$ are consistent with unity for $p_T > 2\text{ GeV}$. For baryons, the $R_{pPb}$ of both $\Lambda$ and $\Xi^-$ reach unity at around 7 GeV. This is consistent with the charged-particle $R_{pPb}$ [22], which also shows no modification in the $p_T$ range from 7 to 20 GeV. In the intermediate $p_T$ range from 3 to 6 GeV, Cronin-like enhancements are visible and clear mass ordering is observed for baryons with the greater mass showing larger $R_{pPb}$. The observed mass ordering is consistent with expectations from the radial-flow effect in hydrodynamic models [30]. The calculations from EPOS LHC, including collective flow in pp and pPb collisions, are compared to data in Fig. 3. They indeed show clear mass ordering for baryon $R_{pPb}$ in this $p_T$ range, with even stronger mass ordering in the calculations. At higher $p_T$, $R_{pPb}$ calculated from EPOS LHC is clearly smaller than the data because of the strong screening in nuclear collisions in EPOS which reduces the number of binary collision in the initial state [30]. It is not clear from current measurements whether effects from recombination [27–29] play a role. This can be addressed
by similar studies with more identified particles, such as the measurements of proton and φ meson $R_{dAu}$ at RHIC [5]. For $p_T$ less than 3 GeV, the predicted $R_{pPb}$ from EPOS LHC agrees with data for each particle species. The values of $R_{pPb}$ for $K^0_S$ and $\Lambda$ become less than unity for $p_T$ less than 2 GeV, which is consistent with the $R_{pPb}$ of charged particles in this $p_T$ range and expected from both the radial flow and nuclear shadowing effects [30, 36].

The $R_{pPb}$ of $K^0_S$, $\Lambda$, and $\Xi^-$ at $-1.8 < y_{CM} < 0$ and $0 < y_{CM} < 1.8$ are presented as functions of $p_T$ in Fig. 4. Because of the limited statistical precision, the $R_{pPb}$ of $\Omega^-$ is not shown in the p- and Pb-going direction separately. The $R_{pPb}$ of all three species are found to be larger in the Pb-going direction than the p-going direction, with a stronger mass splitting between the heavier and the lighter particles in the Pb-going direction. This trend is consistent with expectations from the radial-flow effect in hydrodynamic models [30, 37]. The Cronin effect with the parton multiple scattering interpretation predicts a stronger enhancement in the p-going direction with a larger $R_{pPb}$, which is inconsistent with our data. However, this could be explained by the prediction that this effect is small compared to the nuclear shadowing effect [36, 48] at LHC energies. The accessed parton momentum fraction $x$ in the nucleus is less than 0.02 for
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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 accessed $x$ value of the nucleon is expected to be smaller in the nucleus than a free proton [22, 49], a picture which agrees with the data presented.

6.2 The $Y_{\text{asy}}$ of $K^0_S$ and $\Lambda$

The invariant $p_T$-differential spectra of $K^0_S$ and $\Lambda$ at $-1.8 < y_{\text{CM}} < -1.3$, $-1.3 < y_{\text{CM}} < -0.8$, $-0.8 < y_{\text{CM}} < -0.3$, $0.3 < y_{\text{CM}} < 0.8$, $0.8 < y_{\text{CM}} < 1.3$, and $1.3 < y_{\text{CM}} < 1.8$ in pPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV are presented in Fig. 5. Spectra in different $y_{\text{CM}}$ ranges are scaled by factors of $10^9$, with $y_{\text{CM}} > -0.8 < y_{\text{CM}} < -0.3$ not scaled.

Figure 6 shows the $Y_{\text{asy}}$ as functions of $p_T$ for $K^0_S$ and $\Lambda$ for different rapidity ranges. It is found that $Y_{\text{asy}}$ of both $K^0_S$ and $\Lambda$ in the forward $y_{\text{CM}}$ ranges rise up to a certain $p_T$, and then approach unity at higher $p_T$. The values of $Y_{\text{asy}}$ are larger than one in all three rapidity ranges. The values of $Y_{\text{asy}}$ are larger in the forward region, consistent with expectations from nuclear shadowing. The $Y_{\text{asy}}$ of $K^0_S$ and $\Lambda$ in the above three $|y_{\text{CM}}|$ ranges are compared to $Y_{\text{asy}}$ of charged particles in similar $y_{\text{CM}}$ ranges. It is found that the $Y_{\text{asy}}$ of $K^0_S$ and $\Lambda$ are larger than that of charged particles, and the $p_T$ value of the charged-particle $Y_{\text{asy}}$ peak is between that of $K^0_S$ and $\Lambda$ in forward $|y_{\text{CM}}|$ ranges. These detailed structures, with mass dependence or meson-baryon difference, can provide constraints to models such as hydrodynamic and recombination, which also have mass ordering effect and number of constituent quark differences, respectively. The results of $Y_{\text{asy}}$ are compared to EPOS LHC calculations in the three rapidity ranges. The calculated $Y_{\text{asy}}$ increase from mid-rapidity to forward rapidity, consistent with the trend in data, but fail to describe the particle-species dependence in the forward rapidity.

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The transverse momentum spectra of $K^0_S$, $\Lambda$, $\Xi^-$, and $\Omega^-$ in pp and pPb collisions are measured in ranges of center-of-mass rapidity. With the efficiency corrected spectra, the nuclear modification factor of $K^0_S$, $\Lambda$, and $\Xi^-$ in $-1.8 < y_{\text{CM}} < 1.8$, $-1.8 < y_{\text{CM}} < 0$, and $0 < y_{\text{CM}} < 1.8$ are measured. Because of the limited statistical precision, $R_{pPb}$ of $\Omega^-$ is only measured for $-1.8 < y_{\text{CM}} < 1.8$. In the intermediate $p_T$ range from 3 to 6 GeV, Cronin-like enhancements are visible and clear mass ordering is observed, being consistent with expectations from a radial-flow effect in hydrodynamic models. For each particle species, $R_{pPb}$ in the Pb-going side is higher than that of the p-going side. The asymmetries in $K^0_S$ and $\Lambda$ yields between equivalent positive and negative $y_{\text{CM}}$ 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 to that of charged particles. It is found that the values of $y_{\text{CM}}$ are larger than unity in all three $y_{\text{CM}}$ ranges and become larger in the forward region. The calculated trend of $R_{pPb}$ for different particle species in the EPOS LHC model including collective flow is consistent with the data, but the model fails to describe the particle-species dependence of $y_{\text{CM}}$ in the forward rapidity. The results presented in this paper provide new constraints on theoretical model calculations in small collision systems.

References


Figure 3: (Top) Nuclear modification factors of $K_S^0$ (black filled circles), $\Lambda$ (red filled squares), $\Xi^-$ (blue open circles), and $\Omega^-$ (purple open squares) at $-1.8 < y_{CM} < 1.8$ in pPb collisions are presented. The error bars correspond to statistical uncertainties, while the boxes around the markers denote the systematic uncertainties. The $T_{pPb}$ and pp integrated luminosity uncertainties are represented by the shaded areas around one. The results are compared to EPOS LHC predictions including collective flow in pp and pPb collisions [30]. The data and predictions share the same color for each particle species. (Bottom) The ratios of nuclear modification factors of $K_S^0$, $\Lambda$, $\Xi^-$, and $\Omega^-$ of EPOS LHC to measurements are shown. The bands represent the combination of statistical uncertainties and systematic uncertainties.
Figure 4: Nuclear modification factors of $K^0_S$ (black filled circles), $\Lambda$ (red filled squares), and $\Xi^-$ (blue open circles) at $-1.8 < y_{CM} < 0$ (left) and $0 < y_{CM} < 1.8$ (right) in pPb collisions are presented. The error bars correspond to statistical uncertainties, while the boxes around the markers denote the systematic uncertainties. The $T_{ppb}$ and pp integrated luminosity uncertainties are represented by the shaded areas around one. The results are compared to EPOS LHC predictions including collective flow in pp and pPb collisions [30]. The data and predictions share the same color for each particle species.
Figure 5: The invariant $p_T$-differential spectra of $K_0^0$ (left) and $\Lambda$ (right) particles at $-1.8 < y_{CM} < -1.3$, $-1.3 < y_{CM} < -0.8$, $-0.8 < y_{CM} < -0.3$, $0.3 < y_{CM} < 0.8$, $0.8 < y_{CM} < 1.3$, and $1.3 < y_{CM} < 1.8$ in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Spectra in different $y_{CM}$ ranges are scaled by factors of $10^n$, with $-0.8 < y_{CM} < -0.3$ not scaled. The error bars correspond to statistical uncertainties.
Figure 6: $Y_{\text{asym}}$ of $K_S^0$ (black filled circles), $\Lambda$ (red filled squares), and charged particles (blue open squares) at $0.3 < |y_{CM}| < 0.8$, $0.8 < |y_{CM}| < 1.3$, and $1.3 < |y_{CM}| < 1.8$ ($|\eta_{CM}|$ ranges for charged particles) in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The error bars correspond to statistical uncertainties, while the boxes around the markers denote the systematic uncertainties. The results are compared to EPOS LHC predictions including collective flow in pp and pPb collisions [30]. The data and predictions share the same color for each particle species.