Nuclear modification factors of strange and multi-strange particles in pPb collisions with the CMS experiment

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Abstract. Recent observation of collective effects in high-multiplicity pp and pA collisions raise the question of whether QGP can also be formed in the smaller systems. Systematic studies of the strange particle abundance and nuclear modification factors can shed light on this issue. The CMS experiment has excellent strange-particle reconstruction capabilities over a broad kinematic range in pp and pPb collisions. The spectra of $K_0^S$, $\Lambda^+$, $\Xi^-$, $\Xi^+$, and $\Omega^-$, $\Omega^+$ hadrons have been measured in various rapidity regions as a function of $p_T$ in pp and pPb collisions at 5.02 TeV. Based on the measurements of these spectra, nuclear modification factors of $K_0^S$, $\Lambda^+$, $\Xi^-$, $\Xi^+$, and $\Omega^-$, $\Omega^+$ in mid-rapidity are measured. Since pPb is an asymmetric system, the nuclear modification factor of $K_0^S$, $\Lambda^+$, $\Xi^-$, $\Xi^+$, and $\Omega^-$, $\Omega^+$ in Pb-going direction are compared to those in p-going direction. These final results for nuclear modification factors measured out to high-$p_T$ can be helpful in discussing the implications of collective behavior and energy loss. In addition, the measurement of the forward-backward rapidity yield asymmetries of $K_0^S$ and $\Lambda$ as a function of $p_T$ provide sensitivity to initial state effects, such as shadowing in the nuclear parton distributions.

1. Introduction

Particle production in pA and dA, as compared to pp collisions has long been considered as a useful tool to understand particle production mechanism. One way to do the study is 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, $\langle N_{coll} \rangle$, in AB collisions. It is given by

$$ R_{AB}(p_T) = \frac{d^2N_{AB}/dp_Tdy_{CM}}{\langle N_{coll} \rangle d^2N_{pp}/dp_Tdy_{CM}} = \frac{d^2N_{AB}/dp_Tdy_{CM}}{(T_{AB})d^2\sigma_{pp}/dp_Tdy_{CM}}, \quad (1) $$
where \( y_{\text{CM}} \) is the rapidity computed in the center-of-mass frame of the colliding nucleons, and \( (T_{AB}) \), the nuclear overlap function, accounts for the nuclear collision geometry and is calculated from a Glauber model [2]. If nuclear collisions behave as incoherent superpositions of nucleon-nucleon collisions, \( R_{AB} \) is expected to be unity.

Since pPb collision system is an asymmetrical system, the other quantity that is informative to measure is the particle yield rapidity asymmetry (\( Y_{\text{asym}} \)). The definition of \( Y_{\text{asym}} \) is:

\[
Y_{\text{asym}}(p_T) = \frac{d^2N(p_T)/dy_{\text{CM}}dp_T|_{y_{\text{CM}}\in[-a,-b]}}{d^2N(p_T)/dy_{\text{CM}}dp_T|_{y_{\text{CM}}\in[0,1]}},
\]

where \( a \) and \( b \) are always positive and refer to the proton beam direction.

With the measurements of these two quantities for different strange particle species, effects such as the Cronin effect [4], nuclear shadowing effect [5], radial flow effect [6] can be thoroughly studied.

This talk discussed results of measurements of strange and multi-strange particles: \( K_S^0 \), \( \Lambda + \bar{\Lambda} \) (hereafter referred to as \( \Lambda \)), \( \Xi^- + \Xi^+ \) (hereafter referred to as \( \Xi^- \)), and \( \Omega^- + \Omega^+ \) (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 \( \sqrt{s_{NN}} = 5.02 \) TeV [1]. Based on these spectra, \( R_{pPb} \) for each particle species is studied as a function of \( p_T \) in the three rapidity ranges at \( \sqrt{s_{NN}} = 5.02 \) TeV. The \( R_{pPb} \) of the \( \Omega^- \) baryon 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 \( K_S^0 \) 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 \( \sqrt{s_{NN}} = 5.02 \) TeV. The results are compared to calculations from the EPOS LHC model including collective flow in pp and pPb collisions.

2. Results

2.1. Invariant mass peaks

The details of event selection and particle reconstruction can be found in [1]. Figure 1 shows some samples of invariant mass peaks of reconstructed \( K_S^0 \), \( \Lambda \), \( \Xi^- \), and \( \Omega^- \) candidates in the range \(-1.8 < y_{\text{CM}} < 1.8 \) for pPb events. Prominent mass peaks are visible, with little background. Raw yields of strange particles are extracted from these invariant mass peaks by integrating the signal function.

2.2. Nuclear modification factors

With the efficiency-corrected strange-particle spectra, the \( R_{pPb} \) values of \( K_S^0 \), \( \Lambda \), \( \Xi^- \), and \( \Omega^- \) particles are calculated in different \( y_{\text{CM}} \) ranges.

Figure 2 shows that the \( R_{pPb} \) of each particle species at \(-1.8 < y_{\text{CM}} < 1.8 \). For \( p_T > 2 \) GeV, the \( R_{pPb} \) value of \( K_S^0 \) are consistent with unity. For strange baryons (\( \Lambda \), \( \Xi^- \), and \( \Omega^- \)), the \( R_{pPb} \) values increase at low \( p_T \), and reach peaks at around 5 GeV. At higher \( p_T \) (around 7 GeV), the \( R_{pPb} \) values of \( \Lambda \) and \( \Xi^- \) drop to unity. At intermediate \( p_T \) (2 to 7 GeV), the \( R_{pPb} \) values of baryons show clear mass dependence, which is consistent with expectations from the radial-flow
Figure 1. Invariant mass distribution of $K_0^S$ (upper left), $\Lambda$ (upper right), $\Xi^-$ (lower left), and $\Omega^-$ (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. Figure from [1].

effect in hydrodynamic models [6]. Data are compared to Monte Carlo simulations, here EPOS LHC is used. Details about EPOS LHC can be found in [3]. EPOS LHC predicts the mass dependence qualitatively, but with even larger mass dependence.

The $R_{\text{pPb}}$ values of $K_0^S$, $\Lambda$, and $\Xi^-$ particles for $-1.8 < y_{\text{CM}} < 0$ and $0 < y_{\text{CM}} < 1.8$ are presented as functions of $p_T$ in Figure 3. Because of the limited statistical precision, the $R_{\text{pPb}}$ of $\Omega^-$ baryon is not shown in the p- and Pb-going direction separately. The $R_{\text{pPb}}$ 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 [6].
Figure 2. (Upper) Nuclear modification factors for $K_S^0$ (black filled circles), $\Lambda$ (red filled squares), $\Xi^-$ (blue open circles), and $\Omega^-$ (purple open squares) particles for $-1.8 < y_{CM} < 1.8$ in pPb collisions are presented. The vertical bars correspond to statistical uncertainties, and the horizontal bars represent the bin width, while the 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, that 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 $K_S^0$, $\Lambda$, $\Xi^-$, and $\Omega^-$ particles of EPOS LHC predictions to the measurements are shown. The bands represent the combination of statistical uncertainties and systematic uncertainties. Figure from [1].

2.3. Particle yield rapidity asymmetry

Figure 4 shows the $Y_{asym}$ as functions of $p_T$ for $K_S^0$ and $\Lambda$ for different rapidity ranges. In forward $y_{CM}$ ranges, the $Y_{asym}$ values of $K_S^0$ and $\Lambda$ increase to a certain $p_T$, and drop to unity at higher
Figure 3. Nuclear modification factors of $K_{S}^{0}$ (black filled circles), $\Lambda$ (red filled squares), and $\Xi^{-}$ (blue open circles) particles for $-1.8 < y_{CM} < 0$ (left) and $0 < y_{CM} < 1.8$ (right) in pPb collisions are presented. 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 $T_{pPb}$ and pp integrated luminosity uncertainties are represented by the shaded areas around one. The results are compared to the EPOS LHC predictions, that include collective flow in pp and pPb collisions [3]. The data and predictions share the same color for each particle species. Figure from [1].

$p_{T}$. For all three $|y_{CM}|$ ranges measured, the values of $Y_{\text{asym}}$ are larger than unity. The $Y_{\text{asym}}$ values increase with $|y_{CM}|$ range, which is consistent with expectations from nuclear shadowing. The $Y_{\text{asym}}$ of $K_{S}^{0}$ and $\Lambda$ in the above three $|y_{CM}|$ ranges are compared to the $Y_{\text{asym}}$ of charged particles in similar $\eta_{CM}$ ranges. From the comparison, it is found that the $Y_{\text{asym}}$ value of charged particles are smaller than that of $K_{S}^{0}$ and $\Lambda$, and the peak position of the charged-particle $Y_{\text{asym}}$ is between that of $K_{S}^{0}$ and $\Lambda$ in forward $|y_{CM}|$ ranges. The results of $Y_{\text{asym}}$ are compared to EPOS LHC calculations in the three rapidity ranges. The calculated $Y_{\text{asym}}$ increases from mid-rapidity to forward rapidity, consistent with the trend in data, but fails to describe the particle species dependence at forward rapidities.

3. Summary

The transverse momentum spectra of $K_{S}^{0}$, $\Lambda$, $\Xi^{-}$, and $\Omega^{-}$ particles in proton-proton and proton-lead collisions are measured in ranges of center-of-mass rapidity. With the efficiency-corrected spectra, the nuclear modification factor and particle yield rapidity asymmetry are calculated. The data are compared to the calculations from EPOS LHC, which predicts the data in a qualitative way. These measurements can help understand particle production mechanism and constrain theoretical models.
Figure 4. The $Y_{\text{asym}}$ of $K_S^0$ (black filled circles), $\Lambda$ (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 $\sqrt{s_{NN}} = 5.02$ 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 to the EPOS LHC predictions, that include collective flow in pp and pPb collisions [3]. The data and predictions share the same color for each particle species. Figure from [1].
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