Multiplicity and rapidity dependence of strange hadron production in pp, pPb, and PbPb collisions at the LHC postprint

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Full Text

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The CMS Collaboration*

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∗See Appendix A for the list of collaboration members

1 Introduction

Studies of strange-particle production in high energy collisions of protons and heavy ions provide important means to investigate the dynamics of the collision process. Earlier studies of relativistic heavy ion collisions at the BNL RHIC and CERN SPS colliders indicated an enhancement of strangeness production with respect to proton-proton (pp) collisions [1, 2], which was interpreted to be due to the formation of a high-density quark-gluon medium [3]. In gold-gold (AuAu) collisions at RHIC, strong azimuthal correlations of final-state hadrons were observed, suggesting that the produced medium behaves like a near-perfect fluid undergoing a pressure-driven anisotropic expansion [2]. Studies of strangeness production and dynamics in heavy ion collisions have provided further insight into the medium's fluid-like nature and essential evidence for its partonic collectivity [2, 4].

In recent years, the observation of a long-range "ridge" at small azimuthal separations in two-particle correlations in pp [5] and proton-lead (pPb) [6–8] collisions with high event-by-event charged-particle multiplicity (referred to hereafter as "multiplicity") has provided an indication for collective effects in systems that are an order of magnitude smaller than heavy ion collisions. The nature of the observed long-range particle correlations in high multiplicity pp and pPb collisions is still under intense debate [9]. While the collective flow of a fluid-like medium provides a natural interpretation [10–13], other models attribute this behavior to the initial correlation of gluons [14–18], or the anisotropic escape of particles [19].

Studies of identified particle production and correlations in high multiplicity pp and pPb collisions provide detailed information about the underlying particle production mechanism. Identified particle (including strange-hadron) transverse momentum (p__T) spectra and azimuthal anisotropies in lead-lead (PbPb) collisions at the CERN LHC have been studied [20, 21] and described by hydrodynamic models [22]. Similar measurements have been performed in pPb collisions as a function of multiplicity, where evidence for a common velocity boost to produced particles, known as "radial flow" [23, 24], and for a mass dependence of the anisotropic flow [25, 26] have been observed. When comparing pPb and PbPb systems at similar multiplicities, a stronger radial velocity boost is seen in the smaller pPb collision system [26]. This could be related to a much higher initial energy density in a high multiplicity but smaller system, resulting in a larger pressure gradient outward along the radial direction, as predicted in Ref. [27]. To perform a quantitative comparison, a common average radial-flow velocity from different collision systems can be extracted from a simultaneous fit to the spectra of various particle species, based on the blast-wave model [28].

Inspired by hydrodynamics, the blast-wave model assumes a common kinetic freeze-out temperature and radial-flow velocity for all particles during the expansion of the system. The dependence of spectra shapes for identified hadrons on the multiplicity has been observed in high energy electron and proton-antiproton collisions [29, 30], but this observation was not explored extensively in the hydrodynamic context. The blast-wave fit has been studied in pp, deuterium-gold, and AuAu collisions at RHIC [31]. In pp collisions, it is shown that color reconnection processes could also describe the observed multiplicity dependence of identified particle spectra [32].

It is of interest to study possible collective phenomena in very high multiplicity pp collisions, as demonstrated by the observation of long-range particle correlations in these events [5]. Since pp events represent an even smaller system than pPb events, a stronger radial-flow boost might be present compared to pPb and PbPb events at a comparable multiplicity [27]. Furthermore, in a pPb collision, the system is not symmetric in pseudorapidity ( ). If a fluid-like medium is formed, its energy density could be different on the p- and Pb-going sides, which could lead to an asymmetry in the collective radial-flow effect as a function of . Hydrodynamical models predict that the average p_T (or, equivalently, the average transverse kinetic energy K_{ET} , where K_{ET} m_T − m, with m_T = √(p_T^2 + m^2) and m the particle mass) of produced particles is larger in the Pb-going direction than in the p-going direction, while this trend could be reversed in models based on gluon saturation [33]. Measurement of identified particle p_T spectra as a function of could thus help to constrain theoretical models.

This Letter presents measurements of strange-particle p_T spectra in pp, pPb, and PbPb collisions as a function of the multiplicity in the events. Specifically, we examine the spectra of K^0_S, Λ, and Ξ^- particles, where the inclusion of the charge-conjugate states is implied. The data were collected with the CMS detector at the LHC. With the implementation of a dedicated high-multiplicity trigger, the pp and pPb data samples exhibit multiplicities comparable to that observed in peripheral PbPb collisions, where "peripheral" refers to 50–100% centrality, with centrality defined as the fraction of the total inelastic cross section. The most central collisions have 0% centrality. This overlap in mean multiplicity allows the three systems, with drastically different collision geometries, to be directly compared. The large solid-angle coverage of the CMS detector permits the strange-particle p_T spectra to be studied in different rapidity ranges, and thus the study of possible asymmetries with respect to the p- and Pb-going directions in pPb collisions.

2 Detector and Data Samples

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, which provides an axial field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker (with 13 and 14 layers in the central and endcap regions, respectively), a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The tracker covers the pseudorapidity range $| \; | < 2.5$. Reconstructed tracks with $1 < p_T < 10$ GeV typically have resolutions of 1.5–3% in p_T and 25–90 (45–150) µm in the transverse (longitudinal) impact parameter [34]. The ECAL and HCAL each cover $| \; | < 3.0$ while forward hadron calorimeters (HF) cover $3 < | \; | < 5$. Muons with $| \; | < 2.4$ are measured with gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [35]. The Monte Carlo (MC) simulation of the particle propagation and detector response is based on the GEANT4 [36] program.

The data samples used in this analysis are as follows: pp collisions collected in 2010 at $\sqrt{s} = 7$ TeV, pPb collisions collected in 2013 at $\sqrt{s_{NN}} = 5.02$ TeV, and PbPb collisions collected in 2011 at $\sqrt{s_{NN}} = 2.76$ TeV, with integrated luminosities of 6.2 pb^{-1}, 35 nb^{-1}, and 2.3 μb^{-1}, respectively. For the pPb data, the beam energies are 4 TeV for the protons and 1.58 TeV per nucleon for the lead nuclei. The data were collected in two different run periods: 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 periods. 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, corresponding to a rapidity of 0.465. As a consequence, the rapidity of a particle in the nucleon-nucleon center-of-mass frame (y_{cm}) is detected in the laboratory frame (y_{lab}) with a shift, $y_{lab} = y_{cm} + 0.465$. The pPb particle yields reported in this Letter are presented in terms of y_{cm}, rather than y_{lab}, for better correspondence with the results from the pp and PbPb collisions.

3 Selection of Events and Tracks

The triggers, event reconstruction, and event selection are the same as those discussed for pp, pPb, and PbPb collisions in Refs. [5, 37]. They are briefly outlined in the following paragraphs for pp and pPb collisions, which are the main focus of this Letter. A subset of peripheral PbPb data collected in 2011 with a minimum-bias trigger is reprocessed using the same event selection and track reconstruction algorithm as for the present pPb and pp analyses, in order to more directly compare the three systems at the same multiplicity. Details of the 2011 PbPb analysis can be found in Refs. [37, 38].

Minimum-bias pPb events are triggered by requiring at least one track with p_T > 0.4 GeV to be found in the pixel tracker. Because of hardware limitations in the data acquisition rate, only a small fraction (10^{-3}) of triggered minimum-bias events are recorded. In order to collect a large sample of high-multiplicity pPb collisions, a dedicated high-multiplicity trigger is implemented using the CMS Level-1 (L1) and high-level trigger (HLT) systems [39]. At L1, the total transverse energy summed over the ECAL and HCAL is required to exceed either 20 or 40 GeV, depending on the multiplicity requirement as specified below. Charged particles are reconstructed at the HLT level using the pixel detectors. It is required that these tracks originate within a cylindrical region (30 cm in length along the direction of the beam axis and 0.2 cm in radius in the direction perpendicular to that axis) centered on the nominal interaction point. For each event, the number of pixel tracks (N_{online}^{trk}) with | | < 2.4 and p_T > 0.4 GeV is determined for each reconstructed vertex. Only tracks with a distance of closest approach 0.4 cm or less to one of the vertices are included. The HLT selection requires N_{online}^{trk} for the vertex with the largest number of tracks to exceed a specific value. Data are collected in pPb collisions with thresholds N_{online}^{trk} > 100 and 130 for events with an L1 transverse energy threshold of 20 GeV, and N_{online}^{trk} > 160 and 190 for events with an L1 threshold of 40 GeV. While all events with N_{online}^{trk} > 190 are accepted, only a fraction of the events from the other thresholds are retained. This fraction is dependent on the instantaneous luminosity. Data from both the minimum-bias trigger and the high-multiplicity trigger are retained for offline analysis. Similar high-multiplicity triggers, with different thresholds, were developed for pp collisions, with details given in Ref. [5].

In the subsequent analysis of all collision systems, hadronic events are selected by requiring the presence of at least one energy deposit larger than 3 GeV in each of the two HF calorimeters. Events are also required to contain a primary vertex within 15 cm of the nominal interaction point along the beam axis and 0.15 cm in the transverse direction, where the primary vertex is the reconstructed vertex with the largest track multiplicity. At least two reconstructed tracks are required to be associated with this primary vertex, a condition that is important only for minimum-bias events. 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. [34].

In the pPb data sample, there is a 3% probability to have at least one additional interaction in the same bunch crossing (pileup). The procedure used to reject pileup events in pPb collisions is described in Ref. [37]. It is based on the number of tracks associated with each reconstructed vertex and the distance between different vertices. A purity of 99.8% for single pPb collision events is achieved for the highest multiplicity pPb range studied in this Letter. For the pp data, the average number of collisions per bunch crossing is 1.2. However, pp interactions that are well separated from each other do not interfere. Thus, among events identified as containing pileup, the event is retained if the separation between the primary vertex and any other vertex exceeds 1 cm. In such events, only tracks from the highest multiplicity vertex are used.

With the above criteria, 97% (98%) of the simulated pPb events generated with the EPOS LHC [40] (HIJING 2.1 [41]) programs are selected. Similarly, 94% (96%) of the pp events simulated with the PYTHIA 6 Tune Z2 [42] (PYTHIA 8 Tune 4C [43]) programs are selected.

The event-by-event charged-particle multiplicity N_{offline}^{trk} is defined using primary tracks, i.e., tracks that satisfy the high-purity criteria of Ref. [34] and, in addition, the following criteria designed to improve track quality and ensure the tracks emanate from the primary vertex. The impact parameter significance of the track with respect to the primary vertex in the direction along the beam axis, dz/σ(dz), is required to be less than 3, as is the corresponding impact parameter in the transverse plane, d_T/σ(d_T). The relative p_T uncertainty, σ(p_T)/p_T, must be less than 10%. To ensure high tracking efficiency and to reduce the rate of misreconstructed tracks, the tracks are required to satisfy | | < 2.4 and p_T > 0.4 GeV. Based on simulated samples generated with the HIJING program, the efficiency for primary track reconstruction is found to be greater than 80% for charged particles with p_T > 0.6 GeV and | | < 2.4. For the multiplicity range studied in this Letter, no dependence of the tracking efficiency on multiplicity is found and the rate of misreconstructed tracks is 1–2%.

The quantity N_{corrected}^{trk} is the corresponding multiplicity corrected for detector and algorithm inefficiencies in the same kinematic region (| | < 2.4 and p_T > 0.4 GeV). The pp, pPb, and PbPb data are divided into classes based on N_{offline}^{trk}. The fraction of the total multiplicity found in each interval and the average number of tracks both before and after accounting for the corrections is listed in Table 1 for the pp data and in Ref. [37] for the pPb and PbPb data. The uncertainty in the average value N_{corrected}^{trk} is evaluated from the uncertainty in the tracking efficiency, which is 3.9% for a single track [44]. For the pp data, six multiplicity intervals, indicated in Table 1, are defined, which are inclusive for the lower bounds and exclusive for the upper bounds. For the pPb and PbPb data, eight intervals are defined. These eight intervals are indicated, e.g., in the legend of Fig. 2 [Figure 2: see original paper]. Note that, unlike pp and PbPb collisions, N_{offline}^{trk} for pPb collisions is not determined in the center-of-mass frame. However, the difference in the N_{offline}^{trk} definition between the laboratory and the center-of-mass frames is found to be minimal and so this difference is ignored.

4 The K^{0}_S, Λ, and Ξ^{-} Reconstruction and Yields

The reconstruction and selection procedures for K^{0}_S, Λ, and Ξ^{-} candidates are presented in Refs. [26, 45]. To increase the efficiency for tracks with low momenta and large impact parameters, both characteristic of the strange-particle decay products, the loose selection of tracks, as defined in Ref. [34], is used.

The K^0_S and Λ candidates (generically referred to as “V0s”) are reconstructed by combining oppositely charged particles to define a secondary vertex. Each of the two tracks must have hits in at least four layers of the silicon tracker, and transverse and longitudinal impact parameter significances with respect to the primary vertex greater than 1. The distance of closest approach of the pair of tracks to each other is required to be less than 0.5 cm. The fitted three-dimensional vertex of the pair of tracks is required to have a ^{2} value divided by the number of degrees of freedom less than 7. Each of the two tracks is assumed to be a pion in the case of the K^0_S reconstruction. As the proton carries nearly all of the momentum in the Λ decay, the higher-momentum track is assumed to be a proton and the other track a pion in the case of the Λ reconstruction. To reconstruct Ξ^- particles, a Λ candidate is combined with an additional charged particle carrying the correct sign, to define a common secondary vertex. This additional track is required to have hits in at least four layers of the silicon tracker, and both the transverse and longitudinal impact parameter significances with respect to the primary vertex are required to exceed 3.

Due to the long lifetime of the K^0_S and Λ particles, the significance of the V0 decay length, which is the three-dimensional distance between the primary and V0 vertices divided by its uncertainty, is required to exceed 5. To remove K^0_S candidates misidentified as Λ particles and vice versa, the Λ (K^0_S) candidate mass assuming both tracks to be pions (the lower-momentum track to be a pion and the higher-momentum track a proton) must differ by more than 20 (10) MeV from the nominal K^0*S (Λ) mass value [46]. To remove photon conversions to an electron-positron pair, the mass of a K*^{0}S or Λ candidate assuming both tracks to have the electron mass must exceed 15 MeV. The angle *{point} between the V0 momentum vector and the vector connecting the primary and V0 vertices is required to satisfy cos* {point} > 0.999. This reduces the contributions of particles from nuclear interactions, random combinations of tracks, and secondary Λ particles originating from the weak decays of Ξ and Ω particles.

To optimize the reconstruction of Ξ^- particles, requirements on the three-dimensional impact parameter significance of its decay products with respect to the primary vertex are applied. This significance must be larger than 3 (4) for the proton (pion) tracks from the Λ decay, and larger than 5 for the direct pion candidate from the Ξ^- decay. To further reduce the background from random combinations of tracks, the corresponding impact parameter significance of Ξ^- candidates cannot exceed 2.5. The three-dimensional decay length significance, with respect to the primary vertex, of the Ξ^- candidate and the associated Λ candidate must exceed 3 and 12, respectively.

The K^0*S, Λ, and* Ξ^- *reconstruction efficiencies are about 15, 5, and 0.7% for p_T 1 GeV, and 20, 10, and 2% for p_T > 3 GeV, averaged over || < 2.4. These efficiencies account for the effects of acceptance, and for the branching fractions of the decay modes in which the strange particles are reconstructed. The invariant mass distributions of reconstructed K*^{0}S, Λ, and Ξ^- candidates with

1 < p_T < 3 GeV are shown in Fig. 1 [Figure 1: see original paper] for pPb events with 220 ≤ N*{offline}^{trk} < 260. Prominent mass peaks are visible, with little background. The solid lines show the result 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 background is modeled with a quadratic function for the* K^0S results, with the analytic form Aq^(1/2) + Bq^(3/2) with q = m - (mπ *+ m_p) for the Λ results, and with the form Cq^D with q = m - (m_Λ + m*π) for the Ξ^- results, where A, B, C, and D are fitted parameters. These fit functions are found to provide a good 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_{raw}^(K^0_S/Λ/Ξ^-).

The raw strange-particle yields are corrected to account for the branching fraction of the reconstructed decay mode, and for the acceptance and reconstruction efficiency of the strange particle, using simulated event samples based on the PYTHIA 6 (pp) or EPOS (pPb and PbPb) event generator and GEANT4 modeling of the detector:

N_{corr}$^{(\mathrm{K}^0 S/\Lambda/\Xi^-)\ =\ N\{\mathrm{raw}\}}$(K^0*S/Λ/$\Xi^-$) × R*{corr}

where R_{corr} is a correction factor from simulation given by the ratio of the raw reconstructed yield to the total generated yield for the respective strange particle, with N_{corr}^(K^0_S/Λ/Ξ^-) the corrected yield.

The raw Λ particle yield includes contributions from the decays of Ξ^- and Ω particles. This “nonprompt” contribution is largely determined by the relative Ξ^- to Λ yield (because the contribution from Ω particles is negligible). The stringent requirements placed on cos _{point} remove a large fraction of the nonprompt Λ component but, from simulation, up to 10% of the Λ candidates at high p_T are nonprompt. If the relative Ξ^- to Λ yield in simulation is modeled precisely, the contamination from nonprompt Λ particles will be removed by the correction procedure of Eq. (1). Otherwise, an additional correction to account for the residual contamination is necessary. As the Ξ^- particle yields are explicitly measured in this analysis, this residual correction factor can be determined directly from the data as:

f_{residual}^Λ,np = 1 + f_{raw},MC^Λ × (N_{corr}$^{\Xi^-/\mathrm{N_\{corr\}}}$Λ) / (N_{MC}$^{\Xi^-/\mathrm{N_\{MC\}}}$Λ)

where f_{raw},MC^Λ denotes the fraction of nonprompt Λ particles in the raw reconstructed Λ sample from the data after applying the corrections of Eq. (1), and N_{MC}$^{\Xi^-/\mathrm{N_\{MC\}}}$Λ are the Ξ^--to-Λ yield ratios from generator-level simulation, respectively. The final prompt Λ particle yield is given by N_{corr}^Λ / f_{residual}^Λ,np. Based on EPOS MC studies, which has a similar Ξ^-/Λ ratio to the data, the residual nonprompt contributions to the Λ yields are found to be negligible in pPb and PbPb collisions, while in pp collisions the correction is 1–3% depending on the p_T value of the Λ particle. Note that N_{corr}^Λ in Eq. (2) is derived using Eq. (1), which in principle contains the residual nonprompt Λ contributions. Nonetheless, by applying Eq. (2) in an iterative fashion, we expect N_{corr}^Λ to approach a result corresponding to prompt Λ particles only. A second iteration of correction is found to have an effect of less than 0.1% on the Λ particle yield. As a cross-check we treat the sample of simulated events generated with the HIJING program like data and verify that we obtain the correct yields at the generator level after applying the correction procedure described above.

5 Systematic Uncertainties

Table 2 summarizes the different sources of systematic uncertainty in the yields of each strange particle species. The values in parentheses correspond to the systematic uncertainties in the forward rapidity regions (−2.4 < y_{cm} < −1.5 and 0.8 < y_{cm} < 1.5) for pPb data, if they differ from those at mid-rapidity. The dominant sources of systematic uncertainty are associated with the strange-particle reconstruction, especially the efficiency determination.

The systematic uncertainty in determining the efficiency of a single track is 3.9% [44]. 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 K^0_S lifetime distribution (cτ) between data and simulation, and similarly for the Λ and Ξ$^-$, which provides a cross-check of the systematic uncertainty. This translates into a systematic uncertainty in the reconstruction efficiency of 7.8% for the K^0_S and Λ particles, and 11.7% for the Ξ$^-$ particles.

Different background fit functions and methods to extract the yields for the K^0_S, Λ, and Ξ$^-$ are compared. The background fit function is varied to a fourth-order polynomial for the K^0_S and Λ studies, and to a linear function for the Ξ$^-$ study. The yields are obtained by integrating over a region that is $±5*timestheaverageresolutionandcenteredatthemean*, *ratherthanovertheentirefittedmassrange.Possibleco* particle misidentified as a Λ particle, or vice versa) is investigated by varying the invariant mass range used to reject misidentified V0 candidates. On the basis of these studies we assign systematic uncertainties of 2–4% 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 1–7%. The impact of finite momentum resolution on the spectra is estimated using the EPOS event generator. Specifically, the generator-level p_T spectra of the strange particles are smeared by the momentum resolution, which is determined through comparison of the generator-level and matched reconstructed-level particle information. The difference between the smeared and original spectra is less than 2%.

The systematic uncertainty associated with nonprompt Λ corrections to the Λ spectra is evaluated through propagation of the systematic uncertainty in the N_{corr}$^{\Xi^-/\mathrm{N_\{corr\}}}$Λ ratio in Eq. (2) to the f_{residual}^Λ,np factor, and is found to be less than 2%. Systematic uncertainties introduced by possible residual pileup effects for pp data are estimated to be 1–3%. This uncertainty is evaluated through both tightening (only one reconstructed vertex allowed per event) and loosening (no event rejection on the basis of the number of vertices) the pileup rejection criteria [37]. The uncertainty associated with pileup is negligible for the pPb and PbPb data since there are very few events in those samples with more than one reconstructed vertex.

In pPb collisions, the direction of the p and Pb beams were reversed during the course of the data collection, as mentioned in Section 2. Comparison of the particle p_T spectra with and without the beam reversal yields an uncertainty of 2–5% for all particle types. The effect of the choice of the rapidity bins is assessed by dividing each bin into two, thereby doubling the number of bins, resulting in a systematic uncertainty of 1–3% for the p_T spectra. For the Ξ^-, the reconstruction efficiency correction is smoothed by averaging adjacent bins in order to compensate for the limited statistical precision of the MC sample. Variations in the smoothing procedure lead to a systematic uncertainty of 5% for the p_T spectra of the Ξ^-.

All sources of systematic uncertainty are uncorrelated and summed in quadrature to define the total systematic uncertainties in the p_T spectra of each strange particle. When calculating ratios of particle yields, most of the systematic uncertainties partially or entirely cancel. For example, the systematic uncertainties due to tracking efficiency and pileup completely cancel for the Λ/K^0_S ratio.

6 Results

6.1 Multiplicity Dependence at Mid-Rapidity

The p_T spectra of $\mathrm{K}^0 S, \Lambda, and\ \Xi^-\ particles\ with\ |y\{\mathrm{cm}\}| < 1$ in pp collisions at √s = 7 TeV (top), pPb collisions at √s = 5.02 TeV (middle), and PbPb collisions at √s_{NN} = 2.76 TeV (bottom) are presented in Fig. 2 [Figure 2: see original paper] for different multiplicity intervals. Due to details in the implementation of the dedicated high-multiplicity trigger thresholds used to select the pp events, the multiplicity intervals for pp events differ slightly from those for pPb and PbPb events. The p_T differential yield is defined as $\mathrm{d}^2\mathrm{N}/(2\pi$ p_T dp_T dy). For the purpose of better visibility, the data are scaled by factors of 2^{-n}, as indicated in the figure legend. A clear evolution of the spectra shape with multiplicity can be seen for each particle species in each collision system. For higher multiplicity events, the spectra tend to become flatter (i.e., "harder"), indicating a larger K_{ET} value. Within each collision system, heavier particles (e.g., Ξ^-) exhibit a harder spectrum than lighter particles (K^0_S), especially for high-multiplicity events.

To examine the differences in the multiplicity dependence of the spectra in greater detail, the ratios Λ/K^0_S and Ξ^-/Λ of the yields are shown in Fig. 3 [Figure 3: see original paper] as a function of p_T for different multiplicity ranges in the pp, pPb, and PbPb systems. The results for the Λ/K^0_S ratio are shown in Fig. 3 (top). For p_T $<$ 2 GeV, the Λ/K^0_S ratio is seen to be smaller in high-multiplicity events than in low-multiplicity events for a given p_T value. In pp and pPb collisions, this trend is similar to what has been observed between peripheral and central PbPb collisions [20]; this trend is not as evident for the PbPb data in Fig. 3 (top right) because in the present study only PbPb events of 50–100% centrality are considered. At higher p_T, this multiplicity ordering of the Λ/K^0_S ratio is reversed. In hydrodynamics models such as those presented in Refs. [47, 48], this behavior can be interpreted as the effect of radial flow. A stronger radial flow is developed in higher-multiplicity events, which boosts heavier particles (e.g., Λ) to higher p_T, resulting in a suppression of the Λ/K^0_S ratio at low p_T. Comparing the various collision systems at low p_T, the difference in the Λ/K^0_S ratio between low- and high-multiplicity events is seen to be largest for the pp data. In the hydrodynamic model of Ref. [27], smaller collision systems like pp produce a larger radial-flow effect than larger systems like pPb or PbPb, for similar multiplicities, which could explain this observation. In previous studies (e.g., Ref. [49]), it has been shown that the average p_T value of various particle species has only a slight center-of-mass energy dependence (10% at high multiplicity). This dependence is not sufficient to explain the differences observed in Fig. 3 between the various systems.

For each multiplicity interval, the Λ/K^0_S ratio reaches a maximum that has a similar value for all three collision processes, and then decreases at higher p_T. The location of the maximum increases with multiplicity from around p_T = 2 to 3 GeV.

The results for the Ξ^-/Λ ratio are shown in Fig. 3 (bottom). In this case, the difference between the low- and high-multiplicity events is much smaller than for the Λ/K^0_S ratio, for all three collisions systems. For all systems, the Ξ^-/Λ ratio increases with p_T and reaches a plateau at around p_T = 3 GeV.

Motivated by the hydrodynamics model, we perform a simultaneous fit of a blast-wave function [28] to the K^0_S and Λ spectra in Fig. 2. The fits are restricted to low p_T because that is the region in which the blast-wave model is valid. The Ξ^- particle is not used in the fit as there are not many Ξ^- at low p_T. The fits are performed for each collision system separately. The fit ranges are 0.1 $<$ p_T $<$ 1.5 GeV for the K^0_S and 0.6 $<$ p_T $<$ 3.0 GeV for the Λ. The fitted function is:

(1/2πp_T) (d^{2}N/dp_{Tdy}) $_0$ r dr m_T I$_0$(p_T sinh / T_{kin}) K$_1$(m_T cosh / T_{kin})

where = tanh^{-1} β_T = tanh^{-1} (β_s(r/R)^n) is the velocity profile, R is the radius of the medium (set to unity in the fit), r is the radial distance from the center of the medium in the transverse plane, n is the exponent of the velocity profile, β_T is the transverse expansion velocity (also known as the radial-flow velocity), *βs is the transverse expansion velocity on the surface of the medium, T*{kin} is the kinetic freeze-out temperature, and I$_0$ and K$_1$ are modified Bessel functions.

The fitted parameters are n, *βs, and T*{kin}. In the blast-wave model, common values of T_{kin} and average radial-flow velocity βT *are assumed for all particle species, as is expected if the system is locally thermalized and undergoes a radial-flow expansion. It is useful to directly compare the extracted values of T*{kin} and β_T from the different systems to study the system-size dependence at similar multiplicities.

The extracted values of T_{kin} and β_T are shown in Fig. 4 [Figure 4: see original paper] for the six pp and for the eight pPb and PbPb multiplicity intervals. In this figure, the multiplicity increases from left to right. The statistical uncertainties are shown as correlation ellipses. Systematic uncertainties, which are evaluated by propagating the systematic uncertainties from the spectra to the blast-wave fits and altering the fit ranges, are on the order of a few percent and are not shown. Examples of the fits are shown in Fig. 5 [Figure 5: see original paper] for a low- and high-multiplicity range in pPb collisions. In general, the fit quality is good for high-multiplicity events except for the lowest p_T range, while for low-multiplicity events there are discrepancies on the order of 5%. However, the discrepancies between the fit and data lie within the systematic uncertainty.

The precise meaning of the T_{kin} and βT *parameters is model dependent, and they should not be interpreted literally as the kinetic freeze-out temperature and radial-flow velocity of the system. The main purpose of Fig. 4 is to provide a qualitative comparison of the spectral shapes in the three systems. In the context of the blast-wave model, when comparing at similar multiplicities, the T*{kin} parameter has the same value within 15% among the three systems, while the β_T parameter is larger when the system is smaller, i.e., βT{pp} > βT{pPb} > βT{PbPb}. This is qualitatively consistent with the prediction of Ref. [27].

The evolution of the p_T spectra with multiplicity can be compared more directly between the three systems through examination of the K_{ET} value. The K_{ET} values at |y_{cm}| < 1 for K^0*S, Λ, and Ξ^- particles as a function of multiplicity are shown in Fig. 6 [Figure 6: see original paper]. Extrapolation of the p_T spectra down to p_T = 0 GeV is a crucial step in extracting the K*{ET} values. For the Ξ^- particle, only results in pPb collisions are shown due to the limitation of the low-p_T reach in pp and PbPb collisions, as can be seen from Fig. 2. Blast-wave fits to the individual spectra, which only consider the spectrum shape but do not impose any physics constraint, are used to obtain the extrapolation. The fraction of the extrapolated yield with respect to the total yield is about 1.2–2.5% for the K^0_S, 5.8–15.1% for the Λ, and 5.4–20.4% for the Ξ^- particles, depending on the multiplicity. Alternative methods to perform the extrapolation are used to evaluate a systematic uncertainty, including use of the predictions from the simultaneous blast-wave fit to the K^0*S and Λ p_T spectra, and a linear extrapolation from the yields in a low range of p_T. The systematic uncertainties from Table 2 are also included in the evaluation of* *the K*{ET} uncertainties.

For the lowest multiplicity range, the K_{ET} values for each particle species are seen to be similar. For all particle species, K_{ET} increases with increasing multiplicity. However, the slope of the increase differs for different particles, with the heavier particles exhibiting a faster growth in K_{ET} for all systems. For a given multiplicity range, the K_{ET} value is roughly proportional to the particle's mass. In PbPb collisions, this can be understood to be due to the onset of radial flow [2, 4]. The observed difference between particle species at high multiplicity is seen to be larger for pp and pPb events than for PbPb events.

6.2 Rapidity Dependence in pPb Events

The rapidity dependence of the p_T spectra of the K^0*S and Λ particles is studied in the pPb data. No results for Ξ^- particles are presented due to statistical limitations. As a pPb collision is asymmetric in rapidity, it is interesting to compare the spectra along the Pb-going (y*{cm} < 0) and p-going (y_{cm} > 0) directions [33]. The p_T spectra of K^0*S and Λ particles in different y*{cm} ranges are shown in Fig. 7 [Figure 7: see original paper] for small (top), intermediate (middle), and large (bottom) average multiplicities.

The Λ/K^0*S ratios from the −1.5 < y*{cm} < −0.8 (Pb-going) and 0.8 < y_{cm} < 1.5 (p-going) rapidity regions are compared in Fig. 8 [Figure 8: see original paper] for multiplicity ranges 0 ≤ N_{offline}^{trk} < 35 and 220 ≤ N_{offline}^{trk} < 260. For both the low-multiplicity and the high-multiplicity events, the Λ/K^0_S ratio from the Pb-going direction lies above the results from the p-going direction, with the largest difference observed at high p_T in the high-multiplicity sample.

As a further study, we calculate K_{ET} , following the procedure outlined in Section 6.1, and examine its dependence on y_{cm} for K^0*S and Λ particles in the pPb collisions. The results are shown in Fig. 9 [Figure 9: see original paper]. Although the systematic uncertainties at forward rapidities are large, the K*{ET} values are seen to become slightly asymmetric as multiplicity increases. At low multiplicities (0 ≤ N_{offline}^{trk} < 35), the ratios of K_{ET} between the Pb-going side (−1.5 < y_{cm} < −0.8) and the p-going side (0.8 < y_{cm} < 1.5) are 1.01 ± 0.01 (syst.) for K^0*S particles and 1.04 ± 0.05 (syst.) for Λ particles, both of which are consistent with unity within the systematic uncertainties (the statistical uncertainties are negligible). However, in the highest multiplicity range, 220 ≤ N*{offline}^{trk} < 260, the ratios become 1.06 ± 0.01 (syst) for K^0*S particles and 1.12 ± 0.06 (syst) for Λ particles, suggesting that an asymmetry in K*{ET} is developed between the Pb-going and p-going sides. The observed asymmetry is found to be slightly larger for Λ than K^0_S particles. This trend is qualitatively consistent with the hydrodynamic prediction for pPb collisions [33].

7 Summary

Measurements of strange hadron (K^0*S, $\Lambda+\bar{\Lambda}$, and $\Xi^-+\bar{\Xi}^+$) transverse momentum spectra in pp, pPb, and PbPb collisions are presented over a wide range of event charged-particle multiplicity and particle rapidity. The study is based on samples of pp collisions at $\sqrt{s}$ = 7 TeV, pPb collisions at $\sqrt{s}$*{NN} = 5.02 TeV, and PbPb collisions at √s_{NN} = 2.76 TeV, collected with the CMS detector at the LHC. In the context of hydrodynamic models, the measured particle spectra are fitted to a blast wave function, which describes an expanding fluid-like system. When comparing at a similar multiplicity, the extracted radial-flow velocity parameters are found to be larger in pp and pPb collisions than that in PbPb collisions. The average transverse kinetic energy K_{ET} of strange hadrons is observed to increase with multiplicity, with a stronger increase for heavier particles. At similar multiplicities, the difference in K_{ET} between the strange-particle species is larger in the smaller pp and pPb systems than in the PbPb system. For pPb collisions, K_{ET} in the Pb-going direction for K^0_S ($\Lambda+\bar{\Lambda}$) is 6% (12%) larger than in the p-going direction for events with the highest particle multiplicities.

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Appendix A: The CMS Collaboration

The full author list is available in the original publication.

Note: Figure translations are in progress. See original paper for figures.