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

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ABSTRACT

Measurements of strange hadron (K^0_S, $\Lambda+\overline{\Lambda}$, and $\Xi^-+\overline{\Xi}^+$) transverse momentum spectra in pp, pPb, and PbPb collisions are presented over a wide range of rapidity and event charged-particle multiplicity. The data were collected with the CMS detector at the CERN LHC in pp collisions at $\sqrt{s} = 7\,\text{TeV}$, pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, and PbPb collisions at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$. The average transverse kinetic energy is found to increase with multiplicity, at a faster rate for heavier strange particle species in all systems. At similar multiplicities, the difference in average transverse kinetic energy between different particle species is observed to be larger for pp and pPb events than for PbPb events. In pPb collisions, the average transverse kinetic energy is found to be slightly larger in the Pb-going direction than in the p-going direction for events with large multiplicity. The spectra are compared to models motivated by hydrodynamics.

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 historically interpreted to be due to the formation of a high-density quark–gluon medium [3]. The abundance of strange particles at different center-of-mass energies is in line with calculations from thermal statistical models [4–6]. 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 and light flavor production and dynamics in heavy ion collisions have provided further insight into the medium's fluid-like nature and evidence for its partonic collectivity [2,7].

In recent years, the observation of a long-range "ridge" at small azimuthal separations in two-particle correlations in pp [8] and proton-lead (pPb) [9–11] 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 in size 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 [12]. While the collective flow of a fluid-like medium provides a natural interpretation [13–16], other models attribute this behavior to the initial correlation of gluons [17–21], or the anisotropic escape of particles [22].

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 [23,24] and described by hydrodynamic models [25,26]. Similar measurements have been performed in pPb collisions as a function of multiplicity, where an indication of a common velocity boost to the produced particles, known as "radial flow" [27,28], and for a mass dependence of the anisotropic flow [29,30] 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 [27,30]. 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. [31]. 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 [32]. Inspired by hydrodynamics, the blast-wave model assumes a common kinetic freeze-out tempera-

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ture and radial-flow velocity for all particles during the expansion of the system. The dependence of spectral shapes for identified hadrons on the multiplicity has been observed in high energy electron and proton–antiproton collisions [33,34], 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 [35]. In pp collisions, it has been shown through studies with simulation that color reconnection processes could describe the observed multiplicity dependence of identified particle spectra [23,36].

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 [8]. 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 [31]. Furthermore, in a pPb collision, the system is not symmetric in pseudorapidity (η). 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 η. Hydrodynamical models predict that the average p_T (or, equivalently, the average transverse kinetic energy $\langle KE_T\rangle$, where $\langle KE_T\rangle \equiv \langle m_T\rangle - m$, with $m_T = \sqrt{m^2 + p_T^2}$ 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 [37]. Measurement of identified particle p_T spectra as a function of η 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 for Λ and Ξ^- particles. 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 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 $|\eta| < 2.5$. 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 [38]. The ECAL and HCAL each cover $|\eta| < 3.0$ while forward hadron calorimeters (HF) cover $3 < |\eta| < 5$. Muons with $|\eta| < 2.4$ 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. [39]. The Monte Carlo (MC) simulation of the particle propagation and detector response is based on the Geant4 [40] 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 $\sqrt{s} = 5.02$ 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. [8,41]. 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. [41,42].

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 [43]. 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_{trk}^{online}) with $|\eta| < 2.4$ 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_{trk}^{online} for the vertex with the largest number of tracks to exceed a specific value. Data are collected in pPb collisions with thresholds $N_{trk}^{online} > 100$ and 130 for events with an L1 transverse energy threshold of 20 GeV, and $N_{trk}^{online} > 160$ and 190 for events with an L1 threshold of 40 GeV. While all events with $N_{trk}^{online} > 190$ 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. [8].