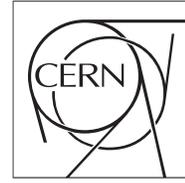**The Compact Muon Solenoid Experiment**

# Conference Report

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# Identified particles in pPb collisions in CMS

Ferenc Siklér for the CMS Collaboration

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Spectra of identified charged hadrons in pPb collisions with the CMS detector at the LHC at $\sqrt{s_{NN}} = 5.02$ TeV are presented. Charged pions, kaons,and protons in the transverse-momentum range $p_{\mathrm{T}} \approx 0.1$–1.7 GeV/$c$ and laboratory rapidity $|y| < 1$ are identified via their energy loss in the silicon tracker. The average $p_{\mathrm{T}}$ increases with particle mass and the charged multiplicity of the event. The increase of the average $p_{\mathrm{T}}$ with charged multiplicity is greater for heavier hadrons. Comparisons to Monte Carlo event generators reveal that EPOS LHC, which incorporates additional hydrodynamic evolution of the created system, is able to reproduce most of the data features, unlike HIJING and AMPT. The average transverse momentum and particle ratio measurements indicate that particle production at LHC energies is strongly correlated with event particle multiplicity.

Presented at *IS2013 International Conference on the Initial Stages in High-Energy Nuclear Collisions*

# Identified particles in pPb collisions by CMS

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**Abstract**

Spectra of identified charged hadrons in pPb collisions with the CMS detector at the LHC at $\sqrt{s_{NN}}$ = 5.02 TeV are presented. Charged pions, kaons, and protons in the transverse-momentum range $p_T \approx$ 0.1–1.7 GeV/$c$ and laboratory rapidity $|y|$ < 1 are identified via their energy loss in the silicon tracker. The average $p_T$ increases with particle mass and the charged multiplicity of the event. The increase of the average $p_T$ with charged multiplicity is greater for heavier hadrons. Comparisons to Monte Carlo event generators reveal that EPOS LHC, which incorporates additional hydrodynamic evolution of the created system, is able to reproduce most of the data features, unlike HIJING and AMPT. The average transverse momentum and particle ratio measurements indicate that characteristics of particle production at LHC energies is strongly correlated with event particle multiplicity.

*Keywords:* pPb, energy loss in silicon, hadron production

## 1. Introduction

The study of hadron production has a long history in high-energy particle and nuclear physics, as well as in cosmic-ray physics. The absolute yields and the transverse momentum ($p_T$) spectra of identified hadrons in high-energy hadron-hadron collisions are among the most basic physical observables. They can be used to test the predictions for non-perturbative quantum chromodynamics (QCD) processes like hadronization and soft-parton interactions, and the validity of their implementation in Monte Carlo (MC) event generators. Spectra of identified particles in proton-nucleus collisions also constitute an important reference for studies of high-energy heavy-ion collisions, where final-state effects are known to modify the spectral shapes and yields of different hadron species.

The present analysis focuses on the measurement of the $p_T$ spectra of charged hadrons, identified mostly via their energy deposits in silicon detectors, in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. The procedures are similar to those previously used in the measurement of pion, kaon, and proton production in pp collisions at several center-of-mass energies [1]. All details of this study are shown in Ref. [2]. A detailed description of the CMS (Compact Muon Solenoid) detector can be found in Ref. [3].

The reconstruction of charged particles in CMS is bounded by the acceptance of the tracker ($|\eta|$ < 2.4) and by the decreasing tracking efficiency at low momentum (greater than about 60% for $p$ > 0.05, 0.10, 0.20, and 0.40 GeV/$c$ for e, $\pi$, K, and p, respectively). Particle identification capabilities using specific ionization are restricted to $p$ < 0.15 GeV/$c$ for electrons, $p$ < 1.20 GeV/$c$ for pions, $p$ < 1.05 GeV/$c$ for kaons, and $p$ < 1.70 GeV/$c$ for protons.
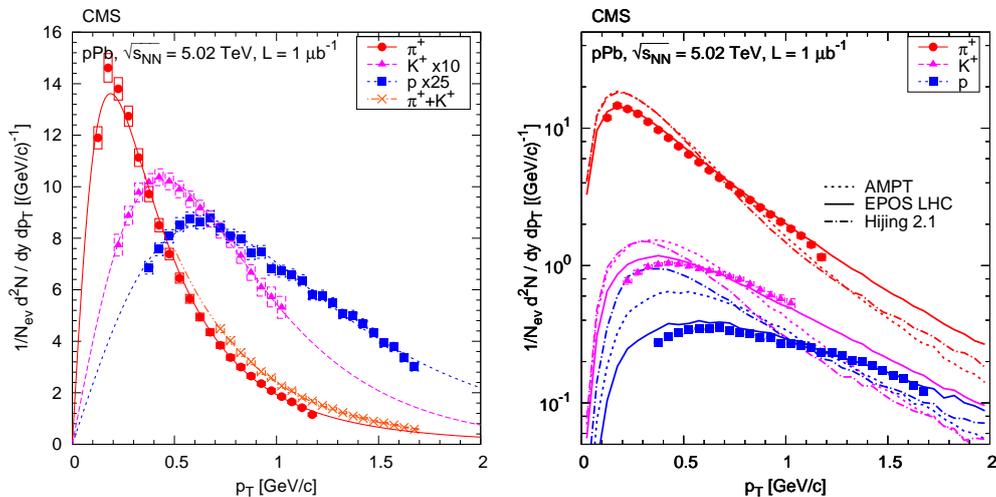
Figure 1: Transverse momentum distributions of identified positively charged hadrons (pions, kaons, protons, sum of pions and kaons) in the range $|y| < 1$, for positively charged particles. Left: kaon and proton distributions are scaled as shown in the legends, fits to Eq. (1) are superimposed. Right: Measured values are plotted together with predictions from AMPT, EPOS LHC, and HIJING. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. The fully correlated normalization uncertainty (not shown) is 3.0%.

## 2. Data analysis

The data were taken in September 2012 during a short pPb run with very low probability of multiple interactions (0.15% "pileup"). A total of 2.0 million collisions were collected. The particle yields reported here have been measured for laboratory rapidity $|y| < 1$ to match the experimentally accessible region.

The final results were corrected to a particle level selection: at least one particle (proper lifetime $\tau > 10^{-18}$ s) with $E > 3$ GeV in the range $-5 < \eta < -3$ and at least one in the range $3 < \eta < 5$; this selection is referred to in the following as the "double-sided" (DS) selection. These requirements are expected to suppress single-diffractive collisions in both the data and MC samples. From the MC event generators studied, the DS selection efficiency for inelastic, hadronic collisions is found to be 94–97%.

An analytical parametrization has been used to approximate the energy loss of charged particles in the CMS silicon tracker, and to estimate the most probable energy loss rate $\varepsilon$ over a given path length. Fit templates, giving the expected $\ln \varepsilon$ distributions for all particle species (electrons, pions, kaons, and protons), were built from tracks. The results of the (iterative) fits are the yields for each particle species and charge in bins of $(\eta, p_T)$ or $(y, p_T)$, both inclusive and divided into classes of reconstructed primary charged-track multiplicity. The measured yields in each bin were first corrected for the misreconstructed-track rate and the fraction of secondary particles. The distributions were then unfolded to take into account the finite $\eta$ and $p_T$ resolutions. An unfolding procedure with linear regularization was used, based on response matrices obtained from MC samples for each particle species. The corrected yields were obtained by applying corrections for acceptance, efficiency, and multiple track reconstruction rate. The yields as a function of $p_T$ were obtained by averaging over rapidity. The systematic uncertainties are very similar to those in Ref. [1].
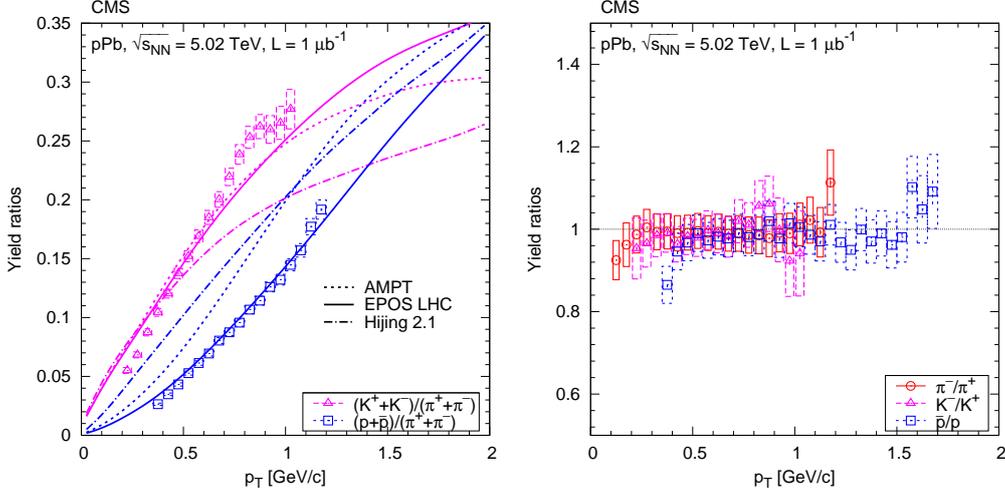
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Figure 2: Ratios of particle yields as a function of transverse momentum. K/$\pi$ and p/$\pi$ values are shown in the left panel, and opposite-charge ratios are plotted in the right panel. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. In the left panel, curves indicate predictions from AMPT, EPOS LHC, and HIJING.

## 3. Results

In previously published measurements of unidentified and identified particle spectra, the following form of the Tsallis-Pareto-type distribution [4, 5] was fitted to the data:

$$\frac{d^2N}{dy\,dp_T} = \frac{dN}{dy} \cdot C \cdot p_T \left[ 1 + \frac{m_T - m}{nT} \right]^{-n},$$
(1)

where $C$ is a normalization constant and $m_T = \sqrt{m^2 + p_T^2}$ (factors of $c$ are omitted from the preceding formulae). The free parameters are the integrated yield $dN/dy$, the exponent $n$, and parameter $T$. The above formula is useful for extrapolating the spectra to zero $p_T$ and very high $p_T$, and for extracting $\langle p_T \rangle$ and $dN/dy$. Its validity for different multiplicity bins was cross-checked by fitting MC spectra in the $p_T$ ranges where there are data points, and verifying that the fitted values of $\langle p_T \rangle$ and $dN/dy$ were consistent with the generated values. Nevertheless, for a more robust estimation of both quantities ($\langle p_T \rangle$ and $\langle dN/dy \rangle$), the data points and their uncertainties were used in the measured range and the fitted functions only for the extrapolation in the unmeasured regions.

### 3.1. Inclusive measurements

The transverse momentum distributions of positively charged hadrons (pions, kaons, protons) are shown in the left panel of Fig. 1, along with the results of the fits to the Tsallis-Pareto parametrization (Eq. (1)). The fits are of good quality with $\chi^2$/ndf values in the range 0.5–2.8. The right panel of Fig. 1 presents the data compared to the AMPT, EPOS LHC, and HIJING predictions. EPOS LHC gives a good description, while other generators predict steeper $p_T$ distributions than found in data.
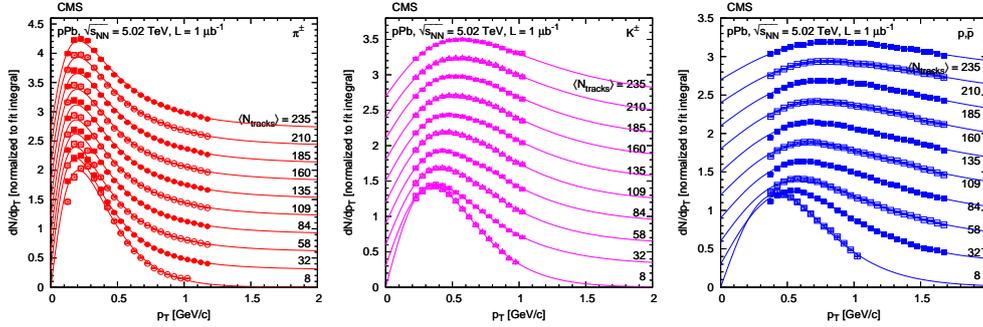
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Figure 3: Transverse momentum distributions of charged pions, kaons, and protons, normalized such that the fit integral is unity, in every second multiplicity class ($\langle N_{\text{tracks}} \rangle$ values are indicated) in the range $|y| < 1$, fitted with the Tsallis-Pareto parametrization (solid lines). For better visibility, the result for any given $\langle N_{\text{tracks}} \rangle$ bin is shifted by 0.3 units with respect to the adjacent bins. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties.

Ratios of particle yields as a function of the transverse momentum are plotted in Fig. 2. While the K/$\pi$ ratios are well described by the AMPT simulation, only EPOS LHC is able to predict both K/$\pi$ and p/$\pi$ ratios. The ratios of the yields for oppositely charged particles are close to one, as expected for LHC energies at midrapidity.

### 3.2. Multiplicity dependent measurements

A study of the dependence on track multiplicity is motivated partly by the intriguing hadron correlations measured in pp and pPb collisions at high track multiplicities [6], suggesting possible collective effects in "central" pp and pPb collisions at the LHC. At the same time, it was seen that in pp collisions the characteristics of particle production ($\langle p_{\text{T}} \rangle$, ratios) at LHC energies are strongly correlated with event particle multiplicity rather than with the center-of-mass energy of the collision [1]. The strong dependence on multiplicity (or centrality) was also seen in dAu collisions at RHIC. In addition, the multiplicity dependence of particle yield ratios is sensitive to various final-state effects (hadronization, color reconnection, collective flow) implemented in MC models used in collider and cosmic-ray physics.

The event multiplicity $N_{\text{rec}}$ is obtained from the number of reconstructed tracks with $|\eta| < 2.4$, where the tracks are reconstructed using the same algorithm as for the identified charged hadrons. (The multiplicity variable $N_{\text{trk}}^{\text{offline}}$, used in Ref. [6], is obtained from a different track reconstruction configuration and a value of $N_{\text{trk}}^{\text{offline}} = 110$ corresponds roughly to $N_{\text{rec}} = 170$.) The event multiplicity was divided into 19 classes. To facilitate comparisons with models, the corresponding corrected charged particle multiplicity in the same acceptance of $|\eta| < 2.4$ ($N_{\text{tracks}}$) is also determined. For each multiplicity class, the correction from $N_{\text{rec}}$ to $N_{\text{tracks}}$ uses the efficiency estimated with the HIJING simulation in ($\eta$, $p_{\text{T}}$) bins. The corrected data are then integrated over $p_{\text{T}}$, down to zero yield at $p_{\text{T}} = 0$ (with a linear extrapolation below $p_{\text{T}} = 0.1$ GeV/$c$). Finally, the integrals for each eta slice are summed.

Figure 3 shows transverse momentum distributions for pions, kaons and protons, in selected multiplicity classes and for $|y| < 1$. The distributions are normalized such that the fit integral is unity. The distributions of negatively and positively charged particles have been summed. The distributions are fitted with the Tsallis-Pareto parametrization with $\chi^2$/ndf values in the range 0.8–4.0 for pions, 0.1–1.1 for kaons, and 0.1–0.7 for protons. For kaons and protons, the
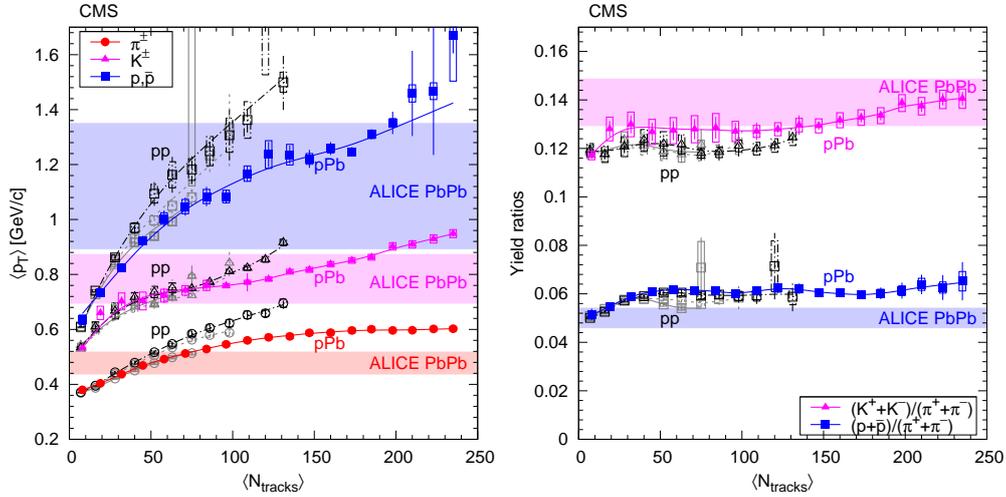
Figure 4: Average transverse momentum of identified charged hadrons (pions, kaons, protons; left panel) and ratios of particle yields (right panel) in the range $|y| < 1$ as a function of the corrected track multiplicity for $|\eta| < 2.4$, for pp collisions (open symbols) at several energies [1], and for pPb collisions (filled symbols) at $\sqrt{s_{NN}} = 5.02$ TeV. Both $\langle p_T \rangle$ and yield ratios were computed assuming a Tsallis-Pareto distribution in the unmeasured range. Error bars indicate the uncorrelated combined uncertainties, while boxes show the uncorrelated systematic uncertainties. For $\langle p_T \rangle$ the fully correlated normalization uncertainty (not shown) is 1.0%. In both plots, lines are drawn to guide the eye (gray solid – pp 0.9 TeV, gray dotted – pp 2.76 TeV, black dash-dotted – pp 7 TeV, colored solid – pPb 5.02 TeV). The ranges of $\langle p_T \rangle$, K/$\pi$ and p/$\pi$ values measured by ALICE in various centrality PbPb collisions (see text) at $\sqrt{s_{NN}} = 2.76$ TeV [7] are indicated with horizontal bands.

parameter $T$ increases with multiplicity, while for pions $T$ slightly increases and the exponent $n$ slightly decreases with multiplicity (not shown).

The K/$\pi$ and p/$\pi$ ratios are flat, or slightly rising, as a function of $\langle N_{\text{tracks}} \rangle$. While none of the models is able to precisely reproduce the track multiplicity dependence, the best and worst matches to the overall scale are given by EPOS LHC and HIJING, respectively. The ratios of yields of oppositely charged particles are independent of $\langle N_{\text{tracks}} \rangle$. The average transverse momentum $\langle p_T \rangle$ is shown as a function of multiplicity in Fig. 4, to be discussed below. As expected from the discrepancies between theory and data, EPOS LHC again gives a reasonable description, while the other event generators presented here underpredict the measured values. For the dependence of $T$ on multiplicity (not shown), the predictions match the pion data well; the kaon and proton values are much higher than in AMPT or HIJING.

*3.3. Comparisons to pp and PbPb data*

The comparison with pp data taken at various center-of-mass energies (0.9, 2.76, and 7 TeV) [1] is shown in Fig. 4, where the dependence of $\langle p_T \rangle$ and the particle yield ratios (K/$\pi$ and p/$\pi$) on the track multiplicity is shown. The plots also display the ranges of these values measured by ALICE in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV for centralities from peripheral (80–90% of the inelastic cross-section) to central (0–5%) [7]. These ALICE PbPb data cover a much wider range of $N_{\text{tracks}}$ than is shown in the plot. Although PbPb data are not available at $\sqrt{s_{NN}} = 5.02$ TeV for comparison, the evolution of event characteristics from RHIC ($\sqrt{s_{NN}} = 0.2$ TeV) to LHC energies [7] suggests that yield ratios should remain similar, while $\langle p_T \rangle$ values will increase by about 5% when going from $\sqrt{s_{NN}} = 2.76$ TeV to 5.02 TeV.
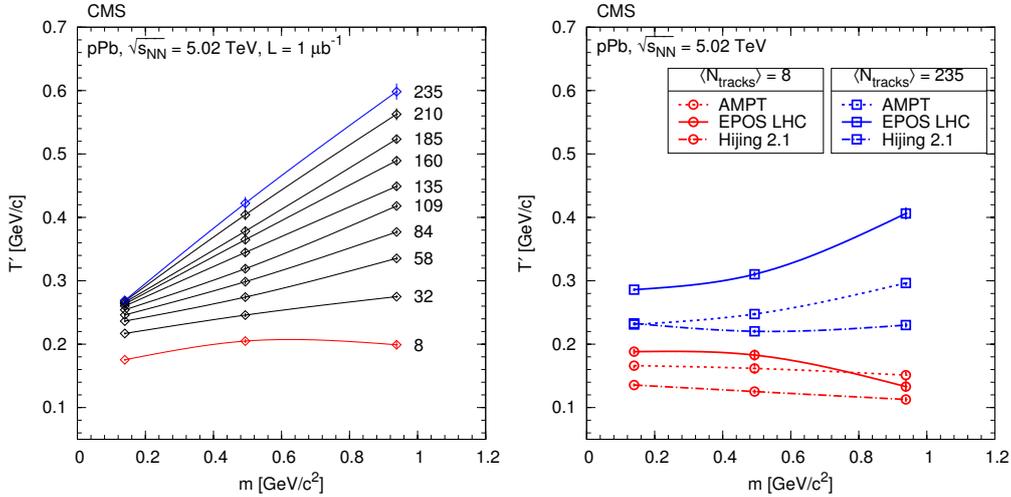
Figure 5: Inverse slope parameters $T'$ from fits of pion, kaon, and proton spectra (both charges) with a form proportional to $p_T \exp(-m_T/T')$. Results for a selection of multiplicity classes, with different $\langle N_{tracks} \rangle$ as indicated, are plotted for pPb data (left) and for MC event generators AMPT, EPOS LHC, and HIJING (right). The curves are drawn to guide the eye.

For low track multiplicity ($N_{tracks} \lesssim 40$), pPb collisions behave very similarly to pp collisions, while at higher multiplicities ($N_{tracks} \gtrsim 50$) the $\langle p_T \rangle$ is lower for pPb than in pp. The first observation can be explained since low-multiplicity events are peripheral pPb collisions in which only a few proton-nucleon collisions are present. Events with more particles are indicative of collisions in which the projectile proton strikes the thick disk of the lead nucleus. Interestingly, the pPb curves (Fig. 4, left panel) can be reasonably approximated by taking the pp values and multiplying their $N_{tracks}$ coordinate by a factor of 1.8, for all particle types. In other words, a pPb collision with a given $N_{tracks}$ is similar to a pp collision with $0.55 \times N_{tracks}$ for produced charged particles in the $|\eta| < 2.4$ range. Both the highest-multiplicity pp and pPb interactions yield higher $\langle p_T \rangle$ than seen in central PbPb collisions. While in the PbPb case even the most central collisions possibly contain a mix of soft (lower-$\langle p_T \rangle$) and hard (higher-$\langle p_T \rangle$) nucleon-nucleon interactions, for pp or pPb collisions the most violent interaction or sequence of interactions are selected.

The transverse momentum spectra could also be successfully fitted ($\chi^2$/ndf in the range 0.7–1.8) with a functional form proportional to $p_T \exp(-m_T/T')$, where $T'$ is called the inverse slope parameter, motivated by the success of Boltzmann-type distributions in nucleus-nucleus collisions. In the case of pions, the fitted range was restricted to $m_T > 0.4$ GeV/$c$ in order to exclude the region where resonance decays would significantly contribute to the measured spectra. The inverse slope parameter as a function of hadron mass is shown in Fig. 5, for a selection of event classes, both for pPb data and for MC event generators (AMPT, EPOS LHC, and HIJING). While the data display a linear dependence on mass with a slope that increases with particle multiplicity, the models predict a flat or slowly rising behavior versus mass and only limited changes with track multiplicity. This is to be compared with pp results [1], where both data and several tunes of the PYTHIA 6 and PYTHIA 8 event generators show features very similar to those in pPb data. A similar trend is also observed in nucleus-nucleus collisions, which is attributed to the effect of radial flow velocity boost.

The rapidity densities are generally about three times greater than in pp interactions at the

6

same energy, while the average transverse momentum increases by about 20%, 10%, and 30% for pions, kaons, and protons, respectively. The factor of three difference in the yields for pPb as compared to pp can be compared with the estimated number of projectile collisions $N_{\text{coll}}/2 = 3.5 \pm 0.3$ or with the number of nucleons participating in the collision $N_{\text{part}}/2 = 4.0 \pm 0.3$, based on the ratio of preliminary pPb and pp cross-section measurements, that have proven to be good scaling variables in proton-nucleus collisions at lower energies.

## 4. Conclusions

Measurements of identified charged hadron spectra produced in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV have been presented, normalized to events with simultaneous hadronic activity at pseudorapidities $-5 < \eta < -3$ and $3 < \eta < 5$. The $p_{\text{T}}$ spectra are well described by fits with the Tsallis-Pareto parametrization. The average $p_{\text{T}}$ is found to increase with particle mass and the event multiplicity.

The EPOS LHC event generator reproduces several features of the measured distributions, a significant improvement from the previous version, attributed to a new viscous hydrodynamic treatment of the produced particles.

Combined with similar results from pp collisions, the track multiplicity dependence of the average transverse momentum and particle ratios indicate that particle production at LHC energies is strongly correlated with event particle multiplicity in both pp and pPb interactions. For low track multiplicity, pPb collisions appear similar to pp collisions. At high multiplicities, the average $p_{\text{T}}$ of particles from pPb collisions with a charged particle multiplicity of $N_{\text{tracks}}$ (in $|\eta| < 2.4$) is similar to that for pp collisions with $0.55 \times N_{\text{tracks}}$. Both the highest-multiplicity pp and pPb interactions yield higher $\langle p_{\text{T}} \rangle$ than seen in central PbPb collisions.

## Acknowledgments

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