

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 shape and yields of different hadron species [1–4].

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 analysis 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 [5].

A detailed description of the CMS (Compact Muon Solenoid) detector can be found in Ref. [6]. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point (IP) and the z axis along the counterclockwise-beam direction. The pseudorapidity η and rapidity y of a particle (in the laboratory frame) with energy E , momentum p , and momentum along the z axis p_z are defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the z axis and $y = \frac{1}{2}\ln[(E + p_z)/(E - p_z)]$, respectively. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter. Within the 3.8 T field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. The tracker measures charged particles within the pseudorapidity range $|\eta| < 2.4$. It has 1440 silicon pixel and 15 148 silicon strip detector modules. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. Steel/quartz-fiber forward calorimeters (HF) cover $3 < |\eta| < 5$. Beam Pick-up Timing for the eXperiments (BPTX) devices were used to trigger the detector readout. They are located around the beam pipe at a distance of 175 m from the IP on either side, and are designed to provide precise information on the Large Hadron Collider (LHC) bunch structure and timing of the incoming beams.

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, π, 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. Pions are identified up to a higher momentum than kaons because of their high relative abundance. In view of the (y, p_T) regions where pions, kaons, and protons can all be identified ($p = p_T \cosh y$), the band $-1 < y < 1$ (in the laboratory frame) was chosen for this measurement, since it is a good compromise between the p_T range and y coverage.

In this paper, comparisons are made to predictions from three MC event generators. The HIJING [7] event generator is based on a two-component model for hadron production in high-energy nucleon and nuclear collisions. Hard parton scatterings are assumed to be described by perturbative QCD and soft interactions are approximated by string excitations with an effective cross section. In version 2.1, in addition to modification of initial parton distributions, multiple scatterings inside a nucleus lead to transverse momentum broadening of both initial and final-state partons, responsible for the enhancement of intermediate- p_T hadron spectra in proton-nucleus collisions. The AMPT [8] event generator is a multi-phase transport model.

It starts from the same initial conditions as HIJING, contains a partonic transport phase, the description of the bulk hadronization, and finally a hadronic rescattering phase. The latest available version (1.26/2.26) is used. The EPOS [9] event generator uses a quantum mechanical multiple scattering approach based on partons and strings, where cross sections and particle production are calculated consistently, taking into account energy conservation in both cases. Nuclear effects related to transverse momentum broadening, parton saturation, and screening have been introduced. The model can be used both for extensive air shower simulations and accelerator physics. The latest version, EPOS LHC [10], contains a three-dimensional viscous event-by-event hydrodynamic treatment. This is a major difference with respect to the HIJING and AMPT models.

2 Data analysis

The data were taken in September 2012 during a 4-hour-long pPb run with very low multiple-interaction rate (0.15% “pileup”). A total of 2.0 million collisions were collected, corresponding to an integrated luminosity of approximately $1 \mu\text{b}^{-1}$. As the dominant uncertainty is systematic in nature, the much larger 2013 pPb dataset was not needed for the analysis. The beam energies were 4 TeV for protons and 1.58 TeV per nucleon for lead nuclei, resulting in a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV. Due to the asymmetric beam energies the nucleon-nucleon center-of-mass in the pPb collisions is not at rest with respect to the laboratory frame but moves with a velocity $\beta = -0.434$ or rapidity -0.465 . Since the higher-energy proton beam traveled in the clockwise direction, i.e. at $\theta = \pi$, the rapidity of a particle emitted at y_{cm} in the nucleon-nucleon center-of-mass frame is detected in the laboratory frame with a shift, $y - y_{\text{cm}} = -0.465$, i.e. a particle with $y = 0$ moves with rapidity 0.465 in the Pb-beam direction in the center-of-mass system. The particle yields reported in this paper have been measured for laboratory rapidity $|y| < 1$.

The event selection consisted of the following requirements:

- at the trigger level, the coincidence of signals from both BPTX devices, indicating the presence of both proton and lead bunches crossing the interaction point; in addition, at least one track with $p_T > 0.4$ GeV/c in the pixel tracker;
- offline, the presence of at least one tower with energy above 3 GeV in each of the HF calorimeters; at least one reconstructed interaction vertex; beam-halo and beam-induced background events, which usually produce an anomalously large number of pixel hits [11], are suppressed.

The efficiencies for event selection, tracking, and vertexing were evaluated using simulated event samples produced with the HIJING 2.1 MC event generator, where the CMS detector response simulation was based on GEANT4 [12]. Simulated events were reconstructed in the same way as collision data events. The final results were corrected to a particle level selection applied to the direct MC output, which is very similar to the data selection described above: 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 in this paper, the DS selection efficiency for inelastic, hadronic collisions is found to be 94–97%.

The simulated ratio of the data selection efficiency to the DS selection efficiency is shown as a function of the reconstructed track multiplicity in the left panel of Fig. 1. The ratio is used to correct the measured events. The results are also corrected for the fraction of DS events

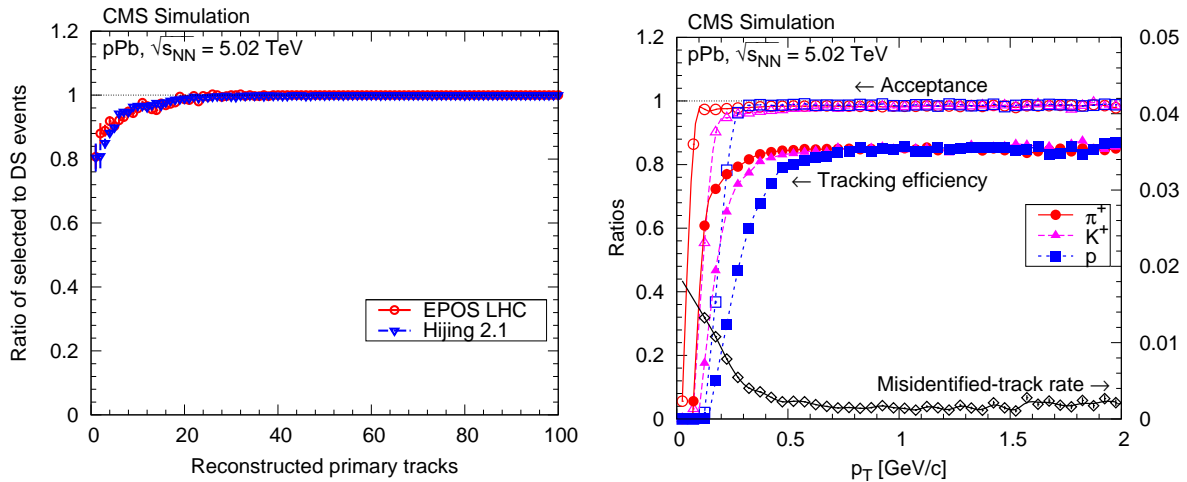


Figure 1: Left: the ratio of selected events to double-sided (DS) events (ratio of the corresponding efficiencies in the inelastic sample), according to EPOS LHC and HIJING MC simulations, as a function of the reconstructed primary charged-particle multiplicity. Right: acceptance, tracking efficiency (left scale), and misreconstructed-track rate (right scale) in the range $|\eta| < 2.4$ as a function of p_T for positively charged pions, kaons, and protons.

without a reconstructed track. This fraction, as given by the simulation, is about 0.1%. Since these events do not contain reconstructed tracks, only the number of DS events N_{ev} must be corrected.

The extrapolation of particle spectra into the unmeasured (y, p_T) regions is model dependent, particularly at low p_T . A high-precision measurement therefore requires reliable track reconstruction down to the lowest possible p_T . The present analysis extends to $p_T \approx 0.1 \text{ GeV}/c$ by exploiting special tracking algorithms [13], used in previous studies [5, 11, 14], to provide high reconstruction efficiency and low background rate. The charged-pion mass was assumed when fitting particle momenta.

When at least two hits are required in the pixel detector, the acceptance of the tracker (C_a) is flat in the region $-2 < \eta < 2$ and $p_T > 0.4 \text{ GeV}/c$, and its value is 96–98% (Fig. 1, right panel). The loss of acceptance at $p_T < 0.4 \text{ GeV}/c$ is caused by energy loss and multiple scattering of particles, both depending on the particle mass. Likewise, the reconstruction efficiency (C_e) is about 75–85%, degrading at low p_T , also in a mass-dependent way. The misreconstructed-track rate (C_f) is very small, reaching 1% only for $p_T < 0.2 \text{ GeV}/c$. The probability of reconstructing multiple tracks (C_m) from a single true track is about 0.1%, mostly due to particles spiralling in the strong magnetic field of the CMS solenoid. The efficiencies and background rates largely factorize in η and p_T , but for the final corrections an (η, p_T) matrix is used.

The region where pPb collisions occur (beam spot) is measured by reconstructing vertices from many events. Since the bunches are very narrow in the transverse direction, the xy location of the interaction vertices is well constrained; conversely, their z coordinates are spread over a relatively long distance and must be determined on an event-by-event basis. The vertex position is determined using reconstructed tracks which have $p_T > 0.1 \text{ GeV}/c$ and originate from the vicinity of the beam spot, i.e. their transverse impact parameters d_T satisfy the condition $d_T < 3\sigma_T$. Here σ_T is the quadratic sum of the uncertainty in the value of d_T and the root-mean-square of the beam spot distribution in the transverse plane. The agglomerative vertex-reconstruction algorithm [15] was used, with the z coordinates (and their uncertainties) of the tracks at the point of closest approach to the beam axis as input. For single-vertex events, there is no mini-

imum requirement on the number of tracks associated with the vertex, even one-track vertices are allowed. If multiple vertices are present, it is enough to keep the one with the highest track multiplicity. The resultant bias is negligible since the pileup rate is extremely small.

The distribution of the z coordinates of the reconstructed primary vertices is Gaussian, with a standard deviation of 7.1 cm. The simulated data were reweighted so as to have the same vertex z coordinate distribution as the data.

The hadron spectra were corrected for particles of non-primary origin ($\tau > 10^{-12}$ s). The main sources of secondary particles are weakly decaying particles, mostly K_S^0 , $\Lambda/\bar{\Lambda}$, and $\Sigma^+/\bar{\Sigma}^-$. While the correction (C_s) is around 1% for pions, it rises up to 15% for protons with $p_T \approx 0.2$ GeV/ c . As none of the mentioned weakly decaying particles decay into kaons, the correction for kaons is small. Based on studies comparing reconstructed K_S^0 , Λ , and $\bar{\Lambda}$ spectra and predictions from the HIJING event generator, the corrections are reweighted by a p_T -dependent factor.

For $p < 0.15$ GeV/ c , electrons can be clearly identified. The overall e^\pm contamination of the hadron yields is below 0.2%. Although muons cannot be separated from pions, their fraction is very small, below 0.05%. Since both contaminations are negligible, no corrections are applied for them.

3 Estimation of energy loss rate and yield extraction

In this paper an analytical parametrization [16] has been used to approximate the energy loss of charged particles in the silicon detectors. The method provides the probability density $P(\Delta|\varepsilon, l)$ of energy deposit Δ , if the most probable energy loss rate ε at a reference path-length $l_0 = 450$ μ m and the path-length l are known. It was used in conjunction with a maximum likelihood estimation method.

For pixel clusters, the energy deposits were calculated as the sum of individual pixel deposits. In the case of strips, the energy deposits were corrected for capacitive coupling and cross-talk between neighboring strips. The readout threshold, the coupling parameter, and the standard deviation of the Gaussian noise for strips were determined from data, using tracks with close-to-normal incidence.

For an accurate determination of ε , the response of all readout chips was calibrated with multiplicative gain correction factors. The measured energy deposit spectra were compared to the energy loss parametrization and hit-level corrections (affine transformation of energy deposits using scale factors and shifts) were introduced. The corrections were applied to individual hits during the determination of the $\ln \varepsilon$ fit templates.

The best value of ε for each track was calculated with the corrected energy deposits by minimizing the joint energy deposit negative log-likelihood of all hits on the trajectory (index i), $\chi^2 = -2 \sum_i \ln P(\Delta_i|\varepsilon, l_i)$. The $\ln \varepsilon$ values in (η, p_T) bins were then used in the yield unfolding. Hits with incompatible energy deposits (contributing to the joint χ^2 with a large amount) were excluded. At most one hit was removed; this affected about 1.5% of the tracks. Finally, fit templates, giving the expected $\ln \varepsilon$ distributions for all particle species (electrons, pions, kaons, and protons), were built from tracks. All kinematical parameters and hit-related observables were kept, but the energy deposits were regenerated by sampling from the analytical parametrization.

Distributions of $\ln \varepsilon$ as a function of total momentum p for positive particles are plotted in

the left panel of Fig. 2 and compared to the predictions of the energy loss method for electrons, pions, kaons, and protons. The remaining deviations were taken into account by means of track-level residual corrections (affine transformation of templates using scale factors and shifts, $\ln \varepsilon \rightarrow \alpha \ln \varepsilon + \delta$).

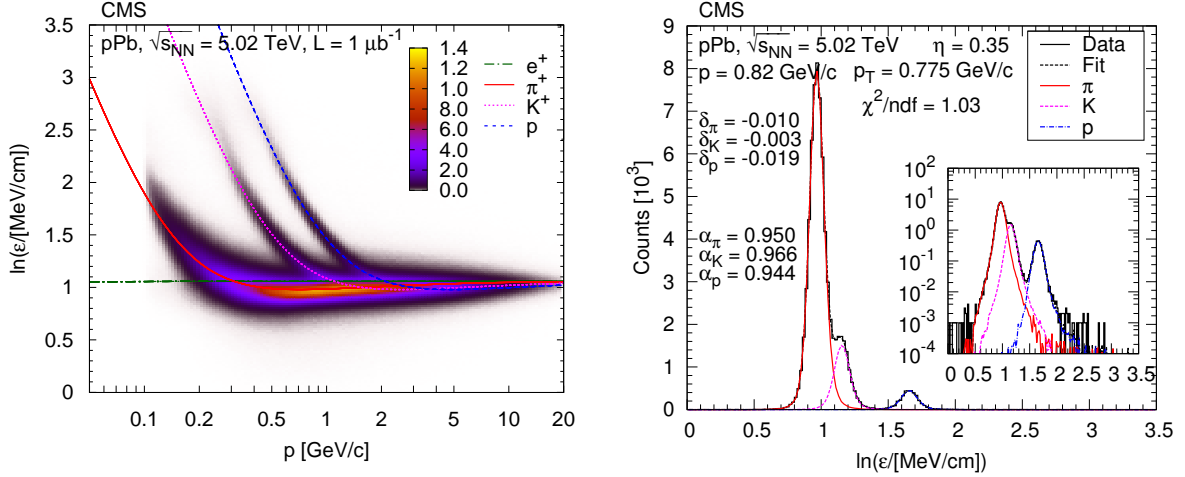


Figure 2: Left: distribution of $\ln \varepsilon$ as a function of total momentum p , for positively charged particles (ε is the most probable energy loss rate at a reference path length $l_0 = 450 \mu\text{m}$). The z scale is shown in arbitrary units and is linear. The curves show the expected $\ln \varepsilon$ for electrons, pions, kaons, and protons [17]. Right: example $\ln \varepsilon$ distribution at $\eta = 0.35$ and $p_T = 0.775 \text{ GeV}/c$. Scale factors (α) and shifts (δ) are indicated (see text). The inset shows the distribution with logarithmic vertical scale.

Low-momentum particles can be identified unambiguously and can therefore be counted. Conversely, at high momentum, the $\ln \varepsilon$ bands overlap (above about $0.5 \text{ GeV}/c$ for pions and kaons and $1.2 \text{ GeV}/c$ for protons); the particle yields therefore need to be determined by means of a series of template fits in $\ln \varepsilon$, in bins of η and p_T (Fig. 2, right panel). For a less biased determination of track-level residual corrections, enhanced samples of each particle type were employed. For electrons and positrons, photon conversions in the beam-pipe and innermost first pixel layer were used. For high-purity π and enhanced p samples, weakly decaying hadrons were selected (K_S^0 , $\Lambda/\bar{\Lambda}$). Some relations and constraints were also exploited [5], this way better constraining the parameters of the fits: fitting the $\ln \varepsilon$ distributions in number of hits (n_{hits}) and track-fit χ^2/ndf slices simultaneously; fixing the distribution n_{hits} of particle species, relative to each other; using the expected continuity for refinement of track-level residual corrections, in neighboring (η, p_T) bins; using the expected convergence for track-level residual corrections, as the $\ln \varepsilon$ values of two particle species approach each other.

The results of the (iterative) $\ln \varepsilon$ fits are the yields for each particle species and charge in bins of (η, p_T) or (y, p_T), both inclusive and divided into classes of reconstructed primary charged-track multiplicity. In the end, the histogram fit χ^2/ndf values were usually close to unity. Although pion and kaon yields could not be determined for $p > 1.30 \text{ GeV}/c$, their sum was measured. This information is an important constraint when fitting the p_T spectra.

The statistical uncertainties for the extracted yields are given by the fits. The observed local variations of parameters in the (η, p_T) plane for track-level corrections cannot be attributed to statistical fluctuations and indicate that the average systematic uncertainties in the scale factors and shifts are about 10^{-2} and $2 \cdot 10^{-3}$, respectively. The systematic uncertainties in the yields in each bin were obtained by refitting the histograms with the parameters changed by these

amounts.

4 Corrections and systematic uncertainties

The measured yields in each (η, p_T) bin, $\Delta N_{\text{measured}}$, were first corrected for the misreconstructed-track rate (C_f) and the fraction of secondary particles (C_s):

$$\Delta N' = \Delta N_{\text{measured}} \cdot (1 - C_f) \cdot (1 - C_s). \quad (1)$$

The distributions were then unfolded to take into account the finite η and p_T resolutions. The η distribution of the tracks is flat and the η resolution is very good. Conversely, the p_T distribution is steep in the low-momentum region and separate corrections in each η bin were necessary. An unfolding procedure with linear regularization [18] was used, based on response matrices obtained from MC samples for each particle species.

The corrected yields were obtained by applying corrections for acceptance (C_a), efficiency (C_e), and multiple track reconstruction rate (C_m):

$$\frac{1}{N_{\text{ev}}} \frac{d^2 N}{d\eta dp_T}_{\text{corrected}} = \frac{1}{C_a \cdot C_e \cdot (1 + C_m)} \frac{\Delta N'}{N_{\text{ev}} \Delta\eta \Delta p_T'} \quad (2)$$

where N_{ev} is the corrected number of DS events (Fig. 1). Bins with acceptance smaller than 50%, efficiency smaller than 50%, multiple-track rate greater than 10%, or containing less than 80 tracks were not used.

Finally, the differential yields $d^2 N/d\eta dp_T$ were transformed to invariant yields $d^2 N/dy dp_T$ by multiplying with the Jacobian E/p and the (η, p_T) bins were mapped into a (y, p_T) grid. As expected, there is no strong y dependence in the narrow region considered ($|y| < 1$) and therefore the yields as a function of p_T were obtained by averaging over rapidity.

The systematic uncertainties are very similar to those in Ref. [5] and are summarized in Table 1. The uncertainties of the corrections related to the event selection and pileup are fully or mostly correlated and were treated as normalization uncertainties: 3.0% uncertainty on the yields and 1.0% on the average p_T . The tracker acceptance and the track reconstruction efficiency generally have small uncertainties (1% and 3%, respectively), but change rapidly at very low p_T (right panel of Fig. 1), leading to a 6% uncertainty on the yields in that range. For the multiple-track and misreconstructed-track rate corrections, the uncertainty is assumed to be 50% of the correction, while for the case of the correction for secondary particles it is 20%. The uncertainty of the fitted yields is in the range 1–10% depending mostly on total momentum.

5 Results

In previously published measurements of unidentified and identified particle spectra [11, 19], the following form of the Tsallis-Pareto-type distribution [20, 21] was fitted to the data:

$$\frac{d^2 N}{dy dp_T} = \frac{dN}{dy} \cdot C \cdot p_T \left[1 + \frac{m_T - m}{nT} \right]^{-n}, \quad (3)$$

Table 1: Summary of the systematic uncertainties affecting the p_T spectra. Values in parentheses indicate uncertainties in the $\langle p_T \rangle$ measurement. Representative, particle-specific uncertainties (π , K, p) are given for $p_T = 0.6 \text{ GeV}/c$.

Source	Uncertainty of the source [%]	Propagated yield uncertainty [%]		
Fully correlated, normalization				
Correction for event selection	3.0 (1.0)	}	3.0 (1.0)	
Pileup correction (merged and split vertices)	0.3			
Mostly uncorrelated				
Pixel hit efficiency	0.3	}	0.3	
Misalignment, different scenarios	0.1			
Mostly uncorrelated, (y, p_T) dependent		π	K	p
Acceptance of the tracker	1–6	1	1	1
Efficiency of the reconstruction	3–6	3	3	3
Multiple-track reconstruction	50% of the corr.	–	–	–
Misreconstructed-track rate	50% of the corr.	0.1	0.1	0.1
Correction for secondary particles	20% of the corr.	0.2	–	2
Fitting $\ln \varepsilon$ distributions	1–10	1	2	1

where

$$C = \frac{(n-1)(n-2)}{nT[nT + (n-2)m]} \quad (4)$$

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 $p_T = 0$ and for extracting $\langle p_T \rangle$ and dN/dy . Its validity was cross-checked by fitting MC spectra and verifying that the fitted values of $\langle p_T \rangle$ and dN/dy were consistent with the generated values. According to some models of particle production based on non-extensive thermodynamics [21], the parameter T is connected with the average particle energy, while n characterizes the “non-extensivity” of the process, i.e. the departure of the spectra from a Boltzmann distribution ($n = \infty$).

As discussed earlier, pions and kaons cannot be unambiguously distinguished at higher momenta. Because of this, the pion-only (kaon-only) $d^2N/dy dp_T$ distribution was fitted for $|y| < 1$ and $p < 1.20 \text{ GeV}/c$ ($p < 1.05 \text{ GeV}/c$); the joint pion and kaon distribution was fitted in the region $|\eta| < 1$ and $1.05 < p < 1.5 \text{ GeV}/c$. Since the ratio p/E for the pions (which are more abundant than kaons) at these momenta can be approximated by p_T/m_T at $\eta \approx 0$, Eq. (3) becomes:

$$\frac{d^2N}{d\eta dp_T} \approx \frac{dN}{dy} \cdot C \cdot \frac{p_T^2}{m_T} \left(1 + \frac{m_T - m}{nT}\right)^{-n}. \quad (5)$$

The approximate fractions of particles outside the measured p_T range depend on track multiplicity; they are 15–30% for pions, 40–50% for kaons, and 20–35% for protons. The average transverse momentum $\langle p_T \rangle$ and its uncertainty were obtained by numerical integration of Eq. (3) with the fitted parameters, under the assumption that the particle yield distributions follow the Tsallis-Pareto function in the unmeasured p_T region.

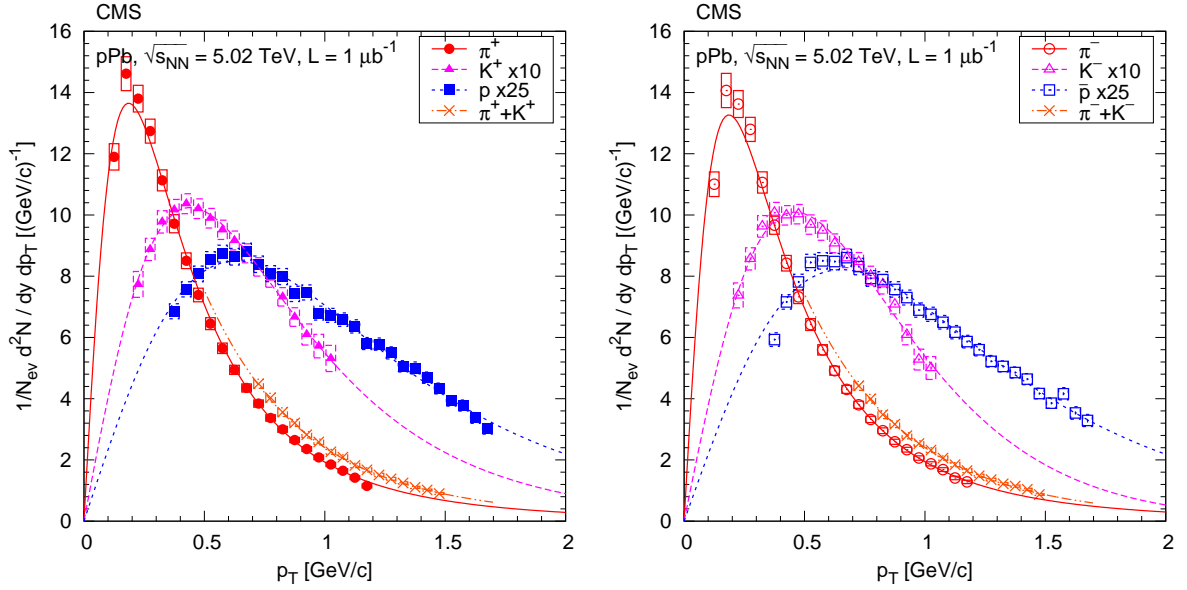


Figure 3: Transverse momentum distributions of identified charged hadrons (pions, kaons, protons, sum of pions and kaons) in the range $|y| < 1$, for positively (left) and negatively (right) charged particles. Kaon and proton distributions are scaled as shown in the legends. Fits to Eqs. (3) and (5) are superimposed. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. The fully correlated normalization uncertainty (not shown) is 3.0%.

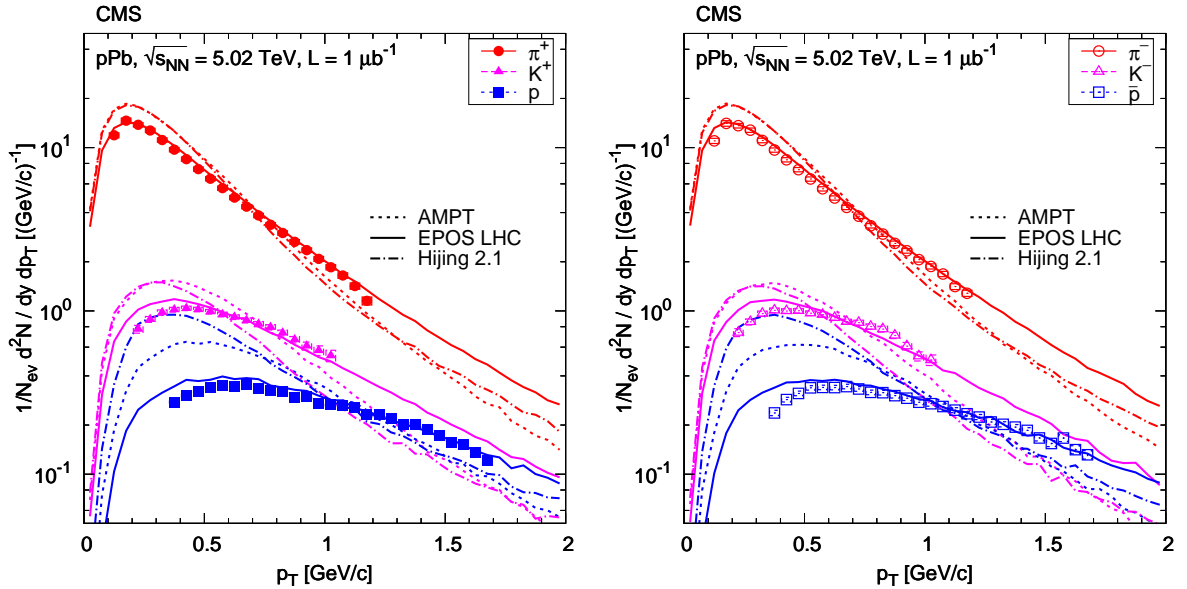


Figure 4: Transverse momentum distributions of identified charged hadrons (pions, kaons, protons) in the range $|y| < 1$, for positively (left) and negatively (right) charged particles. Measured values (same as in Fig. 3) are plotted together with predictions from AMPT, EPOS LHC, and HIJING. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. The fully correlated normalization uncertainty (not shown) is 3.0%.

The results discussed in the following are for laboratory rapidity $|y| < 1$. In all cases, error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. The fully correlated normalization uncertainty is not shown. For the p_T spectra, the average transverse momentum, and the ratio of particle yields, the data are compared to AMPT 1.26/2.26 [8], EPOS LHC [9, 10], and HIJING 2.1 [7] MC event generators.

5.1 Inclusive measurements

The transverse momentum distributions of positively and negatively charged hadrons (pions, kaons, protons) are shown in Fig. 3, along with the results of the fits to the Tsallis-Pareto parametrization (Eqs. (3) and (5)). The fits are of good quality with χ^2/ndf values in the range 0.4–2.8 (Table 2). Figure 4 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.

Table 2: Fit results (dN/dy , $1/n$, and T) for the DS selection shown together with the average transverse momenta $\langle p_T \rangle$ and goodness-of-fit values for charged pions, kaons, and protons. Combined uncertainties are given. Note that the K^- fit returns $1/n$ close to 0, causing the calculated $\langle p_T \rangle$ uncertainty to be artificially small.

Particle	dN/dy	$1/n$	T [GeV/c]	$\langle p_T \rangle$ [GeV/c]	χ^2/ndf
π^+	8.074 ± 0.081	0.190 ± 0.007	0.131 ± 0.003	0.556 ± 0.012	0.88
π^-	7.971 ± 0.079	0.195 ± 0.007	0.131 ± 0.003	0.573 ± 0.014	1.05
K^+	1.071 ± 0.068	0.092 ± 0.066	0.278 ± 0.022	0.832 ± 0.056	0.42
K^-	0.984 ± 0.047	-0.008 ± 0.067	0.316 ± 0.024	0.777 ± 0.003	2.82
p	0.510 ± 0.018	0.151 ± 0.036	0.325 ± 0.016	1.244 ± 0.093	0.81
\bar{p}	0.494 ± 0.017	0.123 ± 0.038	0.349 ± 0.017	1.216 ± 0.075	1.32

Ratios of particle yields as a function of the transverse momentum are plotted in Fig. 5. While the K/π ratios are well described by the AMPT simulation, only EPOS LHC is able to predict both K/π and p/π ratios. The ratios of the yields for oppositely charged particles are close to one, as expected for pair-produced particles at midrapidity.

5.2 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 [22–25], 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 ($\langle p_T \rangle$, ratios) at LHC energies are strongly correlated with event particle multiplicity rather than with the center-of-mass energy of the collision [5]. 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 [26].

The event multiplicity N_{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 [13]. (The multiplicity variable $N_{\text{trk}}^{\text{offline}}$, used in Ref. [23], 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, defined in Table 3. To facilitate comparisons with models, the corresponding corrected charged particle multiplicity in the

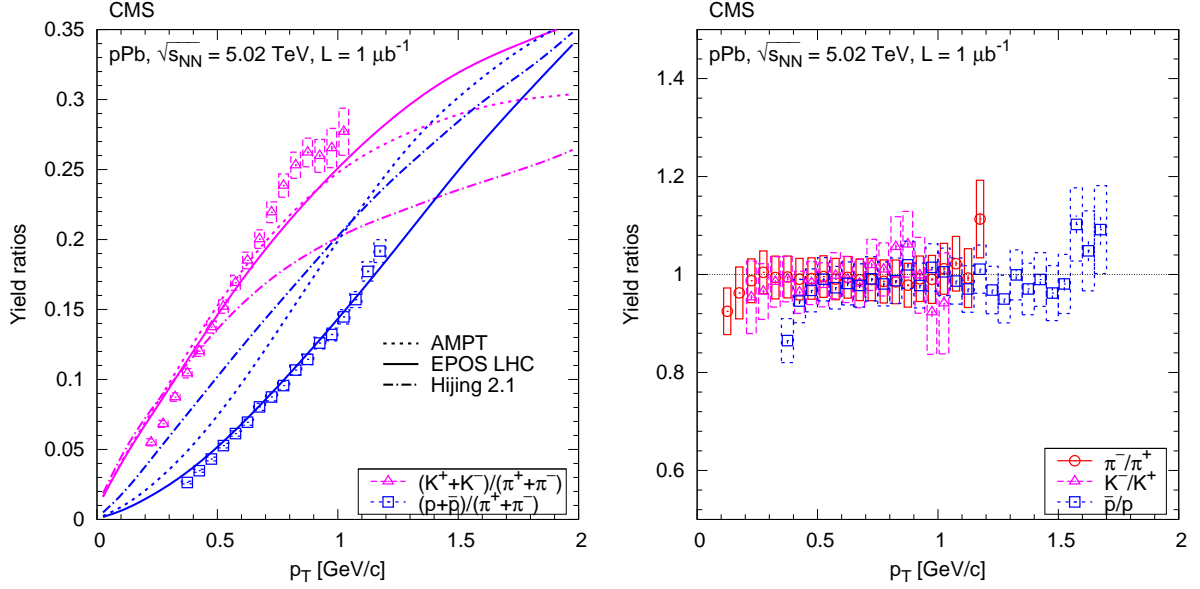


Figure 5: Ratios of particle yields as a function of transverse momentum. K/π and p/π values are shown in the left panel, and opposite-charge ratios are plotted in the right panel. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. In the left panel, curves indicate predictions from AMPT, EPOS LHC, and HIJING.

Table 3: Relationship between the number of reconstructed tracks (N_{rec}) and the average number of corrected tracks ($\langle N_{\text{tracks}} \rangle$) in the region $|\eta| < 2.4$, and also with the condition $p_T > 0.4 \text{ GeV}/c$ (used in Ref. [23]), in the 19 multiplicity classes considered.

N_{rec}	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89	90-99	100-109	110-119	120-129	130-139	140-149	150-159	160-169	170-179	180-189
$\langle N_{\text{tracks}} \rangle$	8	19	32	45	58	71	84	96	109	122	135	147	160	173	185	198	210	222	235
$\langle N_{\text{tracks}} \rangle_{p_T > 0.4 \text{ GeV}/c}$	3	8	15	22	29	36	43	50	58	65	73	80	87	95	103	110	117	125	133

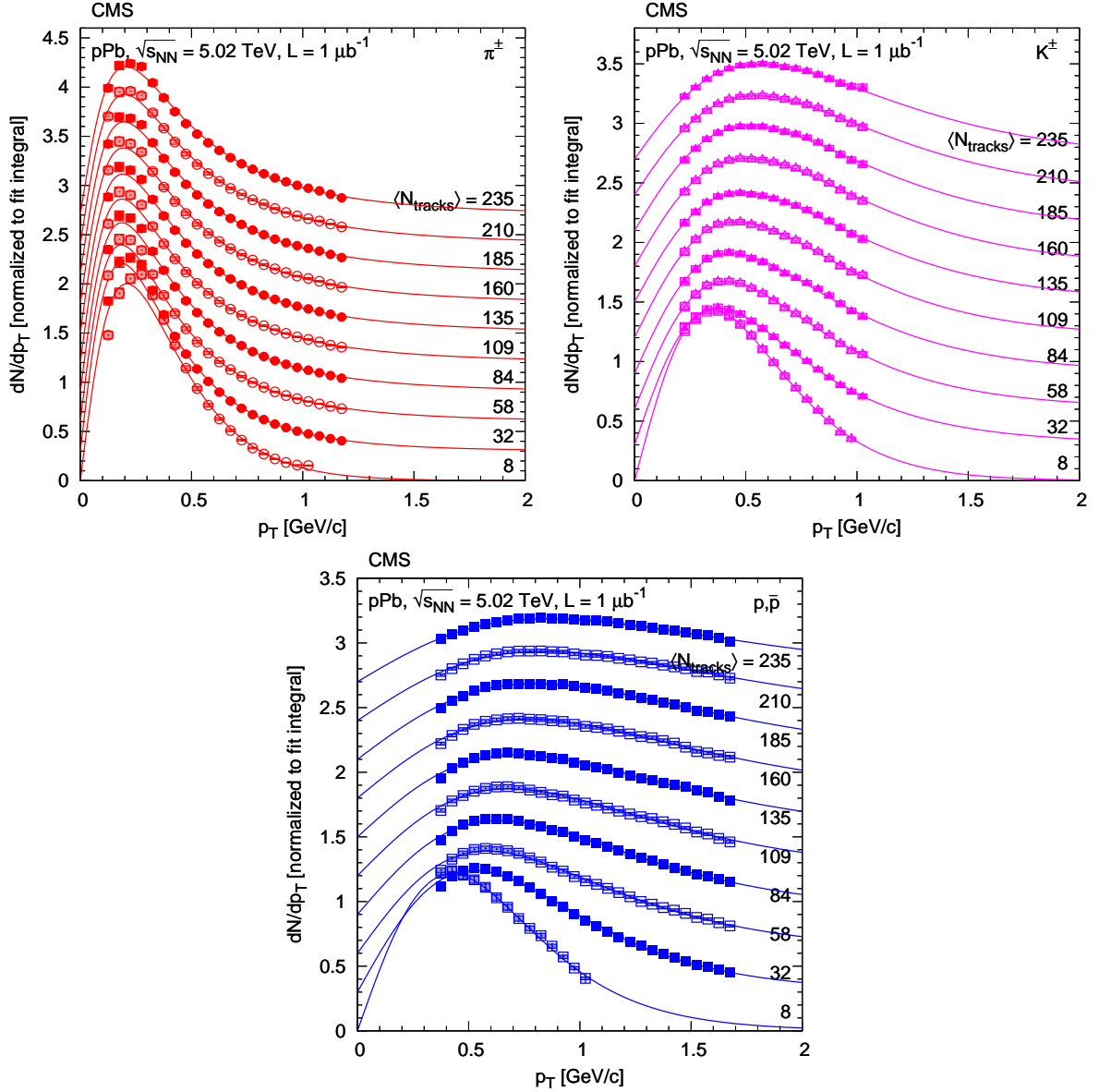


Figure 6: Normalized transverse momentum distributions of charged pions, kaons, and protons in every second multiplicity class ($\langle N_{\text{tracks}} \rangle$ values are indicated) in the range $|\eta| < 1$, fitted with the Tsallis-Pareto parametrization (solid lines). For better visibility, the 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.

same acceptance of $|\eta| < 2.4$ (N_{tracks}) is also determined. For each multiplicity class, the correction from N_{rec} to N_{tracks} uses the efficiency from the simulation with HIJING in (η, p_T) bins, followed by integration over the whole p_T range of the corrected data in slices of η (with a linear extrapolation for $p_T < 0.1$ GeV/c, down to zero yield at $p_T = 0$), and finished by summing the integrals for each η slice. The average corrected charged-particle multiplicity $\langle N_{\text{tracks}} \rangle$, and also its values with the condition $p_T > 0.4$ GeV/c, are shown in Table 3 for each event multiplicity class. The value of $\langle N_{\text{tracks}} \rangle$ is used to identify the multiplicity class in Figs. 6–10.

The normalized transverse-momentum distributions of identified charged hadrons in selected multiplicity classes for $|\eta| < 1$ are shown in Fig. 6 for pions, kaons, and protons. The distribu-

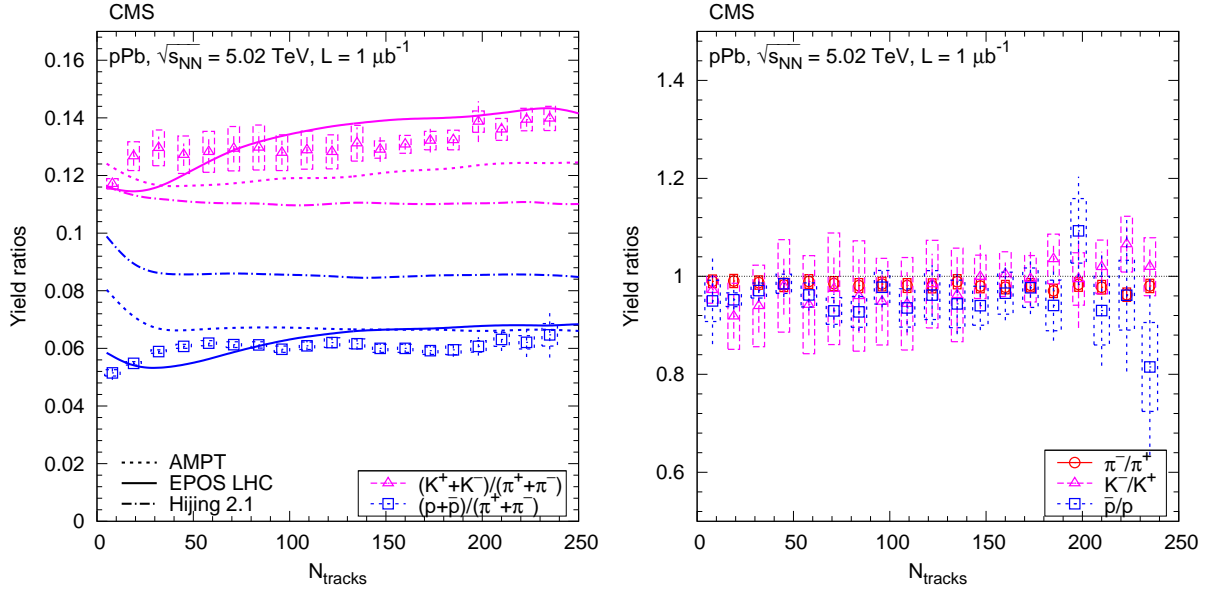


Figure 7: Ratios of particle yields in the range $|y| < 1$ as a function of the corrected track multiplicity for $|\eta| < 2.4$. K/π and p/π values are shown in the left panel, and opposite-charge ratios are plotted in the right panel. Error bars indicate the uncorrelated combined uncertainties, while boxes show the uncorrelated systematic uncertainties. In the left panel, curves indicate predictions from AMPT, EPOS LHC, and HIJING.

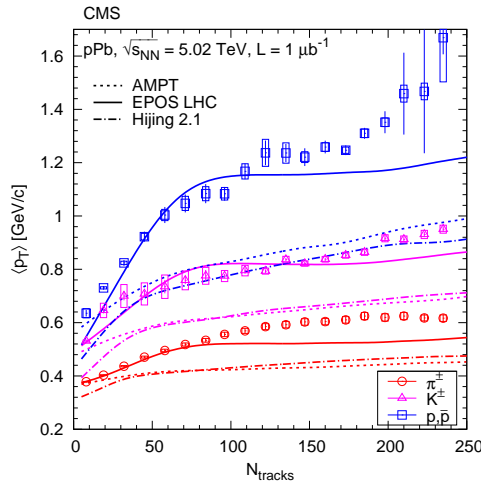


Figure 8: Average transverse momentum of identified charged hadrons (pions, kaons, protons) in the range $|y| < 1$, as a function of the corrected track multiplicity for $|\eta| < 2.4$. Error bars indicate the uncorrelated combined uncertainties, while boxes show the uncorrelated systematic uncertainties. The fully correlated normalization uncertainty (not shown) is 1.0%. Curves indicate predictions from AMPT, EPOS LHC, and HIJING.

tions of negatively and positively charged particles have been summed. The distributions are fitted with the Tsallis-Pareto parametrization. For kaons and protons, the parameter T increases with multiplicity, while for pions both T and the exponent n are independent of multiplicity (not shown).

The ratios of particle yields, obtained by integration of the fitted Tsallis-Pareto function over the whole p_T range, are displayed as a function of track multiplicity in Fig. 7. The K/π and p/π ratios are flat, or slightly rising, as a function of N_{tracks} . 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 N_{tracks} as shown in the right panel of Fig. 7. The average transverse momentum $\langle p_T \rangle$ is shown as a function of multiplicity in Fig. 8. As expected from the discrepancies between theory and data shown in Fig. 4, 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.

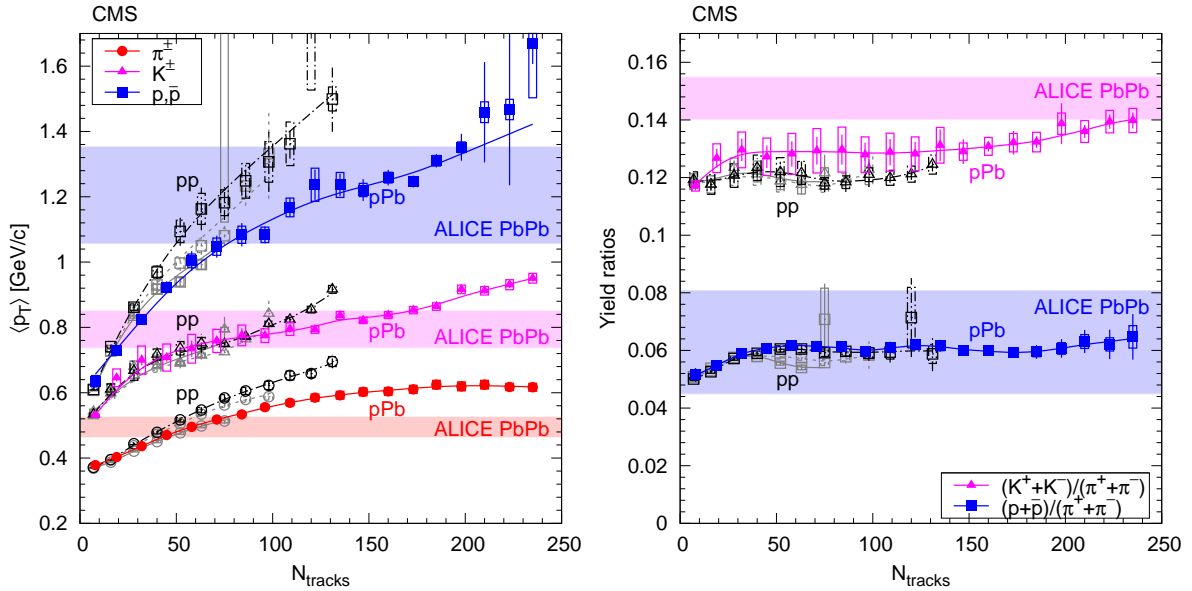


Figure 9: Average transverse momentum of identified charged hadrons (pions, kaons, protons; left panel) and ratios of particle yields (right panel) in the range $|y| < 1$ as a function of the corrected track multiplicity for $|\eta| < 2.4$, for pp collisions (open symbols) at several energies [5], and for pPb collisions (filled symbols) at $\sqrt{s_{NN}} = 5.02$ TeV. 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/π and p/π values measured by ALICE in various centrality PbPb collisions (see text) at $\sqrt{s_{NN}} = 2.76$ TeV [27] are indicated with horizontal bands.

5.3 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) [5] is shown in Fig. 9, where the dependence of $\langle p_T \rangle$ and the particle yield ratios (K/π and p/π) 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%) [27]. These ALICE PbP data cover a much wider range of N_{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, [2, 4, 28]) to LHC energies [27] 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.

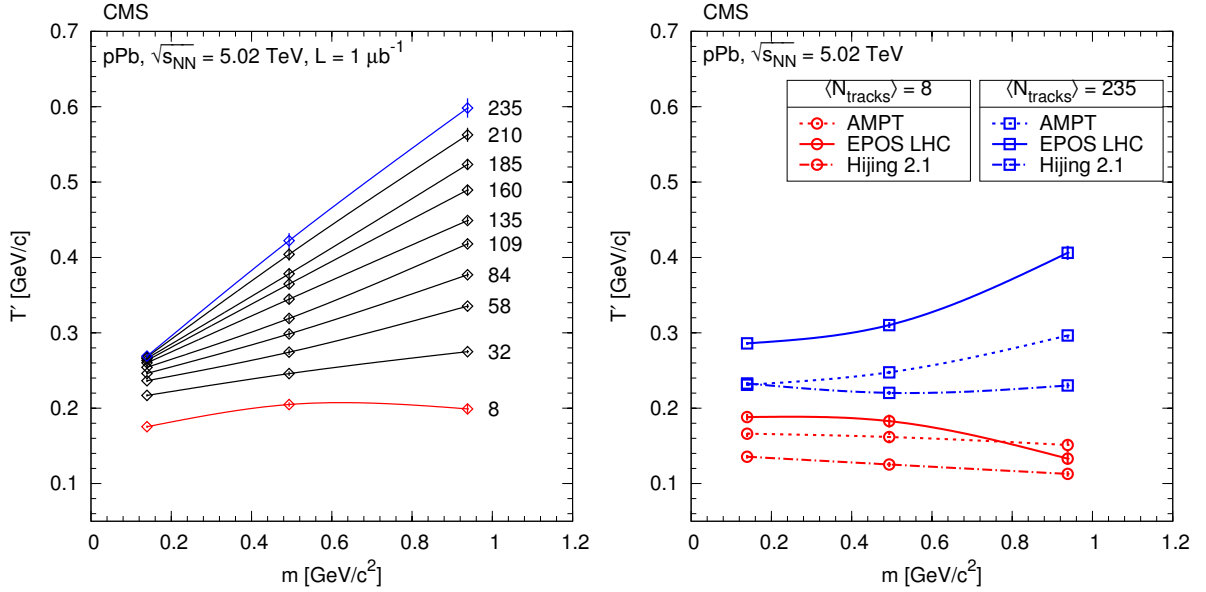


Figure 10: Inverse slope parameters T' from fits of pion, kaon, and proton spectra (both charges) with a form proportional to $p_T \exp(-m_T/T')$. Results for a selection of multiplicity classes, with different N_{tracks} as indicated, are plotted for pPb data (left) and for MC event generators AMPT, EPOS LHC, and HIJING (right). The curves are drawn to guide the eye.

For low track multiplicity ($N_{\text{tracks}} \lesssim 40$), pPb collisions behave very similarly to pp collisions, while at higher multiplicities ($N_{\text{tracks}} \gtrsim 50$) 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. 9, 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 $0.55 \times N_{\text{tracks}}$ 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 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 [29]. 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. 10, for a selection of event classes, both for pPb data and for MC event generators (AMPT, EPOS LHC, and HIJING). While the data

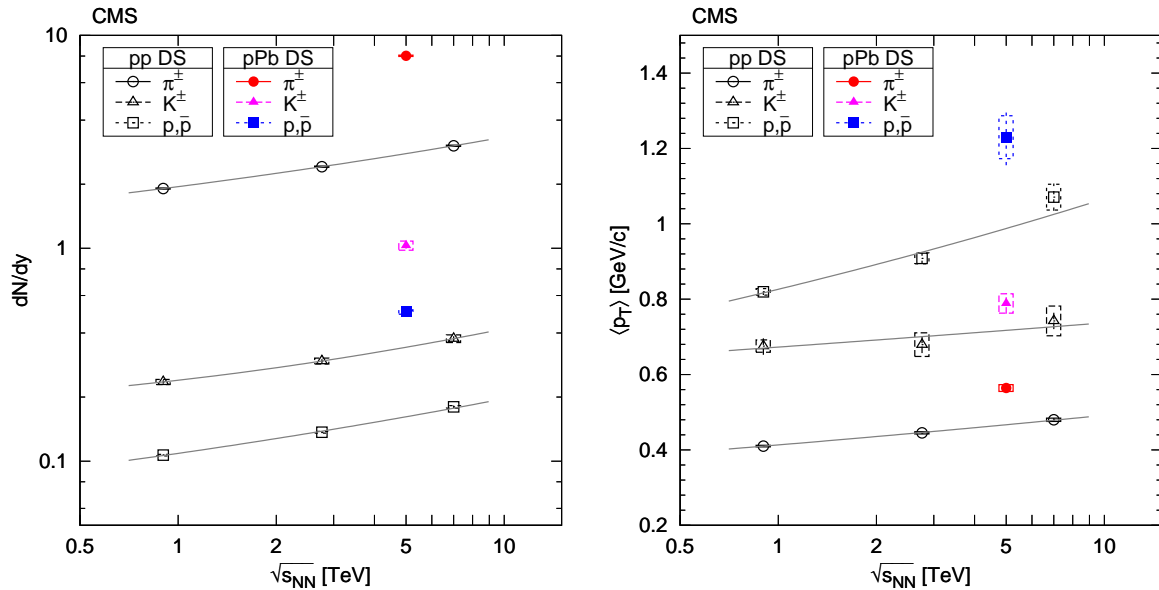


Figure 11: Rapidity densities dN/dy (left) and average transverse momenta $\langle p_T \rangle$ (right) as a function of center-of-mass energy for pp [5] and pPb collisions, for charge-averaged pions, kaons, and protons. Error bars indicate the uncorrelated combined uncertainties, while boxes show the uncorrelated systematic uncertainties. The curves show parabolic (for dN/dy) or linear (for $\langle p_T \rangle$) interpolation on a log-log scale. The pp and pPb data are for laboratory rapidity $|y| < 1$, which is the same as the center-of-mass rapidity only for the pp 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 [5], where both data and the PYTHIA 6.420 event generator [30] show features very similar to those in pPb data. A similar trend is also observed in nucleus-nucleus collisions [2, 4], which is attributed to the effect of radial flow velocity boost [1].

Rapidity densities dN/dy and average transverse momenta $\langle p_T \rangle$ of charge-averaged pions, kaons, and protons as a function of center-of-mass energy are shown in Fig. 11 for pp and pPb collisions, both corrected to the DS selection. To allow comparison at the pPb energy, a parabolic (linear) interpolation of the pp collision values at $\sqrt{s} = 0.9, 2.76, \text{ and } 7 \text{ TeV}$ is shown for dN/dy ($\langle p_T \rangle$). The rapidity densities are generally about three times greater than in pp interactions at the 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 preliminary cross-section measurements, that have proven to be good scaling variables in proton-nucleus collisions at lower energies [31].

6 Conclusions

Measurements of identified charged hadron spectra produced in pPb collisions at $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ have been presented, based on data collected in events with simultaneous hadronic activity at pseudorapidities $-5 < \eta < -3$ and $3 < \eta < 5$. Charged pions, kaons, and protons were identified from the energy deposited in the silicon tracker and other track information. In

the present analysis, the yield and spectra of identified hadrons for laboratory rapidity $|y| < 1$ have been studied as a function of the event charged particle multiplicity in the range $|\eta| < 2.4$. The p_T spectra are well described by fits with the Tsallis-Pareto parametrization. The ratios of the yields of oppositely charged particles are close to one, as expected at mid-rapidity for collisions of this energy. The average p_T is found to increase with particle mass and the event multiplicity.

The results can be used to further constrain models of hadron production and contribute to the understanding of basic non-perturbative dynamics in hadron collisions. 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. Other studied generators (AMPT, HIJING) predict steeper p_T distributions and much smaller $\langle p_T \rangle$ than found in data, as well as substantial deviations in the p/π ratios.

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_T of particles from pPb collisions with a charged particle multiplicity of N_{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 $\langle p_T \rangle$ than seen in central PbPb collisions.

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- 40: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- 41: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland

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- 42: Also at Gaziosmanpasa University, Tokat, Turkey
43: Also at Adiyaman University, Adiyaman, Turkey
44: Also at Cag University, Mersin, Turkey
45: Also at Mersin University, Mersin, Turkey
46: Also at Izmir Institute of Technology, Izmir, Turkey
47: Also at Ozyegin University, Istanbul, Turkey
48: Also at Kafkas University, Kars, Turkey
49: Also at Suleyman Demirel University, Isparta, Turkey
50: Also at Ege University, Izmir, Turkey
51: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
52: Also at Kahramanmaras Sütcü Imam University, Kahramanmaras, Turkey
53: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
54: Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
55: Also at Utah Valley University, Orem, USA
56: Also at Institute for Nuclear Research, Moscow, Russia
57: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
58: Also at Argonne National Laboratory, Argonne, USA
59: Also at Erzincan University, Erzincan, Turkey
60: Also at Yildiz Technical University, Istanbul, Turkey
61: Also at Texas A&M University at Qatar, Doha, Qatar
62: Also at Kyungpook National University, Daegu, Korea