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Multiplicity dependence of the production of identified charged hadrons in pp and pPb collisions from CMS

Ferenc Siklér* **for the CMS Collaboration**
Wigner RCP, Budapest
E-mail: sikler.ferenc@wigner.mta.hu

New results on transverse momentum spectra of identified charged hadrons in proton-proton collisions at $\sqrt{s} = 13$ TeV are presented using the CMS detector at the LHC. Charged pions, kaons, and protons in the transverse-momentum range $p_{\mathrm{T}} = 0.1$–1.7 GeV/c and for laboratory rapidities $|y| < 1$ are identified via their energy loss in the CMS silicon tracker. The p_{T} spectra and integrated yields are compared to lower center-of-mass energy pp, and to similar energy pPb and PbPb results, as well as to Monte Carlo simulations.

For all collision systems studied, the average p_{T} increases with particle mass and with the charged-particle multiplicity of the event as expected from theoretical predictions, among others from those based on gluon saturation. The results show only a slight dependence of the average p_{T} on the center-of-mass energy, indicating that particle production at LHC energies is strongly correlated with the charged-particle multiplicity rather than with the center-of-mass energy of the collision. The observed dependencies show that at TeV energies the characteristics of particle production in hadronic collisions are constrained mostly by the amount of initial parton energy available in a given collision.

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1. Introduction

The study of hadron production has a long history in high-energy particle, nuclear, and 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 improve the modeling of various key ingredients of Monte Carlo (MC) hadronic event generators, such as multiparton interactions, parton hadronization, and final-state effects (such as parton correlations in color, p_{T}, spin, baryon and strangeness number, and collective flow) [1]. The dependence of the hadron spectra and yields on the impact parameter of the proton-proton (pp) collision provides additional valuable information to tune the corresponding MC parameters.

Spectra of identified particles in pp collisions also constitute an important reference for high-energy heavy ion studies, where various final-state effects are known to modify the spectral shape and yields of different hadron species.

The present analysis uses pp collisions collected by the CMS experiment [2] at the CERN LHC at $\sqrt{s} = 13$ TeV and focuses on the measurement of the p_{T} spectra of charged hadrons, identified primarily via their energy depositions in the silicon detectors. The analysis adopts the same methods as used in previous CMS measurements of pion, kaon, and proton production in pp and pPb collisions at $\sqrt{s}$ of 0.9, 2.76, and 7 TeV [3, 4], as well as those performed by the ALICE collaboration at 2.76 and 7 TeV [5, 6]. Further details of the analysis are given in Ref. [7].

2. Results

The results discussed in the following are averaged over the rapidity range $|y| < 1$. In all cases, error bars in the figures 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 $\langle p_{\mathrm{T}} \rangle$, and the ratios of particle yields, the data are compared to the predictions of MC event generators.

2.1 Inclusive measurements

The transverse momentum distributions of positively and negatively charged hadrons (pions, kaons, protons) are shown in Fig. 1 and are compared to the PYTHIA8 [8], EPOS [9], and PYTHIA6 [10] predictions. While pions are described well by all three generators, kaons are best modelled by PYTHIA8 and EPOS. For protons and very low p_{T} pions only PYTHIA8 gives a good description of the data.

Ratios of particle yields as a function of the transverse momentum are plotted in Fig. 2. Only PYTHIA8 is able to predict both the K/π and p/π ratios as a function of p_{T}. The ratios of the yields for oppositely charged particles are close to one (Fig. 2, right), as expected at this center-of-mass energy in the central rapidity region.

2.2 Multiplicity-dependent measurements

The study of the p_{T} spectra as a function of the event track multiplicity is motivated partly by the intriguing hadron correlations measured in pp and pPb collisions at high track multiplicities, suggesting possible collective effects in "central" collisions at the LHC. We have also observed

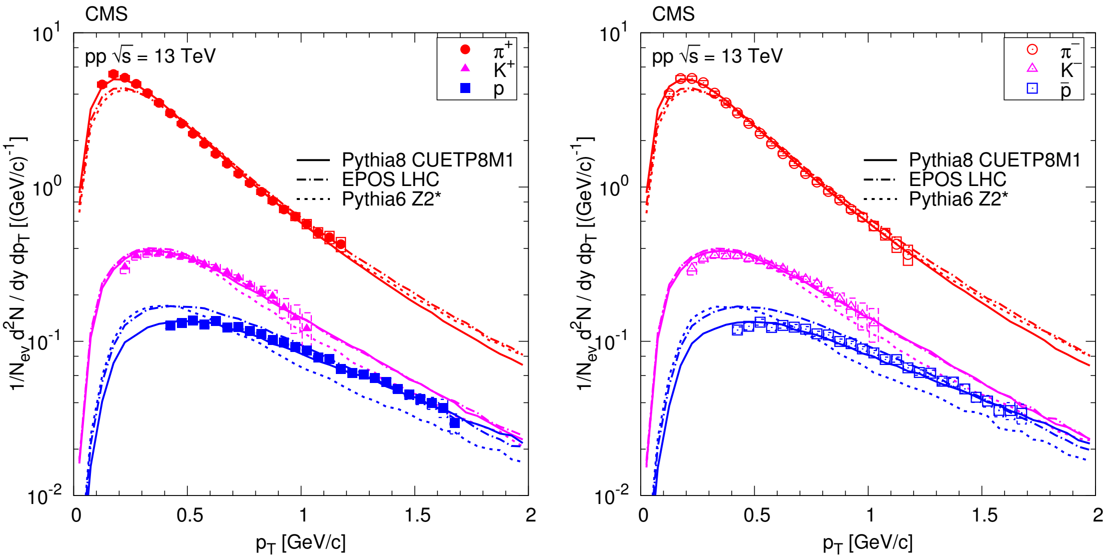

Figure 1: Transverse momentum distributions of identified charged hadrons (pions, kaons, protons) from inelastic pp collisions, in the range $|y| < 1$, for positively (left) and negatively (right) charged particles [7]. Measured values are plotted together with predictions from PYTHIA8, EPOS, and PYTHIA6. Boxes show the uncorrelated systematic uncertainties, while error bars indicate the uncorrelated statistical uncertainties (hardly visible). The fully correlated normalization uncertainty (not shown) is 3.0%.

that in pp collisions at LHC energies [3, 4], the characteristics of particle production ($\langle p_T \rangle$, ratios of yields) are strongly correlated with the particle multiplicity in the event, which is in itself closely related to the number of underlying parton-parton interactions, independently of the concrete center-of-mass energy of the pp collision.

The event track multiplicity, N_{rec}, is defined as the number of tracks with $|\eta| < 2.4$ reconstructed using the same algorithm as for the identified charged hadrons. The event multiplicity is divided into 18 classes. To facilitate comparisons with models, the event charged-particle multiplicity over $|\eta| < 2.4$ (N_{tracks}) is determined for each multiplicity class by correcting N_{rec} for the track reconstruction efficiency, which is estimated with the PYTHIA8 simulation in (η, p_T) bins. The corrected yields are then integrated over p_T, down to zero yield at $p_T = 0$ (with a linear extrapolation below $p_T = 0.1$ GeV$/c$). Finally, the integrals for each η slice are summed up. The Tsallis–Pareto parametrization is fitted to the transverse-momentum distributions of pions, kaons, and protons with χ^2/ndf values in the range 0.3–2.3 for pions, 0.2–2.6 for kaons, and 0.1–0.8 for protons.

The K$/\pi$ and p$/\pi$ ratios as functions of track multiplicity are relatively flat as a function of $\langle N_{tracks} \rangle$, and none of the models is able to accurately reproduce the track multiplicity dependence. The ratios of yields of oppositely charged particles are independent of $\langle N_{tracks} \rangle$. Although PYTHIA8 gives a good description of the (multiplicity integrated) inelastic p_T spectra (Fig. 1), none of the MC event generators reproduces well the multiplicity dependence of $\langle p_T \rangle$ for all particle species. In particular, all generators overestimate the measured values for kaons. Pions are well described by PYTHIA6 and EPOS, while protons are best described by PYTHIA8.

In the lower multiplicity events, with fewer than 50 tracks, we observe a reasonable agreement

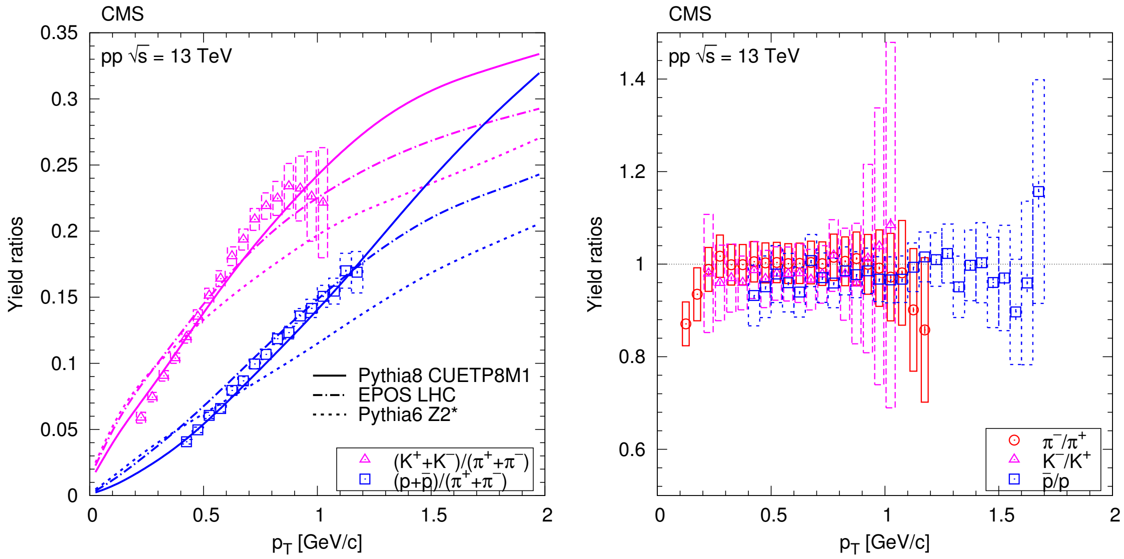

Figure 2: Ratios of particle yields, K/π and p/π (left) and opposite-charge ratios (right), as a function of transverse momentum [7]. Error bars indicate the uncorrelated statistical uncertainties, while boxes show the uncorrelated systematic uncertainties. In the left panel, curves indicate predictions from PYTHIA8, EPOS, and PYTHIA6.

between the data and the MC generator predictions for the different particle yields. However in higher multiplicity events, the measured kaon (proton) yield is smaller (higher) than predicted by the models. This indicates that the MC parameters that control the strangeness and baryon production as a function of parton multiplicity, need additional fine tuning.

2.3 Comparisons with lower energy pp data

The comparison of these results with lower energy pp data taken at various center-of-mass energies (0.9, 2.76, and 7 TeV) [3] is presented in Fig. 3, where the track-multiplicity dependence of $\langle p_T \rangle$ (left) and the particle yield ratios (K/π and p/π, right) are shown. In the previous publication [3], the final results are corrected to a particle-level selection that requires at least one particle (with 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 as the "double-sided" (DS) selection. Average rapidity densities $\langle dN/dy \rangle$ 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. 4 corrected to the DS selection (pp DS'). Based on the predictions of the three MC event generators studied, the inelastic $\langle dN/dy \rangle$ result is corrected upwards by 28%, with an additional systematic uncertainty of about 2%. No such correction is applied in the case of $\langle p_T \rangle$, since the inelastic value is close to the DS' one, with a difference of about 1%.

The average p_T increases with particle mass and event multiplicity at all $\sqrt{s}$, as predicted by all considered event generators. We note that both $\langle p_T \rangle$ and ratios of hadron yields show very similar dependences on the particle multiplicity in the event, independently of the center-of-mass energy of the pp collisions. The $\sqrt{s}$-evolution of the average hadron p_T provides useful information on the so-called "saturation scale" (Q_{sat}) of the gluons in the proton [11]. Minijet-based models such as

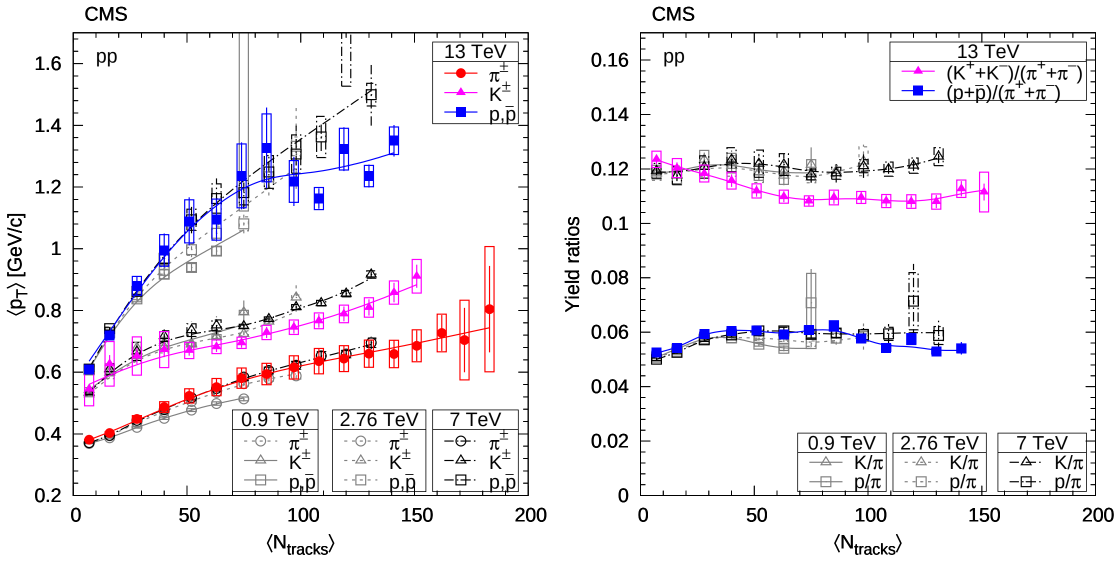

Figure 3: Average transverse momentum of identified charged hadrons (pions, kaons, protons; left panel) and ratios of particle yields (right panel) in the range $|y| < 1$ as functions of the corrected track multiplicity for $|\eta| < 2.4$, for pp collisions at $\sqrt{s} = 13$ TeV (filled symbols) [7] and at lower energies (open symbols) [3]. Both $\langle p_T \rangle$ and yield ratios are 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 – 0.9 TeV, gray dotted – 2.76 TeV, black dash-dotted – 7 TeV, colored solid – 13 TeV).

PYTHIA have an energy-dependent infrared p_T cutoff of the perturbative multiparton cross sections that mimics the power-law evolution of the Q_{sat} characteristic of gluon saturation models [12]. In addition, the latter saturation models consistently connect Q_{sat} to the impact parameter of the hadronic collision, thereby providing a natural dependence of $\langle p_T \rangle$ on the final particle multiplicity in the event.

Acknowledgments

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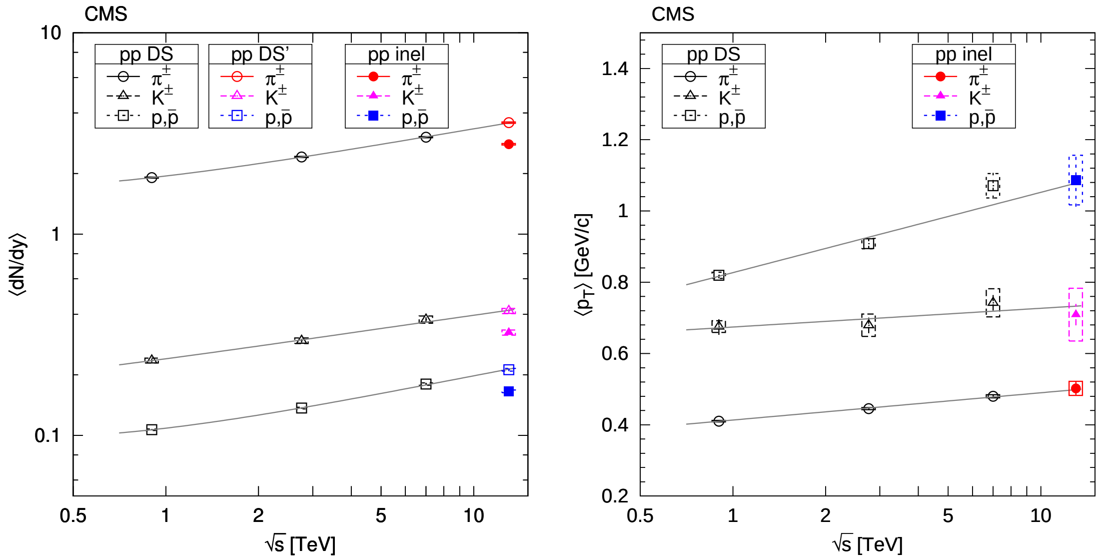

Figure 4: Average rapidity densities $\langle dN/dy \rangle$ (left) and average transverse momenta $\langle p_T \rangle$ (right) for $|y| < 1$ [7] as functions of center-of-mass energy for pp collisions (with data at 0.9, 2.76, and 7 TeV [3]), for charge-averaged pions, kaons, and protons. In the left plot the pp DS' results at 13 TeV have been extrapolated from the inelastic values using simulation. Error bars indicate the uncorrelated combined uncertainties, while boxes show the uncorrelated systematic uncertainties. The curves show parabolic ($\langle dN/dy \rangle$) or linear (for $\langle p_T \rangle$) fits in $\ln s$.

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