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Letter

Universality of identified hadron production in *pp* collisions

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Abstract The shapes of invariant differential cross section for identified $\pi^{\pm}$, $K^{\pm}$, p and $\overline{p}$ production as a function of transverse momentum measured in pp collisions by the PHENIX detector are analyzed in terms of a recently introduced approach. Simultaneous fits of these data to the sum of exponential and power-law terms show a significant difference in the exponential term contributions. This effect qualitatively explains the observed shape of the experimental K/π and p/π yield ratios measured as a function of transverse momentum of produced hadrons. A picture with two types of mechanisms for hadron production is presented. Universality of the power-law term behavior for $\pi^{\pm}$, $K^{\pm}$, p, and $\overline{p}$ production is shown.

There is a large volume of experimental data available on charged particle and identified hadron production in high energy particle collisions collected starting from the very first experiments performed on the Intersecting Storage Rings (ISR) at CERN throughout contemporary high statistics measurements carried out at RHIC and LHC. In most available publications the measured experimental spectra of produced hadrons become a subject for a phenomenological description or for a comparison with selected models in each experiment separately. However, a comparative simultaneous analysis of the whole available data volume could provide a new powerful lever arm to disclose a common underlying dynamics at work in the hadron production in high energy particle collisions. Such systematic analysis have been described in our recent papers [1–3].

In [1,2] it was demonstrated that the spectra of charged hadrons produced in collisions of baryons require an existence of a sizable fraction of an exponential (Boltzmann-like) statistical ensemble of charged hadrons on the top of a power-law (pQCD inspired spectrum shape) functional term. According to [1,2] the overall generic charged hadron spectrum as a function of the produced hadron transverse momentum (P_T) is given by a sum of the exponential and power-law terms

$$\frac{d\sigma}{P_T\,dP_T} = A_e \exp\left(-E_{Tkin}/T_e\right) + \frac{A}{\left(1+\frac{P_T^2}{T^2\cdot n}\right)^n}, \qquad (1)$$

where $E_{Tkin} = \sqrt{P_T^2 + M^2} - M$ with M equal to the produced hadron mass. A_e, A, T_e, T, n are the free parameters to be determined by a fit to the data.

A typical charged particle spectrum as a function of transverse energy, fit to the function (1) is shown in Fig. 1. In addition the contributions of the exponential and power-law terms to the spectrum are shown in Fig. 1 separately. It is observed that the exponential Boltzmann-like term dominates the charged particle spectrum at low P_T values.

Since the absolute majority of produced charged hadrons are charged π it was concluded that the observed charged hadron spectrum shape is also characteristic for charged π. This conclusion was supported by studies of the identified charged π production spectra [1,2].

Though the data on the identified hadron production are sparse and available in a very limited range of the hadron transverse momentum, it is still interesting to analyze the spectra of K and p using the method proposed in [1,2]. This analysis was performed in [3]. It turned out that, contrary to the pions, the spectra of K and p leave relatively little room for the exponential term contribution and could be described by the power-law term only within the experimental errors.

In the present paper an attempt was made to make a simultaneous comparative analysis of the π, K, and p spectra produced at the same collision energy and under the same experimental conditions. For this comparison the data from the PHENIX detector collected in pp collisions run at $\sqrt{(s)} = 200$ GeV were used [5].

As the first step one could note a peculiar behavior of the ratios of differential cross sections K/π and p/π measured in the experiment. These ratios plotted as a function of P_T

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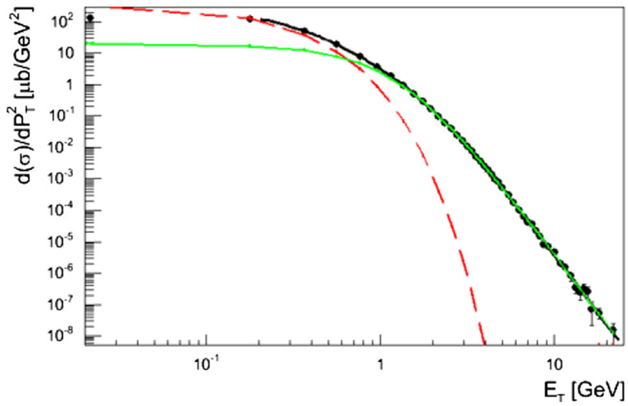

Fig. 1 Charged particle spectrum [4] fit to the function (1): the *red* (*dashed*) curve shows the exponential term and the *green* (*solid*) curve stands for the power-law term

of produced hadrons are shown in Fig. 2a, b. In both cases the ratio reaches a plateau above $P_T \approx 2$ GeV and drops down for low P_T values. Within the framework of the proposed approach based on the formula (1) the observation of this plateau suggests that the parameter n of the power-law term in (1) is likely to be similar for K, p, and π. In the QCD model this is correct at high P_T values since the produced hadron distributions are largely driven by the gluon momentum distribution in the colliding particles.

If so, the identified π, K, and p spectra are fitted simultaneously to the function (1) with the constraint to have the same value for the n parameter in the power-law term for all three spectra together. As the measured charged kaon spectrum is restricted to the low-P_T values it was extended using the available K_s^0 data [6]. The result of this fit procedure is shown in Fig. 3 and Table 1. It is important to note that the values for the parameter T obtained from such a fit procedure turn out to be practically the same for all types of produced hadrons. Such a surprising result was not obvious a priori; as was expected, the Boltzmann-like term for π production dominates, while it gives a much lower contribution in the K spectrum and it is close to zero for the p spectrum. The relative amount of the power-law term contribution to the hadron spectra estimated from the simultaneous fit of the π, K, and p differential cross sections to the function (1) are given in Table 1. It is important to note that the observed significant difference in the exponential contributions to the hadron spectra implies that there is a difference in the hadron production mechanisms rather than an artifact of the fit procedure.

Once arrived at this conclusion, one could explain the peculiar behavior of the K/π and p/π ratios (Fig. 2) as a function of the P_T of produced particles. Figure 4 shows that the ratios of differential cross sections K/π and p/π measured in the experiment and those obtained from the fit are in good agreement with each other. The existence of a large fraction of low-P_T π represented by the Boltzmann exponential statistical distribution suppresses these ratios at low values of P_T. This situation is somewhat similar to that found in [1,2] for π production in pp and heavy ion collisions taken at the same collision energy per nucleon. The ratio of the corresponding differential cross sections as a function of P_T significantly differs from one and is traditionally interpreted as a signature of the nuclear absorption effect. It has been shown in [1,2] that the shape of this ratio is formally defined by a difference of the partial contribution of the exponential term to the sum (1) for minimum bias Au–Au and pp interactions.

Within the framework of the proposed approach the hadron production mechanism could be represented as a sum of two different contributions:

1. release of quasi-thermalized hadrons (mostly π, and much less probable K and p), described by the exponential Boltzmann spectrum, and
2. pQCD-like production of hadrons described by the power-law statistical distribution. The parameters of this distribution do not depend on the type of hadron produced in pp collisions.

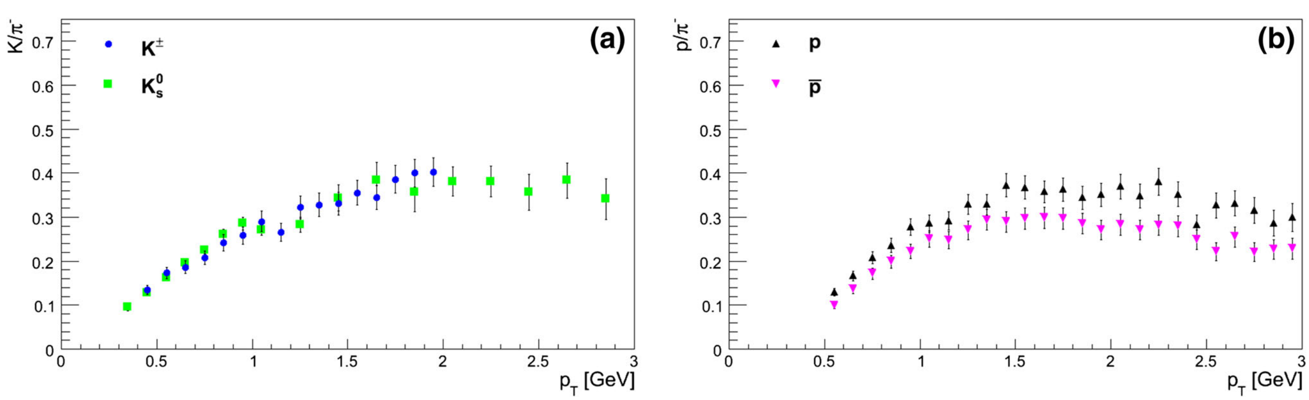

Fig. 2 Ratios of the measured differential cross sections K/π (**a**) and p/π (**b**) measured at PHENIX [5]. For **a** $K^\pm$—*blue circles*, K_s^0—*green squares* [6]. For **b** p/π^-—*black triangles*, $\overline{p}/\pi^-$—*magenta inverted triangles*

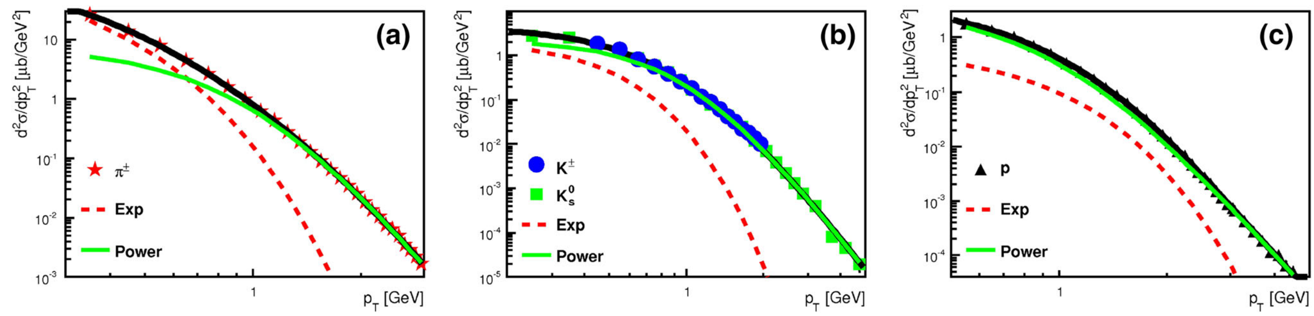

Fig. 3 π, K, and p spectra [5] fit simultaneously: the *red line* shows the exponential term and the *green* one stands for the power law. The exponential term dominates for π spectra only

Fig. 4 K/π and p/π ratios for experimental data [5,6] (*points*) shown over the corresponding ratios obtained from the results of the simultaneous fit (*line*). The *error band* is calculated using the parameter uncertainties obtained from the fit

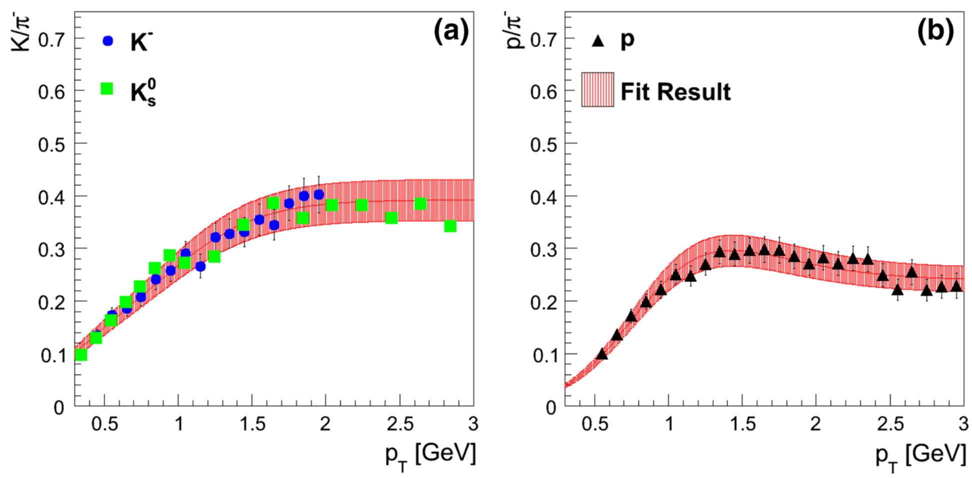

Table 1 Contribution of the power-law (Boltzmann-like) term to the charge particle spectra and T and T_e parameters values obtained from the simultaneous fit (1) of $\pi^{\pm}$, $K^{\pm}$, and p, $\bar{p}$ spectra [5]

Type of hadron	Power-law contribution (%)	T (MeV)	T_e (MeV)
π	25 ± 2	530 ± 17	130 ± 3
K	72 ± 7	544 ± 46	135 ± 19
p	82 ± 8	528 ± 25	245 ± 18

It is worthwhile to note that, as was found in [1,2], a sizable contribution of the thermalized hadrons shows up in the baryonic collisions only. Whilst the interactions with the high energy photons involved as colliding particles do not require an extra exponential statistical distribution to describe the produced hadronic spectra. Moreover, the J/Ψ spectra produced in pp collisions at CDF have also been shown [1,2] to have no exponential term contribution.

In conclusion, it is found that the π production in pp collisions is dominated by a release of quasi-thermalized particles, while the spectra of heavier K, p, and $\overline{p}$ are dominated by pQCD-like production mechanisms, leaving relatively small room for thermalized particle production. For π, K, and p production the parameters of the power-law contribution are practically the same (within the errors) values which depend on global conditions like collision energy [1,2], or type of colliding particles rather than type of produced hadron.

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