

# Anomalous behavior of pion production in high energy particle collisions

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**Abstract** The shape of the invariant differential cross section for charged hadron production as a function of transverse momentum measured in various collider experiments is analyzed. Contrary to the behavior of produced charged kaons, protons, and antiprotons, the pion spectra require an anomalously high contribution of an exponential term to describe the shape.

## 1 Introduction

There exists a large body of experimental data on hadron production in high energy particle collisions. A systematic comparative analysis of this vast volume of available experimental data allows to gain an insight into the hadron production mechanism. In the present paper the production of charged kaons, protons, and antiprotons is analyzed within the framework of the approach developed in the publication [1]. In [1] a new parameterization of the spectrum shape of charged pions inclusively produced in the central rapidity region in high energy particle collisions was proposed. According to [1] the pion spectra are approximated using a modified Tsallis-type function [2, 3]:

$$\frac{d\sigma}{P_T dP_T} = A_e \exp(-E_{T\text{kin}}/T_e) + \frac{A}{(1 + \frac{P_T^2}{T^2 n})^n}, \quad (1)$$

where  $P_T$  is transverse momentum of the produced particle,  $E_{T\text{kin}} = \sqrt{P_T^2 + M^2} - M$  with  $M$  equal to the produced hadron mass.  $A_e$ ,  $A$ ,  $T_e$ ,  $T$ , and “ $n$ ” are the free parameters to be determined by a fit to the data. For the reasons for choice of this particular parameterization (1) see the detailed discussion in [1].

The proposed new parameterization is represented by a sum of an exponential and a power law functional term. The variations of the parameters of this approximation were

studied as function of energy and type of colliding particles, as well as of other experimental conditions. A typical charged particle spectrum as function of transverse energy, fitted with this function (1) is shown in Fig. 1a. This spectrum is dominated by the charged pion contribution and therefore is a good approximation of the charged pion spectrum.

The contributions of the exponential and power law terms of the parameterization (1) to the typical spectrum of charged particles produced in  $pp$  collisions are also shown separately in Fig. 1a. The relative contribution of these terms is characterized by a ratio  $R$  of the power law term alone to the parameterization function each integrated over  $P_T^2$ :

$$R = \frac{AnT}{AnT + A_e(2MT_e + 2T_e^2)(n - 1)} \quad (2)$$

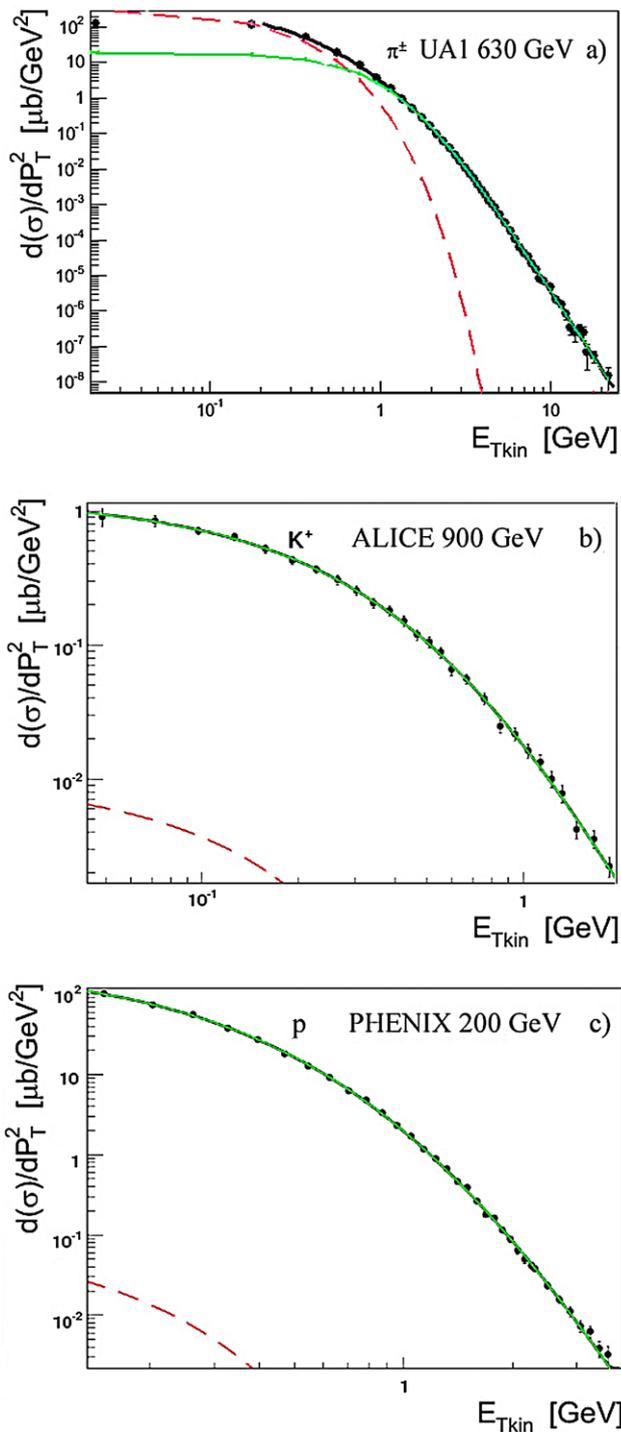
One can notice that for charged particle (mainly charged pions) production the exponential term dominates. Moreover, it was shown [1] that this ratio  $R$  has only weak dependence (if any) on the collision energy in  $pp$  interactions.

The present analysis of produced charged kaon, proton and antiproton spectra is based on the published hadron production data from  $pp$  collisions at RHIC [4] and LHC [5] and AuAu collisions with different centralities at RHIC [6–8]. The data for all these inclusive differential cross section measurements have been taken with a minimum bias trigger conditions and at center of mass energy ( $\sqrt{s}$ ) ranging from 63 to 900 GeV. The results of the analysis are discussed along with those for the pion spectra measured in different experiments [8–14] and reported in [1].

## 2 Anomalies in pion production spectra

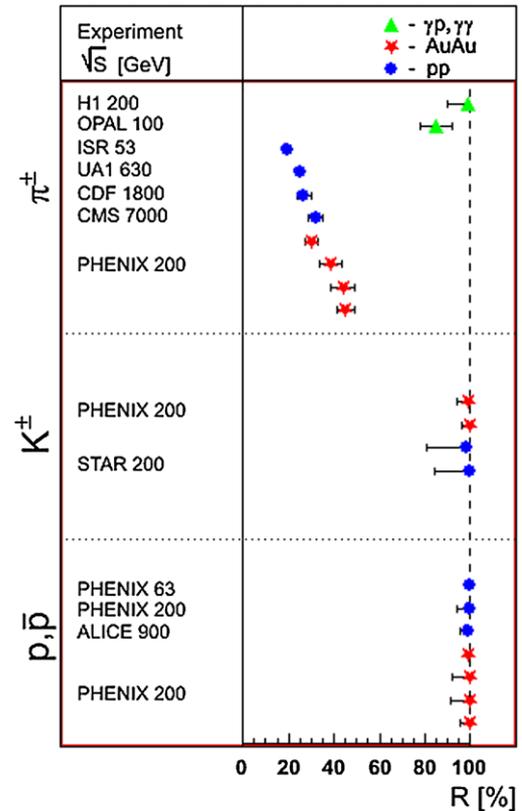
Contrary to the pions, the spectra of charged kaons and protons produced in high energy  $pp$  and AuAu collisions demonstrate a quite different behavior. Fitting these spectra to the parameterization function (1) (Fig. 1b, c) shows no

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**Fig. 1** Pion, kaon and proton spectra fitted with function (1): the dashed line shows the exponential term and the solid one the power law

room for the contribution of the exponential term. The values of the ratio  $R$  obtained for different hadrons produced in various types of high energy interactions are plotted together in Fig. 2. This figure clearly shows that a sizable exponential

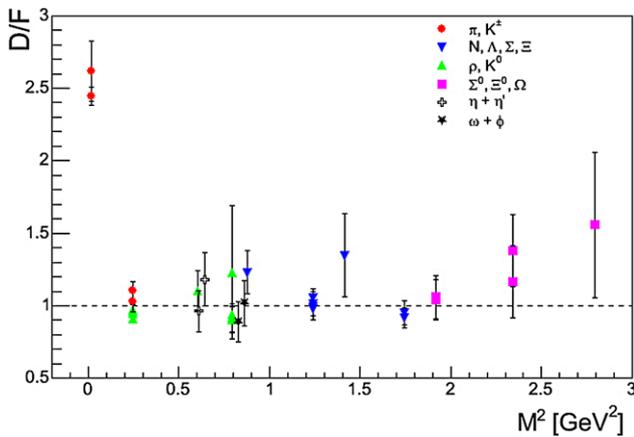


**Fig. 2** Power law term contribution  $R$  for pions, kaons, protons, and antiprotons produced in various collider experiments

term contribution exists only in the pion spectra produced in  $pp$  and heavy ion collisions.

It is known that the vast majority of pions in hadronic collisions is produced via multiple cascade decays of the heavier hadronic resonances. This might result in a transformation of some part of the initial power law spectrum of the produced short-lived heavy hadrons into an exponential decay pion distribution. These arguments could lead to an explanation of the observed anomaly in the pion production behavior. It is also hypothesized that charged kaons and baryons are more frequently produced directly in collisions than pions do. This hypothesis was tested using the PYTHIA MC event generator [15, 16]. Despite the models used in the present event generators for direct hadron production in particle collisions are purely phenomenological, the cascade decay processes are described in these models quite accurately. The events were generated for high energy  $pp$  collisions using PYTHIA 8.1 with a minimum bias set of parameters. The contribution of the exponential term to the final pion spectrum in this model is minimal and does not exceed 15 %.

It is interesting to note that the observed anomalous pion spectra shape dominated by the exponential Boltzman-like statistical distribution is found in baryon–baryon collisions only. As is seen from Fig. 2 the pions produced in  $\gamma\gamma$  and



**Fig. 3** The relative excess of the pion production rate over all other particles observed in hadronic decays of  $Z$ -bosons. The data are taken from [17]

in  $\gamma p$  interactions do not allow any sizable exponential contribution to the spectra.

Finally, it is worth mentioning that pions have been previously found to demonstrate an anomalous behavior as concerns the absolute production rates with respect to all other hadrons. It was shown [17] that all hadrons produced in hadronic decays of  $Z$ -bosons are produced with a probability described by an exponential function of the hadron mass squared. Only pions are produced about three times more frequently than is expected from the extrapolation of this exponential function down to the pion mass value. The ratio of the measured hadron production rates to the exponential function approximating them is shown in Fig. 3. This anomaly has not found any consistent explanation yet. Whether this anomaly of the pion production rate observed in the hadronic  $Z$ -boson decays and the anomaly of the pion production spectrum shape reported here are directly related to each other is unknown. Nevertheless, it is interesting to note that the size of the effect in both cases is of the same order.

### 3 Conclusion

In conclusion the spectra shapes of inclusive charged hadrons produced in high energy collisions were analyzed. It was

found that only pions produced in baryonic interactions require a sizable exponential term in their production spectra. This anomalous behavior did not find a consistent explanation yet.

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