Verification of Z-scaling in pp Collisions at RHIC

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Abstract. New experimental data on inclusive spectra of identified particles produced in pp collisions at the RHIC are used to test z-scaling. Energy and multiplicity independence of the scaling function is established. The RHIC data confirm z-scaling observed at U70, ISR, SpS and Tevatron energies. The obtained results are of interest to search for new physics phenomena of particle production in high transverse momentum and high multiplicity region at RHIC, Tevatron and LHC.

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INTRODUCTION

Study of scaling regularities in high energy collisions is always subject of intense experimental and theoretical investigations [1]-[9]. Some scalings can reflect fundamental symmetries in Nature. Basic principles to study such symmetries at small scales are self-similarity, locality and fractality. New scaling (z-scaling) for description of high-p_T particle production in inclusive reactions was established in [10]. Properties of z-presentation of numerous experimental data confirm self-similarity, locality and fractality of hadron interactions at high energies. The Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) gives wide possibilities to perform experimental measurements and test scaling regularities in a new physics domain.

We present results of analysis of new data on high-p_T particle spectra obtained at the RHIC. The data confirm z-scaling observed at the U70, ISR, SpS and Tevatron.

Z-SCALING

Search for an adequate, physically meaningful but still sufficiently simple form of the self-similarity parameter z plays a crucial role in our approach. For inclusive reactions we define the scaling variable

$$z = \frac{s_{\perp}^{1/2}}{W} \tag{1}$$

as ratio of the minimal transverse kinetic energy $s_{\perp}^{1/2}$ of underlying constituent subprocess and relative number W of such configurations of the colliding system which can contribute to production of inclusive particle with the momentum p. The number of configurations is expressed via the multiplicity density $dN/d\eta|_0$ at pseudorapidity

$\eta = 0$ and kinematical characteristics x_1, x_2 and y of the subprocess as follows

$$W = (dN/d\eta|_0)^c \cdot \Omega(x_1, x_2, y), \tag{2}$$

where

$$\Omega(x_1, x_2, y) = (1 - x_1)^{\delta_1}(1 - x_2)^{\delta_2}(1 - y)^{\varepsilon}. \tag{3}$$

Here x_1 and x_2 are momentum fractions of the colliding objects (hadrons or nuclei). The y is momentum fraction of outgoing constituent from the subprocess carried by the inclusive particle. The δ_1, δ_2 and ε are anomalous fractal dimensions of the incoming and outgoing objects, respectively. The variable z has character of a fractal measure

$$z = z_0 \Omega^{-1}. \tag{4}$$

Its divergent part Ω^{-1} describes resolution at which the collision of the constituents can be singled out of inclusive reaction. With increasing resolution the measure z tends to infinity. The x_1, x_2 and y are determined in a way to minimize the resolution $\Omega^{-1}(x_1, x_2, y)$ taking into account the energy-momentum conservation of the binary subprocess written in the form

$$(x_1 P_1 + x_2 P_2 - p/y)^2 = (x_1 M_1 + x_2 M_2 + m_2/y)^2. \tag{5}$$

Here P_1, P_2 and M_1, M_2 are 4-momenta and masses of the colliding objects. The p is 4-momentum of the inclusive particle. The parameter m_2 is minimal mass introduced to satisfy the internal conservation laws (for baryon number, isospin, strangeness,...).

The relative number W of the configurations which include the constituent subprocess is expressed via entropy of the rest of the colliding system as follows

$$S = \ln W. \tag{6}$$

Using equations (2) and (3), we get

$$S = c \ln [dN/d\eta|_0] + \ln [(1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y)^{\varepsilon}] \tag{7}$$

Exploiting analogy with the thermodynamical formula

$$S = c_V \ln T + R \ln V + const. \tag{8}$$

we can consider multiplicity density $dN/d\eta|_0$ as a quantity characterizing "temperature" of the colliding system and the parameter c as "heat capacity" of the medium. The second term in (7) is related to volume of the configurations in space of the momentum fractions which can contribute to production of the inclusive particle with the momentum p. Note that minimal resolution Ω^{-1} of the fractal measure z with respect to constituent subprocesses corresponds to maximal entropy S of the rest of the system.

In accordance with self-similarity principle we search for the scaling function

$$\psi(z) = \frac{1}{N\sigma_{in}} \frac{d\sigma}{dz} \tag{9}$$

depending on the single variable z. Here σ_{in} is the inelastic cross section of the inclusive reaction and N is particle multiplicity. The function $\psi(z)$ is expressed in terms of the

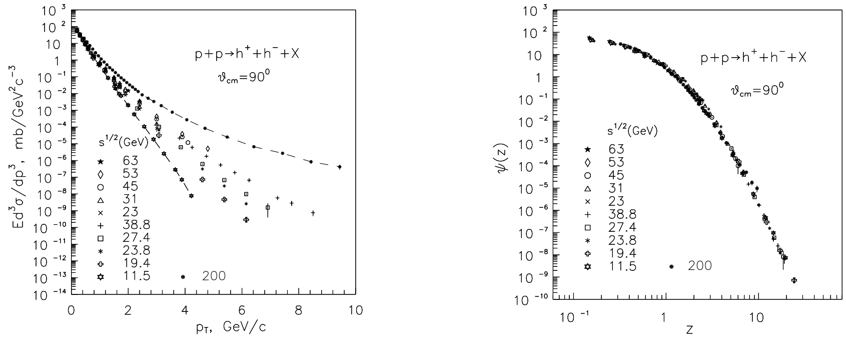

FIGURE 1. (a) Inclusive cross sections of charged hadrons produced in pp collisions at $\sqrt{s} = 11.5-63$ and 200 GeV and $\theta_{cm} \simeq 90^0$ as a functions of the transverse momentum p_T. The experimental data are taken from [12]-[15] and [11]. (b) The corresponding scaling function.

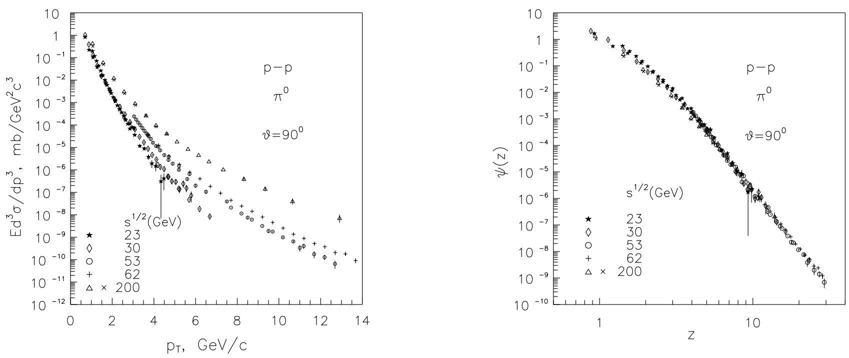

FIGURE 2. The dependence of the inclusive cross section of π^0-meson production on the transverse momentum p_T in pp collisions at $\sqrt{s} = 30, 53, 62$ and 200 GeV and the angle θ_{cm} of 90^0. The experimental data are taken from [17, 18, 19, 20, 21] and [16]. (b) The corresponding scaling function.

experimentally measured inclusive invariant cross section $Ed^3\sigma/dp^3$ and multiplicity density $dN/d\eta$ as follows

$$\psi(z) = -\frac{\pi s}{(dN/d\eta)\sigma_{in}} J^{-1} E \frac{d^3\sigma}{dp^3}. \quad (10)$$

Here s is the center-of-mass collision energy squared. The Jacobian J of transformation to the variables (z, η) depends on the momentum p of the inclusive particle. The $\psi(z)$ has meaning of probability density to produce inclusive particle with the corresponding value of the variable z.

Z-SCALING AT RHIC

We analyze experimental data on minimum bias pp spectra of different hadrons $(h^{\pm}, \pi^0, \pi^-, K_S^0)$ measured at the RHIC. Comparison of the RHIC data with data obtained at the U70, ISR, SpS and Tevatron is used to test z-scaling.

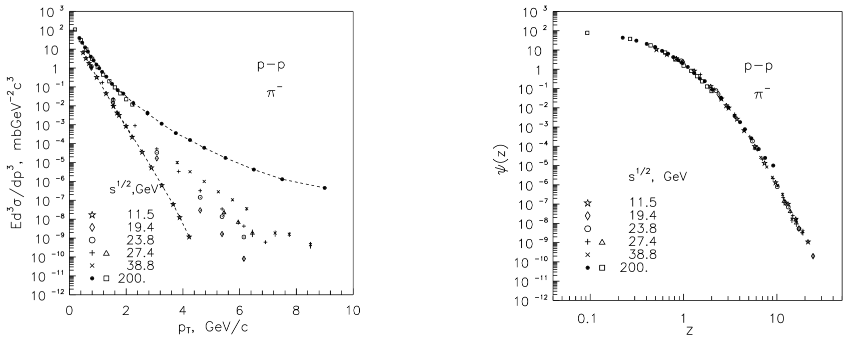

FIGURE 3. (a) Inclusive cross sections of charged hadrons produced in pp collisions at $\sqrt{s} = 11.5 - 38.8$ and 200 GeV and $\theta_{cm} \simeq 90^0$ as a functions of the transverse momentum p_T. The experimental data are taken from [12, 13, 14] and [11]. (b) The corresponding scaling function.

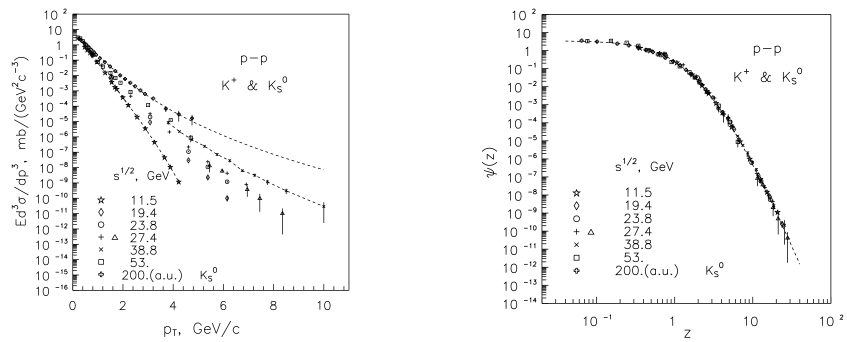

FIGURE 4. (a) The inclusive cross sections of K^+- and K_S^0-mesons produced in pp collisions in the central rapidity range as a function of the transverse momentum at $\sqrt{s} = 11.5 - 53$ GeV and 200 GeV. Experimental data are taken from [12, 13, 14, 15] and [23]. (b) The corresponding scaling function.

Energy independence of $\psi(z)$

The high-p_T spectra of charged hadrons produced in pp collisions at the energy $\sqrt{s} = 200$ GeV within $|\eta| < 0.5$ were measured by the STAR Collaboration [11]. The inclusive cross sections obtained at the U70 [12], Tevatron [13, 14], ISR [15] and RHIC are presented in Fig.1a. The spectra have strong energy dependence at high p_T. Fig.1b shows z-presentation of the same data. The scaling function demonstrates energy independence and power law, $\psi(z) \sim z^{-\beta}$, for $z > 4$. Results of analysis of the STAR data at $\sqrt{s} = 200$ GeV confirm z-scaling observed at lower energies.

The PHENIX Collaboration measured the inclusive spectrum of π^0-mesons produced in pp collisions at $\sqrt{s} = 200$ GeV for $|\eta| < 0.35$ and p_T up to 13 GeV/c [16]. The p_T- and z-presentations of data for π^0-meson spectra obtained at ISR [17, 18, 19, 20, 21] and RHIC are shown in Figs.2a and 2b, respectively. Energy dependence of the inclusive cross sections increases with p_T. The PHENIX data at $\sqrt{s} = 200$ GeV confirm energy independence and power law of the scaling function for π^0-mesons.

The STAR Collaboration measured the inclusive spectrum of π^--mesons produced in pp collisions at $\sqrt{s} = 200$ GeV for $|\eta| < 0.5$ up to $p_T = 9$ GeV/c [22]. The data

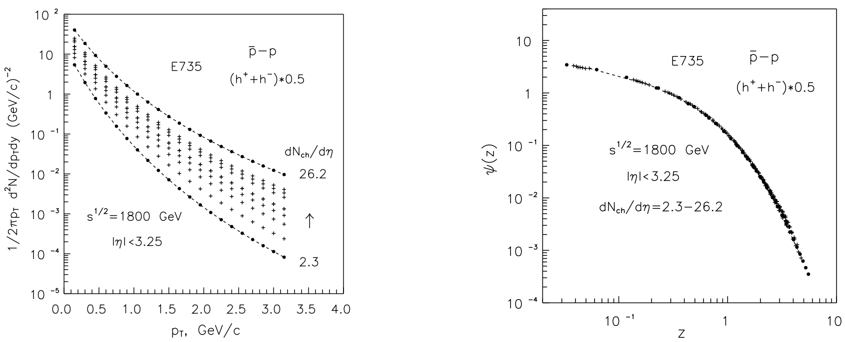

FIGURE 5. a) Multiplicity dependence of charged hadron spectra in $\bar{p}p$ collisions at $\sqrt{s} = 1800$ GeV. Experimental data are obtained by the E735 Collaboration [24]. (b) The corresponding scaling function.

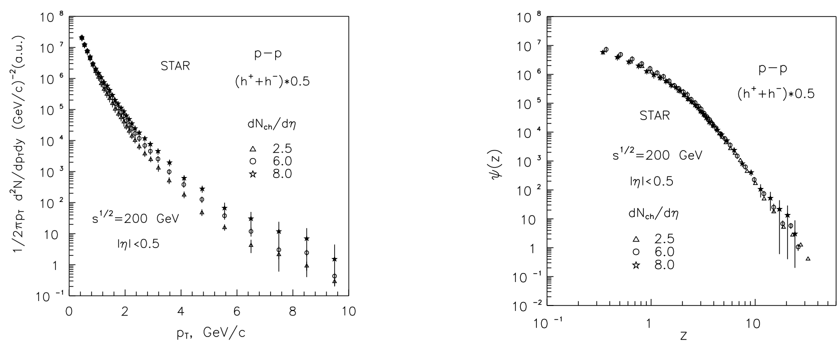

FIGURE 6. (a) Multiplicity dependence of charged hadron spectra in pp collisions at $\sqrt{s} = 200$ GeV. Experimental data are obtained by the STAR Collaboration [25]. (b) The corresponding scaling function.

obtained at the STAR, U70 [12] and Tevatron [13, 14] are shown in Fig.3a. The energy dependence of the p_T-spectra is in contrast with the scaling depicted in Fig.3b.

The p_T-spectra and the scaling function $\psi(z)$ for data on K^+ and K_S^0-mesons obtained at the U70 [12], Tevatron [13, 14], ISR [15] and RHIC [23] are presented in Figs. 4a and 4b, respectively. The shape of the scaling function for K_S^0 is found to be in good agreement with $\psi(z)$ for K^+-mesons. Using parametrization of $\psi(z)$, the dependence of inclusive spectrum of K_S^0-mesons on transverse momentum at $\sqrt{s} = 200$ GeV is plotted by the dashed line in Fig.4a.

Multiplicity independence of $\psi(z)$

We analyze data on charge hadron production in pp and $p\bar{p}$ collisions at different multiplicities and energies. The E735 Collaboration measured the multiplicity dependence of charged hadron spectra in $p\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV for $dN_{ch}/d\eta = 2.3-26.2$, $|\eta| < 3.25$ and $p_T = 0.15-3$ GeV/c [24]. Strong dependence of the spectra on multiplicity is shown in Fig.5a. The z-presentation of the data is plotted in Fig.5b. Independence of the scaling function $\psi(z)$ on multiplicity was found for same value of $c = 0.25$.

The STAR Collaboration measured multiplicity dependence of inclusive spectra of charged hadrons produced in pp collisions at $\sqrt{s} = 200$ GeV for $|\eta| < 0.5$ [25]. Fig.6a demonstrates strong dependence of the spectra on multiplicity. The STAR data confirm multiplicity independence of the scaling function $\psi(z)$ established in $p\bar{p}$ collisions at higher energies. The value of the heat capacity $c = 0.25$ is found to be the same as for UA1[26], E735 and CDF [27] data.

Additional confirmation of the z-scaling was obtained at RHIC. The scaling manifests self-similarity and fractality in hadron interactions at high energies.

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