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z-SCALING AND INCLUSIVE PARTICLE
PRODUCTION IN pp COLLISIONS AT HIGH-p_T

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z-скейлинг и инклюзивное рождение частиц
в *pp*-взаимодействиях при больших p_T

Свойства рождения частиц в *pp*-взаимодействиях являются основой для анализа *pA*- и *AA*-взаимодействий и проверки теории. С использованием *z*-скейлинга проанализированы данные по инклюзивным сечениям рождения частиц в *pp*-взаимодействиях, полученные на ускорителях U70, ISR, тэватрон и RHIC. Этот скейлинг отражает симметрию структуры сталкивающихся адронов, их взаимодействий и образования частиц. Показано, что новые данные по спектрам заряженных адронов и π^0-мезонов в *pp*-взаимодействиях, полученные на RHIC, подтверждают *z*-скейлинг.

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z-Scaling and Inclusive Particle Production
in *pp* Collisions at High-p_T

The properties of particle production in *pp* collisions are basis for analysis of *pA* and *AA* interactions and verification of theory. We analyzed inclusive particle spectra using *z*-scaling established in proton–proton and proton–antiproton collisions at the U70, ISR, Tevatron and RHIC. This scaling reflects symmetry of hadron structure, interaction and particle formation. It is shown that new data on charged hadron and π^0-meson spectra obtained in *pp* collisions at the Relativistic Heavy Ion Collider confirm the *z*-scaling.

INTRODUCTION

With advent of Relativistic Heavy Ion Collider at BNL (USA) new era of tremendous accumulation of data in high energy domain began. Excellent possibilities to search for new physics phenomena and verification of theory are opened.

Particle production with high transverse momenta is of specific interest. It is traditionally connected with local character of hadron interactions which are believed to have adequate description in the theory of QCD. Locality of the interaction is expressed in terms of the hadron constituents. Scaling features of high-p_T hadron spectra reflects self-similarity of the constituent interactions. Therefore, search and verification of scaling regularities at the RHIC energy domain are important. This would stimulate more profound investigations of particle production at the RHIC and later at the LHC.

Up to date, the investigation of hadron properties in the high energy collisions has revealed widely known scaling laws. From the most popular and famous, let us mention the Feynman scaling [1] observed in inclusive particle production, the Bjorken scaling [2] in deep inelastic scattering (DIS), y-scaling [3] valid in DIS on nuclei, limiting fragmentation established for nuclei [4], scaling behaviour of the cumulative particle production [5–7], the Koba–Nielsen–Olesen (KNO) scaling [8], and others. Another expression of self-similarity in hadronic interactions is described by quark counting rules [9]. All these scalings have restricted range of validity. The established violations indicate manifestation of dynamical mechanisms of constituent interactions in the region beyond their applicability. In particular, this led to discovery of QCD evolution in DIS.

New method to study the properties of particle structure, constituent interactions and particle formation is z-scaling [10]. The scaling was observed in proton–(anti)proton high energy collisions at the U70, ISR, S$\bar{p}$pS and Tevatron. In this paper we verify z-scaling using new data on charged hadron and π^0-meson spectra obtained in pp collisions at the Relativistic Heavy Ion Collider.

1. BASIC PRINCIPLES OF z-SCALING

The idea of z-scaling is based on the principles of locality, self-similarity and fractality of hadronic interactions. The principles reflect structure of colliding objects, features of the underlying constituent interactions and mechanism of

particle production. Their most pronounced manifestation is expected in the inclusive production of particles with large transverse momenta.

1.1. Locality Principle. Locality of hadron interactions is considered at constituent level. We assume that gross features of the inclusive particle distributions for the reaction

$$M_1 + M_2 \rightarrow m_1 + X \qquad (1)$$

can be described in terms of the constituent sub-process

$$(x_1 M_1) + (x_2 M_2) \rightarrow m_1 + (x_1 M_1 + x_2 M_2 + m_2) \qquad (2)$$

satisfying to the condition

$$(x_1 P_1 + x_2 P_2 - p)^2 = (x_1 M_1 + x_2 M_2 + m_2)^2. \qquad (3)$$

The x_1 and x_2 are fractions of the incoming four momenta P_1 and P_2 of the colliding objects with the masses M_1 and M_2. The p is four-momentum of the inclusive particle with the mass m_1. The parameter m_2 is introduced to satisfy the internal conservation laws (for isospin, baryon number, strangeness, and so on). Equation (3) describes the energy-momentum conservation for the elementary constituent sub-process.

1.2. Self-Similarity Principle. Self-similarity is scale-invariant property connected with dropping of certain dimensional quantities out of physical picture of the interaction. Self-similarity parameters are constructed as specific combinations of these quantities. The scaling function $\psi(z)$ depends in a self-similar manner on a single variable z. The variable z is dimensionless combination of quantities which characterize particle production in high energy inclusive reactions. It depends on momenta and masses of colliding and inclusive particles, multiplicity density and fractal dimensions of the incident objects. The scaling function is expressed via the invariant differential cross section $E d^3\sigma/dp^3$ as follows:

$$\psi(z) = -\frac{\pi s}{(dN/d\eta)\sigma_{\text{in}}} J^{-1} E \frac{d^3\sigma}{dp^3}. \qquad (4)$$

Here s is the collision center-of-mass energy squared, σ_{in} is the inelastic cross section, J is the corresponding Jacobian, and $dN/d\eta$ is the particle multiplicity density. The function $\psi(z)$ is normalized as

$$\int_0^\infty \psi(z)dz = 1. \qquad (5)$$

The relation allows us to give the physical meaning of the scaling function $\psi(z)$ as probability density to form a particle with the corresponding value of the variable z.

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1.3. Fractality Principle. Principle of fractality states that variables used in the description of the process diverge in terms of the resolution [11, 12]. This property is characteristic for the scaling variable

$$z = z_0 \Omega^{-1}, \tag{6}$$

where

$$\Omega(x_1, x_2) = (1 - x_1)^{\delta_1}(1 - x_2)^{\delta_2}. \tag{7}$$

The variable z has character of a fractal measure. For a given production process (1), its finite part z_0 is the ratio of the transverse energy released in the binary collision of constituents (2) and the average multiplicity density $dN/d\eta|_{\eta=0}$. The divergent part Ω^{-1} describes the resolution at which the collision of the constituents can be singled out of this process. The $\Omega(x_1, x_2)$ represents relative number of all initial configurations containing the constituents which carry fractions x_1 and x_2 of the incoming momenta. The δ_1 and δ_2 are the anomalous fractal dimensions of the colliding objects (hadrons or nuclei). The momentum fractions x_1 and x_2 are determined in a way to minimize the resolution $\Omega^{-1}(x_1, x_2)$ of the fractal measure z with respect to all possible sub-processes (2) subjected to the condition (3). The variable z was interpreted [10] as a particle formation length.

2. INGREDIENTS AND PROPERTIES OF z-SCALING

One of the ingredients in the definition of the variable z is the particle multiplicity density $dN/d\eta|_{\eta=0}$ in central region of collision. We have used the experimental data for this quantity in our analysis. Another ingredients are the anomalous fractal dimensions δ of the colliding objects. It was found that, for the nucleon–nucleon collisions, δ does not depend on the colliding energy $\sqrt{s}$ and other kinematical variables (p_T, θ).

Using experimental data on high-p_T particle production in pp and $\bar{p}p$ collisions at the U70, ISR, S$\bar{p}$pS and Tevatron, we have established energy and angular independence of the scaling function $\psi(z)$ for the same value of δ. In the region of large z, the scaling function reveals power behavior, $\psi(z) \sim z^{-\beta}$. The asymptotic behavior of $\psi(z)$ reflects self-similarity and fractality of hadron interactions at small scales.

3. FIRST VERIFICATION OF z-SCALING AT THE RHIC

In the present analysis of new RHIC data we verify the energy independence of the scaling function $\psi(z)$ in pp collisions at $\sqrt{s} = 200$ GeV. We have used the data on inclusive cross sections of charged hadron [13] and π^0-meson production

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[18] obtained by the STAR and PHENIX collaborations, respectively. Inclusive spectra were measured in the central region of collision and cover the transverse momentum range up to $p_T = 13$ GeV/c.

The invariant differential cross section for charged hadrons produced in pp collisions as a function of the transverse momentum is shown in Fig. 1, a. Different symbols correspond to data at different colliding energies $\sqrt{s} = 11.5 - 200$ GeV. The experimental data demonstrate strong energy dependence of the cross sections which increases with p_T. The energy dependence of the cross sections is contrasted with the energy independence of z-presentation of the data shown in Fig. 1, b. Data measured by the STAR collaboration cover the range of z from 0.3 up to 10. This includes asymptotic power regime which starts approximately at $z > 4$. The result shows that the STAR data confirm the energy independence of the z-scaling for charged particles produced in pp collisions.
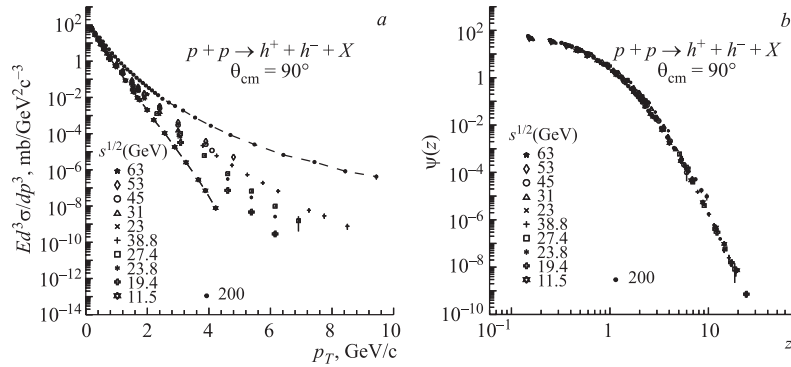

Fig. 1. a) Inclusive cross sections of charged hadrons produced in pp collisions at $\sqrt{s} = 11.5 - 63$ and 200 GeV for $\theta_{cm} \simeq 90^0$ as functions of the transverse momentum. Experimental data are taken from [14–17] and [13]. b) z-presentation of the same data

The invariant differential cross section for neutral pions produced in pp collisions as a function of the transverse momentum is shown in Fig. 2, a. The plotted data from the ISR were obtained at the energies $\sqrt{s} = 23 - 62$ GeV. The PHENIX data from the RHIC were measured at $\sqrt{s} = 200$ GeV. Both data sets correspond to the central rapidity region. The differential cross sections strongly depend on the collision energy in the similar way as for the charged particles. The corresponding z-presentation of data is shown in Fig. 2, b. The data measured by the PHENIX collaboration cover the range of z from 1 up to 13. One can see that these data are in good agreement with z-scaling for π^0-meson production
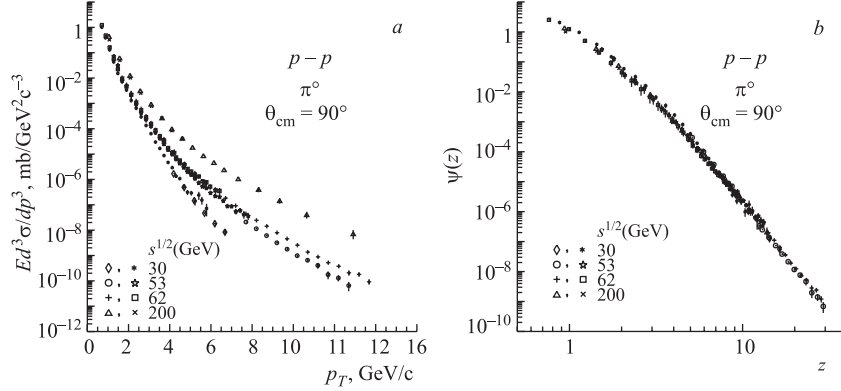
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Fig. 2. *a*) The dependence of the inclusive cross section of π^0-meson production on the transverse momentum in *pp* collisions at $\sqrt{s} = 30, 53, 62$ and 200 GeV for the angle $\theta_{cm} \simeq 90^0$. The experimental data are taken from [19–23] and [18]. *b*) The corresponding scaling function $\psi(z)$

obtained at the ISR energies. The power asymptotic regime is clear observed in this case as well. The result shows that the PHENIX data confirm the energy independence of the z-scaling for neutral mesons produced in *pp* collisions.

CONCLUSIONS

z-scaling is specific feature of inclusive high-p_T particle production established in proton–proton and proton–antiproton collisions. The scaling was observed in numerous data obtained at the U70, ISR, S$\bar{p}$pS and Tevatron.

In this paper we exploit new data on inclusive production of charged hadrons and π^0 mesons measured by the STAR and PHENIX collaborations to verify the z-scaling. We have shown that these data confirm the energy independence of the scaling function $\psi(z)$. The STAR and PHENIX data allow one to test asymptotic regime of the scaling function for $z > 4$. They confirm that asymptotic regime of $\psi(z)$ at high-z is governed by a power law, $\psi(z) \sim z^{-\beta}$. The slope parameter β is independent of center-of-mass energy $\sqrt{s}$ and transverse momentum p_T over a wide kinematical range. This is consequence of constant value of δ characterizing nucleon fractal structure at different scales. In conclusion, the RHIC data confirm z-scaling in the range of $\sqrt{s} = 11.5 - 200$ GeV and $p_T = 0.5 - 13$ GeV/c. We consider that established properties of data z-presentation could give additional constraints on phenomenological quantities (parton distribution and fragmentation functions, etc.) in calculations of hard processes using QCD.

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The obtained results demonstrate that self-similarity and fractality are features of hadron structure, interactions and particle formation which reflect specific symmetries in Nature. z-scaling can be used as a tool to search for new phenomena using hard probed such as high-p_T hadrons, direct photons, heavy quarkonia and jets at the RHIC, Tevatron and LHC.

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