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z SCALING AT RHIC

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The concept of z scaling reflecting the general regularities of high-p_T particle production is reviewed. Properties of data z presentation are discussed. New data on high-p_T particle spectra obtained at the RHIC are analyzed in the framework of z presentation. It was shown that these experimental data confirm z scaling. Predictions of strange particle spectra are considered to be useful for understanding of strangeness origin in mesons and baryons and search for new physics phenomena at the RHIC.

Представлен обзор концепции z-скейлинга, отражающего общие особенности рождения частиц с большими поперечными импульсами. Обсуждаются свойства z-представления экспериментальных данных. Представлены результаты анализа новых данных, полученных на RHIC. Получены новые экспериментальные подтверждения z-скейлинга. Приведены предсказания сечений рождения странных мезонов и барионов с большими поперечными импульсами в p–p-взаимодействиях, представляющие интерес для понимания природы странности и поиска новой физики на RHIC.

INTRODUCTION

Search for scaling regularities in high-energy particle collisions is always to be a subject of intense investigations [1–10]. Commissioning of the Relativistic Heavy Ion Collider (RHIC) at the Brookhaven National Laboratory (BNL) gives new possibilities of performing experimental investigations in a new physics domain. The RHIC is a next generation of proton–proton colliders after ISR designed to accelerate protons at center-of-mass energy range $\sqrt{s} = 50{-}500$ GeV aimed to clarify origin of proton's spin and discover a new state of nuclear matter, Quark Gluon Plasma.

High energy of colliding particles and high transverse momentum of produced particles are most suitable for precise QCD test of production processes with hard probes like high-p_T hadrons, direct photons and jets. Therefore, search for general regularities of high-p_T single inclusive particle spectra of hadron–hadron and hadron–nucleus collisions are of interest to establish complementary restrictions for theory.

The universal phenomenological description (z scaling) of high-p_T particle-production cross sections in inclusive reactions is developed in [11, 12]. The approach is based on properties of particle structure, their constituent interaction and particle formation such as locality, self-similarity and fractality. The scaling function ψ and scaling variable z are expressed via experimental quantities such as the inclusive cross section $Ed^3\sigma/dp^3$ and the multiplicity density of charged particles $dN/d\eta$. Data z-presentation is found to reveal symmetry properties (energy and angular independence, A- and F-dependence, power law). The properties of ψ at high z are assumed to be relevant to the structure of space-time at

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small scales [13–15]. The function $\psi(z)$ is interpreted as the probability density to produce a particle with a formation length z.

In the report we present the results of analysis of new data on high-p_T particle spectra obtained at the RHIC. The obtained results are compared with other ones based on the data obtained at lower collision energy $\sqrt{s}$. The results are considered as a new confirmation of z scaling at the RHIC.

1. z SCALING

The idea of z scaling is based on the assumptions [6] that gross feature of inclusive particle distribution of the process (1) at high energies can be described in terms of the corresponding kinematic characteristics

$$M_1 + M_2 \to m_1 + X \tag{1}$$

of the constituent subprocess written in the symbolic form

$$(x_1 M_1) + (x_2 M_2) \to m_1 + (x_1 M_1 + x_2 M_2 + m_2), \tag{2}$$

satisfying the condition

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

The equation is the expression of locality of hadron interaction at constituent level. The x_1 and x_2 are fractions of the incoming momenta P_1 and P_2 of the colliding objects with masses M_1 and M_2. They determine the minimum energy, which is necessary for production of the secondary particle with mass m_1 and four-momentum p. The parameter m_2 is introduced to satisfy the internal conservation laws (for baryon number, isospin, strangeness, and so on).

Equation (3) reflects minimum recoil mass hypothesis in the elementary subprocess. To connect kinematic and structural characteristics of the interaction, the quantity Ω is introduced. It is chosen in the form

$$\Omega(x_1, x_2) = m(1 - x_1)^{\delta_1}(1 - x_2)^{\delta_2}, \tag{4}$$

where m is a mass constant and δ_1 and δ_2 are factors relating to the anomalous fractal dimensions of the colliding objects. The fractions x_1 and x_2 are determined to maximize the value of $\Omega(x_1, x_2)$, simultaneously fulfilling the condition (3):

$$d\Omega(x_1, x_2)/dx_1|_{x_2 = x_2(x_1)} = 0. \tag{5}$$

The fractions x_1 and x_2 are equal to unity along the phase space limit and cover the full phase space accessible at any energy.

Self-similarity is a scale-invariant property connected with dropping of certain dimensional quantities out of physical picture of the interactions. It means that dimensionless quantities for the description of physical processes are used. The scaling function $\psi(z)$ depends in a self-similar manner on the single dimensionless variable z. It is expressed via the invariant cross section $Ed^3\sigma/dp^3$ as follows:

$$\psi(z) = -\frac{\pi s}{(dN/d\eta)\sigma_{\text{in}}} J^{-1} E \frac{d^3\sigma}{dp^3}. \tag{6}$$

Here, s is the center-of-mass collision energy squared; σ_{in} is the inelastic cross section; J is the corresponding Jacobian. The factor J is the known function of the kinematic variables, the momenta and masses of the colliding and produced particles.

The function $\psi(z)$ is normalized as follows:

$$\int_0^\infty \psi(z)dz = 1. \tag{7}$$

The relation allows us to interpret the function $\psi(z)$ as a probability density to produce a particle with the corresponding value of the variable z.

The principle of fractality states that the variables used in the description of the process diverge in terms of the resolution. This property is characteristic for the scaling variable

$$z = z_0 \Omega^{-1}, \tag{8}$$

where

$$z_0 = \sqrt{\hat{s}_\perp}/(dN/d\eta). \tag{9}$$

The variable z is a fractal measure in character. For the 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 subprocesses (2) subjected to the condition (3). The variable z was interpreted as a particle formation length.

The scaling function of high-p_T particle production, as shown below, is described by the power law, $\psi(z) \sim z^{-\beta}$. Both quantities, ψ and z, are scale-dependent. Therefore we consider the high-energy hadron–hadron interactions as interactions of fractals. In the asymptotic region the internal structure of particles, interactions of their constituents and mechanism of real particle formation manifest self-similarity over a wide scale range.

2. z SCALING BEFORE RHIC

It was established [11, 12] that data z presentation reveals the properties such as the energy and angular scaling, the power law, A- and F-dependences of the scaling function $\psi(z)$. Numerous experimental data on high-p_T particle spectra obtained at U70, ISR, SpS and Tevatron used in the analysis [11, 12] are compatible with each other in z presentation and give us a good reference frame for future analysis of RHIC data.

Let us remind some properties of p_T presentation. The first one is the strong dependence of the cross section on energy $\sqrt{s}$. The second feature is a tendency that the difference between particle yields increases with the transverse momentum p_T and the energy $\sqrt{s}$. The third one is a nonexponential behavior of the spectra at $p_T > 4$ GeV/c. The energy independence of data z presentation means that the scaling function $\psi(z)$ has the same shape for different $\sqrt{s}$ over a wide p_T range.

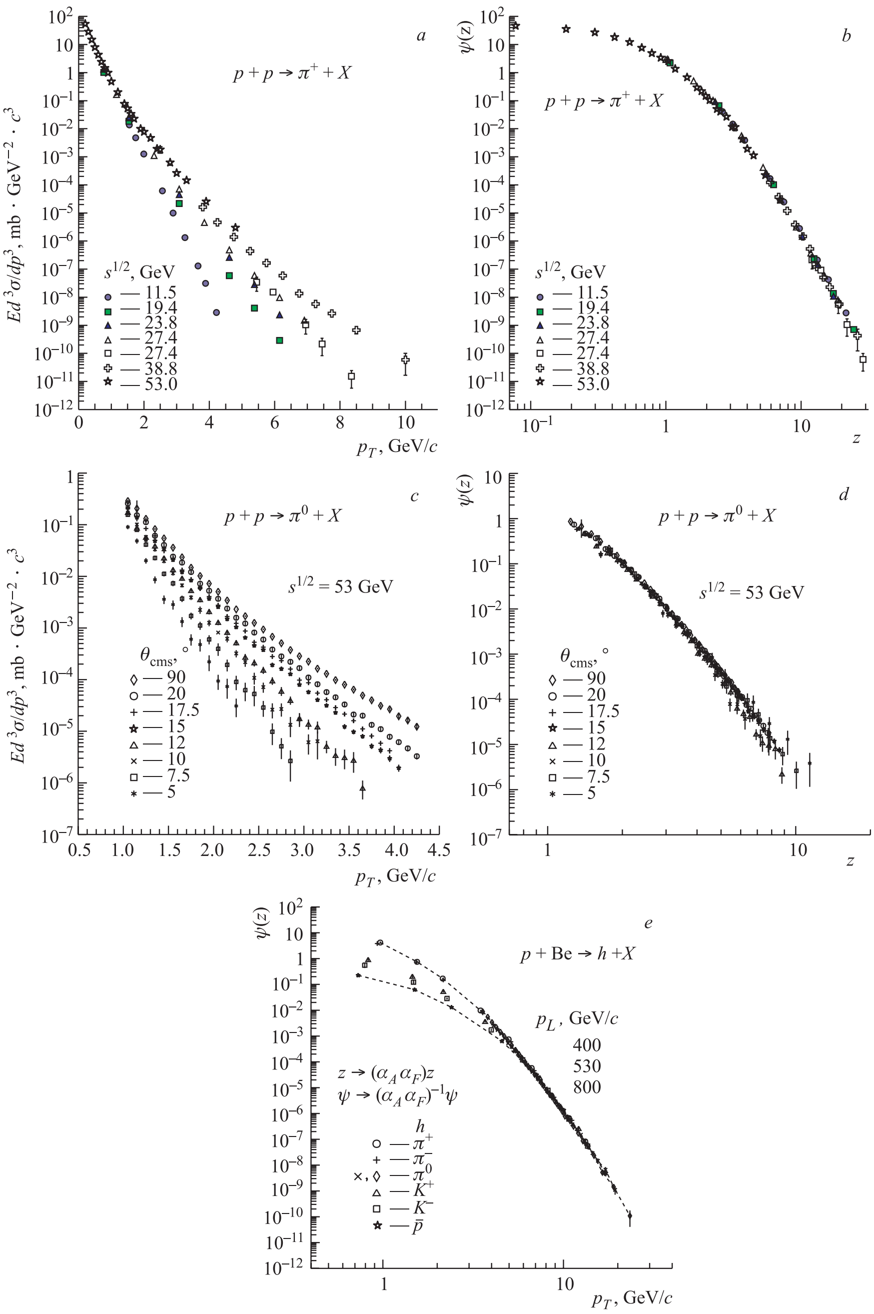

Fig. 1. The p_T (*a, c*) and z presentations of experimental data on inclusive cross section of particles produced in p–p collisions. The energy (*b*), angular (*d*) independence and F-dependence (*e*) of the function $\psi(z)$. Experimental data are taken from [17–21]

Figure 1, *a* shows the dependence of the cross section of π^+-meson production in p–p interactions on transverse momentum p_T at $\sqrt{s} = 11.5-53$ GeV in a central rapidity range. The data cover a wide transverse momentum range, $p_T = 0.2-10$ GeV/c.

Figure 1, *b* demonstrates z presentation of the same data sets. One can see that the scaling function $\psi(z)$ demonstrates independence from collision energy $\sqrt{s}$ over a wide energy and transverse momentum range at $\theta_{\rm cms} \simeq 90°$.

As seen from Fig. 1, *b* the scaling function reveals a linear z-dependence on the log-log scale at high z. It corresponds to the power law, $\psi(z) \sim z^{-\beta}$. The value of the slope parameter β is independent of the energy $\sqrt{s}$ over a wide range of high transverse momentum. This is considered as an indication that the mechanism of particle formation reveals self-similar and fractal properties.

The p_T presentation demonstrates a strong angular dependence as well. Figure 1, *c* shows the dependence of the cross section of π^0-meson production in p–p collisions on transverse momentum at $\sqrt{s} = 53$ GeV and the center-of-mass angle $\theta_{\rm cms} = (5-90)°$.

The angular independence of data z presentation means that the scaling function $\psi(z)$ has the same shape for different values of an angle $\theta_{\rm cms}$ of produced particle over a wide p_T and $\sqrt{s}$ range. Figure 1, *b* demonstrates z presentation of the same data sets and experimental confirmation of the angular scaling of $\psi(z)$.

The z presentation of data gives an indication of F-independence of the scaling function [16]. The property means that the scaling function $\psi(z)$ for different species of produced hadrons $(\pi^{\pm,0}, K^{\pm}, \bar{p})$ at high z is described by the power law, $\psi(z) \sim z^{-\beta}$, and the slope parameter β is independent of flavor content of produced hadrons. Figure 1, *e* illustrates the F-independence of $\psi(z)$ at high z for hadron production in p–Be collisions. For comparison of different data sets the transformation $z \to (\alpha_A \alpha_F) z$, $\psi \to (\alpha_A \alpha_F)^{-1} \psi$ of the scaling variable z and the scaling function ψ have been used. The parameters α_A and α_F are independent of energy $\sqrt{s}$ and momentum p_T. The property is considered as universality of the particle formation mechanism over a wide range of small scales. We assume that it relates to a structure of space-time itself.

3. z SCALING AT RHIC

Recently the STAR and PHENIX collaborations have presented new data on inclusive high-p_T particle spectra measured at the RHIC in p–p collisions at $\sqrt{s} = 200$ GeV. In the section the data are compared with other ones and used as an experimental test of z scaling.

3.1. Charged Hadrons. The high-p_T spectra of charged hadrons produced in p–p and Au–Au collisions at energy $\sqrt{s} = 200$ GeV within $|\eta| < 0.5$ were measured by the STAR collaboration [17]. The results are presented in Fig. 2, *a*. The p_T distribution of charged hadrons produced in Au–Au collisions were measured at different centralities. The shape of the cross section drastically changes as centrality increases. The spectrum for p–p collisions is similar to the spectrum observed in the peripheral Au–Au collisions. The STAR data [17] for p–p collisions correspond to nonsingle diffraction cross section. Other experimental data correspond to inelastic cross section. Therefore, in the analysis the multiplicity particle density $dN/d\eta$ for nonsingle diffraction interaction for STAR data was used. The RHIC data and other ones for p–p collisions obtained at the U70 [18], Tevatron [19, 20] and ISR [21] are shown in Fig. 2, *b*. The charged hadron spectra were measured over a wide kinematic range:

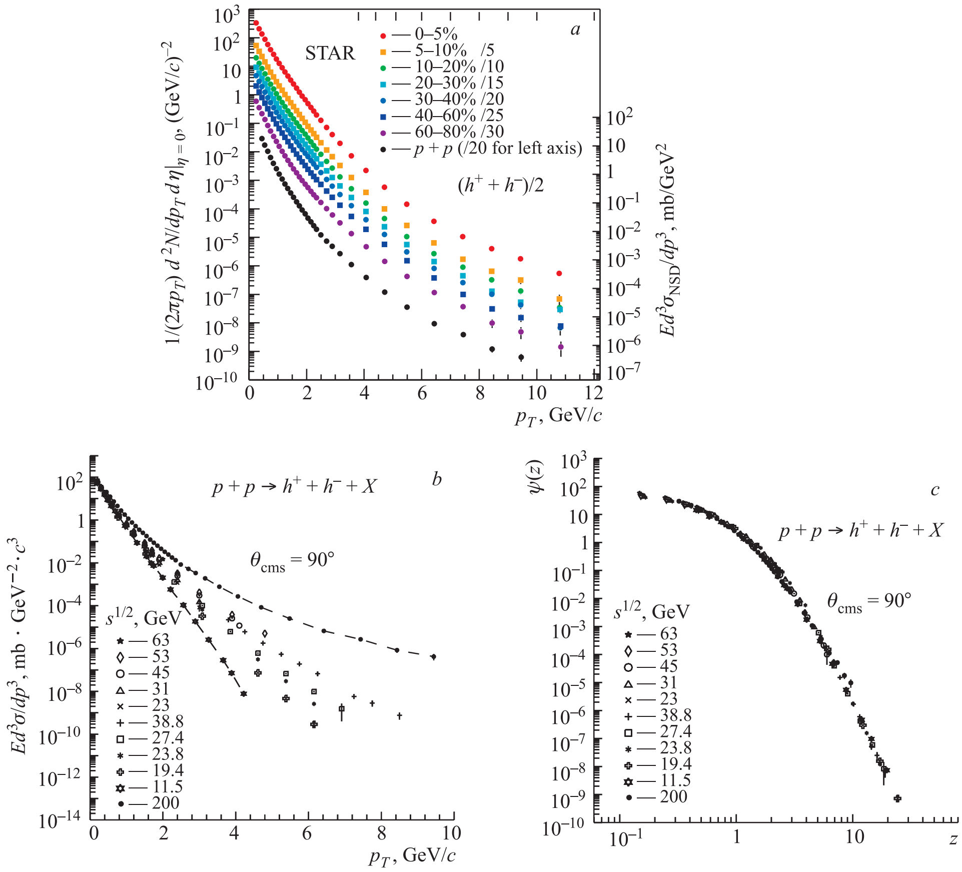

Fig. 2. *a*) Experimental data [17] on the inclusive cross sections of charged hadrons produced in Au–Au and p–p collisions at $\sqrt{s}_{nn} = 200$ GeV and $\theta_{\rm cms} \simeq 90^\circ$ as a function of the transverse momentum p_T. p_T (*b*) and z presentations (*c*) of data taken from [17–21]

$\sqrt{s} = 11.5{-}200$ GeV and $p_T = 0.5{-}9.5$ GeV/c. The strong energy dependence and the power behavior of particle p_T spectrum are found to be clear. The energy independence of data z presentation shown in Fig. 3, *c* is confirmed. Verification of the asymptotic behavior of ψ at $\sqrt{s} = 200$ GeV and reach of value of z up to 30 and more are of interest.

3.2. π^0 **Mesons.** The PHENIX collaboration published the new data [25] on the inclusive spectrum of π^0 mesons produced in p–p collisions in the central rapidity range at RHIC energy $\sqrt{s} = 200$ GeV. The transverse momenta of π^0 mesons were measured up to 13 GeV/c. The p_T and z presentations of data for π^0-meson spectra obtained at ISR [26–30] and RHIC [25] are shown in Fig. 3, *a, b*. One can see that p_T spectra of π^0-meson production reveal the properties similar to those found for charged hadrons. The new data [25] on π^0-meson inclusive cross sections obtained at the RHIC, as seen from Fig. 3, *b*, are in good agreement with our earlier results [11]. Thus, we can conclude that the available experimental data on high-p_T π^0-meson production in p–p collisions confirm the property of the energy independence of $\psi(z)$ in z presentation.

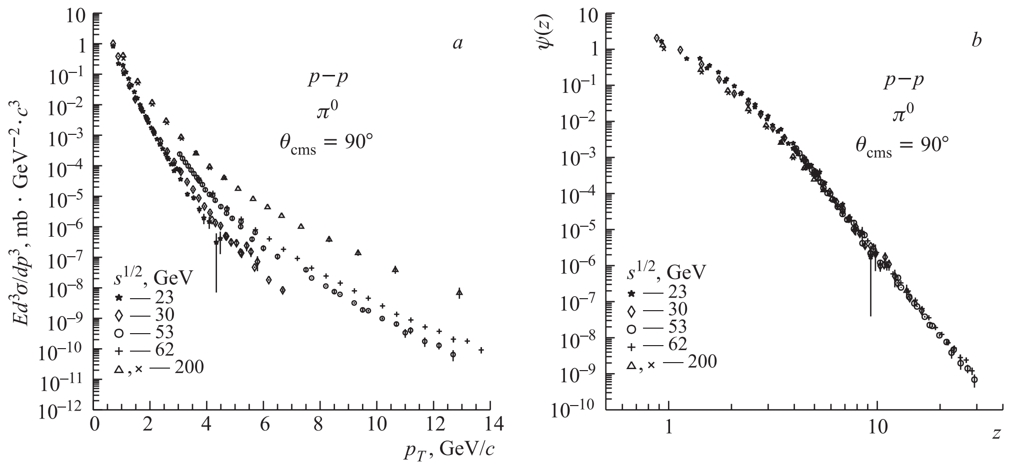

Fig. 3. *a*) The dependence of the inclusive cross section of π^0-meson production on the transverse momentum p_T in *p–p* collisions at $\sqrt{s} = 23, 30, 53, 62$ and 200 GeV and the angle $\theta_{\rm cms}$ of 90°. The experimental data are taken from [25–30]. *b*) The corresponding scaling function $\psi(z)$

3.3. η **Mesons.** New data on η-meson spectra in *p–p* collisions at $\sqrt{s} = 200$ GeV in the range $p_T = 1.2{-}8.5$ GeV/*c* are presented by the PHENIX collaboration in [23]. The η/π^0 ratio is found to be 0.54 ± 0.05 in the range $p_T = 3.5{-}9$ GeV/*c*. The value is in agreement with existing data. We compare the data with other ones obtained at $\sqrt{s} = 30, 31.6, 38.8, 53$ and 63 GeV [24, 36]. Data p_T and z presentations are shown in Fig. 4, *a, b*. As seen from Fig. 4, *b*, the results of our new analysis confirm the energy independence of the scaling function for η-meson production in *p–p* collisions over a wide $\sqrt{s}$ and p_T range. Note that the new result on the η/π^0 ratio gives an indication of flavor independence of the scaling function at high z.

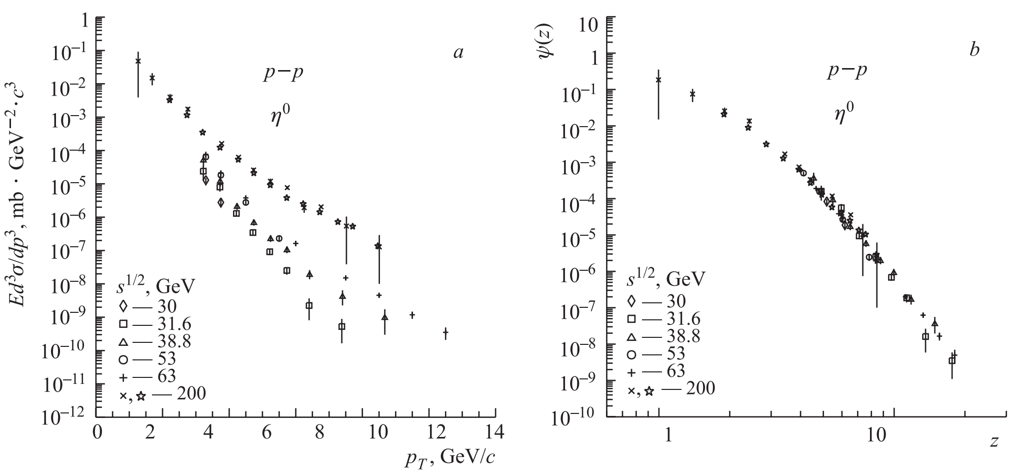

Fig. 4. *a*) The inclusive cross section of η mesons produced in *p–p* collisions in the central rapidity range as a function of the transverse momentum p_T at $\sqrt{s} = 30{-}63$ and 200 GeV. Experimental data are taken from [23, 24, 36]. *b*) The corresponding scaling function $\psi(z)$

3.4. Λ and $\bar{\Lambda}$ Hyperons. Here we analyze the new data obtained by the STAR collaboration [31] on p_T spectra of neutral strange particles $(K_S^0, \Lambda, \bar{\Lambda})$ produced in p–p collisions at $\sqrt{s} = 200$ GeV. The transverse momentum spectra are shown in Fig. 5, *a*. We have not any other data to compare with the STAR data and construct the scaling function. Therefore, the F-dependence of z presentation was used to determine the scaling function for Λ and $\bar{\Lambda}$. The experimental data (see Fig. 3) on inclusive cross section of π^0 mesons produced in p–p collisions at $\sqrt{s} = 23{-}200$ GeV are used to construct the asymptotics of $\psi(z)$. The dashed line shown in Fig. 5, *b*, is the fit of the data. As seen from Figs. 3, *b* and 5, *b* the scaling function is described by the power law, $\psi(z) \sim z^{-\beta}$, on the log-log scale at high z. The

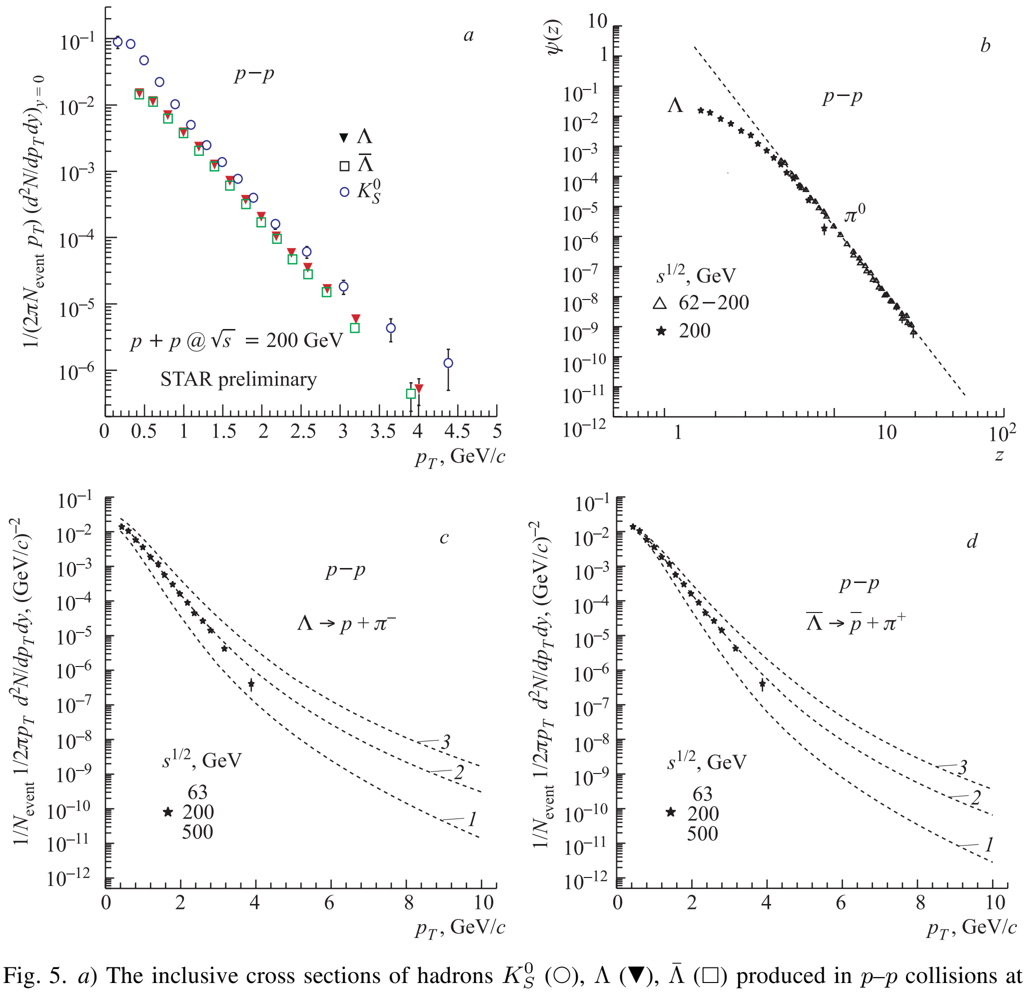

Fig. 5. *a*) The inclusive cross sections of hadrons K_S^0 (○), Λ (▼), $\bar{\Lambda}$ (□) produced in p–p collisions at $\sqrt{s} = 200$ GeV in the central rapidity range as a function of the transverse momentum p_T. Experimental data are taken from [31]. *b*) z presentation of Λ (★) and π^0 (△) experimental data on cross sections. Predictions of the inclusive spectra for Λ (*c*) and $\bar{\Lambda}$ (*d*) production in p–p collisions at $\sqrt{s} = 63$ (*1*), 200 (*2*), 500 (*3*) GeV and $\theta_{\rm cms} \simeq 90°$

transformation of the variable z and the scaling function ψ for Λ (Fig. 5, *b*) and $\bar{\Lambda}$ in the form $z \to \alpha_F z$, $\psi \to \alpha_F{}^{-1}\psi$ was used for coincidence of the asymptotics for $\Lambda, \bar{\Lambda}$ and π^0. Note that the scaling function $\psi(z)$ for Λ reveals different behavior in low- and high-z ranges. It is valid for $\bar{\Lambda}$ as well. The parameterizations of $\psi(z)$ for Λ and $\bar{\Lambda}$ were used to predict particle spectra (see Fig. 5, *c, d*) at $\sqrt{s} = 63, 200$ and 500 GeV at high p_T.

3.5. ϕ Mesons. Recently the STAR collaboration has presented the new data [32] on spectra of ϕ mesons produced in Au–Au and nonsingly diffractive p–p collisions at energy $\sqrt{s} = 200$ GeV. The decay mode $\phi \to K^+K^-$ was used to reconstruct ϕ mesons up to $p_T = 3.7$ GeV/*c*.

The cross sections as a function of the difference of the transverse mass m_t and the mass of ϕ meson m_ϕ are shown in Fig. 6, *a*. The data can be used to test z scaling and verify models

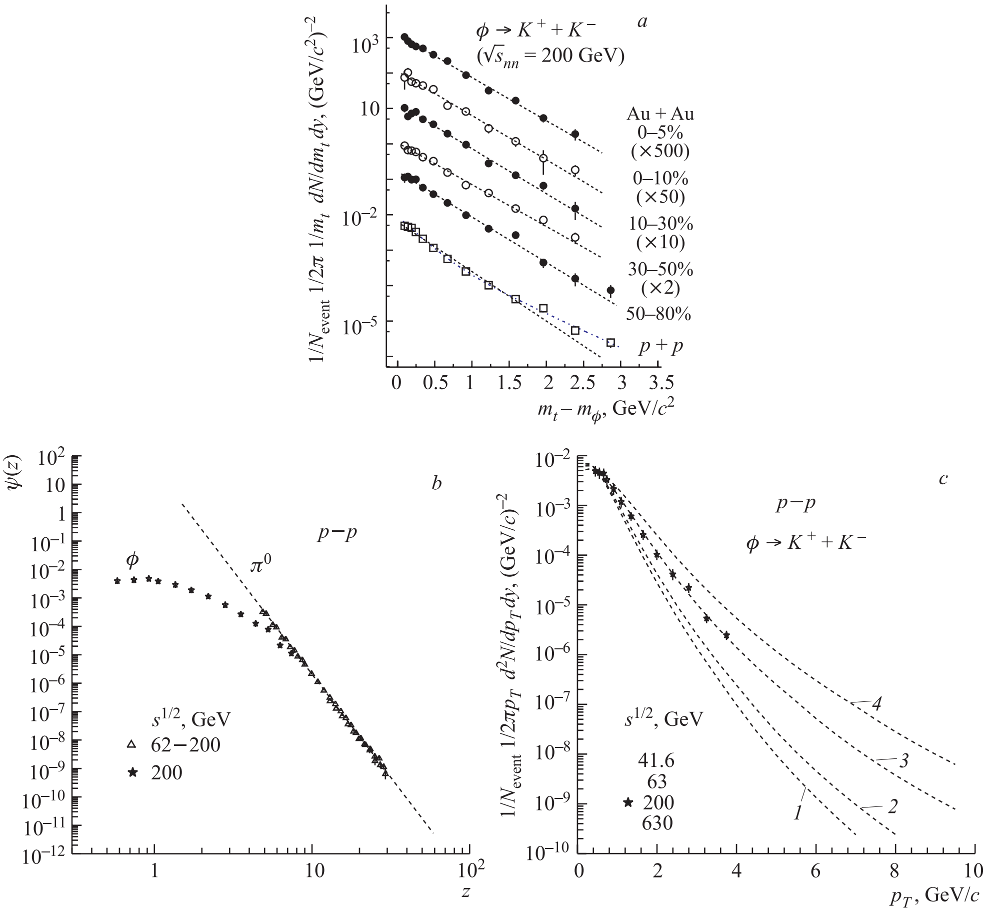

Fig. 6. *a*) The inclusive cross sections of ϕ mesons produced in Au–Au and p–p collisions at $\sqrt{s}_{nn} =$ 200 GeV in the central rapidity range as a function of $m_t - m_\phi$. Experimental data are taken from [32]. *b*) z presentation of ϕ ($\bigstar$) and π^0 ($\triangle$) experimental data on cross sections. *c*) Predictions of the inclusive spectra for ϕ-meson production in p–p collisions at $\sqrt{s} = 41.6$ (*1*), 63 (*2*), 200 (*3*), 630 (*4*) GeV and $\theta_{\rm cms} \simeq 90^\circ$

of strange particle formation. The p_T distribution of ϕ mesons produced in Au–Au collisions measured at different centralities reveals exponential behavior. The slope of spectra changes with the centrality. The spectrum for p–p collisions at high p_T shows power behavior. The scaling functions for ϕ and the asymptotics for π^0 are shown in Fig. 6, *b*. The F-dependence of data z presentation was used to predict ϕ-meson spectra at $\sqrt{s} = 41.6, 63, 200$ and 630 GeV and $\theta_{\rm cms} = 90°$ at high p_T. Note also that p–p spectra of ϕ mesons are important to study the nuclear modification factor R_AA over a wide p_T range and obtain direct information about the dense nuclear matter at hadron formation.

3.6. Ξ^- and $\bar{\Xi}^+$ Hyperons. The STAR Time Projection Chamber (TPC) provides excellent tracking of charged particles with good momentum resolution [33]. Present statistics are

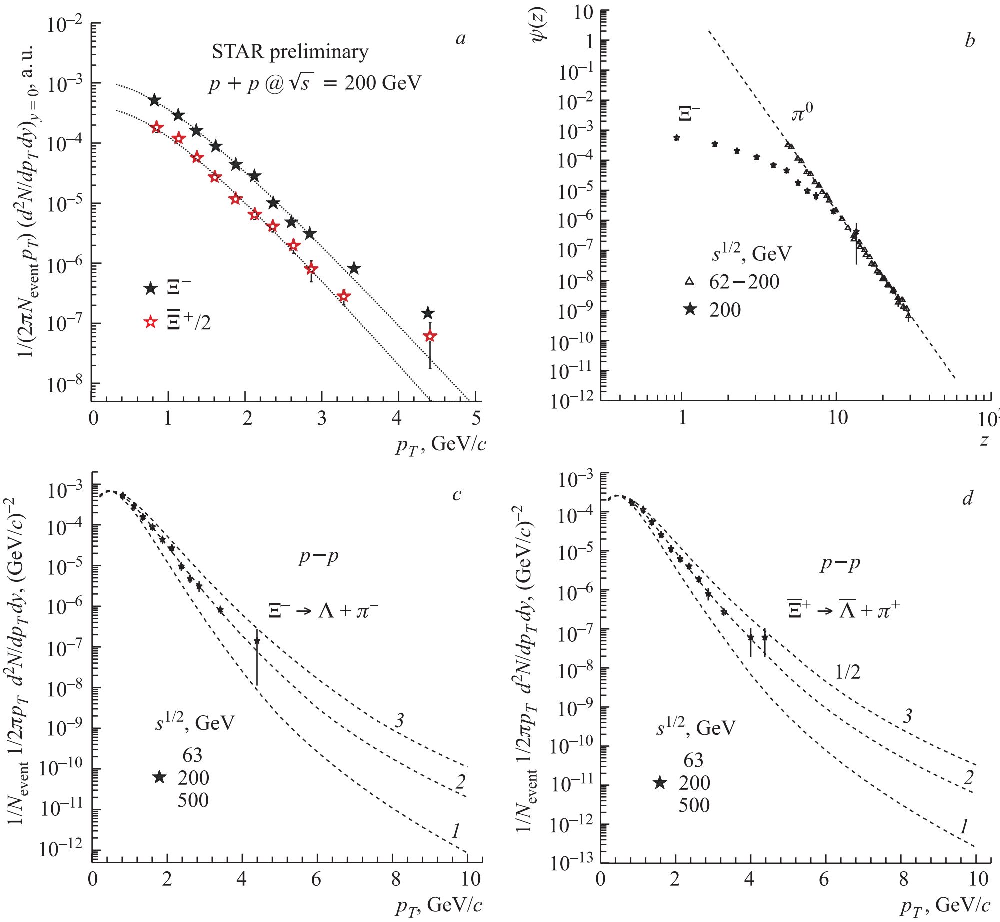

Fig. 7. *a*) The inclusive cross sections of Ξ^- (★) and $\bar{\Xi}^+/2$ (☆) hyperons produced in p–p collisions at $\sqrt{s} = 200$ GeV in central rapidity range as a function of the transverse momentum p_T. Experimental data are taken from [34]. *b*) z presentation of Ξ^- (★) and π^0 (△) experimental data on cross sections. Predictions of the inclusive spectra for Ξ^- (*c*) and $\bar{\Xi}^+$ (*d*) production in p–p collisions at $\sqrt{s} = 63$ (*1*), 200 (*2*), 500 (*3*) GeV and $\theta_{\rm cms} \simeq 90°$

sufficient to reconstruct Ξ^- and $\bar{\Xi}^+$ hyperons over a wide p_T range [34]. The decay mode $\Xi^- \to \Lambda\pi^-$ was used to reconstruct Ξ^- up to $p_T = 4$ GeV/c. Mid-rapidity transverse momentum spectra for Ξ^- and $\bar{\Xi}^+$ from p–p collisions at energy $\sqrt{s} = 200$ GeV and $|y| < 0.75$ are shown in Fig. 7, *a*.

The flavor independence of ψ at high z for different pieces allows us to construct the scaling function of Ξ^- (see Fig. 7, *b*) and $\bar{\Xi}^+$ over a wide z range using the asymptotics for π^0 mesons and to predict inclusive cross sections of Ξ^-- and $\bar{\Xi}^+$-hyperon production at high p_T. The transverse momentum spectra for Ξ^- and $\bar{\Xi}^+$ are shown in Fig. 7, *c, d*, respectively.

As shown in [35] the PYTHIA simulation of Ξ^- spectrum in p–p collisions at $\sqrt{s} = 200$ GeV does not reproduce the STAR data. Therefore, our predictions can be used to tune various PYTHIA parameters. To study azimuthal correlation of strange and charged particles and strange tagged jet production in p–p collisions, statistics should be gained. Moreover, sophisticated algorithms could essentially decrease background and increase efficiency of strange particle reconstruction as well.

3.7. K_S^0 Mesons. Here we compare the STAR data [31] for K_S^0-meson cross sections with the data for K^+ mesons obtained at the U70 [18], Tevatron [19, 20] and ISR [21] at lower energies 11.5, 19.4, 23.8, 27.4, 38.8 and 53 GeV. The data p_T and z presentations are shown in Fig. 8, *a, b*, respectively. As seen from Fig. 8, *a*, the energy dependence of the cross section enhances with p_T. The shape of the scaling function for K_S^0 mesons coincides with a similar one for K^+ mesons in the range $z = 0.2-3.0$. It gives evidence that the mechanism of neutral and charged strange K-meson formation is the same one and it reveals property of self-similarity.

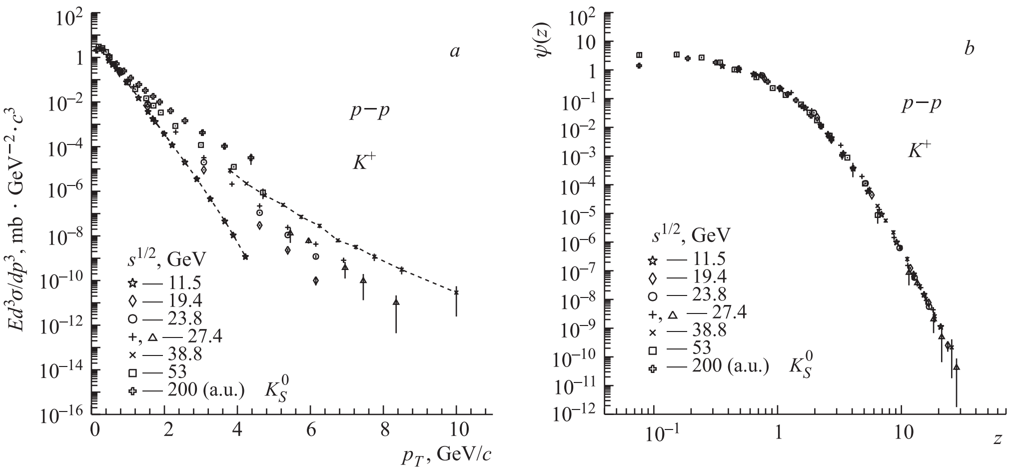

Fig. 8. *a*) The inclusive cross sections of K^+ and K_S^0 mesons produced in p–p collisions in the central rapidity range as a function of the transverse momentum p_T at $\sqrt{s} = 11.5-53$ and 200 GeV. Experimental data are taken from [18–21] and [31]. *b*) The corresponding scaling function $\psi(z)$

3.8. π^+ Mesons. The PHENIX collaboration presented in [22] the new data on inclusive cross section of identified hadrons ($\pi^\pm, K^\pm, p, \bar{p}$) produced in p–p collisions at $\sqrt{s} = 200$ GeV in the central rapidity range. Transverse momentum of particles is measured up to 2.2 GeV/c.

Data p_T and z presentations for π^+ mesons are shown in Fig. 9. We compare the data with other ones obtained at the U70 [18], Tevatron [19, 20] and ISR [21] at lower energies $\sqrt{s} = 11.5{-}53$ GeV. As seen from Fig. 9, *b*, the scaling function corresponding to data [22] is in good agreement with our results obtained previously [11].

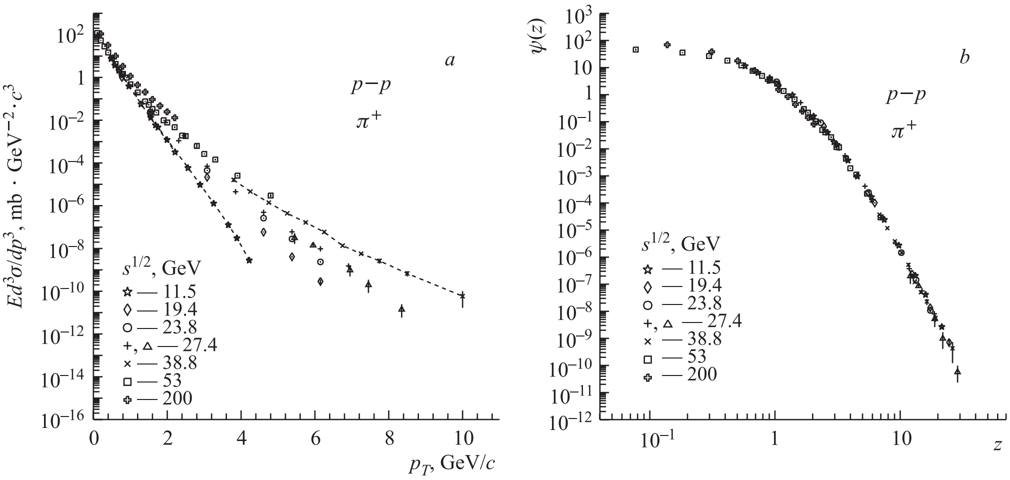

Fig. 9. *a*) The inclusive cross section of π^+ mesons produced in *p–p* collisions in the central rapidity range as a function of the transverse momentum p_T at $\sqrt{s} = 11.5{-}53$ and 200 GeV. Experimental data are taken from [18–21] and [22]. *b*) The corresponding scaling function $\psi(z)$

CONCLUSION

Analysis of new experimental data on high-p_T hadrons ($h^{\pm}$, π^0, η, Λ, $\bar{\Lambda}$, ϕ, Ξ^-, $\bar{\Xi}^+$, K_S^0, π^+) produced in *p–p* collisions at the RHIC in the framework of data z presentation was performed.

The scaling function $\psi(z)$ and scaling variable z are expressed via the experimental quantities, the invariant inclusive cross section $Ed^3\sigma/dp^3$ and the multiplicity density of charged particles $\rho(s,\eta)$. The scaling function ψ is interpreted as a probability density to produce a particle with the formation length z.

The general regularities of high-p_T particle production described by z scaling were found to be valid in the new kinematical range accessible at the RHIC. Using the properties of z scaling, predictions of spectra of strange particles ($\Lambda, \bar{\Lambda}, \phi, \Xi^-, \bar{\Xi}^+$) produced in *p–p* collisions at RHIC energies in high-p_T range were made. The obtained results are considered to be useful for understanding of strangeness origin in mesons and baryons. New evidence that the mechanism of particle formation reveals self-similar and fractal properties in high-p_T range was obtained.

Thus, we conclude that the new data obtained at the RHIC confirm the general concept of z scaling. Further inquiry and search for violation of the scaling can give information on new physics phenomena in high-energy hadron collisions and determine the domain of applicability of strong interaction theory.

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