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SELF-SIMILARITY OF PARTICLE PRODUCTION IN SOFT AND HIGH-p_T REGIONS

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Зборовский И., Токарев М. В. E2-2009-24
Самоподобие в рождении частиц в области малых и больших p_T

Изучаются скейлинговые особенности поперечных спектров частиц, измеренных на ускорителях ISR, RHIC и Tevatron, в рамках z-скейлинга. Установлены новые свойства скейлинговой функции $\psi(z)$ в $pp/\bar{p}p$-столкновениях — флейворная независимость и насыщение при малых z. Показано, что z-скейлинг, наблюдаемый в $pp/\bar{p}p$-взаимодействиях, нарушается для рождения пионов в AuAu-столкновениях на RHIC. Обсуждаются особенности динамики адронных и ядерных взаимодействий на конституентном уровне. Обосновывается вывод о предпочтительности изучения режима насыщения при малых z для поиска фазовых переходов в адронной материи в $pp/\bar{p}p$- и AA-столкновениях на действующих установках U70, RHIC, Tevatron, LHC и планируемых ускорителях NICA (Дубна) и FAIR (Дармштадт).

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Zborovský I., Tokarev M. V. E2-2009-24
Self-Similarity of Particle Production in Soft and High-p_T Regions

Self-similar features of transverse momentum spectra measured at ISR, RHIC and Tevatron are studied in the framework of z-scaling. New properties of the scaling function $\psi(z)$ in $pp/\bar{p}p$ collisions are established. These are flavor independence including particles with heavy flavor content and saturation at low z. The z-scaling in $pp/\bar{p}p$ interactions is confronted with data on pion yields obtained in AuAu collisions at RHIC. A microscopic scenario of hadron and nucleus interactions at a constituent level in terms of momentum fractions is discussed. The saturation regime of $\psi(z)$ at low z is preferable in searching for phase transitions of hadron matter created in $pp/\bar{p}p$ and AA collisions at U70, RHIC, Tevatron, LHC and at the future accelerators NICA (Dubna) and FAIR (Darmstadt).

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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1. HADRON PRODUCTION AT A CONSTITUENT LEVEL

One of the methods allowing systematic analysis of data on inclusive cross sections over a wide range of the collision energies, multiplicity densities, transverse momenta, and angles of the produced particles is based on the z-scaling observed in high energy proton–(anti)proton collisions (see [1] and references therein). The approach reflects self-similarity as one of the basic symmetries in hadron production at the constituent level. It is expressed by existence of solutions depending on self-similarity parameters constructed as suitable combinations of some observable quantities. For the inclusive reactions, $M_1 + M_2 \to m_1 + X$, such solution is represented by a scaling function

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

of a single self-similarity variable z. Here σ_{in} is the inelastic cross section and N is the particle multiplicity. The variable z depends on the momenta and masses of the colliding and inclusive particles, dynamical characteristics of the produced system, and some parameters which allow physical interpretation. It is expressed in terms of a constituent subprocess which underlies the production of the inclusive particle (m_1). According to internal conservation laws, the subprocess is accompanied by creation of a corresponding counterpart (m_2) (see Fig. 1).

The scaling variable

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

is a ratio of the transverse kinetic energy $s_\perp^{1/2}$ of the constituent subprocess consumed on production of (m_1) and (m_2) and maximal relative number W of such configurations of the colliding system which can contribute to their production. The mass constant m_N is fixed arbitrarily at the value of nucleon mass. Number of configurations is related to the entropy of the system as follows:

$$S = \ln W + \ln W_0. \tag{3}$$

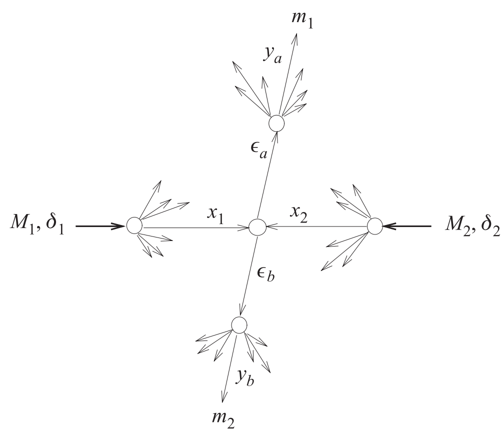

Fig. 1. Sketch of the constituent subprocess

Relative number of the configurations W which involve the constituent subprocess characterized by the momentum fractions x_1, x_2, y_a, and y_b is written in the form

$$W = (dN_{\rm ch}/d\eta|_0)^c \cdot \Omega(x_1, x_2, y_a, y_b). \tag{4}$$

The the multiplicity density of charged particles $dN_{\rm ch}/d\eta|_0$ in the central interaction region (at pseudorapidity $\eta = 0$) characterizes temperature of the system. The explicit dependence of W on $dN_{\rm ch}/d\eta|_0$ separates the temperature-dependent part of the entropy S. The parameter c plays a role of «specific heat» of the produced medium. The quantity W is proportional to the relative phase-space volume

$$\Omega(x_1, x_2, y_a, y_b) = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\epsilon_a}(1-y_b)^{\epsilon_b} \tag{5}$$

in space of the momentum fractions $\{x_1, x_2, y_a, y_b\}$. The x_1 and x_2 are momentum fractions of the colliding hadrons (or nuclei) carried by the interacting constituents. The structure of the colliding objects is expressed by parameters δ_1 and δ_2. The y_a and y_b are momentum fractions of the produced objects (a) and (b) which carry the inclusive particle (m_1) and its counterpart (m_2), respectively. The fragmentation of the objects is characterized by ϵ_a and ϵ_b. It was found that δ_1, δ_2, ϵ_a, and ϵ_b do not depend on kinematical variables. They are interpreted as fractal dimensions in the corresponding space of the momentum fractions. For $pp/\bar{p}p$ collisions we set $\delta_1 = \delta_2 \equiv \delta$. In the case of nucleus–nucleus collisions there are relations $\delta_1 = A_1\delta$ and $\delta_2 = A_2\delta$, where A_1, A_2 are the atomic numbers [2]. We assume that the fragmentation of the objects moving in the scattered and recoil directions can be described by the same parameter $\epsilon_a = \epsilon_b \equiv \epsilon_F$ which depends on the type (F) of the inclusive particle. The momentum conservation of the constituent subprocess is connected with a recoil mass M_X written in the form

$$(x_1P_1 + x_2P_2 - p/y_a)^2 = M_X^2, \quad M_X \equiv x_1M_1 + x_2M_2 + m_2/y_b. \qquad (6)$$

Here P_1, P_2 and M_1, M_2 are 4-momenta and masses of the colliding objects. We determine the momentum fractions x_1, x_2, y_a, and y_b from maximization of the entropy $S(x_1, x_2, y_a, y_b)$ under the condition (6). This defines the most preferable underlying subprocess from which the inclusive particle (m_1) with the 4-momentum p can be created.

2. SELF-SIMILARITY IN $pp/\bar{p}p$ COLLISIONS

The self-similarity of hadron production in $pp(\bar{p}p)$ collisions at high energies is manifested by the energy, angular, and multiplicity independence of the scaling function $\psi(z)$ for different types of the inclusive hadrons. This was shown in [1] for charged and identified $(\pi, K, \bar{p})$ hadrons produced in pp collisions over a wide range of the center-of-mass energy $\sqrt{s}$, detection angle $\theta_{\rm cms}$, and multiplicity density $dN/d\eta$. The energy, angular, and multiplicity independence of $\psi(z)$ was obtained for the constant values of $\delta = 0.5$ and $c = 0.25$. The parameter ϵ_F increases with the hadron mass. The values of $dN_{\rm ch}/d\eta|_0$ were taken for the inelastic collisions. The scaling function is sensitive to the mass m_2 for small production angles $\theta_{\rm cms}$. This parameter was determined from the corresponding exclusive reactions at the kinematical limit ($x_1 = x_2 = y_a = y_b = 1$). Using Eq. (6), this gives $m_2 = m(\pi^+)$, $m_2 = m(K^+)$, and $m_2 = m(p)$, for the inclusive production of π^-, K^-, and antiprotons, respectively. The same relation, $m_2 = m_1$, is used here for all types of inclusive hadrons. For comparison of the z-presentation of the spectra for different hadron species we exploit the transformation

$$z \to \alpha_F z, \quad \psi \to \alpha_F^{-1}\psi. \qquad (7)$$

The scale transformation allows one to collapse the scaling functions of different hadrons onto a single curve. The corresponding coefficients α_F are ratios of the constants W_0 for single hadron species. We have chosen $\alpha_\pi = 1$ for pions as a reference.

Figure 2 shows z-presentation of the spectra of negative pions, kaons, antiprotons, and $\Lambda's$ produced in pp collisions over the range $\sqrt{s} = 19-200$ GeV and $\theta_{\rm cms} = 3-90°$. The symbols represent data on differential cross sections measured in the central [3] and fragmentation [4] regions, respectively. The analysis comprises the inclusive spectra of particles [5] measured up to very small transverse momenta ($p_T \simeq 45$ MeV/c for pions and $p_T \simeq 120$ MeV/c for kaons or

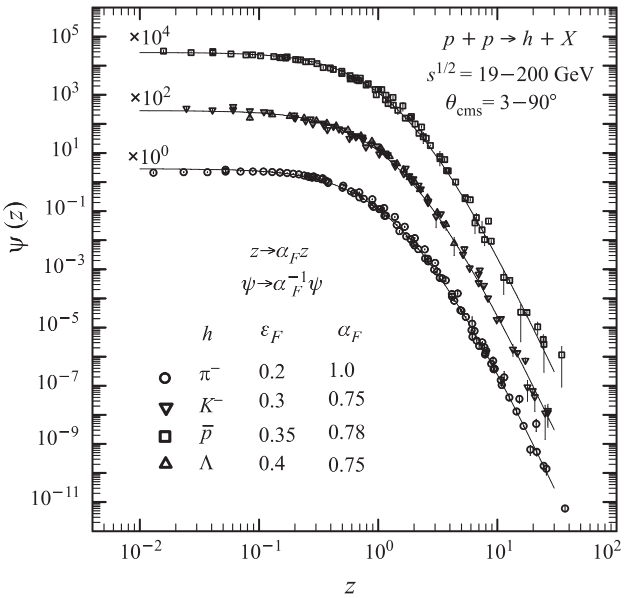

Fig. 2. The energy, angular, and flavor independence of z-scaling in pp collisions. The solid lines represent the same curve. Data are taken from [3, 4, 5]

antiprotons). The solid lines and single data sets are shifted by multiplicative factors for clarity.

The indicated values of the parameters ϵ_F and α_F are consistent with the energy, angular, multiplicity, and flavor independence of the z-presentation of spectra for different hadrons. The parameters are independent of kinematical variables ($\sqrt{s}, p_T$, and $\theta_{\rm cms}$). The distributions of different hadrons are sufficiently well described by a single curve over a wide z range $(0.01-30)$. The scaling function reveals a saturation for $z < 0.1$. These properties reflect self-similarity of hadron production in pp interacions.

Figure 3, a shows similar results for other hadrons $(\rho, \omega, \phi, K^*, \Xi)$ [6] produced in pp collisions at $\sqrt{s} = 200$ GeV and $\theta_{\rm cms} = 90^\circ$. The data on inclusive spectra are compared with the pion distributions measured at RHIC. The shape of $\psi(z)$ is described by the same curve as depicted in Fig. 2. The solid line at the lowest $z \simeq 0.007$ corresponds to the STAR data on K^* resonances measured in the region where the scaling function is saturated.

The inclusive spectra of heavy hadrons $(J/\psi, D^0, B, \Upsilon)$ [7] obtained at the Tevatron energies $\sqrt{s}$ =1800 and 1960 GeV allow us to verify the new properties of the z-scaling in $p\bar{p}$ collisions. The data include measurements up to small

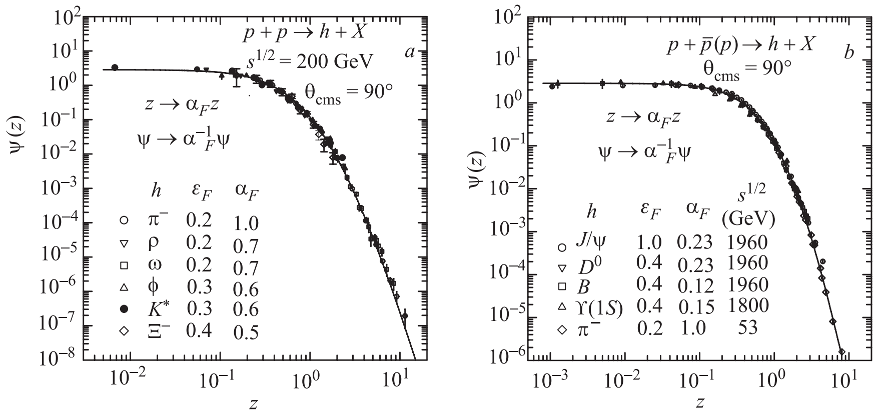

Fig. 3. The flavor independence of z-scaling. The spectra of π^-, ρ, ω, ϕ, K^*, Ξ hadrons [6] produced in pp collisions at RHIC (a) and $J/\psi, D^0, B, \Upsilon$ mesons [7] produced in $\bar{p}p$ collisions at Tevatron (b) in z-presentation. The solid lines are the same curves as in Fig. 2

transverse momenta ($p_T \simeq 125$ MeV/c for charmonia, $p_T \simeq 290$ MeV/c for bottomia, and $p_T \simeq 500$ MeV/c for B mesons). Figure 3, b shows the spectra of $J/\psi, D^0, B$, and Υ mesons in z-presentation. The scaling function reveals a saturation in the range $z = 0.001{-}0.1$ and is the same as for hadrons with light flavors. The parameters ϵ_F and α_F are found to be independent of $\sqrt{s}, p_T$, and $\theta_{\rm cms}$. They are consistent with the energy, angular, and multiplicity independence of the z-scaling.

The approach based on the z-scaling concept allows us to develop a microscopic scenario of particle production in terms of the constituent interactions. Here we discuss some features of this scenario. The method of determination of the momentum fractions makes it possible to analyze kinematics of the constituent interactions in the framework of the developed approach. The dependence of the momentum fractions y_a and y_b on the kinematical variables (p_T, $\theta_{\rm cms}$, $\sqrt{s}$) describes features of the fragmentation process. The fraction y_a characterizes dissipation of the energy and momentum of the object produced by the underlying constituent interaction into the near side of the inclusive particle. This effectively includes energy losses of the scattered partons moving in the direction of the registered particle as well as feed down processes from prompt resonances out of which the inclusive particle may be created. The fraction y_b governs the recoil mass $M_X \sim m_2/y_b$ in the constituent subprocess. Its value characterizes the dissipation of energy in the away side direction of the inclusive particle.

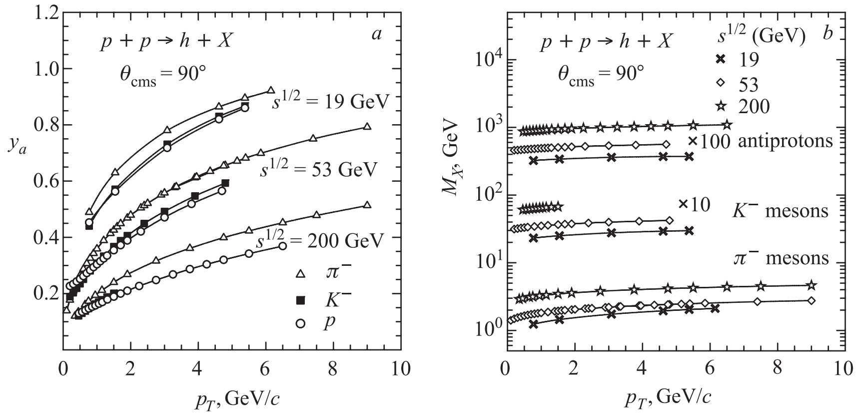

Fig. 4. The dependence of the fraction y_a (a) and the recoil mass M_X (b) on the transverse momentum p_T for π^-, K^-, and $\bar{p}$ produced in the pp collisions at $\sqrt{s} = 19, 53$, and 200 GeV. The symbols correspond to data measured at $\theta_{\rm cms} = 90°$

Figure 4, a shows the dependence of y_a on the transverse momentum p_T for the negative pions, kaons, and antiprotons produced in pp collisions at the energies $\sqrt{s} = 19, 53, 200$ GeV and $\theta_{\rm cms} = 90°$. All curves demonstrate a non-linear monotonic growth with p_T. It means that the energy dissipation associated with the production of a high-p_T particle is smaller than for the inclusive processes with lower transverse momenta. This feature is similar for all inclusive reactions at all energies. The decrease of the fractions y_a with the increasing collision energy is another property of the considered mechanism. It corresponds to more energy dissipation at higher energies. This can be due to the larger energy losses and/or due to the heavy prompt resonances. The third characteristic is a slight decrease of y_a with the mass of the inclusive particle. It implies more energy dissipation for creation of heavier hadrons as compared with hadrons with smaller masses.

The dependences of y_b and M_X on p_T reflect kinematical properties of the recoil system. Figure 4, b shows the dependence of the recoil mass on the transverse momentum of the negative pions, kaons, and antiprotons produced in pp collisions at the energies $\sqrt{s} = 19, 53$, and 200 GeV in the central rapidity region. For the sake of clarity, the values of M_X are presented on a log-scale with the multiplication factors 10 and 100 for K^- and $\bar{p}$, respectively. All curves demonstrate small growth at low p_T followed by a successive flattening. They reveal a characteristic increases with the collision energy and mass of the inclusive particle. The qualitative properties of the p_T dependence of M_X are similar for different hadrons. The corresponding values of the momentum fraction y_b are much less than y_a for $p_T > 1\,\mathrm{GeV}/c$. This means that, for sufficiently large p_T, the momentum balance in the production of an inclusive particle from a subprocess is more likely compensated with many particles with smaller momenta than by a single particle with a higher momentum moving in the opposite direction.

3. SELF-SIMILARITY OF PION PRODUCTION IN AA COLLISIONS

The measurements of particle spectra at RHIC led to the discovery of a substantial suppression of hadron yields in nucleus–nucleus collisions relative to proton–proton data. The suppression is observed in the region of high transverse momenta, typically more than few GeV/c. It is usually connected with the energy radiations of the outgoing high-p_T partons propagating through dense matter formed in the central collisions of heavy nuclei. The energy losses in the dense medium are substantially larger than in the vacuum. One of the measurable quantities characterizing the medium is the multiplicity density of the produced particles. We present some ideas how to quantify the energy losses exploiting a specific connection between the suppression of the spectra and the corresponding multiplicity density of particles produced in nuclear collisions. The ideas are motivated by the assumption of self-similarity of hadron interactions at a constituent level both in pp and AA collisions. This is demonstrated here on pion spectra obtained at RHIC.

The STAR Collaboration measured the spectra of negative pions [8] produced in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV. The spectra were taken at various centralities, characterized by different multiplicity densities $dN_{\mathrm{ch}}/d\eta|_0$ of charged particles produced in the central interaction region. They cover a wide range of the transverse momentum, $p_T = 0.35 - 10$ GeV/c. The yields change more than eight orders of magnitude in this range. The centrality dependence of the pion spectra is plotted in z-presentation in Fig. 5, a. The corresponding pp data are represented by the solid line. The parameter $\epsilon \equiv \epsilon_\pi = 0.2$ was fixed at the same value as for scaling analysis of pions in the pp collisions. The fractal dimension δ_{Au} of the colliding nuclei was determined in accordance with the additive property $\delta_A = A\delta$ obtained for pA interactions [2] with the same value of $\delta = 0.5$ as for pp data. The corresponding total multiplicity densities $dN_{\mathrm{ch}}/d\eta|_0$ of charged particles produced in AuAu collisions have been used in formula (4). They depend on the centrality of the nuclear collisions. In the case of pp interactions, the multiplicity density $dN_{\mathrm{ch}}/d\eta|_0$ for the non-single-diffractive pp events was used in (4) for comparative reasons.

As seen from Fig. 5, a, the spectra in pp and peripheral AuAu collisions coincide each other with good accuracy in z-presentation for $c_{\mathrm{AuAu}} = 0.11$. This value is consistent with the energy independence of z-presentation of the pion spectra in the peripheral AuAu collisions. The result indicates that the form of the

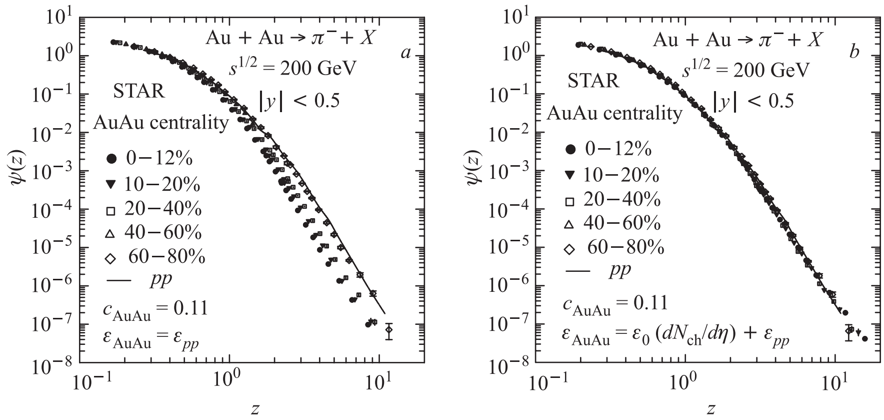

Fig. 5. The inclusive spectra of negative pions produced in pp and AuAu collisions [8] for different centralities at $\sqrt{s_{NN}} = 200$ GeV in z-presentation for a) constant and b) multiplicity-dependent parameter ϵ. The solid lines represent the scaling function for pp collisions

pion spectra in peripheral AuAu collisions is unsensitive to modifications of the production mechanism by nuclear medium when compared with pp interactions. The influence of nuclei is included here with a drop-off in the «specific heat» from its value $c_{pp} = 0.25$ obtained in pp collisions. One can see from Fig. 5, a that the AuAu spectra are suppressed in the high-z region relatively to the pp scaling function $\psi(z)$ as the centrality increases. The largest suppression is for the most central collisions.

The same scaling behavior as for pp collisions can be obtained for AuAu interactions for all centralities. As shown in Fig. 5, b, this can be achieved by the parameter ϵ allowing it to be a function of the multiplicity density $dN_{\rm ch}/d\eta$. For that purpose we have used

$$\epsilon_{AA} = \epsilon_0(dN_{\rm ch}/d\eta) + \epsilon_{pp} \qquad (8)$$

with a suitable choice of the coefficient ϵ_0. For AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV we obtained $\epsilon_0 = 0.0028$. The increase of ϵ with the multiplicity density is connected with a decrease of the momentum fractions y_a and y_b. This results in larger energy losses in the final state. The energy losses depend on the amount of the traversed medium which converts them into the multiplicity of the produced particles. The larger ϵ the more energy losses of the secondary partons. The multiplicity density characterizes the produced medium and is connected in a such way to the parton energy losses in this medium.

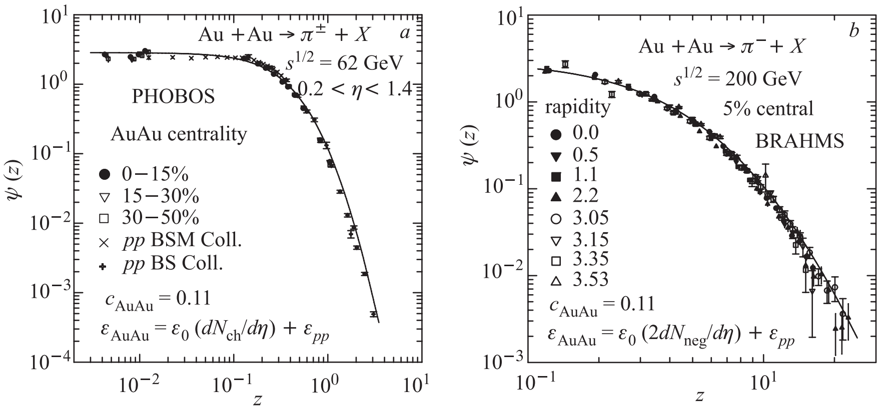

Fig. 6. *a*) The saturation of $\psi(z)$ at low z for pions produced in pp and AuAu collisions [9] at different centralities. *b*) The angular independence of $\psi(z)$ for π^- mesons measured in central AuAu collisions [10] at different rapidities. The fit lines in both figures are the same

In the soft-p_T (low-z) region, the z-presentation of pion spectra is insensitive to the value of ϵ. The single parameter which governs the shape of the scaling function in this region is the «specific heat» c. We have analyzed data [9] on the centrality dependence of the soft pions measured by the PHOBOS Collaboration in AuAu collisions at $\sqrt{s_{NN}} = 62$ GeV at RHIC. As shown in Fig. 6, *a*, the AuAu data extend the scaling behavior observed in pp collision for small z (< 0.01). The nuclear data on pion production confirm the saturation (approximate constancy) of the scaling function in this region.

Another aspect of the scaling behavior in AuAu collisions is the angular independence. This is illustrated in Fig. 6, *b* where data [10] on π^--meson production in AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV measured by the BRAHMS Collaboration at various rapidities are shown in z-presentation. The angular scaling was obtained by the same value of ϵ_0 as used in Fig. 5, *b* when $dN_{\rm ch}/d\eta$ was replaced by $2(dN_{\rm neg}/d\eta)$ in formula (8).

The dependences of the fraction y_a and the recoil mass M_X on the transverse momentum p_T of π^- mesons produced in pp and AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV are shown in Fig. 7, *a* and 7, *b*, respectively. The fraction y_a demonstrates a monotonic growth with p_T. It means that the energy losses associated with the production of a high-p_T pion are smaller than for the inclusive processes with lower transverse momenta. The decrease of y_a with centrality in AuAu collisions represents larger energy losses in the central collisions as compared with the pp and peripheral AuAu interactions. A slight increase of

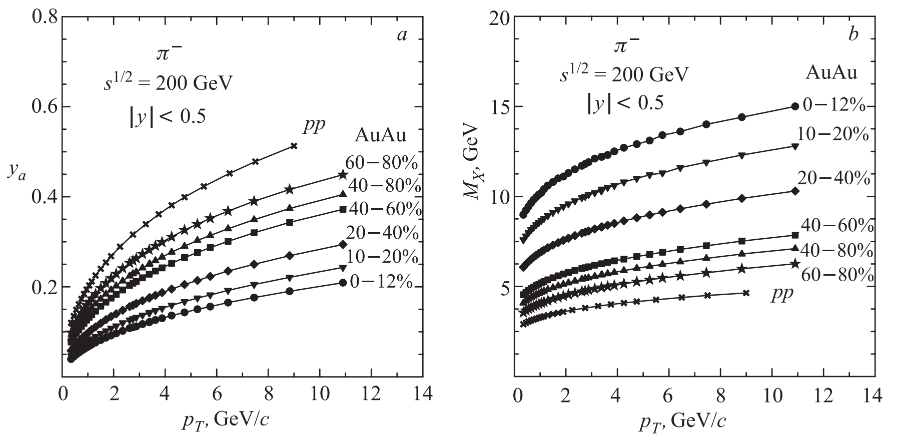

Fig. 7. The dependence of the fraction y_a (a) and the recoil mass M_X (b) on the transverse momentum p_T for π^- mesons produced in pp and AuAu collisions at different centralities. The symbols correspond to data measured at $\sqrt{s_{NN}} = 200$ GeV and $|y| < 0.5$

the recoil mass M_X with p_T is characteristic for pp collisions. The values of M_X and their growth with p_T become larger with centrality in AuAu interactions. This means that the momentum balance in a subprocess underlying the pion production is compensated with growing number of particles moving in the away side direction when the centrality of the nuclear collisions increases.

CONCLUSIONS

We have studied the spectra of the inclusive particles produced in pp and $\bar{p}p$ collisions in z-presentation. New properties of the z-scaling — the flavor independence and the saturation of the scaling function $\psi(z)$ at low z, were established. This includes hadrons with light and heavy quarks produced in high energy pp and $p\bar{p}$ collisions. A saturation regime of $\psi(z)$ was observed for $z < 0.1$. The approximate constancy of $\psi(z)$ was demonstrated up to $z \simeq 10^{-3}$ for charmonia and bottomia. We have compared the spectra of the inclusive particles produced in $pp/\bar{p}p$ interactions with data on pion distributions measured in gold–gold collisions at RHIC. The z-presentation of the pion spectra in AuAu collisions reveals scaling features identical with the z-scaling in the elementary collisions. This includes the centrality and angular independence of the scaling provided the fragmentation dimension ϵ increases linearly with the multiplicity density in AuAu collisions. The saturation of the scaling function $\psi(z)$ for small z (< 0.01) was extended to nuclear data on pion production at $\sqrt{s_{NN}} = 62$ GeV measured by the

PHOBOS Collaboration. The parameter c which governs multiplicity dependence of z at small p_T was interpreted as a «specific heat» of the produced medium. It was found to be constant and smaller in AuAu than in pp collisions. In the hard-p_T (large-z) region, the scaling function manifests typical power behavior, $\psi(z) \simeq z^{-\beta}$, with a constant value of the slope parameter β. A microscopic scenario of the constituent interactions in terms of the momentum fractions was presented. Some conclusions on the energy losses and recoil mass in the final state were drawn.

The obtained results may be exploited to search for and study of new physics phenomena in particle production in the high energy proton–proton and nucleus–nucleus collisions at RHIC, Tevatron, LHC and at the future accelerators FAIR in Darmstadt and NICA in Dubna.

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