E2-2007-162

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# SCALING FEATURES OF PARTICLE PRODUCTION IN $A + A$ COLLISIONS AT **RHIC** IN $z$-PRESENTATION

Presented at the International Conference «New Trends of High-Energy Physics», September 15–22, 2007, Yalta, Crimea, Ukraine

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Зборовский И., Токарев М. В. E2-2007-162
Скейлинговые особенности рождения частиц
в $A + A$-столкновениях на RHIC в $z$-представлении

Приводятся новые аргументы в подтверждение существования свойства самоподобия в инклюзивном рождении частиц в столкновениях адронов и ядер высоких энергий. Сравниваются скейлинговые закономерности адронных спектров в протон-протонных и ядро-ядерных соударениях в $z$-представлении. Обсуждается микроскопический сценарий механизма потерь энергии частицами в рамках теории $z$-скейлинга. Представлены результаты анализа экспериментальных данных по адронным спектрам, полученных на коллайдерах ФНАЛ, ЦЕРН и БНЛ.

Работа выполнена в Лаборатории высоких энергий им. В. И. Векслера и А. М. Балдина ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2007

Zborovsky I., Tokarev M. V. E2-2007-162
Scaling Features of Particle Production in $A + A$ Collisions
at RHIC in $z$-Presentation

New arguments in favor of self-similarity of the inclusive particle production in high energy collisions of hadrons and nuclei are discussed. Scaling features of hadron spectra from nuclear interactions are compared with the $z$-scaling observed in $p + p$ collisions. The microscopic scenario on the energy losses of particles in the framework of $z$-scaling is discussed. The performed analysis is based on the phenomenological study of data obtained at FNAL, CERN, and BNL.

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

Preprint of the Joint Institute for Nuclear Research. Dubna, 2007

## INTRODUCTION

The measurements of particle spectra at the Relativistic Heavy Ion Collider (RHIC) led to the discovery of a substantial suppression of hadron yields in nucleus–nucleus collisions relative to proton–proton data [1]. The suppression is observed in the region of high transverse momenta, typically more than few GeV/$c$. It is 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 vacuum. Quantification of the effect in the final state is a difficult problem depending on complicated calculations and model assumptions.

In this contribution we analyze hadron spectra measured in heavy ion collisions at the RHIC and suggest microscopic interpretation of spectra suppression in the framework of $z$-scaling. The approach is based on general principles valid in $p+p$ and $A+A$ interactions. Both systems represent collisions of extended objects interacting in terms of their constituents. Production of particles from the constituent interactions is governed by the principles of self-similarity, locality, and fractality. The self-similarity of hadron production is valid both in soft and hard physics. The locality and fractality are applied to hard processes at small scales. The principles are manifested by the $z$-scaling [2] observed in proton–proton collisions at high energies. The scaling includes particle spectra for various selection criteria with different multiplicities $N_{\mathrm{ch}}$. The general principles apply in the nucleus–nucleus interactions as well. We demonstrate that particle spectra for different centrality classes in $A+A$ collisions with different multiplicity densities $dN_{\mathrm{ch}}/d\eta$ manifest similar scaling behavior as in $p+p$ collisions. Performed analysis shows that this holds in a wide range of transverse momentum $p_T$ for production of mesons and in the high-$p_T$ region for baryons.

## 1. SCALING VARIABLE $z$ AND SCALING FUNCTION $\psi(z)$

The transverse momentum distribution for the reaction

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

depends on the masses $M_1, M_2, m_1,$ and 4-momenta $P_1, P_2, p$ of the colliding and inclusive particles. According to the internal conservation laws (for isospin, baryon number, strangeness, etc.), production of the particle $(m_1)$ is usually considered with simultaneous formation of its antiparticle $(m_2)$. We assign a self-similarity parameter $z$ for any inclusive particle with the 4-momentum $p$ produced in the collisions of hadrons and nuclei. The variable

$$z = s_{\perp}^{1/2}/(W \cdot m) \tag{2}$$

is a ratio of the transverse kinetic energy $s_{\perp}^{1/2}$ of an underlying constituent subprocess consumed on production of the system $(m_1)+(m_2)$ and maximal relative number $W$ of such configurations of the colliding system, which can contribute to the production of $(m_1) + (m_2)$. The constant $m$ is fixed at the value of nucleon mass. Number of the configurations includes all conceivable constituent subprocesses in reaction (1).

Relative number of the configurations containing subprocesses characterized by the fractions $x_1, x_2, y_a,$ and $y_b$ of the corresponding 4-momenta (Fig. 1) is written in the form

$$W = (dN_{\rm ch}/d\eta|_0)^c \, \Omega(x_1, x_2, y_a, y_b), \tag{3}$$

$$\Omega(x_1, x_2, y_a, y_b) = (1-x_1)^{\delta_1}(1-x_2)^{\delta_2}(1-y_a)^{\epsilon_a}(1-y_b)^{\epsilon_b}. \tag{4}$$

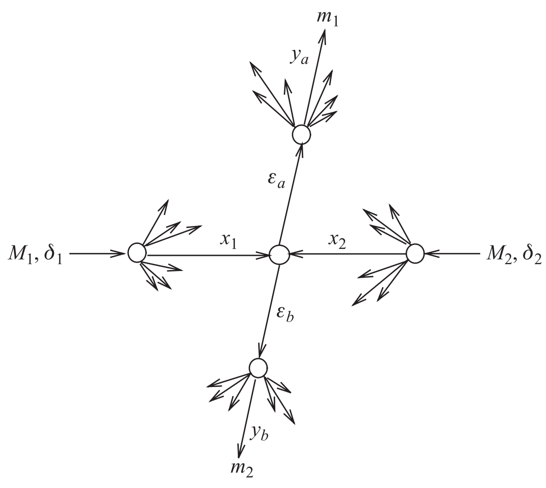


Fig. 1. Hadron/nucleus interactions at the constituent level

The constituent subprocess which can contribute to the production of the inclusive particle with the 4-momentum $p$ is subject to the condition

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

The underlying constituent subprocess, in terms of which the variable $z$ is determined, is singled out of reaction (1) exploiting the principle of maximal entropy

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

under the condition (5). The fractions $x_1, x_2, y_a$, and $y_b$ corresponding to the maximum of $S$ are used for evaluation of $W$ for every momentum $p$ of the inclusive particle. The obtained analytical formulae for $x_i$ can be decomposed into two parts ($x_i = \lambda_i + \chi_i$) which contribute to production of $(m_1)$ and $(m_2)$, respectively. The transverse kinetic energy $s_\perp^{1/2}$ has the form

$$s_\perp^{1/2} = y_a(s_\lambda^{1/2} - M_1\lambda_1 - M_2\lambda_2) - m_1 + y_b(s_\chi^{1/2} - M_1\chi_1 - M_2\chi_2) - m_2, \tag{7}$$

where $s_\lambda = (\lambda_1 P_1 + \lambda_2 P_2)^2$ and $s_\chi = (\chi_1 P_1 + \chi_2 P_2)^2$. Using the equation $p_\perp/y_a = \tilde{p}_\perp/y_b$ of transverse momentum balance in the underlying subprocess, expression (7) can be approximated by $s_\perp^{1/2} \simeq (p_\perp^2 + m_1^2)^{1/2} - m_1 + (\tilde{p}_\perp^2 + m_2^2)^{1/2} - m_2$ in the central interaction region.

As the entropy (6) is determined up to an arbitrary constant $\ln W_0$, the scaling variable is defined up to the transformation $z \to W_0\, z$. The constant $W_0$ related to absolute number of the microscopic configurations of the system drops out from the description. On the basis of formulae (3), (4), (6), and in analogy with the thermodynamical entropy for ideal gas,

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

we interpret the parameter $c$ as a «specific heat» of the produced medium. The multiplicity density $dN_{\mathrm{ch}}/d\eta|_0$ of particles in the central interaction region characterizes a «temperature» of the colliding system. The factor $\Omega$ depends on a relative volume and parameters $\delta_1, \delta_2, \epsilon_a$, and $\epsilon_b$ relate to fractal dimensions in the space of the momentum fractions $\{x_1, x_2, y_a, y_b\}$. Further analysis is simplified by the assumption that fragmentation of the scattered and recoil constituents is characterized by the same parameter $\epsilon_a = \epsilon_b \equiv \epsilon$ which depends on the type of the inclusive particle. We also set $m_2 = m_1$ for all types of the inclusive hadrons. The variable $z = z_0\Omega^{-1}$ has character of a fractal measure which diverges with increasing resolution. The divergent factor $\Omega^{-1}$ describes resolution at which the underlying constituent subprocess can be singled out of reaction (1).

The scaling function is expressed in terms of the experimentally measured inclusive invariant cross section $Ed^3\sigma/dp^3$ and multiplicity density $dN/d\eta$ as follows:

$$\psi(z) = -\frac{\pi s A_1 A_2}{(dN/d\eta)\sigma_{\rm inel}} J^{-1} E \frac{d^3\sigma}{dp^3}. \quad (9)$$

Here $s$ is the square of the center-of-mass energy of the corresponding $NN$ system, $A_1$ and $A_2$ are atomic weights, $\sigma_{\rm inel}$ is the inelastic cross section, and $J$ is the corresponding Jacobian.

## 2. $z$-SCALING IN $p+p$ COLLISIONS

Let us remind main features of the $z$-scaling in proton–proton interactions [2] characterized by a proton fractal dimension $\delta \equiv \delta_1 = \delta_2$ in the initial state. We have analyzed experimental data on inclusive cross sections of hadrons ($h^\pm$, $\pi^-$, $K^-$, $K^0_S$, $\bar{p}$, $\Lambda$, ...) measured in $p+p$ collisions at FNAL, ISR, and RHIC.

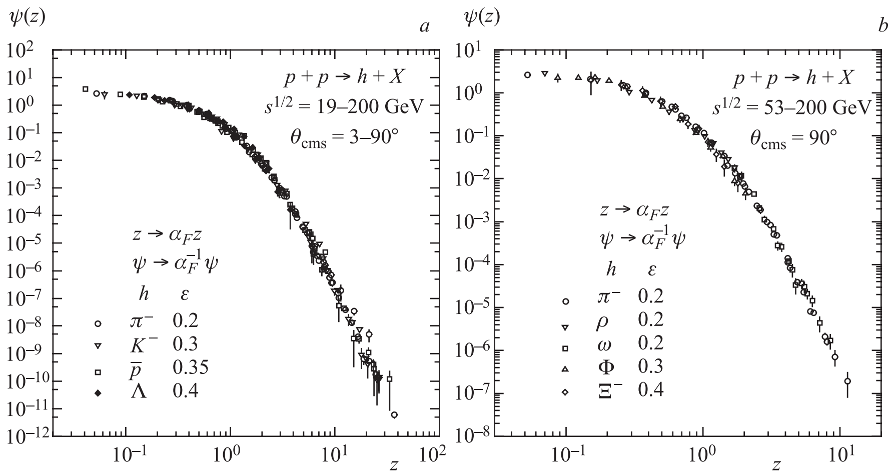


Fig. 2. The spectra of inclusive hadrons produced in $p+p$ collisions in $z$-presentation

The data cover a wide range of collision energy, transverse momenta, and angles of the produced particles. Spectra from minimum-biased events and events with various multiplicity selection criteria have been studied. The energy, angular, and multiplicity independence of the scaling function $\psi(z)$ was established. It gives strong constraints on the values of the parameters $c$, $\delta$, and $\epsilon$. It was shown that the parameters are constant in the considered kinematic region. Non of the parameters depends on multiplicity. The scaling is consistent with $c = 0.25$ and

$\delta = 0.5$ for all types of the analyzed inclusive hadrons. The value of $\epsilon$ increases with mass of the hadron. The shape of the scaling function $\psi(z)$ is found to be the same for different hadron species over a wide range of $z$. This is illustrated in Fig. 2 where spectra of different hadrons are reduced to a single curve.

Here we have used a transformation $z \to \alpha_F z$ which does not change the shape of the scaling function in the log–log plot. The constants $\alpha_F$ are ratios of $W_0's$ for different particle species. The obtained result gives strong support for the assumption that flavor independence of the scaling function $\psi(z)$ could be valid for particles with heavy flavor content as well. Similar applies to $p+p$ reactions with various multiplicity selection criteria for different centralities.

## 3. SCALING FEATURES OF PARTICLE SPECTRA IN $A+A$ COLLISIONS

We have analyzed data [1] on inclusive distributions of charged and identified particles measured in Au+Au, Cu+Cu, and $d$+Au collisions at the RHIC. The data for various inclusive particles and different centralities cover a wide range of the transverse momentum. First, we exploit the experimental cross sections for charged hadrons produced in the peripheral gold–gold collisions at the energies $\sqrt{s_{NN}} = 63, 130$, and 200 GeV. The spectra are presented in dependence on the variable $z$ in Fig. 3, $a$. Here the parameter $\epsilon = 0.2$ was fixed at the same value as obtained from the scaling analysis of the charged particles in $p+p$ collisions. The fractal dimensions of the colliding nuclei $\delta_1 = \delta_2 \equiv \delta_A$ were determined in

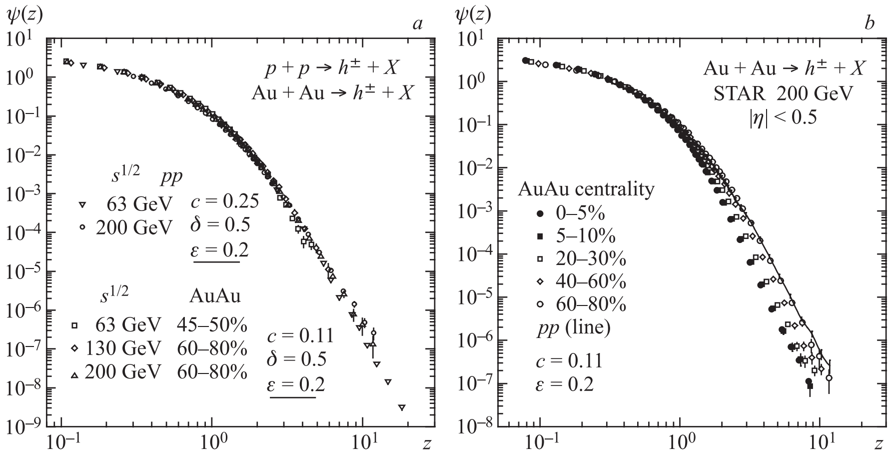


Fig. 3. $a$) Spectra of charged hadrons produced in $p+p$ and peripheral Au+Au collisions at different energies in $z$-presentation. $b$) $z$-presentation of the charged hadron spectra in Au+Au collisions for different centralities at $\sqrt{s_{NN}} = 200$ GeV

accordance with the additive property $\delta_A = A\delta$ for $p$+$A$ interactions [2] with the same value of $\delta = 0.5$ as for $p$+$p$ data. The total multiplicity densities $dN_{\rm ch}/d\eta|_0$ of charged particles produced in $A + A$ collisions have been used in formula (3) for all types of inclusive hadrons produced in nuclear interactions. In the case of proton–proton interactions, the corresponding multiplicity density $dN_{\rm ch}/d\eta|_0$ for the non-single-diffractive $p + p$ events was used in (3) for comparative reasons. Energy independence of $z$-presentation of the spectra in the peripheral Au+Au collisions was obtained for $c_{\rm AuAu} = 0.11$. Moreover, as seen from Fig. 3, $a$, the spectra in $p + p$ and peripheral Au+Au collisions coincide each other with good accuracy in $z$-presentation.

With this preparation we calculate $\psi(z)$ for particle spectra with different centralities characterized by different values of $dN_{\rm ch}/d\eta|_0$ in Au+Au collisions. The result shown in Fig. 3, $b$ demonstrates clear suppression of $z$-presentation of the spectra with increasing centrality in nuclear collisions relative to the $z$-scaling observed in $p + p$ interactions (solid line).

Figure 4, $a$ shows that the same scaling behavior as for $p + p$ collisions can be obtained for Au+Au interactions for all centralities. It gives a specific dependence of the parameter $\epsilon$ on multiplicity density. Similar holds for Cu+Cu (Fig. 4, $b$) and $d$+Au (Fig. 5) systems for charged and identified $(\pi^-, K^-, \phi, ...)$ mesons (Figs. 5, 6) at various energies $\sqrt{s_{NN}} = 62 - 200$ GeV.

We note here that a deviation from the scaling behavior was found for antiprotons and $\Lambda$ baryons produced in the central Au+Au collisions for small

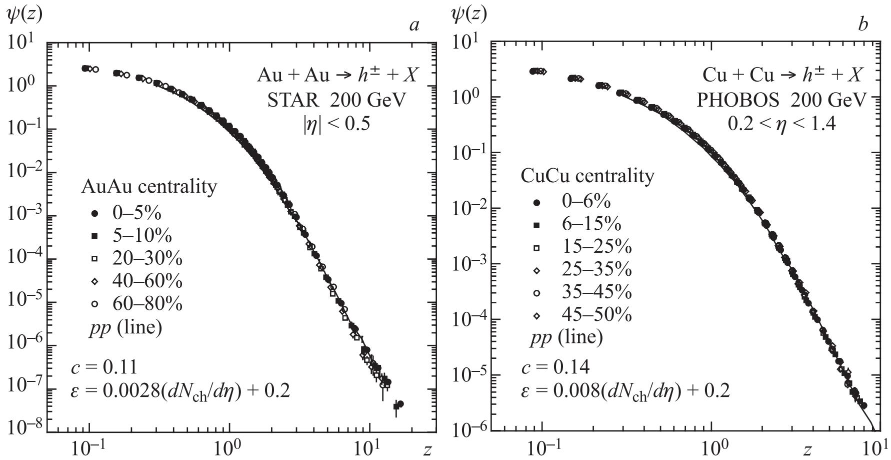


Fig. 4. $a$) $z$-presentation of spectra of charged hadrons produced in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for $\epsilon$ dependent on multiplicities. Solid line represents $z$-scaling for $p + p$ collisions. $b$) The same for Cu+Cu interactions

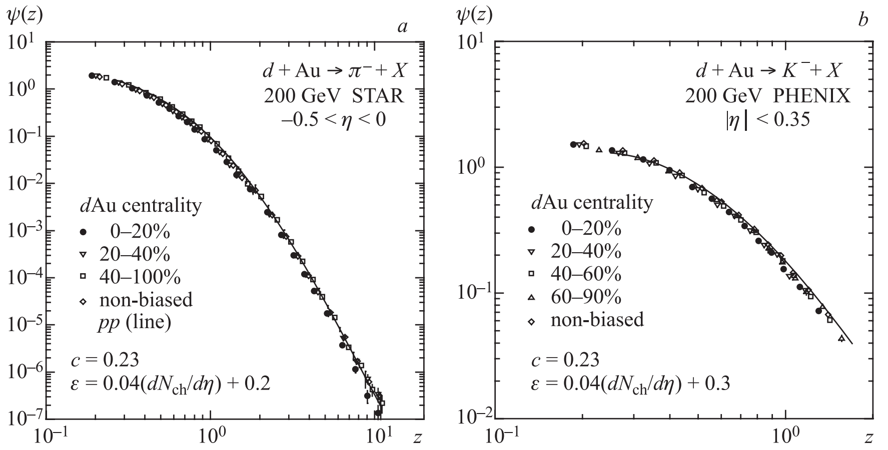


Fig. 5. *a*) $z$-presentation of spectra of $\pi^-$ mesons produced in $d$+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV for different centrality classes. *b*) The same for $K^-$-meson production

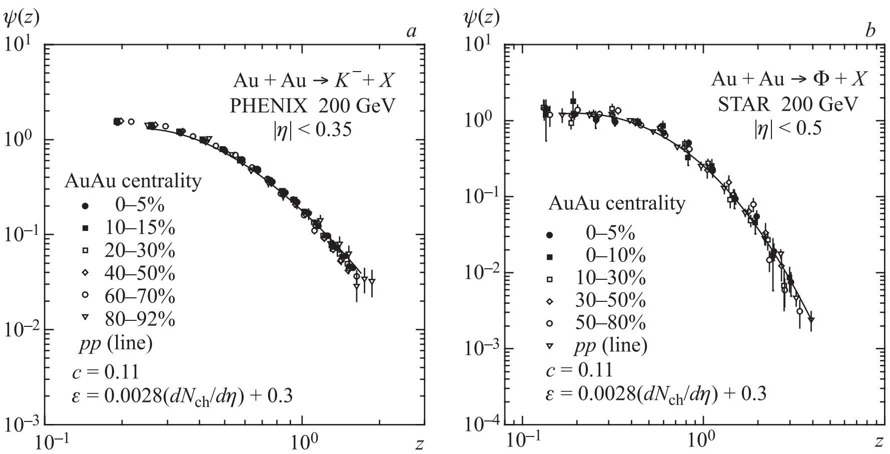


Fig. 6. *a*) $z$-presentation of spectra of $K^-$mesons produced in Au+Au collisions at $\sqrt{s_{NN}} =$ 200 GeV for different centrality classes. *b*) The same for Φ-meson production

and moderate $p_T$. This can be connected with a coalescence mechanism in the produced medium. However, data on antiproton and Λ-baryon production indicate scaling behavior in the high $z$ region, where $\psi(z)$ for $p+p$ and Au+Au coincide each other (not shown here).

The requirement of maximal entropy (6) gives information on the momentum fractions. The values of $y_b$ are considerably smaller than $y_a$. This means that 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 higher momentum moving in the opposite direction. The value of $y_b$ governs the recoil mass (5) in the subprocess. The fraction $y_a$ characterizes energy losses in formation of the inclusive particle in the final state. The larger energy losses the smaller $y_a$. Typical dependences of $y_a$ on the transverse momentum of the inclusive particle are depicted for different energies in Fig. 7. One can see that production of an inclusive particle with high $p_T$ is connected with larger energy losses in the central nuclear collisions as compared with peripheral and $p+p$ interactions. A comparison of Figs. 7, $a$ and 8, $a$ demonstrates that the energy losses are larger in the central interaction region than in the fragmentation region. Figure 8, $b$ shows very small increase of energy losses in $d$+Au system as compared with $p+p$ collisions.

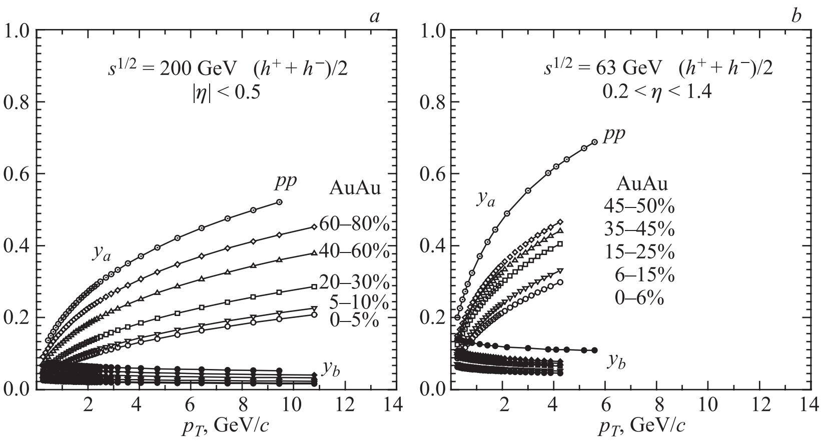

Fig. 7. Momentum fractions of the scattered $(y_a)$ and recoil $(y_b)$ constituents carried by $(m_1)$ and $(m_2)$ as function of $p_T$ of the inclusive particle at different energies and centralities

To conclude, we have studied a self-similar pattern in hadron production expressed via the $z$-presentation of $p_T$-spectra in different colliding systems. The self-similarity parameter $z$ is a function of the multiplicity density of charged particles $dN_{\rm ch}/d\eta|_0$ which is different for various centralities and center-of-mass energies. The variable $z$ depends on the parameters $c$, $\delta_1$, $\delta_2$, and $\epsilon$, interpreted as a «specific heat» of the produced medium, fractal dimensions of the colliding objects, and a fractal dimension of the fragmentation process, respectively. For $p$+$p$ collisions, the parameters have been determined from the condition of simultaneous energy, angular, and multiplicity independence of the scaling function $\psi(z)$. Assuming self-similarity of nuclear interactions at the constituent level, these requirements were extended to $A+A$ collisions for various centralities. It

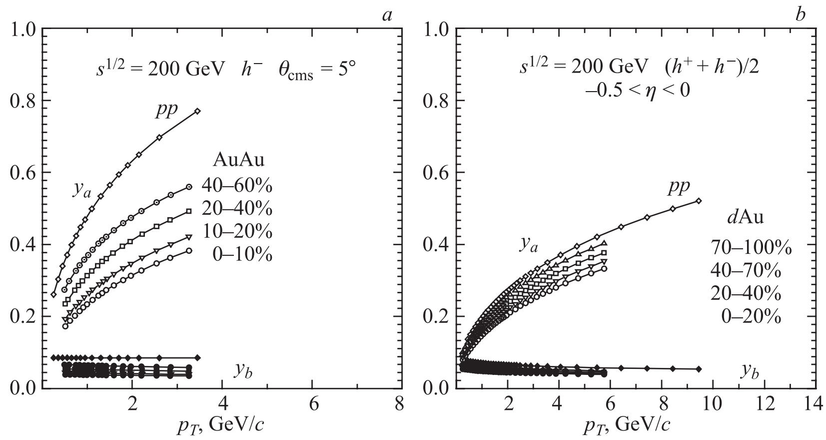


Fig. 8. The same dependences as shown in Fig. 7 for the fragmentation region of Au+Au collisions ($a$) and for the central region of $d$+Au collisions ($b$)

turns out that data on charged and identified hadrons can be described by a single scaling form $\psi(z)$ provided $c$ and $\epsilon$ are changed. The obtained values $c_{pp} = 0.25$, $c_{d\mathrm{Au}} = 0.23$, $c_{\mathrm{CuCu}} = 0.14$, and $c_{\mathrm{AuAu}} = 0.11$ of the «specific heat» decrease with the system size. The fragmentation dimension $\epsilon$ increases with the centrality as expressed by its linear dependence on the particle multiplicity density for $A+A$ collisions. Exploiting the requirement of the self-similarity and maximum entropy, we have quantified typical energy losses (the decrease of the fraction $y_a$ and $y_b$) of secondary partons in the colliding system. Performed analysis shows that the energy losses increase with centrality and center-of-mass energy of the collisions following specific dependences on the transverse momentum $p_T$ of the inclusive particle.

**Acknowledgements.** The investigations have been supported by the IRP AVOZ10480505, by the Grant Agency of the Czech Republic under the contract No.202/07/0079 and by the special program of the Ministry of Science and Education of the Russian Federation, grant RNP.2.1.1.5409.

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Received on October 31, 2007.

Корректор *Т. Е. Попеко*

Подписано в печать 19.02.2008.
Формат 60 × 90/16. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,93. Уч.-изд. л. 1,32. Тираж 415 экз. Заказ № 56114.

Издательский отдел Объединенного института ядерных исследований
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