New Scaling Behavior of low-p_T Hadron Production in proton-(anti)proton collisions at RHIC and Tevatron

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Abstract
Data on inclusive cross sections of particles produced in high energy proton-(anti)proton collisions at ISR, RHIC, and Tevatron are analyzed in the framework of z-scaling. New properties of the scaling function $\psi(z)$ - flavor independence and saturation at low z, are established. The approach can be useful for searching for new physics phenomena in particle production at RHIC, Tevatron, and LHC.

1 Introduction

The search for new physics in soft- and high-p_T regions is one of the main goals of investigations at Relativistic Heavy Ion Collider (RHIC) at BNL and Large Hadron Collider (LHC) at CERN [1–4]. Experimental data on particle production at high energy and multiplicity provide constraints for different theoretical models. Processes with high transverse momenta of produced particles are suitable for a precise test of perturbative Quantum Chromodynamics (QCD). The soft regime is preferred for verification of non-perturbative QCD and investigation of phase transitions in non-Abelian theories.

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 Ref. [5] and references therein). Here we show [6] that in the high energy pp and $p\bar{p}$ collisions the shape of the scaling function $\psi(z)$ is independent of the hadron type including production of hadrons with heavy flavor content. A saturation of $\psi(z)$ is found at low z. The single parameter c which controls the behavior of $\psi(z)$ at low z is interpreted as a "specific heat" of the produced medium. The scaling in pp and $p\bar{p}$ collisions is consistent with a constant value of c. A possible change in this parameter could be an indication of a phase transition in the matter produced in high energy collisions.

2 z-Scaling

At sufficiently high energies, the collision of extended objects like hadrons and nuclei is considered as an ensemble of individual interactions of their constituents. The constituents are partons in the parton model or quarks and gluons in the theory of QCD. Multiple interactions are assumed to be similar. This property represents a self-similarity of the hadronic interactions at a constituent level. A single interaction of the constituents is illustrated in Fig. 1.

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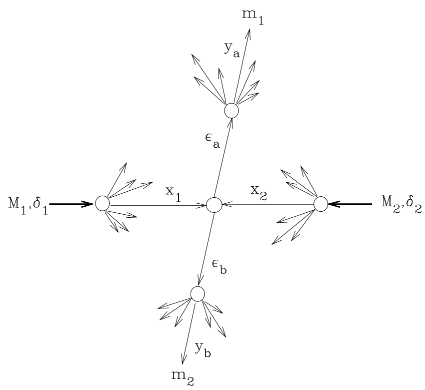

Fig.1. Diagram of the constituent subprocess.

The structures of the colliding objects (M_1) and (M_2) are characterized by parameters δ_1 and δ_2. The interacting constituents carry the fractions x_1, x_2 of the incoming momenta P_1, P_2. The inclusive particle (m_1) carries the momentum fraction y_a of the scattered constituent with a fragmentation characterized by a parameter ϵ_a. The fragmentation of the recoil constituent is described by ϵ_b and the momentum fraction y_b. The associate production of (m_2) ensures conservation of the additive quantum numbers.

The constituent subprocess is considered as a binary collision of the constituents (x_1M_1) and (x_2M_2) resulting in the scattered (m_1/y_a) and recoil $(M_X = x_1M_1 + x_2M_2 + m_2/y_b)$ objects in the final state. The momentum conservation law of the subprocess is connected with a recoil mass which we write as follows

$$(x_1P_1 + x_2P_2 - p/y_a)^2 = M_X^2. \tag{1}$$

This equation is expression of the locality of the hadron interaction at a constituent level. It represents a constraint on the fractions x_1, x_2, y_a, and y_b. The structure of the colliding objects and the fragmentation are characterized by the parameters $\delta_{1,2}$ and $\epsilon_{a,b}$, respectively. The structural parameters are connected with the corresponding momentum fractions by the function

$$\Omega(x_1, x_2, y_a, y_b) = (1 - x_1)^{\delta_1}(1 - x_2)^{\delta_2}(1 - y_a)^{\epsilon_a}(1 - y_b)^{\epsilon_b}. \tag{2}$$

The quantity Ω is proportional to relative number of all such constituent configurations which contain the configuration defined by the fractions x_1, x_2, y_a, and y_b. We use $\delta_1 = \delta_2 \equiv \delta$, $M_1 = M_2$, $\epsilon_a = \epsilon_b \equiv \epsilon_F$, and $m_2 = m_1$ in the analysis of proton-(anti)proton interactions. The parameters δ and ϵ_F were found to have constant values. They are interpreted as fractal dimensions in the space of the momentum fractions. We determine the fractions x_1, x_2, y_a, and y_b in a way to maximize the function Ω under the condition (1). The maximal value of Ω is used in the definition of the scaling variable z which has the form

$$z = z_0\Omega^{-1}. \tag{3}$$

The part $z_0 = s_\perp^{1/2}/(dN_{ch}/d\eta|_0)^c$ is proportional to the transverse kinetic energy $s_\perp^{1/2}$ of the subprocess consumed on the production of (m_1) and (m_2). The charged multiplicity density

$dN_{ch}/d\eta|_0$ at $\eta = 0$ and constant c have thermodynamical interpretation. The scaling function

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

is expressed in terms of the inclusive cross section, multiplicity density $dN/d\eta$ of the particular hadron species, and total inelastic cross section. Here s is square of the center-of-mass energy, and J is the corresponding Jacobian. The function $\psi(z)$ is normalized to unity.

3 Properties of the scaling function

The z-dependence of data on inclusive spectra of hadrons produced in pp and $\bar{p}p$ collisions at ISR, S$p\bar{p}$S, RHIC, and Tevatron reveals the energy, angular, and multiplicity independence [5]. Here we analyze the experimental data (see [6] and reference therein) on the transverse momentum spectra obtained at RHIC and Tevatron. New properties of the scaling function $\psi(z)$ - the flavor independence and saturation at low z for different hadrons are established.

3.1 Flavor independence of $\psi(z)$

We exploit the transformation $z \to \alpha_F z,\ \ \psi \to \alpha_F^{-1}\psi$ for comparison of the shape of the scaling function $\psi(z)$ for different hadron species. The parameter α_F is a scale independent quantity. The transformation does not change the shape of $\psi(z)$. It preserves the energy, angular, and multiplicity independence of the z-presentation of particle spectra.

Figure 2(a) shows the z-dependence of the spectra of negative pions, kaons, antiprotons, and $\Lambda' s$ produced in pp collisions over the range $\sqrt{s} = 19 - 200$ GeV and $\theta_{cms} = 3^0 - 90^0$. The analysis comprises the inclusive spectra 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 antiprotons). The distributions of different hadrons are sufficiently well described by a single curve over a wide z-range ($0.01-30$). The solid lines and experimental data are shifted by multiplicative factors for reasons of clarity. The parameters ϵ_F and α_F are found to be independent of $\sqrt{s}, p_T$, and θ_{cms}. They are consistent with the energy, angular, and multiplicity independence of the z-scaling.

Figure 2(b) shows similar results for other hadrons ($\rho, \omega, \phi, K^*, \Xi$) produced in pp collisions at $\sqrt{s} = 200$ GeV and $\theta_{cms} = 90^0$. 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(a). The black circle 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. We conclude that RHIC data on pp collisions confirm the flavor independence of the z-scaling including the production of particles with small p_T.

The inclusive spectra of heavy hadrons ($J/\psi, D^0, B, \Upsilon$) obtained at the Tevatron energies $\sqrt{s}$ =1800 and 1960 GeV allow us to verify the new property of the z-scaling in $p\bar{p}$-collisions. The data include measurements up to small 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(a) shows the spectra of $J/\psi, D^0, B$, and Υ mesons in the z-presentation. The scaling function is the same for hadrons with light and heavy flavors in the range $z = 0.001 - 4$. The corresponding values of the parameters α_F and ϵ_F are shown in Fig. 3(a). Figure 3(b) demonstrates results of the combined analysis of the RHIC and Tevatron data on J/ψ-meson spectra measured in pp and $p\bar{p}$ collisions at $\sqrt{s} = 200, 1800, 1960$ GeV and $\theta_{cms} = 22^0, 90^0$ as a function of z.

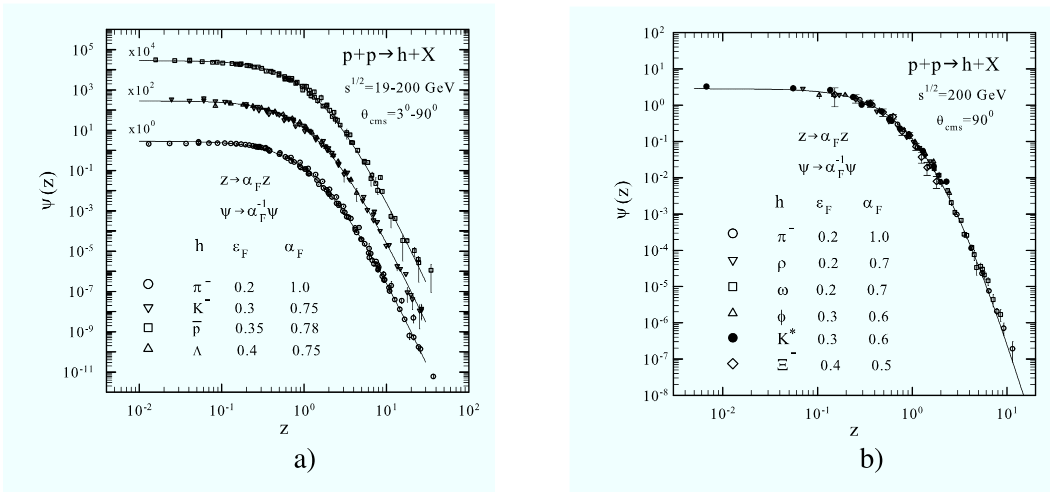

Fig. 2. The flavor independence of z-scaling. The spectra of π^-, K^-, $\bar{p}$, Λ (a) and ρ, ω, ϕ, K^*, Ξ (b) hadrons produced in pp collisions as a function of z. Data are obtained at CERN, FNAL, and BNL. The solid line is a fit of the data.

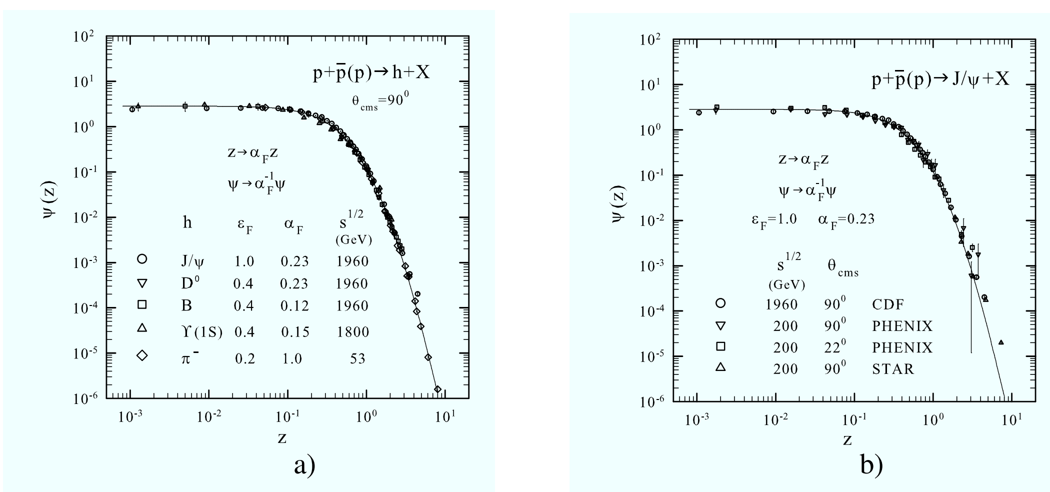

Fig. 3. The flavor independence of z-scaling. The spectra of $J/\psi, D^0, B, \Upsilon, \pi^-$ (a) and J/ψ (b) mesons produced in $pp/p\bar{p}$ collisions in z-presentation. Data are obtained at Tevatron and RHIC. The solid line is the same as shown in Fig. 2.

From this analysis we conclude that ISR, RHIC, and Tevatron data on inclusive spectra manifest the flavor independence of the scaling function $\psi(z)$ over a wide range of z. We would like to stress that the obtained result is based on p_T distributions of the cross sections $Ed^3\sigma/dp^3$ which reveal strong dependence on the energy, angle, multiplicity, and type of the produced particle.

3.2 Saturation of $\psi(z)$

As seen from Figs. 2 and 3, the z-presentation of hadron distributions demonstrates independence on the variable z in the soft (low p_T) region. The saturation is manifested by the pion, kaon, antiproton and especially J/ψ and Υ spectra in the range $z = 10^{-3} - 10^{-1}$. The similar independence is observed for other hadrons ($K^*, B, \rho, ...$) at low p_T. A characteristic of the saturation is the slope parameter β of the scaling function which is diminishing with the decreasing z. The value of $\beta = dln\psi(z)/dlnz$ is approximately zero for $z < 0.1$.

One can assume that the asymptotic behavior of $\psi(z)$ at $z \rightarrow 0$ is universal and reflects properties of the produced system consisting of its constituents (hadrons or quark and gluons). The universal scaling behavior in this region suggests that mechanism of particle production at low p_T is governed by soft self-similar processes which reveal some kind of a mutual equilibrium leading to the observed saturation.

4 Conclusions

The experimental data on inclusive cross sections of different hadrons measured at ISR, RHIC, and Tevatron were analyzed. The data cover a wide range of the collision energies, the transverse momenta, and the production angles. New properties of the z-scaling - the flavor independence and the saturation of $\psi(z)$ at low z, were established. The flavor independence of the z-scaling means that the shape of $\psi(z)$ is the same for different hadrons. A saturation regime of the function $\psi(z)$ was observed for $z < 0.1$. The approximate constancy of $\psi(z)$ was demonstrated up to $z \simeq 10^{-3}$ for charmonia and bottomia. The variable z depends on the parameters δ, ϵ_F, and c. The parameters δ and ϵ_F characterize structure of the colliding objects and fragmentation process, respectively. Their values are fixed by the energy, angular, and multiplicity independence of $\psi(z)$ in the high-p_T part of the spectra. The parameter c is interpreted as "specific heat" of the produced medium. The z-scaling is consistent with $c = 0.25$ and $\delta = 0.5$ for all types of the analyzed inclusive hadrons. The value of ϵ_F increases with the mass of the produced hadron. It was found that the parameters are independent of kinematical variables.

We conclude that soft and hard regimes of hadron production manifest self-similarity of particle production at a constituent level. 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 proton-antiproton collisions at RHIC, Tevatron, and LHC.

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References

[1] BRAHMS Collaboration, I. Arsene *et al.*, Nucl.Phys. **A757**, 1 (2005).

[2] PHOBOS Collaboration, B.Back *et al.*, Nucl.Phys. **A757**, 28 (2005).

[3] STAR Collaboration, J. Adams *et al.*, Nucl.Phys. **A757**, 102 (2005).

[4] PHENIX Collaboration, K. Adcox *et al.*, Nucl.Phys. **A757**, 184 (2005).

[5] I.Zborovský and M.Tokarev, Phys.Rev. **D75**, 094008 (2007).

[6] I.Zborovský and M.Tokarev, arXiv:0809.1033 (hep-ph).