Saturation of Hadron Production in Proton-(anti)Proton Collisions at Low P_T

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Abstract

Experimental data on inclusive cross sections of the hadrons produced in high energy proton-(anti)proton collisions are analyzed in the z-scaling approach. Saturation of the scaling function $\psi(z)$ for $z < 0.1$ (low transverse momenta) was found. The first results on charged hadron spectra in pp collisions obtained by the CMS Collaboration at the LHC have confirmed the saturation down to the value of $z \simeq 0.05$. The CMS data on K_s^0-meson production at $s^{1/2} = 7$ TeV extend the saturation region even to a lower value of $z \simeq 0.002$ in the new energy domain. A microscopic scenario of hadron production at a constituent level based on the z-scaling is discussed in the saturation regime.

1 Introduction

The inclusive spectra carry information about the particle production mechanism and provide sensitive tool to probe dynamics of constituent interaction. Experimental data on hadron distributions from $pp/p\bar{p}$ collisions are a benchmark to investigate more complex processes in AA collisions. One of the methods based on mutual comparison of the data on inclusive cross sections at different collision energies, multiplicity densities, transverse momenta and detection angles, is based on z-scaling [1]. The approach reflects self-similarity as one of the basic symmetries in the hadron production at the constituent level. The scaling regularity includes the region of high transverse momenta as well as processes with small momenta and high multiplicities. The variable

$$z = \frac{\sqrt{s_\perp}}{W} \tag{1}$$

is the ratio of two quantities. The transverse kinetic energy $\sqrt{s_\perp}$ of the constituent sub-process consumed on production of the inclusive particle and its recoil partner (its antiparticle), is expressed in units of the nucleon mass. The quantity W is the maximal relative number of the constituent configurations $\{x_1, x_2, y_a, y_b\}$ which includes the configurations satisfying the kinematical condition

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

Here $M_X = x_1M_1 + x_2M_2 + m/y_b$ is a recoil mass, P_1, P_2, p, and M_1, M_2, m are the 4-momenta and masses of the colliding and inclusive particles, respectively. The value of W is related to the entropy of the rest of the system:

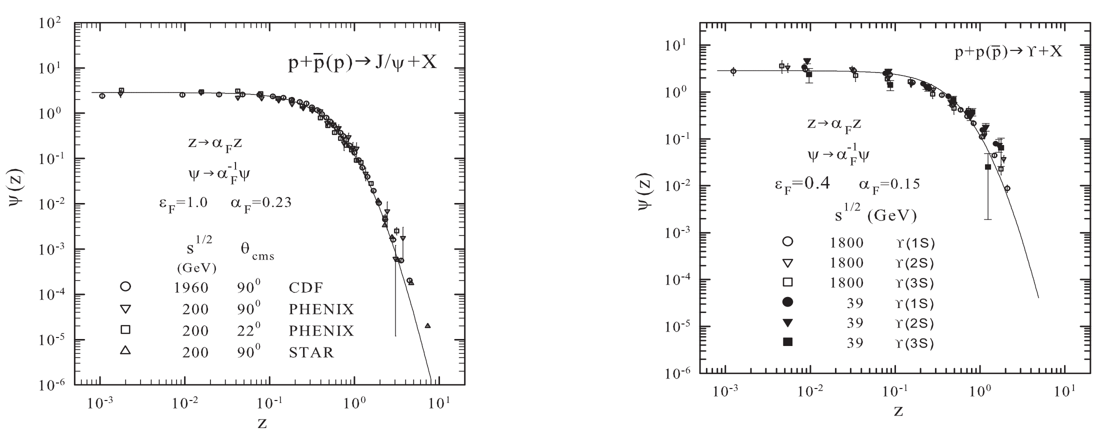
$$S = \ln W + \ln W_0. \tag{3}$$

The absolute number of configurations W_0 depends on the hadron type (F) and drops out of the z-scaling. The scaling functions $\psi(z)$ for different hadrons collapse onto a single curve by means of the transformation: $z \to \alpha_F z$, $\psi \to \alpha_F^{-1}\psi$, where $\alpha_F = W_0^F/W_0^\pi$. The transformation preserves the energy, angular and multiplicity independence of z-presentation of hadron spectra as well as normalization of $\psi(z)$ to unity.

2 z-Scaling in soft $pp/p\bar{p}$ interactions

In this contribution we focus on the soft region of the $pp/p\bar{p}$ interactions where collective phenomena at various levels can take place. The bulk of the produced matter at low-p_T consists of multitude of strongly interacting constituents. Though there is no direct information on the type of the constituents, the microscopic scenario based on the z-scaling allows us to extract information on kinematics of the constituent sub-processes. This is obtained by the assumption on self-similarity of hadron interactions at the constituent level and translated into the functional form of variable z.

The scaling variable z includes a combination of the kinematical characteristics of the constituent sub-processes with some parameters (c, δ, ϵ_F) describing the system. Parameter c has analogy with the specific heat of the produced matter. The parameters δ and ϵ_F are fractal dimensions of the colliding protons (antiprotons) and the fragmentation process, respectively. The determination of the parameters by self-similarity arguments from the measured spectra gives dependencies of the momentum fractions $\{x_1, x_2, y_a, y_b\}$ on the collision energy and centrality, transverse momentum, detection angle, and type of the produced particle. This provides a microscopic scenario of the underlying constituent sub-processes. This approach is applied for arbitrary momenta of the inclusive particle. For $pp/p\bar{p}$ collisions it has been found that $c = 0.25$, $\delta = 0.5$, and ϵ_F depends on the type of the inclusive hadron.

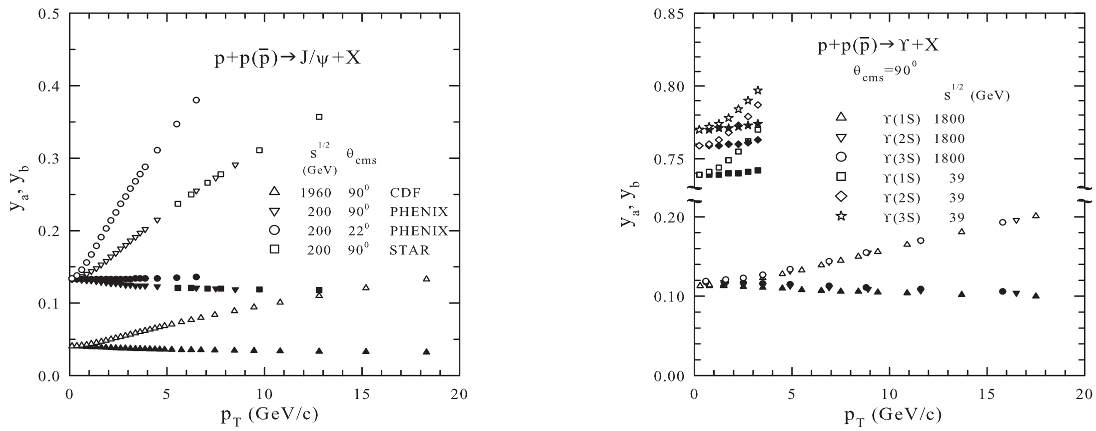


a) b)

Figure 1: (a) The spectra of J/ψ-mesons measured at $\sqrt{s} = 200$ GeV for $\theta_{cms} = 90^0, 22^0$ and at $\sqrt{s} = 1960$ GeV for $\theta_{cms} = 90^0$ in z-presentation. (b) The spectra of $\Upsilon(1S)$-, $\Upsilon(2S)$-, and $\Upsilon(3S)$-mesons measured at $\sqrt{s} = 39$ and 1800 GeV in z-presentation.

The soft processes in $pp/p\bar{p}$ interactions are typical for the low-p_T particle production with small z. In this region the saturation of the scaling function $\psi(z)$ for $z < 0.1$ was observed [1]. The measurements of spectra for identified particles extend the approximate constancy of $\psi(z)$ to even lower values of z. The z-presentation of inclusive spectra of pions, kaons, and antiprotons measured at ISR energies revealed the saturation in the region of $0.01 < z < 0.1$.

This was confirmed by the measurements of K^* resonance at RHIC at the value of $z \simeq 0.007$ [2]. The inclusive spectra of heavier hadrons ($J/\psi, D^0, B, \Upsilon$) obtained at the Tevatron energies $\sqrt{s}$ =1800 and 1960 GeV have manifested the saturation of the z-scaling in $p\bar{p}$ collisions down to $z \simeq 0.001$.



a) b)

Figure 2: The p_T-dependence of the momentum fractions y_a and y_b for (a) J/ψ- and (b) Υ-mesons produced in $pp/p\bar{p}$ collisions by different kinematical conditions. The empty and full symbols correspond to y_a and y_b, respectively.

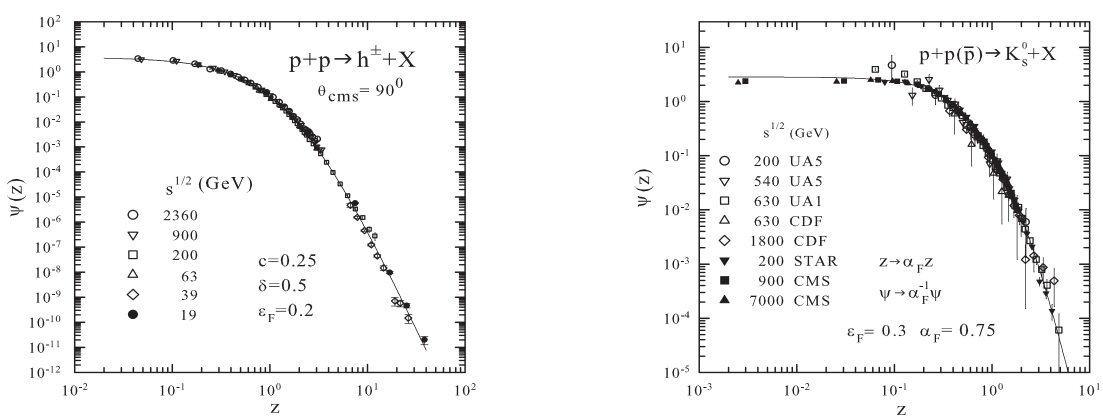
Figure 1(a) demonstrates results of the combined analysis of the RHIC [3, 4] and Tevatron [5] data on J/ψ-meson spectra measured in pp and $p\bar{p}$ collisions at the energies $\sqrt{s} = 200$, 1960 GeV and angles $\theta_{cms} = 22^0, 90^0$ in z-presentation. Similar results are shown in Fig. 1(b) for different mass states ($1S, 2S, 3S$) of Υ-mesons produced at $\sqrt{s} = 39$ GeV [6] and $\sqrt{s} = 1800$ GeV [7], respectively. The solid line in Fig.1(b) is the same fit as shown in Fig. 1(a). As seen from Figs. 1(a) and 1(b), the z-presentation of the J/ψ and Υ spectra manifests saturation in the range $z = 10^{-3} - 10^{-1}$ for different collision energies, production angles, and respective mass states of Υ-meson.

The dependencies of the fractions y_a (empty symbols) and y_b (full symbols) on the transverse momentum p_T of the inclusive particle are shown in Fig. 2. The momentum fraction y_a characterizes the energy loss ($\Delta E \sim 1 - y_a$) by formation of the inclusive particle. The energy loss increases with the collision energy $\sqrt{s}$ and decreases with the transverse momentum p_T. It is considerably larger in the central region ($\theta_{cms} = 90^0$) than in the fragmentation ($\theta_{cms} = 22^0$) one. Production of the J/ψ-meson is accompanied with extra large energy losses and recoil mass M_X when compared with other hadrons. It corresponds to relatively small values of y_a, y_b and the large value of $\epsilon_{J/\psi} = 1$ as required by the energy independence of $\psi(z)$. For Υ-meson, the energy loss is sensitive to its respective mass state at $\sqrt{s} = 39$ GeV. It was found to be the smallest for the $3S$ state. The energy loss increases and is equalized for all three mass states of Υ at $\sqrt{s} = 1800$ GeV.

The values of y_b become considerably smaller than the values of y_a as p_T increases. This means that the momentum balance in the production of the inclusive particle from the subprocess is more likely compensated by the states with higher multiplicity of particles having smaller momenta than by a single particle with a higher momentum moving in the opposite direction. The observed property is directly related with the recoil mass in the constituent collision. For high collision energies it is well approximated by $M_X \simeq m/y_b$. At low transverse momenta both fractions y_a and y_b become equal to each other. It means that, at low p_T, the objects produced in the constituent collision into the near- and away-side direction, have equal masses. As a consequence, the approximate relation $v_p = p/m \simeq v_q = q/M_X$ is valid, where q is 4-momentum of the fragmenting objects in the scattered or recoil directions. This implies equal velocities v_p and v_q of the detected particles and their fragmenting ancestors though the mass of the ancestors M_X increases with the collision energy. This kinematics is in tune with the ideas of coherence in production of particles at low p_T.

3 New LHC data and saturation of $\psi(z)$ at low z

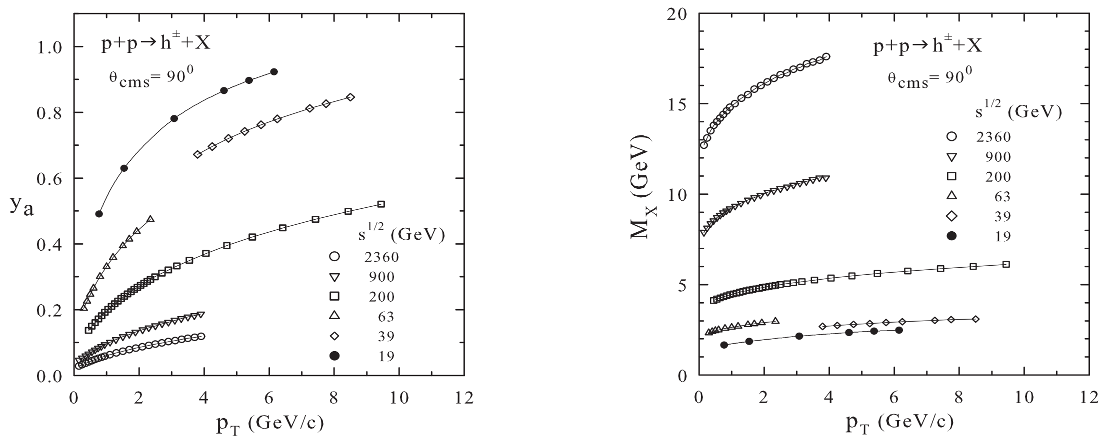
In this section we analyze the first data on transverse momentum distributions of the charged hadrons and neutral kaons produced in pp collisions at the LHC. The CMS Collaboration measured the spectra [8] of charged hadrons at the energies $\sqrt{s} = 900$ and 2360 GeV in the central rapidity range. Figure 3(a) shows z-presentation of the spectra in comparison with the data from RHIC [9], ISR [10], and FNAL (the fixed target) [11, 12] in the energy range $\sqrt{s_{NN}} = 19 - 2360$ GeV at $\theta_{cms} \simeq 90^0$. The CMS data have revealed similar tendencies as the data at lower energies. As it is seen from Fig. 3(a) the first LHC data on the charged hadron distributions have confirmed the energy independence of the scaling function with the same values of parameters δ, ϵ_F, and c. At low p_T, the data extend the saturation region of $\psi(z)$ for non-identified hadrons down to a value of $z \simeq 0.05$. The saturation of the scaling function is examined in the new energy range. The behavior of $\psi(z)$ at even lower z can be investigated by increasing the collision energy $\sqrt{s}$, or the multiplicity density $dN_{ch}/d\eta$, or by decreasing the transverse momentum. There is a special opportunity for neutral kaons to be measured for very small p_T.



a) b)

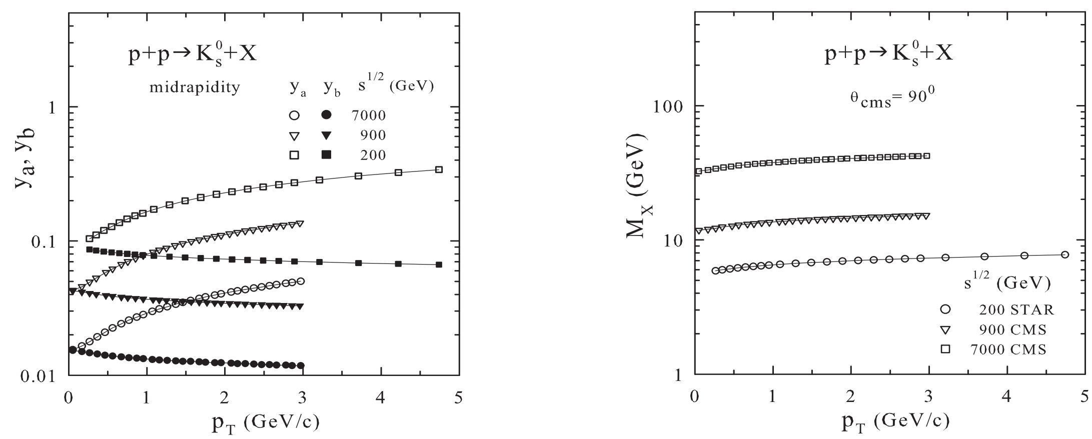
Figure 3: (a) The spectra of the charged hadrons produced in pp collisions at $\sqrt{s} = 19 - 2360$ GeV and $\theta_{cms} = 90^0$ in z-presentation. (b) The spectra of K_s^0-mesons produced in $pp/p\bar{p}$ collisions at $\sqrt{s} = 200 - 7000$ GeV and $\theta_{cms} = 90^0$ in z-presentation.

The CMS Collaboration at LHC measured the spectra of K_s^0-mesons [13] produced in pp collisions at the energies $\sqrt{s} = 900$ and 7000 GeV in the central rapidity range. The data include measurements at small transverse momentum $p_T \simeq 50$ MeV/c. Figure 3(b) shows z-presentation of the spectra in comparison with the data from the Collaborations STAR [14], UA5 [15], UA1 [16], and CDF [17] in the energy range $\sqrt{s_{NN}} = 200 - 7000$ GeV at $\theta_{cms} \simeq 90^0$. In the measured p_T range, the new LHC spectra are consistent with the z-scaling observed at lower energies. The saturation of the scaling function $\psi(z)$ for K_s^0-mesons is confirmed down to a value of $z \simeq 0.002$. When compared with Figs. 1(a) and 1(b), the constancy of $\psi(z)$ is verified in the new LHC energy domain for $z \simeq (0.002 - 0.1)$.



a) b)

Figure 4: The dependence of the fraction y_a (a) and the recoil mass M_X (b) on the transverse momentum p_T for the charged hadrons produced in the pp collisions at $\sqrt{s} = 19 - 2360$ GeV.



a) b)

Figure 5: The p_T-dependence of the fractions y_a, y_a (a) and the recoil mass M_X (b) for K_s^0-mesons produced in pp collisions at the energies $\sqrt{s} = 200, 900$, and 7000 GeV.

Figure 4(a) shows the growth of the energy loss $\Delta E \sim 1 - y_a$ with $\sqrt{s}$. For $p_T \simeq 4$ GeV/c, the energy loss is about 20% at $\sqrt{s} = 19$ GeV and 90% at $\sqrt{s} = 2360$ GeV. Figure 4(b) demonstrates the p_T-dependence of M_X for the charged hadrons produced in pp collisions at $\sqrt{s} = 19 - 2360$ GeV. The recoil mass at the LHC energy is considerably larger than at RHIC and SPS energies. For $p_T \simeq 4$ GeV/c it was found to be about $M_X \simeq 18$ GeV at $\sqrt{s} = 2360$ GeV which is much higher than the value of $M_X \simeq 2$ GeV at $\sqrt{s} = 19$ GeV. The similar tendencies are seen for K_s^0-mesons from Figs. 5(a) and 5(b). As at lower energies (Fig.2), equality $y_a \simeq y_b$ and large M_X at low p_T indicate the coherence in the soft processes at $\sqrt{s} = 7000$ GeV.

4 Conclusions

New data on charged hadron and K_s^0-meson production in pp collisions measured by the CMS Collaboration at the LHC, have confirmed the saturation of the scaling function $\psi(z)$ observed at lower energies at the ISR, SPS, RHIC, and Tevatron. A microscopic scenario of the hadron production based on the z-scaling was used to estimate the characteristic increase of the energy loss and recoil mass in the constituent interactions in the low-z region with the increasing collision energy $\sqrt{s}$. The universal scaling behavior in the saturation region suggests that mechanism of the particle production at low p_T is governed by soft self-similar processes which reveal some kind of a mutual equilibrium. The momentum fractions y_a and y_b at low p_T indicate the coherence in the processes with soft particle production.

5 Acknowledgments

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