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M.V.Tokarev*

THE VIOLATION OF Z-SCALING AS A POSSIBLE SIGNAL OF QUARK COMPOSITENESS

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*E-mail: tokarev@sunhe.jinr.dubna.su

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1 Introduction

The search of new particles and the study of their structure and general features of the interactions were traditionally the main goals of the high energy accelerators and colliders (SLAC, ISR, $Sp\bar{p}S$, Tevatron, HERA). Numerous experimental data obtained from hadron-hadron and lepton-hadron interactions show that the general tendencies can manifest themselves mostly in the high energy region. They reflect specific characteristics of the elementary constituent interactions.

This is especially actual in connection with the commission of the large accelerators of hadrons and nuclei - RHIC at Brookhaven and LHC at CERN. The main physical goals of the investigations on these colliders are to search for quark-gluon plasma - the hot and superdense phase of the nuclear matter, and new physics phenomena due to new interactions beyond the Standard Model, new particles and quark compositeness. Therefore it is extremely important to find the main features of $pp/\bar{p}p$ interaction (physics laws, scalings, etc.) in order to study the violation of scalings in extreme kinematic conditions (higher energy and transverse momentum, heavier mass particle production) and to study, in particular, the influence of nuclear matter in the heavy ion interactions. The colliders, $Sp\bar{p}S$ at CERN and Tevatron at Fermilab, provide the excellent possibility to study the features of $\bar{p}p$ interactions at colliding energy $\sqrt{s} = 630 - 1800\ GeV$. In future such investigations will be possible at LHC ($\sqrt{s} = 14\ TeV$) and at the collider of new generation - Very Large Hadron Collider ($\sqrt{s} = 50 - 200\ TeV$) [1].

Up to date, the investigation of hadron properties in the high energy collisions has revealed widely known scaling laws. From the most popular and famous let us mention the Bjorken scaling observed in deep inelastic scattering (DIS) [2], y-scaling valid in DIS on nuclei [3], limiting fragmentation established for nuclei fragmentation [4], scaling behaviour of the cumulative particle production [5, 6, 7], KNO scaling [8] and others.

The common feature of the mentioned processes indicates the local character of the interactions which leads to the conclusion about dimensionless constituents taking part in the interactions. However, detailed experimental study of the established scaling laws has shown certain violations of these. This can be connected with the dynamics concerning the transition from the perturbative QCD quarks and gluons to the observed hadrons.

The fact that the interaction is local naturally leads to the conclusion of the scale-invariance of the hadron interactions cross sections. The invariance is a special case of the automodelity principle which is an expression of self-similarity [5, 9]. This principle reflects the dropping of certain dimensional quantities or parameters out of the physical picture of the interactions. Therefore the appearance of dimensional parameter in definitive kinematical conditions leads to the violation of the scale-invariance and can be as a signal of internal structure of particle participating in the interaction and the new interactions beyond SM.

The production of large transverse momentum jets in hadron-hadron collision at high energies at $Sp\bar{p}S$ in CERN observed by the UA2 [10] and UA1 [11] collaborations confirming the hints of jet production in the experiment of the AFS collaboration [12] at ISR is one of the outstanding discovery supporting the theory of strong interaction - quantum chromodynamics (QCD). New experimental results [13] obtained by the CDF collaboration on jet production have been compared with calculation in next-to-leading QCD approximation and a discrepancy at high transfer energy $E_T > 200\ GeV$ has been found.

The search of new particles and new physics phenomena is connected with the increase of the colliding energy. The superhigh energy of Tevatron provides the research of *top* quark [14] and the quark compositeness. It is considered [15, 16, 17] that the existence of quark and lepton substructure will be signaled by the appearance of the contact interactions. At present the energy scale Λ of the new interaction is not known. It is considered [18] that the contact interactions can affect jet, direct photon, Drell-Yan pairs production and the effects will be most important with the growth of $\sqrt{s}$. The existence of the interaction can be responsible for the violation of electroweak symmetry instead of the dynamical breaking via Higg's mechanism.

The results obtained by the CDF and D0 collaborations based on analysis of jet and direct photon production have given the restriction on the value of anomalous dipole moments of quarks [20]. The repetition of the three generators of quarks and leptons strongly suggests that they are composite structures made up of more fundamental fermions. The search of the indicators of quark compositeness and particles of new generation (supersymmetry particles - squark, gluino, etc.) is performed at Tevatron [19] and is planned to perform at the Very Large Hadron Collider at the colliding energy $\sqrt{s} = 50 - 200\ TeV$.

One of indicators of the compositeness of quarks may be the violation of the new scaling, z-scaling, [21] in $\bar{p}p(pp)$-collisions at superhigh energy $\sqrt{s}$ in the high $p_\perp$-range.

In the paper the new scaling, z-scaling, for direct photon and jet production in $\bar{p}p$-collisions at high energy is considered. It is shown that the scaling function $H(z)$ depends on one dimensionless variable z and is expressed via the inclusive invariant cross section and the particle multiplicity at pseudorapidity $\eta = 0$. The obtained results are compared with available experimental data obtained by the UA1, UA2, CDF and D0 collaborations and support the scaling behaviour of direct photon and jet production. The verification of the z-scaling will be possible at the future superhigh energy hadron colliders LHC and VLHC. The hypothesis that the violation of z-scaling in $\bar{p}p(pp)$-collisions at superhigh colliding energy $\sqrt{s}$ in the high z-range can clarify the matter on compositeness of quarks is suggested.

2 Z-scaling in $\bar{p}p$ and pp Interactions at High Energies

In the section we shall follow the general scheme suggested in [21] to construct the scaling function. According to the self-similarity principle we choose the dimensionless variable z as a physically meaningful variable which could reflect the self-similarity (scale-invariance) as a general pattern of the hadron production. Then the scaling function $\psi(z)$ has to satisfy the equation

$$\frac{d\sigma}{dz} \equiv \psi(z). \tag{1}$$

The invariant differential cross section for the production of the inclusive particle m_1 depends on two variables, say $q_\perp$ and $q_\parallel$, through $z = (x_1(q_\perp, q_\parallel), x_2(q_\perp, q_\parallel))$ in the following way: vspace.1cm

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{s\pi}\left(\frac{d\psi(z)}{dz}\frac{\partial z}{\partial x_1}\frac{\partial z}{\partial x_2} + \psi(z)\frac{\partial^2 z}{\partial x_1 \partial x_2}\right). \tag{2}$$

At the high energies ($\sqrt{s} > 30\ GeV$) the expression (2) can be written in the form [21]

$$H(z) = \frac{4M^2(dN(0)/d\eta)^2}{4h(x_1, x_2)} \cdot E\frac{d^3\sigma}{dq^3}, \tag{3}$$

where $h(x_1, x_2)$ is known function [21].

The function $H(z)$ depends on one variable z specified as follows:

$$z = \frac{s_x^{1/2}}{\Delta M \cdot dN(0)/d\eta}, \tag{4}$$

The coefficient ΔM and $s_x^{1/2}$ are expressed via the kinematic variables, momenta and masses of colliding and produced particles:

$$\Delta M = 2M - m_1 - (x_1 M + x_2 M + m_2), \tag{5}$$

$$s_x^{1/2} = [x_1^2 M^2 + x_2^2 M^2 + 2x_1 x_2 (P_1 P_2)]^{1/2}, \tag{6}$$

with M, m_1, m_2 being nucleon and produced particles, respectively. The fractions x_1 and x_2 of the colliding nucleon momenta P_1 and P_2 are expressed in units of the nucleon mass:

$$x_1 = \frac{(P_2 q) + M_2 m_2}{(P_1 P_2) - M_1 M_2}, \quad x_2 = \frac{(P_1 q) + M_1 m_2}{(P_1 P_2) - M_1 M_2}. \tag{7}$$

Here P_1, P_2 and q are momenta of colliding nucleons and produced particles, respectively. Note that the fraction x_1 and x_2 are less than 1 for all values of q.

The relation (3) connects the inclusive differential cross section and the multiplicity density with the scaling function $H(z)$. The properties of the functions $\psi(z)$ and $H(z)$ under scale transformations of their argument z have been described in [21]. The assumption that $H(z)$ as the function of z reflects the features of mechanism of hadronization of parton and is proportional to fragmentation function has been argued in [21]. It is assumed that the fragmentation function D_q^h depends on the relative formation length z/z_{max} of the produced particle m_1.

Really, the variable z can be interpreted in terms of parton-parton collision with the subsequent formation of a string stretched by the leading quark out of which the inclusive particle is formed. The minimal energy of the colliding constituents is just the energy of the string which connects the two objects in the final state of the parton subprocess. The off-shell behaviour of the subprocess corresponds to a scenario in which the string has the maximal possible space-like virtuality. The string evolves further, splits into pieces decreasing so its virtuality. The resultant number of the string pieces is proportional to the number or density of the final hadrons measured in experiment. Therefore, we interpret the ratio

$$\sqrt{s_h} \equiv \sqrt{s_x}/(dN(0)/d\eta) \tag{8}$$

as a quantity proportional to the energy of a string piece $\sqrt{s_h}$ which does not split any more but during the hadronization converts into the observed hadron. The process of string splitting is self-similar in the sense that the leading piece of a string forgets the string history and its hadronization does not depend on the number and behaviour of other pieces.

The factor ΔM in the definition of z is proportional to the kinetic energy of the two objects in the final state of the parton subprocess and it can be considered therefore as something which reflects the tension of the string. We write therefore

$$\sqrt{s_h} = \Delta M \cdot \lambda, \tag{9}$$

where λ can be considered as the length of the elementary string peace or more precisely the ratio of the length to its characteristic (e.g. average or maximal) value.

The dimensional properties of the scaling function $H(z)$ (if $[z] = [fm]^0$ and $[z] = [fm]^1$ then $[H] = [fm]^2$ and $[H] = [fm]^0$, respectively) allow us to assume

$$H(\bar{z}) \sim D^h(\lambda). \tag{10}$$

So, we interpret the variable z as a quantity proportional to the formation length, at which the inclusive hadron is formed from its QCD ancestor. In this picture we interpret the variable z as a hadronization parameter, namely as hadronization length. The scaling function $H(z)$ reflects local properties of the hadronization process.

3 Z-scaling for Jet and Direct Photon Production in $\bar{p}p$ Interactions at High Energies

Before analyzing the results on z-scaling for direct photon and jet production in $\bar{p}p$ collisions we would like to remind of the results concerning the function $H(z)$ for charged hadrons produced in $pp(\bar{p}p)$-collisions at $\sqrt{s} = 63 - 1800\ GeV$ and $\theta \simeq 90^0$. The function $H(z)$ is shown in Figure 1. The experimental data are taken from [26, 28, 29]. Note that the data on inclusive cross sections at $\sqrt{s} = 630\ GeV$ [29] cover the kinematic region of transverse momenta of the secondary charged particles up to $q_\perp = 24\ GeV/c$. The results demonstrate the universality, the z-scaling, found in pp and $\bar{p}p$ collisions at high energies. At present there are not data on direct photon and jet production in pp-collisions at high energies ($\sqrt{s} > 63\ GeV$). We suppose, based on available D0 and CDF experimental data, that the general features of z-scaling of direct photon and jet production in pp-collisions may be the same as in $\bar{p}p$-collisions. However the direct experiment at pp-collider is necessary to verify the suggestion.

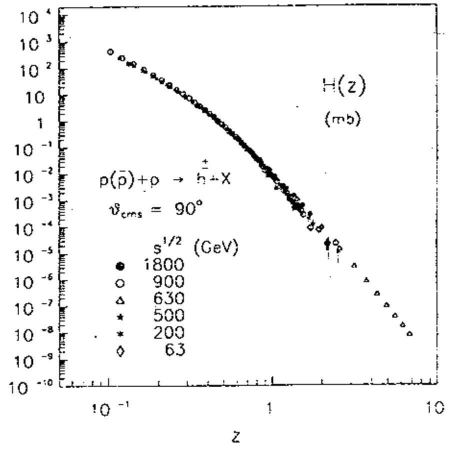

Figure 1. Scaling function $H(z)$ for charged particle production. Experimental data on inclusive differential cross section for charged hadrons in the $pp(\bar{p}p)$ interactions at $\theta = 90^0$ and $\sqrt{s} = 63 - 1800\ GeV$ are taken from **[26, 27, 29]**.

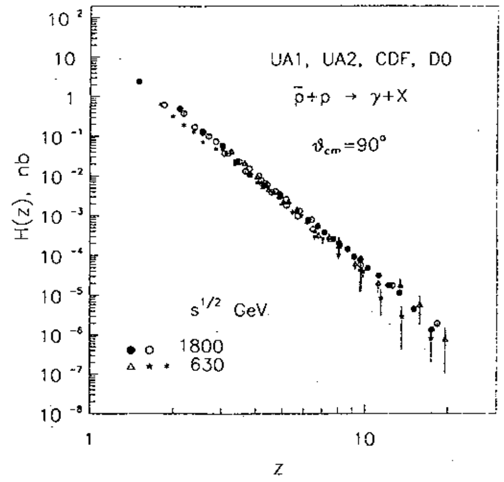

Figure 2. Dependence of $H(z)$ for direct photon production in $\bar{p}p$ interactions on z at colliding energy $\sqrt{s} = 630, 1800\ GeV$ and pseudorapidity $\eta \simeq 0$. Experimental data on inclusive differential cross section for direct photon production obtained by UA1, UA2, CDF and D0 Collaborations $\triangle$ - UA1 [30], $\star$ - UA2 [31], $\circ, \ast$ - CDF [32, 33], $\bullet$ - D0 [34] are used

Figures 2 and 3 show the dependence of the function $H(z)$ on z for direct photon and jet production at energy $\sqrt{s} = 630 - 1800\ GeV$ and pseudorapidity $\eta \simeq 0$, respectively. The available experimental data on inclusive cross section of direct photon and jet production are taken from [30]-[34] and [35, 36].

The results presented in Figure 2 for direct photon production show that the description of experimental data in terms of z-representation demonstrates the scaling behaviour.

Figure 3 shows the dependence of $H(z)$ on z obtained at the colliding energy $\sqrt{s} =$ 546, 630 and 1800 GeV. The results demonstrate the dependence of $H(z)$ on the colliding energy $\sqrt{s}$ of jet production in $\bar{p}p$-collision. So far as the jet is a group of particles moving along the direction inside the cone in (η, ϕ) space with close longitudinal momenta relative to their transverse ones the jet hadronization should be determined by hadronization of individual particles. In the central region the influence of spectators on jet hadronization is supposed to be smaller than in the beam fragmentation range. Therefore we believe that the jet hadronization can be different in these ranges and dependent on energy $\sqrt{s}$. The z-scaling means, from our point of view [21], the universality of mechanism of hadronization - the transition of "point-like" parton to observed particle or jet. The hypothesis of the energy scaling predicts that the jet production cross section should be independent of colliding energy $\sqrt{s}$. The available experimental results do not confirm it. We suppose that the energy scaling of $H(z)$ will be valid at energy higher than $\sqrt{s} = 1800\ GeV$. Therefore the experimental verification of the suggestion is necessary to perform.

It should be emphasized that the cross sections are measured in the central rapidity range for the transverse momentum of particle, jet and direct photon up to 24 GeV/c, 400 GeV and 100 GeV/c, respectively. It is considered that the elementary subprocesses in the kinematic range (high energy and high transverse momentum) are hard ones and can be described in the framework of perturbative QCD. Direct photon production is sensitive to the gluon luminosity inside a hadron because it is mainly produced by quark-gluon scattering. For the same reason this process is also sensitive to the anomalous couplings of quarks and gluons. Chromomagnetic (CMDM) and chromoelectric (CEDM) dipole moments couplings of quarks are important because a nonzero value for the CEDM is a clear signal of CP violation. The effects of the anomalous couplings have been studied in [22]-[25]. According to [22]-[25] the effective Lagrangian for the interactions between a quark and a gluon including the CMDM and CEDM form factors is written in the form

$$\mathcal{L}_{eff} = g_s \bar{q} T^a [-\gamma^\mu G^a_\mu + \frac{k}{4m_q}\sigma^{\mu\nu} G^a_{\mu\nu} - \frac{i\tilde{k}}{4m_q}\sigma^{\mu\nu}\gamma^5 G^a_{\mu\nu}] q, \qquad (11)$$

where g_s is effective coupling constant, m_q is the mass of quark, $k/4m_q$ and $i\tilde{k}/4m_q$ are CMDM and CEDM of the quark q. The Lagrangian gives an effective qqg vertex and also induces a $qqgg$ interaction which is absent in SM. It was shown in [24, 25] that the nonzero values of CMDM and CEDM will increase the total and differential cross section of direct photon production, especially in the high $p_\perp$-range. The increase of the cross section due to the anomalous moments causes the enhancement of $H(z)$ in the high z-range.

The experimental verification of z-scaling of direct photon production and comparison with the results obtained in the framework of QCD could give an unambiguous conclusions on the value of dipole moment couplings and CP violation.

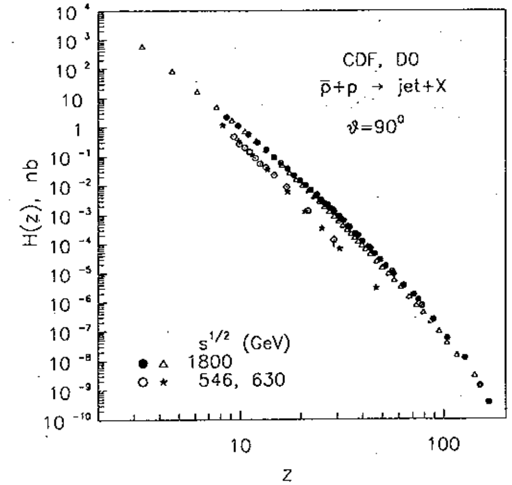

Figure 3. Scaling function $H(z)$ for jet production. Experimental data on inclusive differential cross section for jet production in the $\bar{p}p$ interactions at $\sqrt{s} = 546, 630$ and 1800 GeV are taken from [35, 36]

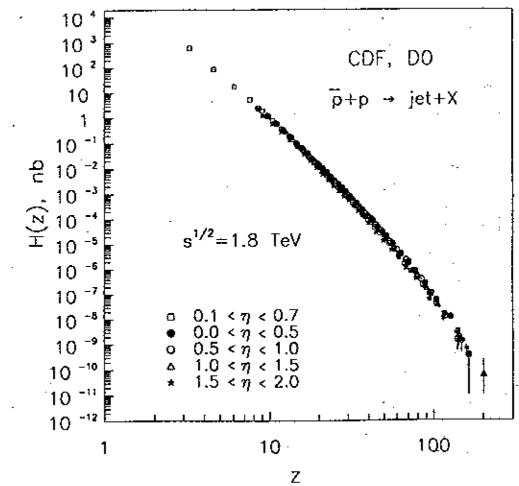

Figure 4. Scaling function $H(z)$ for jet production. Experimental data on inclusive differential cross section for jet production in the $\bar{p}p$ interactions at $\sqrt{s} = 1800\ GeV$ and different rapidity intervals are taken from [35, 36]

We suppose that the contact interaction signaling on the quark compositeness [15, 16, 17] can modify the z-scaling too.

Figure 4 shows the dependence of $H(z)$ on z for jet production at $\sqrt{s} = 1800\ GeV$ and for different rapidity intervals. It was found that the angular scaling for jet production is valid in the central rapidity range $|\eta| = 0 - 2$.

The angular dependence of $H(z)$ on z as well as the energy one may be sensitive to the anomalous couplings of quarks and gluons. Therefore the experimental verification of z-scaling of jet production in the central rapidity range and comparison with the results obtained in the framework of QCD could also give supplementary information on compositeness of quarks and gluons.

4 Conclusions

The z-scaling for direct photon and jet production in the $\bar{p}p$-collisions at the high energy is considered. It was shown that the available experimental data obtained by the UA1, UA2 and CDF, D0 collaborations at $Sp\bar{p}S$ and Tevatron colliders on jets and direct photon as well as for charged particle production demonstrate the scaling behaviour. The scaling function $H(z)$ is expressed via two experimental observables - the invariant inclusive cross section $Ed^3\sigma/dq^3$ and the multiplicity density $dN/d\eta(s)$ of particle production at pseudorapidity $\eta = 0$.

The obtained results for $H(z)$ give us strong arguments to conclude that the z-scaling of direct photon production in the $\bar{p}p$-collisions at the energy $\sqrt{s} = 630 - 1800\ GeV$ and $\eta \simeq 0$ is observed.

The function $H(z)$ vs z for jet production demonstrates the dependence of the colliding energy $\sqrt{s}$. The independence of $H(z)$ of the produced jet angle in the central rapidity range $0 < |\eta| < 2$ takes place.

The more detail experimental study of the z-scaling of direct photon and jet production in $\bar{p}p$- and pp-collisions at the energy $\sqrt{s} > 1800\ GeV$ will be possible in future experiments planned to perform at Tevatron (Fermilab) and LHC (CERN). The scaling proposed can be an excellent "instrument" in searching for new phenomena both in hadron-hadron, hadron-nucleus and nucleus-nucleus interactions. The verification of the violation of z-scaling is proposed to search the anomalous couplings and quark compositeness at the collider of new generation - Pipetron.

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