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# Z-SCALING AND PROMPT PHOTON PRODUCTION IN HADRON-HADRON COLLISIONS AT HIGH ENERGIES

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# 1 Introduction

A search for general properties of quark and gluon interactions beyond Quantum Chromodynamics (QCD) in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions is one of the main goals of high energy particle and relativistic nuclear physics. A high colliding energy allows us to study hadron-hadron collisions in the framework of perturbative QCD [1].

At present systematic investigations of prompt photon production at a colliding energy up to $\sqrt{s} = 1800\ GeV$ are performed at Tevatron by the CDF [2] and D0 [3] Collaborations. A high energy of colliding hadrons and a high transverse momentum of produced photons guarantee that QCD can be used to describe the interaction of hadron constituents.

Prompt photon production is one among very few signals which can provide direct information on the partonic phase of interaction. 'Penetrating probes', photons and dilepton pairs are traditionally considered to be one of the best probes for quark-gluon plasma (QGP) [4]. Direct photons do not feel strong forces, they provide both an undisturbed picture of the collision at very short times and a comparison sample for understanding the interaction between quarks and gluons and the surrounding nuclear matter.

It is considered that the fragmentation of partons into hadrons might be one of the least understandable features of QCD [5]. Even though the primary scattering process is described in term of perturbative QCD, the hadronization chain contains very low $q_\perp$-hadrons, respective to the parent parton. Therefore, the whole process is clearly a non-perturbative phenomenon involving final state interactions which have to conserve colour and baryon number. In contrast to the foregoing, it is often assumed that the direct photon production probes the parton-parton interaction without the ambiguities associated with jet identification, fragmentation and energy measurement. It is considered that there is a possibility to identify the process which is well understood from the theoretical point of view and in which the gluon contribution can be determined. In $pp$ collisions at high energies, the dominant mode of direct photon production is through the process of Compton scattering ($gq \rightarrow \gamma q$). The cross section is thus sensitive to the gluon distribution at low momentum fraction $x$.

A search for general properties of prompt photon production in hadron-hadron collisions is of great interest, especially in connection with commissioning such large accelerators of nuclei as RHIC [6, 7] at Brookhaven and LHC [8] at CERN. The main physical goal of investigations on these colliders is to search for quark-gluon plasma, the hot and superdense phase of nuclear matter. Therefore, the features of direct photon production observed in hadron-hadron interactions allow us to extract nuclear effects and to study the influence of nuclear matter on the mechanism of photon formation in $pA$ and $AA$ collisions. A comparison of the cross sections of direct photons produced in hadron-hadron, hadron-nucleus and nucleus-nucleus interactions both in central and non-central rapidity regions allows us to understand in detail underlying physical phenomena due to the presence of nuclear matter. It is considered that nuclear matter can transit from a usual hadronic phase to an exotic state, named partonic phase or QGP.

However, the direct photon production in the partonic phase of hadron-hadron interactions can differ from that in the hadronic phase. The process is connected with the space-time evolution of a primary (point-like) photon. During the evolution, the primary photon interacts with vacuum and nuclear fields through $q\bar{q}$-pair fluctuations and forms a "coat". The process of bare photon "dressing" is photon hadronization. Photon hadronization is the process forming the hadronic (non-perturbative) component of the photon structure function. The existence of the hadronic component of the photon is established in the investigations of deep-inelastic electron-proton scattering with jet production at HERA [9]. It is possible that the photon hadronization has features which differ from the particle hadronization but they might have general features, too.

We consider the direct photon production based on the concept of $z$-scaling. The hypothesis of the $z$-scaling of prompt photon production in $pp$ collisions has been suggested in [10] and studied in [11]. Based on the physics sense of the scaling function $H(z)$ and the variable $z$, we can study a fundamental process - photon hadronization and hadron content of the photon in different processes, for example, in $pp$ and $\bar{p}p$ collisions. The function $H(z)$ describes the probability to form the hadronic component of the photon with formation length $z$ and, consequently, the space-time evolution of the process.

In this paper, we use the formalism of $z$-scaling [12] for the description of direct photon production in $pp$ and $\bar{p}p$ collisions at high energies. The paper is organized as follows. The scaling is based on such fundamental principles of nature as self-similarity, locality, scale-relativity, fractality, and scale-relativity. First, one reflects the dropping of certain dimensional quantities or parameters out of the physical picture of interactions. Second, one concludes that the momentum-energy conservation law is locally valid for interacting constituents. Third, the fractality principle says that both the structure of interacting particle and its formation mechanism are self-similar in a kinematic range. Fourth, the scale relativity principle states that the structures of interactions and interacting objects reveal self-similarity and fractality on any scale [13, 14].

It has been found [12] that the scaling function $H(z)$ is expressed via two experimental observables, inclusive cross section $Ed^3\sigma/dq^3$ and the multiplicity density of charged particles $dN/d\eta|_{\eta=0} = \rho(s)$. The function $H(z)$ is found to be independent of center-of-mass energy $\sqrt{s}$ and the angle of produced particle $\theta$. The symmetry properties of $H(z)$ allow us to connect the scaling functions for different particles $(\pi^{\pm}, K^{\pm})$. The transformation parameter $a^{h/\pi^+}$ is interpreted as a relative formation length. The scaling function $H(z)$ describes the probability to form the hadron with formation length $z$. The universality of $H(z)$ means that the hadronization mechanism of particle production is of universal nature. So, the function is well defined in hadron-hadron collisions, and therefore it can be used to study the feature of prompt photon production as well as hadrons.

The $z$-scaling of direct photon production in $pp$ and $\bar{p}p$ collisions at high energies is studied in this paper. The general concept of $z$-scaling is described in Section 2. Such fundamental principles as self-similarity, locality, scale-relativity and fractality are used to construct the scaling function $H(z)$. The properties of the function $H(z)$, as well as energy and angular independence, are verified. The results of our analysis of the available experimental data and their comparison with usual data presentation of the data are given in Section 3. The available experimental data for direct photon production are shown to confirm both the energy and angular scaling of $H(z)$ over a wide range of $\sqrt{s}$ and $\theta_\gamma$. The obtained results and their interpretation are discussed in Section 4. Based on the physical meaning of the function $H(z)$ as a probability to form the photon with formation length, the conclusion is drawn that $H(z)$ describes the space-time evolution of the photon hadronic component. The universality of the scaling function $H(z)$ is used to predict the cross sections of photon production at RHIC, LHC and VLHC energies. Some conclusions are summarized in Section 5.

## 2 General concept of $z$-scaling

Let us consider the inclusive process

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

where $M_1$ and $M_2$ are the masses of colliding hadrons and $m_1$ is the mass of produced inclusive particle. In accordance with Stavinsky's ideas [15], the gross features of the inclusive particle distributions for reaction (1) at high energies can be described in terms of the corresponding kinematic characteristics of the exclusive parton subprocess

$$(x_1M_1) + (x_2M_2) \to m_1 + (x_1M_1 + x_2M_2 + m_2). \tag{2}$$

The parameter $m_2$ is a minimum mass introduced in connection with internal conservation laws (for isospin, baryon number and strangeness). The $x_1$ and $x_2$ are the scale-invariant fractions of the incoming 4-momenta $P_1$ and $P_2$ of colliding objects

$$x_1 = \frac{(P_2q) + M_2m_2}{(P_1P_2) - M_1M_2}, \qquad x_2 = \frac{(P_1q) + M_1m_2}{(P_1P_2) - M_1M_2} \tag{3}$$

The secondary particle carries away momentum $q$. The centre-of-mass energy of subprocess (1) is defined as

$$\hat{s} = x_1^2 \cdot M_1^2 + x_2^2 \cdot M_2^2 + 2x_1 \cdot x_2 \cdot (P_1P_2) \tag{4}$$

and represents the energy of colliding constituents necessary for the production of the inclusive particle. The cross section of the inclusive particle production in hadron-hadron interactions in the framework of the parton model is governed by the minimum energy of colliding constituents

$$\sigma \sim 1/s_{\min}(x_1, x_2). \tag{5}$$

The fractions $x_1$ and $x_2$ which correspond to the minimum value of (2) were found in [12] under an additional constraint

$$\frac{\partial\Delta_q(x_1, x_2)}{\partial x_1} = 0, \qquad \frac{\partial\Delta_q(x_1, x_2)}{\partial x_2} = 0. \tag{6}$$

where $\Delta_q(x_1, x_2)$ is given by the equation

$$(x_1P_1 + x_2P_2 - q)^2 = (x_1M_1 + x_2M_2 + m_2)^2 + \Delta_q(x_1, x_2) \tag{7}$$

So, the fractions $x_1$ and $x_2$ minimize the value of $\Delta_q$, simultaneously fulfilling the symmetry requirement of the problem, i.e. $x_1 = x_2$ for the inclusive particle detected at 90° in the corresponding $NN$ centre-of-mass system.

In accordance with the self-semilarity principle, we search for the solution

$$\frac{d\sigma}{dz} \equiv \psi(z), \tag{8}$$

where $\psi(z)$ has to be a scaling function, and we choose the variable $z$ as a physically meaningful variable which could reflect self-similarity as a general pattern of hadron production. As shown in [12, 14], the choice of $z$ in the form

$$z = \frac{2\sqrt{s}}{M \cdot \Omega \cdot \rho(s)}, \tag{9}$$

allows us to obtain a universal description of the spectra of particles ($h = h^{\pm}, \pi^{\pm}, K^{\pm}, p^{-}$) produced in $pp$ and $\bar{p}p$ collisions at high energies over a high transverse momentum range. The coefficient $\Omega$ is considered to describe the tension of a string stretched by partons. The dynamic quantity $\rho(s)$ represents the average multiplicity density of charged particles produced in the central region of collisions at a given energy $\sqrt{s}$. The coefficient $\Omega$ depending on $x_1$ and $x_2$ is introduced to take into account various degrees of "softness" of the subprocesses underlying secondary particle production. The factor for particle production in the central rapidity range, can be written as

$$\Omega = [(1-\lambda_1)\cdot(1-\lambda_2)]^{\delta}. \tag{10}$$

Here, the coefficients $\lambda_1$ and $\lambda_2$ are expressed via the fractions $x_1$ and $x_2$ as follows

$$\lambda_1 = x_1 + \sqrt{x_1 \cdot x_2 \cdot \frac{(1-x_1)}{(1-x_2)}}, \qquad \lambda_2 = x_2 + \sqrt{x_1 \cdot x_2 \cdot \frac{(1-x_2)}{(1-x_1)}}. \tag{11}$$

The invariant differential cross section for the production of inclusive particle $m_1$ depends on two variables, $q_\perp$ and $q_\parallel$, through $z = z(x_1, x_2)$ and $x_{1,2} = x_{1,2}(q_\perp, q_\parallel)$ in the following way:

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{s\pi}\left[\frac{d\psi(z)}{dz}\frac{\partial z}{\partial x_1}\frac{\partial z}{\partial x_2} + \psi(z)\frac{\partial^2 z}{\partial x_1 \partial x_2}\right]. \tag{12}$$

Using (9), (12), we can obtain the expression

$$E\frac{d^3\sigma}{dq^3} = -\frac{1}{16\pi\rho(s)^2 M^2}\left[\frac{d\psi(z)}{dz}h_1(x_1,x_2) + \frac{\psi(z)}{z}h_2(x_1,x_2)\right]. \tag{13}$$

The functions $h_1$ and $h_2$ are proportional to the partial derivatives

$$h_1 = \frac{\partial z}{\partial x_1}\cdot\frac{\partial z}{\partial x_2}, \qquad h_2 = \frac{z\partial^2 z}{\partial x_1 \partial x_2}, \tag{14}$$

and $h_1 \simeq h_2$ in a high energy region ($\sqrt{s} > 30$ GeV). Therefore, the scaling function $H(z)$ is defined by the equation

$$H(z) \equiv -\frac{1}{16\pi}\left[\frac{d\psi(z)}{dz} + \frac{\psi(z)}{z}\right]. \tag{15}$$

Using (13) and (15), we obtain the relation

$$H(z) = \frac{(M_1+M_2)^2\rho^2(s)}{4h_1}\cdot E\frac{d^3\sigma}{dq^3} \tag{16}$$

connecting the inclusive differential cross section and multiplicity density $\rho(s)$ with the scaling function $H(z)$.

The properties of the scaling functions $\psi(z)$ and $H(z)$ under scale transformations of their argument $z$ can be written in the following form:

$$z \to \frac{z}{a}, \qquad H(z) \to \frac{1}{a^2}\cdot H(\frac{z}{a}). \tag{17}$$

Calculating $H(z)$ for the $p + p \to \gamma + X$ and $\bar{p} + p \to \gamma + X$ processes, we assume that $m_1 = m_2 = 0$. The fit of the experimental data to the multiplicity density of charged particles in the form $\rho(s) = 0.74s^{0.105}$ [16, 17] is used.

## 2.1 Features of Photon Hadronization

Now we would like to discuss a qualitative picture of direct photon production. There is a similar picture for hadron production. The variable $z$ is interpreted in terms of parton-parton collision with the subsequent formation of a string stretched by the leading quark of which the inclusive particle is formed [12]. The minimum energy of colliding constituents $s_{min}^{1/2}$ is just the energy of the string which connects the two objects in the final state of subprocess (2) where the string has the maximum space-like virtuality. Further the string evolved splits into pieces thus decreasing its virtuality. The resultant number of string pieces is proportional to the number/density of final hadrons measured in the experiment. Therefore, the ratio

$$\sqrt{s_h} \equiv \sqrt{s}/\rho(s) \tag{18}$$

is interpreted as a quantity proportional to the energy of a string piece $\sqrt{s_h}$ which is not split yet but converts into the observed hadron during the hadronization.

For direct photon production in $pp$ collisions, the dominant process is Compton scattering, $gq \to \gamma q$. At the first moment after its emission by quark, the photon is a point-like massless particle. The future evolution of the photon is governed by the quantum field dynamics. The process is known as the renormalization of the photon wave function. Really, the process corresponds to the formation of the hadron content of the photon. Some part of the process can be described in the framework of perturbative QCD, and the other one requires including nonperturbative effects. Both mechanisms of photon formation are experimentally studied (the first one, photon remnant of jet production in deep inelastic scattering and the second one, particle production in the framework of the vector dominant mechanism.)

The factor $\Omega$ is interpreted in [12, 14] as a quantity proportional to the tension of a string stretched between partons in a binary parton-parton collision. The value of $\Omega$ depends on the kinematical variables $x_i$ and the parameter $\delta$. This parameter reflects a dynamic nature of the string and should reflect its fractal structure. There is an internal tension in such a string. Splitting the string leads to sharing the string energy among two parts. One of them represents the masses of the remnants and the other one their mutual kinetic energy. Fractal dimension $\delta$ reflects directly the sharing amount. The value of the fractal dimension for direct photon production is found to be 2.

In the framework of the proposed scenario, the variable $z$

$$z \sim \sqrt{s_\perp}/\Omega \tag{19}$$

is considered to be proportional to the energy per one average parton-parton collision. In such an average collision, the string is converted into the final state having formation length $z$. Therefore, the scaling function should be proportional to the fragmentation function of the photon

$$H(z) \sim D^\gamma(z). \tag{20}$$

So, in this picture we interpret the variable $z$ as a hadronization length. The scaling function $H(z)$ reflects local properties of the hadronization process.

## 3 Z-scaling and Direct Photon Production

Before the results on direct photon production in $pp$ and $\bar{p}p$ collisions are analysed we would like to remind of the results on the $z$-scaling for charged hadrons produced in hadron-hadron collisions at $\sqrt{s} = 53 - 1800$ $GeV$ and $\theta = 90°$.

Figure 1(a) shows the dependence of the cross section on momentum $q_\perp$ for different values of energy $\sqrt{s}$. The experimental data are taken from [18, 19, 20, 21]. Note that the data on the inclusive cross section cover the kinematic region of the transverse momentum of secondary particles up to $q_\perp = 10$ $GeV/c$. The absolute values of the cross section change by a few orders with increasing $\sqrt{s}$ at high $q_\perp$. The scaling function $H(z)$ for the processes at the same energy $\sqrt{s}$ is shown in Figure 1(b). One can see that the obtained results demonstrate the universality - the $H(z)$ independence of colliding energy over a wide momentum range of produced particles. [2] Since the scaling function is well defined for particle production in hadron-hadron collisions, it is reasonable to use the concept of $z$-scaling for the analysis of direct photon production, too.

### 3.1 Energy Independence of $H(z)$

The hypothesis of energy scaling predicts that the direct photon production cross section will be independent of center-of-mass energy $\sqrt{s}$. We verify the hypothesis

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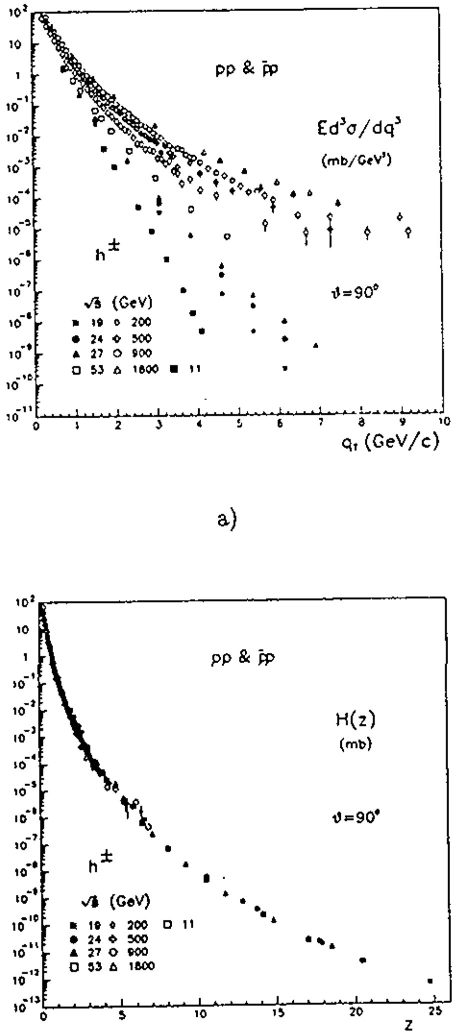
[2] The points for $H(z)$ at $\sqrt{s} = 11$ $GeV$ are obtained at a multiplicity density of $1.2\rho(s)$. Author is grateful to I.Zborovsky for discussion of the problem.



a)

b)

**Figure 1.** (a) Inclusive cross section of charged particle production in $pp$ and $\bar{p}p$ collisions at different center-of-mass energies $\sqrt{s}$ and at angle $\theta = 90^0$ as a function of transverse momentum $q_\perp$. Experimental data are taken from [18, 19, 20, 21]. (b) The corresponding scaling function $H(z)$.

for direct photon production in $pp$ and $\bar{p}p$ collisions using the available experimental data.

Figure 2(a) presents the dependence of the cross section of the $p + p \to \gamma + X$ process on photon momentum $q_\perp$ at $\sqrt{s} = 23.63$ $GeV$ and a produced angle $\theta$ of $90^0$. The experimental data on the cross section obtained by the collaborations WA70[22], R806[23], R807[24], R108[25], R110[26] are used. The data demonstrate the dependence of the cross section on colliding energy. Figure 2(b) shows the $z_\perp$-presentation in comparison with the $q_\perp$-presentation of the same data. Taking into account the experimental errors, we can conclude that the scaling function $H(z)$ of $\gamma$-direct production in $pp$ collisions demonstrates an energy independence.

Similar results are obtained for the $\bar{p} + p \to \gamma + X$ process. Figure 3(a) shows the dependence of the cross section on momentum $q_\perp$ for photon production in $\bar{p}p$ collisions at SppS and Tevatron energies $\sqrt{s} = 546, 630$ and 1800 $GeV$ and a produced angle $\theta$ of $90^0$. The experimental data on the inclusive cross section obtained at SppS and Tevatron by the UA1[27], UA2[28] and D0[3], CDF[2] collaborations, respectively, are used. The scaling function $H(z)$ corresponding to the same data is shown in Figures 3(b).

Figure 4 shows the $q_\perp$- and $z$-presentations of the data on direct photon production obtained by the CDF[2] collaboration at $\sqrt{s} = 630$ and 1800 $GeV$.

Thus, based on the obtained results, we can conclude that the energy scaling, the independence of the function $H(z)$ of direct photon production of colliding energy, is really observed both in $pp$ and $\bar{p}p$ collisions.

Taking into account the physical interpretation of $H(z)$ as the function describing the hadronization process, we can conclude that the formation of the hadronic component of the photon is a universal process. We would like to emphasize that at $\sqrt{s} = 1800$ $GeV$ (see Figure 4) the value of $H(z)$, which is proportional to the probability to find the photon with fixed hadronization length $z$, changes by more than 6 orders when the hadronization length itself changes from 5 to 80 and the transverse momentum $q_\perp$ of the photon changes from 10 to 120 $GeV/c$. The fact reflects the space-time evolution of the hadronic component formation of the photon.

## 3.2 Angular Independence of $H(z)$

Now, we would like to verify the angular scaling of direct photon production in $\bar{p}p$ collisions. The angular scaling means that the function $H(z)$ is independent of the angle $\theta$ of the produced photon.

Figure 5(a) shows the dependence of the cross section of the $\bar{p} + p \to \gamma + X$ process on the transverse momentum of the photon at $\sqrt{s} = 546$ and 630 $GeV$ for different rapidity intervals: $|\eta| = 0.0 - 0.8, 0.8 - 1.6, 1.6 - 3.0$. The experimental data [27] obtained by the UA1 collaboration were used. Figure 5(b) shows $H(z)$ as a function of variable $z$ obtained for the same data.

Figures 6(a) and 6(b) demonstrate the $q_\perp$- and $z$-presentation of the direct photon production data [28] obtained by the UA2 collaboration.

Thus, we have found that the function $H(z)$ at SppS energies is independent of the angle $\theta$ of the produced photon.

The angular independence of the scaling function is found at a Tevatron energy,

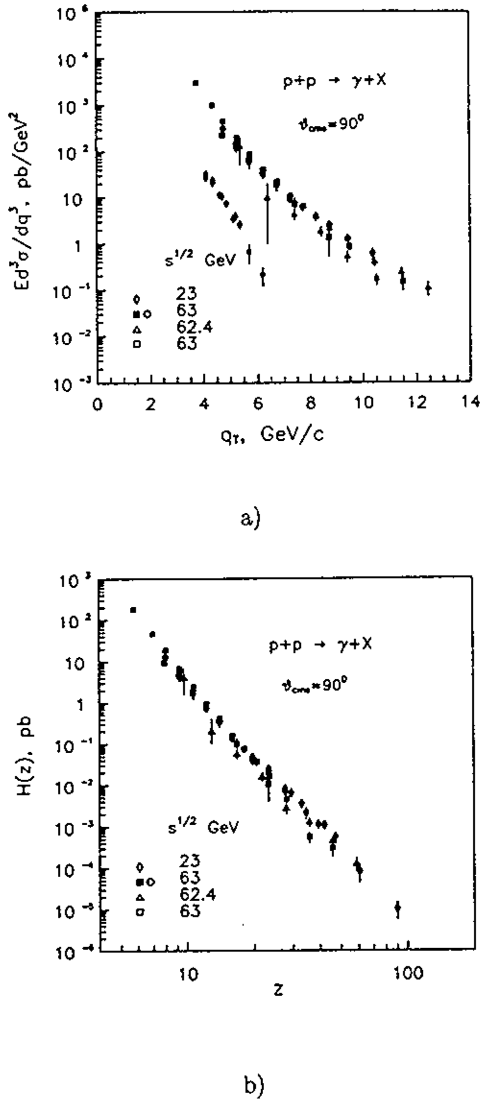


**Figure 2.** (a) Dependence of the inclusive cross section of direct photon production in $pp$ collisions on $q_\perp$ at energy $\sqrt{s} = 23, 63$ $GeV$ and pseudorapidity $\eta \simeq 0$. Experimental data on the cross section ◇ - WA70[22], • - R806[23], ○ - R807[24], △ - R108[25], □ - R110[26] are used. (b) The corresponding scaling function $H(z)$.

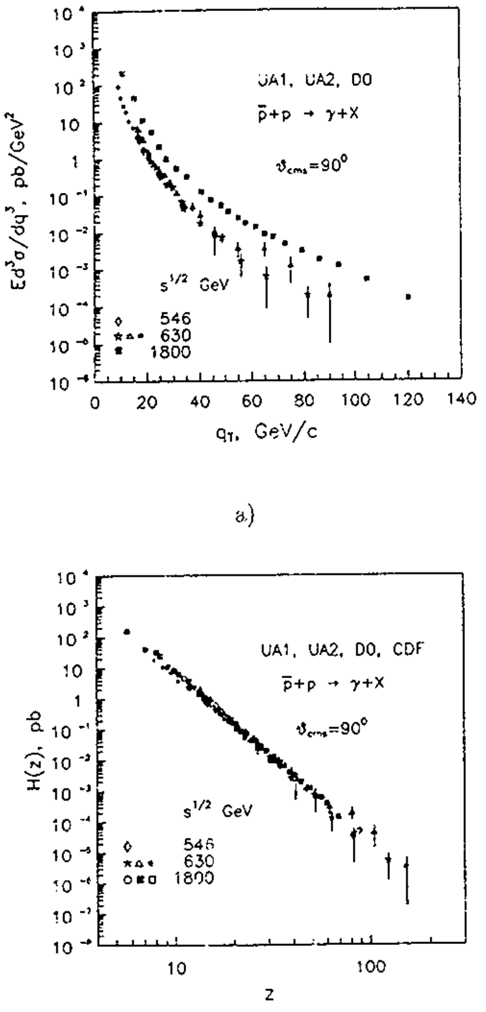


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**Figure 3.** (a) Dependence of the inclusive cross section of direct photon production in $\bar{p}p$ collisions on $q_\perp$ at energy $\sqrt{s} = 630, 1800\ GeV$ and pseudorapidity $\eta \simeq 0$. Experimental data on the cross section obtained by the D0, CDF, UA1 and UA2 collaborations • - D0 [3], ∘, $*$ - CDF [2, 17], △ - UA1 [27], ⋆ - UA2 [28] are used. (b) The corresponding scaling function $H(z)$.

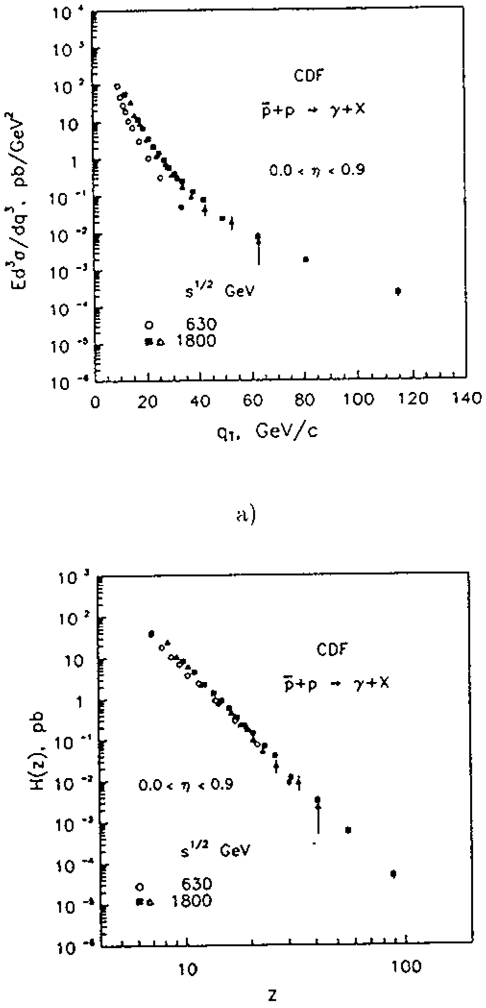

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**Figure 4.** Dependence of the inclusive cross section of direct photon production in $\bar{p}p$ collisions on $q_\perp$ vs energy $\sqrt{s}$ at pseudorapidity $\eta \simeq 0$. Experimental data on the cross section obtained by the CDF collaboration - •, △ [2] at $\sqrt{s} = 1800\ GeV$ and - ∘ [17] at $\sqrt{s} = 630\ GeV$ are used.

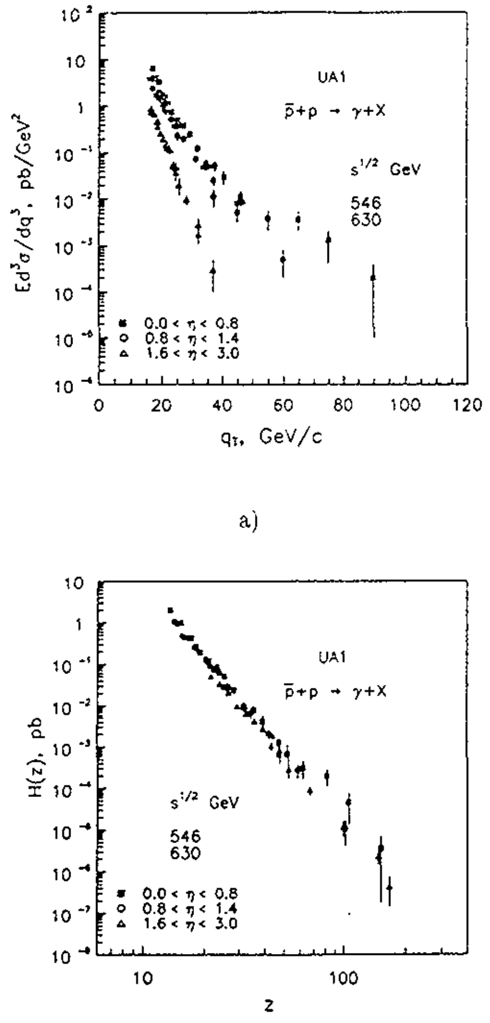

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**Figure 5.** (a) Dependence of the inclusive cross section of direct photon production in $\bar{p}p$ collisions on momentum $q_\perp$ for different pseudorapidity intervals at energy $\sqrt{s} = 546, 630$ $GeV$. Experimental data on the cross section obtained by the UA1 collaboration [27] are used. (b) The corresponding scaling function $H(z)$.

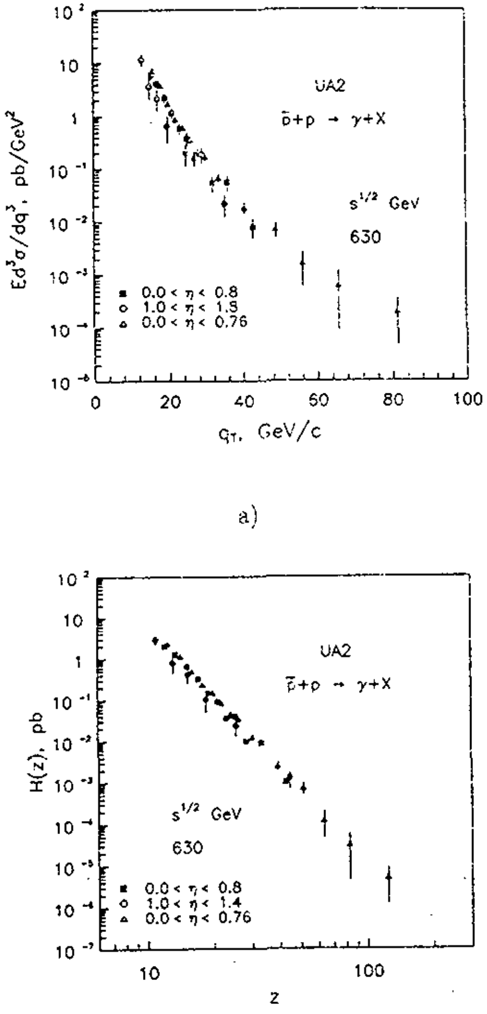

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**Figure 6.** (a) Dependence of the inclusive cross section of direct photon production in $\bar{p}p$ collisions on momentum $q_\perp$ for different pseudorapidity intervals at energy $\sqrt{s} = 630$ $GeV$. Experimental data on the cross section obtained by the UA2 collaboration [28] are used. (b) The corresponding scaling function $H(z)$.

too. The D0 collaboration has carried out the measurements [3] of the inclusive cross section of direct photon production at $\sqrt{s} = 1800$ $GeV$ and two rapidity intervals $|\eta| = 0.0 - 0.9, 1.6 - 2.5$. Figure 7, presenting the dependence of the $Ed^3\sigma/dq^3$ cross section and scaling function $H(z)$ on transverse momentum $q_\perp$ and variable $z$, respectively, confirms the conclusion.

### 3.3 Symmetry and Fractality Properties of $H(z)$

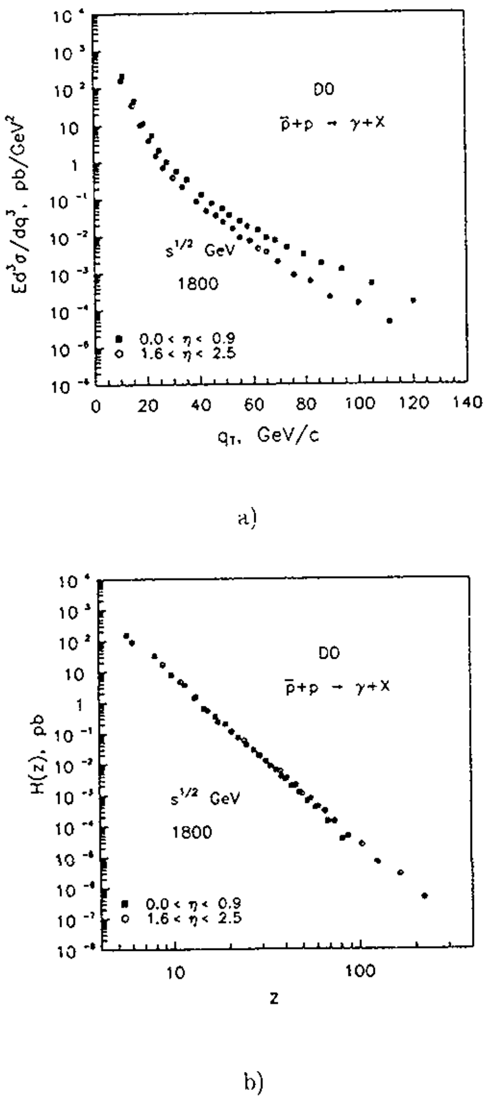
Here, we would like to study the symmetry property of the scaling function $H(z)$ for direct photon production in $pp$ and $\bar{p}p$ collisions. According to the general properties of $H(z)$ found for particle production, the scaling function changes under the scale transformation $z \to a^{-1}z$ as follows $H(z) \to a^{-2}H(a^{-1}z)$. The property allows us to connect the scaling functions for particles of different flavour content and argue the universality of the hadronization mechanism for different produced particles.

Figure 8 presents the scaling function $H(z)$ of direct photon production in $\bar{p}p$ and $pp$ collisions. The solid and dashed lines are the fits of the experimental data [3, 2, 17, 27, 28] and [22, 23, 24, 25, 26] for $\bar{p}p$ and $pp$ collisions, respectively. One can see from Figure 8 that both data sets demonstrates linear dependence of $H(z)$ on $z$ in log-log scale. This means, from our point of view, that the hadronization of the photon reveals a similar fractal behaviour $H(z) \sim z^{-\alpha}$ in these processes. Here, $\alpha$ is the fractal dimension of photon hadronization. The values of the slope parameter is found to be different ones for $pp$ and $\bar{p}p$ collisions: $\alpha_{pp} > \alpha_{\bar{p}p}$. We would like to give here a qualitative explanation of the result. Direct photons are mainly produced in $pp$ and $\bar{p}p$ collisions through the Compton and annihilation processes, respectively. In the first and second cases, the cross section is proportional to $G(x_1) \cdot q_V(x_2)$ and to $\bar{q}_V(x_1) \cdot q_V(x_2)$, respectively. The suppression of the gluon distribution $G(x_1)$ in the proton in comparison to the valence distribution $\bar{q}_V(x_1)$ in the antiproton leads to the relation $H^{\bar{p}p}_\gamma > H^{pp}_\gamma$.

Thus, the obtained results give us some arguments to assume that the $z$-scaling of direct photon production in $pp$ and $\bar{p}p$ collisions should be observed at an energy beyond ISR and Tevatron ones. Based on the universality of the scaling function $H(z)$ for $pp$ (Figure 9a) and $\bar{p}p$ (Figure 9b) collisions, we predict the dependence of the $\gamma$-direct cross section on the momentum of produced photon at RHIC and Tevatron energies, $\sqrt{s} = 500$ and $2000$ $GeV$, for different values of pseudorapidity, $\eta = 0, 1, 2$ and $0, 3, 4$, respectively.

Figure 10 shows the predictions of the $q_\perp$-dependence of the cross section of the $p+p \to \gamma + X$ process at an angle $\theta$ of $90^0$ for ISR, RHIC, LHC and VLHC energies. One can see that results obtained at $\sqrt{s} = 23$ and $63$ $GeV$ and shown by solid lines are in a good agreement with the experimental data [22, 24].

A further experimental verification of the energy and angular scaling of $H(z)$ is of great interest to search for new phenomena at a higher colliding energy and transverse momentum of produced photons. The violation of the $z$-scaling of direct photon production can be a signature of physics phenomena beyond the Standard Model.



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b)

**Figure 7.** (a) Dependence of the inclusive cross section of direct photon production in $\bar{p}p$ collisions on momentum $q_\perp$ for different pseudorapidity intervals at energy $\sqrt{s} = 1800$ $GeV$. Experimental data on the cross section obtained by the D0 collaboration [3] are used. (b) The corresponding scaling function $H(z)$.

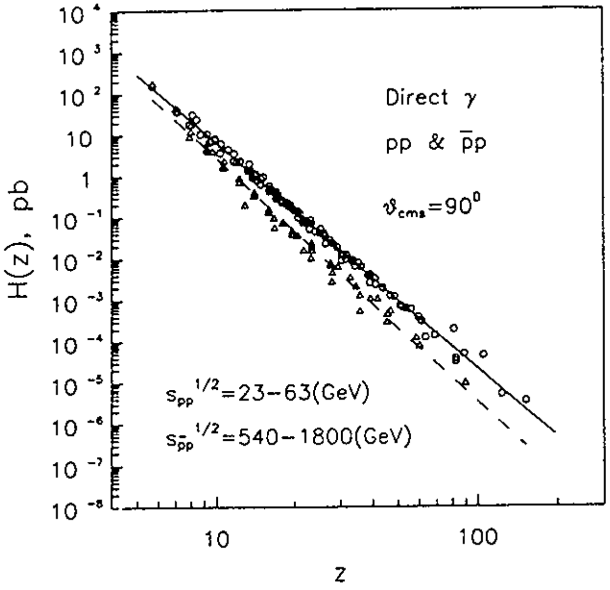
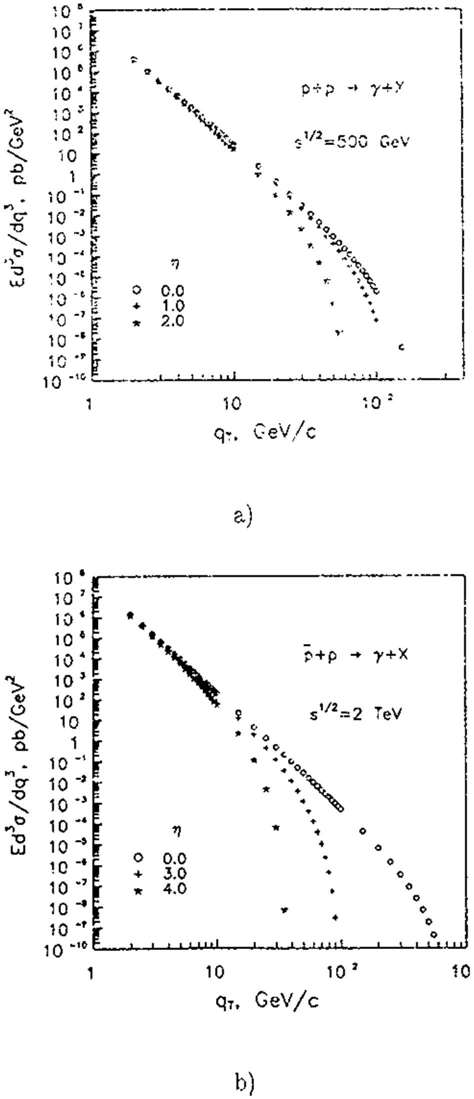


**Figure 8.** Scaling function $H(z)$ of direct photon production in $pp$ and $\bar{p}p$ collisions. Solid and dashed lines are obtained by fitting the function taken in the form $H(z) \sim z^{-\alpha}$ of the data [3, 2, 17, 27, 28] and [22, 23, 24, 25, 26], respectively.



a)

b)

**Figure 9.** Dependence of the inclusive cross section of the $p+p \rightarrow \gamma + X$(a) and $\bar{p}+p \rightarrow \gamma + X$ (b) processes on transverse photon momentum $q_\perp$ for different values of pseudorapidity $\eta = -0.5ln(tg(\theta/2))$ at RHIC and Tevatron energies.

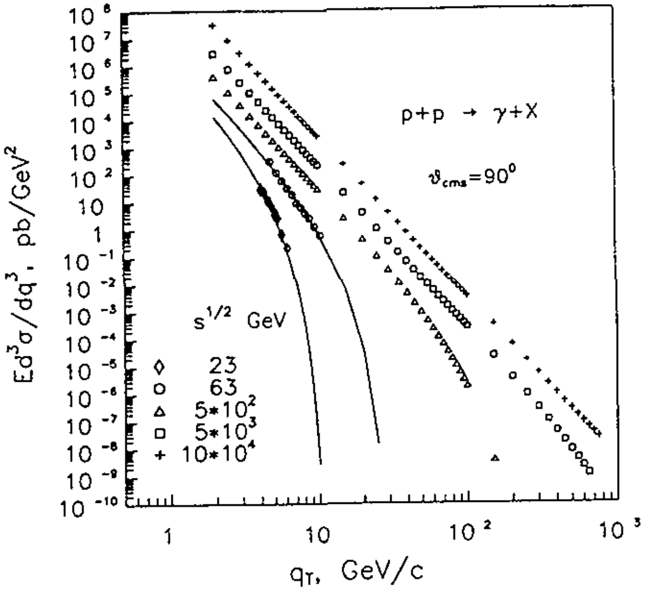


**Figure 10.** Dependence of the inclusive cross section for the $p+p \rightarrow \gamma + X$ processes on transverse photon momentum $q_\perp$ at $\theta = 90^0$ for ISR, RHIC, LHC and VLHC energies. Experimental data ($\diamond, \circ$) are taken from [22] and [24], respectively.

# 4 Results and Discussion

Here, we would like to describe a qualitative picture of the proposed scenario for prompt photon production. In general, it is based on the scenario proposed in [12, 14] for particle production in $pp$ and $\bar{p}p$ collisions. We would like to remind of the main features of the $z$-scaling. The scaling function $H(z)$ and scaling variable $z$ are expressed via experimental observables. The $H(z)$ is a universal function of the variable $z$. The scaling functions for different types of particles are connected by symmetry transformation with parameter $a^{h/\pi^-}$. The factor $a^{h/\pi^-}$ $(h = \pi^-, K^\pm)$ represents the ratio of formation lengths for various hadrons. The knowledge of a relative formation length $a^{h/\pi^-}$ of any particle $(h)$ and scaling function for $\pi^+$-meson allows us to restore the scaling function for every $h$. In this sense, we can say that the scaling function is the same for different types of produced particles. The property is named the flavour independence of $H(z)$.

Our results support in general the properties of the $z$-scaling for direct photon production in $pp$ and $\bar{p}p$ collisions at a high energy. However, there are some differences. Based on available experimental data, we establish that $H(z)$ is an energy and angular independence over a wide range of $\sqrt{s}$ and $\theta$. The $z$-dependence of $H(z)$ reveals a power behaviour, with the different value of slope parameter, for direct photon production in $pp$ and $\bar{p}p$ collisions. It was determined that $\alpha_{pp} > \alpha_{\bar{p}p}$. Note also that the form of the scaling functions for direct and indirect (via hadron decay) photon production [12, 14] differs from one another. It is due to different mechanisms of photon formation.

The value of the variable $z$ depends on the factor $\Omega$, which we interpret as a quantity proportional to the tension of the formed string which is the ancestor of the produced photon.

We consider two kinematical regions: one is characterized by high transverse momenta $q_\perp$ which correspond to low $x_{1,2} < 0.1$ at high energies and another by extremely high longitudinal momenta $q_\parallel$ which give $x_1(x_2) \rightarrow 1$ and $x_1 + x_2 \simeq 1$. The first region is the central region of secondary particle production and the second one is the fragmentation region of one of the incoming particles. The dependence of $x_1$ and $x_2$ on the momentum of produced photon $q$ is illustrated in Figure 11(a,b). The points correspond to D0 [3] and UA1 [27] kinematics, respectively. Figure 11(a) shows a clear difference between $x_1$ and $x_2$ in the fragmentation region of the incoming hadron $M_1$ $(\theta_1 = 15^0)$ and in the central fragmentation region $M_1$ $(\theta_1 = 90^0)$. Similar results for the dependence of $x_1$ and $x_2$ on $q$ for UA1 [27] kinematics are shown in Figure 11(b). The intervals of $x_1, x_2$ and $q$ for the central and fragmentation ranges of UA1 kinematics are $x_1 = 2.69 \cdot 10^{-2} - 1.43 \cdot 10^{-1}$, $q = 17 - 90$ $(GeV/c)$ and $x_1 = 2.61 \cdot 10^{-1} - 5.85 \cdot 10^{-1}$, $x_2 = 2.62 \cdot 10^{-3} - 5.89 \cdot 10^{-3}$, $q = 83 - 186$ $(GeV/c)$, respectively. The intervals of $x_1, x_2$ and $q$ for the central and fragmentation ranges of D0 kinematics are $x_1 = 5.56 \cdot 10^{-3} - 6.06 \cdot 10^{-2}$, $q = 10 - 109$ $(GeV/c)$ and $x_1 = 4.32 \cdot 10^{-2} - 4.57 \cdot 10^{-1}$, $x_2 = 7.15 \cdot 10^{-4} - 7.58 \cdot 10^{-3}$, $q = 39.5 - 418.$ $(GeV/c)$, respectively.

The string tension in the central region is higher than in the fragmentation one, $\Omega \sim [(1-\lambda_1)(1-\lambda_2)]^2$. It corresponds to the ideas [12] of the hadronization process in which the produced bare quark (quark forming the hadronic component of the photon wave function) dresses itself dragging out some matter (sea $q\bar{q}$ pairs, gluons)

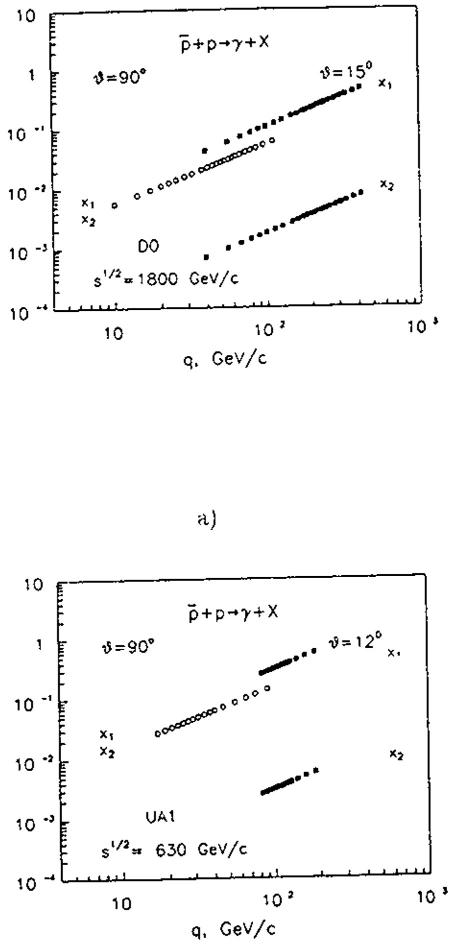


Figure 11. Dependence of $x_1$ and $x_2$ on the momentum $q$ of direct photons produced in the beam and central fragmentation regions for D0 [3] and UA1 [27] kinematics.

of the vacuum forming such a string. The string connects the leading quark (quarks) of the hadronic component of the photon with the virtual object with effective mass $(x_1M_1 + x_2M_2)$. The momentum of this object compensates a high momentum of the produced photon. The photon "dressing" in the central region is more intensive than that in the fragmentation region. In our opinion, it can be connected with the substantially lower relative velocities of the partons of the photon "coat" relative to the vacuum in the central region than those in the fragmentation one. It is easier to obtain an additional mass for a slowly moving quark. Such a quark is strongly decelerated with the string which has a high tension. Consequently, the hadronic component of the photon generated from this quark is formed along a smaller formation length.

We study the regime of local parton interactions of incident hadrons at high energies ($\sqrt{s} > 20\ GeV$) and transverse momenta of the secondary direct photon ($q_\perp > 4.\ GeV/c$). In this regime, the quark distribution functions of incoming hadrons are separated, and therefore the scaling function $H(z)$ describes directly the universality of the fragmentation process of secondary partons into observable direct photons. Nevertheless, the boundary condition and fractal dimension are essential for photon formation. One can see from Figure 8 that $H_\gamma^{\bar{p}p}(z) > H_\gamma^{pp}(z)$ and $\alpha_{pp} > \alpha_{\bar{p}p}$.

## 5 Conclusions

The inclusive prompt photon production in $pp$ and $\bar{p}p$ collisions at high energies has been considered. The function $H(z)$ describing the new scaling, $z$-scaling, of photon production was used to verify the energy and angular independence of direct photon production in the processes. A general concept of the $z$-scaling based on fundamental principles: self-similarity, locality, scale-relativity and fractality, is described. The function $H(z)$ is expressed via experimental observables - the inclusive cross section of produced photons and the multiplicity density of charged particles. The results of our analysis based on the available experimental data obtained at ISR, SppS and Tevatron give us some arguments to conclude that the $z$-scaling of prompt photon production in $pp$ and $\bar{p}p$ collisions at high energies and over a high $q_\perp$ range is observed. The found energy and angular scaling of $H(z)$ is interpreted as the universality of the photon hadronization mechanism. The function $H(z)$ is proportional to the probability to form the hadronic component of the real photon with formation length $z$. The scaling function $H(z)$ reflects general properties of photon formation and demonstrates power behaviour, $H(z) \sim z^{-\alpha}$, for both $p + p \to \gamma + X$ and $\bar{p} + p \to \gamma + X$ processes with different values of the coefficient $\alpha$. It was determined that $\alpha_{pp} > \alpha_{\bar{p}p}$. Based on obtained results we conclude that the power behaviour of $H(z)$ reflects the fractal property of photon formation.

We consider that the $z$-scaling can be an excellent "instrument" in searching for new phenomena both in hadron-hadron, hadron-nucleus and nucleus-nucleus interactions. Direct photon production in these processes is one of the best reactions to study the mechanism of photon hadronization and the hadron content of the photon.

A more detailed experimental study of the $z$-scaling of direct photon production, in particular $z$-scaling violation over a high $q_\perp$ range, in $pp$ and $\bar{p}p$ collisions at high energies will be possible in future experiments planned to perform at RHIC (BNL), Tevatron (Fermilab), HERA (DESY) and LHC (CERN).

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