Z-SCALING, HIGH-pT DIRECT PHOTON AND 0-MESON PRODUCTION AT RHIC AND LHC

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Abstract
The scaling properties of direct photon production in pp; pp and pA collisions at high energies is reviewed. The experimental data on the cross sections obtained at ISR, SpS and Tevatron are used in the analysis. The properties of data z-presentation, the energy and angular independencies, the power law, and A-dependence are discussed. The use of z-scaling to search for new physics phenomena in hadron-hadron, hadron-nucleus and nucleus-nucleus collisions is suggested. The violation of z-scaling characterized by the change of the fractal dimension is considered as a new and complimentary signature of a nuclear phase transition. The cross sections of direct photon, 0- and 0-meson production in pp and pPb collisions at RHIC and LHC energies are predicted.

1. INTRODUCTION
Direct photon production due to small cross section of electromagnetic interactions is one among very few signals which can provide direct information on the partonic, early phase of interaction. 'Penetrating probes', direct photons and dilepton pairs are traditionally considered to be one of the best probes for Quark-Gluon Plasma (QGP) [1, 2, 3].

Direct photons are produced through different mechanisms (Compton scattering, quark annihilation, bremsstrahlung of quarks and gluons). Decay of hadrons such as 0- and 0-mesons is a source of background for direct photon production. Therefore it is important to establish general features of photon production in hadron-hadron (pp; pp; p etc.) collisions and then to search for their violation at extremal conditions (high multiplicity particle density, high pT etc.) taking place in hadron-nucleus and nucleus-nucleus collisions.

The description of direct photon production in the framework of QCD [4, 5, 6] and comparison with available experimental data reveal numerous ambiguities. Some of them are theoretical and connected with the choice of the factorization scheme, renormalization, factorization and fragmentation scales and with considerations of higher order QCD corrections. The other ones are relevant to consistency among different experimental data sets. The third ones are phenomenological and are introduced to correct theory by the model dependent manner (for example "kT"-smearing effect).

Nuclear effects such as multiple parton interactions, nuclear shadowing, energy loss are not small [5] and should be taken into account for calculations of direct photon cross section in heavy ion collisions. These effects modify nuclear structure functions, photon fragmentation functions and add uncertainties in the theoretical calculations of cross sections.

We use the concept of z-scaling to analyze numerous experimental data on direct photon cross sections for pp, pp and pA collisions at high pT and to make some predictions for 0- and 0-produced in pp and pA collisions at the RHIC and LHC energies. The method of data analysis is complementary to a method of direct calculations developed in the framework of QCD and methods based on Monte Carlo generators. The use of the method allow us to obtain additional constraints in order to reduce the theoretical uncertainties and to estimate more reliably the photon cross section and background.
2. **Z-SCALING**

The idea of z-scaling [9]-[22] is based on the assumptions that inclusive particle distribution of the process $P_1 + P_2 \rightarrow q + X$ (1) of the exclusive elementary subprocess [23] and that the scaling function depending on a single variable $z$ exists and can be expressed via the dynamic quantities, invariant inclusive cross section $E \frac{d^3}{d^3 q}$ of the process (1) and particle multiplicity density $(s; )$.

The elementary parton-parton collision is considered as a binary sub-process which satisfies the condition

$$\left(x_1 P_1 + x_2 P_2 \rightarrow q + X\right) = \left(x_1 M_1 + x_2 M_2 + m_2\right)^2 :$$  (2)

The equation reflects minimum recoil mass hypothesis in the elementary sub-process. To connect kinematic and structural characteristics of the interaction, the coefficient $\alpha(x_1; x_2)$ is introduced. It is chosen in the form

$$\alpha(x_1; x_2) = m(x_1; x_2) = m_2 :$$  (3)

The variables $x_1, x_2$ are equal to unity along the phase space limit and cover the full phase space accessible at any energy.

### 2.1 Scaling function $(z)$ and variable $z$

The scaling function $(z)$ is written in the form [11]

$$(z) = \frac{s_A}{\lambda(s; )} J \int_{\text{inel}} E \frac{d}{\frac{d^3}{d^3 q}} :$$  (5)

Here $s_A$ is the inelastic cross section, $s_A' = A$ and $s$ are the center-of-mass energy squared of the corresponding $A$ and $N$ systems, $A$ is the atomic weight and $A(s; )$ is the average particle multiplicity density. The factor $J$ is the known function of the kinematic variables, the momenta and masses of the colliding and produced particles [11].

The function is normalized as

$$z_{\text{min}} \int_{z_{\text{min}}}^{z_{\text{max}}} (z) dz = 1 :$$  (6)

The equation allows us to give the physical meaning of the function $(z)$ as a probability density to form a particle with the corresponding value of the variable $z$.

In accordance with the approach suggested in [11], the variable $z$ is taken in the form (7) as a simple physically meaningful variable reflecting self-similarity and fractality as a general pattern of hadron production at high energies

$$z = \frac{p_0 \bar{s}_0}{A(s)} :$$  (7)

Here $p_0$ is the minimal transverse energy of colliding constituents necessary to produce a real hadron in the reaction (1). The factor $\bar{s}_0$ is given by (3) and $A(s; ) = A(s; )$. The form of $z$ determines its variation range $(0; 1 )$. These values are scale independent and kinematically accessible at any energy.

One of the features of the procedure to construct $(z)$ and $z$ described above is the joint use of the experimental quantities characterizing hard $(E \frac{d^3}{d^3 q})$ and soft $(A(s; ))$ processes of particle interactions.
Let us clarify the physical meaning of the variable \( z = \frac{p_T}{s} \). The value \( \frac{p_T}{s} \) is the minimal transverse energy of colliding constituents necessary to produce a real hadron in the reaction. It is assumed that two point-like and massless elementary constituents interact with each other in the initial state and convert into real hadrons in the final state. The conversion is not instant process and is called hadronization or particle formation. The microscopic space-time picture of the hadronization is not understood enough at present time. We assume that number of hadrons produced in the hard interaction of constituents is proportional to \( \Lambda \). Therefore the value \( \frac{p_T}{s} = \Lambda \) corresponds to the energy density per one hadron produced in the sub-process. The factor \( \Lambda \) is relative number of all initial configurations containing the constituents which carry the momentum fractions \( x_1 \) and \( x_2 \). This factor thus represents a tension in the considered sub-system with respect to the whole system. Taking into account the qualitative scenario of hadron formation as a conversion of a point-like constituent into a real hadron we interpreted the variable \( z \) as particle formation length.

3. PROPERTIES of \( z \)-SCALING

In this section we discuss properties of the \( z \)-scaling for direct photons produced in pp, \( p\bar{p} \) and \( pA \) collisions. They are the energy and angular independencies of data \( z \)-presentation, the power law of the scaling function \( z \) at very high-\( p_T \) and \( \Lambda \)-dependence of \( z \)-scaling. All properties are asymptotic ones because they reveal themselves at extreme conditions (high \( p_T \) and \( \Lambda \)). Numerous experimental data obtained at ISR [24]-[29], SpS [30]-[33] and Tevatron [34]-[38] were used in the analysis.

3.1 Energy independence

The energy independence of data \( z \)-presentation means that the scaling function \( (z) \) has the same shape for different \( \frac{p_T}{s} \) over a wide \( p_T \) range.

Figures 1(a,c) show the dependence of the cross section of direct photon production in \( p\bar{p} \) and \( pp \) interactions on transverse momentum \( p_T \) at different \( \frac{p_T}{s} \) over a central rapidity range. We would like to note that the data cover a wide transverse momentum range, \( p_T = 19 \ 63 \text{ GeV} = \text{c} \) and \( p_T = 24 \ 1800 \text{ GeV} = \text{c} \) for \( p\bar{p} \) and \( pp \), respectively.

Let us note some features of the photon spectra. The first one is the strong dependence of the cross section on energy \( \frac{\sqrt{s}}{p_T} \). The second feature is a tendency that the difference between photon yields increases with the transverse momentum \( p_T \) and the energy \( \frac{\sqrt{s}}{p_T} \). The third one is a non-exponential behavior of the spectra at \( q_T > 4 \text{ GeV} = \text{c} \).

Figures 1(b,d) show \( z \)-presentation of the same data sets. Taking into account the experimental errors we can conclude that the scaling function \( (z) \) demonstrates energy independence over a wide energy and transverse momentum range at \( \frac{\sqrt{s}}{p_T} \), \( 90^0 \).

3.2 Angular independence

The angular independence of data \( z \)-presentation means that the scaling function \( (z) \) has the same shape for different values of the angle \( \cos \theta \) of produced photon over a wide \( p_T \) range and \( \frac{p_T}{s} \). Taking into account the energy independence of \( (z) \) it will be enough to verify the property at some \( \frac{p_T}{s} \).

To analyze the angular dependence of the scaling function \( (z) \) we use some data sets. The first one obtained at Tevatron [37] includes the results of measurements of the invariant cross section \( E \text{d}^3 \alpha = \text{d}q_T^2 \) at \( \frac{p_T}{s} = 1800 \text{ GeV} \) over a momentum and angular ranges of \( p_T = 10 \ 115 \text{ GeV} = \text{c} \) and \( 0^0 < j \ j < 2^\circ \). The second one is the E706 data set [38] for direct photons produced in \( pp \) collisions at \( \frac{p_T}{s} = 31^0 \text{ and } 38^\circ \text{ GeV} \) and in the rapidity range \( 1^\circ < j < 75^\circ \).

Figures 2(a) and 3(a) show the dependence of the cross section of direct- production in \( pp \) and \( p\bar{p} \) collisions on transverse momentum at the fixed \( \frac{p_T}{s} \) and for different rapidity intervals. A strong angular dependence of the cross section was experimentally observed for D0 data and was found to be much smaller for E706 data. The last data have been averaged over the central rapidity range and therefore the angular dependence of the data is weak.
Fig. 1: Dependence of inclusive cross sections of direct photon production on transverse momentum in $pp$ (a) and $p+p$ (c) collisions at $\sqrt{s} = 19$ 1800 GeV. Experimental data are taken from [24]-[38]. The corresponding scaling functions $z$ for $pp$ and $p+p$ collisions are shown in (b) and (d).
Fig. 2: (a) Dependence of the inclusive cross section of direct photon production on transverse momentum in \( pp \) collisions for pseudorapidity intervals \((0.0,0.9)\) and \((1.6,2.5)\) at \( \sqrt{s} = 1800 \) GeV. The experimental data on cross sections obtained by D0 Collaboration [37] are used. (b) The corresponding scaling function \( (z) \).

Fig. 3: (a) Dependence of inclusive cross sections of direct photon production on transverse momentum in \( pp \) collisions at \( \sqrt{s} = 24.3; 31.6; 38.8 \) and \( 63 \) GeV. Experimental data \(+\) and \( \gamma \) are taken from [28, 30] and [38], respectively. (b) The corresponding scaling function \( (z) \).
Figures 2(b) and 3(b) demonstrate z-presentation of the same data sets. The obtained results show that the function \( z \) is independent of the angle \( \theta \) over a wide range of transverse momentum \( P_T \) and energy \( \sqrt{s} \). This is the experimental confirmation of the angular scaling of data z-presentation.

We would like to note that absolute normalization factors for [24, 28] and [38] data sets are found to be different. The ratio is about factor 0.5.

### 3.3 Power law

Here, we discuss a new feature of data z-presentation for direct-photon production. This is the power law of the scaling function, \( \langle z \rangle _{r} \).

As seen from Figures 2(b) and 3(b) the data sets demonstrate a linear z-dependence of \( \langle z \rangle \) on the log-log scale at high z. The quantity \( \langle z \rangle _{r} \) is a slope parameter.

Taking into account the accuracy of the available experimental data, we can conclude that the behavior of \( \langle z \rangle \) for direct photons produced in \( pp \) and \( pp \) collisions reveals a power dependence and the value of the slope parameter is independent of the energy \( \sqrt{s} \) over a wide range of high transverse momentum. It was also found that \( pp > pp \).

Direct photons are mainly produced in \( pp \) and \( pp \) collisions through the Compton and annihilation processes, respectively. This fact causes different values of the slope parameters \( pp \) and \( pp \).

The existence of the power law, \( \langle z \rangle _{r} = 31 \), means, from our point of view, that the mechanism of particle formation reveals fractal behavior.

### 3.4 A-dependence

A study of A-dependence of particle production in hA and A\# collisions is traditionally connected with nuclear matter influence on particle formation. The difference between the cross sections of particle production on free and bound nucleons is normally considered as an indication of unusual physics phenomena like EMC-effect \( J = \) suppression and Cronin effect [44].

A-dependence of z-scaling for particle production in pA collisions was studied in [12]. It was established z-scaling for different nuclei (A = D \( \rightarrow p \) b) and type of produced particles ( \( \pi^0 \rightarrow K ; p \)). The symmetry transformation of the scaling function \( \langle z \rangle \) and variable z under the scale transformation \( z ! \rightarrow z ! \) \( \rightarrow \lambda 1 \) was suggested to compare the scaling functions for different nuclei. It was found that depends on the atomic number only and can be parameterized by the formula \( \langle A \rangle = 0.9 A^{0.15} \) [12].

We use the parameterization \( \langle A \rangle \) to study A-dependence of direct photon production in pA collisions. New data [38] obtained by E706 Collaboration are used in the analysis. The experimental cross sections have been measured for pB e and pC u collisions at \( \sqrt{s} = 31.6 \) and 38 \# G eV and cover the \( p_T \)-range \( (3 \rightarrow 11) \) G eV = c.

Figure 4(a) demonstrates the spectra of photons produced in proton-nucleus collisions. As seen from Figure 4(a) the \( p_T \)-spectra shows the strong energy dependence. The difference between spectra at \( \sqrt{s} = 31.6 \) and 38 \# G eV increases with \( p_T \). The z-presentation of the same data is shown in Figure 4(b). The scaling functions for both targets, B e and C u, coincide each other. This is the direct confirmation that a nuclear effect for direct photon production can be described by the same function \( \langle A \rangle \) as for hadrons produced in proton-nucleus collisions [12]. The shape of the scaling functions is found to be a linear one on the log-log scale for both cases. The fit of the data is shown by the solid line in Figure 4(b).

The value of the slope parameter \( \rho_{pB} \) is constant over a wide \( p_T \) range and equal to 7.07. The fact means that the nuclear matter changes the probability of photon formation with different formation length z and does not change the fractal dimension of the mechanism of photon formation (photon "dressing").

Taking into account an experimental accuracy of data used in the analysis, the obtained results show that the fractal dimension \( z \) and the slope parameter \( \rho_{pB} \) is independent of A. Therefore the experimental investigations of A-dependence of z-scaling for direct photons produced in hadron-nucleus
Fig. 4: Dependence of inclusive cross sections of direct photon (a) and $^0$-meson (c) production on transverse momentum in $p\bar{p}$ and $pCu$ collisions at $\sqrt{s} = 31.6$ and $38.8$ GeV. Experimental data are taken from [38]. The corresponding scaling functions ($z$) for and $^0$ are shown in (b) and (d).
collisions at RHIC and LHC energies are very important to obtain any indications on nuclear phase transition and formation of QGP.

The main source of the background for direct photon production are and mesons decay. Therefore it is important to obtain a reliable estimation of the background. This can be done by using the scaling function of mesons for calculation of cross sections at the corresponding energy. We use experimental data on meson cross sections to construct the scaling function .

Figure 4 shows the dependence of inclusive cross section of meson produced in proton-nucleus collisions on transverse momentum and the results of z-presentation of the same data sets. The values of the fractal dimension were found to be different, 0.5 and 0.8, for and production, respectively. The values of the slope parameter of were found to be different as well.

4. DIRECT , and PRODUCTION

The properties of z-scaling found for direct- , and -meson production allow us to calculate spectra of photons produced in pp and pA collisions at RHIC and LHC energies.

4.1 pp and p collisions

Results of our analysis of numerous experimental data on direct photon production in pp and pp collisions in the framework of z-scaling scheme show that the fractal dimension is independent of energy over a wide range of transverse photon momentum. Therefore the violation of z-scaling could give indications on modification of the mechanism of direct photon formation by a new type of interaction beyond Standard Model. A change of the fractal dimension is suggested to be the quantitative measure of the z-violation.

Figure 5(a) shows that the scaling functions for direct photon, and reveal the power law in high-z range. It was found that and . Figure 5(b) demonstrates the power law for direct photon production in pp collisions as well. The slope parameter is found to be 4.58 and . As seen from Figure 5(c) the asymptotic shapes of for meson production in pp and pp are different. Both ones have a power dependence and . The properties of the scaling functions for direct and were used to estimate the dependence of the ratio of inclusive cross sections on transverse momentum at . Figure 5(d) shows that the ratio increases with and it is different for pp and pp collisions. The ratio has the crossover point at 60 GeV for pp and 110 GeV for pp collisions, respectively.

Figure 6 shows our predictions of the dependence of the inclusive cross section on transverse momentum for direct photon (a), and (b) in pp collisions at RHIC and LHC energies and at the angle of 90°. The results for the cross sections at ISR energy of are also shown for comparison. The verification of the predictions is very important because it allows us to confirm or disconfirm the new scaling of photon production and to determine the region of the scaling validity.

4.2 pA collisions

It is assumed that direct photons produced in heavy ion collisions at RHIC and LHC could give a direct indication of phase transition to the new state of nuclear matter, QGP.

Taking into account an experimental accuracy of data used in the analysis, the obtained results show that the fractal dimension and the slope parameter are independent of A.

Figure 7 demonstrates our predictions of the dependence of the inclusive cross section on transverse momentum for direct photon (a), (b) and (c) in pPb collisions at RHIC and LHC energies and at the angle of 90°. A change of the shape of photon spectra means a modification of the mechanism of photon
Fig. 5: (a) The scaling function of direct photon, $^0$-meson and $^0$-meson production in $p\bar{p}$ collisions. (b) The scaling function of direct photon production in $p\bar{p}$ and $p\bar{p}$ collisions. (c) The scaling function of $^0$-mesons produced in $p\bar{p}$ and $p\bar{p}$ collisions. (d) The $\frac{\sigma}{N}$ ratio versus transverse momentum in $p\bar{p}$ and $p\bar{p}$ collisions at $p_T = 2.5$ and 1.4 TeV. Experimental data are taken from [24]-[43].
Fig. 6: Dependence of inclusive cross sections of direct photon (a), $\pi^0$-meson (b) and $\eta$-meson (c) production on transverse momentum in pp collisions at $\sqrt{s} = 24 \, 14000$ GeV. Experimental data are taken from [28, 30, 40, 41]. Solid lines and points $\bullet, \triangle, \ast$ are the calculated results. (d) Dependence of the variable $z$ of direct photons produced in pp collisions on transverse momentum $p_T$ at energy $\sqrt{s} = 24 \, 14000$ GeV and $\phi_{em} = 90^\circ$.
Fig. 7: Dependence of inclusive cross sections of direct photon (a), $\phi$-meson (b) and $\eta$-meson (c) production on transverse momentum in $pPb$ collisions at $\sqrt{s} = 31$ 8800 GeV. Points (4 ; ; ; ) are the calculated results.
formation in transition region.

5. $z \ p_T$ PLOT

The $z \ p_T$ plot allows us to determine the high transverse momentum range interesting for searching for the kinematic region where the $z$-scaling can be violated. Figure 6(d) shows the $z \ p_T$ plot for the $pp \ X$ process at $\sqrt{s} = 24 \ 14000 \text{ GeV}$. As seen from Figure 3(b) the scaling function $(z)$ is measured up to $z > 20$. The function $(z)$ demonstrates the power behavior in the range. Therefore the kinematic range $z > 20$ is of more preferable for experimental investigations of $z$-scaling violation. The condition determines the low boundaries for $p_T$ ranges, $p_T > 5; 10; 16; 22; 35; 45$ and $52 \text{ GeV}/c$ at different energy $\sqrt{s} = 24; 63; 200; 500; 2000; 7000$ and $14000 \text{ GeV}$, respectively.

6. CONCLUSION

Analysis of the numerous experimental data on high-$p_T$ direct photon and $0^-$-meson production in $pp$, $pp$ and $pA$ collisions obtained at ISR, SpS and Tevatron in the framework of $z$-scaling concept was presented. It was shown that the general concept of $z$-scaling is valid for photon production in hadron-hadron and hadron-nucleus collisions.

The scaling function $(z)$ and scaling variable $z$ are expressed via the experimental quantities, momenta and masses of colliding and produced particles and the invariant inclusive cross section $\frac{d^3 \sigma}{d^3 q}$ and the multiplicity density of charged particles $A(s; \ )$. The physics interpretation of the scaling function as a probability density to produce a particle with the formation length $z$ is argued. The quantity $z$ has the property of the fractal measure and is the anomalous fractal dimension describing the intrinsic structure of the interaction constituents revealed at high energies. The fractal dimensions of nuclei satisfy the relation $A = A \ N$.

It was shown that the properties of $z$-scaling, the energy and angular independence, the power law $(z)$ and $A$-dependence are confirmed by the numerous experimental data obtained at ISR, SpS and Tevatron.

A comparison of the scaling function of direct photon and $0^-$-meson production in $pp$ and $pA$ was performed and different asymptotic behavior of $(z)$ was found. It was shown that $p_T$-dependence of the ratio of direct photon and $0^-$-meson inclusive cross sections for $pp$ and $pA$ collisions has the different crossover points. Based on the universality of the scaling function, the predictions of direct photon, $0^-$ and $0^-$-meson cross sections in $pp$ and $pPb$ collisions at RHIC and LHC energies were made. The $z \ p_T$ plot was used to establish the kinematic range that is of more preferable for experimental investigations of $z$-scaling violation.

The violation of $z$-scaling due to the change of the value of the fractal dimension is suggested to search for a new physics phenomena such as quark compositeness, new type of interactions, nuclear phase transition in $pp$, $pA$ and $AA$ collisions at RHIC and LHC.

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