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STUDY OF NEW SCALING OF DIRECT PHOTON PRODUCTION IN *pp* COLLISIONS AT HIGH ENERGIES USING MC SIMULATION

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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 the perturbative QCD as well as lepton-hadron interactions. It is considered that possible discrepancies with perturbative QCD predictions can be indicators of new physics phenomena (quark compositeness, new types of interaction beyond the Standard Model etc.)

Systematic investigations of prompt photon production in pp and $\bar{p}p$ interactions at a colliding energy $\sqrt{s}$ of up to 1800 GeV are performed at ISR and SppS and at the Tevatron by WA70[1], R806[2], R807[3], UA1[4], UA2[5], and by the CDF [6, 7] and D0 [8] collaborations, respectively. High colliding energies of hadrons guarantee that the perturbative QCD can be used to describe the interaction of hadron constituents. Therefore, there is hopefulness to extract direct information on fundamental gluon distributions in the proton.

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 at Brookhaven and LHC 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. Prompt photon production is one among very few signals which can provide direct information on the partonic, early phase of interaction. 'Penetrating probes', photons and dilepton pairs are traditionally considered to be one of the best probes for quark gluon plasma (QGP) [9]. Therefore, the main 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 photon formation in pA and AA collisions. A comparison of cross sections direct photons produced in hadron-hadron, hadron-nucleus and nucleus-nucleus gives us a detailed understanding of the underlying physical phenomena due to the presence of nuclear matter.

The new scaling of particle production in pp and $\bar{p}p$ collisions has been suggested in [10]. The scaling is based on such fundamental principles of nature as self-similarity and locality. First, one reflects the dropping of certain dimensional quantities or parameters out of the physical picture of the interactions. Second, one concludes that the momentum-energy conservation law is locally valid for interacting constituents. Based on the available experimental data of particle production in pp and $\bar{p}p$ collisions obtained by different collaborations at ISR, SppS and Tevatron, the main features of the scaling - energy independence, angular independence and flavour independence of the scaling function $H(z)$, have been found. 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.

The hypothesis of the z-scaling of prompt photon production in pp collisions has been suggested in [11] and studied in [14]. Based on physics meaning 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, in particular

pp collisions, with prompt photon production. 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.

We would like to note that the available experimental data on direct photon production in pp collisions over a high momentum range are not enough to verify the hypothesis. Therefore, to study the problem we use such Monte Carlo codes as PYTHIA [15] for the simulation of direct photon production. At high energies and momentum transfer, a dominant mode of direct photon production is through gluon Compton scattering [16] although a contribution is due to the annihilation process, too. The cross section is thus sensitive to the gluon distribution at low momentum fraction x. The separation of the parton subprocesses and the determination of the contribution of the basic mechanism are main tasks to extract direct information on the gluon distribution. We consider that the scaling function $H(z)$ can be different for various parton subprocesses. Therefore, a general scheme of the use of the proposed z-scaling can be an effective method to study both the scaling itself and the physics models included in different Monte Carlo codes.

In the paper, we study the new scaling of direct photon production in pp collisions at high energies using Monte Carlo simulation. The description of a general concept of the z-scaling is presented in Section 1. The scaling calculation technique is described in Section 2. The results of MC simulations used to construct the scaling function and discussion are presented in Section 3. The results are summarized in Section 4.

2 General concept of z-scaling

In this section, we follow the general scheme suggested in [10] 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 particle production in hadron-hadron collision. Then, the scaling function $\psi(z)$ has to satisfy the equation

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

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

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

This can be shown by partial differentiating using the Jacobian transformation which tends to a value of $-2q_\perp/(sE)$ at high energies.

It is shown [10] that there is the scaling function $H(z)$ expressed via the experimental observables, the invariant differential cross section $Ed^3\sigma/dq^3$ for the production of the inclusive particle m_1 and the multiplicity density of charged particles $dN/d\eta = \rho(s)$ at pseudorapidity $\eta = 0$. The function can be written at high energies ($\sqrt{s} > 30\ GeV$) in the form

$$H(z) = \frac{(M_1+M_2)^2[\rho(s)]^2}{4h(x_1,x_2)} \cdot E\frac{d^3\sigma}{dq^3}, \quad (3)$$

where M_1, M_2 are masses of colliding nucleons and the notation $M_1 = M_2 = M$ is used. The function $H(z)$ depends on one variable z specified as follows

$$z = \frac{2\cdot\sqrt{\hat{s}}}{M\cdot\Omega\cdot\rho}. \quad (4)$$

The function $h(x_1,x_2) = \partial z/\partial x_1 \cdot \partial z/\partial x_2$ is expressed via the fractions x_1 and x_2 of the colliding nucleon momenta P_1 and P_2

$$x_1 = \frac{(P_2q)+M_2m_2}{(P_1P_2)-M_1M_2}, \qquad x_2 = \frac{(P_1q)+M_1m_2}{(P_1P_2)-M_1M_2}. \quad (5)$$

The coefficient Ω is expressed via the kinematic variables: momenta (P_1, P_2 and q) and masses of colliding and produced particle (m_1). The energy of the parton subprocess $\sqrt{\hat{s}}$ is written in the form

$$\hat{s} = x_1^2\cdot M_1^2 + x_2^2\cdot M_2^2 + 2x_1\cdot x_2\cdot(P_1P_2). \quad (6)$$

The factor, describing the string tension [12] between partons in the binary parton-parton collision Ω, depends on the fractions x_1, x_2 and reads as

$$\Omega = [(1-\lambda_1)\cdot(1-\lambda_2)]^2 \quad (7)$$

Here the coefficients λ_1 and λ_2 are expressed via x_1 and x_2 as follows

$$\lambda_1 = x_1 + \sqrt{x_1\cdot x_2\cdot\frac{(1-x_1)}{(1-x_2)}}, \qquad \lambda_2 = x_2 + \sqrt{x_1\cdot x_2\cdot\frac{(1-x_2)}{(1-x_1)}}. \quad (8)$$

The particle multiplicity density $\rho(s)$ is the function of colliding energy $\sqrt{s}$ and experimentally measurable. We use the fit of the experimental data in the form $\rho(s) = 0.74s^{0.105}$ [13].

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 [10]. It is assumed that $H(z)$, as the function of z, reflects the features of the hadronization mechanism of parton and is proportional to the fragmentation function. The fragmentation function D_q^h is considered to depend on the relative formation length z of the produced particle m_1. 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 minimum energy of the colliding constituents $s_{min}^{1/2}$ 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 the scenario where the string has a maximum space-like virtuality. Further, the string evolves, splits into pieces so decreasing its virtuality. The resultant number of string pieces is proportional to the number or density of the final hadrons measured in the experiment. Therefore, we interpret the ratio

$$\sqrt{s_h} \equiv \sqrt{\hat{s}}/\rho(s) \tag{9}$$

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

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

$$\sqrt{s_h} = \Omega \cdot \lambda, \tag{10}$$

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

The dimensional properties of the scaling function allow us to assume

$$H(z) \sim D^h(\lambda). \tag{11}$$

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

3 Description of scaling calculation technique

The procedure of calculating the scaling function $H(z)$ for direct photons was divided into three steps: the Monte Carlo simulation of events with γ-direct production in pp collisions, events analysis using PAW [19] to construct the fitting function for the obtained cross section, and the calculation of the scaling function and corresponding invariant cross sections at different values of kinematic variables $(\sqrt{s}, \theta_\gamma, q_\perp)$.

Figure 1 shows a flow diagram for the used procedure. Now, we describe the blocks of the diagram in more detail.

The data for the simulating of prompt γ-production in pp collisions (the number of events is N_{event}, colliding energy $\sqrt{s}$, the cutting transverse momentum of photon $q_\perp^{cut}$, and angular acceptance $\Delta\theta_\gamma$) (FORT.21) are used as input ones for the PYTHIA[15] program (ZPP). Three types of parton subprocesses $gq \to \gamma q$, $q\bar{q} \to \gamma g$ and $q\bar{q} \to \gamma\gamma$ are used for simulation. The contributions of the processes to prompt photon production are dominant ones (see Table 1). The results of the simulations (the momenta and angles of photons, subprocess number) are stored in ntuple. The unnormalized cross sections of parton subprocesses vs the transverse momentum of the photon $(q_\perp)$ are booked in the histogram (PP.HIST). The normalization coefficient calculated by PYTHIA is recorded in the output file (OUT1.0).

At the second step, the histograms of the cross sections are used to find out a convenient analytic form $(Ed^3\sigma/dq^3 = exp(a + b \cdot q_\perp))$ for the cross sections. The

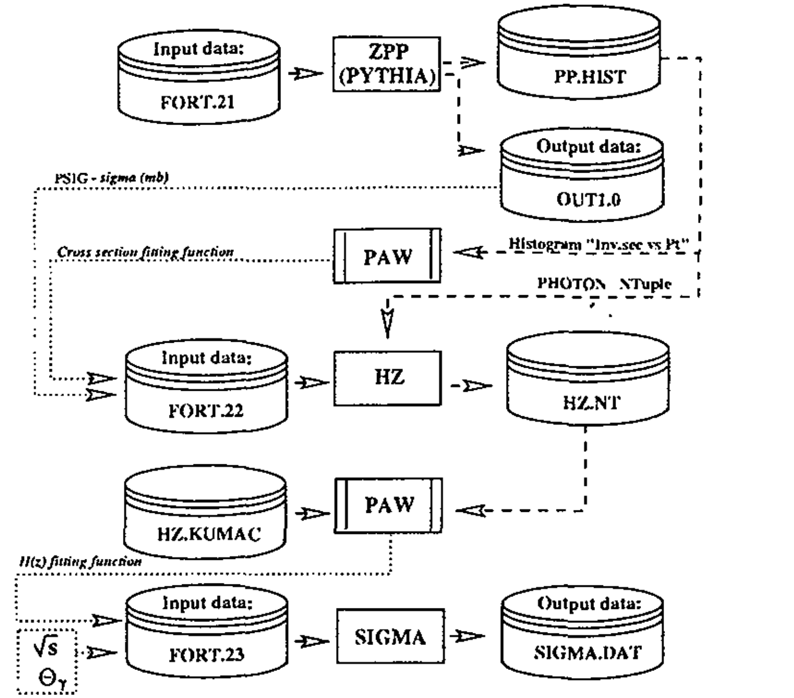

Figure 1. Flow diagram for procedure of calculation of scaling function $H(z)$.

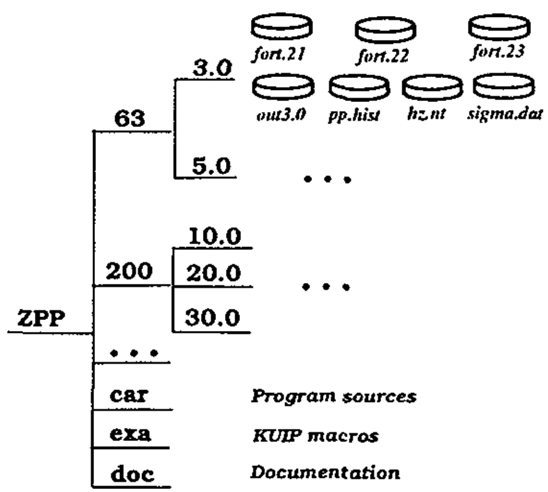

Figure 2. Directory tree structure.

coefficients (a, b) are determined for each $q_\perp$ cutting intervals at a given energy $\sqrt{s}$. At $\sqrt{s} = 63\ GeV$, the cutting momenta are chosen to be 2, 5 and 10 GeV/c.

The analytic form of the cross section constructed at the previous step is used to calculate the scaling function $H(z)$. The coefficients a, b, colliding energy $\sqrt{s}$, the density of the charged particle distribution $\rho(s)$ taken from file FORT.22 are used by the HZ program as input data. Output is the ntuple containing the values of the cross sections and $H(z)$ as a function of transverse momentum $q_\perp$, of the angle θ of produced photon, of the scaling variable z and energy $\sqrt{s}$.

The universality of the scaling function $H(z)$ allows us to predict the absolute values of the cross section of the photon produced at a different colliding energy $\sqrt{s}$, angle θ and photon momentum $q_\perp$. For this purpose it is convenient to fit the scaling function in the form $H(z) = a_1/z^{a_2}$. The coefficients a_1, a_2, colliding energy $\sqrt{s}$, angle θ, the density of charged particle distribution $\rho(s)$ taken from file FORT.23 are used by the SIGMA program to calculate the predicted values of the cross sections (SIGMA.DAT).

3.1 Directory tree names logic

All the calculations were made on SUN and IBM platforms under SOLARIS and AIX operation systems and with CERNLIB [17] libraries. For convenient and easy-use purpose, the input and output files were stored in separate directories created like a tree (Figure 2).

The first level, named ZPP, contains subdirectories **car** , **doc** and **exa** , for program sources, program descriptions and kumacs, respectively. At the same level subdirectories for each energy (for example, **63, 200, 500**) are created. Each "energy" subdirectory contains subdirectories for different kinematic cuts (for example, level **63** contains **3.0** and **5.0** levels corresponding to $q_\perp$ cutting momenta of 3 GeV/c and 5 GeV/c, respectively). Each "bottom" subdirectory contains input file FORT.21 and simulation results (OUT1.0 and PP.HIST).

4 Results and discussion

We would like to describe a qualitative picture of the scenario for prompt photon production in pp collisions. It is generally based on the scheme suggested in [10] for charged particle production in pp or $\bar{p}p$ collisions.

Figure 3(a) shows the MC results of the prompt photon cross section $Ed^3\sigma/dq^3$ as a function of transverse momentum $q_\perp$ at an energy of $\sqrt{s} = 63, 200$ and 500 GeV and an angle of $\theta = 90^0$. From Figure 3(a) one can see that the experimental data [3] *are in good agreement with the simulation results at* $\sqrt{s} = 63\ GeV$.

The hypothesis of energy scaling predicts that the direct photon production cross section will be independent of center of mass energy $\sqrt{s}$. As seen from Figure 3(a), the values of the cross section at $\sqrt{s} = 63\ GeV$ and $\sqrt{s} = 200\ GeV$ differ from one another by more than one order at $q_\perp > 10\ GeV/c$. Thus, the energy scaling of the cross section in $q_\perp$-presentation is violated.

The z-dependence of the scaling function $H(z)$ at the same energies is shown in Figure 3(b). The dependence demonstrates the universality - the independence of

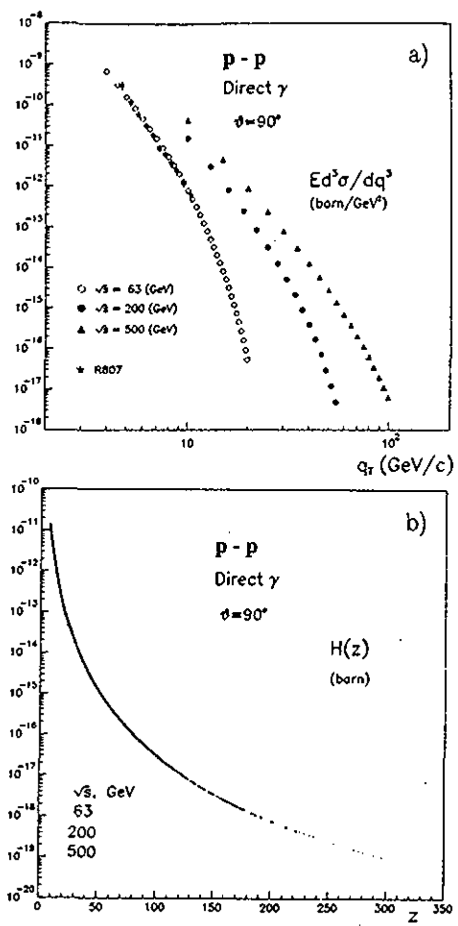

Figure 3. (a) Inclusive cross section of prompt γ-production in pp collisions as a function of transverse momentum $q_\perp$ for different c.m.s. energies $\sqrt{s} = 63, 200, 500\ GeV$ and at a produced angle of $\theta = 90^0$. Experimental data ($\star$) are taken from [3]. Points - $\bullet$, $\circ$, $\triangle$, are MC simulation results. (b) The corresponding scaling function $H(z)$.

$H(z)$ of colliding energy $\sqrt{s}$. We have found that the behaviour of $H(z)$ is a linear one in the log-log scale

$$H(z) \sim z^{-\alpha}. \qquad (12)$$

The slope parameter α is found to be 5.215 ± 0.005. The experimental determination of the parameter and the comparison of its value with the QCD predictions are of great interest. The experimental results can stimulate studying the possibility to describe the z-scaling in the framework of QCD. The power dependence of $H(z)$ in accordance with the scenario proposed in [12], reflects the fractality of the photon formation mechanism. This can mean that the scaling function describes the universal mechanism of photon hadronization, and the z-dependence of $H(z)$ describes the space-time evolution of the hadron content formation of the photon.

Table 1. Total cross section of parton subprocesses at $\sqrt{s} = 63$, 200 and 500 GeV and different cuts of $q_\perp$

Colliding energy $\sqrt{s} = 63$ GeV, $N = 10^6$-pp events, $\theta = 90^0 \pm 3^0$						
parton	$q_\perp^{cut} = 2$ GeV/c		$q_\perp^{cut} = 5$ GeV/c		$q_\perp^{cut} = 10$ GeV/c	
subprocess	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb
$gq \to \gamma q$	24474	2.730E-04	42243	5.330E-06	70741	4.649E-08
$\bar{q}q \to \gamma g$	5222	6.161E-05	6223	8.097E-07	7046	4.741E-09
$\bar{q}q \to \gamma\gamma$	43	2.395E-07	62	4.045E-09	89	2.996E-11
Colliding energy $\sqrt{s} = 200$ GeV, $N = 10^6$-pp events, $\theta = 90^0 \pm 3^0$						
parton	$q_\perp^{cut} = 10$ GeV/c		$q_\perp^{cut} = 20$ GeV/c		$q_\perp^{cut} = 30$ GeV/c	
subprocess	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb
$gq \to \gamma q$	31721	3.024E-06	49096	6.924E-08	65705	3.216E-09
$\bar{q}q \to \gamma g$	5750	5.581E-07	7684	1.119E-08	8699	4.420E-10
$\bar{q}q \to \gamma\gamma$	58	3.372E-09	116	8.258E-11	140	3.406E-12
Colliding energy $\sqrt{s} = 500$ GeV, $N = 5 \cdot 10^6$-pp events, $\theta = 90^0 \pm 1^0$						
parton	$q_\perp^{cut} = 10$ GeV/c		$q_\perp^{cut} = 20$ GeV/c		$q_\perp^{cut} = 30$ GeV/c	
subprocess	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb	N_γ	σ_{tot}, mb
$gq \to \gamma q$	33861	1.649E-05	47319	9.670E-07	58865	1.365E-07
$\bar{q}q \to \gamma g$	6267	2.880E-06	9172	1.855E-07	11608	2.673E-08
$\bar{q}q \to \gamma\gamma$	82	1.812E-08	110	1.360E-09	178	2.114E-10

The total cross sections of the Compton and annihilation subprocesses and the number of prompt photons N_γ are presented in Table 1. From Table 1 one can see that the dominant parton subprocess for direct photon production is a Compton one. The number of prompt photons for $N = 10^6$-pp events increases with $\sqrt{s}$ and $q_\perp^{cut}$. We use the cut of $q_\perp$ to increase the statistical accuracy. The statistical error is proportional to $\sim 1/\sqrt{N_\gamma}$ and for Compton subprocess it is less than 1% for $\sqrt{s} = 63 - 500$ GeV, $q_\perp^{cut} > 2$ GeV/c and $\theta = 90^0 \pm 3^0$. As one can see from Table 1, the main contribution to the cross section is due to Compton scattering. Therefore, the study of the gluon distribution in the proton over the kinematic range is unambiguous.

The universality of $H(z)$ (see Figure 3b) allows us to make predictions of the $q_\perp$-dependence of the photon production cross section at energies beyond ISR.

Figure 4 shows our predictions of the dependence of $Ed^3\sigma/dq^3$ on transverse photon momentum $q_\perp$ at RHIC and LHC energies ($\sqrt{s} = 500$ GeV and $\sqrt{s} = 5, 14$ TeV) and at an angle of $\theta = 90^0$. The results for the cross section at ISR energy of $\sqrt{s} = 63$ GeV are also shown in Figure 4 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 its validity.

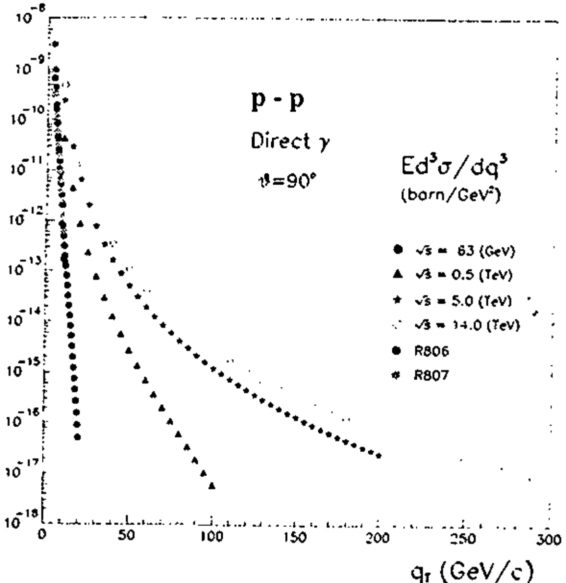

Figure 4. Inclusive cross section of prompt γ-production in pp collisions as a function of transverse momentum $q_\perp$ for different c.m.s. energies $\sqrt{s} = 0.063, 0.5, 5.0$ and 14.0 TeV at an angle of $\theta = 90^0$. Experimental data are taken from [2, 3].

5 Conclusions

The new scaling, z-scaling, of prompt photon production in pp collisions at high energies has been studied using Monte Carlo simulation. The general concept of z-scaling is shown to be valid for photon production in pp collisions. The scaling function $H(z)$ is expressed via two experimental observables: the inclusive cross section of photon production $Ed^3\sigma/dq^3$ and the multiplicity density of charged particles $\rho(s)$. The description of z-scaling calculation technique is presented. The technique includes the use of the MC PYTHIA code and CERN library programs. The comparison of the MC results on the inclusive cross section with the experimental data obtained at ISR is made, and a good agreement with the data is found. The parametrization of the scaling function $H(z)$ is obtained. According to the physics interpretation of the z-scaling, the function $H(z)$ is proportional to the probability to produce the photon with formation length z. The $H(z)$ dependence on z is shown to be a linear one on a log-log scale. The power behaviour of $H(z) \sim z^{-\alpha}$ from our point of view reflects the fractality of photon formation mechanism. Based on the universality of the scaling function $H(z)$, some predictions of the prompt photon production cross section at RHIC and LHC energies are made.

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