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Z-scaling and Prompt Photon Production in pp Collisions at STAR

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Abstract

The new scaling, z-scaling, is used to study the prompt photon production in pp-collisions at high energies. The scaling function $H(z)$ is expressed via the inclusive cross section of photon production $Ed^3\sigma/dq^3$ and the particle multiplicity density $dN/d\eta$ at pseudorapidity $\eta = 0$. The dependence of $H(z)$ on the scaling variable $z = s_x^{1/2}/(\Delta M \cdot dN(0)/d\eta)$, the center-of-mass energy $\sqrt{s}$ is investigated. The available experimental data on direct photon production in pp interactions obtained at the ISR at the energy $\sqrt{s} = 23, 63\ GeV$ confirm the scaling and are used to construct $H(z)$. Based on the universality of $H(z)$ the dependence of the invariant cross section for the $pp \to \gamma X$ process on photon momentum q_T at RHIC energy $\sqrt{s} = 200, 500\ GeV$ were predicted. The systematic errors for the cross section using the energy and angular resolution of the STAR EMC detector were estimated.

The obtained results can be of interest for future experiments at RHIC to search for signals of the quark-gluon plasma formation in hadron-nucleus and nucleus-nucleus collisions.

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1 Introduction

A search for general properties of prompt photon production in hadron-hadron collisions is of great interest, especially with connection to the commissioning of the large accelerators of nuclei, RHIC at Brookhaven and the LHC at CERN. The main physical goal of the investigations on these colliders is to search for quark-gluon plasma - the hot and superdense phase of the nuclear matter. Therefore the main features of direct photon production observed in hadron-hadron interactions allow one to extract nuclear effects and to study the influence of nuclear matter in pA and AA collisions.

A comparison of direct photon produced in hadron-hadron, hadron-nucleus and nucleus-nucleus both in the central and non-central rapidity regions allows us a detailed understanding of the underlying physical phenomena due to the presence of the nuclear matter.

High transverse momentum direct photon production is one among very few signals which can provide direct information on the partonic, early phase ofthe interaction. The 'penetrating probes', photons and dilepton pairs are traditionally considered to be one of the best probes for QGP

It is considered that the fragmentation of partons into hadrons is perhaps one of the least understood features of QCD. Even though the primary scattering process is described in term of perturbative QCD the hadronization chain contains very low, respective to the parent parton, q_T hadrons. Therefore the whole process is clearly a non-perturbative phenomena involving final state interactions which have to conserve color and baryon number.

It is often assumed, in contrast with the point mentioned above, that the direct photon production probes the parton-parton interaction without the ambiguities associated with jet identification, fragmentation and energy measurement.

At the leading order in perturabative theory there are two subprocesses: the annihilation process $q\bar{q} \to \gamma g$ and the Compton process $qg \to \gamma q$ which contribute to the direct photon cross section. Depending on the values of $\sqrt{s}$ and q_T^{γ}, either of theses two subprocesses can dominate. In pp collisions the Compton process dominates over essentially all the q_T range. This makes direct photon production useful for constraining the gluon distribution.

We consider that photon hadronization may have features which are different of particle hadronization. The general feature both photon and particle hadronization are assumed to be too.

The scaling function $H(z)$ describing the hadronization of particles produced in pp and $p\bar{p}$ collisions at high energies have been found in [4]. The function is proportional to the probability to create the hadron with formation length z. The function reflects the universality of the hadronization mechanism. This phenomena is known as z-scaling.

The verification of the z-scaling of direct photon production in pp collisions at high energy can be useful to study the mechanism of photon hadronization. The function $H(z)$ describes probability dependence to form hadronic component of photon with formation length z and consequently the space-time evolution of the process.

In this paper the direct photon production in pp collisions at high energies and high q_T range is studied. The scaling function $H(z)$ for the $pp \to \gamma X$ process is found. The available experimental data [1, 2, 3] are used to construct $H(z)$ and to confirm the z-scaling at $\theta \simeq 90^0$. Based on the universality of $H(z)$, the dependence of the inclusive cross section on q_T at $\sqrt{s} = 200, 500\ GeV$ is predicted and the estimations of systematic errors for the cross section due to energy and angular resolution of the STAR EMC detector are calculated.

2 Z-scaling in pp Interactions at High Energies

In this section we shall follow the general scheme suggested in [4] 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

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

It was shown [4] that there is the scaling function $H(z)$ which is determined by the equation

$$H(z) \equiv -\frac{1}{16\pi}\left(\frac{d\psi(z)}{dz} + \frac{\psi(z)}{z}\right). \tag{2}$$

and expressed via the invariant differential cross section $Ed^3\sigma/dq^3$ for the production of the inclusive particle m_1 and the particle multiplicity $dN/d\eta$ at pseudorapidity $\eta = 0$. This function can be written at high energies ($\sqrt{s} > 30\ GeV$) in the form

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

Here M is the nucleon mass, $h(x_1,x_2)$ is a known function, x_1 and x_2 are the fractions of the colliding nucleon momenta P_1 and P_2.

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 is proportional to the string tension, $s_x^{1/2}$ is the energy of the parton subprocess. Both of them are expressed via the kinematic variables, momenta and masses of the colliding and produced particles.

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 [4]. The assumption that $H(z)$ as a function of z reflects the features of the mechanism of hadronization of the parton and is proportional to the fragmentation function has been argued in [4]. 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.

In reality, the variable z can be interpreted in terms of the 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 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

$$\sqrt{s_h} \equiv \sqrt{s_x}/(dN(0)/d\eta) \tag{5}$$

as a quantity proportional to the energy of a string piece $\sqrt{s_h}$ which doesn't 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

$$\sqrt{s_h} = \Delta M \cdot \lambda, \tag{6}$$

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 maximal) value.

The dimensional properties of the scaling function allow us to assume

$$H(\bar{z}) \sim D^h(\lambda). \tag{7}$$

So, we interpret the variable z as a quantity proportional to the formation length, on 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 Direct Photon Production in pp Interactions at High Energies

Before analyzing the results on z-scaling for direct photon in pp collisions we would like to remind the reader of the main result concerning the function $H(z)$ for charged hadrons produced in pp and $\overline{p}p$-collisions at $\sqrt{s} = 63 - 1800\ GeV$ and $\theta \simeq 90^0$. The function $H(z)$, as it was shown in [4], demonstrates the universality, the z-scaling, in a wide kinematic range of colliding energy $\sqrt{s}$ (from 23 up to 1800 GeV) and the transverse momentum q_T (up to 10 (GeV/c) and the angle θ of produced particles.

At present there are data on direct photon production in pp-collisions in the high q_T region only at energies $\sqrt{s} \leq 63\ GeV$. We suppose [5], based on our analysis of available D0 and CDF experimental data, that the general features of z-scaling of direct photon production in pp-collisions may be the same as in $\bar{p}p$-collisions. However direct experiments at a pp-collider are necessary to verify this suggestion. The verifications of z-scaling for direct photon production in pp interactions will be possible at the Relativistic Heavy Ion Collider (RHIC) at $\sqrt{s}$ up to 500 GeV and $q_T > 20\ (GeV/c)$. It will greatly extend the investigation domain.

Figure 1 shows the dependence of the invariant inclusive cross section $Ed^3\sigma/dq^3$ on the photon transverse momentum q_T. The experimental data at $\sqrt{s} = 23, 62\ GeV$ and $\theta \simeq 90^0$ have been obtained at the ISR [1, 2, 3]. We would like to note that the absolute values for the cross section at $\sqrt{s} = 23\ GeV$ and $\sqrt{s} = 63\ GeV$ differ by more than one order at the high q_T range.

The hypothesis of the energy scaling predicts that the scaling function $H(z)$ will be independent of pp center of mass energy $\sqrt{s}$.

Figure 2 shows the dependence of the function $H(z)$ of the $pp \to \gamma X$ process on the variable z at the colliding energy $\sqrt{s} = 23$ and 63 GeV/c and the angle $\theta \simeq 90^0$. The experimental data on the inclusive cross section [1, 2, 3] are used to construct $H(z)$.

The result allows us to conclude that the energy scaling - the independence of the function $H(z)$ of direct photon production on colliding energy in the range $\sqrt{s} = 23 - 63\ GeV$ and at $\theta \simeq 90^0$, is observed.

Based on the energy scaling of $H(z)$ for direct photon production the dependence of the inclusive cross section on photon momentum q_T at the energy $\sqrt{s}$ reached at RHIC is predicted.

Figure 3 demonstrates the dependence of $Ed^3\sigma/dq^3$ on q_T at energy $\sqrt{s} = 23, 63, 200$ and 500 GeV and $\theta = 90^0$. Solid lines are calculation results, points are experimental data [1, 2, 3]. The absolute values of the cross section at the transverse momentum $q_T = 10\ (GeV/c)$ for $\sqrt{s} = 63$ and 500 GeV differ from each other by more than 2 orders of magnitude and reachs $\sim 4 \cdot 10^{-5}\ (pb/GeV^2)$ at $\sqrt{s} = 500\ GeV$ and $q_T = 60\ (GeV/c)$.

From an experimental point of view, the study of direct photon production has several advantages with respect to the study of jets: the energy resolution of electromagnetic calorimeters is generally better than the resolution of hadronic calorimeters, and systematic uncertainties in the photon energy scale are smaller. Furthermore, since photons do not fragment, the direction and energy of photons is straightforward to measure in the calorimeter without the need for a jet algorithm to reconstruct a jet [6].

The electromagnetic calorimeter ofthe STAR detector [7] consists of two parts - a barrel and an EndCap. The first covers $|\eta| < 1$, the second $1 < |\eta| < 2$, respectively, and both are 2π in azimuth.

We use the energy and angular resolution of the EMC

$$\Delta E/E = 0.16/\sqrt{E}, \qquad \Delta\eta = 0.05,$$

respectively, to estimate the systematic errors for the cross section of direct photon production at the STAR.

Figure 4 shows the dependence of $Ed^3\sigma/dq^3$ on q_T at energy $\sqrt{s} = 63, 200$ and $500\ GeV$ and $\theta = 90^0$. Solid lines are calculation results, points with error bars are estimations of systematic errors for the cross section obtained using the energy and angular resolution of the STAR EMC detector [7].

The obtained results show that the study of energy and q_T dependences of prompt photon production are preferable at high $\sqrt{s}$ and $q_T > 10\ (GeV/c)$.

Figure 5(a,b,c) show the dependence of the cross section on q_T at $\sqrt{s} = 63, 200, 500\ GeV$ and at the different angles of the produced photon $\theta = 15^0, 30^0, 45^0$ and 90^0. Solid lines are calculation results, points with error bars are estimations of systematic errors for the cross section obtained using the energy and angular resolution of the STAR EMC detector [7].

Taking into account the physical meaning 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 note that the hadronization length z increases from 1.5 to 20 as the transverse momentum $q_\perp$ of the photon changes from 10 to 110 GeV/c at $\sqrt{s} = 500\ GeV$. This fact reflects the space-time evolution of the hadronic component formation of the photon.

The obtained results show that the direct measurements of prompt photon cross sections in pp-collisions in the high q_T region at different $\sqrt{s}$ up to 500 GeV are desirable to verify the energy independence of $H(z)$ at RHIC.

4 Conclusion

The inclusive prompt photon production in pp-collisions at high energy has been considered. It was shown that the available experimental data for prompt photon production in pp-collisions at high energies confirm the z-scaling. The scaling function $H(z)$ for the $pp \rightarrow \gamma X$ reaction is constructed. It is expressed via two observables - the invariant inclusive cross section $Ed^3\sigma/dq^3$ of the $pp \rightarrow \gamma X$ process and the multiplicity density $dN/d\eta(s)$ of particle production at pseudorapidity $\eta = 0$. The found scaling function $H(z)$ has been used to predict the dependence of the inclusive cross section $Ed^3\sigma/dq^3$ on the transverse momentum q_T of the produced photon and the colliding energy $\sqrt{s}$. The estimations of systematic errors for the cross section due to energy and angular resolutions of the STAR EMC detector have been obtained. The values of the errors found allow us to consider that the study of the energy and angular dependence of direct photon production in pp-collision with the STAR detector gives one the possibility to obtain information on basic parton subprocesses, features of photon hadronization and to extract the gluon distribution function.

The scaling proposed can be an excellent "instrument" in searching for new phenomena not only in hadron-hadron but in hadron-nucleus and nucleus-nucleus interactions. Direct photon production in these interactions is one of the best reactions to study the mechanism of photon hadronization.

Acknowledgement

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Figure Captions

Fig. 1 Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63$ GeV and $\theta = 90^0$. Experimental data are taken from $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

Fig. 2 Scaling function $H(z)$ for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63$ GeV and $\theta = 90^0$. Points are experimental data taken from $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

Fig. 3 Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63, 200, 500$ GeV and $\theta = 90^0$. Solid lines are calculation results, points are experimemtal data taken from $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

Fig. 4 Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 63, 200, 500$ GeV and $\theta = 90^0$. Solid lines are calculation results, error bars are estimations of systematic errors forthe cross section due to the energy and angular resolution of the STAR EMC detector.

Fig. 5(a-c) Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 63, 200, 500$ GeV and $\theta = 15^0, 30^0, 45^0, 90^0$. Solid lines are calculation results, error bars are estimations of systematic errors for the cross section due to the energy and angular resolution of the STAR EMC detector.

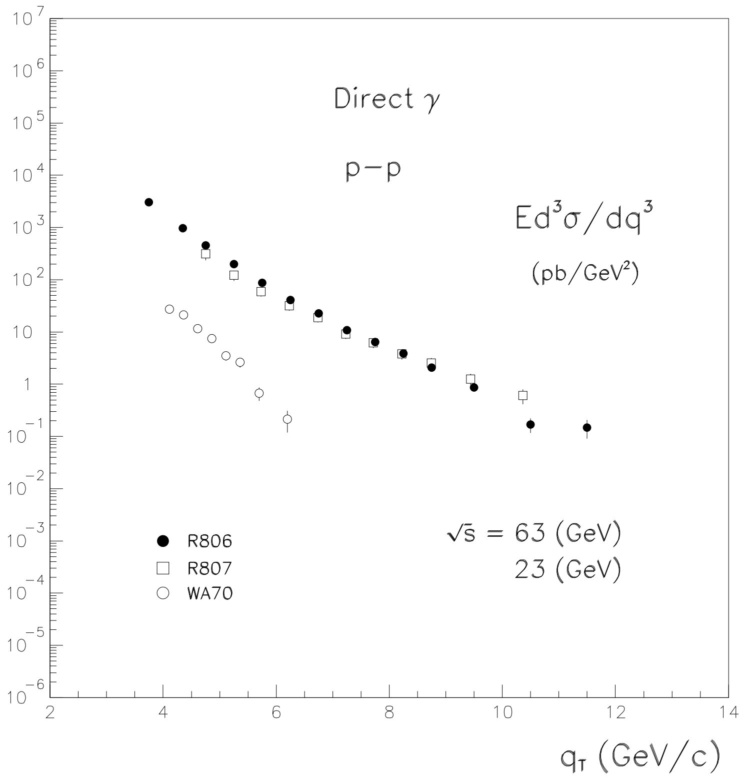


Figure 1. Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63\ GeV$ and $\theta = 90^0$. Experimental data are taken from $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

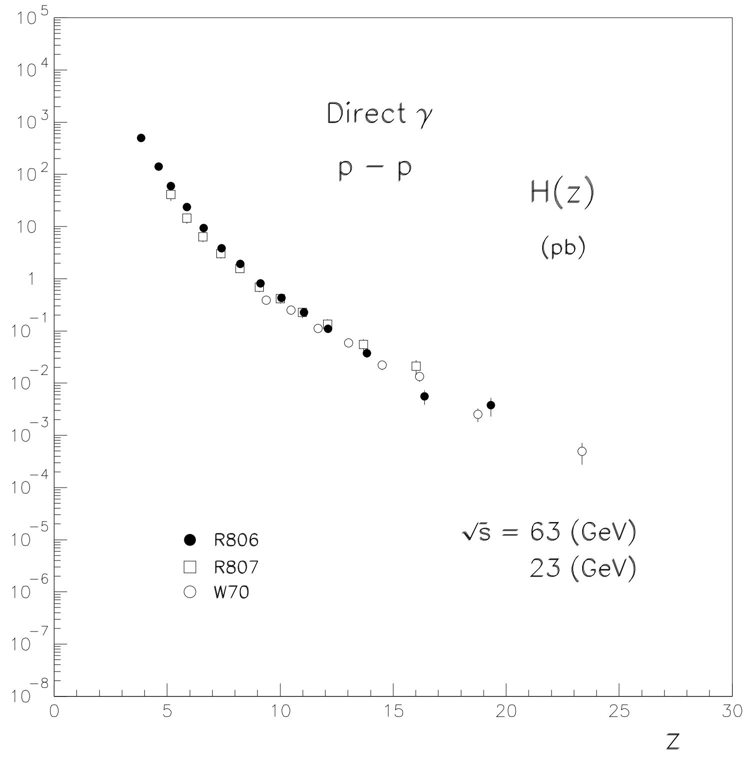


Figure 2. Scaling function $H(z)$ for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63\ GeV$ and $\theta = 90^0$. Experimental data are taken from $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

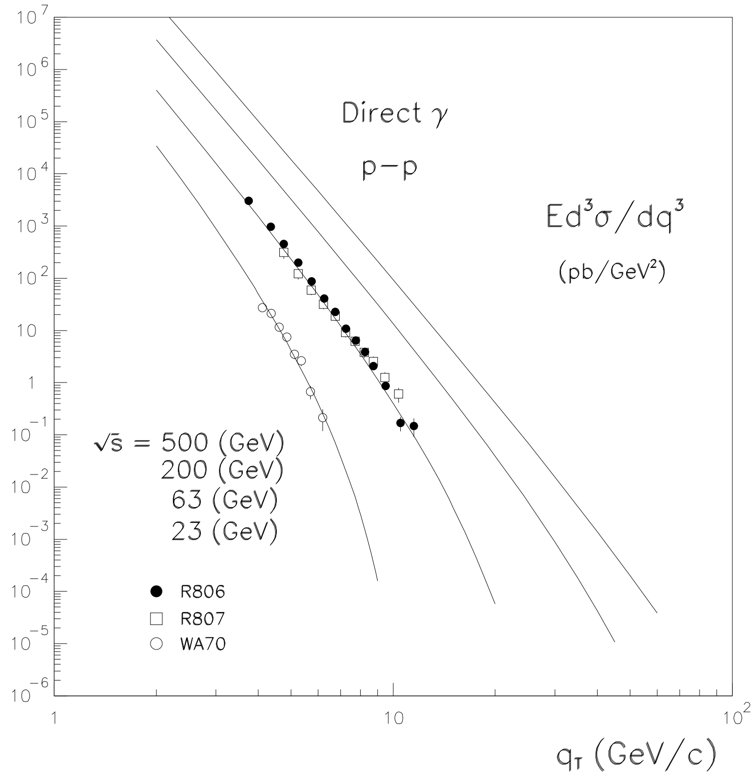


Figure 3. Inclusive differential cross section for prompt photon production in the pp interaction at $\sqrt{s} = 23, 63, 200, 500$ GeV and $\theta = 90^0$. Solid lines are calculation results, points are experimemtal data $\bullet$ - [1], $\overline{\sqcup}$ - [2] $\circ$ - [3].

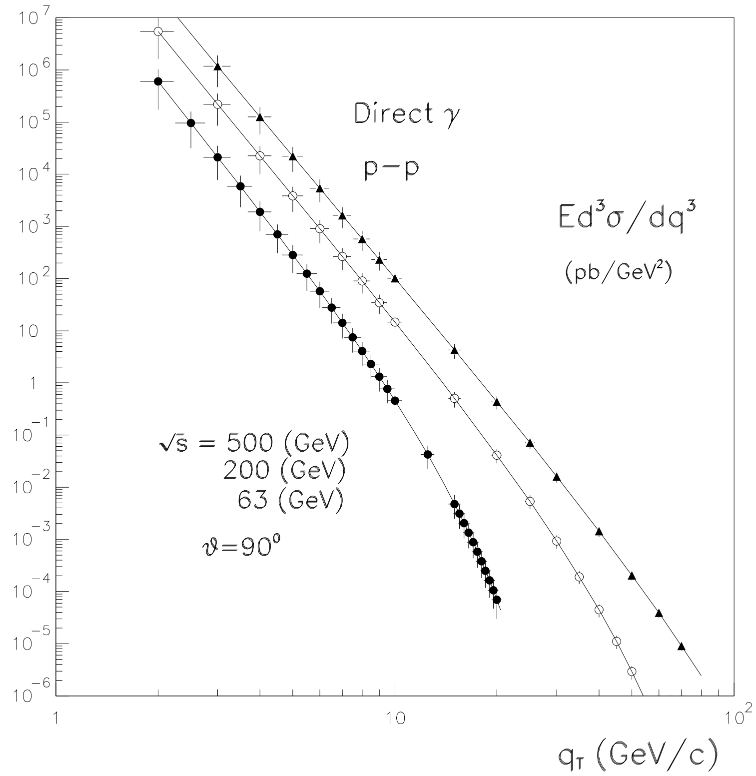


Figure 4. Inclusive differential cross section for prompt photon production in the *pp* interaction at $\sqrt{s} = 63, 200, 500$ GeV and $\theta = 90^0$. Solid lines are calculation results, error bars are estimations of systematic errors for the cross section due to the energy and angular resolution of the STAR EMC detector.

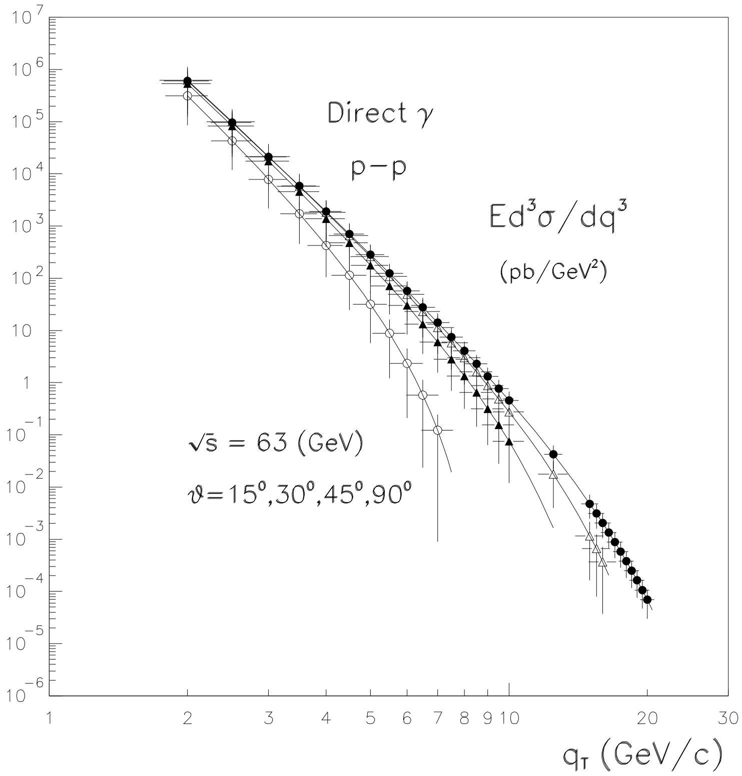
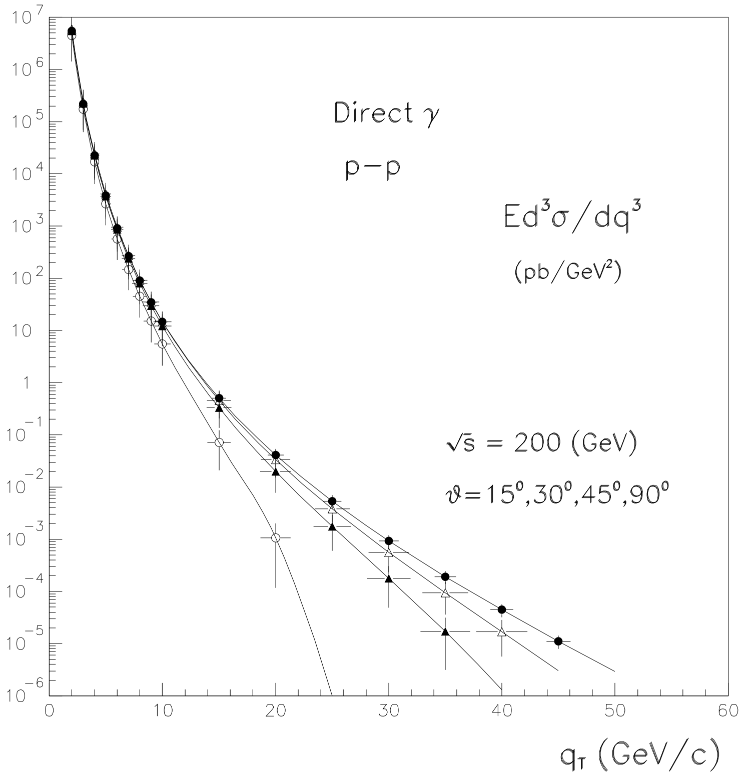
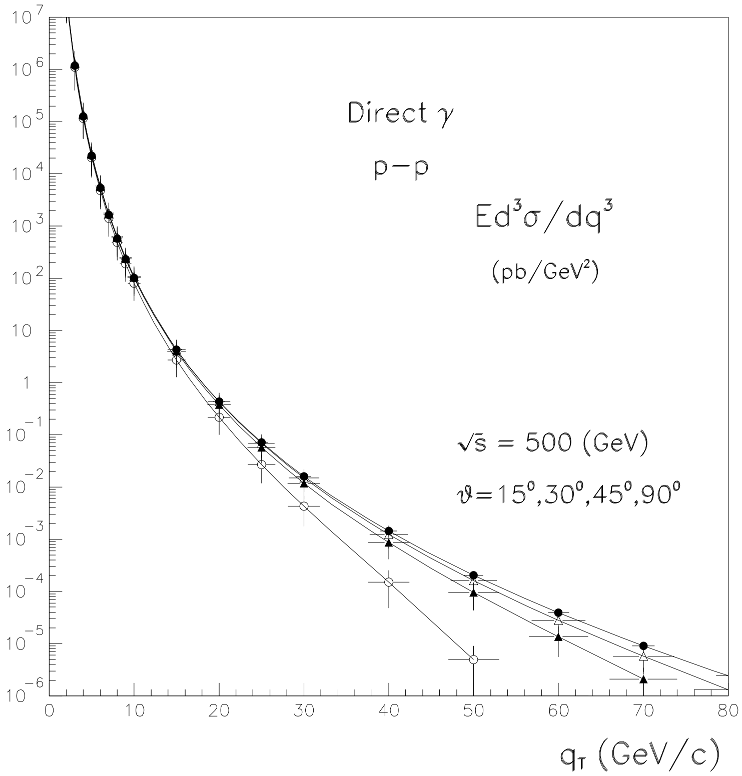


Figure 5a. Inclusive differential cross section for prompt photon production in the *pp* interaction at $\sqrt{s} = 63, 200, 500\ GeV$ and $\theta = 15^0, 30^0, 45^0, 90^0$. Solid lines are calculation results, error bars are estimations of systematic errors for the cross section due to the energy and angular resolution of the STAR EMC detector.



Direct γ
p−p
$Ed^3\sigma/dq^3$
(pb/GeV^2)
$\sqrt{s}$ = 200 (GeV)
ϑ=15^0,30^0,45^0,90^0
q_T (GeV/c)

Figure 5b.



Direct γ
p−p
$Ed^3\sigma/dq^3$
(pb/GeV^2)
$\sqrt{s}$ = 500 (GeV)
$\vartheta=15^o,30^o,45^o,90^o$
q_T (GeV/c)

Figure 5c.