DIRECT PHOTON PRODUCTION IN HIGH ENERGY HADRONIC AND NUCLEAR COLLISIONS: MEASURED DATA VERSUS A MODEL

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This work is in response to the stimulus received from our fairly successful attempt at understanding in the recent past the problem of direct photon production only in gold–gold and lead–lead collisions from the viewpoint of a non-standard approach. The same nonconventional formalism would, once again, be applied to analyze the vast array of measurements on the inclusive cross sections of direct photons produced in several purely nuclear or hadronuclear collisions at very high energies. Besides, some of the cross section ratios would also be calculated and be compared with data on them. All this reveals and indicates a modest agreement between the model-based calculations and the actual measurements. The authors would also endeavor here to adduce the reasons for the discrepancies, if any.

Keywords: Relativistic heavy ion collisions; inclusive production; quark–gluon plasma.

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1. Introduction

Electromagnetic signals like prompt or direct photons are considered to constitute an interesting penetrating probe for investigations into the status of the proposed quark–gluon plasma (QGP) signatures. The word "prompt" or "direct," in this context, indicates only the basic fact that these photons are not the product of neutral pions. The origin is somewhat different and so it is open to various interpretations. The observation of "direct" photon (γ_d) in hadronic and nuclear collisions, especially at high transverse momentum (p_T), has been viewed as one of the suggested signature of the possible formation of a strongly interacting matter, the quark–gluon plasma (QGP).[1–3] Since the mean free paths of the produced photons are considerably larger than the size of the nuclear volume, photons produced throughout all stages of the collisions will remain observable in the final state and they are considered to be the best markers of the entire space–time evolution of the collisions. The other important reason for the measurement of single photons and dileptons is the fact that, once produced they hardly ever interact; and so they leave the system with their energies and momenta unaltered. Their production cross-sections, which are undoubtedly very important observables, should provide valuable information about the formation of hot and dense matter, the so-called exotic stage of matter, anticipated to be created in such collisions.

This work is, in fact, a continuation and an extension of one of our previous work[4] on production of direct photons in only the very recent Au Au and Pb Pb collisions. We obtained, therein, a fair degree of success in explaining data on direct photon production with the help of a nonconventional approach. Now, in the present work, based on the same approach, we would try to encompass the large array of data on direct photon production in numerous hadron-induced nuclear collisions and purely nuclear collisions with a view to providing an alternative interpretation, if possible, for all of them. In other words, the general validity or the correctness of the approach would be tested against much wider background and perspective.

The difficulty in direct photon measurement in high energy particle and nuclear collisions arises mainly from the background comprising the decays of π^0 and η mesons after freeze-out of the collision systems.[5] So, one has to be careful about the efficiencies of γ and π^0 identification and the uncertainties related to η measurement.[6] The γ_d/π^0 ratio, in regard to the direct photon measurement, can provide us a measure of the difficulty of the experimental environment for making direct photon measurement.[7] Obviously, in calculating the γ_d/π^0 ratio, we have borne in mind that π^0 constitutes the primary background to photon production and we have completely neglected here the uncertainty of η measurements.

The problem of production of direct photons in high energy PP, $P\bar{P}$, PA and AB collisions and also in various pion-induced hadronuclear interactions involved and still involves extensive studies — both experimental and theoretical,[6–20] especially in the domain of large transverse momentum at different high energies. We will concentrate here on the nature of inclusive cross-sections for direct photon production and also on the explanation for the γ_d/π^0 ratio-behaviors in different ultrarelativistic particle-, nucleus-induced collisions at very high energies and also at large transverse momenta. Our objective, here, is to interpret a substantial part of the data, if not the whole, measured by different groups at different energies,[6–16,19,20] from the viewpoint of a non-standard model which has no direct QGP tag, but has some new physical ideas incorporated therein. And this we consider to be of much importance to us, especially because of our fairly successful treatment of the available data on direct photon production in Au − Au and Pb − Pb collisions in a previous work.[4]

The plan of the paper is as follows. Subsection 2.1 deals with the model that we would like to apply here for the present study. In Subsec. 2.2 we try to provide the framework for converting the results of PP collisions to those for AB reactions. In Sec. 3 we focus on the results obtained and their model-based interpretations. Section 4 represents the concluding remarks.

2. Direct Photon Production in NA and AA Interactions: An Approach

Here, in the first subsection, we deal with the production of direct photons in nucleon–nucleon (NN) interactions. Subsequently, in the next one, we focus on the approach to convert the results of NN collisions to the corresponding values for the case(s) of nucleus–nucleus collision. The pion induced collision, if any, shall also be treated at par with nucleon-induced interactions but with specific considerations about its mass and pseudoscalar nature.

2.1. *Proposed mechanism for direct photon production in PP collisions*

We will use here a particular version of Sequential Chain Model (SCM)[21–24] to study some of the main characteristics and observations related to production of π-mesons and direct photons in different collisions at high energies. Let us first recapitulate some of the salient features and important physical characteristics of the SCM model valid for hadron–hadron and lepton–hadron collisions. According to this model, high energy hadronic interactions boil down, essentially, to the pion–pion interactions; as the protons are conceived in this model as $P = (\pi^+\pi^0\vartheta)$, where ϑ is a spectator particle needed for the dynamical generation of quantum numbers of the nucleons. The production of pions in the present scheme occurs as follows: the incident energetic π-mesons in the structure of the projectile proton (nucleon) emits a rho (ϱ)-meson in the interacting field of the pion lying in the structure of the target proton, the ϱ-meson then emits a π-meson and is changed into an omega (ω)-meson, the ω-meson then again emits a π-meson and is transformed once again into a ϱ-meson and thus the process of production of pion-secondaries continue in the sequential chain of rho-omega-pi mesons. The two ends of the diagram contain the baryons exclusively. Figures 1 and 2 depict the mechanisms for production of pions of all three varieties in PP and πP collisions respectively.

The production of direct photons in proton–proton collisions is somewhat similar to that of pion production in this model. The π-meson emits a ϱ-meson, the ϱ-meson then emits a π-meson and is changed into a ω-meson, the ω-meson emits a photon, which is called the direct photon (γ_d) from the viewpoint of the present model, and the π-meson is transformed once again into ϱ-meson and the process of direct photon production continues. Figures 3 and 4 represent diagrammatically the suggested physical mechanisms for direct (prompt) photon production. It is to be noted that direct photon could also be produced by decay of secondary ϱ^0

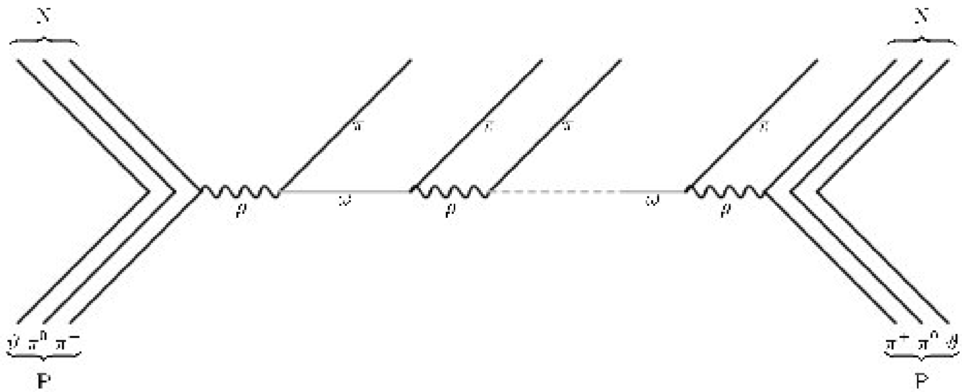

Fig. 1. Schematic diagram of multiple production of pions in PP scattering in the present scheme.

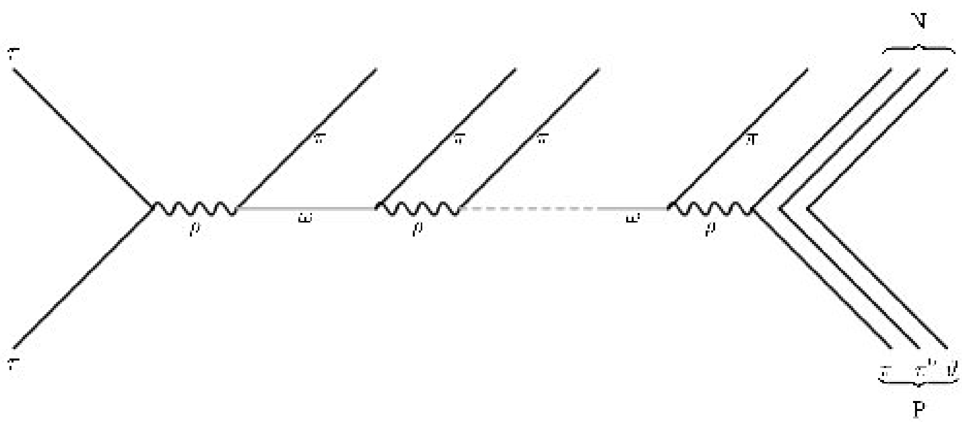

Fig. 2. Schematic diagram of multiple production of pions in πP scattering in the present scheme.

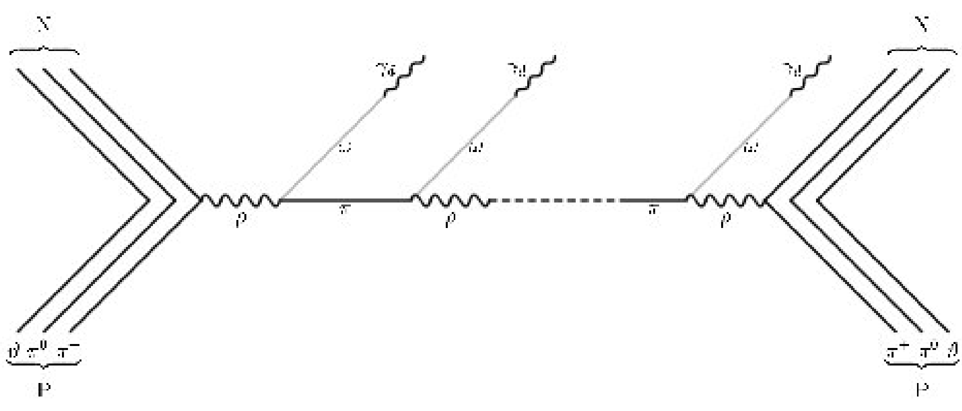

Fig. 3. Schematic diagram of multiple production of "direct" photons in PP scattering according to the present model.

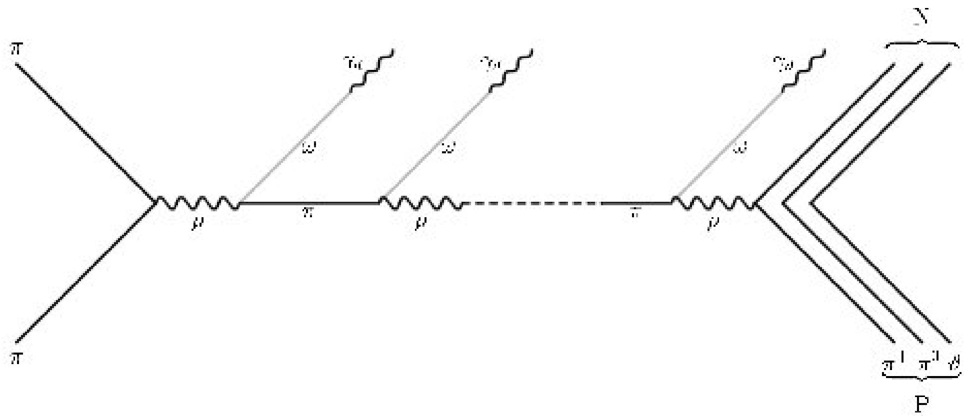

Fig. 4. Schematic diagram of multiple production of "direct" photons in πP scattering in the present model.

mesons in the vertical chain in the place of ω^0 decay, save at the two vertices for the projectile and the target in which cases the chains have compulsorily to start or to end up with $\varrho\pi\pi$ for the present scheme of multiple production and for the suggested model of direct photon production as well.

It can be stated that the present model is totally a field-theoretic one and the expressions are derived here from the kinematics of the infinite momentum frame for the inclusive production cross-sections and average multiplicity values of direct photons and pions (of any variety) produced in the chain. The expressions for inclusive cross-sections of the direct photons and of pions are to be assorted now from some of our previous works.[21–23] And we proceed in the following way.

The inclusive cross-section for production of direct photon was calculated by one of the authors, [SB], by using Feynman diagram technique[23] and is given by

$$E\frac{d^3\sigma}{dp^3}\bigg|_{PP\to\gamma_d x} = \frac{\mathrm{CRT}}{4\pi}\,\frac{f^2_{\varrho\omega\pi}}{16\pi^2}\,\Psi(x, p_T, s)\,, \tag{1}$$

where CRT is the "constituent rearrangement term" arising out of the partons inside the proton. It is established that hadrons (baryons and mesons) are composed of few partons. At large transverse momenta in the high energy interaction processes the partons undergo some dissipation losses due to the impact and impulse of the projectile on the target and they suffer some forced shifts of their placements or configurations. The transitions may occur from top-to-top and bottom-to-bottom (H-type diagrams) or cross-wise from top-to-bottom and bottom-to-top (X-type diagrams) or in-between. This phenomenon means undesirable loss of energy, in so far as the particle production mechanisms are concerned. This is, again, dependent on the c.m. energy of the interactions, i.e. on $\sqrt{s_{NN}}$. This damping term is finally expressed (in terms of p_T for large-p_T domain) in the form $\sim (p_T)^{-4n\theta}$ where n = no. of partons undergoing the rearrangement of position and θ = a phase term, with maximum value equal to unity and normally is $\ll 1$.[23] Denoting $4n\theta$

by N_R, we may express, the value of CRT as $\sim p_T^{-N_R}$, wherein the choice of N_R would depend on the following factors: (i) the names of the interacting projectile and target, (ii) the natures of the secondaries emitted from a specific hadronic interaction and (iii) the magnitude of the momentum transfer in a specific reaction. However, the factor $f^2_{\rho\omega\pi}/4\pi$ in above equation is the coupling strength for $\rho\omega\pi$ coupling; the term $\Psi(x, p_T, s)$ is a well-known structure functions containing for production of direct photons or pions, as the case may be, with x as the Feynman scaling variable, p_T the transverse momenta and s being the square of the c.m. energy. For large p_T, we have $\Psi(x, p_T, s) \to \phi(s)\exp(-65\langle n_{\gamma_d}\rangle_{PP}x_T)$ with $\phi(s)$ is the function of s only, $x_T = 2p_T/\sqrt{s}$ and $\langle n_{\gamma_d}\rangle$ is the average multiplicity of the photon. The average multiplicity of the direct photon is calculated and it is given by the undernoted relation

$$\langle n_{\gamma_d}\rangle_{PP} = \left[\frac{f^2_{\rho\omega\pi}g^2_{\omega\gamma_d}(p^2_{\gamma_d})_{\max}}{64\pi^2}\right]^{1/3} \simeq \langle n_{\pi^0}\rangle_{PP}\left(\frac{\alpha}{15}\right)^{1/3}. \tag{2}$$

In Eq. (2) given above, α is the fine structure constant. Here, the factors, $f^2_{\rho\omega\pi}/4\pi$ and $g^2_{\omega\gamma_d}/4\pi$ are the coupling strengths for $\rho\omega\pi$ coupling and for $\omega\gamma_d$ coupling respectively. Besides, the factor $[(p^2_{\gamma_d})]_{\max}$ is the sum of the square of the momentum for emitted individual direct photon which is expressible finally in terms of the c.m. energy of the system with some high energy assumptions. The term $\langle n_{\pi^0}\rangle$ represents the average multiplicity of neutral pi mesons.

The expression for inclusive cross-section for production of direct photon at high transverse momentum now reduces to

$$E\frac{d^3\sigma}{dp^3}\bigg|_{PP\to\gamma_d X} \simeq C_{\gamma_d}\frac{1}{(p_T)^{N_R}}\left(\frac{1000}{s}\right)^{1/5}\exp\left(-65\langle n_{\gamma_d}\rangle_{PP}x_T\right), \tag{3}$$

where, for example, $C_{\gamma_d} \simeq 0.7$ for energy region of Intersecting Storage Ring (ISR) experiments and it is different for different energy region.

Following the same procedure, the expressions for inclusive cross-section for the neutral pions can be written in the following form:

$$E\frac{d^3\sigma}{dp^3}\bigg|_{PP\to\pi^0 X} \simeq C_{\pi^0}\frac{1}{(p_T)^{8.4}}\left(\frac{1000}{s}\right)^{1/5}\exp(-4.7\langle n_{\pi^0}\rangle_{PP}x_T), \tag{4}$$

where $|C_\pi| \simeq 90$ for ISR energy region and it increases with the increase of inelastic cross-sections and is different for different energy region and where

$$\langle n_{\pi^0}\rangle_{PP} \simeq \langle n_{\pi^+}\rangle_{PP} \simeq \langle n_{\pi^-}\rangle_{PP} \simeq 1.1s^{1/5}. \tag{5}$$

2.2. *The link-up between nucleon−nucleon collisions and nucleus−nucleus interactions*

In order to build the bridge between nucleon–nucleon interactions and the nucleus–nucleus reactions, we proceed in the method suggested by Wong.[25] As a first step in the process we will have to consider a nuclear reaction $A+B \to Q+X$, where A and

B are projectile and target nucleus respectively and Q is the detected particle which in the present case would either be direct photon or neutral pion. In a reaction of this type, for the impact parameter b, we assume, there are $n'(b)$ number of inelastic nucleon–nucleon collisions. Each collision contributes to the production of particles.

In order to build the bridge between nucleon–nucleon interactions and the nucleus–nucleus collisions, we proceed in the path suggested by Wong.[25] As a first step in the process, let us consider a nuclear reaction $A + B \to C + X$, where A and B are projectile and target nucleus respectively. In such a collision, for the impact parameter b, we assume that there are $n'(b)$ number of inelastic nucleon–nucleon collisions. Each collision contributes to the production of particles. If all the collisions contribute in the same way, the inclusive cross-section $(Ed^3\sigma/dp^3)$ for the nucleus–nucleus collisions would just be $n'(b)$ times the inclusive cross-section for the nucleon–nucleon collisions.

However, the contributions from all of the collisions are not the same. One can envisage that in a nucleus–nucleus collision, those nucleon–nucleon collisions which occur later in the process contribute less than those collisions from earlier collisions, because of the stopping of the baryons of one nucleus as they go through the other nucleus. The degree of stopping depends on the thickness of the projectile and the target nuclei. Initial indirect evidences for the stopping of the baryon matter came first from WA80 collaboration for studying of ^{16}O collisions on various targets. In the experimental measurement one sets up a "Zero Degree Calorimeter (ZDC)" which collects the particles within 0.3° of the incident beam (meaning detecting at very small angle nearing zero). It measures the amount of energy which is transmitted into the forward direction during the collisions; and also it measures the centrality of the collisions. The stopping of the incident projectile will be effective, only if and when the target nucleus is considerably heavy. The probability for the incident nucleus (nucleon) to loose a large fraction of its incident energy would be quite large ($\sim$ 10% to 20%) depending on some other factors occurring in a particular collision. One observes that there are greater degradations of the energies of the colliding nucleons in central collisions as compared to peripheral ones. The slight decrease of the transverse energy per collision with the decrease of the impact parameter is an indication of the effect of energy degradation, when nucleons of the projectile-nucleus traverse through the target-nucleus. So, for heavy nuclei and high energy nuclear collisions which entail the involvement of a large number of nucleons and multiple binary collisions, the role of the energy degradation factor is certainly not negligible. If and when one uses this stopping effect to the first power in the thickness of the projectile and of the target-nucleus, the resultant effect of energy degradation should lead to a reduction factor of the form $1/[1 + a'(A^{1/3} + B^{1/3})]$. Thus, the relationship between the inclusive cross-section for nucleus–nucleus interactions and that for nucleon–nucleon collisions is given by

$$\left(E\frac{d^3\sigma}{dp^3}\right)\bigg|_{AB} \cong \frac{n'(b)}{1+\kappa(A^{1/3}+B^{1/3})}\left(E\frac{d^3\sigma}{dp^3}\right)\bigg|_{PP}, \tag{6}$$

where κ is a parameter that is to be chosen. The value of κ, following Wong, is taken here to be ~ 0.09. And the expression for $n'(b)$ is given by

$$n'(b) = \frac{ABT(b)\sigma_{\rm in}}{1 - [1 - T(b)\sigma_{\rm in}]^{AB}}, \tag{7}$$

where $\sigma_{\rm in}$ is total inelastic cross-section and $T(b)$, the thickness function, can be estimated by a Gaussian distribution

$$T(b) = \frac{1}{2\pi\beta^2} e^{-b^2/2\beta^2}, \tag{8}$$

where

$$\beta^2 = \beta_A^2 + \beta_B^2 + \beta_p^2, \tag{9}$$

and

$$\beta_A = \frac{r_0' A^{1/3}}{\sqrt{3}} \tag{10}$$

with $r_0' = 1.05$ fm, and β_p, the thickness function parameter for nucleon–nucleon collision, is 0.68 fm. For central collisions, $T(b)$ does not vanish and the denominator can be approximated to unity. Therefore, we get,

$$\left(E\frac{d^3\sigma}{dp^3}\right)\Bigg|_{AB} \simeq \frac{3\sigma_{\rm in}}{2\pi(r_0')^2}\frac{AB}{A^{2/3}+B^{2/3}}\frac{1}{1+\kappa(A^{1/3}+B^{1/3})}e^{-b^2/2\beta^2}\left(E\frac{d^3\sigma}{dp^3}\right)\Bigg|_{PP}. \tag{11}$$

The expression (11) provides the necessary route for converting the results of direct photon production in nucleon–nucleon collisions obtained in the framework of SCM to those for nucleus–nucleus collisions which we are specially interested in for this work.

3. Details of Calculations and Presentation of the Results

In this section, we will present the results obtained on the basis of the model-dependent calculations and will compare them with the data available from the measurements made by different groups for different collisions at varying energies. In the first subsection, the results on the analyzes of the inclusive cross-section for production of direct photon are presented; the output on the γ_d/π^0 ratios is presented in the next subsection.

3.1. *Inclusive cross-section for direct photon (γ_d) in various interactions at different energies*

The inclusive cross-sections for direct photons in different interactions are to be calculated now. The calculated values in the light of the sequential chain model (SCM) can be written in the following generalized form:

$$E\frac{d^3\sigma}{dp^3}\Bigg|_{AB\to\gamma_d x} = a{p_T}^{-N_R}\exp(-\Delta p_T), \tag{12}$$

where a, N_R and Δ are the parameters to be chosen under certain physical constraints. Using Eqs. (3) and (11), the following set of relations are obtained and used for these parameters a, and Δ:

$$a \simeq C_{\gamma_d} \frac{3\sigma_{\rm in}}{2\pi(r_0')^2} \frac{AB}{A^{2/3}+B^{2/3}} \frac{1}{1+\kappa(A^{1/3}+B^{1/3})} e^{-b^2/2\beta^2} \left(\frac{1000}{s}\right)^{1/5}, \qquad (13)$$

and

$$\Delta \simeq \xi s^{-0.3}. \qquad (14)$$

The "a"-factor in the expression (12) accommodates a wide range of variation because of the existence of large differences in the normalizations of the direct photon cross-sections by the various experimental groups and for different types of interactions. The normalizations, in most cases, are different for different projectile-initiated reactions. This is, indeed, the case with the authors of Refs. 7 and 16 from whom we have quoted, here, some relevant points afterwards. The main motivation behind putting the final form of the inclusive cross-sections for production of direct photons in the form of expression (13) is primarily to check whether this somewhat simplified form could explain the measured data, at least, in the qualitative way. In fact, for some nuclear reactions (like the cases of S Au and Pb Pb interactions in the column 1 of Table 1 here), the measured observable by the experimentalists is not the invariant inclusive cross-sections as such; rather they are the event-averaged indicators for the inclusive cross-sections for which their order of magnitudes are so distinctly different. These factors and uncertainties, explain, in part, why the values of parameter a in Eq. (12) [given in the third column of Table 1 for various interactions] are so widely divergent. Besides, there are some other sources as well. Moreover, it is seen from the above expression (13) that the parameter "a" has a specific dependence on the number of nucleons participating in nuclear reactions involving nucleus (A), nucleus (B) and on the center-of-mass energy ($\sqrt{s}$).

It is clear from the expression (14), that the parameter Δ has a particular energy dependence given in the specific form with ξ as a numerical factor arising out of proportionality constant and is treated here as constant at a definite energy. A careful scrutiny of Table 1 gives rise to the following observations on the pattern of the values of the parameters a, N_R and Δ. And these patterns look somewhat consistent in the following way:

(i) At the same energy the values of "N_R" and "Δ" are the same for both pion-induced and nucleon (proton)-induced reactions; but the "a" values for the former type of collisions are a bit larger than those for the latter type of reactions. This is somewhat natural in the sense that a-factor is a product arising mainly out of the amplitude terms and with small or no s-, p_T- or x_T-dependence. Besides, the energetic projectile pions, being lighter than proton, can penetrate deeper into the structure of the nucleon, and thus increase the thickness function parameter, β_p, in Eq. (9). This, in turn, might be a contributing factor to the rise of "a"-values in all the pion-initiated collisions.

Table 1. Presentation of the parameter values: calculations of the inclusive cross-sections.

Reactions	$\sqrt{s}$ (GeV)	a (pb GeV$^{N_R-2}\cdot\Delta^{-N_R}$)	N_R	Δ (GeV/c)$^{-1}$	Data Refs.	Figs. No.
$pp \to \gamma_d + x$	22.9	3.0×10^6	1.2	2.332	14	5
$\pi p \to \gamma_d + x$	22.9	5.8×10^6	1.2	2.332	14, 16	6
$pp \to \gamma_d + x$	24.3	5.0×10^6	1.2	2.240	11	7
$p\bar{p} \to \gamma_d + x$	630.0	2.1×10^3	1.7	0.125	10	8
$p\,\mathrm{Be} \to \gamma_d + x$	31.4	2.3×10^7	2.5	1.740	7, 9	9
$\pi\,\mathrm{Be} \to \gamma_d + x$	31.4	2.8×10^7	2.5	1.740	9, 16	10
$p\,\mathrm{Be} \to \gamma_d + x$	38.6	2.8×10^7	2.2	1.670	7, 9	11
$pC \to \gamma_d + x$	19.4	6.0×10^7	1.4	2.560	19	12
$\pi C \to \gamma_d + x$	19.4	1.4×10^8	1.4	2.560	16, 19	13
$S\,\mathrm{Au} \to \gamma_d + x$	19.4	1.14	2.2	2.560	12	14
$\mathrm{Pb\,Pb} \to \gamma_d + x$	17.2	1.42	2.5	2.760	1, 2, 6, 8	15
$\mathrm{Au\,Au} \to \gamma_d + x$	130.0	1.60	2.6	0.622	—	16

(ii) The inverse s-dependence of the Δ-values represented by expression (14) is also spectacularly corroborated by the values used and given in Table 1.

(iii) The N_R parameters are functions of both the number of participating nucleons (or partons) and of the energy. The factor N_R in the expression (12) arises out of the constituent rearrangement (CR) in the structure of basic nucleon–nucleon collisions at high energies and at large transverse momenta.

This is very much dependent on the momentum transfer in the reactions. The issue has already been discussed here at length in Subsec. 2.1. The values of N_R (tabulated in the fourth column of Table 1) are the results of all these considerations. The average number of participating projectile and target nucleons is taken from a previous work by Kadija *et al.*[26]

In Table 1 we present the values of a, N_R and Δ for different interactions and at different energies. The corresponding figure-number is also cited in the last column. The accompanying references for the experimental data, except for the last one, are shown in the sixth column of the same table. The solid curves drawn in the diagrams presented in Figs. 5–15 demonstrate the results calculated on the basis of the model under consideration here. For the case of Au + Au reaction at $\sqrt{s} = 130$ GeV in the Relativistic Heavy Ion Collider (RHIC) experiments at Brookhaven, now we simply make a prediction on the inclusive production of direct photon production. The diagram in Fig. 16 illustrates this theoretical prediction. In doing so the values of "a," "N_R" and "Δ" parameters have been chosen in the following way: firstly, we have been guided by both the results of S + Au and Pb + Pb collision by neglecting the small difference in interaction energy between the two. By a sort of crude averaging we obtain the initial values of the parameters for Au + Au reaction supposed to occur at about $\sqrt{s} \sim 18$ GeV approximately. The tabulated values for the three parameters then obtained by inserting some small energy-dependent factor on these averages to convert them to the usable values at $\sqrt{s} = 130$ GeV.

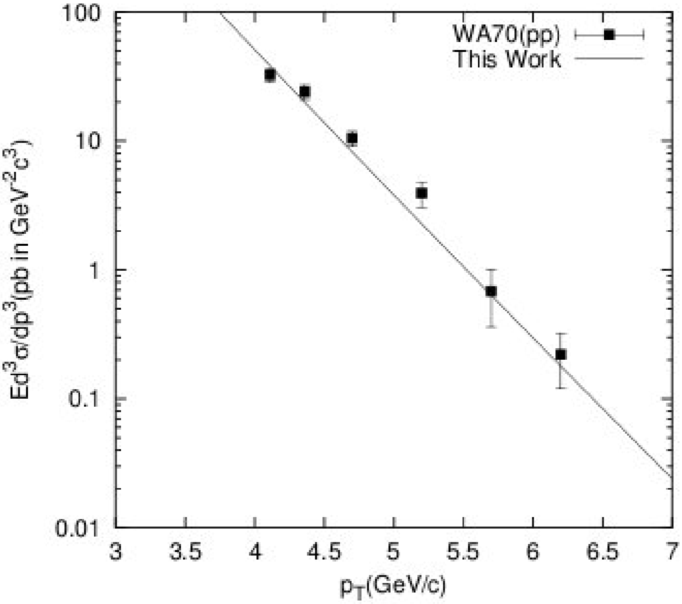

Fig. 5. Plot of the invariant cross-section for single prompt photon production in proton–proton collisions at incident beam momentum 280 GeV/c as a function of p_T. The data points are from Ref. 14. The results arrived at on the basis of SCM are shown by the solid curve.

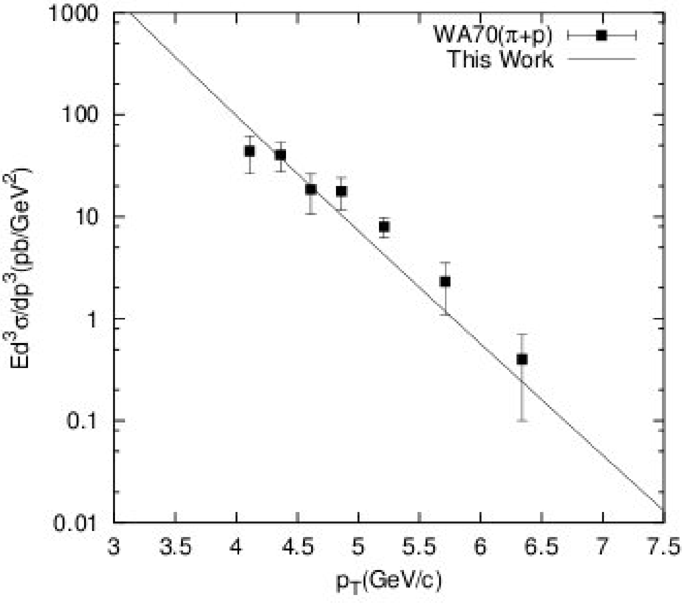

Fig. 6. Plot of the invariant cross-section for single prompt photon production in π-proton collisions at incident beam momentum 280 GeV/c as a function of p_T. The data points are from Ref. 14. The results arrived at on the basis of SCM are shown by the solid curve.

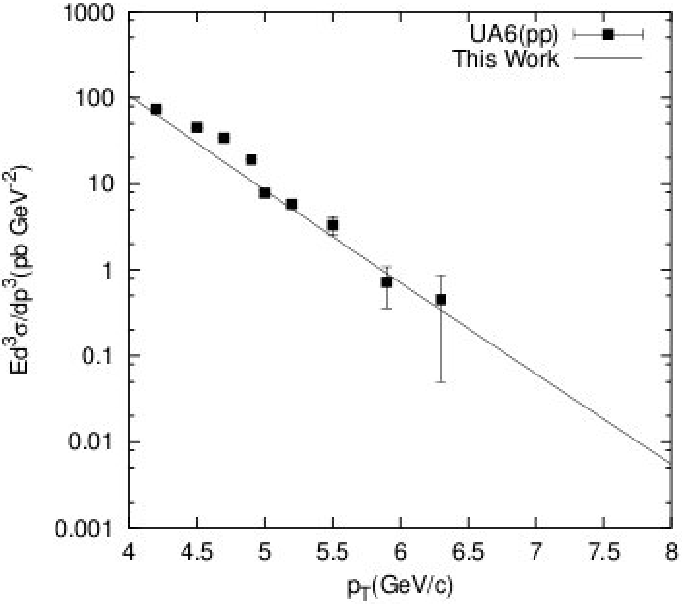

Fig. 7. Plot of the invariant cross-sections for single prompt photon production in proton–proton collisions at $\sqrt{s} = 24.3$ GeV as a function of p_T. The data points are taken from Ref. 11. The solid curve shows the SCM based theoretical result.

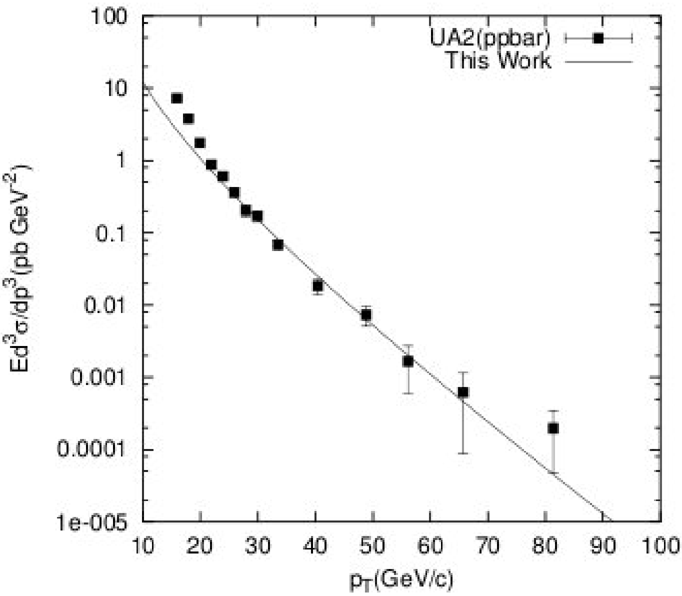

Fig. 8. Plot of the invariant cross-section for single prompt photon production in proton–antiproton collisions at a center-of-mass energy of 630 GeV as a function of photon transverse momentum. The data set is taken from UA2 group (Ref. 10). The line depicts the SCM based theoretical results.

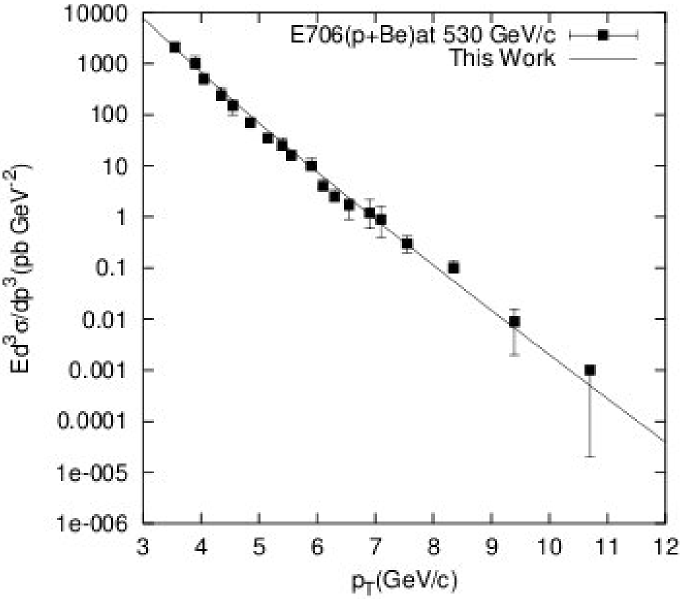

Fig. 9. Plot of the invariant cross-section for single prompt photon production in proton-beryllium collisions at incident beam momentum 530 GeV/c as a function of p_T. The data are taken from E706 group (Ref. 9). The SCM based results are shown by the solid curve.

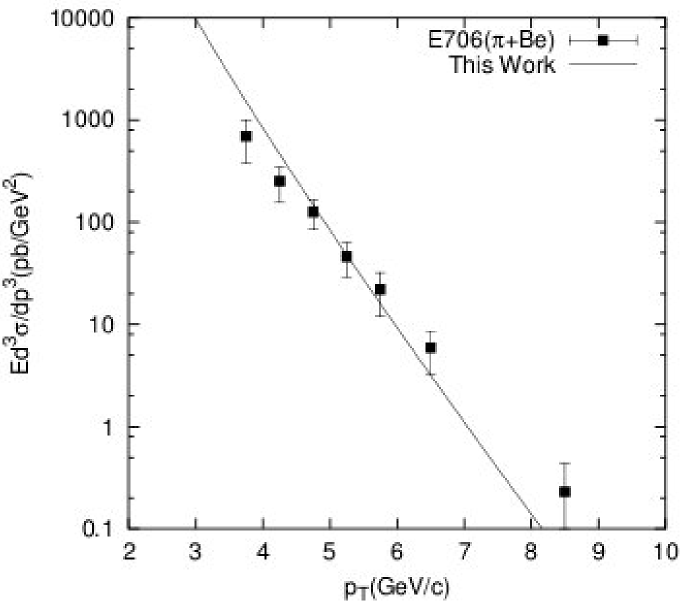

Fig. 10. Plot of the invariant cross-section for single prompt photon production in π-Be collisions at incident beam momentum 530 GeV/c as a function of photon's transverse momentum. The data are taken from E706 group (Refs. 9 and 16). The results arrived at on the basis of SCM are shown by the solid curve.

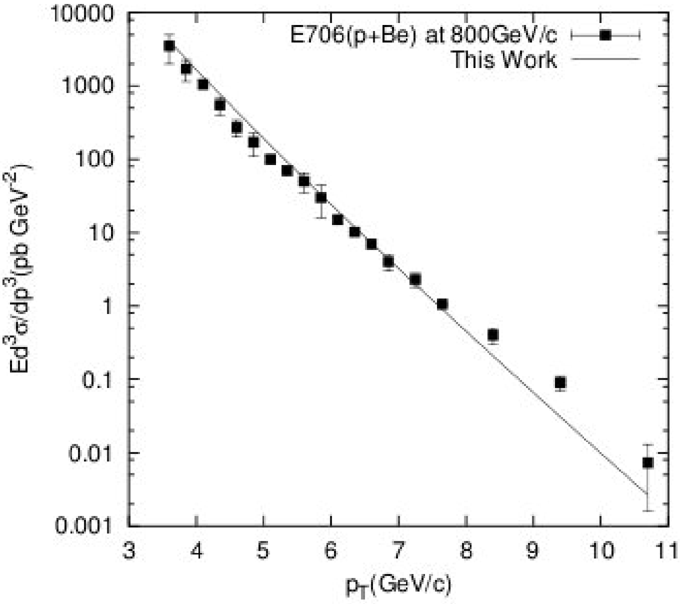

Fig. 11. Plot of the invariant cross-section for single prompt photon production in proton-beryllium collisions at incident beam momentum 800 GeV/c as a function of photon's transverse momentum. The data points are from Refs. 7 and 9. The solid line is drawn on the basis of the SCM.

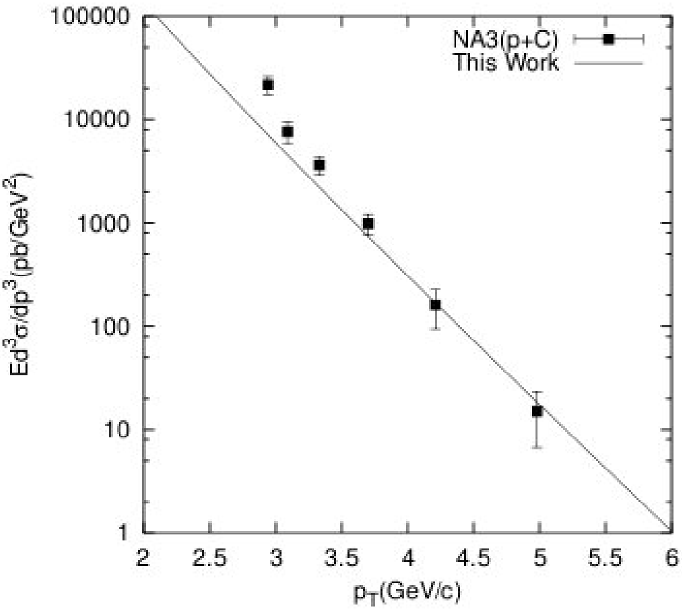

Fig. 12. Plot of the invariant cross-section for single prompt photon production in proton-carbon collisions at incident beam momentum 200 GeV/c as a function of p_T. The data points are from Ref. 19. The solid curve depicts the SCM based theoretical results.

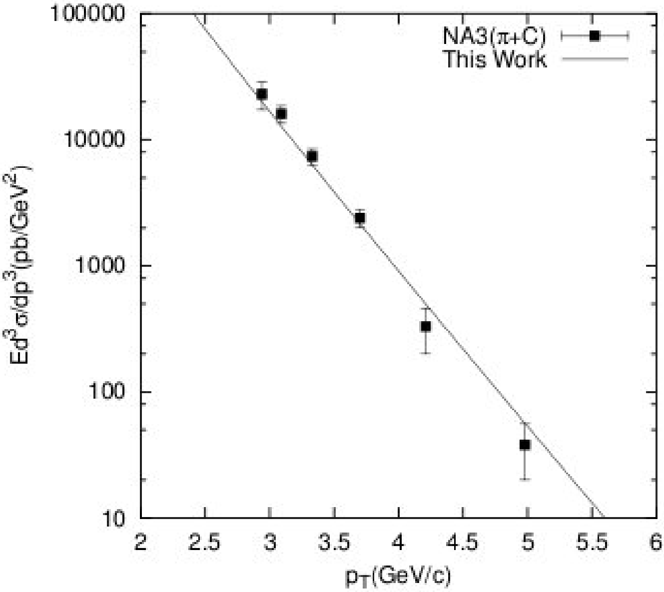

Fig. 13. Plot of the invariant cross-section for single prompt photon production in π-C collisions at incident beam momentum 200 GeV/c as a function of photon's transverse momentum. The data are taken from NA3 group (Refs. 19 and 16). The SCM-based results are shown by the solid curve.

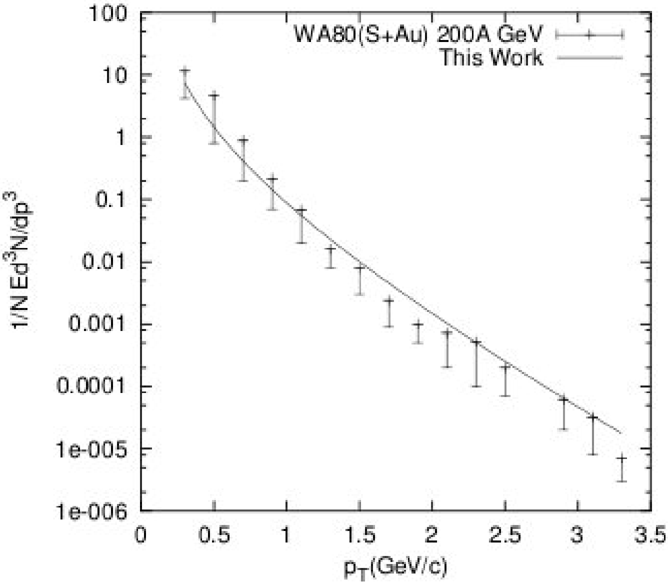

Fig. 14. Plot of the invariant excess photon yields for the most central collisions in $S + \mathrm{Au}$ collisions at beam energy 200 A GeV against photon's transverse momentum. The data are taken from Ref. 12. The solid curve represents theoretically the direct photon production on the basis of the SCM.

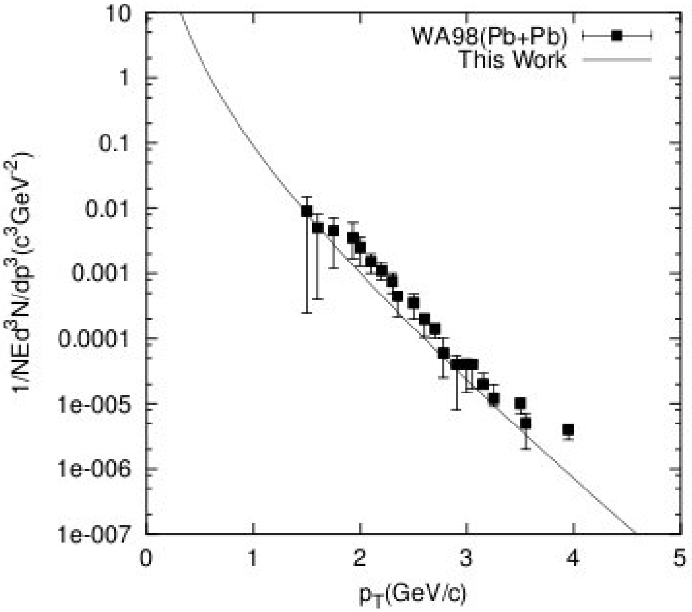

Fig. 15. Plot of the invariant direct photon multiplicity for central Pb + Pb collisions at beam energy 158 A GeV vs. the transverse momentum p_T. The data points are from WA98 collaboration (Refs. 8, 6, 1 and 2). The solid curve represents SCM-based result.

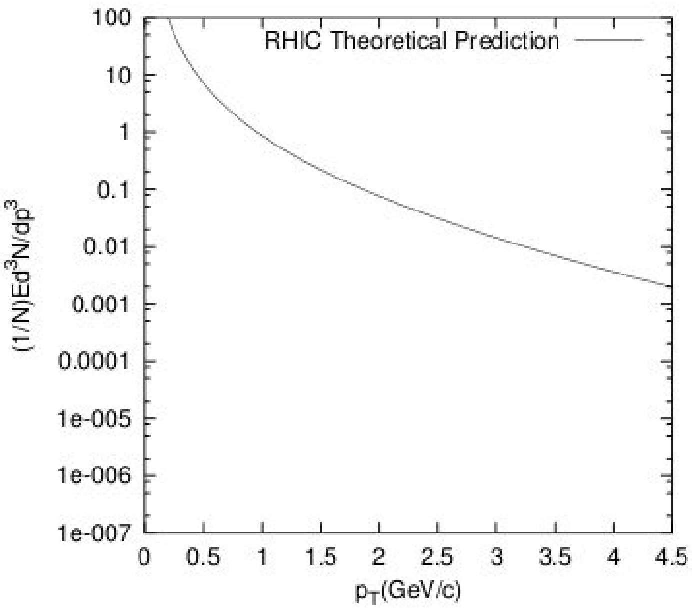

Fig. 16. Predicted plot of direct photon measurement in the light of SCM for central Au + Au collisions at $\sqrt{s} = 130$ GeV.

However, in this context, we would like to put stress on certain observations and features which are extremely relevant for assessing whatever little is done here with the help of SCM with some assumptions and approximations. Apanasevich *et al.*[7] in their studies on direct photon production in proton–nucleon interaction remarked (i) that photon and pion data show disagreement with theory which, by implication, is the Standard Model (SM) approach; (ii) that the different data sets also disagree with each other; and (iii) that the theoretical results could never provide great confidence in the theory nor in the quality of all the data. Besides, Vogelsang and Whalley[16] commented very succinctly that it was difficult to compare directly the various data sets on direct photon production, because they were measured at different beam momenta, at different c.m. energy of interaction, for different ranges in p_T (transverse momentum of the detected direct photon) and also in x (Feynman scaling variable). Quoting the authors of Ref. 16, let us put: "Direct comparison is difficult and the theory curves serve to provide a common ⟨base-line⟩."

Against this background, it is very difficult on our part to put extreme emphasis on the strict validity of the expressions (12), (13) and (14), because they could really not be tested with the fully consistent sets of data for different hadronic and nuclear interactions owing to the gross limitations arising out of the circumstances prevailing in the experiments and described in the preceding paragraph. As a result of this, in actual working of them some tacit assumptions have always automatically entered into the numerical computations. Obviously, we ourselves cannot ever remedy these problems for which we would rather prefer here to judiciously tone down our claim, if any, on the successes of the model.

3.2. *The γ_d/π^0 cross-section ratios*

The direct photon to pion ratio has consistently been treated as an important physical observable. So, we are interested now to study the nature of some ratio-behaviors in a few high energy collisions on which data are to hand. If the measurements are reliable even to a limited extent, the nature of the ratios gives a handy tool to examine finally the efficacy of the model and also to cross-check the findings with the laboratory data. But the available data, in this context, are too sparse. However, in the next we attempt to analyze a few ratios with the help of the SCM. Using Eqs. (3) and (4), the generalized form of the γ_d/π^0 ratio can be expressed in the following form:

$$\left.\frac{\gamma_d}{\pi^0}\right|_{AB} = a^r {p_T}^{N_R^r} \exp(-\Delta^r p_T)\,, \tag{15}$$

with $a^r \simeq C_{\gamma_d}/C_{\pi^0}$, $N_R^r \simeq N_R^{\pi^0} - N_R^{\gamma_d}$ and $\Delta^r \simeq \xi^{\gamma_d} - \xi^{\pi^0}$, where the superscript r denotes the ratio-values.

In the adjoining table (Table 2) we have indicated the values used in our calculations for the parameters occurring in expression (15). The results are graphically shown in the diagrams presented in Figs. 17–20. By studying only the four ratio-behaviors for four different interactions we cannot make any strong judgement on

Table 2. Used parameters values: the ratios of cross-sections.

Reactions	$\sqrt{s}$ (GeV)	a^r	N_R^r	Δ^r (c/GeV)	Data Refs.	Figs. No.
$pp \to \gamma_d + x$	22.9	2.0×10^{-5}	6.9	0.55	7, 14	17
$p\text{Be} \to \gamma_d + x$	19.4, 23.6	9.6×10^{-3}	3.5	0.55	16, 20	18
$pC \to \gamma_d + x$	19.4	7.5×10^{-5}	6.9	0.55	19	19
$\text{PbPb} \to \gamma_d + x$	17.2	8.1×10^{-5}	6.9	0.55	6	20

the nature of concavity-convexity aspect of the prompt photon ratios. Still, the fair agreement in their natures with measured data acts as a source of encouragement to proceed further in future with such studies.

4. Summary and Outlook

Even a cursory glance at the tables and diagrams of this work reveals a fair agreement between the measurements and model-based calculations for most of the observables. Our main interest in this work is to describe theoretically the qualitative features of the transverse momentum (p_T) dependence of the inclusive cross-sections for direct photons produced in various proton- or nucleus-induced collisions; and also to explain some other related features for production of the same particle. In the quantitative plane, suitable normalizations as indicated by the values of "a" in Table 1 have throughout been adopted and used. As the model

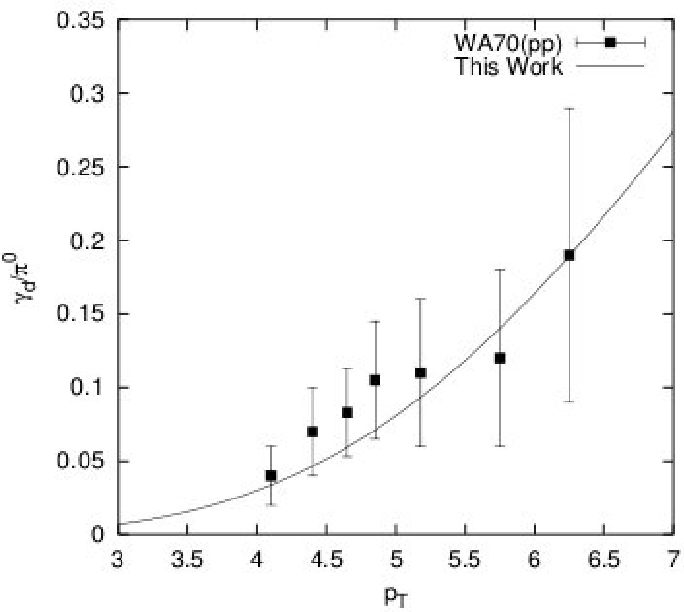

Fig. 17. Plot of ratio of the direct photon to neutral pion (as a function of p_T) production in central $p+p$ collisions. Data are taken from Ref. 14. The solid line shows the SCM-based theoretical results.

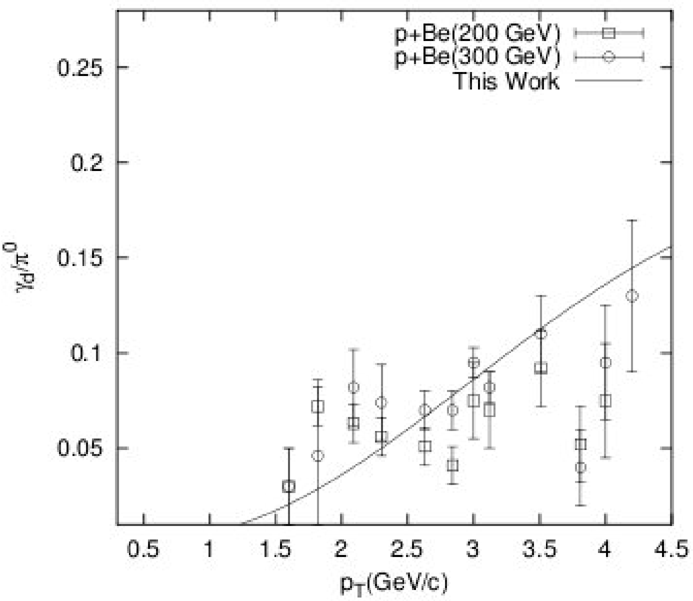

Fig. 18. Plot of the ratio of the direct photon to neutral pion produced in central $p + Be$ collisions at 200 and at 300 GeV as a function of p_T. Data are taken from Ref. 20. The solid line shows the SCM-based theoretical results.

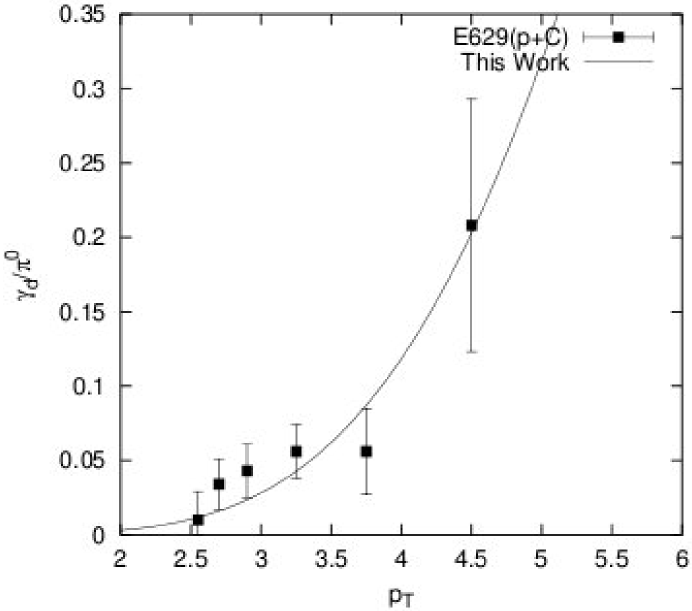

Fig. 19. Plot of the ratio of the direct photon multiplicity to pion multiplicity in central $p + C$ collisions at 200 GeV vs. p_T. Data are taken from Ref. 19. The solid line shows the SCM-based theoretical results.

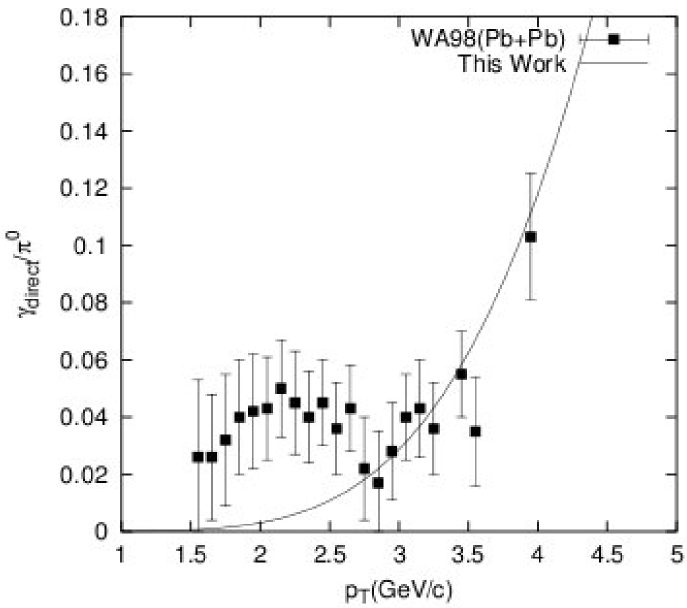

Fig. 20. Plot of ratio of the direct photon multiplicity to pion multiplicity in central Pb + Pb collisions at 158A GeV as a function of p_T. Data are taken from Ref. 6. The solid line shows the SCM-based theoretical results.

has some parameters which have dynamical features and as the model does not just aim at fitting the experimental data in a purely phenomenological way, the question of χ^2/ndf does not arise here.

The satisfactory agreement between model-based results and the experimental data measured earlier or even in the recent past raises naturally the following sensitive points and issues:

(i) The chosen approach and method are modestly successful in explaining both the old and up-to-date data on direct photon production in several collisions at high energies. And, quite obviously, the model is of non-"standard" type. This observation automatically prompts one to question the status of gluons in High Energy Physics; and also to cast doubts on the uniqueness of the relationship between the "hypothetical" gluons and the direct photons.

(ii) Our model is not based on any of the ideas of what is known as the physics of quark–gluon plasma (QGP).[27] But the applied model serves the experimental data modestly well. The implication is obvious: the QGP approach might not be the singular or any unique one to interpret the real observations.

(iii) Combining the content of the previous points and summing up the physical facts introduced here, we may now humbly put up a claim that the model presented here might have the potentiality of throwing a viable alternative to the "standard" approach.

(iv) By a change of the definition and of outlook, the prompt or direct photons, in the framework of the present model, are perceived to be the simple product of the decay of secondary ω-mesons (and the ϱ-mesons as well) which might emanate in the processes of multiple production of hadrons. Obviously, these vector mesons are not produced too profusely due to the consecutive operation of the two very small but measurable couplings terms of $\varrho - \omega - \pi$ and $\omega - \gamma$ (or $\varrho - \gamma$). Thus, physically and essentially, this constitutes a vector meson dominance approach for production of direct photons.

(v) The present model incorporates almost intrinsically the idea of violation of the Feynman scaling; and this is evident from the nature of the expressions for inclusive cross-sections shown by several equations given in the main part of work.

(vi) In our approach, as the basic pion–pion interaction holds the key to explain the features of particle production phenomena in general, the globality aspect of high energy collisions, with regard to production of even the direct photons, is logically ingrained in and almost automatically executed by the present mechanism.

(vii) But a note of caution is necessary here. The sources of uncertainties contained and reflected by "a" parameter (discussed here previously in the text in some greater detail) are so numerous that it is difficult to arrive, on the basis of it, at any definite conclusion(s) on any of the related issues. In our opinion, this constitutes a gross limitation of all the direct photon studies made so far either phenomenologically or theoretically. This is specially so because of the fact that the total elimination of the background sources of uncertainty is practically impossible.

(viii) Once these experimental limitations could somehow be overcome by rigorous and systematic measurements made by various robust and established groups, the verification of the model proposed here would be relatively an easier task, as this model envisages production of direct photons in terms of all the known and well-measured coupling terms and some other standard particle physics considerations. This provides a justification for our preferential bias to the present mechanism, despite all its shortcomings arising mainly out of the circumstantial constraints explained earlier in the text.

In understanding the behavior of γ_d/π^0 ratios we find modestly good agreement with data. But the slope of the ratio-values in the $p -$ Be collisions (Fig. 18) is quite different from what these ratios exhibit in other collisions. Despite getting so far fair agreement with available experimental data taken on an overall basis and within the large uncertainty range, the chances of cropping-up of discrepancies — small or large — in future cannot be ruled out. This is not to put an end to our modest claim made here; but only for a moderation of it in the light of the oncoming measurements by the various experimental groups.

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