

Challenges of direct photon production at forward rapidities and large p_T

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Abstract. Direct photons produced in interactions with nuclear targets represent a cleaner probe for investigation of nuclear effects than hadrons, since photons have no final state interaction and no energy loss or absorption is expected in the produced hot medium. Therefore, besides the Cronin enhancement at medium-high transverse momenta p_T and isospin effects at larger p_T , one should not expect any nuclear effects. However, this fact is in contrast to the PHENIX data providing an evidence for a significant large- p_T suppression at mid rapidities in central $d + Au$ and $Au + Au$ collisions that cannot be induced by coherent phenomena (gluon shadowing, Color Glass Condensate). We demonstrate that such an unexpected results is subject to deficit of energy induced universally by multiple initial state interactions (ISI) towards the kinematic limits (large Feynman x_F and/or large $x_T = 2p_T/\sqrt{s}$). For this reason, in order to enhance the effects of coherence, one should be cautious going to forward rapidities and higher energies. In the LHC kinematic region ISI corrections are irrelevant at mid rapidities but cause rather strong suppression at forward rapidities and large p_T . Numerical calculations of invariant p_T spectra and the nuclear modification factor were performed within two different models, the color dipole formalism and the model based on k_T -factorization, which are successfully confronted with available data from the RHIC and LHC collider experiments. Finally, we perform also predictions for a strong onset of ISI corrections at forward rapidities and corresponding expected suppression can be verified by the future measurements at LHC.

1. Introduction

Direct photons provide an unique tool to study nuclear effects in proton-nucleus and heavy-ion collisions and represent a cleaner probe than hadron production since they have no final state interactions, either energy loss or absorption in the produced hot medium. For this reason, no convolution with the jet fragmentation function is required and no nuclear effects are expected besides the Cronin enhancement and small isotopic corrections. Thus, direct photons can serve as an additional tool to discriminate between overall nuclear effects and the effects coming from final state interactions typical for strongly interacting particles in heavy-ion collisions. Manifestations of nuclear effects are usually studied through the nucleus-to-nucleon ratio, the so called nuclear modification factor, $R_A(p_T) = \sigma_{pA \rightarrow \gamma+X}(p_T)/A \sigma_{pp \rightarrow \gamma+X}(p_T)$ for pA collisions and $R_{AB}(p_T) = \sigma_{AB \rightarrow \gamma+X}(p_T)/AB \sigma_{pp \rightarrow \gamma+X}(p_T)$ for minimum bias (MB) AB collisions.

At medium-high transverse momenta p_T one should take into account the Cronin effect, enhancement of particle production in pA collisions, $R_A(p_T) > 1$. This effect was studied within the color dipole formalism in [1], where the predicted shape and magnitude of the Cronin enhancement were confirmed later by the PHENIX data [2] at RHIC and recently by the ALICE measurements [3] at LHC. However, other models presented in the review [4] were not able to describe successfully the last ALICE data [3].

Since the Cronin enhancement can not be measured precisely by experiments at RHIC and LHC due to difficult identification of direct photons at small and medium-high p_T , in this paper we focused on study of possible nuclear effects in the large- p_T region. In contrast with a naive expectation about an absence of nuclear effects at large p_T the PHENIX data [2] on π^0 production in central dAu collisions provide a clear evidence for a significant suppression at midrapidity, $y = 0$. Such an observation is confirmed also by the PHENIX data on direct photon production in central $AuAu$ collisions [5]. Besides small isotopic corrections, observed attenuation can not be interpreted by the coherence effects (gluon shadowing, color glass condensate) due to large values of Bjorken x .

Alternative interpretation is based on multiple interactions of the projectile hadron and its debris during propagation through the nucleus. The corresponding energy loss is proportional to the hadron energy and the related effects do not disappear at very high energies as was stressed in [6]. In each Fock component the hadron momentum is shared between its constituents: the more constituents are involved, the smaller is the mean energy per parton. This leads to the softer fractional energy distribution of a leading parton, and the projectile parton distribution falls at large $x \rightarrow 1$ steeper on a nuclear target than on a proton.

Such softening of the projectile parton fractional energy distribution can be viewed as an effective energy loss of the leading parton due to initial state multiple interactions (ISI). Enhancement of the weight factors for higher Fock states in the projectile hadron with a large number of constituents leads to reduction of the mean fractional energy of the leading parton compared to lower Fock states which dominate the hard reaction on a proton target. Such a reduction is apparently independent of the initial hadron energy and can be treated as an effective loss of energy proportional to the initial hadron energy. A detailed description and interpretation of the corresponding additional suppression was presented also in Refs. [7, 8, 9].

The effect of initial state energy loss (ISI effect) is not effective at high energies and midrapidities. However, it may essentially suppress the cross section approaching the kinematic bound, either in $x_L = 2p_L/\sqrt{s} \rightarrow 1$ or $x_T = 2p_T/\sqrt{s} \rightarrow 1$ defined at given c.m. energy \sqrt{s} . Correspondingly, the proper variable which controls this effect is $\xi = \sqrt{x_L^2 + x_T^2}$.

The magnitude of suppression was evaluated in Ref. [6, 10]. It was found within the Glauber approximation that each interaction in the nucleus leads to a suppression factor $S(\xi) \approx 1 - \xi$. Summing up over the multiple initial state interactions in a pA collision with impact parameter b one arrives at a nuclear ISI-modified parton distribution function (PDF) $F_{a/p}(x, Q^2) \Rightarrow F_{a/p}^{(A)}(x, Q^2, b)$, where

$$f_{a/p}(x, Q^2) \Rightarrow f_{a/p}^{(A)}(x, Q^2, b) = C_v f_{a/p}(x, Q^2) \frac{e^{-\xi \sigma_{eff} T_A(b)} - e^{-\sigma_{eff} T_A(b)}}{(1 - \xi)(1 - e^{-\sigma_{eff} T_A(b)})}. \quad (1)$$

Here $\sigma_{eff} = 20 \text{ mb}$ [6] is the effective hadronic cross section controlling the multiple interactions. The normalization factor C_v in Eq. (1) is fixed by the Gottfried sum rule, $T_A(\vec{b})$ is the nuclear thickness function at given impact parameter b normalized to the mass number A . It was found that such an additional nuclear suppression due to the ISI effects represents an energy independent feature common for all known reactions, experimentally studied so far, with any leading particle (hadrons, Drell-Yan dileptons, charmonium, etc.).

Using PDFs modified by the ISI energy loss, Eq. (1), one can predict much stronger onset of nuclear suppression in a good agreement with available data from the BRAHMS and STAR [11] experiments at forward rapidities (large x_L) in dA collisions [6, 10]. An alternative interpretation [12] is based on the coherence effects, which should disappear at lower energies because $x \propto 1/\sqrt{s}$ increases. However, according to Eq. (1) the suppression caused by the ISI energy loss scales in Feynman $x_F = x_L$ and should exist at any energy. Thus, by reducing the collision energy one should provide a sensitive test for the models. Expectation of no suppression following from CGC at forward rapidities and small energies is in contradiction with data from the NA49 experiments [13] at SPS obtained at much smaller energy than BRAHMS. This observation confirms an onset of suppression at forward rapidities with entirely interpretation based on the ISI energy loss.

The ISI energy loss also affects the p_T dependence of the nuclear suppression in heavy ion collisions. These effects are calculated similarly to $p(d)A$ collisions using the modified PDFs, Eq. (1), for nucleons in both colliding nuclei.

In order to test theoretical uncertainties, in this paper we calculate p_T -spectra and nuclear suppression of direct photons produced on nuclear targets at RHIC and LHC energy using two different models. Corresponding results obtained within the model based on k_T -factorisation [14] will be compared with the color dipole approach [15].

2. Model based on k_T -factorisation

Here the process of direct photon production to the leading order can be treated as a collision of two hadrons where a quark from one hadron annihilates with an antiquark from the other hadron into a real photon. In vacuum (e.g. in pp collisions), in calculations of the invariant cross section of direct photon production we employ the model proposed in [16]:

$$E \frac{d^3\sigma^{pp \rightarrow \gamma X}}{d^3p} = K \sum_{abd} \int d^2k_{Ta} d^2k_{Tb} \frac{dx_a}{x_{Ra}} \frac{dx_b}{x_{Rb}} g_p(k_{Ta}, Q^2) g_p(k_{Tb}, Q^2) \times F_{a/p}(x_a, Q^2) F_{b/p}(x_b, Q^2) \frac{\hat{s}}{\pi} \frac{d\hat{\sigma}^{ab \rightarrow \gamma d}}{d\hat{t}} \delta(\hat{s} + \hat{t} + \hat{u}), \quad (2)$$

which corresponds to the collinear factorization expression modified by an intrinsic transverse momentum dependence. In Eq. (2) $K \approx 1.0 - 1.5$ is the normalization factor depending on the c.m. energy, $F_{i/p}(x_i, Q^2) = x_i f_{i/p}(x_i, Q^2)$ with PDF $f_{i/p}(x_i, Q^2)$, $d\hat{\sigma}/d\hat{t}$ is the cross section of hard parton scattering, x_a, x_b are fractions of longitudinal momenta of the incoming hadrons. The radial variable is defined as $x_{Ri}^2 = x_i^2 + 4k_{Ti}^2/s$, $\hat{s}, \hat{t}, \hat{u}$ are the parton Mandesltam variables and \vec{k}_{Ti} is transverse momentum of parton.

The distribution of the initial parton transverse momentum is described by the Gaussian form [16],

$$g_p(k_T, Q^2) = \frac{1}{\pi \langle k_T^2 \rangle_N(Q^2)} e^{-k_T^2 / \langle k_T^2 \rangle_N(Q^2)} \quad (3)$$

with the scale dependent parametrization of the mean intrinsic transverse momentum from [16], $\langle k_T^2 \rangle_N(Q^2) = \langle k_T^2 \rangle_0 + 0.2 \alpha_S(Q^2) Q^2$, where $\langle k_T^2 \rangle_0 = 0.2 \text{ GeV}^2$ and 2.0 GeV^2 for quarks and gluons, respectively.

For the hard parton scattering cross section we use regularization masses $\mu_q = 0.2 \text{ GeV}$ and $\mu_G = 0.8 \text{ GeV}$ for quark and gluon propagators, respectively. In all calculations we take the scale $Q^2 = p_T^2$. For PDFs we used MSTW2008 [17] parametrization.

The differential cross section for direct photon production in $p + A$ and $A + A$ collisions then can be treated as

$$E \frac{d^3\sigma^{pA \rightarrow \gamma X}}{d^3p} = \int d^2b T_A(\vec{b}) E \frac{d^3\tilde{\sigma}^{pp \rightarrow \gamma X}}{d^3p} \quad (4)$$

and

$$E \frac{d^3 \sigma^{AB \rightarrow \gamma X}}{d^3 p} = \int d^2 b d^2 s T_A(\vec{s}) T_B(\vec{b} - \vec{s}) E \frac{d^3 \tilde{\sigma}^{pp \rightarrow \gamma X}}{d^3 p}, \quad (5)$$

respectively.

In Eqs. (4) and (5) the pp -invariant cross section has the same form as is given by Eq.(2) except for a modification of PDFs to nuclear ones (nPDF) $F_{i/A}(b, x_i, Q^2) = R_i^A(x, Q^2) \left(\frac{Z}{A} x_i f_{i/p}(x, Q^2) + \left(1 - \frac{Z}{A}\right) x_i f_{i/n}(x, Q^2) \right)$, where $R_i^A(x, Q^2)$ is the nuclear modification factor from EPS09 [18]. Invariant cross section $E d^3 \tilde{\sigma}^{pp \rightarrow \gamma X} / d^3 p$ in Eqs. (4) and (5) contains also a nuclear modified distribution of the initial parton transverse momentum as reads,

$$g_A(k_T, Q^2, b) = \frac{1}{\pi \langle k_T^2 \rangle_A(Q^2, b)} e^{-k_T^2 / \langle k_T^2 \rangle_A(Q^2, b)}, \quad (6)$$

where impact parameter dependent variance $\langle k_T^2 \rangle_A(Q^2, b) = \langle k_T^2 \rangle_N(Q^2) + \Delta k_T^2(b)$ is larger than in pp collisions due to the nuclear k_T -broadening $\Delta k_T^2(x, b) = 2 C(x) T_A(b)$ evaluated within the color dipole formalism [19]. The factor $C(x)$ is related to the dipole cross section $\sigma_{\bar{q}q}$, which describes the interaction of the $\bar{q}q$ pair with a nucleon, as $C(x) = \left. \frac{d\sigma_{\bar{q}q}^N(x, r)}{dr^2} \right|_{r=0}$. Note that for gluons the nuclear broadening is larger due to the Casimir factor 9/4. For the dipole cross section we adopt the GBW parametrization from [20].

3. Color Dipole formalism

The color dipole formalism is treated in the target rest frame, where the process of direct photon production can be viewed as a radiation of a real photon by a projectile quark [15]. Assuming only the lowest $|q\gamma\rangle$ Fock component, the p_T distribution of the photon bremsstrahlung in quark-nucleon interaction can be expressed as a convolution of the dipole cross section $\sigma_{\bar{q}q}^N(\alpha, x)$ and the light-cone (LC) wave functions of the projectile $q + \gamma$ fluctuation $\Psi_{\gamma q}(\alpha, \vec{\rho})$ [15]:

$$\frac{d\sigma(qN \rightarrow \gamma X)}{d \ln \alpha d^2 p_T} = \frac{1}{(2\pi)^2} \int \sum_{in, f} d^2 \rho_1 d^2 \rho_2 e^{i\vec{p}_T \cdot (\vec{\rho}_1 - \vec{\rho}_2)} \Psi_{\gamma q}^*(\alpha, \vec{\rho}_1) \Psi_{\gamma q}(\alpha, \vec{\rho}_2) \Sigma(\alpha, \rho_1, \rho_2, x), \quad (7)$$

where $\Sigma(\alpha, \rho_1, \rho_2, x) = \{ \sigma_{\bar{q}q}^N(\alpha \rho_1, x) + \sigma_{\bar{q}q}^N(\alpha \rho_2, x) - \sigma_{\bar{q}q}^N(\alpha(\vec{\rho}_1 - \vec{\rho}_2, x)) \} / 2$.

The differential hadronic cross section for direct photon production in pp collisions can be expressed as a convolution of the differential cross section, Eq. (7) with corresponding PDFs

$$\frac{d^3 \sigma^{pp \rightarrow \gamma X}}{dx_1 d^2 p_T} = \frac{1}{x_1 + x_2} \int \frac{d\alpha}{\alpha} \sum_q e_q^2 \left(\frac{x_1}{\alpha} f_{q/p} \left(\frac{x_1}{\alpha}, Q^2 \right) + \frac{x_1}{\alpha} f_{\bar{q}/p} \left(\frac{x_1}{\alpha}, Q^2 \right) \right) \frac{d\sigma^{q\bar{p} \rightarrow \gamma p}}{d \ln \alpha d^2 p_T}, \quad (8)$$

where e_q is a quark charge, $\alpha = p_\gamma^+ / p_q^+$ is a fraction of quark LC momenta taken by the photon and Bjorken variables x_1 and x_2 are connected with the Feynman variable as $x_F = x_1 - x_2$ with $x_1 = p_\gamma^+ / p_p^+$ in the target rest frame. In all calculation we use the scale $Q^2 = p_T^2$, for PDFs we take the GRV98 parametrization from [21] and for the color dipole cross section we adopt GBW parametrization [20].

Mechanism of direct photon production in pA and AA collisions is controlled by the mean coherence length, $l_c = \left\langle \frac{2E_q \alpha(\alpha-1)}{\alpha^2 m_q^2 + p_T^2} \right\rangle_\alpha$, where $E_q = x_q s / 2m_N$ and $m_q = 0.2$ GeV are the energy and mass of projectile quark, respectively. The variable $x_q = x_1 / \alpha$ denotes a fraction of the proton momentum carried by the quark. The onset of nuclear shadowing requires a sufficiently long coherence length (LCL), $l_c \gtrsim R_A$, where R_A is the nuclear radius. This LCL limit can be

safely used for the RHIC and LHC kinematic regions especially at forward rapidities and leads to a simple incorporation of shadowing effects via eikonalization of $\sigma_{\bar{q}q}^N(\rho, x)$ [22], i.e. performing the following substitutions in Eq. (7):

$$\sigma_{\bar{q}q}^N(\alpha\rho, x) \Rightarrow \sigma_{\bar{q}q}^A(\alpha\rho, x) = 2 \int d^2s \sigma_{\bar{q}q}^A(\vec{s}, \alpha\rho, x) \quad (9)$$

for proton-nucleus interactions and

$$\sigma_{\bar{q}q}^N(\alpha\rho, x) \Rightarrow \sigma_{\bar{q}q}^{AB}(\alpha\rho, x) = \int d^2b d^2s \left[\sigma_{\bar{q}q}^B(\vec{s}, \alpha\rho, x) T_B(\vec{b} - \vec{s}) + \sigma_{\bar{q}q}^A(\vec{b} - \vec{s}, \alpha\rho, x) T_B(\vec{s}) \right] \quad (10)$$

for heavy-ion collisions where

$$\sigma_{\bar{q}q}^A(\vec{s}, \alpha\rho, x) = 1 - \left(1 - \frac{1}{2A} \sigma_{\bar{q}q}^N(\alpha\rho, x) T_A(\vec{s}) \right)^A. \quad (11)$$

In the LCL limit, besides the lowest $|q\gamma\rangle$ Fock state one should include also higher Fock components containing gluons. They cause an additional suppression, known as the gluon shadowing (GS). Gluon shadowing is incorporated via attenuation factor R_G [23] as the modification of the nuclear thickness function $T_A(\vec{s}) \Rightarrow T_A(\vec{s}) R_G(x_2, Q^2, A, \vec{s})$ in Eq. (9) for $p+A$ interaction and $T_A(\vec{s}) \Rightarrow T_A(\vec{s}) R_G(x_2, Q^2, A, \vec{s})$ and $T_B(\vec{b} - \vec{s}) \Rightarrow T_B(\vec{b} - \vec{s}) R_G(x_1, Q^2, A, \vec{b} - \vec{s})$ in Eq. (10) for heavy-ion collisions.

4. Results

Figs. 1 and 2 show a comparison of both models with PHENIX [24] and CMS [25] data on direct photon production in pp collisions at midrapidity and c.m. energy $\sqrt{s} = 200$ GeV and $\sqrt{s} = 2760$ GeV, respectively. For both energies the model based on k_T -factorisation (blue solid lines) and calculations within the color dipole formalism (red solid lines) agree with data reasonably. However, the former describes the data better in the low- p_T region especially at smaller energies due to an absence in this kinematic region of the precise parametrization of the dipole cross section [20] used in calculations. More precise recent parametrization (see [26], for example) improve an agreement with data at small p_T .

Fig. 3 shows a confrontation of the PHENIX data [5] on direct photon production in $AuAu$ collisions with both models. Experimental values were measured at $\sqrt{s} = 200$ GeV and at midrapidity for several centralities 0 – 10%, 40 – 50% and minimum-bias (MB). Blue and red lines represent calculations within the model based on k_T -factorisation and the color dipole formalism, respectively. The solid and dashed lines represent calculations with and without ISI effect. As was mentioned above, at small and medium-high p_T the different shape and magnitude of the Cronin enhancement predicted within both models is caused predominantly by an absence of the precise parametrization of the dipole cross section [20] used in calculations. We expect that more precise recent parametrization [26] of the dipole cross section used in the color dipole formalism leads to a better agreement with the model based on k_T factorization in the small p_T region. Similarly as was demonstrated above, both models agree well with data in the large- p_T region. Moreover, the data on $R_{AuAu}(p_T)$ at centrality 0 – 10% indicate a significant suppression at large $p_T \gtrsim 17$ GeV that can not be interpreted by coherence effects. Calculations within both models including ISI corrections clearly demonstrate the observed large- p_T attenuation.

Fig. 4 shows predictions of both models for $R_{AuAu}(p_T)$ at forward rapidity $y = 3$ and for the same centralities that are indicated in Fig 3. Here we predict a strong suppression for all centralities due to ISI effects.

In Fig. 5 we compare predictions of both models with available data from CMS experiment [25] on direct photon production in $PbPb$ collisions at c.m. energy $\sqrt{s} = 2760$ GeV for three

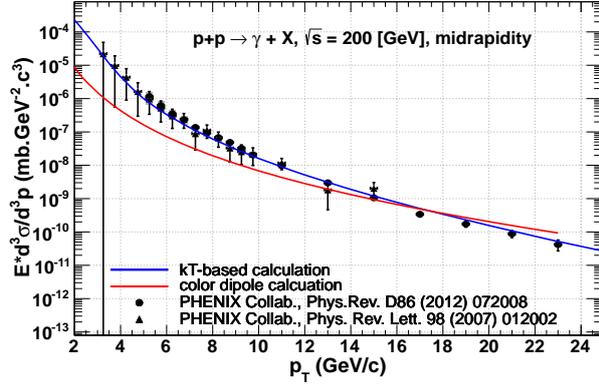


Figure 1. Invariant cross section for direct photon production in pp collisions. The data from the PHENIX experiment [24] are compared with the model based on k_T factorization (blue line) and with calculations based on color dipole formalism (red line).

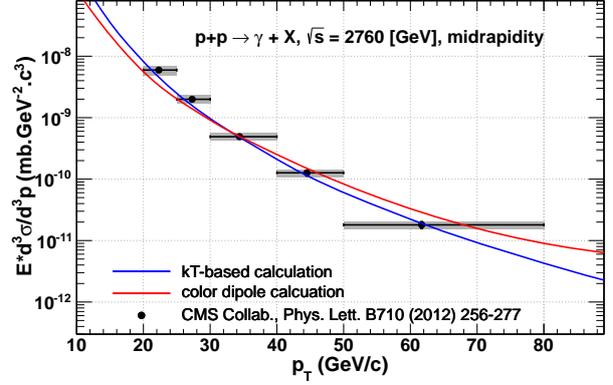


Figure 2. The same as Fig. 1 but with data from CMS experiment [25].

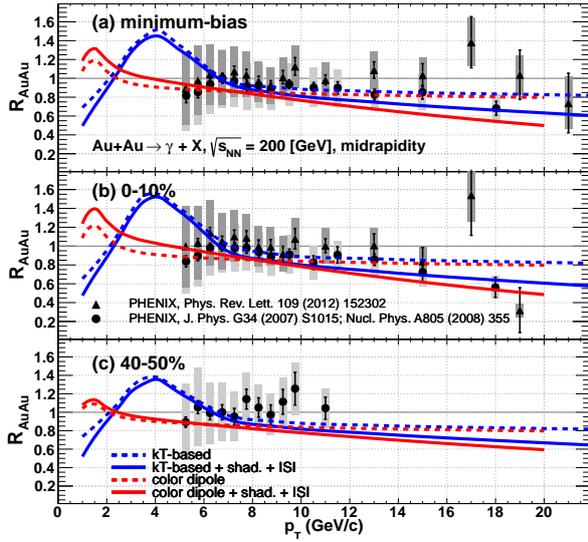


Figure 3. Comparison of the PHENIX data on R_{AuAu} [5] at midrapidity and for several centralities with the model based on k_T factorization (blue line) and with calculations based on the color dipole formalism (red lines). The solid and dashed lines represent calculations with and without ISI effects.

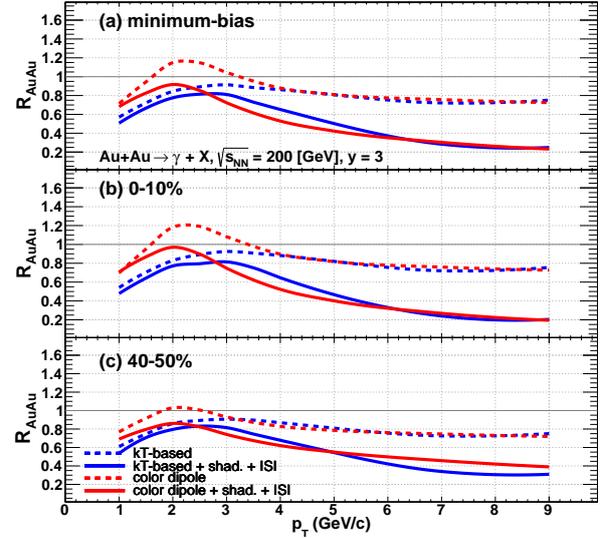


Figure 4. The same as Fig. 3 but at rapidity $y = 3$.

different intervals of centralities. The predictions of both models are qualitatively very close in good accordance with data. They also demonstrate a very weak onset of ISI corrections at large p_T .

Fig. 6 shows predictions from both models for R_{PbPb} at forward rapidity $y = 4$ for the same centrality intervals as are depicted in Fig. 5. We predict a strong suppressions for all centralities due to ISI effects.

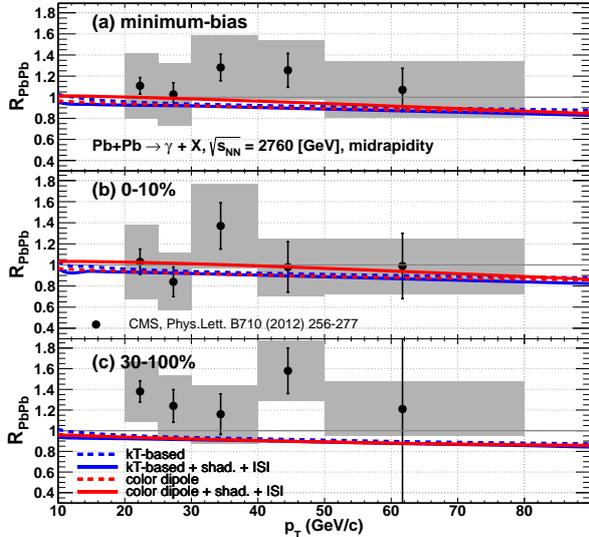


Figure 5. The same as Fig. 3 but with CMS data [25].

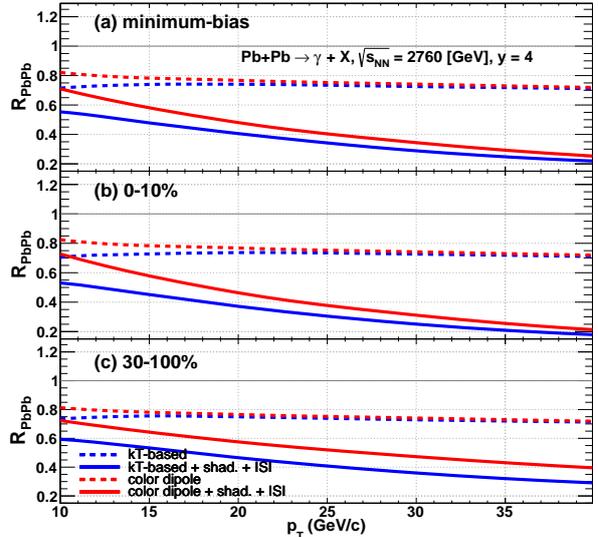


Figure 6. The same as Fig. 4 but at rapidity $y = 4$ and at c.m. energy $\sqrt{s} = 2760$ GeV.

Predictions for $R_{dAu}(p_T)$ from both models are compared in Fig. 7 with PHENIX data [27] on direct photon production in dAu collisions at midrapidity and at $\sqrt{s} = 200$ GeV. Here we predict a sizeable effect of ISI corrections that can be verified in the future by data obtained at very large $p_T \gtrsim 15 - 20$ GeV. The same Fig. 7 also clearly manifests a strong rise of ISI effects with rapidity at fixed p_T values as was discussed in Sect. 1.

Similarly as was mentioned above and presented in Fig. 3 one can see a quantitative difference between both models in predictions of the shape and magnitude of the Cronin enhancement at different rapidities.

Fig. 8 contains predictions for direct photons produced at LHC c.m. energy $\sqrt{s} = 5020$ GeV in pPb collisions at different rapidities $y = 0, 2$ and 4 . Here we predict a significant large- p_T suppression due to ISI effects only at rapidities $y \gtrsim 2$. The expected rise of nuclear attenuation with rapidity can be verified in the future by experiments at LHC.

5. Conclusions

We study production of direct photons in pp , $p(d)A$ and AA collisions at RHIC and LHC energies using two different models: the model based on k_T factorization and the model based on the color dipole formalism. The main motivation for a such investigation was to test the theoretical uncertainties in predictions of corresponding variables that can be verified by available data.

Both models describe reasonable well the data on direct photon production in pp collisions. The model based on k_T -factorisation shows a better agreement with data in the low- p_T region. This fact is a consequence of an absence of the more precise determination of the dipole cross section in this kinematic region as that used in calculations within the color dipole formalism.

Investigating direct photon production on nuclear targets, at small and medium-high values of p_T we found a significant difference between predictions of the shape and magnitude of the Cronin enhancement from both models. However, we expect a better agreement between the both models using more precise recent parameterizations of the dipole cross section as is presented in [26], for example. In the large- p_T region we found a good agreement of both models with available data on nuclear modification factors R_A and R_{AA} at RHIC and LHC.

Besides the Cronin enhancement, isospin corrections and coherence effects we investigated also additional suppression due to initial state effective energy loss (ISI effects). We

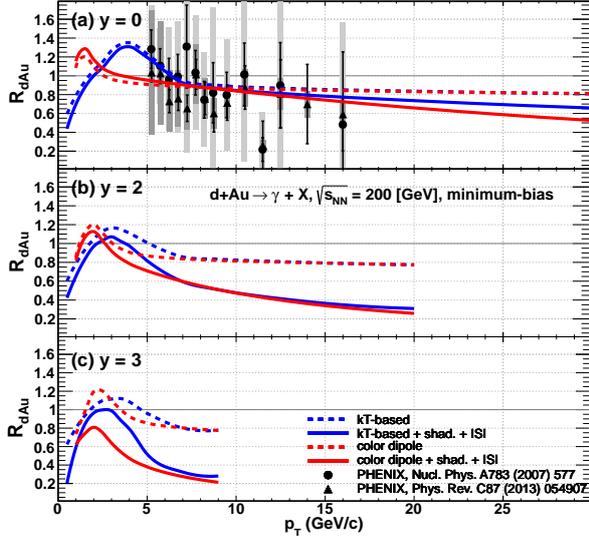


Figure 7. Predictions from both models at different rapidities $y = 0, 2$ and 3 vs. PHENIX data [27] on $R_{dAu}(p_T)$ at midrapidity and at $\sqrt{s} = 200$ GeV

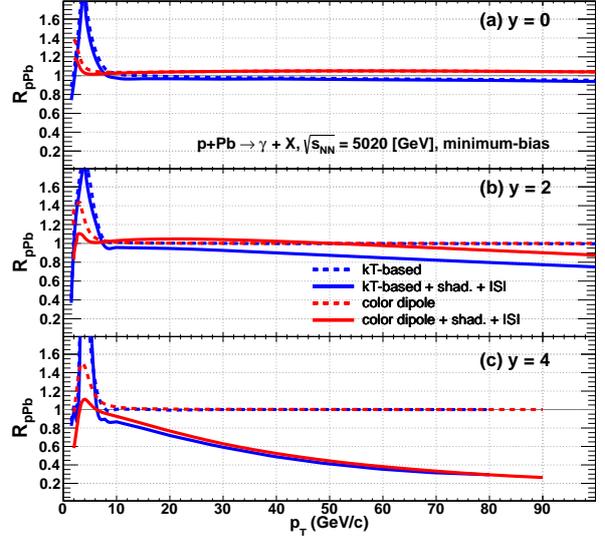


Figure 8. Predictions for R_{pPb} from both models at $\sqrt{s} = 5020$ GeV and at different rapidities $y = 0, 2$ and 4 .

demonstrated that ISI effects cause a strong suppression at forward rapidities and large p_T leading so to breakdown of the QCD factorisation. In the RHIC kinematic region no coherence effects are possible at large p_T . However, the PHENIX data on direct photon production in $AuAu$ interactions clearly indicate a significant large- p_T suppression that can be explained entirely by ISI effects. The ISI effects are practically irrelevant at LHC but we predict a strong nuclear suppression at forward rapidities that can be verified by the future measurements at RHIC and LHC.

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