Direct Photon Production in Proton-Nucleus and Nucleus-Nucleus Collisions

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Abstract

Prompt photons produced in a hard reaction are not accompanied with any final state interaction, either energy loss or absorption. Therefore, besides the Cronin enhancement at medium transverse momenta p_T and small isotopic corrections at larger p_T, one should not expect any nuclear effects. However, data from PHENIX experiment exhibits a significant large-p_T suppression in central $d + Au$ and $Au + Au$ collisions that cannot be accompanied by coherent phenomena. We demonstrate that such an unexpected result is subject to the energy sharing problem near the kinematic limit and is universally induced by multiple initial state interactions. We describe production of photons in the color dipole approach and find a good agreement with available data in $p + p$ collisions. Besides explanation of large-p_T nuclear suppression at RHIC we present for the first time predictions for expected nuclear effects also in the LHC energy range at different rapidities. We include and analyze also a contribution of gluon shadowing as a leading twist shadowing correction modifying nuclear effects at small and medium p_T.

1. Introduction

If a particle with mass M and transverse momentum p_T is produced in a hard reaction then the corresponding values of Bjorken variable in the beam and the target are $x_{1,2} = \sqrt{M^2 + p_T^2}\, e^{\pm y}/\sqrt{s}$. Thus, forward rapidity region $y > 0$ allows to study already at RHIC coherence phenomena (shadowing), which are expected to suppress particle yields.

Observed suppression at large y at RHIC [1] should be interpreted carefully. Similar suppression is observed for any reaction studied so far at any energy. Namely, all fixed target experiments have too low energy for the onset of coherence effects. The rise of suppression with y shows the same pattern as observed at RHIC.

This universality of suppression favors another mechanism which was proposed in [2] and is based on energy conservation effects in initial state parton rescatterings. As a result the effective projectile parton distribution correlates with the nuclear target [2,3] and can be expressed in term of the suppression factor, $S(x) \sim 1 - x$ [2],

$$f_{q/N}^{(A)}\big(x, Q^2, \vec{b}\big) = C\, f_{q/N}\big(x, Q^2\big)\, exp\left[-[1 - S(x)]\, \sigma_{eff} T_A(\vec{b})\right], \tag{1}$$

where $T_A(\vec{b})$ is the nuclear thickness function defined at impact parameter $\vec{b}$, $\sigma_{eff} = 20\,\mathrm{mb}$ [2] and the normalization factor C is fixed by the Gottfried sum rule.

In this paper we study a production of direct photons on nuclear targets. Photons produced in a hard reaction have no final state interactions and so no nuclear effects are expected at large p_T. However, we show that large-p_T photons are universally suppressed by energy deficit in multiple interactions Eq. (1) since the kinematic limit can be approached increasing p_T at fixed y. We study also a rise of this suppression with y in the RHIC and LHC kinematic regions.

2. The color dipole approach

The process of direct photon production in the target rest frame can be treated as radiation of a real photon by a projectile quark. The p_T distribution of photon bremsstrahlung in quark-nucleon interactions reads [4]:

$$\frac{d\sigma(qN \to \gamma\,X)}{d(\ln\alpha)\,d^2p_T} = \frac{1}{(2\pi)^2} \sum_{in,f} \int d^2r_1\,d^2r_2\,e^{i\vec{p}_T\cdot(\vec{r}_1-\vec{r}_2)}\Phi_{\gamma q}^{*\,T}(\alpha,\vec{r}_1)\Phi_{\gamma q}^{T}(\alpha,\vec{r}_2)\,\Sigma(\alpha,r_1,r_2) \quad (2)$$

where $\Sigma(\alpha,r_1,r_2) = \left\{\sigma_{\bar{q}q}(\alpha r_1)+\sigma_{\bar{q}q}(\alpha r_2)-\sigma_{\bar{q}q}(\alpha|\vec{r}_1-\vec{r}_2|)\right\}/2$, $\alpha = p_\gamma^+/p_q^+$ and the light-cone (LC) wave functions of the projectile $q+\gamma$ fluctuation $\Phi_{\gamma q}(\alpha,\vec{r})$ are presented in [4]. Feynman variable is given as $x_F = x_1 - x_2$ and in the target rest frame $x_1 = p_\gamma^+/p_p^+$. For the dipole cross section $\sigma_{\bar{q}q}(\alpha r)$ in Eq. (2) we used GBW [5] parametrization. The hadron cross section is given convolving the parton cross section, Eq. (2), with the corresponding parton distribution functions (PDFs) f_q and $f_{\bar{q}}$ [4],

$$\frac{d\sigma(pp \to \gamma X)}{dx_F\,d^2p_T} = \frac{x_1}{x_1+x_2}\int_{x_1}^{1}\frac{d\alpha}{\alpha^2}\sum_q Z_q^2\left\{f_q\left(\frac{x_1}{\alpha},Q^2\right)+f_{\bar{q}}\left(\frac{x_1}{\alpha},Q^2\right)\right\}\frac{d\sigma(qN\to\gamma X)}{d(\ln\alpha)\,d^2p_T}, \quad (3)$$

where Z_q is the fractional quark charge, PDFs f_q and $f_{\bar{q}}$ are used with the lowest order parametrization from [6] at the scale $Q^2 = p_T^2$.

Assuming production of direct photons on nuclear targets the onset of coherence effets is controlled by the coherence length, $l_c = 2E_q\,\alpha(1-\alpha)/(\alpha^2\,m_q^2 + p_T^2)$, where $E_q = x_q s/2m_N$ and m_q is the energy and mass of the projectile quark. The fraction of the proton momentum x_q carried by the quark is related to x_1 as $\alpha x_q = x_1$.

The condition for the onset of shadowing is a long coherence length (LCL), $l_c \gtrsim R_A$, where R_A is the nuclear radius. Then the color dipole approach allows to incorporate shadowing effects via a simple eikonalization of $\sigma_{\bar{q}q}(x,r)$ [7], i.e. replacing $\sigma_{\bar{q}q}(x,r)$ in Eq. (2) by $\sigma_{\bar{q}q}^{A}(x,r) = 2\int d^2b\left\{1-\left[1-\frac{1}{2A}\,\sigma_{\bar{q}q}(x,r)\,T_A(b)\right]^{A}\right\}$. This LCL limit can be safely used in calculations of nuclear effects in the RHIC and LHC energy regions especially at forward rapidities. Here higher Fock components containing gluons lead to additional corrections, called gluon shadowing (GS). The corresponding suppression factor R_G [8] was included in calculations replacing $\sigma_{\bar{q}q}$ by $R_G\,\sigma_{\bar{q}q}$ in the above expression for $\sigma_{\bar{q}q}^{A}(x,r)$.

3. Predictions for nuclear effects

We start with production of direct photons in $p+p$ collisions. The left panel of Fig. 1 shows model calculations based on Eq. (3) using GRV98 PDFs [6] and demonstrates so a reasonable agreement with data from PHENIX experiment [9]. Another test of the model is a comparison with PHENIX data [10] obtained in $d+Au$ collisions as is depicted in the
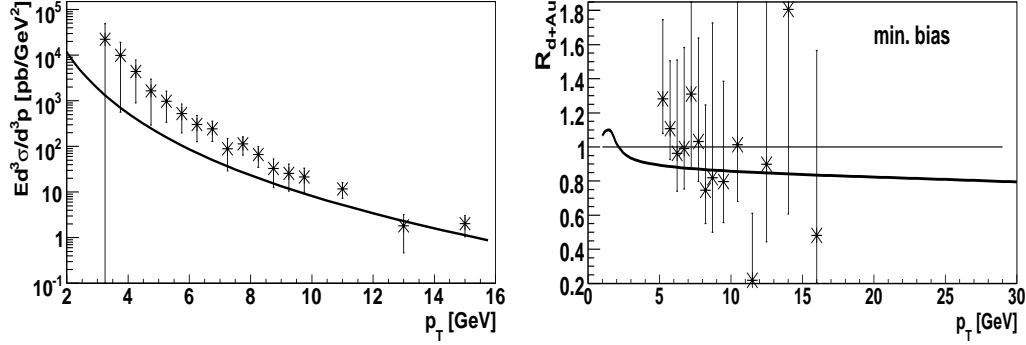
Fig. 1. (Left) Invariant cross section for direct photon production in $p + p$ collisions at $y = 0$ as a function of p_T vs. data from PHENIX experiment [9]. (Right) Ratio of the cross sections in $d + Au$ to $p + p$ collisions $R_{d+Au}(p_T)$ at $\sqrt{s_{NN}} = 200\,\text{GeV}$ vs. preliminary data from PHENIX experiment [10].
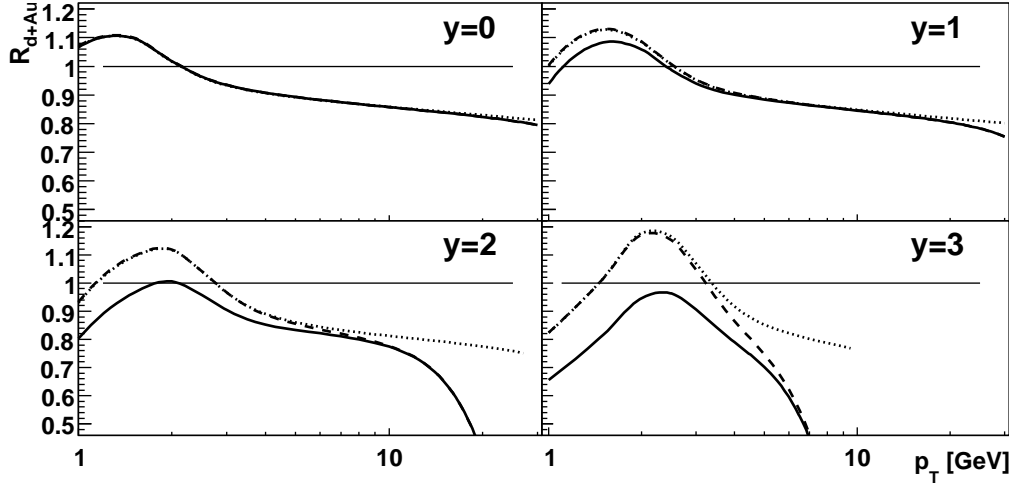

Fig. 2. Ratio of the cross sections in $d + Au$ to $p + p$ collisions $R_{d+Au}(p_T)$ at $\sqrt{s_{NN}} = 200\,\text{GeV}$ and at different fixed values of $y = 0$, 1, 2 and 3. Dotted lines represent calculations without corrections for energy conservation and GS. Dashed lines additionally include corrections for energy deficit Eq. (1) and solid lines also GS.

right panel of Fig. 1. Besides isotopic effects giving a value $R_{d+Au} \sim 0.83$ at large p_T, we predict also an additional suppression coming from corrections for energy conservation Eq. (1).

Since one can approach the kinematic limit increasing p_T we present predictions for nuclear effects at several fixed y as p_T dependence of the nuclear modification factor R_{d+Au} at RHIC energy depicted in Fig. 2 and R_{p+Pb} at LHC energy depicted in Fig. 3. All these Figs. clearly demonstrate a dominance of GS at small and medium p_T and energy conservation effects Eq. (1) at large p_T. Both effects rise rapidly with y. Note that unexpected large-p_T suppression violating so QCD factorization can be tested in the future by the new data from RHIC and LHC experiments especially at forward rapidities.

The same mechanism allows to explain also large-p_T suppression of photons produced in $Au + Au$ collisions at the energies $\sqrt{s_{NN}} =$200 and 62 GeV in accordance with data from PHENIX experiment [11]. Corresponding results can be found in [3]. Large error bars of the data do not allow to provide a definite confirmation for the predicted suppression.
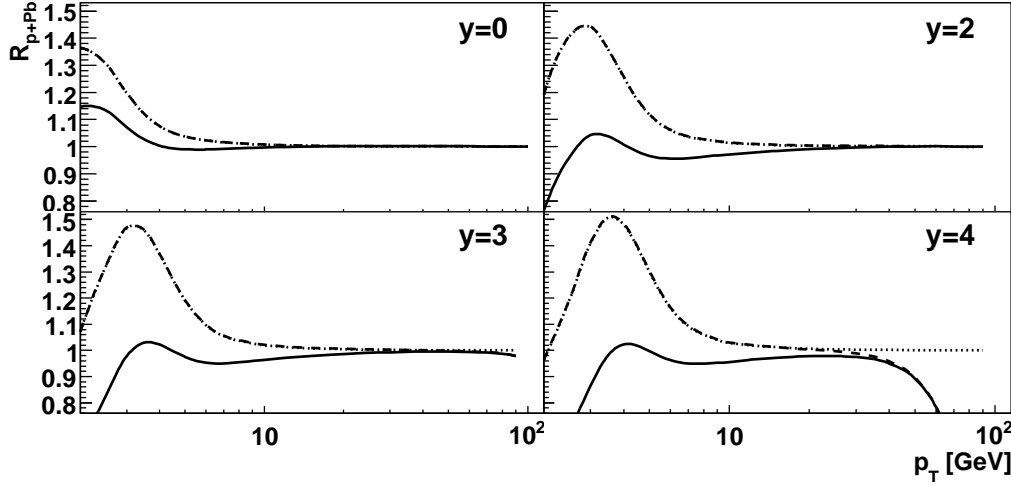
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Fig. 3. The same as Fig. 2 but for the ratio $R_{p+Pb}(p_T)$ at $\sqrt{s_{NN}} = 5.5\,\text{TeV}$ and at fixed $y = 0, 2, 3$ & 4.

4. Summary

Using the color dipole approach we study production of direct photons in collisions on nuclear targets. We demonstrate that at fixed rapidities effects of coherence (GS) dominate at small and medium p_T whereas corrections for energy conservation Eq. (1) are important at larger p_T. Both effects cause a suppression and rise rapidly with rapidity.

First we test this approach in the RHIC kinematic region demonstrating a good agreement with PHENIX data in $p + p$ and $d + Au$ collisons at mid rapidities (see Fig. 1).

Then we present predictions for p_T behavior of nuclear effects at different fixed rapidities in the RHIC and LHC kinematic regions. Since photons have no final state interactions, no suppression is expected at large p_T. However, we specify for the first time the kinematic regions at RHIC and LHC where one can expect and study in the future a rather strong p_T-suppression, which is caused by energy sharing problem Eq. (1).

The same mechanism explains well also a strong suppression at large p_T observed in $Au + Au$ collisions at RHIC in accordance with data from PHENIX experiment.

Acknowledgements

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