EPJ Web of Conferences **66**, 04006 (2014)
DOI: 10.1051/epjconf/ 201466 04006

Direct photons at large p_T: from RHIC to LHC

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Abstract. Using the color dipole formalism we study the production of direct photons in proton-nucleus and nucleus-nucleus collisions at energies corresponding to RHIC and LHC experiments. Prompt photons produced in a hard reaction are not accompanied with any final state interaction, either energy loss or absorption. Therefore, in the RHIC energy range besides small isotopic corrections one should not expect any nuclear effects at large p_T. However, data from the PHENIX experiment indicates a significant large-p_T suppression in $d+Au$ and central $Au+Au$ collisions that cannot be accompanied by coherent phenomena. We demonstrate that such an unexpected result is subject to the energy sharing problem universally induced by multiple initial state interactions (ISI) at large p_T and/or at forward rapidities. In the LHC kinematic region ISI corrections are irrelevant at mid rapidities but cause rather strong suppression at forward rapidities. We present for the first time predictions for expected nuclear effects at large p_T in $p + Pb$ and $Pb + Pb$ collisions at different rapidities. We include and analyze also a contribution of coherent effects associated with gluon shadowing modifying nuclear effects predominantly at small and medium-high p_T.

1 Introduction

Direct photons can serve as a valuable tool to study the properties of nuclear collisions, since they are not accompanied by any final state interaction, either energy loss, or absorption. Therefore, no nuclear effects are expected, besides the Cronin enhancement and small isotopic corrections.

Nuclear effects are usually studied through the nucleus-to-nucleon ratio, the so called nuclear modification factor, $R_A(p_T) = \sigma_{p+A\to\gamma+X}(p_T)/A\,\sigma_{p+p\to\gamma+X}(p_T)$ for $p + A$ collisions and $R_{A+B}(p_T) = \sigma_{A+B\to\gamma+X}(p_T)/AB\,\sigma_{p+p\to\gamma+X}(p_T)$ for $A+B$ collisions, where A and B are corresponding mass numbers.

The Cronin enhancement of particle production, leading to $R_A(p_T) > 1$ at medium-high p_T, was studied in [1] within the color dipole formalism. Predicted magnitude and the shape of this effect was confirmed later by the PHENIX data [2] at RHIC and recently by the ALICE experiment [3] at LHC. However, none from other models presented in [4] was able to describe successfully the last ALICE data [3].

At large p_T the PHENIX data [2, 5, 6] clearly indicate a significant suppression at midrapidity ($\eta = 0$), $R_{dAu}(p_T) < 1$, $R_{AuAu}(p_T) < 1$, that can not be interpreted, besides isotopic corrections, by a weak onset of coherent phenomena (shadowing, Color Glass Condensate (CGC)). Moreover, the BRAHMS and STAR data [7] exhibit much stronger suppression at forward rapidities allowing to reach much smaller target Bjorken $x = p_T e^{-\eta}/\sqrt{s}$, where $\sqrt{s}$ is c.m. energy, and investigate so a stronger onset of coherent phenomena. However, interpretations of large-η suppression at RHIC and

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LHC via assumption that CGC is the dominant source of suppression leads to severe problems in understanding a wider sample of data at smaller energies (see examples in [8]) where no coherence effects are possible.

Besides coherence effects another mechanism, which is not related to coherence and is valid at any energy, was proposed in [8] and applied for description of various processes in $p(d) + A$ interactions [9] and in heavy ion collisions [10]. This mechanism is responsible for a significant suppression at $\xi \to 1$, where $\xi = \sqrt{x_F^2 + x_T^2}$, where x_F is the Feynman variable and $x_T = 2p_T/\sqrt{s}$. Dissipation of energy due to initial state interactions (ISI) [8] leads to breakdown of the QCD factorization at large ξ and to a modification of the proton structure function F_2^p in Eq. (3) replacing the parton distribution function (PDF) by the nuclear modified one, $f_{q(\bar{q})/N}(x, Q^2) \Rightarrow f^{(A)}_{q(\bar{q})/N}(x, Q^2, b)$, where

$$f^{(A)}_{q(\bar{q})/N}(x, Q^2, b) = C_N f_{q(\bar{q})/N}(x, Q^2) \frac{e^{-\xi\sigma_{eff}T_A(b)} - e^{-\sigma_{eff}T_A(b)}}{(1-\xi)\,(1 - e^{-\sigma_{eff}T_A(b)})} \qquad \text{with} \qquad \sigma_{eff} = 20\,mb\,, \tag{1}$$

where $T_A(b)$ is the nuclear thickness function at a given impact parameter b and the normalization factor C_N is fixed by the Gottfried sum rule.

2 Direct photons via color dipole formalism

In the color dipole formalism the process of direct photon production is treated in the target rest frame [11] as radiation of a real photon by a projectile quark. The corresponding p_T distribution of the photon bremsstrahlung in quark-nucleon interactions can be expressed in terms of the light-cone (LC) wave functions of the projectile $q + \gamma$ fluctuation $\Psi_{\gamma q}(\alpha, \vec{\rho})$ and the dipole cross section $\sigma^N_{q\bar{q}}(\alpha\rho, x)$ [11]:

$$\frac{d\sigma(qN \to \gamma X)}{d\ln\alpha d^2p_T} = \frac{1}{(2\pi)^2} \int \sum_{in,f} d^2\rho_1\, d^2\rho_2\, e^{i\vec{p}_T\cdot(\vec{\rho}_1-\vec{\rho}_2)}\, \Psi^*_{\gamma q}(\alpha, \vec{\rho}_1)\, \Psi_{\gamma q}(\alpha, \vec{\rho}_2)\, \Sigma(\alpha, \rho_1, \rho_2, x_2) \tag{2}$$

where $\Sigma(\alpha, \rho_1, \rho_2, x) = \{\sigma^N_{\bar{q}q}(\alpha\rho_1, x) + \sigma^N_{\bar{q}q}(\alpha\rho_2, x) - \sigma^N_{\bar{q}q}(\alpha(\vec{\rho}_1 - \vec{\rho}_2, x))\}/2$, $\alpha = p^+_\gamma/p^+_q$ is a fraction of quark LC momenta taken by the photon and Bjorken variables x_1 and x_2 are linked with the Feynman variable as $x_F = x_1 - x_2$ with $x_1 = p^+_\gamma/p^+_p$ in the target rest frame. For the dipole cross-section $\sigma^N_{q\bar{q}}(\alpha\rho, x)$ in Eq. (2) we used the parametrization from [12]. The hadronic cross-section reads [11],

$$\frac{d\sigma(pp \to \gamma X)}{dx_1 d^2p_T} = \frac{1}{x_1 + x_2} \int_{x_1}^1 \frac{d\alpha}{\alpha} F_2^p\left(\frac{x_1}{\alpha}, Q^2\right) \frac{d\sigma(qN \to \gamma X)}{d\ln\alpha d^2p_T}, \tag{3}$$

where $F_2^p(x, Q^2) = \sum_q Z_q^2(xf_{q/N}(x, Q^2) + xf_{\bar{q}/N}(x, Q^2))$ is the proton structure function at the scale $Q^2 = p_T^2$, Z_q is a fractional quark charge and $f_{q/N}$ resp. $f_{\bar{q}/N}$ are parton distribution functions with GRV98 parametrization from [13].

The dynamics of direct photon production on nuclear targets is controlled by the mean coherence length, $l_c = \left\langle \frac{2E_q\alpha(1-\alpha)}{\alpha^2 m_q^2 + p_T^2} \right\rangle_\alpha$, where $E_q = x_q s/2m_N$ and m_q is the energy and mass of the projectile quark and the fraction of the proton momentum x_q carried by the quark is related to x_1 as $x_q = x_1/\alpha$. The condition for the onset of shadowing is that the coherence length exceeds the nuclear radius R_A, $l_c \gtrsim R_A$. This long coherence length (LCL) limit can be safely used in calculations for the RHIC and LHC energy regions especially at forward rapidities and allows to incorporate shadowing effects via eikonalization of $\sigma^N_{\bar{q}q}(\rho, x)$ [14], i.e. replacing in Eq. (2)

$$\sigma^N_{\bar{q}q} \Rightarrow \sigma^A_{\bar{q}q} = 2\int d^2s\, \sigma^A_{\bar{q}q}(\vec{s}) \qquad \sigma^A_{\bar{q}q}(\vec{s}) = \left(1 - \left(1 - \frac{1}{2A}\sigma^N_{\bar{q}q}T_A(\vec{s})\right)^A\right) \qquad \text{for } p + A \text{ collisions}\,, \tag{4}$$

$$\sigma^{N}_{\bar{q}q} \Rightarrow \sigma^{AB}_{\bar{q}q} = \int d^2b\, d^2s\, \left\{\sigma^{B}_{\bar{q}q}(\vec{s})\, T_A(\vec{b}-\vec{s}) + \sigma^{A}_{\bar{q}q}(\vec{b}-\vec{s})\, T_B(\vec{s})\right\} \qquad \text{for heavy ion collisions}\,. \qquad (5)$$

In the LCL limit higher Fock components containing gluons become important and lead to additional corrections, called gluon shadowing (GS). The corresponding attenuation factor R_G [15] can be incorporated using substitution $T_A(\vec{s}) \Rightarrow T_A(\vec{s})\, R_G(x_2, Q^2, A, \vec{s})$ in Eq. (4) for $p + A$ interactions and substitutions $T_B(\vec{s}) \Rightarrow T_B(\vec{s})\, R_G(x_2, Q^2, B, \vec{s})$ and $T_A(\vec{b}-\vec{s}) \Rightarrow T_A(\vec{b}-\vec{s})\, R_G(x_1, Q^2, A, \vec{b}-\vec{s})$ in Eq. (5) for heavy ion collisions.

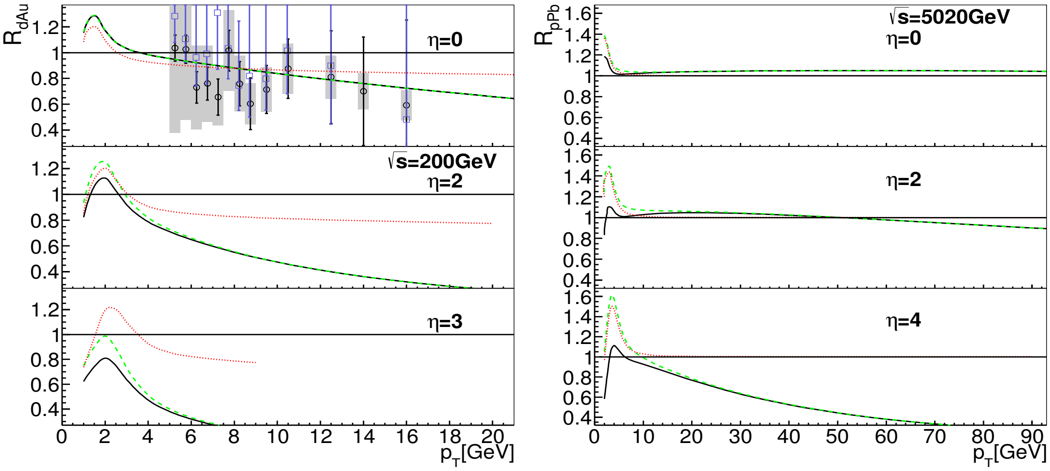

Figure 1. Ratio of direct photon production cross-sections $R_{d+Au}(p_T)$ at $\sqrt{s} = 200$ GeV (left boxes) and $R_{p+Pb}(p_T)$ at $\sqrt{s} = 5020$ GeV (right boxes) at different values of η. The data are from [16] - open blue squares and from [17] - open black circles. Dotted red lines include only the Cronin enhancement and eventual isotopic corrections, while dashed green lines include additionally ISI corrections, Eq. (1) and solid black lines represent full calculations including both effects ISI and gluon shadowing [15].

Figs. 1 and 2 show predictions for nuclear effects at several fixed η in $p(d) + A$ interactions and in heavy ion collisions at RHIC and LHC. Besides $p + Pb$ interactions at LHC, we predict a weak onset of isotopic effects giving values R_{dAu}, R_{AuAu}, $R_{PbPb} \sim 0.8 - 0.83$ at large p_T. At $\eta = 0$ ISI effects, Eq. (1), are not very strong at RHIC but are fully irrelevant at LHC. However they cause a significant large-p_T suppression at forward rapidities that can be clearly distinguished from isotopic effects. Figs. 1 and 2 demonstrate also that coherent effects (shadowing) [15] dominate at small and medium-high p_T while ISI effects are important at large p_T. Coherent effects cause also an additional suppression and rise rapidly with rapidity. Both Figs. show also a good agreement of predictions with available data [5, 6, 16, 17].

3 Summary

We study the production of direct photons in $p(d) + A$ interactions and in heavy ion collisions at RHIC and LHC using the color dipole formalism. Performing predictions for p_T-behavior of nuclear effects at different rapidities, besides Cronin enhancement at medium-high p_T and isotopic corrections, we include in calculations also effects of coherence (gluon shadowing) [15] and ISI effects, Eq. (1). Since photons are not subject to final state interactions, no large-p_T suppression is expected. However, we predict a significant suppression due to corrections for energy conservation constraints in initial state parton rescatterings, Eq. (1). We demonstrate that the nuclear suppression at small and medium p_T is dominated by coherence effects. Both effects grow strongly with rapidity. Predicted large-p_T suppression is in contrast with QCD factorization and can be tested in the future by experiments at RHIC and LHC.

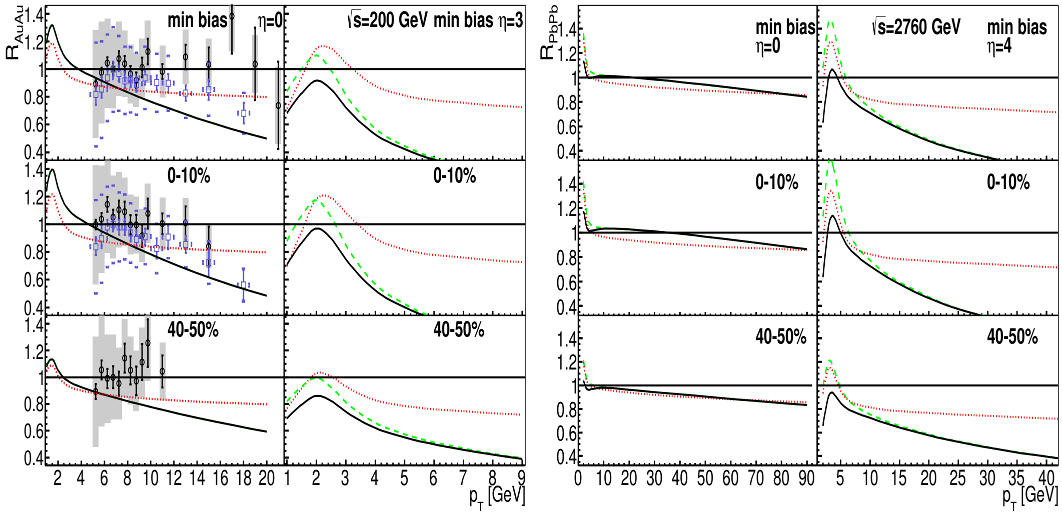

Figure 2. Ratio of direct photon production cross-sections $R_{Au+Au}(p_T)$ at $\sqrt{s}$ = 200 GeV (left boxes) and $R_{Pb+Pb}(p_T)$ at $\sqrt{s}$ = 2760 GeV (right boxes) at two values of rapidity and at different centralities. The data are from [5] - open blue squares and from [6] - open black circles. Specification of curves is the same as in Fig. 1.

Acknowledgements

This work has been supported by the grant 13-02841S of the Czech Science Foundation (GAČR), by the Grant VZ MŠMT 6840770039, by the Slovak Research and Development Agency APVV-0050-11 and by the Slovak Funding Agency 2/0092/10.

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