Isolated photon production and pion-photon correlations in high-energy pp and pA collisions

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A phenomenological study of the isolated photon production in high energy pp and pA collisions at RHIC and LHC energies is performed. Using the color dipole approach we investigate the production cross section differential in the transverse momentum of the photon considering three different phenomenological models for the universal dipole cross section. We also present the predictions for the rapidity dependence of the ratio of pA to pp cross sections. As a further test of the formalism, for different energies and photon rapidities we analyse the correlation function in azimuthal angle ∆φ between the photon and a forward pion. The characteristic double-peak structure of the correlation function around ∆φ ≃ π observed previously for Drell-Yan pair production is found for isolated photon emitted into the forward rapidity region which can be tested by future experiments.

I. INTRODUCTION

The isolated (prompt) photon production in pp and pA high-energy collisions represents an attractive and clean probe for strong interactions in soft [1–3] and perturbative regimes of Quantum Chromodynamics (QCD) [4–6] as well as nuclear effects and medium-induced QCD phenomena [7–9]. This becomes possible due to the absence of QCD-induced final-state interactions associated with absorptive phenomena as well as of an energy loss which is in variance to the di-hadron production channels where the final-state absorptive corrections are typically very large. The prompt photon production in hadron-hadron and hadron-nucleus collisions can be employed to set further constraints on parton density functions (PDFs) in specific kinematic domains not sufficiently well explored by HERA [10–12].

For this purpose, such studies are also in the focus of ongoing and planned measurements at the LHC [2, 13–16] and at RHIC [3, 17–21].

At very low-x, for example, the primordial transverse momentum evolution of incoming partons and non-linear QCD effects such as gluon saturation start to play a significant role whose reliable first-principle analysis represents a long-standing theoretical challenge. In the case of high-energy pA collisions, main issues concern a proper description of initial/final state effects in multiple interactions with a nuclear target. Another widely discussed problem is associated with propagation of partons in the nuclear environment. Such processes, as the Drell-Yan (DY) pair production, studied recently by some of the authors in Refs. [22–24], as well as the isolated photon production at high-pT, provide efficient means for phenomenological analysis of various nuclear effects such as the nuclear shadowing and initial-state interactions determined by saturation [25].

In this paper, we investigate the isolated photon production off the proton and nuclear targets in low-x regime of QCD in the framework of the phenomenological color dipole formalism (see e.g. Refs. [26–32]). In the dipole picture, the real photon production is considered as γ Bremsstrahlung off a fast projectile quark propagating through the low-x color field of the target [26] as illustrated in Fig. 1 (panels (a) and (b)). In this case, the photon radiation occurs both after and before the quark scatters off the target and the corresponding amplitudes interfere. As a result of such interference, the photon Bremsstrahlung process can be viewed as scattering of a qq dipole with a given transverse separation. This in variance to the conventional parton model where the same process in the center-of-mass frame is given by the Compton scattering. The difference between both descriptions illustrates the well known fact that although cross sections are Lorentz invariant, the partonic interpretation of the corresponding processes depends on the reference frame.

The key ingredients of the dipole formula for the differential cross section of the considered process are the light-cone (LC) wave function of the initial state describing the real photon radiation off the projectile quark as well as the

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universal dipole-target cross section related to the dipole $S$ matrix, $\sigma_{q\bar{q}}(x, \rho)$, which can be determined phenomenologically, for example, by a fit to the Deep Inelastic Scattering (DIS) data at low-$x$ \cite{33} or to a Drell-Yan $pp$ data of good quality. At small Bjorken $x$ (or at high energies), the universality of the dipole cross section stems from the fact that color dipoles in QCD are the eigenstates of interaction with a fixed transverse separation, $\rho$ \cite{26}.

Remarkably, since the lifetime of partonic fluctuation in the laboratory frame is enhanced by a factor $\sqrt{s}/m_p$ wrt to the lifetime in the centre-of-mass system, the phenomenological dipole approach appears to effectively take into account the higher-order QCD corrections. For example, it provides the predictions for the DY process at the same level of precision as the Next-to-Leading-Order (NLO) collinear factorisation framework \cite{31}. Besides, as a consequence of universality, the dipole formulation provides a unified description of a variety of inclusive and diffractive observables of particle production processes in lepton-hadron, hadron-hadron, hadron-nucleus and nucleus-nucleus collisions at high energies (for particular examples, see e.g. Refs. \cite{27, 28, 32, 34–36}). In the high-energy limit, the projectile quark effectively probes dense gluonic field in the target with the dipole cross section effectively accounting for the non-linear effects due to multiple scatterings.

The goal of the current work is the following. First, we update the previous studies presenting predictions for the transverse momentum distribution of isolated photons produced at the RHIC and LHC energies. Moreover, we also make predictions for the ratio of the proton-lead ($pPb$) and proton-proton ($pp$) cross sections at the LHC for different values of the photon (pseudo-)rapidity. Second, we present a detailed analysis of the azimuthal correlation between the photon and a pion that emerges from a projectile quark hadronisation at forward rapidities\(^1\) (see Fig. I(c)). In this paper, we present new results for such an observable for $pp$ collisions at RHIC ($\sqrt{s} = 500$ GeV) and LHC ($\sqrt{s} = 14$ TeV), as well for $pAu$ collisions at RHIC ($\sqrt{s} = 200$ GeV) and $pPb$ collisions at the LHC ($\sqrt{s} = 8.8$ TeV). In order to estimate the related theoretical uncertainties in our predictions, we consider three different approaches to saturation effects \cite{33, 37, 38}.

The paper is organized as follows. In Sect. III a brief overview of isolated photon production in the color dipole framework is provided. In Sect. \[III\] we present our numerical results for the transverse momentum distributions of the produced isolated photon as well as the $pA$-to-$pp$ ratio of the production cross sections. Furthermore, the pion-photon azimuthal correlation function is evaluated for $pp$ and $pA$ collisions at the characteristic RHIC and LHC energies for different photon and pion rapidities. Finally, in Sect. \[IV\] our main conclusions are summarized.

II. COLOR DIPOLE PICTURE OF REAL PHOTON BREMSSTRAHLUNG

Consider first the isolated photon production in $pp$ collisions in the target rest frame. In the high energy limit, each of the first two diagrams (a) and (b) in Fig. 1 in the impact-parameter space can be represented as a convolution of the LC wave function of the projectile quark $|q\rangle$ fluctuation into its lowest $|q\gamma\rangle$ Fock state and a scattering amplitude of a quark off the target $T$ at a given impact parameter \cite{27, 28}. Here, $T$ denotes either the proton $p$ or a nucleus target with an atomic mass $A$.

In what follows, we work in terms of usual LC (longitudinal) momentum fractions of the isolated photon, $x_1$ and $x_2$, taken from the incoming proton momenta $p_1$ and $p_2$, respectively, such that

$$x_1 = \frac{p_1^+}{p_1} = \frac{p_T}{\sqrt{s}} e^\eta, \quad x_2 = \frac{p_2^-}{p_2} = \frac{p_T}{\sqrt{s}} e^{-\eta}, \quad x_1 - x_2 \equiv x_F,$$

\(^1\) Similar correlations in di-hadron, real photon-hadron and dilepton-hadron channels have been previously reported in Refs. \cite{33, 34}.\[1\]
where $p_T$, $\eta$ and $x_F$ are the transverse momentum, pseudorapidity and the Feynman variable of the photon. The initial-state quark $|q\rangle$ and the final-state quark accompanied by a Weizäcker-Williams photon, $|q'\gamma\rangle$, propagate at different impact parameters. Indeed, due to the $\gamma$ Bremsstrahlung the final quark gets a transverse shift with respect to the initial one, $\Delta r = \alpha \mathbf{p}$, where $\alpha$ is the fractional LC momentum taken by the radiated photon off the projectile quark and $\mathbf{p}$ is the quark-$\gamma$ transverse separation.

The amplitudes (a) and (b) in Fig.1 corresponding to scattering of $|q\rangle$ and $|q'\gamma\rangle$ Fock states off the target $T$, respectively, interfere. As a result, the matrix element squared for the isolated photon production integrated over the impact parameter of the initial quark is expressed in terms of the universal $q\bar{q}$ dipole-target cross section $\sigma_{q\bar{q}}^f (\Delta r, x)$ as a function of the transverse separation $\Delta r$ and the standard Bjorken variable of the process $x$ which is taken to be equal to $x_2$ in what follow. The cross section for the real photon production differential in photon transverse momentum $p_T$ and pseudorapidity $\eta$,

$$\frac{d\sigma(p_T \rightarrow q\gamma X)}{dp_T^2 d\eta} = \frac{2p_T}{s} \cosh(\eta) \frac{x_1}{x_1 + x_2} \sum_f \int_1^{\alpha^2} \frac{d\alpha}{\alpha^2} \left[ q_f(x_1/\alpha, \mu_F^2) + \bar{q}_f(x_1/\alpha, \mu_F^2) \right] \frac{d\sigma_f(q_T \rightarrow q\gamma X)}{d\ln \alpha^2 p_T}$$  \hspace{1cm} (2)

is typically found in terms of the unpolarised projectile quark (antiquark) collinear PDFs $q_f (\bar{q}_f)$ corresponding to (valence and sea) flavor $f = u, d, s, c$ as functions of the momentum fraction of the projectile quark taken from the parent nucleon $x_q = x_1/\alpha$ and the QCD factorisation scale $\mu_F = p_T \equiv |\mathbf{p}_T|$. The differential cross section of the high-$p_T$ real photon production in the quark-target scattering subprocess is represented in the dipole picture as

$$\frac{d\sigma_f(q_T \rightarrow q\gamma X)}{d\ln \alpha^2 p_T} = \frac{1}{(2\pi)^2} \int d^2 \rho_1 d^2 \rho_2 \exp[i\mathbf{p}_T \cdot (\mathbf{p}_T - \mathbf{\rho}_2)] \Psi(\alpha, \mathbf{p}_T) \Psi^*(\alpha, \mathbf{p}_2, m_f)$$

$$\times \frac{1}{2} \left[ \sigma_{q\bar{q}}^f(\alpha, \mathbf{p}_1, x_2) + \sigma_{q\bar{q}}^f(\alpha, \mathbf{p}_2, x_2) - \sigma_{q\bar{q}}^f(\alpha, \mathbf{p}_1 - \mathbf{p}_2, x_2) \right], \hspace{1cm} (3)$$

where $m_f$ is the constituent quark mass, and $\Psi(\alpha, \mathbf{p}_1, m_f)$ is the LC wave function of the real photon radiation off a quark with flavor $f$. Following Ref. 33, we take the constituent quark mass values to be $m_u = m_d = m_s = 0.14$ GeV and $m_c = 1.4$ GeV in our numerical analysis below. For the cross section differential in photon $p_T$ the quark-$\gamma$ transverse separations amplitude and its conjugated are considered to be different and are denoted as $\rho_{1,2}$. In this case, the overlap of the photon Bremsstrahlung wave functions in Eq. (3), summed over the transverse polarisations of the radiated hard photon, reads

$$\Psi(\alpha, \mathbf{p}_1, m_f)\Psi^*(\alpha, \mathbf{p}_2, m_f) = \frac{\alpha_{em}e_f^2}{2\pi^2} \left\{ m_f^2 \alpha^4 K_0(\tau \rho_1) K_0(\tau \rho_2) + \left[ 1 + (1 - \alpha)^2 \right] \frac{\tau^2 \mathbf{P}_1 \cdot \mathbf{P}_2}{\rho_1 \rho_2} K_1(\tau \rho_1) K_1(\tau \rho_2) \right\}, \hspace{1cm} (4)$$

where $\alpha = 1 - \alpha$, $\alpha_{em}$ is the fine structure constant, $e_f$ is the charge of the projectile quark, $\rho_{1,2} \equiv |\mathbf{\rho}_{1,2}|$, $\tau = \alpha m_f$ and the modified Bessel functions of the second kind are denoted as $K_0$. In fact, the photon transverse momentum provides a hard scale for the considering process which ensures the validity of the perturbative approximation which has been used in the computation of the photon wave function in Eq. (3).

We would like to analyse the correlation in the azimuthal angle between the final-state photon and a hadron emerging due to hadronisation of the projectile (anti)quark associated with the photon radiation. An analogous analysis for the DY process with deeply-virtual photon has been performed earlier in the impact parameter representation in Ref. 30, although the corresponding numerical analysis is very challenging. More recently, in Ref. 24 a numerical calculation of the differential DY cross section derived in Refs. 13 40 has been performed directly in momentum representation. We adopt the same formalism for the considering case of real high-$p_T$ photon production in association with the leading hadron $h$, namely,

$$\frac{d\sigma(p_T \rightarrow h\gamma X)}{dp_T dy_T dh_T } = \frac{\alpha_{em}e_f^2}{2\pi^2} \int_0^{\alpha} \frac{dz_h}{z_h} \sum_f e_f^2 D_{h/f}(z_h, \mu_F^2) x_p q_f(x_p, \mu_F) S_{\perp} F_T(x_T, k_T^2, x_T, z_T^2 (1 + z^2) k_T^2 / P_T^2 (P_T + z k_T^2)^2), \hspace{1cm} (5)$$

where the key kinematical variables are determined as follows

$$x_h \simeq \frac{p_T^h}{\sqrt{s}} e^{y_h}, \hspace{0.5cm} x_p = x_1 + \frac{x_h}{z_h}, \hspace{0.5cm} z = \frac{x_1}{x_p}, \hspace{0.5cm} x_g = x_1 e^{-2\eta} + \frac{x_h}{z_h} e^{-2y_h},$$

$$k_T^2 = \mathbf{p}_T^2 + k_T^2, \hspace{0.5cm} P_T = \bar{z} \mathbf{p}_T - z k_T^2, \hspace{0.5cm} k_T^2 = \frac{P_T^2}{z_h}, \hspace{1cm} (7)$$

Here, for simplicity, we are considering the light quark flavors $f = u, d, s$ only and neglect terms proportional to $m_f$ due to $p_T \gg m_f$. In Eq. (5) $D_{h/f}$ stands for the fragmentation function of the projectile quark $q_f$ (which has emitted
the photon) into a final-state (light) hadron $h$ carrying the transverse momentum $p_T^h$ that is supposed to be detected in a measurement. The remaining kinematic variables are defined as follows: $y_h$ is the rapidity of the hadron $h$ in the final state, respectively, $z_h$ and $x_h$ are the LC momentum fraction taken by the hadron $h$ from the parent quark $q_f$ and the incoming proton. $P_T$ is the relative transverse momentum between the photon and the quark $q_f$, $k_T^q$ is the transverse momentum of the projectile quark $q$ (before it fragments into a hadron $h$), $k_T^h$ is the transverse momentum of the exchanged gluon in the $t$-channel. Finally, $S_{s,p}$ denotes the transverse area of the considered target $T$ whose explicit form is irrelevant for our purposes here, $F_T(x_g, k_T^q)$ represents the so-called unintegrated gluon distribution function (UGDF) in the target $T$. In the saturation regime and for the soft gluon $k_T^q$, the latter can be found in terms of a Fourier transform of the dipole cross section $\sigma_{s,p}^T$. Note, the momentum fractions $z$ and $x_p$ share the same physical meaning as $\alpha$ and $x_q$ introduced above in Eq. (2), respectively. A different notation is used here since $z$ and $x_p$ are now related to the hadron kinematic variables $z_h$, $y_h$ and $p_T^h$ in the final state.

One of the important observables sensitive to the dynamics of saturation is the correlation function $C(\Delta \phi)$ in azimuthal angle $\Delta \phi$ between the final state photon and hadron (for more details, see e.g. Ref. [24]). Assuming the isolated photon to be a trigger particle, the correlation function can be built as follows

$$C(\Delta \phi) = \frac{2\pi \int_{P_T > p_T^{cut}} dP_T d\eta d^2 p_T \int_{P_T > p_T^{cut}} dP_T d\eta d^2 p_T \frac{d\sigma(p T \rightarrow h \gamma X)}{d\eta d^2 p_T} \frac{d\sigma(p T \rightarrow h \gamma X)}{d\eta d^2 p_T}}{1 \int_{P_T > p_T^{cut}} dP_T d\eta d^2 p_T},$$

(8)

in terms of the low cut-off $p_T^{cut}$ on transverse momenta of the resolved $\gamma$ and $h$. In the denominator, we have the cross section for inclusive photon production. For consistency, the latter can be straightforwardly obtained by integrating photon-hadron cross section in Eq. (8) over the hadron momentum and rapidity as well as over $\Delta \phi$. This way, one arrives at the following expression

$$\frac{d\sigma(p T \rightarrow h \gamma X)}{d\eta d^2 p_T} = \frac{\alpha_{em}}{2\pi^2} \int_{x_p}^{1} \frac{dz}{z} \int d^2 k_T^g \sum_{f} e_f^2 x_p q_f(x_p, \mu_F) S_{\perp}(x_g, k_T^g) \frac{z^2 (1 + z^2) k_T^{g2}}{p_T^2 (P_T - z k_T^g)^2},$$

(9)

For the numerical analysis of the isolated photon observables we need to specify a reliable parametrization for the dipole cross section $\sigma_{qg}^p(r, x)$. The latter contains an important information about possible non-linear QCD (or saturation) effects in the hadronic state (see for a detailed discussion of saturation phenomena, e.g. Ref. [37]). In the case of $pp$ collisions, we should specify the universal dipole cross section off the proton target. Due to universality of dipoles as eigenstates of interaction in QCD, such a quantity is typically obtained from a phenomenological analysis of the precision data on DIS available from the HERA collider. For comparison with previous results existing in the literature, we traditionally consider the phenomenologically very successful Golec-Biernat–Wusthoff (GBW) model [33] relying on a simple saturated ansatz

$$\sigma_{qg}^p(r, x) = \sigma_0 \left(1 - e^{-r^2 q_0^2(x)^4}/4\right),$$

(10)

with the proton saturation scale

$$Q_{s,p}^2(x) = Q_0^2 \left(x / x_0\right)^{\lambda},$$

(11)

where the model parameters $Q_0^2 = 1$ GeV$^2$, $x_0 = 3.04 \times 10^{-4}$, $\lambda = 0.288$ and $\sigma_0 = 23.03$ mb were obtained from the fit to the DIS data. Besides, we consider the solution of the Balitsky-Kovchegov equation [47, 48] with running coupling obtained in Ref. [38] as an alternative model for the dipole-proton cross section, denoted as AAMQS hereafter. Likewise, its initial conditions were constrained by a fit to the HERA DIS data. Finally, yet another phenomenological saturation model for $\sigma_{qg}^p(r, x)$ based upon the Color Glass Condensate (CGC) approach [49]

$$\sigma_{qg}^p(r, x) = \sigma_0 \left\{ \begin{array}{ll} N_0 \left(1 - \exp^{-A \ln^2(B r Q_{s,p})}\right) & r Q_{s,p} \leq 2 \\ 1 - \exp^{-A \ln^2(B r Q_{s,p})} & r Q_{s,p} > 2 \end{array} \right.\right.$$

(12)

has been utilised for comparison and in order to estimate the sensitivity of our predictions to dynamics of the saturation effects. Here, $\kappa = \chi'(\gamma_s)/\chi(\gamma_s)$, where $\chi$ is the LO BFKL characteristic function, and the coefficients $A$ and $B$ are uniquely determined from the continuity condition for the dipole cross section and its derivative with respect to $r Q_{s,p}$ at $r Q_{s,p} = 2$.

While the dipole cross section off the proton target is well-constrained and tested by ample $ep$ and $pp$ phenomenology, in the case of a heavy nucleus target the data are not as precise as for the proton one while the modelling of the
corresponding dipole cross section is still a subject of continuous debates. One possible alternative present in several studies in the literature is to consider the Glauber-Mueller (GM) approach based upon resummation of all the multiple elastic rescattering diagrams for the $q\bar{q}$ dipole propagation through the nucleus target. In this model, the dipole-nucleus cross section reads

$$\sigma_{Aq\bar{q}}^A(r, x) = 2 \int d^2b_A \left\{ 1 - \exp \left[ -\frac{1}{2} \sigma_{q\bar{q}}^p(r, x) T_A(b_A) \right] \right\},$$

where $T_A(b_A)$ is the nuclear thickness function which is typically obtained from the Woods-Saxon distribution for the nuclear density normalized to the atomic mass $A$, and $b_A$ is the impact parameter of the dipole with respect to the nucleus center. Another possibility is to consider a solution the running-coupling Balitsky-Kovchegov (rcBK) equation for the nuclear case discussed e.g. in Refs. [52, 53], which takes into account mutual interactions of the gluonic ladders exchanged between the dipole and the nucleus. These two approaches include different diagrams and have distinct predictions for the onset of the saturation phenomena.

In the next Section, we perform a numerical analysis of the nuclear modification factor $R_{pA}$ (the $pA$-to-$pp$ ratio of the differential cross sections) and the azimuthal correlation for isolated photon production and compare predictions obtained with these two models for the dipole cross section off the nucleus.

III. NUMERICAL RESULTS

In this Section, we present numerical results for the isolated photon production in the $pp \rightarrow \gamma X$ process in the framework of color dipole formalism. In this analysis, we employ three phenomenological parametrizations for the dipole cross section discussed above and use the CT10 NLO parametrization for the projectile quark PDFs [54] (both sea and valences quarks are included).

In Fig. 2 we compare our predictions with the PHENIX data for isolated photon production at mid-rapidity in $pp$ collisions at $\sqrt{s} = 0.2$ TeV obtained by using three distinct models for the dipole cross section off the proton target. We can see that the GBW and AAMQS models describes the data quite well while the CGC model underestimates the data. Note that our results rely on existing parameterisations for the dipole cross section fitted to the HERA data, without any additional free parameters. In particular, no NLO $K$-factor has been imposed in the calculations, in contrast to the collinear QCD approach where such factor is required.

In Fig. 3 we present our predictions for isolated photon production in $pp$ collisions at $\sqrt{s} = 0.5$ TeV and for two distinct values for the photon pseudo-rapidity, $\eta = 2$ (left panel) and $\eta = 4$ (right panel). Here, we have selected

![Graph showing isolated photon transverse-momentum spectra in pp collisions at $\sqrt{s} = 0.2$ TeV and at mid-rapidity, $\eta = 0$, obtained using different models for the dipole cross section discussed in the text. The experimental data are from the PHENIX experiment.]
forward rapidities in order to probe small values of $x_2$ in the validity domain of the dipole approach. We expect that in this case the direct photon $p_T$ spectra are more sensitive to the treatment of the saturation effects.

The results presented in Fig. 3 (left panel) confirm that this expectation is valid already for $\eta = 2$. Here, the predictions for the photon spectrum are similar at small $p_T$’s but start to deviate significantly at $p_T > 6$ GeV. In particular, the AAMQS result, associated to the solution of the rcBK equation, predicts larger values for the spectra at large $p_T$’s than those for the GBW and CGC models.

In contrast, the results for $\eta = 4$ shown in Fig. 3 (right panel) indicate that at such large rapidities one cannot distinguish the predictions of the different dipole models. Indeed, the dipole approach becomes more precise for smaller values of $x_2$. In addition, such small difference between the dipole model predictions is partly due to the fact that here we probing the photon $p_T$ spectrum in the edge of the phase space where its behaviour is determined essentially by the kinematics of the process.

Our predictions for $pp$ collisions at the LHC energy ($\sqrt{s} = 14$ TeV) and for two different values of the photon pseudo-rapidity are presented in Fig. 4. Similarly to what was observed at RHIC energies, we found that the AAMQS prediction yields a higher spectrum than the other models, particularly, at large photon transverse momenta while the CGC and GBW parametrizations provide similar predictions. In principle, future experimental data at large $p_T$ can be used to discriminate between the AAMQS and GBW models. Note that at small $p_T$, however, the AAMQS prediction becomes slightly below the GBW one.

In order to estimate the impact of the nuclear effects in the predictions for the isolated photon production in
proton-lead ($pPb$) collisions at the LHC ($\sqrt{s} = 14$ TeV), in Fig. 5 we present our predictions for the photon transverse momentum dependence of the nuclear modification factor $R_{pA}$ defined as a ratio between the nuclear and proton differential cross sections, normalized by the atomic mass $A$. The predictions derived using the Glauber-Mueller approach for the dipole-nucleus cross section, Eq. (13), are denoted as “GM” in the figure. This model predicts that $R_{pA}$ becomes smaller than one at small $p_T$ while the nuclear effects become essentially negligible at large $p_T$. Moreover, the position of the maximum depends on the rapidity and shifts towards larger $p_T$’s when the rapidity is increased. In contrast, when a solution of the BK equation with QCD running coupling (denoted as “rcBK” in the figure) is used to evaluate the photon spectra in $pp$ and $pPb$ collisions at forward rapidities, the ratio $R_{pA}$ is below unity in the whole considered range of $p_T$’s, in agreement with the results obtained in Ref. [8]. Our results indicate that a future experimental analysis of the nuclear modification factor at forward rapidities can be very useful to discriminate between these two approaches.

In order to probe the underlying dynamics of particle production at forward rapidities, one should study other observables sensitive to QCD dynamics at small $x$, in particular to QCD non-linear and saturation phenomena. An appealing possibility is to consider the correlation function $C(\Delta \phi)$ defined in Eq. (8), which is strongly sensitive to the details of the dipole model. The previous results for the associated DY + pion production [22, 24] have demonstrated
that the effect of saturation implies a notable smearing of the back-to-back scattering profile predicted by the standard collinear formalism. An addition of the NLO corrections in the collinear framework would not account for a dip found at $\Delta \phi = \pi$ in the correlation function which is a direct manifestation of the saturation phenomenon.

Our goal here is to make the corresponding predictions for the isolated photon + pion $h = \pi$ associated production in $pp$ and $pA$ collisions at RHIC and LHC energies. As was typically done in earlier studies, let us initially consider the GBW model for the dipole cross section off the proton target which corresponds to the soft UGDF in the proton

$$F_p(x_g, k_T^2) = \frac{1}{\pi Q^2_{s,p}(x_g)} e^{-k_T^2/Q^2_{s,p}(x_g)},$$

(14)

with the saturation scale given in Eq. (11). Following Ref. [22], the nuclear UGDF, $F_A$, can also be approximately described by Eq. (14) replacing the proton saturation scale by a nucleus one:

$$Q^2_{s,p} \rightarrow Q^2_{s,A}(x) = A^{1/3} c(b) Q^2_{s,p}(x),$$

(15)

where $c = c(b)$ is the profile function of impact parameter $b$ (for central collisions, we use $c = 0.85$ following Ref. [40]). Moreover, in practical calculations we adopt the CT10 NLO parametrization for the parton distributions and the Kniehl-Kramer-Potter (KKP) fragmentation function $D_{h/f}(z_h, \mu_F^2)$ of a quark into a neutral pion [56]. In our analysis, the minimal transverse momentum ($p_T^{min}$) for the photon and the pion in Eq. (8) will be assumed to be the same and equal to 1.0 (3.0) GeV for RHIC (LHC) energies.

In Fig. 6 we present our predictions using the GBW model for the correlation function in the case of $pp$ and $pAu$ collisions at RHIC ($\sqrt{s} = 0.2$ TeV) and for two configurations for the photon and pion rapidities. We consider two distinct kinematical configurations, first, when both photon and pion are produced at forward rapidities, with $\eta = y_{\pi} = 3$, and, second, when the photon is produced at forward rapidity ($\eta = 3$) but the pion is produced at central rapidity ($y_{\pi} = 0$). Such configurations can be experimentally studied by the STAR Collaboration in both $pp$ and $pA$ collisions. It is important to emphasize that the saturation scale increases for smaller values of $x_g$, with $x_g = x_1 e^{-2\eta} + \frac{2z}{1-z} e^{-2y_{\pi}}$, and for larger nuclei. Therefore, larger pion and photon rapidities imply the increasing saturation scale. Consequently, one should expect a larger decorrelation at forward rapidities and at larger values of the atomic mass $A$.

In addition, for forward rapidities, the transverse momentum of the produced particles is limited by the phase space and, in general, does not assume a large value. Therefore, for this kinematical range, the saturation scale becomes non-negligible in comparison to the typical transverse momentum of the back-to-back scattered particles. In this case, the saturation scale induces a noticeable decorrelation between them. Such an expectation is confirmed by the results presented in Fig. 6. For the two configurations of rapidities mentioned above, we predict the presence of a double-peak in the correlation function in $pp$ collisions with a dip at $\Delta \phi = \pi$, in consistency with the DY + pion analysis of Ref. [22], [24]. Moreover, the width of the double peak increases when both rapidities are large. For $pAu$ collisions, the decorrelation grows, with the correlation function being almost flat for $\eta = y_{\pi} = 3$. Such a large decorrelation can, in principle, be probed in future experimental measurements at RHIC.

Our predictions for the correlation function in $pp$ and $pPb$ collisions at $\sqrt{s} = 8.8$ TeV are presented in Fig. 7. In the case of $pp$ collisions, we notice a smearing of the back-to-back correlation when the rapidities are increased, which is directly related to the growth of the saturation scale. A similar behavior is predicted for the DY + pion process [22], [24]. In contrast, for $pPb$ collisions at the same center-of-mass energy, we predict a larger decorrelation, in particular for $\eta = y_{\pi} = 5$.

In order to analyze the impact of the atomic mass on the correlation function, in Fig. 8 we present our predictions for $C(\Delta \phi)$ in $pA$ collisions at $\sqrt{s} = 8.8$ TeV, different values of $A$ and $\eta = y_{\pi} = 4.4$. As expected due to a growth
observe that both models predict a similar behaviour for the correlation function and differ mainly in the near-side region. In Fig. 9 we present a comparison between the GBW predictions and those derived using the AAMQS model. We are interested to compare these results with those obtained by using the solution of the rcBK equation discussed above. The target. For the latter, so far we have used Eq. (14) inspired by the GBW model as input in our calculations. It is the accompanied high-pT pion being produced at forward rapidities. In the case of pA collisions, a larger nuclear of the saturation scale with $A$, we observe that the decorrelation becomes stronger for heavier nuclei. Such a result indicates that, in principle, the study of $C(\Delta \phi)$ for a fixed energy and for given set of rapidities can be used to probe the $A$-dependence of the nuclear saturation scale $Q_{s,A}$.

Finally, let us discuss how the above predictions for the correlation function depend on modelling of the UGDF in the target. For the latter, so far we have used Eq. (14) inspired by the GBW model as input in our calculations. It is interesting to compare these results with those obtained by using the solution of the rcBK equation discussed above. In Fig. 9 we present a comparison between the GBW predictions and those derived using the AAMQS model. We observe that both models predict a similar behaviour for the correlation function and differ mainly in the near-side ($\Delta \phi = 0$) region, which is dominated by the leading jet fragmentation. Such a result is anticipated from the previous studies [40, 42, 43] which have demonstrated that the behaviour of $C(\Delta \phi)$ in the away-side ($\Delta \phi = \pi$) region is not strongly dependent on the large transverse momentum tail of the UGDF.

IV. SUMMARY

In this paper, we performed a detailed phenomenological analysis of the isolated photon production in $pp$ and $pA$ collisions at typical RHIC and LHC energies in the framework of color dipole approach. We employed three different phenomenological saturation models for the dipole-target scattering and analysed differential distributions of prompt photons in transverse momentum $p_T$. Besides, we have investigated the correlation function $C(\Delta \phi)$ in azimuthal angle between the real high-$p_T$ photon produced in association with a leading pion emerging via fragmentation of a projectile quark which emits the photon. This observable has been studied in $pp$ and $pA$ collisions at RHIC and LHC energies and at different rapidities of final states. In $pp$ collisions, the correlation function exhibits a double-peak structure close to $\Delta \phi \simeq \pi$ in certain kinematical configurations corresponding to both the real high-$p_T$ photon and the accompanied high-$p_T$ pion being produced at forward rapidities. In the case of $pA$ collisions, a larger nuclear
saturation scale enforces a stronger decorrelation between the photon and the pion. The correlation function is a more exclusive observable than the standard transverse momentum spectra of the isolated photon and appears to be strongly sensitive to the details of theoretical modelling of the saturation phenomena in QCD. A future measurement of this observable at different RHIC and the LHC energies would be capable of setting stronger constraints on the unintegrated gluon density in the small-$x$ and small-$k_T$ domains as well as on the dipole model parametrizations, thus, enabling to directly probe the saturation scale.

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