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# Exploring gluon saturation with photons in high-energy hadron-hadron collisions

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We numerically compute the inclusive photon production in $\mathrm{p}+\mathrm{p}$ collisions within the Color Glass Condensate framework as determined through the valence $qg \to q\gamma$ leading-order channel and the $gg \to q\bar{q}\gamma$ next-to-leading-order channel, respectively. We find the $gg \to q\bar{q}\gamma$ channel accounts for more than 90% of the cross section at the center of mass energies of $\sqrt{s} = 7$ TeV and 13 TeV. The obtained numerical results compare well with the ATLAS and CMS $\mathrm{p}+\mathrm{p}$ data for inclusive isolated photon production within the region where $x < 0.01$ in either of the colliding protons.

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## 1. Introduction

We are motivated by the large gluon occupations at the LHC and its potential to explore the physics of gluon saturation. The inclusive photon production cross section was measured in p+p collisions by ATLAS [1] ($\sqrt{s} = 7$ TeV) and CMS [2, 3, 4] ($\sqrt{s} = 2.76$ TeV and 7 TeV) up to photon rapidity $|\eta_\gamma| \leq 2.5$, partially covering also the region $x < 0.01$ where deviations to the photon spectrum from the collinear perturbative QCD results, and due to the effect of saturation of gluons, are expected. The latter is described by the Color Glass Condensate (CGC) effective field theory (EFT) wherein the gluon distributions become transverse momentum dependent and strongly modified in the infrared, at around the saturation scale $Q_S$.

We have used the CGC EFT and applied it to inclusive photon production: $\mathrm{p}+\mathrm{p} \to \gamma + X$. We used the dilute-dense framework where all-order rescatterings on the dense target, together with its non-linear quantum evolution effects, are taken into account, so that the forward collision region probes the small-$x$ content of the target proton.

The leading-order (LO) contribution comes from the $q \to q\gamma$ channel (in the target background). The main formula for the inclusive cross section is given as [5, 6, 7, 8] (with recent applications in [9])

$$\frac{\mathrm{d}\sigma^{\mathrm{LO}}}{\mathrm{d}^2\boldsymbol{k}_{\gamma\perp}\mathrm{d}\eta_\gamma} = S_\perp \sum_f \frac{\alpha_e q_f^2}{16\pi^2} \int_{\boldsymbol{q}_\perp} \int_{x_{p,\min}}^1 \mathrm{d}x_p\, f_{q,f}^{\mathrm{val}}(x_p, Q^2) \tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{q}_\perp + \boldsymbol{k}_{\gamma\perp})$$
$$\times \frac{1}{q^+ l^+} \Bigg\{ -4m_f^2 \left[ \frac{l^{+2}}{(q\cdot k_\gamma)^2} + \frac{q^{+2}}{(l\cdot k_\gamma)^2} + \frac{k_\gamma^{+2}}{(l\cdot k_\gamma)(q\cdot k_\gamma)} \right] \tag{1.1}$$
$$+ 4\left(l^{+2} + q^{+2}\right) \left[ \frac{l\cdot q}{(l\cdot k_\gamma)(q\cdot k_\gamma)} + \frac{1}{q\cdot k_\gamma} - \frac{1}{l\cdot k_\gamma} \right] \Bigg\},$$

where $f_{q,f}^{\mathrm{val}}(x_p, Q^2)$ is the valence quark distribution so that the sum runs over the valence $f = u, d$ flavors only. For consistency reasons we are taking only the valence content at LO, whereas the sea quark contribution is taken into account by the $g \to q\bar{q}\gamma$ NLO channel to be discussed below. The distribution of gluons in the target is described by a fundamental Wilson line dipole $\tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{k}_\perp)$. For further details see also [10].

At NLO we take into account the $g \to q\bar{q}\gamma$ [11] channel as dominating the mid-rapidity region over the remaining $q \to qg\gamma$ [12] and $g \to q^*\bar{q}^* \to \gamma$ [13] channels also present at this order. The inclusive cross section is given as [11] (see also [10])

$$\frac{\mathrm{d}\sigma^{\mathrm{NLO}}}{\mathrm{d}^2\boldsymbol{k}_{\gamma\perp}\mathrm{d}\eta_\gamma} = S_\perp \sum_f \frac{\alpha_e \alpha_S N_c^2 q_f^2}{64\pi^4 (N_c^2 - 1)} \int_{\eta_q \eta_p} \int_{\boldsymbol{q}_\perp \boldsymbol{p}_\perp \boldsymbol{k}_{1\perp} \boldsymbol{k}_\perp} \frac{\varphi_p(Y_p, \boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2} \tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{k}_\perp) \tilde{\mathcal{N}}_{t,Y_t}(\boldsymbol{P}_\perp - \boldsymbol{k}_{1\perp} - \boldsymbol{k}_\perp)$$
$$\times \left[ 2\tau_{g,g}(\boldsymbol{k}_{1\perp}; \boldsymbol{k}_{1\perp}) + 4\tau_{g,q\bar{q}}(\boldsymbol{k}_{1\perp}; \boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}) + 2\tau_{q\bar{q},q\bar{q}}(\boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}; \boldsymbol{k}_\perp, \boldsymbol{k}_{1\perp}) \right], \tag{1.2}$$

at large $N_c$. Here $\varphi_p(Y_p, \boldsymbol{k}_{1\perp})$ is the unintegrated gluon distribution (UGD) in the projectile proton and the sum $\sum_f$ runs over $f = u, d, s, c, b$ flavors in our computation.

## 2. Calculation setup and numerical results

For the parton distribution functions (PDFs) we use the central CTEQ6M set [14]. The gluon UGD of the proton is fixed by its relation to the adjoint dipole: $\varphi_p(Y_p,\boldsymbol{k}_{1\perp}) = S_\perp N_c \boldsymbol{k}_{1\perp}^2 \mathcal{N}_{p,Y_p}(\boldsymbol{k}_{1\perp})/4\alpha_S$. The gluon dipoles are evolved according to the running coupling Balistsky-Kovchegov equation (rcBK) [15, 16], with the initial condition set by the McLerran-Venugopalan (MV) model [17] at $x = 0.01$ that provides a good description of the $J/\Psi$ production in p+p [18]. The region $x > 0.01$ is fixed by the matching to the gluon PDF as in [18]. For the quark masses we took $m_u = m_d = 0.005$ GeV, $m_s = 0.095$ GeV, $m_c = 1.3$ GeV and $m_b = 4.5$ GeV. We have varied their values according to their current experimental uncertainties leading to about 10% deviations in the cross section that is taken into account as a part of our systematics.

We calculate the spectrum of isolated photons that is obtained by applying an isolation cone $R$ as

$$\theta\Big(\sqrt{(\eta_\gamma-\eta)^2+(\phi_\gamma-\phi)^2}-R\Big)\,, \tag{2.1}$$

with $\eta$ and $\phi$ being the rapidity and the azimuthal angle of the quark. This constraint suppresses collinear emissions within the hadron jets such as decay photons but also fragmentation photons.

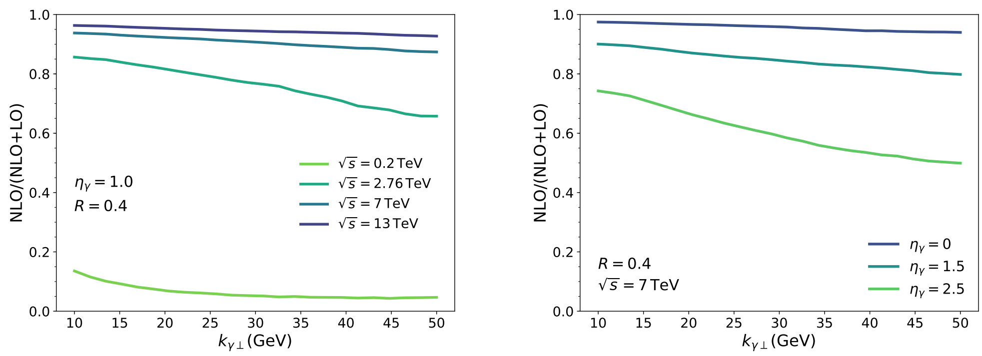


**Figure 1:** Fraction of the inclusive photon cross section from the NLO $gg \to q\bar{q}\gamma$ channel relative to the total NLO+LO contribution, as a function of $k_{\gamma\perp}$ for different collision energies (left panel) and different $\eta_\gamma$ (right panel).

In the following we show the numerical results based on the LO and NLO contributions described in the previous section and compare with the relevant experimental data. The LHC data from CMS and ATLAS account for photons with $k_{\gamma\perp} \sim 20$ GeV. We have numerically established [10] that at such transverse momenta the full-CGC formula (1.2) is already well approximated by its $k_\perp$-factorized form[1]

$$\frac{\mathrm{d}\sigma^{\rm NLO}_{k_\perp\text{-fact}}}{\mathrm{d}^2\boldsymbol{k}_{\gamma\perp}\mathrm{d}\eta_\gamma} = S_\perp \sum_f \frac{\alpha_e\alpha_S N_c^2 q_f^2}{64\pi^4(N_c^2-1)} \int_{\eta_q\eta_p}\int_{\boldsymbol{q}_\perp\boldsymbol{p}_\perp\boldsymbol{k}_{1\perp}} \frac{\varphi_p(Y_p,\boldsymbol{k}_{1\perp})}{\boldsymbol{k}_{1\perp}^2}\mathcal{N}_{t,Y_t}(\boldsymbol{P}_\perp-\boldsymbol{k}_{1\perp}) \\ \times\big[2\tau_{g,g}(\boldsymbol{k}_{1\perp})+\tau_{q,q}(\boldsymbol{k}_{1\perp})+\tau_{\bar{q},\bar{q}}(\boldsymbol{k}_{1\perp})+2\tau_{g,q}(\boldsymbol{k}_{1\perp})+2\tau_{g,\bar{q}}(\boldsymbol{k}_{1\perp})\big]\,. \tag{2.2}$$

[1] $k_\perp$-factorization becomes broken at lower $k_{\gamma\perp}$: at around $k_{\gamma\perp} \sim 1$ GeV the breaking is about 10%, see [10].

With this observation the rest of the results will be presented using (2.2).

On Fig. 1 we show the fractional contribution of the NLO cross section to the full LO+NLO result with varying the collision energy (left panel) and photon rapidity (right panel) using the isolation cut $R = 0.4$. Whereas at the $\sqrt{s} = 0.2$ TeV RHIC energy NLO provides a correction to the full cross section, the increase to the LHC energy marks the NLO contribution to more than 60% at 2.76 TeV and more than 90% at 7 TeV and 13 TeV. Similar trends are found when moving from the mid-rapidity to the forward photon rapidities.

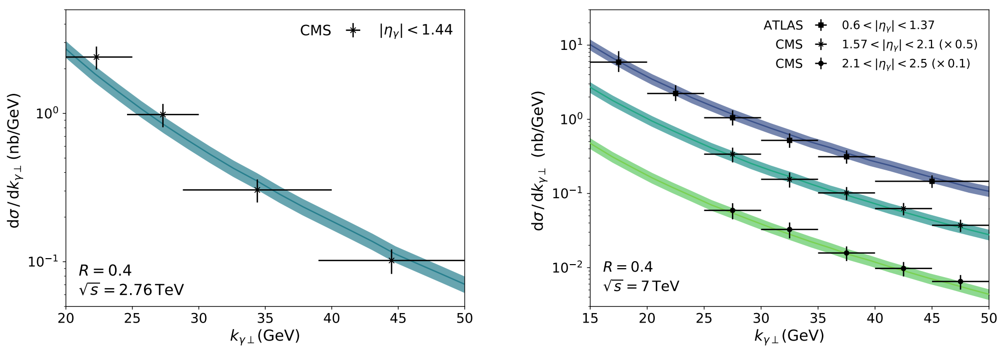


**Figure 2:** Comparison to the p+p photon data at $\sqrt{s} = 2.76$ TeV (left panel, CMS [2]) and $\sqrt{s} = 7$ TeV (right panel, ATLAS [1], CMS [4] across several rapidity bins. The central lines are obtained with a $K$-factor of $K = 2.4$.

The left panel on Fig. 2 gives a comparison to the CMS data at 2.76 TeV [2] where we find a good agreement by using an overall $K$-factor of $K = 2.4$. On right panel Fig. 2 we compare with the ATLAS [1] and CMS [4] data at 7 TeV; a good agreement is found using the same $K = 2.4$.

## 3. Conclusions

We have for the first time numerically computed the CGC NLO $g \to q\bar{q}\gamma$ contribution to inclusive photon production $\mathrm{p+p} \to \gamma X$. We have found that the NLO channel dominates by more than 90% over the LO $qg \to q\gamma$ channel at the $\sqrt{s} = 7$ TeV and 13 TeV energies. Our results demonstrate fair agreement with the available LHC data. Working still within the dilute-dense formalism our formulas are suitable for future applications of photon production in p+A collisions where the saturation effects are expected to be more pronounced.

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