Prompt photons at high energies has provided a direct probe of the dynamics of the strong interactions \[1\]. Usually photons are called prompt if they are coupled to the interacting quarks. In the framework of QCD the dominant production mechanism for the prompt photons at Tevatron and LHC colliders is the Compton scattering \(q + g \rightarrow \gamma + q\) (See, e.g. Refs. \[2, 3\]). It is clear that the cross section of such process is sensitive to the gluon distribution in the proton or nuclei \[4\]. In particular, LHC probes the gluon distribution at \(x_g \approx 10^{-5}\) \[5\]. Usually the parton distributions in a proton are described by the DGLAP evolution equations \[5\] and the cross section is calculated using collinear factorization. More recently, the \(k_T\)-factorization, which takes into account effects of finite virtualities and transverse momenta of the incoming partons, has been applied to calculate the prompt photon production cross section \[6, 7\]. In this case, the cross section is given in terms of the unintegrated parton distributions, which are solution of the BFKL or CCFM evolution equations, for instance. However, at high energies (small-x), these linear evolution equations predict a strong growth of the gluon distributions, which implies a large density of gluons in this regime and the violation of the unitarity. Consequently, new dynamical effects associated to the unitarity corrections are expected to stop its further growth (For recent reviews see Ref. \[8\]).

About 24 years ago, Gribov, Levin and Ryskin (GLR) \[8\], followed by Mueller and Qiu (MQ) \[9\], performed a detailed study of the small-x regime and argued that at large densities the physical processes of interaction and recombination of partons become important and should be considered in the QCD evolution, implying a nonlinear evolution equation. In the last two decades, the solution and possible generalizations of the GLR-MQ equation have been studied in great detail (See e.g. Ref. \[10\]). Currently, one believe that the small-x gluons in a hadron wavefunction should form a color glass condensate (CGC) which is described by an infinite hierarchy of coupled evolution equations for the correlators of Wilson lines \[11\]. In the absence of correlations, the first equation in the Balitsky-JIMWLK hierarchy decouples and is then equivalent to the equation derived independently by Kovchegov \[12\]. The resulting BK equation is almost equivalent to the GLR-MQ equation for the unintegrated gluon distribution, with the solutions presenting similar characteristics \[13\]. Experimentally, there are strong evidences of the nonlinear (saturation) effects at DESY-HERA. In particular, the DESY \(e p\) HERA data in the small-x and low-Q\(^2\) region can be successfully described in terms of saturation models \[14\], with the measured cross sections presenting the geometric scaling property \[15\]. Moreover, in Ref. \[16\] the authors have shown that adding nonlinear corrections to the evolution, based on gluon recombination as derived in \[9, 10\], can improve the overall leading order (LO) fits to the HERA DIS data. Its main results are that when nonlinear terms are included, the resulting gluon distribution is reduced with respect to the solution of the LO BFKL equation and the slowing of the \(Q^2\) evolution leads to an enhancement of the small-x gluon distribution at \(Q^2 \lesssim 10\ \text{GeV}^2\) relative to the LO DGLAP gluon distributions. It implies similar enhancements in the cross sections which are strongly dependent on the gluon distribution with respect those calculated using the solution of the LO DGLAP evolution equation. In \[17\] the charm quark production has been estimated at LHC energies and a substantial enhancement was predicted. As the prompt photon production cross section is directly dependent on the behavior of the gluon distribution, one can expect a similar enhancement of the cross section.

Our goal in this paper is estimate the magnitude of this enhancement and determine the kinematic region...
where this effect should be more important. We consider prompt photon production via the QCD processes $q + \bar{q} \rightarrow \gamma + g$ and $q + g \rightarrow \gamma + q$ in order to investigate by which amount nonlinear effects contribute to the hard process. Our main focus is the production of prompt photons in the kinematical region accessible at CERN LHC energy. Moreover, as a by product, we also estimate the contribution of these effects for the double photon production, which constitutes an important QCD background to the Higgs ($h$) production chain $pp \rightarrow hX \rightarrow \gamma \gamma X$.

Lets now present a brief review of the prompt photon production. Two types of processes contribute to the cross section: the so-called direct piece, where the photon originates from fragmentation piece, in which the photon originates from the fragmentation of a final state parton. As the second component can be almost completely reduced by isolation criterion used in the experimental data analysis, we focus our study only in the direct component, which provide a clean probe of the hard scattering dynamics. In this case, we have that the prompt photon production cross section is given by [1]

$$\frac{d\sigma_{pp\rightarrow \gamma X}}{dy dp_T^2} = \sum_{i,j,k} \int_{x_{T}^{\text{min}}}^{1} dx_1 f_i(x_1, Q^2) f_j(x_2, Q^2)$$

$$\frac{x_1 x_2}{2x_1 x_2 - x_T^2} \frac{d\sigma_{ij\rightarrow \gamma k}}{dt}(Q^2, x_1, x_2),$$  \hspace{1cm} (1)

where $x_T = 2p_T/\sqrt{s}$, $y$ and $p_T$ are the rapidity and transverse momentum of the produced photon, $f_i(x, Q^2)$ are the parton densities, $x_1$ and $x_2$ are the momentum fractions of the partons involved in the hard process. In this case we have that $x_2 = \frac{2x_T + y}{2x_1 - x_T y}$ and $x_1^{\text{min}} = \frac{2x_T - y}{2x_1 + x_T y}$. $Q^2$ is the hard scale and $\frac{d\sigma}{dt}$ are the partonic cross sections, which are perturbatively calculable [18]. The contributing LO subprocesses are $qg \rightarrow q\gamma$ (Compton), $q\bar{q} \rightarrow g\gamma$ (annihilation), followed by the subdominant diagrams $q\bar{q} \rightarrow \gamma\gamma$ (pure EM), $gg \rightarrow \gamma\gamma$ and $gg \rightarrow g\gamma$. The correspondent LO matrix elements and partonic cross sections can be found in Refs. [1, 18]. Using Eq. (1) to calculate the cross section, we implicitly are assuming the validity of the collinear factorization. It is important to emphasize that factorization breaking is predicted by CGC physics in several processes (See e.g. [19]). In what follows we calculate the prompt photon production cross section considering the EHKQS [16] and CTEQ6 [20] sets for the parton distributions and estimate the ratio among these predictions in order to quantify the magnitude of the enhancement expected at LHC. We analyze the rapidity and transverse momentum dependence of this ratio. As the EHKQS sets are only evolved to leading order (LO), we work the cross sections also at leading order. It implies that our predictions should be considered an upper bound, since the NLO small-$x$ gluon distributions are typically reduced relative to LO, implying a smaller enhancement.

In Fig. 1 we present our estimates for the rapidity dependence of the ratio $R_y$ defined by

$$R_y \equiv \frac{d\sigma(\text{EHKQS})}{dy}/\frac{d\sigma(\text{CTEQ6})}{dy}.$$  \hspace{1cm} (2)

We consider two different values for the factorization and renormalization scales: $Q = p_T$ and $Q = 2p_T$, where $p_T$ is the photon transverse momentum. Moreover, in order to calculate the differential cross section $d\sigma/dy$ we have assumed two distinct values for the minimum photon transverse momentum: $p_T^{\text{min}} = 1$ and 2 GeV. The results show an enhancement of low-$p_T$ photons - the lower $p_T^{\text{min}}$ the more significant enhancement of prompt photon production. We also notice a larger enhancement for central rapidities. The choice of the hard scale also affects the magnitude of the nonlinear effects, by choosing $Q = p_T$ one has a bigger enhancement. In particular, for $p_T^{\text{min}} = 1$ GeV and $Q = p_T$, we predict a factor of two for

![FIG. 1: (color online) Rapidity dependence of the ratio $R_y$ for two different choices of the hard scale $Q$ and minimum transverse momentum $p_T^{\text{min}}$.](image1)

![FIG. 2: (color online) Transverse momentum dependence of the ratio $R_{p_T}$ for two different choices of the hard scale $Q$.](image2)
the enhancement of the rapidity distribution associated to the nonlinear effects in the central rapidity region.

In Fig. 3 we present our estimates for the transverse momentum dependence of the ratio $R_{p_T}$ defined by

$$R_{p_T} \equiv \frac{d\sigma(EHKQ)}{d^2p_T} \frac{d\sigma(CTEQ6)}{d^2p_T} .$$

Similarly to our previous analysis we also consider two different choices for the scale $Q$. Moreover, we have integrated the rapidity distribution in the range $|y| < 3$, which will be studied in LHC. We have that an enhancement is predicted in the region of small transverse momentum $p_T < 10$ GeV. At larger scales the nonlinearities die out since these terms are proportional to $1/Q^2$.

Consequently, the EHKQS gluons become similar to the CTEQ6 one, so that the enhancement disappears at large $p_T$. This behavior is also expected in charm production \cite{17}. From the Fig. 4 we can see that the nonlinear effects imply an enhancement of $20\%$ in the small-$p_T$ region if we assume $Q = 2p_T$. On the other hand, for $Q = p_T$ this enhancement can be larger than $10\%$. The enhancement in the low range of transverse momenta has important implications, mainly if we remember that the magnitude of prompt photon production in proton-proton collisions is used as baseline to estimate nuclear medium effects in nucleus-nucleus collisions \cite{21}. In particular, a signature of quark-gluon plasma formation is the thermal photon production, which manifests by an enhancement in the inclusive photon spectrum at $p_T$ values below $\approx 15$ GeV at LHC (For recent reviews see Refs. \cite{22,23}). The pre-requisite for the extraction of the thermal signal is a precise control of the photon production rate in proton-proton collisions, which can be strongly modified by the nonlinear effects, as demonstrated above. Consequently, our results indicate that a detailed study of the prompt photon production in $pp$ collisions at LHC is necessary before to consider the thermal photon production as a precise signal of QGP formation.

One can analyze the contribution of the nonlinear effects for the diphoton production, characterized by the subprocesses $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$, which have been included in our calculations. Although the gluon-gluon initiated process is not the dominant one, it contributes significantly for the $\gamma\gamma$ cross section. This may imply in bigger nonlinear effects, since both initial state small-$x$ gluons should be amplified in the region $Q^2 \leq 10$ GeV$^2$. In Fig. 4 we present our results for the rapidity dependence of the ratio $R_y$, calculated including only the $q\bar{q}$ and $gg$ contributions. We consider the same two choices of factorization and renormalization scales as before: $Q = p_T$ and $Q = 2p_T$, and we have assumed the value of $p_T^{min} = 1$ GeV for the minimum photon transverse momentum. We can see that the enhancement due to nonlinear effects is more significant here than for single photon production - probably due the relative importance of the two gluon initiated contribution. In fact, if we had considered only the $gg \rightarrow \gamma\gamma$ and neglected the $q\bar{q} \rightarrow \gamma\gamma$ contribution (just for theoretical study), the $R_y$ ratio would increase to almost 5 (1.5) for the $Q = p_T$ ($Q = 2p_T$) choice. Anyway, in the full LO contribution some of this increased enhancement remains.

This result motivates a more detailed analysis of diphoton production, which is considered the main background for Higgs production via gluon fusion (See e.g. Ref. \cite{24}). In terms of the diphoton invariant mass $M_{\gamma\gamma}$ and photon rapidities $y_1$ and $y_2$, the cross section can be written as

$$\frac{d\sigma_{pp \rightarrow \gamma\gamma}}{dy_1dy_2dM_{\gamma\gamma}} = \sum_{ij} x_1 f_i(x_1, Q^2) x_2 f_j(x_2, Q^2) \frac{M_{\gamma\gamma}}{1 + \cosh(y_1 - y_2)} \frac{d\bar{\sigma}_{ij \rightarrow \gamma\gamma}}{dt} (Q^2, x_1, x_2) ,$$

where $x_1 = \frac{p_T}{\sqrt{s}} [e^{y_1} + e^{-y_2}]$ and $x_2 = \frac{p_T}{\sqrt{s}} [e^{-y_1} + e^{y_2}]$.
\( R_{M,\gamma} \) defined by
\[
R_{M,\gamma} = \frac{d\sigma(EHKQS)}{M_{\gamma\gamma}} / \frac{d\sigma(CTEQ6)}{M_{\gamma\gamma}} .
\] (5)

In Fig. 4 we present our predictions for the behavior of this ratio in the kinematical range of \( M_{\gamma\gamma} < 50 \text{ GeV} \) considering two distinct values of the hard scale \( Q \). We have that in this range an enhancement is predicted, mainly at small values of the factorization scale \( Q \) and diphoton invariant mass. On the other hand, for larger values of \( M_{\gamma} \) the nonlinear effects can be disregarded. Since the typical \( p_T \) of photons needed to produce a Higgs would be around 50 GeV each, the nonlinear effects here considered will not be important for the QCD background to Higgs (For a discussion of nonlinear effects in Higgs production see e.g. Ref. [22]). On the other hand, the enhancement in the low invariant mass region is predicted so the nonlinear contributions could be tested in this range.

In summary, in this paper we have investigated the prompt photon production considering the collinear factorization and the EHKQS parton distributions, which are solutions of the GLR-MQ evolution equations and describe quite well the \( e\pi \) HERA data. Our results demonstrate that the nonlinear effects implies a large enhancement of the cross section for single and double photon production, which could be tested at LHC. In particular, the magnitude of the single photon production at small-\( p_T \) should be constrained before using thermal photon production as a signature of the QGP formation. On the other hand, the nonlinear effects can be disregarded in the kinematical range where double photon production is an important background for Higgs production.

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