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Estimating gluon saturation in dijet photoproduction in UPC

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Abstract
We study dijet production in the ultra-peripheral heavy ion collisions (UPC) at LHC within the saturation formalism. More precisely, we use an approach which is the large-p_T approximation to the Color Glass Condensate on one hand, and the small-x limit of the transverse momentum dependent (TMD) factorization on the other. The direct component of the dijet production in UPC at small x probes the so-called Weizsäcker-Williams (WW) TMD gluon distribution, which is not accessible in more inclusive processes, where rather the dipole TMD gluon distribution is probed. Although the WW TMD gluon distribution is not known from data, it can be calculated from the data-restricted dipole TMD gluon distribution using the mean field approximation. Using such approximated WW distribution we calculate various dijet observables in UPC and estimate the saturation effects.

Keywords
UPC, saturation, TMD gluon distributions, jets.

1 Introduction

The phenomenon of gluon saturation is most often described within the Color Glass Condensate (CGC) effective theory [1]. Within this picture, a scattering is described by an interaction of a (color) dipole with a shock-wave corresponding to the color field of a nucleus. Depending on the color flow in the particular process, the interaction with the shock-wave involves color averages of various number of the Wilson line operators: average of two Wilson lines (a dipole) appears in simplest inclusive processes, while also quadrupoles and more complicated correlators are possible. In CGC these correlators can be in principle calculated in the classical McLerran-Venugopalan (MV) model [2] with some free parameters, but truly, they contain a non-perturbative information.

Indeed, in certain limit, the CGC correlators can be related [3] to the small x limit of transverse momentum dependent (TMD) gluon distributions, known from the semi-inclusive collinear factorization (see e.g. [4]). It turns out that the TMD approach gives a transparent and universal interpretation to the two fundamental objects appearing in CGC [5]: the correlator of the dipole operator (two Wilson lines), and the correlator of the gluon number operator. The first object appears in the description of inclusive particle production and can be reformulated as an unintegrated gluon distribution (UGD), dubbed thus the dipole UGD. The second object, the true gluon number distribution (called the Weizsäcker-Williams (WW) UGD) does not explicitly appear in formulae for any process within CGC. It is however related to the quadrupole correlator which appears in two particle production processes. In particular, for two particle production in γA collision in the near back-to-back configuration, the WW UGD is the only gluon distribution probed [3]. Within the TMD approach, the two gluon distributions are represented by the hadronic matrix element of bilocal gluon operator with fields displaced in the light-cone and transverse directions. To ensure the gauge invariance, the Wilson links have to be inserted, but their structure turns out to be different for the dipole UGD and the WW UGD. Here, let us only mention that for the latter they can be removed by a choice of gauge so that the gluon number interpretation is apparent.

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The dipole UGD is well studied and there are several fits to inclusive DIS data. This is not the case for the WW UGD. In the view of the above discussion, it is a fundamental quantity and needs to be constrained from data as well. The future Electron Ion Collider will definitely provide a good source of data. Before that, however, it is interesting to investigate the ultra-peripheral heavy ion collisions (UPC) at LHC to see what possibilities it provides (for a review of UPC see [6]). In our study presented in [7], which we summarize in the following report, we took the following strategy. First, we have calculated the WW UGD using the so-called Gaussian approximation from the realistic dipole UGD. Next, using such approximated WW UGD we calculate various observables for the direct component of UPC at LHC within a framework similar to [8]. We concentrate mainly on the saturation effects as these are what make the dipole and WW UGDs different.

2 Framework

We use the standard approach to set up the UPC collisions: we consider a photon flux from a heavy ion in the equivalent photon approximation (see e.g. [6]). What is truly interesting, is the γA hard collision which we calculate as described in the following section.

Since we are interested in jet production at LHC, we assume that the typical transverse momentum P_T of produced particles is rather large, definitely larger than the saturation scale Q_s, $P_T \gg Q_s$. Another requirement is that we want to probe the nucleus at as small x as possible to justify the usage of the saturation formalism. Let us note, that although we deal with rather large P_T, we still can be sensitive to the saturation effects. This is because we study a dijet system, and, unlike in the inclusive jet production, the p_T of jets does not translate into the transverse momentum entering the gluon distribution. Rather, it is the dijet imbalance what enters.

The factorization formula within the framework of [8] but adjusted to the present process reads

$$d\sigma_{\gamma A\rightarrow 2\,\mathrm{jet}+X} = \sum_{\{q,\bar{q}\}} \int \frac{dx_A}{x_A} \int d^2k_T\, x_A G_1\left(x_A, k_T\right)\, d\sigma_{\gamma g^*\rightarrow q\bar{q}}\left(x_A, k_T\right)\,, \tag{1}$$

where xG_1 is the Weizsäcker-Williams UGD. The partonic cross section $d\sigma_{\gamma g^*\rightarrow q\bar{q}}$ is calculated using the LO amplitude for the process $\gamma g^* \rightarrow q\bar{q}$, where g^* denotes the off-shell gluon. It is calculated in the high energy approximation, where the momentum of the gluon has only one longitudinal component, parallel to the parent hadron. That is, taking the momentum of the nucleus to be p_A, the momentum of g^* is $k_A^\mu = x_A p_A^\mu + k_T^\mu$, where $p_A^\mu = (1,0,0,-1)\sqrt{s}/2$ and $k_T^\mu = \left(0, k_T^1, k_T^2, 0\right)$. The off-shell gluon couples eikonally to the rest of the process, that is via the vector p_A. The amplitude $\gamma g^* \rightarrow q\bar{q}$ constructed in such a way is gauge invariant and is essentially the same as used in the high energy factorization (HEF) [9]. In practical Monte Carlo calculations we used the helicity amplitudes calculated using the program described in [10] but extended to quarks. The two-particle phase space is constructed with account of the initial state transverse momentum k_T. The factorization formula (1) has two limits which are well settled QCD results: when $k_T \sim P_T \gg Q_s$ the formula recovers the HEF result, because in that dilute limit any saturation effects are gone, in particular then the WW UGD and dipole UGD become equal. Second, in the limit $k_T \sim Q_s \ll P_T$ it reproduces the leading power limit of CGC formula [3].

The formula (1) is not actually completely correct as there is no hard scale dependence in the gluon distribution xG_1. Since we aim at rather large transverse momenta of jets $\sim P_T$, the hard scale adequate to the process is of the same order: $\mu \sim P_T$. Thus, in the saturation region $k_T \sim Q_s$ we have $\mu \gg k_T$ which gives rise to Sudakov-type logs which should be resummed. The general formalism to do so was developed in [11] and is rather complicated. Here, instead, we use a physical interpretation of the Sudakov form factor as a probability not to emit partons between scales k_T and P_T and apply it to Monte Carlo generated events. The procedure was described in [12] and has a similar effect on linear evolution as the hard scale dependence in widely used Kimber-Martin-Ryskin (KMR) model [13].

As mentioned in the Introduction, the WW UGD appearing in (1) was calculated using the Gaussian approximation following the methodology of [14] (another possible approach was presented in [15]).

In the Gaussian approximation the relation between the WW UGD xG_1 and the dipole UGD xG_2 reads:

$$\nabla^2_{k_T} G_1\left(x, k_T\right) = \frac{4\pi^2}{N_c S_\perp(x)} \int \frac{d^2 q_T}{q_T^2} \frac{\alpha_s(k_T^2)}{\left(\vec{k}_T - \vec{q}_T\right)^2} xG_2\left(x, q_T\right) G_2\left(x, \left|\vec{k}_T - \vec{q}_T\right|\right), \tag{2}$$

where $S_\perp(x)$ is the effective transverse area of the target. Instead of using the pure Balitsky-Kovchegov (BK) evolution equation [16,17] for the dipole UGD, we used a more involved Kwiecinski-Martin-Stasto equation [18] with the nonlinear term [19], which includes subleading effects that may be important at non-asymptotically small x. This evolution equation reads: (below we set $xG_2\left(x, k_T\right) \equiv \mathcal{F}\left(x, k_T^2\right)$ for more compact expression):

$$\begin{aligned}\mathcal{F}\left(x, k_T^2\right) &= \mathcal{F}_0\left(x, k_T^2\right) + \frac{\alpha_s(k_T^2) N_c}{\pi} \int_x^1 \frac{dz}{z} \int_{k_{T0}^2}^{\infty} \frac{dq_T^2}{q_T^2} \left\{ \frac{q_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) \theta\left(\frac{k_T^2}{z} - q_T^2\right) - k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\left|q_T^2 - k_T^2\right|} \right. \\ &+ \left. \frac{k_T^2 \mathcal{F}\left(\frac{x}{z}, k_T^2\right)}{\sqrt{4q_T^4 + k_T^4}} \right\} + \frac{\alpha_s(k_T^2)}{2\pi k_T^2} \int_x^1 dz \left\{ \left(P_{gg}(z) - \frac{2N_c}{z}\right) \int_{k_{T0}^2}^{k_T^2} dq_T^2 \mathcal{F}\left(\frac{x}{z}, q_T^2\right) + z P_{gq}(z) \Sigma\left(\frac{x}{z}, k_T^2\right) \right\} \\ &- d \frac{2\alpha_s^2(k_T^2)}{R^2} \left\{ \left[\int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \mathcal{F}\left(x, q_T^2\right) \right]^2 + \mathcal{F}\left(x, k_T^2\right) \int_{k_T^2}^{\infty} \frac{dq_T^2}{q_T^2} \ln\left(\frac{q_T^2}{k_T^2}\right) \mathcal{F}\left(x, q_T^2\right) \right\}. \end{aligned} \tag{3}$$

Above $\Sigma\left(x, k_T\right)$ is the accompanying singlet sea quark distribution and R is the target radius appearing from the integration of the impact parameter dependent gluon distribution assuming the uniform distribution of matter. The parameter d, $0 < d \leq 1$ is set to $d = 1$ for proton and can be varied for nucleus to study theoretical uncertainty. The initial condition $\mathcal{F}_0$ was fitted to the inclusive DIS HERA in [20] with $R \approx 2.4\,\mathrm{GeV}^{-1}$. In what follows we shall name this set KS (Kutak-Sapeta) UGD. The Pb nucleus was modelled using the Woods-Saxon formula $R_A = A^{1/3} R$ where A is the mass number. In the present work we use $d = 0.5$ value for the Pb ion.

3 Results

The results for the WW UGD are presented in Fig. 1. Let us notice, in particular, that for large k_T the xG_1 and xG_2 gluons become equal, as required by the dilute limit of Eq. (1). The cuts for numerical studies are presented in Table 1. We note, that the main issue for saturation studies is that in order to have small x on the nucleus side, the photon flux should be probed at rather larger x, for which, however, the flux becomes small. This forces us to go to rather small p_T of jets to see significant effects.

Table 1: The kinematic cuts used in calculations of the dijet cross section in the ultra-peripheral Pb-Pb collisions.

CM energy	$\sqrt{s} = 5.1\,\mathrm{TeV}$
rapidity	$0 < y_1, y_2 < 5$
transverse momentum	$p_{T1}, p_{T2} > p_{T0},\ p_{T0} = 25,\ 10,\ 6\,\mathrm{GeV}$

In the present report we shall concentrate on the results for nuclear modification ratios defined as $R_{\gamma A} = d\sigma_{AA}^{UPC} / A d\sigma_{Ap}^{UPC}$ that is, the photon flux in both numerator and denominator originates from a nucleus. More results are given in our original work [7]. In Fig. 2 we present the results for $R_{\gamma A}$ as a function of the azimuthal angle between the dijets. Again, the maximal suppression for 6 GeV jets in the back-to-back region is about 20%. The Sudakov resummation model widens the suppression towards smaller $\Delta\phi$. In Fig. 3 we show $R_{\gamma A}$ as a function of the p_T of jets (for the leading and subleading jets). We see that the maximal suppression is about 20% for p_T of jets as low as $\sim$ 6 GeV. Interestingly, the leading twist nuclear shadowing model [21] predicts similar overall suppression, but the slope is different. The Sudakov resummation model changes the spectra only slightly, especially for the subleading jet.

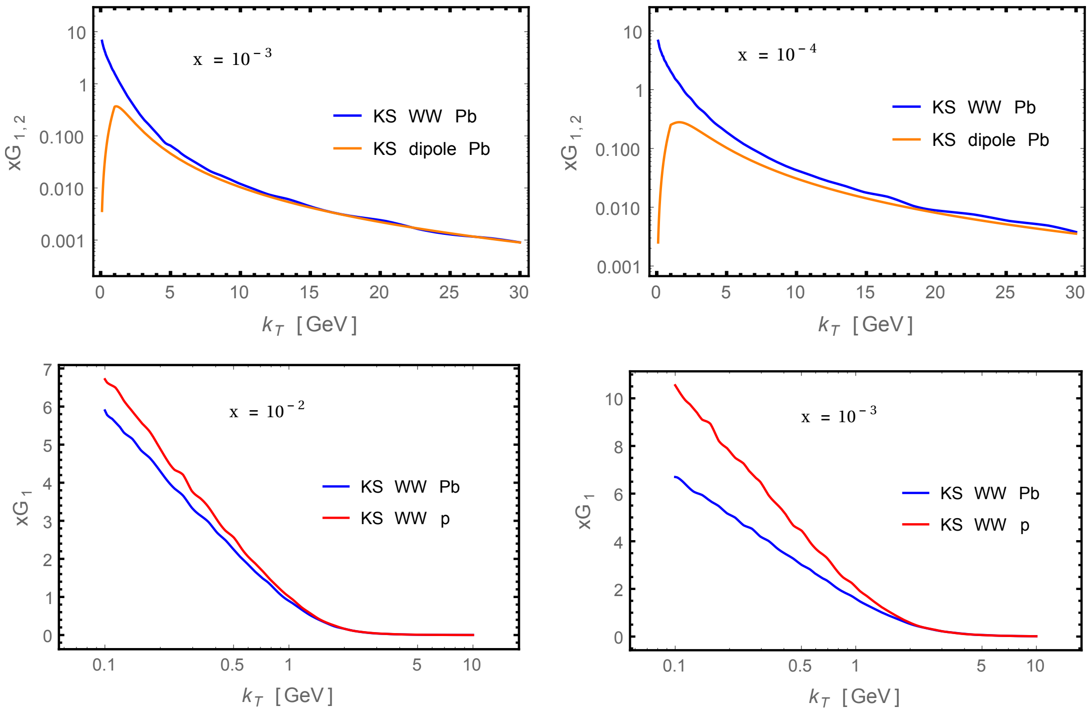

Fig. 1: The Weizsäcker-Williams (WW) unintegrated gluon distributions for proton and lead obtained from the KS dipole distributions [20]. The top row compares the WW UGD for Pb with the dipole UGD for Pb for two values of x. The bottom row shows the WW UGD for proton and lead as a function of k_T for two values of x.

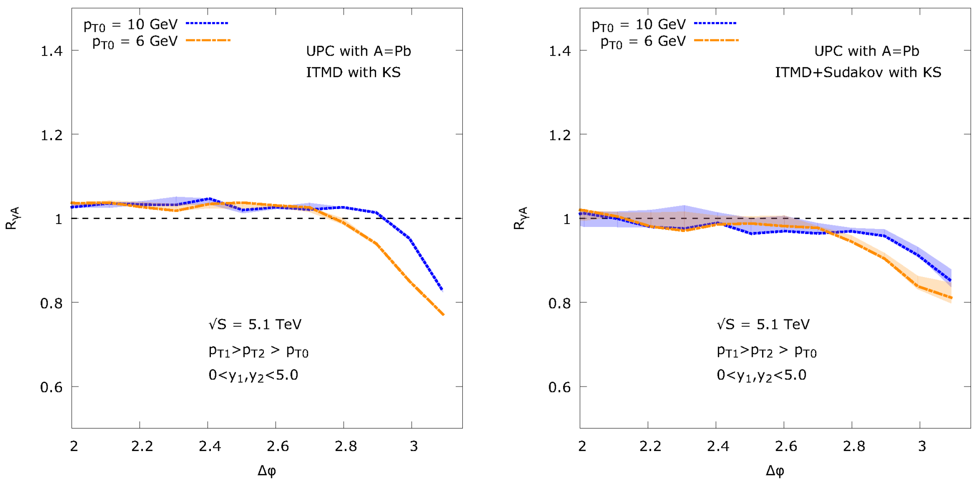

Fig. 2: Nuclear modification ratio as a function of the azimuthal angle between the jets, with (right) and without (left) the Sudakov resummation model.

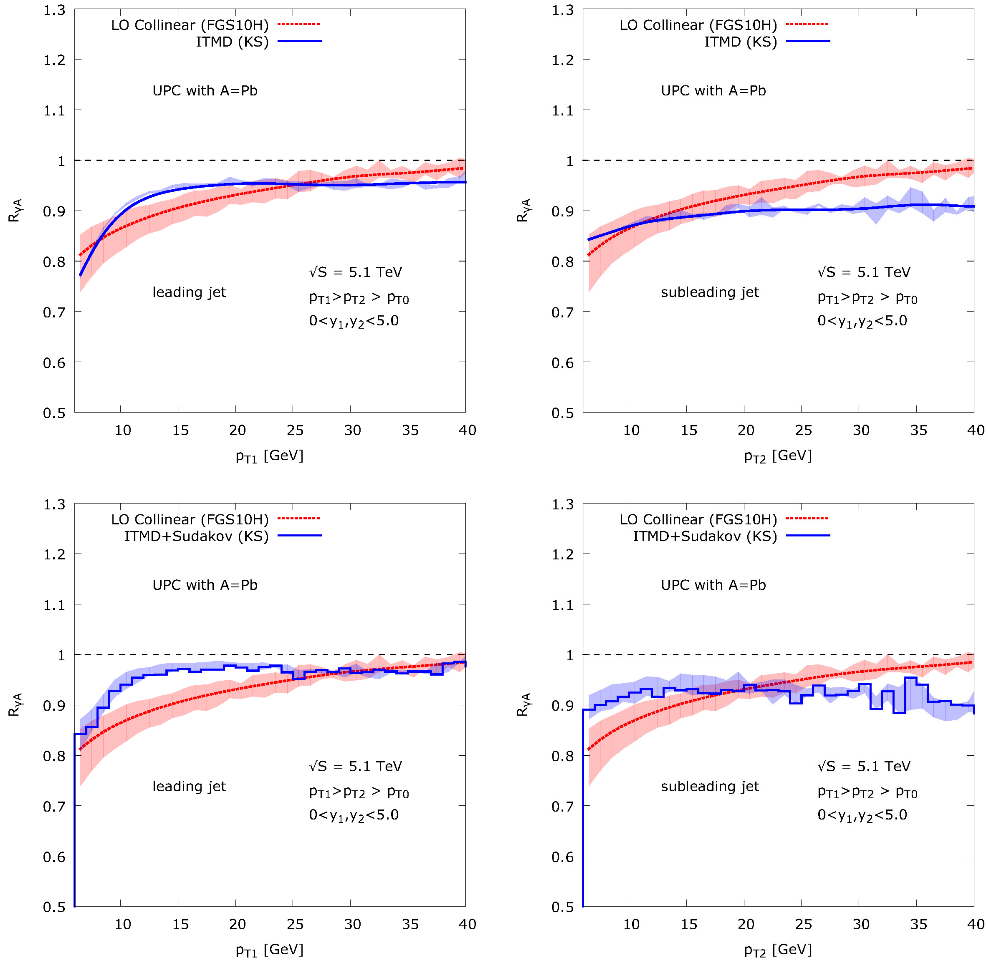

Fig. 3: Nuclear modification ratios as a function of the transverse momenta for leading (left column) and subleading (right column) jets. The bottom row shows the effect of the Sudakov resummation model applied to the generated events. For comparison we show the results from the LO collinear factorization using nuclear PDFs with the leading twist nuclear shadowing.

4 Conclusions

We have calculated the direct component of the dijet production cross section in ultra-peripheral heavy ion collision at LHC. Such process is sensitive to the Weizsäcker-Williams (WW) unintegrated gluon distribution (UGD) of nucleus, which is basically unknown from the data. According to our calculations with the approximate WW UGD obtained from the data-restricted dipole UGD using the Gaussian approximation, the saturation effects are visible, though moderate. Due to the saturation, we observe a suppression of γA differential cross sections comparing to γp of about 20% in the approximately back-to-back region for the jets with p_T 6-10 GeV. Similar effects are however observed for a different mechanism then saturation, namely the leading twist nuclear shadowing.

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