Photon-Hadron Interactions in pA/AA Collisions and the QCD Dynamics

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In this contribution we study the photoproduction of heavy quarks in coherent proton-nucleus (pA) and nucleus-nucleus (AA) interactions for RHIC and LHC energies and analyze if this process can be used to determine the QCD dynamics at high energies. The integrated cross section and rapidity distribution are estimated. Our results indicate that the nonlinear dynamics can be proven in those reactions, which are well suited for studing saturation effects.

Keywords: Ultraperipheral heavy ion collisions; QCD dynamics; Small-x Physics

I. INTRODUCTION

Over the last decade much progress has been realized towards understanding the QCD dynamics at high energies. The successful operation of the DESY *ep* collider HERA has opened a new era of experimental and theoretical investigation into the deep structure of the proton and, in general, of hadronic interactions. Some of the most important observations are the striking rise of the proton structure function $F_2(x,Q^2)$ for small values of the Bjorken variable x ($< 10^{-2}$), the large contribution of diffractive processes in this kinematical range and the geometric scaling (For a recent review, see e.g. Ref. [1]). Theoretically, at small x, due to the large gluon density, we expect the transition of the regime described by the linear dynamics, where only the parton emissions are considered, for a new regime where the physical process of recombination of partons become important in the parton cascade and the evolution is given by a nonlinear evolution equation. This regime is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wavefunction (parton saturation), with the transition being specified by a typical scale, which is energy dependent and is called saturation scale Q_{sat} (For recent reviews see Ref. [2]). Although the HERA experimental results have a natural interpretation in terms of the saturation physics, due to the kinematical limitations of the experiment none of these phenomena can be taken as a conclusive evidence for a new regime of the QCD dynamics. Currently, the HERA II run has obtained much more precise experimental data, but they are limited at center of mass energies smaller than 300 GeV, where deviations between linear and saturation predictions are small. Consequently, our understanding of the correct QCD dynamics at high energies is still an open question. As HERA will stop its operations, in principle, in 2007, and the QCD dynamics must be known as precisely as possible in order to maximize the discovery potential for new physics at the next generation of colliders, the study of alternatives which could constrain the QCD dynamics is timely and necessary.

In this contribution we summarize our studies about the photoproduction of heavy quarks in coherent proton-nucleus (pA) and nucleus-nucleus (AA) interactions at RHIC and LHC energies [3, 4] and analyze if this process can be used to determine the QCD dynamics at high energies (For similar studies on pp collisions, see Ref. [5]). The main advantage of using colliding hadron and nuclear beams for studying photon induced interactions is the high equivalent photon energies and luminosities that can be achieved at existing and future accelerators.

II. COHERENT pA/AA INTERACTIONS

Lets start considering the proton-nucleus interaction at large impact parameter ($b > R_p + R_A$) and at ultrarelativistic energies. In this regime we expect the electromagnetic interaction to be dominant. When we consider the electromagnetic field associated to the proton and ion, we have that due to the coherent action of all protons in the nucleus, the electromagnetic field surrounding the ion is very larger than the proton one. This result can be easily understood if we use the Weiszäcker-Williams method to calculate the equivalent flux of photons from a charge Z nucleus a distance b away, which is given by (For recent reviews see Ref. [7])

$$\frac{d^3N_\gamma(\omega,b^2)}{d\omega\, d^2b} = \frac{Z^2\alpha_{em}\eta^2}{\pi^2\,\omega\, b^2}\left[K_1^2(\eta) + \frac{1}{\gamma_L^2}K_0^2(\eta)\right] \quad (1)$$

where ω is the photon energy, γ_L is the Lorentz boost of a single beam and $\eta = \omega b/\gamma_L$; $K_0(\eta)$ and $K_1(\eta)$ are the modified Bessel functions. From the above expression we have that photon spectrum of a nucleus with charge Z is proportional to Z^2. Due to asymmetry in the collision, with the ion being likely the photon emitter, we have that the photon direction is known, which will implicate an asymmetry in the rapidity distribution (see below). The coherence condition limits the photon virtuality to very low values ($Q^2 \leq 1/R_A^2$), which implies that for most purposes, these can be considered as real. Therefore, coherent pA collisions can be used in order to study photon-proton interactions.

The requirement that photoproduction is not accompanied by hadronic interaction (ultraperipheral collision) can be done by restricting the impact parameter b to be larger than the sum of the proton and the nuclear radius. Therefore, the total photon flux interacting with the target nucleus is given by Eq. (1) integrated over the transverse area of the target for all impact parameters subject to the constraint that the proton and the nucleus do not interact hadronically. An analytic approximation for pA collisions can be obtained using as integration limit $b > R_p + R_A$, producing [7]

$$\frac{dN_\gamma(\omega)}{d\omega} = \frac{2Z^2\alpha_{em}}{\pi\omega}\left[\bar{\eta}K_0(\bar{\eta})K_1(\bar{\eta}) + \frac{\bar{\eta}^2}{2}\,\mathcal{U}(\bar{\eta})\right] \quad (2)$$

where $\bar{\eta} = \omega(R_p + R_A)/\gamma_L$ and $\mathcal{U}(\bar{\eta}) = K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})$. The cross section for the photoproduction of a final state X in a coherent pA collisions will be given by,

$$\sigma(Ap \to XY) = \int_{\omega_{min}}^{\infty} d\omega \frac{dN_\gamma(\omega)}{d\omega}\,\sigma_{\gamma p \to XY}\left(W_{\gamma p}^2\right), \quad (3)$$

where $\omega_{min} = M_X^2/4\gamma_L m_p$, $W_{\gamma p}^2 = 2\,\omega\sqrt{S_{\rm NN}}$ and $\sqrt{S_{\rm NN}}$ is the c.m.s energy of the proton-nucleus system. Considering $pPb\,(Ar)$ collisions at LHC, the Lorentz factor is $\gamma_L = 4690\,(5000)$, giving the maximum c.m.s. γN energy $W_{\gamma p} \approx 1500\,(2130)$ GeV. Therefore, while studies of photoproduction at HERA are limited to photon-proton center of mass energies of about 200 GeV, photon-proton interactions at LHC can reach one order of magnitude higher on energy. Consequently, studies of γp interactions at LHC could provide valuable information on the QCD dynamics at high energies. In contrast, in ultraperipheral heavy ion collisions we have a photon-nucleus interaction, which allows to probe the modifications in the QCD dynamics associated to the nuclear medium. In this case, the Lorentz factor for LHC is $\gamma_L = 2930$, giving the maximum c.m.s. γA energy $W_{\gamma A} \leq 950$ GeV. Moreover, the impact parameter b should be larger than twice the nuclear radius and $\bar{\eta} = 2\omega R_A/\gamma_L$. Although the maximum center of mass energy in ultraperipheral heavy ion collision is smaller than in pA interactions, it is an important alternative to study the saturation physics, since the saturation scale grows with a power of the atomic number (see below).

In this work we consider that the produced state X represents a $Q\overline{Q}$ pair. Since photon emission is coherent over the entire nucleus and the photon is colorless we expect that the events to be characterized by one rapidity gap, with Y being the remaining of the proton.

III. QCD DYNAMICS AT HIGH ENERGIES

The photon-hadron (nucleus) interaction at high energy (small x) is usually described in the infinite momentum frame of the hadron in terms of the scattering of the photon off a sea quark, which is typically emitted by the small-x gluons in the proton. However, in order to disentangle the small-x dynamics of the hadron wavefunction, it is more adequate to consider the photon-hadron scattering in the dipole frame, in which most of the energy is carried by the hadron, while the photon has just enough energy to dissociate into a quark-antiquark pair before the scattering. In this representation the probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation r long after the interaction, which then scatters off the target [8]. The main motivation to use this color dipole approach, is that it gives a simple unified picture of inclusive and diffractive processes. In particular, in this approach the heavy quark photoproduction cross section reads as,

$$\sigma(\gamma p(A) \to Q\overline{Q}X) = \sum_{h,\bar{h}}\int dz\, d^2r\, \Psi^\gamma_{h,\bar{h}}\,\sigma_{dip}(x,r)\,\Psi^{\gamma *}_{h,\bar{h}} \quad (4)$$

where $\Psi^\gamma_{h,\bar{h}}(z,\,r)$ is the light-cone wavefunction of the photon [8]. The quark and antiquark helicities are labeled by h and $\bar{h}$. The variable r defines the relative transverse separation of the pair (dipole) and z $(1-z)$ is the longitudinal momentum fractions of the quark (antiquark). The basic blocks are the photon wavefunction, Ψ^γ and the dipole-target cross section, σ_{dip}. For photoproduction we have that longitudinal piece does not contribute, since $|\Psi_L|^2 \propto Q^2$, and the total cross section is computed introducing the appropriated mass and charge of the charm or bottom quark.

We have that the total cross sections for heavy quark production in dipole approach are strongly dependent on the dipole-hadron cross section σ_{dip}, which contains all information about the target and the strong interaction physics. In the Color Glass Condensate (CGC) formalism [10–12], σ_{dip} can be computed in the eikonal approximation, resulting

$$\sigma_{dip}(x,r) = 2\int d^2b_\perp\,\left[1 - \mathrm{S}\,(x,r,b_\perp)\right], \quad (5)$$

where S is the S-matrix element which encodes all the information about the hadronic scattering, and thus about the non-linear and quantum effects in the hadron wave function. The function S can be obtained by solving an appropriate evolution equation in the rapidity $y \equiv \ln(1/x)$. The main properties of S are: (a) for the interaction of a small dipole ($r \ll 1/Q_{\rm sat}$), $S(r) \approx 1$, which characterizes that this system is weakly interacting; (b) for a large dipole ($r \gg 1/Q_{\rm sat}$), the system is strongly absorbed which implies $S(r) \ll 1$. This property is associate to the large density of saturated gluons in the hadron wave function. In our analysis of heavy quark production in coherent pA interactions we will consider the phenomenological saturation model proposed in Ref. [13] which encodes the main properties of the saturation approaches, with the dipole cross section parameterized as follows

$$\sigma_{dip}^{\rm CGC}(x,r) = \sigma_0 \begin{cases} \mathcal{N}_0\left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\rm eff}(x,r)}, & \text{for } \bar{\tau} \leq 2, \\ 1 - \exp\left[-a\ln^2(b\,\bar{\tau})\right], & \text{for } \bar{\tau} > 2, \end{cases}$$

where $\bar{\tau} = rQ_{\rm sat}(x)$ and the expression for $\bar{\tau} > 2$ (saturation region) has the correct functional form, as obtained from the theory of the Color Glass Condensate (CGC) [10]. For the color transparency region near saturation border ($\bar{\tau} \leq 2$), the behavior is driven by the effective anomalous dimension

$\gamma_{\rm eff}(x,r) = \gamma_{\rm sat} + \frac{\ln(2/\tilde{\tau})}{\kappa\lambda y}$, where $\gamma_{\rm sat} = 0.63$ is the LO BFKL anomalous dimension at saturation limit. Hereafter, we label this model by CGC. Furthermore, for our analysis of photonuclear production of heavy quarks in ultraperipheral heavy ion collisions we will consider distinct available high energy approaches besides the useful collinear approach [3]: the semihard formalism and the saturation model generalized to photonuclear collisions. In the $k_\perp$-factorization (semihard) approach, the relevant QCD diagrams are considered with the virtualities and polarizations of the initial partons, carrying information on their transverse momenta. The scattering processes are described through the convolution of off-shell matrix elements with the unintegrated parton distribution, $\mathcal{F}(x,k_\perp)$. Considering only the direct component of the photon, the cross section reads as [14],

$$\sigma_{tot}^{\gamma p(A)} = \frac{\alpha_{em}\, e_Q^2}{\pi} \int dz\, d^2p_{1\perp}\, d^2k_\perp\, \frac{\alpha_s\, \mathcal{F}(x,k_\perp^2)}{k_\perp^2} \times$$
$$\left\{ A(z) \left(\frac{p_{1\perp}}{D_1} + \frac{(k_\perp - p_{1\perp})}{D_2} \right)^2 + m_Q^2 \left(\frac{1}{D_1} + \frac{1}{D_2} \right)^2 \right\}$$

where $D_1 \equiv p_{1\perp}^2 + m_Q^2$ and $D_2 \equiv (k_\perp - p_{1\perp})^2 + m_Q^2$ and $A(z) = [z^2 + (1-z)^2]$. The transverse momenta of the heavy quark (antiquark) are denoted by $p_{1\perp}$ and $p_{2\perp} = (k_\perp - p_{1\perp})$, respectively. The heavy quark longitudinal momentum fraction is labeled by z. For the scale μ in the strong coupling constant we use the prescription $\mu^2 = k_\perp^2 + m_Q^2$. We use also the simple ansatz for the unintegrated gluon distributions, $\mathcal{F}_{\rm nuc} = \frac{\partial xG_A(x,k_\perp^2)}{\partial \ln k_\perp^2}$ where $xG_A(x,Q^2)$ is the nuclear gluon distribution (see [3] for details in the numerical calculations). We also consider an extension of the ep saturation model [15] through Glauber-Gribov formalism for photonuclear collisions. In this model the nuclear dipole cross section is given by [16],

$$\sigma_{dip}^{A}(\tilde{x}, r^2, A) = \int d^2b\, 2 \left\{ 1 - \exp\left[-\frac{1}{2} A\, T_A(b)\, \sigma_{dip}^{p}(\tilde{x}, r^2) \right] \right\},$$

where b is the impact parameter of the center of the dipole relative to the center of the nucleus and the integrand gives the total dipole-nucleus cross section for fixed impact parameter. The nuclear profile function is labelled by $T_A(b)$. The parameterization for the dipole cross section takes the eikonal-like form, $\sigma_{dip}^{p}(\tilde{x}, r^2) = \sigma_0 \left[1 - \exp\left(-Q_s^2(\tilde{x})\, r^2/4 \right) \right]$, where one has used the parameters from saturation model, which include the charm quark with mass $m_c = 1.5$ GeV and the definition $\tilde{x} = (Q^2 + 4m_Q^2)/W_{\gamma A}^2$. The saturation scale $Q_s^2(x) = (x_0/x)^\lambda$ GeV^2, gives the onset of the saturation phenomenon to the process. The equation above sums up all the multiple elastic rescattering diagrams of the $q\bar{q}$ pair and is justified for large coherence length, where the transverse separation r of partons in the multiparton Fock state of the photon becomes as good a conserved quantity as the angular momentum, namely the size of the pair r becomes eigenvalue of the scattering matrix.

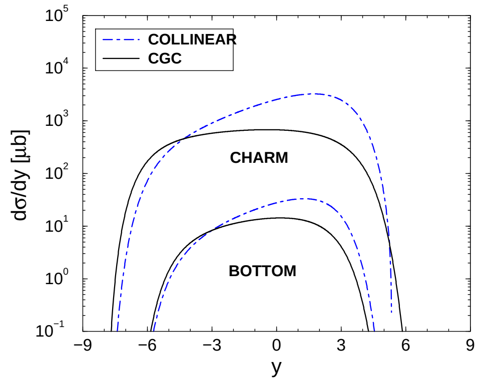

FIG. 1: Rapidity distribution for heavy quark photoproduction on pA reactions for LHC energy (see text).

IV. RESULTS

The distribution on rapidity y of the produced final state can be directly computed from Eq. (3), by using its relation with the photon energy ω, i.e. $y \propto \ln(2\omega/m_X)$. Explicitly, the rapidity distribution is written down as,

$$\frac{d\sigma\,[A + p(A) \to X + Y]}{dy} = \omega \frac{dN_\gamma(\omega)}{d\omega}\, \sigma_{\gamma p(A) \to XY}(\omega)\,. \quad (6)$$

Consequently, given the photon flux, the rapidity distribution is thus a direct measure of the photoproduction cross section for a given energy. In Fig. 1 we present our results for the heavy quark photoproduction at LHC energies. For comparison, we also present the predictions from the linear dynamics, denoted collinear hereafter, which is calculated assuming that the collinear factorization is valid and that the gluon distribution can be described by the GRV98 parametrization (For more details see Ref. [5]). In Tab. I one presents the correspondent integrated cross sections (event rates), using a luminosity of $\mathcal{L}_{\rm pPb} = 7.4 \times 10^{29}$ cm^{2}s^{-1}. We have verified for completeness that for RHIC energy the difference between the predictions for the rapidity distribution is small, which is expect due to small value of the photon-proton center of mass energy. However, at LHC we can observe a large difference between the predictions and having high rates. For instance, for charm quark CGC gives a cross section a factor 3 lower than collinear and a factor 2 for bottom. This deviation holds even in case of experimental cuts on rapidity. Therefore, photoproduction of heavy quarks should provide a feasible and clear measurement of the underlying QCD dynamics at high energies. Since RHIC is obtaining data for dAu interactions and LHC is to be commissioned, these processes could be analyzed in the next years. The advantages are a clear final state (rapidity gap and low momenta particles) and no competing effect of dense nuclear environment if compared with hadroproduction.

The present results can be directly compared with those obtained in Ref. [17], which use only collinear approach. The orders of magnitude are similar for RHIC and LHC, with main deviations coming from different choices for the gluon pdfs

	X	**COLLINEAR**	**CGC**
LHC	$c\bar{c}$	17 mb (10^{10})	5 mb ($1 \cdot 10^9$)
	$b\bar{b}$	155 μb (10^8)	81 μb ($6 \cdot 10^7$)

TABLE I: *The integrated cross section (event rates/month) for the photoproduction of heavy quarks in pA collisions at LHC.*

$Q\overline{Q}$	**Collinear**	**SAT-MOD**	**SEMIHARD I (II)**
$c\bar{c}$	2056 mb	862 mb	2079 (1679.3) mb
$b\bar{b}$	20.1 mb	10.75 mb	18 (15.5) mb

TABLE II: *The photonuclear heavy quark total cross sections for ultraperipheral heavy ion collisions at LHC ($\sqrt{S_{\rm NN}} = 5500$ GeV) for PbPb.*

and distinct factorization scale. Our estimates considering CGC (collinear) for RHIC are 142 (110) μb for charm and 0.15 (0.10) μb for bottom. The rapidity distributions can be also contrasted with estimations in Refs. [3, 5], where the heavy quark photoproduction in AA and pp collisions have been computed. To see what is difference in the order of magnitude among them let us perform a few parametric estimates. Roughly, the photon flux on nuclei is approximately Z^2 the flux on proton, $dN_\gamma^A/d\omega \propto Z^2\, dN_\gamma^p/d\omega$. Moreover, for heavy quarks have been not verified large nuclear shadowing [3] such that $\sigma_{\gamma A} \approx A\,\sigma_{\gamma p}$. The ratio between pA production and pp (or AA) can be estimated as $R_{pA/pp(AA)} = \frac{d\sigma_{pA}/dy}{d\sigma_{pp(AA)}/dy}$. Therefore, using Eq. (6), one obtains $R_{pA/pp} \propto Z^2$ and the enhancement reaches a factor 10^4 for heavy nuclei in the comparison between photoproduction on pA and in energetic protons. On the other hand, one obtains $R_{pA/AA} \propto A^{-1}$ and then pA is suppressed in relation to AA by a factor A. However, the larger pA luminosity, which is two order of magnitude higher than for AA, counteracts this suppression for the event rates.

Finally, let us now compute the integrated cross section for heavy quark production in ultraperipheral heavy ion collisions considering the distinct models (For a detailed analyzes of the rapidity distribution see [3]). The results are presented in Table II for charm and bottom pair production. The collinear approach gives a larger rate, followed by the semihard approach. The saturation model gives a closer ratio for charm to bottom production. we have that the photonuclear production of heavy quarks allow us to constraint already in the current nuclear accelerators the QCD dynamics since the main features from photon-nuclei collisions hold in the coherent ultraperipheral reactions.

V. SUMMARY

The QCD dynamics at high energies is of utmost importance for building a realistic description of $pp/pA/AA$ collisions at LHC. In this limit QCD evolution leads to a system with high gluon density. We have shown if such system there exists at high energies it can be proven in coherent pA collisions at LHC. We propose one specific final state (heavy quarks) where the experimental identification could be feasible.

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