Small-x Physics at Coherent pA/AA Interactions at LHC

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We report on our recent investigations in photonuclear production of heavy quarks and vector mesons in ultraperipheral collisions at nucleus-nucleus and proton-nucleus reactions. They are initiated by quasi-real photons coming from one of the nuclei or hadron in interactions taking place at large impact parameter. We focus on the role played by the high energy theoretical/phenomenological approaches in photon-nuclei scattering, namely the strength of parton saturation phenomenon and high energy nuclear shadowing. In particular, our theoretical predictions are compared with the recent experimental measurements on coherent ρ (STAR) and J/Ψ (PHENIX) photoproduction at RHIC and estimates for LHC are given.

Keywords: Heavy Ion Collisions; Quantum Chromodynamics; Parton Saturation Effects

I. INTRODUCTION

In the last years, there has been a lot of interest in the description of electron-nucleus collisions at high energies. The results of current analysis show that future electron-nucleus colliders at HERA and RHIC, probably could determine whether parton distributions saturate and constrain the behavior of the nuclear gluon distribution in the full kinematical range [1, 2]. However, until these colliders become reality we need to consider alternative searches in the current and/or scheduled accelerators which allow us to constrain the QCD dynamics. In this contribution, we summarize our investigations in Refs. [3–5] about the possibility of using ultraperipheral heavy ion collisions (UPC's) as a photonuclear collider and study the heavy quark and/or vector meson production assuming distinct approaches for the QCD evolution.

A special class of events in nucleus-nucleus (or proton-nucleus) reactions at high energies is their coherent interaction. The scatterings take place at larger impact parameter of the collision, $b \gg R_A + R_B$, where R_i are the radii of the interacting nuclei (or charged hadrons), $i = A, B$. This is the reason they are called ultraperipheral collisions. The final state is characterized by low particle multiplicity and dominance of low-p_T transverse momenta. The interaction between the nuclei is predominantly electromagnetic in this case, where they have an associated flux of equivalent (quasi-real) photons. This flux is computed through the quantity called number of equivalent photons, $dN/d\omega$, where ω is the center of mass photon energy. Then, real-photons from one of nuclei initiate photonuclar reactions. In heavy ion collisions, the large number of photons coming from colliding nuclei will allow to study photoproduction, with energies $W_{\gamma A}$ reaching about 1 TeV at LHC. 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 $\gamma p(A)$ interactions at LHC could provide valuable information on the QCD dynamics at high energies. The photonuclear cross section for coherent nucleus-nucleus collisions is given by the convolution between the photon flux from one of the nuclei and the cross section for the photon-nucleus scattering. The expression for the production of a given final state Y ($Y = Q\overline{Q}, V$) ultraperipheral heavy ion collisions is then given by,

$$\sigma_{AA\to AYX}\left(\sqrt{S_{\rm NN}}\right) = \int_{\omega_{min}}^{\infty} d\omega\, \frac{dN(\omega)}{d\omega}\, \sigma_{\gamma A\to YX}\left(W_{\gamma A}\right), \quad (1)$$

where $\omega_{min} = M_Y^2/4\gamma_L m_p$, $\sqrt{S_{\rm NN}}$ is the c.m.s energy of the nucleus-nucleus system and γ_L is the Lorentz boost of a single beam. The Lorentz factor for LHC is $\gamma_L = 2930$, giving the maximum c.m.s. γA energy $W_{\gamma A} \leq 950$ GeV. For the case of coherent proton-nucleus collision, where the real-photons from the nucleus interacts with a proton, we now have,

$$\sigma_{pA\to YX}\left(\sqrt{S_{\rm pN}}\right) = \int_{\omega_{min}}^{\infty} d\omega\, \frac{dN(\omega)}{d\omega}\, \sigma_{\gamma p\to YX}\left(W_{\gamma p}\right). \quad (2)$$

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 twice the nuclear radius, $R_A = 1.2A^{1/3}$ fm, in the AA case and than $(R_p + R_A)$ in the pA case. An analytic approximation for AA collisions can be obtained using as integration limit $b > 2R_A$, producing

$$\frac{dN}{d\omega} = \frac{2Z^2\alpha_{em}}{\pi\omega}\left[\bar{\eta}K_0(\bar{\eta})K_1(\bar{\eta}) + \frac{\bar{\eta}^2}{2}\left(K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})\right)\right], (3)$$

where $\bar{\eta} = 2\omega R_A/\gamma_L$ for nucleus-nucleus and $\bar{\eta} = \omega(R_p + R_A)/\gamma_L$ for proton-nucleus. The quantities $K_{0,1}(x)$ are the modified Bessel functions. Therefore, the main ingredient for computing the production of the specific final state Y at UPC's is the information about its cross section in photon-nuclei interactions, $\sigma_{\gamma A\to YX}$, as defined in Eq. 1 or in photon-proton interactions, $\sigma_{\gamma p\to YX}$, as defined in Eq. 2. In what follows, we perform phenomenology on heavy quarks and vector mesons production using the available high energy approaches. The emphasis is placed in the energies and experimental cuts for LHC.

II. HEAVY QUARK PRODUCTION

For our further analysis on photonuclear production of heavy quarks we will consider distinct high energy approaches, which are contrasted against the collinear approach [3]: (a) semihard formalism, (b) saturation model (within the color dipole formalism) and (c) Color Glass Condensate (CGC) approach. The main goal is a comparison among those approaches and show whether the production at UPC's allows disentangle the underlying QCD dynamics at high energies.

(a) *Semihard formalism*: 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 (See, e.g. Ref. [6]),

$$\sigma^{\text{semihard}}_{\gamma A\to Q\bar{Q}X} = \frac{\alpha_{em}\, e_Q^2}{\pi}\int dz\, d^2p_{1\perp}\, d^2k_\perp\, \frac{\alpha_s\,\mathcal{F}_{\text{nuc}}(x,k_\perp^2)}{k_\perp^2}\times \left\{A(z)\left(\frac{p_{1\perp}}{D_1}+\frac{(k_\perp-p_{1\perp})}{D_2}\right)^2 + m_Q^2\left(\frac{1}{D_1}+\frac{1}{D_2}\right)^2\right\} \quad (4)$$

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, $\mathcal{F}_{\text{nuc}}=\frac{\partial xG_A(x,k_\perp^2)}{\partial \ln k_\perp^2}$ where $xG_A(x,Q^2)$ is the nuclear gluon distribution (see Ref. [3] for details in the numerical calculations).

(b) *Saturation model*: Based on the color dipole formalism, it can be extended to eA through Glauber-Gribov formalism. In this model the cross section for the heavy quark photoproduction on nuclei targets is given by [7, 8],

$$\sigma^{\text{dipole}}_{\gamma A\to Q\bar{Q}X} = \int_0^1 dz\int d^2r\,|\Psi_T(z,r,Q=0)|^2\,\sigma^{\text{A}}_{dip}(\tilde{x},r;A)\,, \quad (5)$$

where the transverse wave function is known [8, 9]. The nuclear dipole cross section is given by [7, 8],

$$\sigma^{\text{A}}_{dip} = 2\int d^2b\left\{1-\exp\left[-\frac{1}{2}A\,T_A(b)\,\sigma^{\text{p}}_{dip}(\tilde{x},r^2)\right]\right\}\,, \quad (6)$$

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 labeled by $T_A(b)$. The parameterization for the dipole cross section takes the eikonal-like form, $\sigma_{dip}^{\text{SAT-MOD}}(\tilde{x},r^2)=\sigma_0\left[1-\exp\left(-Q_s^2(\tilde{x})\,r^2/4\right)\right]$, 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.

(c) *Color Glass Condensate*: The regime of a CGC is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron/nuclear wavefunction (parton saturation) and very high values of the QCD field strength $F_{\mu\nu}\approx 1/\alpha_s$ (For a review see, e.g, [1]). The large values of the gluon distribution at saturation suggests the use of semi-classical methods, which allow to describe the small-x gluons inside a fast moving nucleus by a classical color field. For our phenomenological purpose here, one takes a parameterization for the dipole cross section which takes into account the main features of the CGC theory. It reads as [10],

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

where $\bar{\tau}=rQ_{\text{sat}}(x)$ 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) [1]. For the color transparency region near saturation border ($\bar{\tau}\le 2$), the behavior is driven by the effective anomalous dimension $\gamma_{\text{eff}}(x,r)=\gamma_{\text{sat}}+\frac{\ln(2/\bar{\tau})}{\kappa\lambda y}$, where $\gamma_{\text{sat}}=0.63$ is the LO BFKL anomalous dimension at saturation limit.

Having summarized the theoretical models, let us present the numerical calculation of their total cross section at UPC's in nucleus-nucleus collisions. We focus mostly on LHC domain where small values of x would be probed. In the following, one considers the charm and bottom masses $m_c=1.5$ GeV and $m_b=4.5$ GeV , respectively. Moreover, for PbPb collisions at LHC, one has the c.m.s. energy of the ion-ion system $\sqrt{S_{\text{NN}}}=5500$ GeV. The results are presented in Table I. The collinear approach gives a larger rate, followed by the semihard approach (using GRV98 gluon pdf's). The saturation model and CGC formalisms give similar results, including a closer ratio for charm to bottom production. Concerning the CGC approach, our phenomenological educated guess for the color field correlator seems to produce quite reliable estimates. Therefore, the photonuclear production of heavy quarks allow us to constrain already in the current nuclear accelerators the QCD dynamics since the main features from photon-nuclei collisions hold in the UPC reactions. It should

	$Q\bar{Q}$	**Collinear**	**SAT-MOD**	**SEMIHARD**	**CGC**
AA	$c\bar{c}$	2056 mb	862 mb	1679 mb	633 mb
	$b\bar{b}$	20 mb	11 mb	16 mb	9 mb
pA	$c\bar{c}$	17 mb	–	–	5 mb
	$b\bar{b}$	155 μb	–	–	81 μb

TABLE I: *Heavy quark integrated cross sections for coherent AA and pA interactions at LHC.*

	HEAVY ION	$J/\Psi\,(3097)$	$\phi\,(1019)$	$\omega\,(782)$	$\rho\,(770)$
AA	Ca	436 μb	12 mb	14 mb	128 mb
	Pb	41.5 mb	998 mb	1131 mb	10069 mb
pA	Pb	95 μb	–	–	14mb

TABLE II: *Integrated cross sections for vector meson production in coherent AA and pA interactions at LHC energy.*

be noticed that we have computed the integrated cross section by integrating all rapidities. Experimental cuts should diminish their magnitude, but they are still large. The experimental signal should be clear. 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 in heavy quark production. Finally, the CGC and color dipole calculations are more stable concerning changes in the quark mass (a few percent difference). Moreover, the value of central value for quark mass is determined by a fit to accelerator data rather than being a free parameter.

In Table I we also present the results for coherent proton-nucleus collisions at LHC. For comparison, we present the predictions from the linear dynamics (collinear), which is calculated assuming that the collinear factorization is valid and that the gluon distribution can be described by the GRV98 parameterization. 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. This has been verified in the case of vector meson production when considering experimental cuts [4]. 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.

III. VECTOR MESON PRODUCTION

Let us consider the scattering process $\gamma A \rightarrow VA$ in the QCD dipole approach, where V stands for both light and heavy mesons. The main motivation for using this approach is the easy intuitive interpretation and its successful data description in the proton case. The scattering process can be seen in the target rest frame as a succession in time of three factorizable subprocesses: i) the photon fluctuates in a quark-antiquark pair (the dipole), ii) this color dipole interacts with the target and, iii) the pair converts into vector meson final state. In the color dipole formalism, the corresponding imaginary part of the amplitude at zero momentum transfer reads as [13, 14],

$$Im\,\mathcal{A}_{\gamma A\rightarrow VA} = \sum_{h,\bar{h}} \int dz\, d^2r\, \Psi^{\gamma}_{h,\bar{h}},\sigma_{dip}^{\rm target}(\tilde{x},r)\,\Psi^{V*}_{h,\bar{h}}, \qquad (7)$$

where $\Psi^{\gamma}_{h,\bar{h}}(z,\,r)$ and $\Psi^{V}_{h,\bar{h}}(z,\,r)$ are the light-cone wavefunctions of the photon and vector meson, respectively. The quark and antiquark helicities are labeled by h and $\bar{h}$ and reference to the meson and photon helicities are implicitly understood. 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).

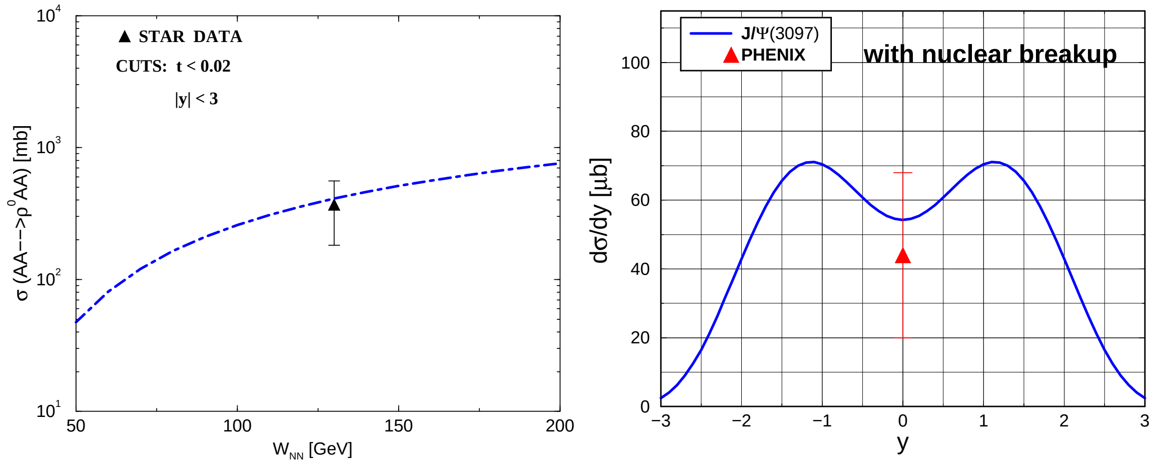
In the dipole formalism, the light-cone wavefunctions $\Psi_{h,\bar{h}}(z,\,r)$ in the mixed representation (z,r) can be completely determined using light cone perturbation theory. On the other hand, for vector mesons, the light-cone wavefunctions are not known in a systematic way and they are thus obtained through models (For a recent detailed discussion see Ref. [12]). Here we follows the analytically simple DGKP approach [15], which assumes that the dependencies on r and z of the wavefunction are factorised, with a Gaussian dependence on r. We keep the original parameters of the model. The main shortcoming of this approach is that it breaks the rotational invariance between transverse and longitudinally polarized vector mesons [12]. However, as it describes reasonably the HERA data for vector meson production, as pointed out in Ref. [16], we will use it here.

The corresponding parameters for the meson wavefunctions are presented in Table 1 of Ref. [11]. Following Ref. [14], we have estimated contribution from real part for the photoproduction of vector mesons: it is about 3% for light mesons and it reaches 13% for J/Ψ [11]. Additionally for heavy mesons we have taken into account the skewness effects, associated to off-forward features of the process, which are increasingly important in this case. Finally, the photonuclear cross section is given by

$$\sigma^{tot}_{\gamma A\rightarrow VA} = \frac{\left[Im\,\mathcal{A}_{\gamma A\rightarrow VA}\right]^2}{16\pi}\,(1+\beta^2)\int_{t_{min}}^{\infty} dt\,|F(t)|^2\,, \qquad (8)$$

with $t_{min} = (m_V^2/2\,\omega)^2$. The quantity β is the ratio between the imaginary and real part of the amplitude. We have used an analytical approximation[17] of the Woods-Saxon distribution as a hard sphere, with radius R_A, convoluted with a Yukawa potential with range $a = 0.7$ fm in order to compute the nuclear form factor, $F(t)$.

Recently, the STAR Collaboration at RHIC published the first experimental measurement of coherent ρ production in gold-gold UPC's at $\sqrt{s} = 130$ GeV [18]. The energy dependence of the cross section is presented in Fig 1-a. Our theoretical prediction in the curve takes into account the experimental cuts, which gives $\sigma_{\rm theory}(|y|\leq 3) = 410$ mb, in good agreement with the STAR measurement $\sigma_{\rm STAR}(|y|\leq 3) = 370\pm 170\,({\rm stat})\pm 80\,({\rm syst})$ mb. Furthermore, the PHENIX



(a) (b)

FIG. 1: (a) Energy dependence of coherent ρ photoproduction at RHIC. (b) Rapidity distribution of coherent J/Ψ photoproduction (with nuclear breakup) at RHIC (see text).

Collaboration has measurements of the cross section for coherent J/Ψ photoproduction in UPC at midrapidity at $\sqrt{s} =$ 200 GeV [19], accompanied by nuclear breakup. The rapidity distribution is shown in Fig 1-b in comparison with our prediction. The theoretical estimation gives $d\sigma/dy|_{y=0} = 58$ μb, which is in agreement with the PHENIX measurement $d\sigma_{\rm PHENIX}/dy|_{y=0} = 48 \pm 16\,({\rm stat}) \pm 18\,({\rm syst})$ μb. Finally, in Table II one shows the predictions for the integrated cross sections for coherent nucleus-nucleus interactions at LHC. The experimental feasibility and signal separation on the reaction channels presented here are reasonably clear, namely applying a (low) transverse momentum cut $p_T < 1$ GeV and two rapidity gaps in the final state for the meson case. In contrast, for heavy quarks we have only one rapidity gap.

In Table II we also present the result for coherent proton-nucleus reactions at LHC, considering both light (Ar) and heavy (Pb) ions. It should be noticed that the coherent production of mesons is currently measured at RHIC for the AA case. Therefore, the present estimation could be tested in dAu collisions with a good experimental feasibility. Disregarding the parton saturation phenomenon, we have that the predictions for J/Ψ production are somewhat similar to the linear pQCD approach, which is expected, since the heavy vector meson production is dominated by small pair separations, where the saturation physics does not contribute significantly. On the other hand, the photoproduction of ρ mesons is dominated by physics below saturation scale. The difference is huge, as shown in Ref. [5], reaching 3 orders of magnitude in rapidity distribution, which demonstrate the importance of the saturation physics on this process.

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