Heavy Quarks and Meson Production in Ultraperipheral Heavy Ion Collisions

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We report on our recent investigations in photonuclear production of heavy quarks and vector meson in ultraperipheral heavy ion collisions. 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: Quantum Chromodynamics, Ultraperipheral Heavy Ion Collisions; High Energy Dynamics.

1. 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 constraint 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 constraint the QCD dynamics. In this contribution, we summarize our investigations in Refs. \(^3,^4\) about the possibility of using ultraperipheral heavy ion collisions (UPC’s) as a photonuclear collider and study the heavy quark and vector meson production assuming distinct approaches for the QCD evolution.

In heavy ion collisions the large number of photons coming from one of the colliding nuclei will allow to study photoproduction, with energies \(W_{\gamma A}\) reaching to 950 GeV for the LHC. The photonuclear cross sections are given by the convolution between the photon flux from one of the nuclei and the cross section for the scattering photon-nuclei. The expression for the production of a given final state \(Y\)
\(Y = Q \overline{Q}, V\) ultraperipheral heavy ion collisions is then given by,

\[
\sigma_{AA \rightarrow AY X} \left(\sqrt{S_{\text{NN}}}\right) = \int_{\omega_{\text{min}}}^{\infty} d\omega \frac{dN(\omega)}{d\omega} \sigma_{\gamma A \rightarrow Y X} \left(W_{\gamma A}^2 = 2\omega \sqrt{S_{\text{NN}}}\right) \quad (1)
\]

where \(\omega_{\text{min}} = M_Y^2/4\gamma_L m_p, \sqrt{S_{\text{NN}}}\) is the c.m.s energy of the nucleus-nucleus system and \(\gamma_L\) is the Lorentz boost of a single beam. The Lorentz factor for LHC is \(\gamma_L = 2930\), giving the maximum c.m.s. energy \(W_{\gamma A} \leq 950\) GeV. 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, \(R_A = 1.2 A^{1/3}\) fm. An analytic approximation for \(AA\) collisions can be obtained using as integration limit \(b > 2 R_A\), producing

\[
\frac{dN(\omega)}{d\omega} = 2 Z^2 \alpha_{\text{em}} \pi \omega \left[ \bar{\eta} K_0 (\bar{\eta}) K_1 (\bar{\eta}) + \frac{\bar{\eta}^2}{2} \left(K_2 (\bar{\eta}) - K_0 (\bar{\eta}) \right) \right] \quad (2)
\]

where \(\bar{\eta} = 2\omega R_A/\gamma_L\) and \(K_{0,1}(x)\) 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, \(\sigma_{\gamma A \rightarrow Y X}\), as defined in Eq. 1. In what follows, we perform phenomenology on heavy quarks and vector mesons production using the available high energy approaches.

2. Photonuclear production of heavy quarks

For our further analysis on photonuclear production of heavy quarks we will consider distinct high energy approaches, which are contrasted against the collinear approach \(^3\): (i) semihard formalism, (ii) saturation model (within the color dipole formalism) and (iii) 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.

(i) **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. \(^5\)),

\[
\sigma_{\gamma A \rightarrow Q \overline{Q} X}^{\text{semihard}} = \frac{\alpha_{\text{em}} e_Q^2}{\pi} \int dz \, d^2 p_{1\perp} \, d^2 k_{\perp} \alpha_s \mathcal{F}_{\text{nucl}}(x, k_{\perp}) \left\{ A(z) \left( \frac{p_{1\perp}}{D_1} + \frac{(k_{\perp} - p_{1\perp})}{D_2} \right)^2 + m_Q^2 \left( \frac{1}{D_1} + \frac{1}{D_2} \right)^2 \right\} \quad (3)
\]

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 \( \mu \) in the strong coupling constant we use the prescription \( \mu^2 = k_1^2 + m_Q^2 \). We use also the simple ansatz for the unintegrated gluon distributions, \( F_{\text{nnuc}} = \frac{\partial xG_A(x, k_1^2)}{\partial \ln k_1^2} \) where \( xG_A(x, Q^2) \) is the nuclear gluon distribution (see Ref.\(^3\) for details in the numerical calculations).

(ii) **Saturation model:** Based on the color dipole formalism, it is an extension of the \( ep \) saturation model through Glauber-Gribov formalism. In this model the cross section for the heavy quark photoproduction on nuclei targets is given by \(^6,7\),

\[
\sigma_{\gamma A \rightarrow QQX}^{\text{dipole}} = \int_0^1 dz \int d^2r \left| \Psi_T(z, r, Q^2 = 0) \right|^2 \sigma_{\text{dip}}^\lambda(\tilde{x}, r^2, A),
\]

where the transverse wave function is known \(^7,8\). The nuclear dipole cross section is given by \(^6,7\),

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

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 labeled by \( T_A(b) \). The parameterization for the dipole cross section takes the eikonal-like form, \( \sigma_{\text{dip}}^\lambda(\tilde{x}, r^2) = \sigma_0 \left[ 1 - \exp \left( -Q_0^2(\tilde{x}) r^2/4 \right) \right] \), where one has used the parameters from saturation model, which include the charm quark with mass \( m_c = 1.5 \text{ GeV} \) and the definition \( \tilde{x} = (Q^2 + 4 m_Q^2)/W_A^2 \). The saturation scale \( Q_0^2(x) = (x \lambda)^3 \text{ GeV}^2 \), 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.

(iii) **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. In Refs. \(^9\) the heavy quark production in UPC’s has been analyzed in the CGC formalism. In Ref. \(^3\), we have improved that analysis using a realistic photon flux and a color field correlator including quantum radiation effects. The input photoproduction cross section reads as \(^3\),

\[
\sigma_{\gamma A \rightarrow QQX}^{\text{CGC}} = \frac{\alpha_{\text{em}} e_q^2}{2\pi^2} \int dk_+^2 \left[ \pi R_A^2(\lambda, k_+) \right] \left[ 1 + \frac{4(k_+^2 - m_Q^2)}{k_+ \sqrt{k_+^2 + 4m_Q^2}} \arctanh \frac{k_+}{\sqrt{k_+^2 + 4m_Q^2}} \right],
\]

where we define the rapidity \( Y \equiv \ln(1/x) = \ln(2\omega_\gamma \gamma_L/4m_Q^2) \) and \( e_q \) is the quark charge. In Ref. \(^3\), we obtained the following analytical expression for the color field
Table 1. The photonuclear heavy quark cross sections for UPC’s at LHC.

| $Q^2$ | Collinear | SAT-MOD | SEMIHARD I (H) | CGC |
|-------|-----------|---------|---------------|-----|
| $c\bar{c}$ | 2056 mb | 862 mb | 2079 (1679.3) mb | 633 mb |
| $b\bar{b}$ | 20.1 mb | 10.75 mb | 18 (15.5) mb | 8.9 mb |

correlator considering a suitable ansatz for the dipole-nucleus cross section,

$$\tilde{C}(x, k_\perp) = \frac{4\pi}{Q^2_{sA}(x)} \exp\left(-\frac{k^2_{\perp}}{Q^2_{sA}(x)}\right),$$

where we have assumed for the nuclear saturation scale, $Q^2_{sA}(x) = A^{1/3} \times Q^2_s(x)$.

Having summarized the theoretical models for heavy quark photoproduction, let us present the numerical calculation of their total cross section at UPC’s. 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 $\sqrt{s_{NN}} = 5500$ GeV. The results are presented in Table 1. The collinear approach gives a larger rate, followed by the semihard approach (labels I and II refer to GRV94 and 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 constraint already in the current nuclear accelerators the QCD dynamics since the main features from photon-nuclei collisions hold in the UPC reactions.

### 3. Photonuclear production of vector mesons

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

$$\Im A_{\gamma A \rightarrow VA} = \sum_{h, \bar{h}} \int dz \, d^2r \, \Psi^\gamma_{h, \bar{h}}(z, r, Q^2) \sigma^{\text{target}}_{\text{dip}}(\bar{x}, r) \Psi^{V^*_h}(z, r),$$

where $\Psi^\gamma_{h, \bar{h}}(z, r)$ and $\Psi^{V^*_h}(z, r)$ 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.
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 re-
cent detailed discussion see Ref. 11). Here, we follows the analytically simple DGKP
approach 14, 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 rota-
tional invariance between transverse and longitudinally polarized vector mesons 11.
However, as it describes reasonably the HERA data for vector meson production,
as pointed out in Ref. 15, we will use it here.

The corresponding parameters for the meson wavefunctions are presented in
Table 1 of Ref. 10. Following Ref. 13, 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 $J/\Psi$ 10. Additionally for heavy mesons we have take into account
the skewedness effects, associated to off-forward features of the process, which are
increasingly important in this case. Finally, the photomuclear cross section is given
by

$$
\sigma_{tA\rightarrow VA}^\text{tot} = \frac{|ImA_{tA\rightarrow VA}|^2}{16\pi} (1 + \beta^2) \int_{t_{min}}^{\infty} dt |F(t)|^2 ,
$$

with $t_{min} = (m_V^2/2\omega)^2$. The quantity $\beta$ is the ratio between the imaginary and real
part of the amplitude. We have used an analytical approximation 16 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 $\rho$ production in gold-gold UPC’s at $\sqrt{s} = 130$ GeV. The energy dependence of the cross section is presented in Fig 1-a. Our theoretical prediction in the curve take into account the experimental cuts, which gives $\sigma_{\text{theory}}(|y| \leq 3) = 410$ mb, in good agreement with the STAR measurement $\sigma_{\text{STAR}}(|y| \leq 3) = 370 \pm 170 \text{(stat)} \pm 80 \text{(syst)}$ mb. Furthermore, the PHENIX Collaboration has preliminary measurements of the cross section for coherent $J/\Psi$ photoproduction in UPC at midrapidity at $\sqrt{s} = 200$ GeV, accompanied by nuclear breakup. The rapidity distribution is shown in Fig 1-b in comparison with our prediction. The theoretical estimation gives $d\sigma/dy|_{y=0} = 58 \mu$b, which is in agreement with the PHENIX measurement $d\sigma_{\text{PHENIX}}/dy|_{y=0} = 48 \pm 16 \text{(stat)} \pm 18 \text{(syst)} \mu$b. Finally, in Table 2 one shows the predictions for the integrated cross sections for LHC. The experimental feasibility and signal separation on the reaction channels presented here are reasonably clear, namely applying a (low) transverse momentum cut $p_T < 1$ and two rapidity gaps in the final state for the meson case. In contrast, for heavy quarks we have only one rapidity gap.

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