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Diffractive photoproduction of heavy quarks in hadronic collisions

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In this article we study the diffractive photoproduction of heavy quarks in hadronic ($pp/pA/AA$) interactions for Tevatron and LHC energies. The integrated cross section and rapidity distribution for the process $h_1h_2 \rightarrow h_1h_2Q\bar{Q}$ ($h_i = p, A$ and $Q = c, b$) are estimated using the color glass condensate (CGC) formalism. Our results indicate that this production channel has larger cross sections than the competing reactions of double diffractive production and coherent AA reactions initiated by two-photon collisions.

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I. INTRODUCTION

The QCD dynamics at high energies is of utmost importance for building a realistic description of $pp/pA/AA$ collisions at LHC. Theoretically, at high energies the QCD evolution leads to a system with high gluon density, characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wave function (parton saturation). The transition is specified by a typical scale, which is energy dependent and is called saturation scale Q_{sat} (For recent reviews see Ref. [1]). Signals of parton saturation have already been observed both in ep deep inelastic scattering at HERA and in deuteron-gold collisions at RHIC (See, e.g. Refs. [2,3]). However, the observation of this new regime still needs confirmation and so there is an active search for new experimental signatures. Among them, the observables measured in diffractive processes deserve special attention. As shown in Ref. [4], the total diffractive cross section is much more sensitive to large-size dipoles than the inclusive one. As saturation effects screen large-size dipole (soft) contributions, it appears that a fairly large fraction of the cross section is hard and hence eligible for a perturbative treatment. Therefore, the study of diffractive processes becomes fundamental in order to constrain the QCD dynamics at high energies.

In this paper we propose to study diffractive interactions in ultraperipheral collisions of hadrons, which can be defined as collisions where no hadronic interactions occur because the large spatial separation between projectile and target and the interaction is mediated by the electromagnetic field (For recent reviews see Ref. [5]). In particular, we analyze the *diffractive* heavy quark photoproduction in $pp/pA/AA$ collisions, which at the Large Hadron Collider (LHC) will allow photon-hadron interactions to be studied at energies higher than at any existing accelerator. In relativistic heavy ion colliders, the heavy nuclei give rise to strong electromagnetic fields, which can interact with each other. In a similar way, these processes also occur when considering energetic protons in $pp(\bar{p})$ colliders. Over the past years a comprehensive analysis of the *inclusive* heavy quark [6–12] production in ultraperipheral heavy ion collisions was made considering different theoretical approaches. As a photon stemming from the electromagnetic field of one of the two colliding nuclei can interact with one photon of the other nucleus (two-photon process) or can penetrate into the other nucleus and interact with its hadrons (photon-nucleus process), both possibilities has been studied in the literature. In principle, the experimental signature of these two processes is distinct and it can easily be separated. While in two-photon interactions we expect the presence of two rapidities gaps and no hadron breakup, in the inclusive heavy quark photon-hadron production the hadron target we expect only one rapidity gap and the dissociation of the hadron. One of the main motivations to analyze the diffractive heavy quark photoproduction is that we expect the presence of two rapidity gaps in the final state, similarly to two-photon interactions. Consequently, it is important to determine the magnitude of this cross section in order to estimate the background for two-photon interactions. As discussed in Refs. [8–10], the heavy quark production in $\gamma\gamma$ interactions is approximately two or 3 orders of magnitude smaller than the inclusive photoproduction cross sections. However, the magnitude of the diffractive photoproduction cross section is still an open question. Another motivation for our study is that the contribution of this process can be important in proton-proton collisions, where there is a dedicated program to search evidence of the Higgs and/or new physics in central double diffractive production processes [13], which also are characterized by two rapidity gaps and has as a main background the exclusive $b\bar{b}$ production.

II. ULTRAPERIPHERAL COLLISIONS

The basic idea in ultraperipheral hadron collisions is that the total cross section for a given process can be factorized in terms of the equivalent flux of photons of the hadron projectile and the photon-photon or photon-target production cross section [5]. In particular, the photon-hadron interactions can be divided into exclusive and inclusive reactions. In the first case, a certain particle is produced while the target remains in the ground state (or is only internally excited). On the other hand, in inclusive interactions the particle produced is accompanied by one or more particles from the breakup of the target. The typical examples of these processes are the exclusive vector meson production, described by the process $\gamma h \to Vh$ ($V = \rho, J/\Psi, \Upsilon$), and the inclusive heavy quark production [$\gamma h \to XY$ ($X = c\bar{c}, b\bar{b}$)], respectively. In the last years we have discussed in detail both processes considering pp [11,14], pA [15] and AA [10,14] collisions as an alternative to constrain the QCD dynamics at high energies. Here we propose to analyze another exclusive process, characterized by the diffractive photoproduction of heavy quarks and described by the $\gamma h \to Xh$ reaction. In this case, the cross section for the diffractive photoproduction of a final state X in a ultraperipheral hadron-hadron collision is given by

$$\sigma(h_1 h_2 \to h_1 h_2 X) = \int_{\omega_{\min}}^{\infty} d\omega \frac{dN_\gamma(\omega)}{d\omega} \sigma_{\gamma h \to Xh}(W_{\gamma h}^2), \quad (1)$$

where ω is the photon energy and $\frac{dN_\gamma(\omega)}{d\omega}$ is the equivalent flux of photons from a charged hadron. Moreover, $\omega_{\min} = M_X^2/4\gamma_L m_p$, γ_L is the Lorentz boost of a single beam, $W_{\gamma h}^2 = 2\omega\sqrt{S_{\rm NN}}$ and $\sqrt{S_{\rm NN}}$ is the c.m.s energy of the hadron-hadron system. It is important to emphasize that the equivalent photon energies at the LHC will be higher than at any existing accelerator. For instance, considering pPb collisions at LHC, the Lorentz factor is $\gamma_L = 4690$, giving the maximum c.m.s. γh energy $W_{\gamma p} \approx 1500$ GeV. Therefore, while studies of photoproduction at HERA are limited to photon-proton center of mass energies of about 200 GeV, photon-hadron interactions at LHC can reach 1 order of magnitude higher on energy. Consequently, studies of γh interactions at LHC could provide valuable information on the QCD dynamics at high energies. In this work we consider that the produced state X represents a $Q\bar{Q}$ pair. Since photon emission is coherent over the entire proton/nucleus and the photon is colorless we expect that the diffractive events to be characterized by two rapidity gaps, in contrast with the inclusive heavy quark production. In these two-rapidity gaps events the heavy quark pair is produced in the central rapidity region, whereas the beam particles often leave the interaction region intact, and can be measured using very forward detectors.

In the calculations what follows we consider that the photon spectrum for a nuclei is given by [5]

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

where $\bar{\eta} = \omega R_{\rm eff}/\gamma_L$ and $\mathcal{U}(\bar{\eta}) = K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})$, with $R_{\rm eff} = R_p + R_A$ ($R_{\rm eff} = 2R_A$) for pA (AA) collisions. On the other hand, for a proton, we assume that the photon spectrum is given by [16],

$$\frac{dN_\gamma(\omega)}{d\omega} = \frac{\alpha_{\rm em}}{2\pi\omega}\left[1 + \left(1 - \frac{2\omega}{\sqrt{S_{NN}}}\right)^2\right]\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right), \quad (3)$$

with the notation $\Omega = 1 + [(0.71{\rm GeV}^2)/Q_{\min}^2]$ and $Q_{\min}^2 = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{S_{NN}})] \approx (\omega/\gamma_L)^2$.

III. QCD DYNAMICS AT HIGH ENERGIES

The photon-hadron 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 describe diffractive interactions and disentangle the small-x dynamics of the hadron wave function, 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 $\boldsymbol{r}$ long after the interaction, which then scatters off the target [17]. 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 diffractive heavy quark photoproduction cross section [$\gamma h \to Q\bar{Q}h, h = p, A$] reads as,

$$\sigma_{T,L}^D = \int d^2{\rm b}dzd^2\boldsymbol{r}|\Psi_{T,L}^\gamma(z, \boldsymbol{r}, Q^2)|^2\mathcal{N}^2(\bar{x}, \boldsymbol{r}, {\rm b}), \quad (4)$$

where $\Psi_{T,L}^\gamma$ is the light-cone wave function of the photon [17]. The variable $\boldsymbol{r}$ 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 wave function, Ψ^γ and the dipole-target forward amplitude $\mathcal{N}$. 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.

In the color glass condensate (CGC) formalism [18–20], $\mathcal{N}$ encodes all the information about the hadronic scattering, and thus about the nonlinear and quantum effects in the hadron wave function. The function $\mathcal{N}$ can be obtained by solving an appropriate evolution equation in the rapidity $y \equiv \ln(1/x)$. The main properties of $\mathcal{N}$ are: (a) for the interaction of a small dipole ($\boldsymbol{r} \ll 1/Q_{\rm sat}$), $\mathcal{N} \ll 1$, which characterizes that this system is weakly interacting; (b) for a large dipole ($\boldsymbol{r} \gg 1/Q_{\rm sat}$), the system is strongly absorbed which implies $\mathcal{N} \approx 1$. This property is associate to the large density of saturated gluons in the hadron wave function.

In our analysis of diffractive heavy quark production in photon-nucleus interactions we will consider the phenomenological saturation model proposed in Ref. [21] which describes the experimental data for the nuclear structure function, with the forward dipole-nucleus amplitude parameterized as follows

$$\mathcal{N}_A(\bar{x}, \boldsymbol{r}, \mathrm{b}) = 1 - \exp[-\tfrac{1}{2} A T_A(\mathrm{b}) \sigma_0 \mathcal{N}_p(\bar{x}, \boldsymbol{r}^2)], \quad (5)$$

where $T_A(b)$ is the nuclear profile function, which will be obtained from a 3-parameter Fermi distribution for the nuclear density, and $\bar{x} = \frac{Q^2+4m_f^2}{W_{\gamma p}^2}$. (For details see, e.g., Ref. [22]). Moreover, $\mathcal{N}_p$ describes the dipole-proton interaction. In the literature there are several phenomenological models for this quantity. Here we will consider the Golec Biernat-Wusthoff model [4], which encodes the basic properties of the saturation physics and assumes that

$$\mathcal{N}_p(\bar{x}, \boldsymbol{r}^2) = \left[1 - \exp\left(-\frac{Q_s^2(\bar{x})\boldsymbol{r}^2}{4}\right)\right], \quad (6)$$

with $Q_s^2(\bar{x}) = (\frac{x_0}{\bar{x}})^\lambda \mathrm{GeV}^2$ being the saturation scale, which depends on energy and defines the onset of the saturation phenomenon. The parameters were obtained from a fit to the HERA data producing $\sigma_0 = 23.03(29.12)$ mb, $\lambda = 0.288(0.277)$ and $x_0 = 3.04 \times 10^{-4}(0.41 \times 10^{-4})$ for a 3-flavor (4-flavor) analysis [4]. It is important to emphasize that Eq. (5) 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, i. e. the size of the pair r becomes eigenvalue of the scattering matrix. In our calculations of the diffractive heavy quark production in hadronic collisions we will assume that the forward dipole-target amplitude is given by Eq. (5) in the case of a nuclear target and by Eq. (6) for a proton target.

IV. RESULTS

The distribution on rapidity Y of the produced final state can be directly computed from Eq. (1), 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,

$$\frac{d\sigma[h_1 h_2 \to h_1 h_2 X]}{dy} = \omega \frac{dN_\gamma(\omega)}{d\omega} \sigma_{\gamma h \to Xh}(\omega). \quad (7)$$

Consequently, given the photon flux, the rapidity distribution is thus a direct measure of the diffractive photoproduction cross section for a given energy. In Figs. 1 and 2 we present our results for the diffractive heavy quark photoproduction at LHC energies.

In Table I one presents the correspondent integrated cross sections. We have that the larger cross sections are obtained in the AA mode, followed by pA and pp modes. However, the event rates should be higher in the pp mode as its luminosity is several orders of magnitude larger, Namely, the corresponding luminosities are $\mathcal{L}_{\mathrm{pp}} = 10^{34}\ \mathrm{cm}^{-2}\,s^{-1}$, $\mathcal{L}_{\mathrm{pPb}} = 7.4 \times 10^{29}\ \mathrm{cm}^2\,s^{-1}$ and $\mathcal{L}_{\mathrm{PbPb}} = 4.2 \times 10^{26}\ \mathrm{cm}^2\,s^{-1}$.

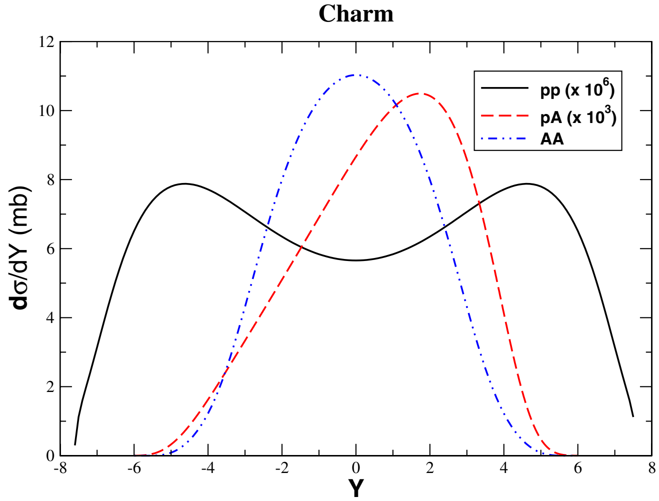

FIG. 1 (color online). Rapidity distribution for diffractive charm photoproduction on $pp/pA/AA$ reactions for LHC energies (see text).

Let us now compare the results to processes having similar final state configuration. This analysis is important since they are competing reactions. In Ref. [23], the double diffractive (DD) production of heavy quarks has been computed (without considering rapidity gap survival correction, which diminishes the cross section). Summarizing those estimations, one has for charm $\sigma_{c\bar{c}}^{\mathrm{DD}} = 45$–$208$ pb (Tevatron) and $\sigma_{c\bar{c}}^{\mathrm{DD}} = 4 - 6.56 \times 104$ pb (LHC). For bottom, one has $\sigma_{b\bar{b}}^{\mathrm{DD}} = 17 - 78$ pb (Tevatron) and $\sigma_{b\bar{b}}^{\mathrm{DD}} = 0.5 - 1.5 \times 10^4$ pb (LHC). Our result for the pp mode are at least 1 order of magnitude larger. Other process with similar configuration is the double photon process in the AA mode. In Ref. [9], we obtain the following values for coherent PbPb collision at LHC energies: for charm, $\sigma_{c\bar{c}}^{\gamma\gamma} = 1.8$ mb and for bottom $\sigma_{c\bar{c}}^{\gamma\gamma} = 2\ \mu$b. Our results are higher by a factor 30 for charm and a factor 5 for bottom.

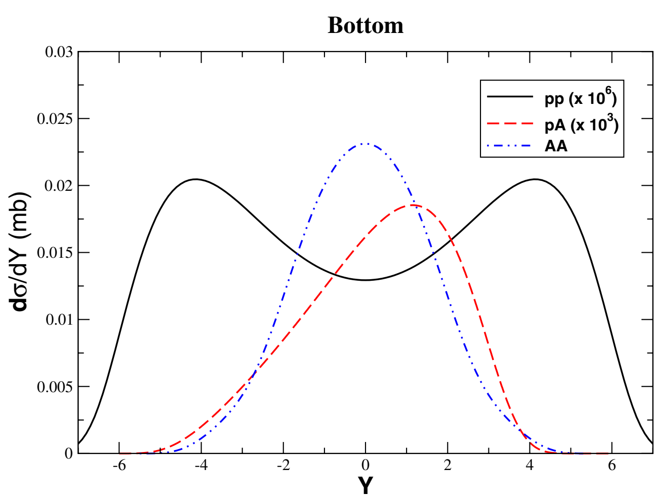

FIG. 2 (color online). Rapidity distribution for diffractive bottom photoproduction on $pp/pA/AA$ reactions for LHC energies (see text).

TABLE I. The integrated cross section for the diffractive photoproduction of heavy quarks in $pp/pA/AA$ collisions.

h_1h_2	Collider	$c\bar{c}$	$b\bar{b}$
$pp(\bar{p})$	RHIC	3.4 nb	3×10^{-3} nb
	TEVATRON	12.6 nb	0.021 nb
	LHC	92.0 nb	0.2 nb
pA	LHC	54.0 μb	0.09 μb
AA	LHC	59.0 mb	0.01 mb

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. In this article we have studied the diffractive photoproduction of heavy quarks, which provide a feasible and clear measurement of the underlying QCD dynamics at high energies. The advantages of this process are the clear final state (rapidity gaps and low momenta particles) and no competing effect of dense nuclear environment if compared with hadroproduction. However, as the present analysis is predominantly phenomenological several points deserve more detailed studies. For instance, the model dependence as well as estimative of background processes and the analysis of the experimental separation have to be further addressed.

It is important to emphasize that the same reaction, $h_1h_2 \rightarrow h_1h_1X$, also occurs via fusion of two Pomerons, the so-called central diffraction processes. However, the transverse momenta of the scattered hadrons are predicted to be much larger than in two-photon interactions, which implies that the separation between these two processes is feasible. In the case of diffractive photoproduction we expect an asymmetric distribution of the scattered hadrons, since photon and Pomeron exchange are present in the process. Moreover, as almost all of the photoproduced heavy quarks, similar to the vector mesons, should have small transverse momenta, it is possible to introduce a selection criterion to separate the diffractive photoproduction processes.

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[1] E. Iancu and R. Venugopalan, hep-ph/0303204; V. P. Goncalves and M. V. T. Machado, Mod. Phys. Lett. A **19**, 2525 (2004); H. Weigert, Prog. Part. Nucl. Phys. **55**, 461 (2005); J. Jalilian-Marian and Y. V. Kovchegov, Prog. Part. Nucl. Phys. **56**, 104 (2006).

[2] J. P. Blaizot and F. Gelis, Nucl. Phys. **A750**, 148 (2005).

[3] V. P. Goncalves, M. S. Kugeratski, M. V. T. Machado, and F. S. Navarra, Phys. Lett. B **643**, 273 (2006).

[4] K. Golec-Biernat and M. Wüsthoff, Phys. Rev. D **59**, 014017 (1998); **60**, 114023 (1999).

[5] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, and Y. Kharlov, Phys. Rep. **364**, 359 (2002); C. A. Bertulani, S. R. Klein, and J. Nystrand, Annu. Rev. Nucl. Part. Sci. **55**, 271 (2005).

[6] Ch. Hofmann, G. Soff, A. Schafer, and W. Greiner, Phys. Lett. B **262**, 210 (1991); N. Baron and G. Baur, Phys. Rev. C **48**, 1999 (1993); M. Greiner, M. Vidovic, Ch. Hofman, A. Schafer, and G. Soff, Phys. Rev. C **51**, 911 (1995); F. Krauss, M. Greiner, and G. Soff, Prog. Part. Nucl. Phys. **39**, 503 (1997); F. Gelis and A. Peshier, Nucl. Phys. **A697**, 879 (2002).

[7] V. P. Gonçalves and C. A. Bertulani, Phys. Rev. C **65**, 054905 (2002).

[8] S. R. Klein, J. Nystrand, and R. Vogt, Phys. Rev. C **66**, 044906 (2002).

[9] V. P. Gonçalves and M. V. Machado, Eur. Phys. J. C **29**, 37 (2003).

[10] V. P. Goncalves and M. V. T. Machado, Eur. Phys. J. C **31**, 371 (2003).

[11] V. P. Goncalves and M. V. T. Machado, Phys. Rev. D **71**, 014025 (2005).

[12] M. Strikman, R. Vogt, and S. White, Phys. Rev. Lett. **96**, 082001 (2006).

[13] V. A. Khoze, A. D. Martin, and M. G. Ryskin, Eur. Phys. J. C **23**, 311 (2002); hep-ph/0605189.

[14] V. P. Goncalves and M. V. T. Machado, Eur. Phys. J. C **40**, 519 (2005).

[15] V. P. Goncalves and M. V. T. Machado, Phys. Rev. C **73**, 044902 (2006).

[16] M. Drees and D. Zeppenfeld, Phys. Rev. D **39**, 2536 (1989).

[17] N. N. Nikolaev, B. G. Zakharov, Phys. Lett. B **332**, 184 (1994); Z. Phys. C **64**, 631 (1994).

[18] E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. **A692**, 583 (2001); E. Ferreiro, E. Iancu, A. Leonidov, and L. McLerran, Nucl. Phys. **703**, 489 (2002).

[19] I. I. Balitsky, Nucl. Phys. **B463**, 99 (1996); Y. V. Kovchegov, Phys. Rev. D **60**, 034008 (1999).

[20] J. Jalilian-Marian, A. Kovner, L. McLerran, and H. Weigert, Phys. Rev. D **55**, 5414 (1997); J. Jalilian-Marian, A. Kovner, and H. Weigert, Phys. Rev. D **59**, 014014 (1998); **59**, 014015 (1998); **59**, 034007 (1999); A. Kovner, J. Guilherme Milhano, and H. Weigert, Phys. Rev. D **62**, 114005 (2000); H. Weigert, Nucl. Phys. **A703**, 823 (2002).

[21] N. Armesto, Eur. Phys. J. C **26**, 35 (2002).

[22] V. P. Goncalves and M. V. T. Machado, Eur. Phys. J. C **30**, 387 (2003).

[23] M. Heyssler, Z. Phys. C **73**, 299 (1997).