

The QCD pomeron in ultraperipheral heavy ion collisions: I. The double J/Ψ production

V.P. Gonçalves^{1,a}, M.V.T. Machado^{2,b}

¹ Instituto de Física e Matemática, Universidade Federal de Pelotas, Caixa Postal 354, CEP 96010-090, Pelotas, RS, Brazil

² High Energy Physics Phenomenology Group, IF-UFRGS, Caixa Postal 15051, CEP 91501-970, Porto Alegre, RS, Brazil

Received: 12 December 2002 /

Published online: 7 March 2003 – © Springer-Verlag / Società Italiana di Fisica 2003

Abstract. The contribution of the QCD pomeron to the process $AA \rightarrow AA J/\Psi J/\Psi$ is discussed. We focus on the photon–photon collision, with the quasi-real photon coming from the Weizsäcker–Williams spectrum of the nuclei. We calculate the cross section for this process considering the solution of the LLA BFKL equation at zero momentum transfer using a small t approximation for the differential cross section of the subprocess. Furthermore, the impact of non-leading corrections to the BFKL equation is also analyzed. In both cases the cross section is found to increase with the energy, predicting considerable values for the LHC energies. Moreover, we compare our results with the Born two-gluon approximation, which is energy independent at the photon level. Our results indicate that the experimental analyses of this process can be useful to discriminate the QCD dynamics at high energies.

1 Introduction

Understanding the behavior of high energy hadron reactions from a fundamental perspective within QCD is an important goal of particle physics. The behavior of scattering in the limit of high energy and fixed momentum transfer is described in QCD, at least in situations in which perturbation applies, by the Balitskii–Fadin–Kuraev–Lipatov (BFKL) pomeron [1]. Attempts to test experimentally this sector of QCD have started in the last years, mainly considering processes where specific conditions are satisfied, which minimize the contributions of the other mechanisms competing with the QCD pomeron and guarantee the validity of the perturbative QCD methods. In particular, the virtualities of the gluons along the ladder should be large enough to assure the applicability of the perturbative expansion. The hard scale may be provided either by the coupling of the ladder to scattering particles, which contain a hard scale themselves, or by a large momentum transfer carried by the gluons. Furthermore, to distinguish the BFKL from DGLAP evolution effects it is convenient to focus on processes in which the scales on both ends of the ladder are of comparable size. Some examples are the measurements of forward jets in deeply inelastic events at low values of the Bjorken variable x in lepton–hadron scattering, jet production at large rapidity separations in hadron–hadron collisions and off-shell photon scattering at high energy in e^+e^- colliders, where the photons are produced from the lepton beams by bremsstrahlung (for a recent review of BFKL searches, see e.g. [2]). This last

process presents some theoretical advantages as a probe of QCD pomeron dynamics compared to the other ones because it does not involve a non-perturbative target [3–5]. Moreover, such a reaction presents analogies with the process of scattering of two quarkonia, which has been proposed as a gedanken experiment to investigate the high energy regime in QCD [6]. In such a case, non-perturbative effects are suppressed by the smallness of the quarkonium radius.

Another possibility for the study of the QCD pomeron is the vector meson pair production in $\gamma\gamma$ collisions [7]. At very high energies $s \gg -t$, diffractive processes such as $\gamma\gamma \rightarrow$ neutral vector (or pseudoscalar) meson pairs with virtual or real photons can test the QCD pomeron (odderon) in a detailed way utilizing the simplest possible initial state. As in the case of the large angle exclusive $\gamma\gamma$ processes, the scattering amplitude is computed by convoluting the hard scattering pQCD amplitude for $\gamma\gamma \rightarrow q\bar{q}q\bar{q}$ with the vector meson wave functions. For heavy vector mesons, this cross section can be calculated using the perturbative QCD methods. First calculations considering the Born two-gluon approximation have been done in [7]. More recently, the double J/Ψ production in $\gamma\gamma$ collisions has been proposed as a probe of the hard QCD pomeron [8]. There, the hard QCD pomeron is presumably the dominant mechanism. Theoretical estimates of the cross sections presented in [8] have demonstrated that measurement of this reaction at a Photon Collider should be feasible.

In this paper we study the possibilities for investigating QCD pomeron effects in a different context, namely in photon–photon scattering at ultraperipheral heavy ion

^a e-mail: barros@ufpel.tche.br

^b e-mail: magnus@if.ufrgs.br

collisions. In this case, the cross sections are enhanced since the $\gamma\gamma$ luminosity increases as Z^4 , where Z is the atomic number [9, 10]. Here, we will focus our analyses on double diffractive J/Ψ production in $\gamma\gamma$ collisions, with the photons coming from the Weizsäcker–Williams spectrum of the nuclei. This process is unique since in principle it allows one to test the QCD pomeron for arbitrary momentum transfers, where the hard scale is already provided by the relative large mass of the charm quark. Here, our goal is twofold: to analyze the potentiality of this process to constrain the QCD dynamics at high values of energy and to provide reliable estimates for the cross sections concerning that reaction. We calculate the cross section considering suitable approximations for the $\gamma\gamma \rightarrow J/\Psi J/\Psi$ subprocess. In particular, we estimate it considering the two-gluon exchange (Born level), the leading order solution of the BFKL equation, as well as estimate the corrections on the energy dependence associated to the next-to-leading effects through the pomeron intercept (for a review on NLO BFKL corrections, see e.g. [11] and references therein). Shortly, we have found that the two-gluon exchange mechanism gives rise to a constant $\gamma\gamma$ cross section at large c.m.s. two-photon energy W . To higher orders in perturbation theory, the iteration of gluons in the t -channel promotes this constant to logarithms, and the perturbative expansion of the cross section at high energy has the form

$$\sigma_{\gamma\gamma} \propto \sigma^{(0)} \left[1 + \sum_{k=1}^{\infty} a_k [\alpha_s \ln(W^2/s_0)]^k \right] + \dots, \quad (1)$$

where s_0 is the scale of the order of the charm mass squared, the summation represents the series of the leading logarithms on energy to all orders in the strong coupling constant α_s , and the ellipsis stands for non-leading terms. The sum of the leading logarithmic terms is made by the BFKL equation at leading order, which predicts that the cross section grows exponentially, $\sigma \propto W^{2\omega_{\mathbb{P}}}$, where $\omega_{\mathbb{P}} = 4 \ln 2 N_c \alpha_s / \pi$ in the LLA solution. It has recently been demonstrated that the NLO corrections to the BFKL equation are large. The main effect is a reduced value of the so-called Lipatov exponent $\omega_{\mathbb{P}}$. Since then the effects of higher orders have been studied for measurable processes, but the conclusions are not unambiguous [2]. This situation should be improved in the future with the next generation of linear colliders, such as the Japan Linear Collider (JLC) at KEK, TeV Energy Superconducting Linear Accelerator (TESLA) at DESY and CERN Linear Collider (CLIC), etc. However, until these colliders become reality it is important to consider alternative searches in the current accelerators which allow us to constrain the QCD dynamics.

This paper is organized as follows. In the next section (Sect. 2) we present a brief review of the ultraperipheral heavy ion collisions and the main formulae to describe the photon–photon process in these reactions. In Sect. 3 we consider the double J/Ψ production in $\gamma\gamma$ collisions and estimate this cross section considering distinct approximations to the QCD pomeron dynamics. There, we calculate the total cross sections for the subprocess for each approx-

imation and present our results for double J/Ψ production in ultraperipheral heavy ion collisions. Finally, we present a summary of our main conclusions in Sect. 4.

2 Ultraperipheral heavy ion collisions

In ultraperipheral relativistic heavy ion collisions the ions do not interact directly with each other and move essentially undisturbed along the beam direction [9]. The only possible interaction is due to the long range electromagnetic interaction and diffractive processes. Due to the coherent action of all the protons in the nucleus, the electromagnetic field is very strong and the resulting flux of equivalent photons is large. 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). For a recent review, see e.g. [10]. In particular, the photoproduction of heavy quarks as a probe of the high density effects have been recently emphasized in [12], where the color glass condensate formalism [13] was used to estimate the cross section and transverse momentum spectrum. Similarly, the elastic photoproduction of vector mesons in ultraperipheral heavy ion collisions was studied recently in [14], demonstrating that this process can be used to constrain the nuclear gluon distribution, which determines the dynamics at high energies. For other studies of QCD dynamics in one-photon processes see [15]. Here, we will restrict our analyzes for the two-photon process and its potentiality to investigate the QCD dynamics.

Relativistic heavy ion collisions are a potentially prolific source of $\gamma\gamma$ collisions at high energy colliders. The advantage of using heavy ions is that the cross sections varies as $Z^4 \alpha^4$ rather than just as α^4 . Moreover, the maximum $\gamma\gamma$ collision energy $W_{\gamma\gamma}$ is $2\gamma/R_A$, about 6 GeV at RHIC and 200 GeV at LHC, where R_A is the nuclear radius and γ is the center-of-mass system Lorentz factor of each ion. In particular, the LHC will have a significant energy and luminosity reach beyond LEP2 and could be a bridge to $\gamma\gamma$ collisions at a future e^+e^- linear collider. For two-photon collisions, the cross section for the reaction $AA \rightarrow AA J/\Psi J/\Psi$, represented in Fig. 1, will be given by

$$\begin{aligned} \sigma_{AA \rightarrow AA J/\Psi J/\Psi} &= \int \frac{d\omega_1}{\omega_1} n_1(\omega_1) \int \frac{d\omega_2}{\omega_2} n_2(\omega_2) \\ &\quad \times \sigma_{\gamma\gamma \rightarrow J/\Psi J/\Psi}(W = \sqrt{4\omega_1\omega_2}), \end{aligned} \quad (2)$$

where the photon energy distribution $n(\omega)$ is calculated within the equivalent photon or Fermi–Weizsäcker–Williams (FWW) approximation [16]. In general, the total cross section $AA \rightarrow AA \gamma\gamma \rightarrow AAX$, where X is the system produced within the rapidity gap, factorizes into the photon–photon luminosity $d\mathcal{L}_{\gamma\gamma}/d\tau$ and the cross section of the $\gamma\gamma$ interaction,

$$\sigma_{AA \rightarrow AA J/\Psi J/\Psi}(s) = \int d\tau \frac{d\mathcal{L}_{\gamma\gamma}}{d\tau} \hat{\sigma}_{\gamma\gamma \rightarrow J/\Psi J/\Psi}(\hat{s}), \quad (3)$$

where $\tau = \hat{s}/s$, $\hat{s} = W^2$ is the square of the center-of-mass (c.m.s.) system energy of the two photons and s of the ion-ion system. The $\gamma\gamma$ luminosity is given by the convolution of the photon fluxes from two ultrarelativistic nuclei:

$$\frac{d\mathcal{L}_{\gamma\gamma}(\tau)}{d\tau} = \int_{\tau}^1 \frac{dx}{x} f(x) f(\tau/x), \quad (4)$$

where the photon distribution function $f(x)$ is related to the equivalent photon number $n(\omega)$ via $f(x) = (E/\omega) n(xE)$, with $x = \omega/E$ and E is the total energy of the initial particle in a given reference frame. The remaining quantity to be determined in order to proceed is the quantity $f(x)$, which has been investigated by several groups (for more details, see e.g. [10]). Here, we consider the photon distribution of [17], providing a photon distribution which is not factorizable. The authors of [17] produced practical parametric expressions for the differential luminosity by adjusting the theoretical results, which reads

$$\frac{d\mathcal{L}_{\gamma\gamma}}{d\tau} = \left(\frac{Z^2\alpha}{\pi}\right)^2 \frac{16}{3\tau} \times \begin{cases} \xi(z), & 0.05 < z < 5, \\ \left[\ln\left(\frac{1.234}{z}\right)\right]^3, & z < 0.05, \end{cases} \quad (5)$$

where $z = mR/\gamma = 2MR(\tau^{1/2})$, m is the mass of the system produced in the two-photon collision, M is the nucleus mass, R its radius and $\xi(z)$ is given by

$$\xi(z) = \sum_{i=1}^3 A_i e^{-b_i z}, \quad (6)$$

from an adjustment to the numerical integration of the photon distribution, with an accuracy of $\sim 2\%$ in the referred region on z . The adjustable parameters are the following: $A_1 = 1.909$, $A_2 = 12.35$, $A_3 = 46.28$, $b_1 = 2.566$, $b_2 = 4.948$, and $b_3 = 15.21$.

The approach given above excludes possible final state interactions of the produced particles with the colliding particles, allowing reliable calculations of ultraperipheral heavy ion collisions. Therefore, to estimate the double J/Ψ production it is only necessary to consider a suitable QCD model for the double heavy meson production. In the context of the analysis presented here, it is worth mentioning that estimates for the double pion (light mesons) production in ultraperipheral heavy ion collisions have been presented in [18]. In addition, there was found a negligible contribution of pomeron-pomeron (considered in the Regge approach) interaction for very heavy ions, whereas this is non-negligible for the lightest ions.

3 Double J/Ψ production

The process $\gamma\gamma \rightarrow J/\Psi J/\Psi$ is a clean reaction testing the BFKL pomeron physics and provides estimates for the heavy meson production in photon induced processes. The hard scale involved in the reaction, that is the charm mass, and the presence of the photon as the initial state as it turns out make it suitable for a perturbative treatment.

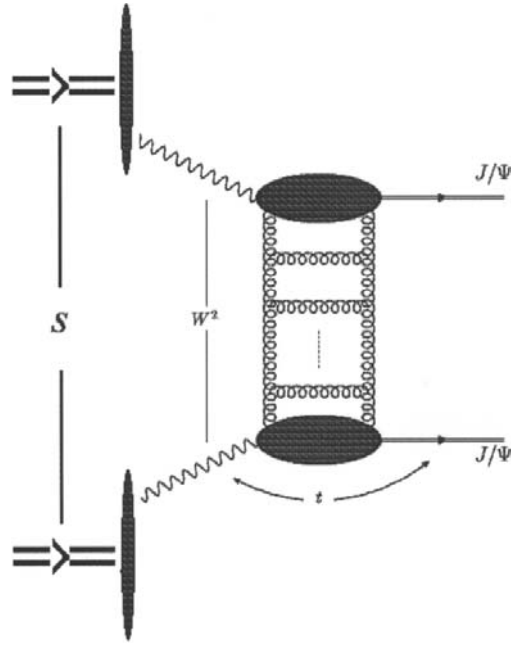


Fig. 1. The QCD pomeron exchange mechanism in ultraperipheral heavy ion collisions

The non-perturbative content is provided only by the J/Ψ light-cone wave function, which is well constrained through the experimental measurement of its leptonic width $\Gamma_{J/\Psi \rightarrow l^+l^-}$. In the following we use the high energy factorization and the BFKL dynamics in order to perform estimates for the referred reaction. Our general formulae for the differential cross section and imaginary part of the scattering amplitude are given as follows [8],

$$\frac{d\sigma(\gamma\gamma \rightarrow J/\Psi J/\Psi)}{dt} = \frac{|\mathcal{A}(W^2, t)|^2}{16\pi}, \quad (7)$$

$$\text{Im}\mathcal{A}(W^2, t) = \int \frac{d^2\mathbf{k}}{\pi} \frac{\Phi_{\gamma J/\Psi}(\mathbf{k}, \mathbf{q}) \tilde{\Phi}_{\gamma J/\Psi}(W^2, \mathbf{k}, \mathbf{q})}{(\mathbf{k} + \mathbf{q}/2)^2 (\mathbf{k} - \mathbf{q}/2)^2}, \quad (8)$$

where W is the center-of-mass energy of the two-photon system and the photon-meson impact factor is denoted by $\Phi_{\gamma J/\Psi}$. At the Born level $\tilde{\Phi} = \Phi$ and the reaction is described by two gluons (a bare approximation for the QCD pomeron), which have transverse momenta $\mathbf{q}/2 \pm \mathbf{k}$ and where the momentum transfer is $t = -\mathbf{q}^2$. When considering the complete gluon ladder contribution, the quantity $\tilde{\Phi}$ contains the impact factor and the gluon emission on the ladder, which is driven by the QCD dynamics. At the LLA level, the BFKL ladder contribution for the t -channel exchange provides the following expression for it:

$$\begin{aligned} \tilde{\Phi}_{\gamma J/\Psi}(W^2, \mathbf{k}, \mathbf{q}) &= \int d^2\mathbf{k}' \frac{\mathbf{k}^2}{k'^2} F(W^2, \mathbf{k}, \mathbf{k}', \mathbf{q}) \Phi_{\gamma J/\Psi}(\mathbf{k}', \mathbf{q}), \end{aligned} \quad (9)$$

where

$$\Phi_{\gamma J/\Psi}(\mathbf{k}, \mathbf{q}) = \mathcal{C} \left[\frac{1}{m_c^2 + \mathbf{q}^2} - \frac{1}{m_c^2 + \mathbf{k}^2} \right], \quad (10)$$

and $F(W^2, \mathbf{k}, \mathbf{k}', \mathbf{q})$ is the solution of the LLA BFKL equation at $t \neq 0$. Equation (10) defines the impact factor in the non-relativistic approximation. We have considered the following parameters for the further calculations:

$$\begin{aligned} m_c &= m_{J/\Psi}/2 = 1.55 \text{ GeV} , \\ \mathcal{C} &= (\alpha_{\text{em}}^{1/2})\alpha_s(\mu^2)e_c(8/3)\pi m_c f_{J/\Psi} , \\ \text{with } e_c &= 2/3 \text{ and } f_{J/\Psi} = 0.38 \text{ GeV} . \end{aligned}$$

In order to compute the total cross section for the process, we would need to consider the LLA BFKL non-forward solution [19] (for a derivation in the momentum space, see e.g. [20]) in (9), put all together to obtain the amplitude and then integrate (7) over $0 \leq |t| \leq \infty$. Further refinements can be considered. For instance, the infrared contributions by modifying the gluon propagator can still be investigated, as done in [21] for the Born case and in [8] for the full resummation. Moreover, non-leading corrections could also be implemented in a numerical calculation, for instance along the lines of [8]. Here, we follow a different procedure, since we are interested mostly in the energy dependence of the process. We will consider a small t approximation, providing accuracy enough for our purposes in the present work, in such a way that the total cross section can be written as

$$\begin{aligned} \sigma_{\text{tot}}(\gamma\gamma \rightarrow J/\Psi J/\Psi) \\ = \frac{1}{B_{J/\Psi J/\Psi}} \left. \frac{d\sigma(\gamma\gamma \rightarrow J/\Psi J/\Psi)}{dt} \right|_{t=0} , \end{aligned} \quad (11)$$

with

$$\begin{aligned} \frac{d\sigma(\gamma\gamma \rightarrow J/\Psi J/\Psi)}{dt} \\ = \frac{|\mathcal{A}(W^2, t=0)|^2}{16\pi} \exp(-B_{J/\Psi J/\Psi} \cdot |t|) , \end{aligned} \quad (12)$$

where $B_{J/\Psi J/\Psi}$ is the corresponding slope parameter. This quantity is not available from experimental measurements, instead of the slope $B_{J/\Psi p}$ obtained from J/Ψ photoproduction [22]. In the following we should estimate this quantity using information about the Born two-gluon approximation, where $F = \delta^2(\mathbf{k} - \mathbf{k}')$. In this particular case the amplitude reads

$$\mathcal{A}_{\text{Born}}(W^2, t) = \int \frac{d^2\mathbf{k}}{\pi} \frac{\Phi_{\gamma J/\Psi}(\mathbf{k}, \mathbf{q})\Phi_{\gamma J/\Psi}(\mathbf{k}, \mathbf{q})}{(\mathbf{k} + \mathbf{q}/2)^2(\mathbf{k} - \mathbf{q}/2)^2} , \quad (13)$$

which can be computed analytically if one considers a strong coupling constant not depending on k^2 . Using the impact factor given by (10) and performing the integration over the gluon's transverse momentum, one obtains

$$\mathcal{A}_{\text{Born}}(W^2, t) = \frac{16\mathcal{C}^2}{m_c^2(4m_c^2 + |t|)^2} . \quad (14)$$

Now, we are able to use (14) in order to estimate the B parameter for the double J/Ψ production. This quantity can be computed from the scattering amplitude above by the small t approximation,

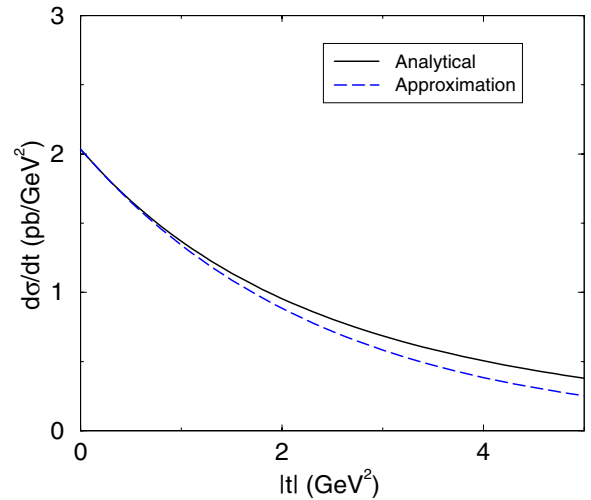


Fig. 2. The comparison between the Born two-gluon analytical calculation (solid line) for the differential cross section and the small t approximation (dashed line)

$$\begin{aligned} B_{J/\Psi J/\Psi} &= \lim_{|t| \rightarrow 0} \frac{d}{dt} \left[\ln \left(\frac{d\sigma_{\text{Born}}}{dt} \right) \right] \\ &= \lim_{|t| \rightarrow 0} \frac{d}{dt} \left[\ln \left(\frac{16\mathcal{C}^4}{\pi m_c^4(4m_c^2 + |t|)^4} \right) \right] , \end{aligned} \quad (15)$$

which gives a slope parameter with value $B_{J/\Psi J/\Psi} = m_c^{-2}$. Moreover, we expect that this estimate has little sensitivity to energy, since it is known that the hard pomeron gives a low α'_p (almost no shrinkage) [23]. That is, the phenomenology on J/Ψ photoproduction has provided $\alpha'_p \simeq 0.1$ [22], instead of the usual $\alpha'_p = 0.25$ from the hadronic analysis, where the corresponding slope is given by $B = b_0 + 2\alpha'_p \ln(s/s_0)$ in the Regge analysis. We have verified also the accuracy of our approximation comparing the analytical calculation, (15), with the small t estimate given by (12). The comparison is shown in Fig. 2, for a fixed coupling constant $\alpha_s(m_{J/\Psi}^2) \simeq 0.289$, in agreement with the estimates at [8]. It is worth mentioning that the typical values measured in elastic J/Ψ photoproduction stay in the range $|t| < 1.5 \text{ GeV}^{-2}$, where our approximation produces the same result as the analytical case.

Having the slope parameter B , and taking (11), one can estimate the total cross section considering the Born two-gluon exchange. It is simple to verify that the normalization for σ_{tot} depends significantly on the strong coupling α_s . We have obtained that the cross section takes values of order a few pb, having a lower bound if the typical HERA value $\alpha_s = 0.2$ is used as well as an upper bound for $\alpha_s(m_c^2)$. These estimates are corroborated by previous calculations [7], and some results are presented in Table 1, considering different values of α_s . The results are also consistent with [8], where the calculations were done beyond the leading log approximation. For instance, we have found $\sigma_{\text{tot}} = 3.6 \text{ pb}$ using the running $\alpha_s(\mathbf{k}^2 + m_c^2)$ and $s_0 = 0.16 \text{ GeV}^2$ (this is the parameter accounting for the infrared cutoff). The refined study of [8] gives a close result, $\sigma_{\text{tot}} \approx 2\text{--}2.6 \text{ pb}$. Our estimates are quite reliable in

Table 1. The estimates for $\sigma_{\text{tot}}(\gamma\gamma \rightarrow J/\Psi J/\Psi)$ at the Born level for different α_s values

| α_s | scale | σ_{tot} |
|--------------------|-----------------------|-----------------------|
| $\alpha_s = 0.300$ | $\simeq m_c^2$ | 4.88 pb |
| $\alpha_s = 0.289$ | $\simeq m_{J/\Psi}^2$ | 4.21 pb |
| $\alpha_s = 0.250$ | HERA | 2.35 pb |
| $\alpha_s = 0.200$ | HERA | 0.97 pb |

view of the approximations considered here. It should be stressed that other additional sources of uncertainty are the charm mass and the non-relativistic approximation for the impact factor.

In order to perform a LLA BFKL calculation, the following solution for the evolution equation in the forward case was considered (see the pedagogical reviews on [20, 23]),

$$F(W^2, \mathbf{k}, \mathbf{k}') = \frac{1}{\sqrt{2\pi^3 a \mathbf{k}^2 \mathbf{k}'^2}} \frac{1}{\sqrt{\ln(W^2/\bar{s})}} \left(\frac{W^2}{\bar{s}} \right)^{\omega_{\mathbb{P}}} \times \exp \left[-\frac{\ln^2(\mathbf{k}^2/\mathbf{k}'^2)}{2a \ln(W^2/\bar{s})} \right], \quad (16)$$

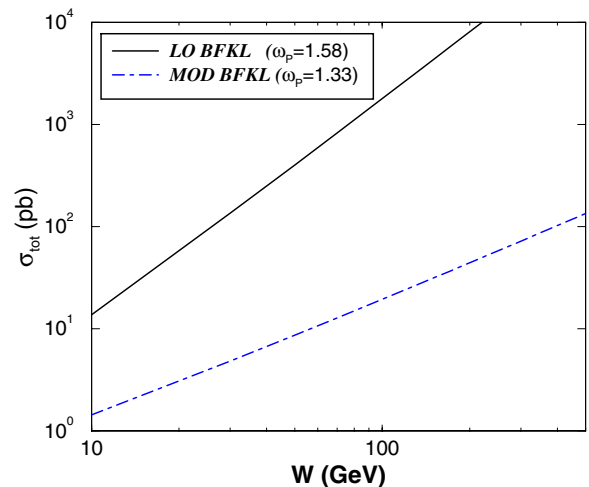
where

$$\omega_{\mathbb{P}} = \frac{3\alpha_s}{\pi} 4 \ln 2, \quad a = \frac{3\alpha_s}{\pi} 28\zeta(3) \quad (17)$$

and $1 + \omega_{\mathbb{P}}$ is the pomeron intercept in the leading logarithmic approximation, which depends on α_s . We have taken $\bar{s} = 1 \text{ GeV}^2$. The results are sensitive to the choice for the intercept, providing an enhancement of the total cross section by one/two orders of magnitude in relation to the Born level at the considered energy range. For the further studies we have selected the results using $\alpha_s(\mu^2) = 0.22$, typical at the HERA kinematical regime.

The total cross section is shown in Fig. 3, represented by the solid line, producing an effective behavior given by $W^{4\lambda}$ and where $\lambda = 0.54$. The range on W is the region possibly available at LEP2 and the two-photon process in ultraperipheral heavy ions collisions at LHC. The behavior is considerably steep as a function of energy and it is timely to ask for the NLO corrections to the LLA BFKL equation or unitarity corrections to the LO calculation. Concerning the NLO effects, the correction looks like $\omega_{\mathbb{P}}^{\text{NLO}} = \omega_{\mathbb{P}}(1 - N\bar{\alpha}_s)$, where $\bar{\alpha}_s = 3\alpha_s/\pi$. The value $N = 6.5$, obtained in the literature [24], turns out to have corrections too large and even producing negative values if large α_s values are considered. The complete resummation of the non-leading effects, mostly collinear-enhanced contributions, is currently argued for in order to provide reliable calculations (see [11] for a review).

For practical purposes in our further investigation below, we have considered the modification of the pomeron intercept in order to be consistent with the stable higher order resummation results [25], which give $\omega_{\mathbb{P}} \simeq 0.3$ at the HERA kinematic regime. Even a lower effective exponent is found concerning the NLO BFKL using the BLM

**Fig. 3.** The estimates for the total $\gamma\gamma$ cross section using LLA BFKL solution (solid curve) and non-leading effects (dot-dashed curve)

scheme for the renormalization scale setting [26]. For a full calculation we would need the NLO impact factor, which is not completely known [27]. However, one can use the LO impact factor, assuming that the main energy-dependent NLO corrections come from the NLO BFKL sub-process rather than from the photon impact factors [26]. In order to simulate the NLO effects, we have used a value $\omega_{\mathbb{P}} = 0.37$, shown in the dot-dashed curve of Fig. 3. The effective behavior obtained is given by $W^{4\lambda}$, with $\lambda = 0.29$, which value is somewhat close to $\lambda \simeq 0.23$ – 0.29 obtained in [8].

It is time to compare our estimates with the more refined works in [8] and in [28]. In the former, the most part of the NLO correction comes from considering a kinematical constraint. That is, the effects from restricting the range for the term of real emission in the BFKL equation, imposed upon the available phase space, corresponding to the requirement that the virtuality of the exchanged gluons in the BFKL ladder is dominated by the transverse momentum squared. Such a procedure covers up to 70% of the NLO corrections to the pomeron intercept. As discussed above, our results are similar. In [28], the dipole-dipole approach is considered and predictions to double meson (light and heavy) production are given. There, the result for the total cross section $\gamma\gamma \rightarrow J/\Psi J/\Psi$ is one or two order of magnitude below the one presented here and in [8].

Having determined the $\gamma\gamma$ cross section we can estimate the double J/Ψ cross section in ultraperipheral heavy ion collision [see (3)]. In Fig. 4 we present the energy dependence of the cross section, considering the Pb + Pb collisions and distinct approximations for the $\gamma\gamma$ subprocess. We have found that the LLA BFKL solution predicts large values of cross section for LHC energies in comparison with the Born approximation. Basically, we have that the ratio between the BFKL prediction and the two-gluon cross section is around 40 at $s^{1/2} = 5500 \text{ GeV}$. If the non-leading corrections are considered, as discussed above, we

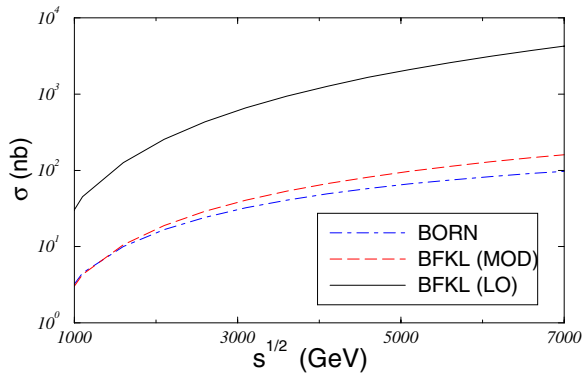


Fig. 4. The estimates for the double J/Ψ production in ultraperipheral heavy ion collisions considering the LLA BFKL solution (solid curve), non-leading effects (dashed curve) and the Born approximation (dot-dashed curve)

see that this ratio is reduced to approximately 1.7. Therefore, our results indicate that if the NLO corrections to the BFKL approach are accounted in the approximation considered here, a future experimental analysis of double J/Ψ production in ultraperipheral heavy ion collisions could not constrain the QCD dynamics, since the BFKL(NLO) result is similar to the Born prediction. Only accurate measurements would allow one to discriminate between the two cases. Moreover, it is important to note that the NLO corrections can be larger, implying a full suppression of energy enhancement associated with the iteration of gluons in the t -channel present in the QCD dynamics at high energies. However, if the energy dependence of the $\gamma\gamma$ cross section would yield a large intercept, closer to the LO prediction, the analyses of ultraperipheral heavy ion collisions can be useful.

Using the results for the cross section shown in Fig. 4 we can estimate the expected number of events for the LHC luminosity. For PbPb collisions with center-of-mass energies equal to $s^{1/2} = 5500$ A GeV, luminosities of $\mathcal{L}_{AA} = 4.2 \times 10^{26} \text{ cm}^{-2}\text{s}^{-1}$ are used. Consequently, during a standard 10^6 s/month heavy ion run at the LHC, we predict approximately 30, 50 and 1100 events for Born, BFKL (MOD) and BFKL (LO), respectively. It is interesting to compare these predictions with the results for double J/Ψ production at LEP2, since the $\gamma\gamma$ center-of-mass energies are similar. Considering an integrated luminosity of 500 pb^{-1} in three years and $s^{1/2} = 175$ GeV, almost 70 events are expected taking into account the non-leading corrections to the BFKL approach [8]. Therefore, we predict a large number of events in ultraperipheral heavy ion collisions, allowing future experimental analyses, even if the acceptance for the J/Ψ detection were low. It should be stressed that the LHC probably will operate in its heavy ion mode only four weeks per year.

Some comments related to background processes are in order here. We did not consider the additional contribution of the pomeron–pomeron process in the present calculations. It has been verified that such reactions would be non-negligible for light ions, while they are significantly suppressed for heavy ions [18]. In the particular case

of the double heavy meson production this contribution deserves more detailed studies, since the current treatments rely on the Regge formalism instead of a QCD approach. An important background for the photon–photon processes is the photonuclear interactions, since the reactions have similar kinematics. For the process considered here, the diffractive J/Ψ production in photon–pomeron interactions [14, 29] should contribute significantly. In particular, because the cross section for this process is large, the probability of having double (independent) production of J/Ψ in a single nucleus–nucleus collision, associated to multiple interactions, is non-negligible [29]. However, in principle, an analysis of the impact parameter dependence should allow one to separate the two classes of reactions, since two-photon interactions can occur at a significant distance from both nuclei, while a photonuclear interaction must occur inside or very near a nucleus. We note that the experimental separation between the two classes of processes is an important point, which deserves more studies. An additional contribution in two-photon ultraperipheral collisions is the meson production accompanied by mutual Coulomb dissociation. It has been estimated that these reactions increase the total cross section by an amount of $\sim 10\%$ at RHIC/LHC energies [30]. We disregarded this contribution in our calculations, since we believe that it is smaller than the theoretical uncertainty, associated, for example, to the choice of the running coupling constant, charm mass, etc.

4 Summary

Dedicated measurements have been proposed for detecting and studying the large $1/x$ logarithm resummation effects in QCD. Experimentally establishing the BFKL effect in the data is very important for the understanding of the high energy limit in QCD scattering. In the last years, many studies with this objective have been realized, but the conclusions are not unambiguous. This situation should be improved in the future with the next generation of linear colliders. As an alternative, in this paper we propose to investigate QCD pomeron effects in a different context, namely, in photon–photon scattering at ultraperipheral heavy ion collisions. We have analyzed the potentiality of this process to constrain the QCD dynamics at high values of energy and provide reliable estimates for the cross sections concerning that reaction. In particular, we analyze in detail the double J/Ψ production, considering distinct approximations for the QCD dynamics. We have a LO BFKL cross section much larger than the two-gluon cross section. Unfortunately, the higher order corrections of the BFKL equation are large, reducing the ratio between BFKL and two-gluon cross section. It makes it difficult to discriminate between non-leading effects and the Born approximation. However, the number of events predicted for LHC is large, allowing a future experimental analysis of this process as well as more detailed studies of the QCD dynamics.

As a last comment, it is important to note that there are limitations on the perturbative treatment that are in-

trinsic to the BFKL equation, which come from the region of very high s . The BFKL equation is known to give rise to violation of the unitarity bound at asymptotically large energies. Consequently, the growth of the cross section predicted by the BFKL equation cannot continue indefinitely, and unitarity corrections (saturation effects) must arise to slow it down. They correspond to multiple bare pomeron exchanges and multi-pomeron interactions, taming the steep increase at high energies. We expect that the inclusion of these effects in our calculations should imply a similar behavior of the non-leading BFKL predictions presented here. More detailed studies related to the unitarity corrections and BFKL dynamics will be analyzed in the sequel of this paper [31], where we calculate the heavy quark production in ultraperipheral heavy ion collisions and investigate the saturation effects in the cross section.

Acknowledgements. The authors thank C.A. Bertulani, S. Klein, A. Natale and C. Roldão for helpful discussions. We are particularly grateful to L. Motyka for his careful reading of the manuscript and for his valuable comments. M.V.T.M. thanks the support of the High Energy Physics Phenomenology Group at the Physics Institute, UFRGS, and the hospitality of the IFM-UFPel, where this work was accomplished. This work was partially financed by the Brazilian funding agencies CNPq and FAPERGS.

References

1. L.N. Lipatov, Sov. J. Nucl. Phys. **23**, 338 (1976); E.A. Kuraev, L.N. Lipatov, V.S. Fadin, JETP **45**, 1999 (1977); I. I. Balitskii, L.N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978)
2. A. De Roeck, Acta Phys. Pol. B **33**, 2749 (2002)
3. J. Bartels, A. De Roeck, H. Lotter, Phys. Lett. B **389**, 742 (1996); A. Bialas, W. Czyz, W. Florkowski, Eur. Phys. J. C **2**, 683 (1998); J. Kwiecinski, L. Motyka, Eur. Phys. J. C **18**, 343 (2000); J. Bartels, C. Ewerz, R. Staritzbichler, Phys. Lett. B **492**, 56 (2000); N.N. Nikolaev, B.G. Zakharov, V.R. Zoller, JETP **93**, 957 (2001)
4. S.J. Brodsky, F. Hautmann, D.E. Soper, Phys. Rev. D **56**, 6957 (1997); Phys. Rev. Lett. **78**, 803 (1997)
5. M. Boonekamp, A. De Roeck, C. Royon, S. Wallon, Nucl. Phys. B **555**, 540 (1999)
6. A.H. Mueller, Nucl. Phys. B **415**, 373 (1994); A.H. Mueller, B. Patel, *ibid.* **425**, 471 (1994); N.N. Nikolaev, B.G. Zakharov, Phys. Lett. B **332**, 184 (1994); Z. Phys. C **64**, 631 (1994)
7. L.F. Ginzburg, S.L. Panfil, V.G. Serbo, Nucl. Phys. B **284**, 685 (1987); **296**, 569 (1988); L.F. Ginzburg, D. Yu. Ivanov, *ibid.* **388**, 376 (1992)
8. J. Kwiecinski, L. Motyka, Phys. Lett. B **438**, 203 (1998); Acta Phys. Pol. B **30**, 1817 (1999)
9. C.A. Bertulani, G. Baur, Phys. Rep. **163**, 299 (1988)
10. G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, Y. Kharlov, Phys. Rep. **364**, 359 (2002)
11. G.P. Salam, Acta Phys. Pol. B **30**, 3679 (1999)
12. F. Gelis, A. Peshier, Nucl. Phys. A **697**, 879 (2002); **707**, 175 (2002)
13. E. Iancu, A. Leonidov, L. McLerran, Nucl. Phys. A **692**, 583 (2001)
14. V.P. Gonçalves, C.A. Bertulani, Phys. Rev. C **65**, 054905 (2002)
15. L. Frankfurt, M. Strikman, M. Zhalov, Phys. Lett. B **537**, 51 (2002); Phys. Lett. B **540**, 220 (2002)
16. C.A. Bertulani, A. Nathan, Nucl. Phys. A **554**, 158 (1993)
17. R.N. Cahn, J.D. Jackson, Phys. Rev. D **42**, 3690 (1990)
18. C.G. Roldão, A.A. Natale, Phys. Rev. C **61**, 064907 (2000)
19. L.N. Lipatov, Sov. Phys. JETP **63**, 904 (1986)
20. J.R. Forshaw, D.A. Ross, Quantum chromodynamics and the pomeron (Cambridge University Press, 1997)
21. M.B. Gay Ducati, W.K. Sauter, Phys. Lett. B **521**, 259 (2001)
22. C. Adloff et al. [H1 Collaboration], Phys. Lett. B **483**, 23 (2000); J. Breitweg et al. [ZEUS Collaboration], Eur. Phys. J. C **6**, 603 (1999)
23. E. Barone, E. Predazzi, High-energy particle diffraction (Springer Verlag, 2002)
24. V. Fadin, L.N. Lipatov, Phys. Lett. B **429**, 127 (1999)
25. M. Ciafaloni, D. Colferai, Phys. Lett. B **452**, 372 (1999)
26. S.J. Brodsky, V.S. Fadin, V.T. Kim, L.N. Lipatov, G.B. Pivovarov, JETP Lett. **70**, 155 (1999); JETP Lett. **76**, 249 (2002)
27. J. Bartels, S. Gieseke, C.F. Qiao, Phys. Rev. D **63**, 056014 (2001); Erratum: **65**, 079902 (2002); J. Bartels, S. Gieseke, A. Kyrieleis, Phys. Rev. D **65**, 014006 (2002); J. Bartels, D. Colferai, S. Gieseke, A. Kyrieleis, Phys. Rev. D **66**, 094017 (2002)
28. A. Donnachie, H.G. Dosch, M. Rueter, Phys. Rev. D **59**, 074011 (1999)
29. S.R. Klein, J. Nystrand, Phys. Rev. C **60**, 014903 (1999)
30. A.J. Baltz, S.R. Klein, J. Nystrand, Phys. Rev. Lett. **89**, 012301 (2002)
31. V.P. Gonçalves, M.V.T. Machado, The QCD pomeron in ultraperipheral heavy ion collisions: II. Heavy quark production, hep-ph/0301263