Quarkonium production in coherent hadron-hadron interactions at the LHC

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The photoproduction of quarkonium in coherent hadron-hadron (pp/pA/AA) interactions for LHC energies is an important tool to investigate the QCD dynamics at high energies. In this paper we estimate the integrated cross section and rapidity distribution for J/\Psi and \Upsilon production using the Color Glass Condensate (CGC) formalism. We predict large rates, implying that the experimental identification could be feasible at the LHC.

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\section{I. INTRODUCTION}

In next future the Large Hadron Collider (LHC) at CERN will start its experimental physics program. Currently, there is a great expectation that LHC shall discover the Higgs boson and whatever new physics beyond the Standard model that may accompany it, such as supersymmetry or extra dimensions \cite{1}. However, several questions remain open in the Standard Model, which will be probed in a new kinematical regime at the LHC and determine the background for new physics. In particular, the description of the high energy regime of the Quantum Chromodynamics (QCD) still is a subject of intense debate (For recent reviews see e.g. Ref. \cite{2}). Theoretically, at high energies (small Bjorken-x) one expects the transition of the regime described by the linear dynamics, where only the parton emissions are considered, to a new regime where the physical process of recombination of partons becomes important in the parton cascade and the evolution is given by a nonlinear evolution equation. This regime is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wavefunction (parton saturation), with the transition being specified by a typical scale, which is energy dependent and is called saturation scale \(Q_{\text{sat}}\) \cite{2}. Experimentally, possible 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. Ref. \cite{3,4}). Although the geometrical scaling and the diffractive events observed at HERA, as well as the high-p_{T} suppression observed at RHIC, have a natural interpretation in terms of the saturation physics, none of these phenomena can be taken as a conclusive evidence for a new regime of the QCD dynamics. This is due to the kinematical limitations of the experiments. Consequently, the observation of this new regime still needs confirmation and so there has been an active search for new experimental signatures.

In the last years we have proposed the analysis of coherent hadron-hadron collisions as an alternative way to study the QCD dynamics at high energies \cite{5,6,7,8,9,10}. The basic idea in coherent 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. The main advantage of using colliding hadrons and nuclear beams for studying photon induced interactions is the high equivalent photon energies and luminosities that can be achieved at existing and future accelerators (For a review see Ref. \cite{11}). Consequently, studies of \(\gamma p\) interactions at LHC could provide valuable information on the QCD dynamics at high energies. 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 \(\gamma h \rightarrow Vh\) (\(V = \rho, J/\Psi, \Upsilon\)), and the inclusive heavy quark production (HQQ) \(\gamma h \rightarrow XY\) \((X = c\bar{c}, b\bar{b})\), respectively. Recently, we have discussed both processes considering pp, pA and AA collisions as an alternative to constrain the QCD dynamics at high energies (For recent reviews see Refs. \cite{12,13}). Our results demonstrate that their detection is feasible at the LHC. However, some of these results were obtained considering the saturation model proposed by Golec-Biernat and Wüsthoff (GBW) several years ago \cite{14}. That model has been improved recently considering the current state-of-the-art of saturation physics: the Color Glass Condensate (CGC) formalism \cite{15,16,17}. This fact motivates a revision of some of our previous estimates. In particular, in this paper we revise our predictions for J/\Psi production in coherent pp/pA/AA collisions. Another goal is to present, for the first time, predictions for the \(\Upsilon\) production in coherent collisions considering the CGC formalism.

This paper is organized as follows. In next section (Section \ref{sec:II}) we present a brief review of coherent hadron-hadron interactions, introducing the main formulae. In Section \ref{sec:III} we discuss the QCD dynamics and the saturation model used in the calculations. In Section \ref{sec:IV} we compare our predictions for the \(\gamma p\) cross section with the
HERA data and present the predictions for quarkonium production in hadron-hadron interactions. Moreover, we compare the current results to related approaches available in the literature. Finally, in Section V we summarize our main results and conclusions.

II. COHERENT HADRON-HADRON INTERACTIONS

Let us consider the hadron-hadron interaction at large impact parameter \( b > R_{h_1} + R_{h_2} \) and at ultra relativistic energies. In this regime we expect the electromagnetic interaction to be dominant. In heavy ion colliders, the heavy nuclei give rise to strong electromagnetic fields due to the coherent action of all protons in the nucleus, which can interact with each other. In a similar way, it also occurs when considering ultra relativistic protons in \( pp(\bar{p}) \) colliders. The photon stemming from the electromagnetic field of one of the two colliding hadrons can interact with one photon of the other hadron (two-photon process) or can interact directly with the other hadron (photon-hadron process). One has 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 \[ \] in the literature. Finally, in Section V we summarize our main results and conclusions.

by,

\[ \sigma(h_1 h_2 \rightarrow XY) = \int_{\omega_{\text{min}}}^{\infty} d\omega \int dt \frac{dN_s(\omega)}{d\omega} \frac{d\sigma}{dt}(W_{\gamma p}, t) \]

where \( \frac{d\sigma}{dt} \) is the differential cross section for the process \( (\gamma h \rightarrow Xh), \omega_{\text{min}} = M_X^2/4\gamma_L m_p, W_{\gamma p}^2 = 2\omega/\sqrt{S_{\text{NN}}} \) and \( \sqrt{S_{\text{NN}}} \) is the c.m.s energy of the hadron-hadron system. Some comments are in order here. Firstly, the coherence condition limits the photon virtuality to very low values, which implies that for most purposes, they can be considered as real. Moreover, if we consider \( pp/p\bar{p}/p\bar{p} \) collisions at LHC, the Lorentz factor is \( \gamma_L = 7455/4690/2930 \), giving the maximum c.m.s. \( \gamma N \) energy \( W_{\gamma p} \approx 8390/1500/950 \) 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 one order of magnitude higher on energy. Consequently, studies of coherent interactions at the LHC could provide valuable information on the QCD dynamics at high energies. Secondly, in \( pA \) interactions one have that due to the asymmetry in the collision, with the ion being likely the photon emitter, the photon direction is known, which will implicate an asymmetry in the rapidity distribution (see below). Finally, in this work we consider that the produced state \( X \) represents a quarkonium \( (J/\Psi \text{ or } \Upsilon) \). Since photon emission is coherent over the entire nucleus and the photon is colorless we expect that the events to be characterized by \( Y = h_1 h_2 \) and two rapidity gaps.

III. QCD DYNAMICS AT HIGH ENERGIES

Let us consider photon-hadron scattering in the dipole frame, in which most of the energy is carried by the hadron, while the photon has just enough energy to dissociate into a quark-antiquark pair before the scattering. In this representation the probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation \( r \) long after the interaction, which then scatters off the hadron \[ \text{Dipole picture} \]. In the dipole picture the amplitude for vector meson production reads as (See e.g. Refs. [19, 20, 21])

\[ A(x, \Delta) = \sum_{n, \bar{n}} \int d^2 r \Psi_{n, \bar{n}}^\gamma(x, r, \Delta) \Psi_{n, \bar{n}}^{\psi \bar{\psi}} \]

where \( \Psi_{h, \bar{h}}^\gamma(z, r) \) and \( \Psi_{h, \bar{h}}^{\psi \bar{\psi}}(z, r) \) are the light-cone wavefunction of the photon and of the vector meson, respectively. The quark and antiquark helicities are labeled by \( n \) and \( \bar{n} \), variable \( r \) defines the relative transverse separation of the pair (dipole), \( z = 1 - z \) is the longitudinal momentum fractions of the quark (antiquark), \( \Delta \) denotes the transverse momentum lost by the outgoing proton \( (t = -\Delta^2) \) and \( x \) is the Bjorken variable. Moreover, \( A_{\gamma \bar{\psi}} \) is the elementary amplitude for the scattering of a dipole
of size \( r \) on the target. It is directly related to the \( S \)-matrix element \( S(x, r, b) \) and consequently to the QCD dynamics (see below). One has that \[21\]

\[
A_{\gamma p}(x, r, \Delta) = i \int d^2 b e^{-i b \cdot \Delta} 2[1 - S(x, r, b)]
\]

\[
= i \int d^2 b e^{-i b \cdot \Delta} \frac{d\sigma_{\gamma p}}{d^2 b}, \quad (5)
\]

where one has introduced the differential dipole-target cross section. Consequently, one can express the amplitude for the photoproduction of a vector meson in the final state as follows

\[
A(x, \Delta) = i \int d^2 z d^2 r e^{-i b \cdot \Delta} \Delta (\Psi_v^* \Psi_v) T \frac{d\sigma_{\gamma p}}{d^2 b} \quad (6)
\]

where \( T \) denotes the transverse polarization and one takes into account non-forward corrections to the wave functions \[22\]. Finally, the differential cross section for vector meson photoproduction is given by

\[
\frac{d\sigma}{dt}(\gamma h \to V h) = \frac{1}{16\pi} |A(x, \Delta)|^2 (1 + \beta^2), \quad (7)
\]

where \( \beta \) is the ratio of real to imaginary parts of the scattering amplitude. For the case of heavy mesons, skewness corrections are quite important and they are also taken into account. (For details, see Refs. \[20, 21\]).

The photon wavefunctions appearing in Eq. (6) are well known in literature \[21\]. For the meson wavefunction, we have considered the Gauss-LC model \[21\] which is a simplification of the DGKP wavefunctions. The motivation for this choice is its simplicity and the fact that the results are sensitive to a different model. In photoproduction, this leads only to an uncertainty of a few percent in overall normalization. We consider the quark masses \( m_u = 1.4 \text{ GeV} \) and \( m_d = 4.2 \text{ GeV} \). The parameters for the meson wavefunction can be found in Ref. \[21\] for the \( J/\Psi \) case. Accordingly, we have computed the parameters for the \( \Upsilon \) case.

The \( S \)-matrix element \( S(x, r, b) \) contains all information about the target and the strong interaction physics. In the Color Glass Condensate (CGC) formalism \[13, 16, 17\], it encodes all the information about the non-linear and quantum effects in the hadron wave function. It can be obtained by solving an appropriate evolution equation in the rapidity \( y \equiv \ln(1/x) \) and its main properties are: (a) for the interaction of a small dipole \( (r \ll 1/Q_{\text{sat}}) \), \( S(r) \approx 1 \), which characterizes that this system is weakly interacting; (b) for a large dipole \( (r \gg 1/Q_{\text{sat}}) \), the system is strongly absorbed which implies \( S(r) \ll 1 \). This property is associate to the large density of saturated gluons in the hadron wave function. In our analysis we will consider the saturation model proposed in Ref. \[21\] which generalizes the Iancu-Itakura-Munier (IIM) model \[23\], introducing the impact parameter dependence. In this model the differential dipole-proton cross section is parameterized by

\[
\frac{d\sigma_{\gamma p}}{d^2 b} = 2N_p(x, r, b), \quad \text{where}
\]

\[
N_p(x, r, b) = \begin{cases} 
N_0 \left( \frac{r}{4} \right)^{\gamma_{\text{eff}}}(x, r), & \text{for } \bar{\tau} \leq 2, \\
1 - \exp \left[ -a \ln^2 (b \bar{\tau}) \right], & \text{for } \bar{\tau} > 2,
\end{cases}
\]

\( \bar{\tau} = r Q_{\text{sat}}(x, b) \) and the saturation scale is given by \( Q_{\text{sat}}(x, b) = (x_0/x)^{\lambda/2} \exp(-b^2/2B_{\text{CGC}}) \). The expression for \( \bar{\tau} > 2 \) (saturation region) has the correct functional form, as obtained from the theory of the Color Glass Condensate (CGC) \[13\]. Moreover, \( \gamma_{\text{eff}} = \gamma_{\text{sat}} + \ln(2/x) \) is the effective anomalous dimension, which determines the behavior of the dipole cross section in the color transparency regime \( \bar{\tau} < 2 \) and introduces evolution effects not included in the GBW model. The original parameters of the IIM model were reanalyzed in Ref. \[21\] and are now given by: \( \lambda = 0.159, x_0 = 5.95 \times 10^{-4}, N_0 = 0.417, m_{u/d/s} = 0.14 \text{ GeV} \) and \( m_c = 1.4 \text{ GeV} \). Moreover, we assume in our calculations \( B_{\text{CGC}} = 5.5 \text{ GeV}^{-2} \). Hereafter, we label this model by b-CGC. The corresponding dipole-proton cross section is given by \( \sigma_{\gamma p}(x, r) = 2 \int d^2 b N_p(x, r, b) \).

For photon-nucleus interactions it is possible to extend the b-CGC model described above using the Glauber-Gribov formalism \[24\]. In this case, the nuclear scattering amplitude \( N_A(x, r, b) \) will be parameterized as follows

\[
N_A(x, r, b) = \left\{ 1 - \exp \left[ -\frac{1}{2}AT_A(b) \sigma_{\gamma p}(x, r) \right] \right\},
\]

where \( T_A(b) \) is the nuclear profile function, which will be obtained from a 3-parameter Fermi distribution for the nuclear density.

**IV. RESULTS**

In Fig. 1 we present the predictions of the GBW and b-CGC models for the quarkonium photoproduction at
HERA and compare it with the current experimental data [25, 26]. In particular, it is the first time that the b-CGC model is explicitly compared to the HERA data on vector meson production \(J/\Psi\) and \(\Upsilon\). We have that in the HERA kinematical range both predictions are similar and describe the experimental data. However, these are distinct at larger energies, mainly in the \(J/\Psi\) case. This result motivates the reanalyzes of our previous predictions for \(J/\Psi\) production in coherent hadron-hadron interactions [7, 9]. Moreover, the description of the \(\Upsilon\) production implies that the saturation models are suitable to be used in the calculations of this final state in coherent \(pp/pA/AA\) collisions.

Let us calculate the rapidity distribution and total cross sections for quarkonium production in coherent hadron-hadron collisions. The distribution on rapidity \(y\) of the produced final state can be directly computed from Eq. [3], by using its relation with the photon energy \(\omega\), i.e. \(y \propto \ln(2\omega/m_X)\). Explicitly, the rapidity distribution is written down as,

\[
\frac{d\sigma}{dy} \left[ h_1 + h_2 \to h_1 \otimes X \otimes h_2 \right] = \omega \frac{dN_{\gamma}(\omega)}{d\omega} \sigma_{\gamma h_1 \to Xh_2}(\omega) \tag{8}
\]

where \(\otimes\) represents the presence of a rapidity gap. Consequently, given the photon flux, the rapidity distribution is thus a direct measure of the photoproduction cross section for a given energy. In Fig. 2 and 3 we present respectively our predictions for \(J/\Psi\) and \(\Upsilon\) production in coherent \(pp/pA/AA\) collisions, considering \(A = Pb\) and \(\sqrt{s_{NN}} = 14/8.8/5.5\) TeV, respectively. In the \(pp\) case, the production at mid-rapidity at the LHC probes \(x\)-values of order \((2-7) \times 10^{-4}\). In the \(AA\) case, one gets \((6-20) \times 10^{-4}\).

For \(pA\) collisions we have an asymmetric rapidity distribution since the electromagnetic field surrounding the ion is very larger than the proton one, due to the coherent action of all protons in the nucleus. As a consequence, the photon direction is known. In contrast, for \(pp\) and \(AA\) collisions we have symmetric rapidity distributions. In Table I one presents the correspondent integrated cross sections (event rates), using the expected luminosities. For comparison, we also present our predictions for quarkonium in the ultraperipheral collision of light nuclei. These results can be contrasted with those obtained for \(J/\Psi\) production in Refs. [7, 9, 27, 28, 29]. Firstly, in comparison to our previous estimates for \(J/\Psi\) production in coherent \(pp\) and \(AA\) collisions [7], we have that the b-CGC predictions are almost identical to those obtained using the GBW model. It is directly associated to the fact that the main contribution for the total cross section comes from low energies, where the predictions of the GBW and b-CGC models for the quarkonium \(\gamma p\) production are very similar. In comparison to the estimates obtained in Ref. [28], our results give higher cross section by a factor of order 11\% for Ca nucleus and are almost similar for Pb nucleus. On the other hand, in comparison with Ref. [29] our results are almost 16\% lower for Ca and 41\% lower for Pb. As explained in detail in Ref. [7], the difference between the predictions comes mainly from the distinct QCD approaches used and the different photon flux considered in the calculations. Concerning the \(J/\Psi\) production in coherent \(pp\) collisions, we have that in comparison to that obtained in Ref. [27] our prediction is almost 11\% larger. Finally, for \(pA\) collisions, we have that our predictions are almost 12\% smaller than those obtained in [9], where we have used the IIM model [22], which does not consider the impact parameter dependence of the scattering amplitude.
Let us consider now the $\Upsilon$ production. In this case, our estimate for $pA$ are original in the literature using the CGC approach. In contrast, for $pp$ and $AA$ collision it can be compared with those from Refs. \[27, 30\]. In comparison with Ref. \[27\] we have that our results for $pp$ ($PbPb$) are approximately a factor 4 (2) smaller. This large difference is directly associated to the very steep parameterization used in Ref. \[27\] for the $\gamma p$ cross section ($\sigma_{\gamma p} \propto W^{1.7}$). On the other hand, our predictions for $\Upsilon$ production in $PbPb$ collisions are approximately 30 \% smaller than those obtained in Ref. \[30\] considering the impulse approximation. In comparison with the prediction obtained using the Glauber plus leading twist approximation, our result is approximately 20 \% larger.

Finally, two comments concerning the model used to described the vector meson production and the hadroproduction of vector mesons are in order. Firstly, the vector meson production in general is described by quite distinct approaches for light and heavy mesons. In the light meson case, the old vector meson dominance (VMD) model is often adopted \[28\], whereas for the heavy mesons a leading logarithmic approximation of the collinear approach is considered \[29\]. In this case, the hard QCD scale is given by the vector meson mass. On the other hand, the dipole picture and saturation physics approach used in this paper is the unique theoretical formalism available that describes simultaneously light and heavy vector meson production \[20\], with the transition between light and heavy mesons being dynamically introduced by parton saturation effects (via saturation scale) in the target. Secondly, the vector mesons can also be produced in inclusive and exclusive hadron - hadron interactions. In comparison with inclusive vector meson production, which is characterized by the process $h_1 + h_2 \rightarrow V + X$ (For recent reviews see, e.g., \[31, 32\]), one have that the photoproduction cross section is smaller by approximately three order of magnitudes for proton-proton collisions. For nuclear collisions, this factor is smaller due to presence of shadowing corrections. Although the photoproduction cross section would be a small factor of the hadronic cross section, the separation of this channel is feasible if we impose the presence of two rapidity gaps in the final state. This should eliminate almost all of the hadroproduction events while retaining most of the photoproduction interactions. However, two rapidity gaps in the final state can also be generated in exclusive hadron - hadron interactions, characterized by the process $h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2$. Recently, the exclusive $J/\Psi$ and $\Upsilon$ hadroproduction in $pp/\bar{p}\bar{p}$ collisions were estimated in Ref. \[33\] considering the pomeron-odderon fusion (See also \[34\]). Although there is a large uncertainty in the predictions for pomeron-odderon fusion, it can be of order of our predictions for the photoproduction of vector mesons. As pointed in Ref. \[33\] the separation of odderon and photon contributions should be feasible by the analysis of the outgoing momenta distribution. However, this subject deserves more detailed studies, which we postpone for a future publication.

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. If such system there exists at high energies it can be proven in coherent $pp/pA/AA$ collisions at LHC. In this paper we have analyzed the quarkonium production considering the most recent phenomenological saturation model and demonstrate that it describes the HERA data. We have investigated the $J/\Psi$ and $\Upsilon$ production in coherent hadron-hadron collisions and showed that the experimental identification could be feasible.

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