PHYSICAL REVIEW D **91,** 094014 (2015)

η_c production in photon-induced interactions at a fixed target experiment at LHC as a probe of the odderon

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(Received 3 April 2015; published 13 May 2015)

One of the open questions of the strong interaction theory is the existence of the odderon, which is an unambiguous prediction of quantum chromodynamics, but still not confirmed experimentally. An alternative to probe the odderon is the exclusive η_c photoproduction in hadronic collisions. As the Pomeron exchange cannot contribute to this process, its observation would indicate the existence of the odderon. In this paper we estimate the η_c production in photon-induced interactions in hadronic collisions at the AFTER@LHC experiment. We demonstrate that the experimental analysis of this process is feasible in the AFTER@LHC experiment and that the observation of the η_c production in nuclear collisions is an unambiguous signature of the odderon.

DOI: 10.1103/PhysRevD.91.094014 PACS numbers: 12.38.Aw, 13.85.Lg, 13.85.Ni

I. INTRODUCTION

The AFTER@LHC experiment opens a new kinematical regime where several questions related to the description of quantum chromodynamics (QCD) remain without satisfactory answers [1]. One of these open questions is the odderon, which is a natural prediction of the QCD and which determines the hadronic cross section difference between the direct and crossed channel processes at very high energies. (For a review see Ref. [2].) The current experimental evidence for the odderon is rather scarce. A recent study of the data on the differential elastic pp scattering shows that one needs the odderon to describe the cross sections in the dip region [3] (see also Refs. [4,5]). The difficulties inherent in the description of pp and $p\bar{p}$ collisions and the lack of further data have made it impossible to establish the existence of the odderon in these processes beyond a reasonable doubt.

An alternative to probe the odderon is the study of the diffractive photoproduction of pseudoscalar mesons in hadronic collisions [6]. As the real photon emitted by one of the incident hadrons carries negative C parity, its transformation into a diffractive final state system of positive C parity requires the t-channel exchange of an object of negative C parity. In perturbative QCD, the odderon is a C-odd (C being the charge conjugation) compound state of three Reggeized gluons, with evolution described by the Bartels-Kwiecinski-Praszalowicz (BKP) equation [7], which resums terms of the order $\alpha_s(\alpha_s \log s)^n$ with arbitrary n in which three gluons in a $C = -1$ state are exchanged in the t channel. In contrast, the Pomeron corresponds to a C-even parity compound state of two t-channel Reggeized gluons, given by the solution of the Balitsky-Fadin-Kuraev-Lipatov equation [8]. Consequently, the Pomeron exchange cannot contribute to the production of pseudoscalar mesons and this process can only be mediated by the exchange of an odderon. A particularly promising process is the exclusive η_c photoproduction, since the meson mass provides a hard scale that makes a perturbative calculation possible [9,10].

In what follows we extend the analysis performed in Ref. [6] for the kinematical range probed by the AFTER@LHC experiment. In particular, we estimate the cross sections for the η_c production in photon-induced interactions present in pp, pA and AA collisions. The basic idea is that in hadron-hadron collisions at large impact parameter ($b > R_{h_1} + R_{h_2}$) and at ultrarelativistic energies the electromagnetic interaction is dominant [11]. In heavy ion collisions, 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 ultrarelativistic protons in pp collisions. The photon stemming from the electromagnetic field of one of the two colliding hadrons can interact with one photon of the other hadron (the two-photon process) or can interact directly with the other hadron (the photon-hadron process). Consequently, the η_c can be produced in photon-hadron (γh) and photon-photon ($\gamma\gamma$) interactions, with both processes generating two rapidity gaps in the final state. While the η_c production in γh interactions represented in Fig. 1 is a direct probe of the odderon, its production in $\gamma\gamma$ interactions (see Fig. 2) is an important background, which should be estimated in order to separate the signal associated with the odderon.

This paper is organized as follows. In Sec. II we present a brief review of the main concepts and formulas used in the description of $\gamma\gamma$ and γh interactions in hadronic collisions and in the exclusive η_c photoproduction, which are required

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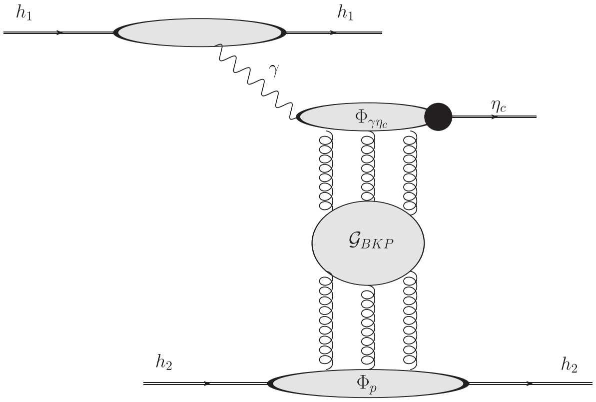

FIG. 1. η_c production in photon-hadron interactions at the AFTER@LHC experiment.

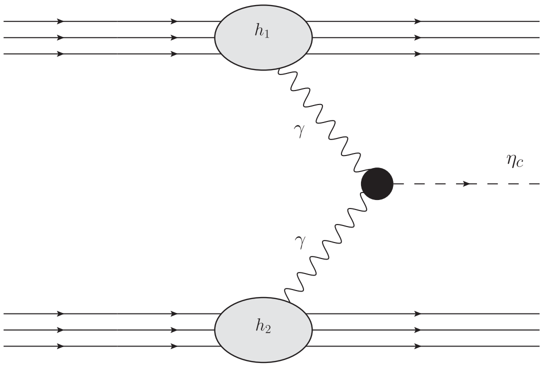

FIG. 2. η_c production in photon-photon interactions at the AFTER@LHC experiment.

to explain our results, which will presented in Sec. III. Finally, in Sec. IV we summarize our main conclusions.

II. PHOTON-INDUCED INTERACTIONS IN HADRONIC COLLIDERS

In hadronic collisions at large impact parameter and at ultrarelativistic energies the photon-induced cross sections for a given process can be factorized in terms of the equivalent flux of photons of the incident hadrons and the photon-photon or photon-target production cross section [11]. The recent experimental results from CDF [12] at Tevatron, STAR [13] and PHENIX [14] at RHIC and ALICE [15,16] and LHCb [17,18] at LHC for photon-induced processes in hadronic collisions have demonstrated that a detailed analysis is feasible and that the data can be used to constrain the description of the hadronic structure at high energies [19] as well as to probe possible scenarios for the physics beyond the Standard Model [20]. These results motivate a detailed analysis of other final states in photon-induced interactions.

Let us initially consider the η_c production in $\gamma\gamma$ interactions. The cross section for the exclusive η_c production in the two-photon fusion process, Fig. 2, is given by [21]

$$\sigma[h_1 h_2 \xrightarrow{(\gamma\gamma)} h_1 \otimes \eta_c \otimes h_2] = \int_0^\infty \frac{d\omega_1}{\omega_1} \int_0^\infty \frac{d\omega_2}{\omega_2} F(\omega_1,\omega_2) \hat{\sigma}_{\gamma\gamma\to\eta_c}(\omega_1,\omega_2) \tag{1}$$

where $\otimes$ represents a rapidity gap in the final state, ω_1 and ω_2 the energy of the photons which participate in the hard process and $\hat{\sigma}_{\gamma\gamma\to\eta_c}$ is the cross section for the subprocess $\gamma\gamma \to \eta_c$, given by

$$\sigma_{\gamma\gamma\to\eta_c} = 8\pi^2(2J+1)\frac{\Gamma_{\eta_c\to\gamma\gamma}}{m_{\eta_c}}\delta(4\omega_1\omega_2 - m_{\eta_c}^2), \tag{2}$$

where J, m_{η_c} and $\Gamma_{\eta_c\to\gamma\gamma}$ are the spin, the mass and the photon-photon partial decay width of the η_c, respectively, and the δ function enforces energy conservation. Moreover, the function F is the folded spectra of the incoming particles (which corresponds to an "effective luminosity" of photons) which we assume to be given by [22]

$$F(\omega_1,\omega_2) = 2\pi \int_{R_{h_1}}^\infty db_1 b_1 \int_{R_{h_2}}^\infty db_2 b_2 \int_0^{2\pi} d\phi N_1(\omega_1, b_1) \times N_2(\omega_2, b_2)\Theta(b - R_{h_1} - R_{h_2}) \tag{3}$$

where b_i are the impact parameters of the hadrons in relation to the photon interaction point, ϕ is the angle between $\mathbf{b}_1$ and $\mathbf{b}_2$, R_i are the projectile radii and $b^2 = b_1^2 + b_2^2 - 2b_1 b_2 \cos\theta$. The theta function in Eq. (3) ensures that the hadrons do not overlap [22]. The Weizsäcker-Williams photon spectrum for a given impact parameter is given in terms of the nuclear charge form factor $F(k_\perp^2)$, where $k_\perp$ is the four-momentum of the quasireal photon, as follows [11]:

$$N(\omega,\boldsymbol{b}) = \frac{\alpha Z^2}{\pi^2\omega}\left| \int_0^{+\infty} dk_\perp k_\perp^2 \frac{F((\frac{\omega}{\gamma})^2 + \vec{b}^2)}{(\frac{\omega}{\gamma})^2 + \vec{b}^2} \cdot J_1(bk_\perp) \right|^2, \tag{4}$$

where J_1 is the Bessel function of the first kind. For a pointlike nucleus one obtains that [11]

$$N(\omega,\boldsymbol{b}) = \frac{\alpha_{\mathrm{em}} Z^2}{\pi^2}\left(\frac{\xi}{b}\right)^2 \left\{ K_1^2(\xi) + \frac{1}{\gamma^2} K_0^2(\xi) \right\}, \tag{5}$$

with $K_{0,1}$ being the modified Bessel function of the second kind, $\xi = \omega b/\gamma v$, v the velocity of the hadron, γ the Lorentz factor and α_{em} the electromagnetic coupling constant. This expression have been derived considering a semiclassical description of the electromagnetic interactions in peripheral collisions, which works very well for heavy ions (see e.g. [21]). For protons, it is more appropriate to obtain the equivalent photon spectrum from its elastic form factors in the dipole approximation (see e.g. [23]). An alternative is to use Eq. (5) assuming $R_p = 0.7$ fm for the proton radius, which implies good agreement with the parametrization of the luminosity obtained in [24] for proton-proton collisions (for a more detailed discussion see Ref. [25]).

In the case of η_c production in photon-hadron interactions the total cross section is given by

$$\sigma[h_1 h_2 \xrightarrow{(\gamma h)} h_1 \otimes \eta_c \otimes h_2] = \sum_{i=1,2} \int dY \frac{d\sigma_i}{dY}, \qquad (6)$$

where $d\sigma_i/dY$ is the rapidity distribution for the photon-target interaction induced by the hadron h_i, which can be expressed as

$$\frac{d\sigma_i}{dY} = \omega n_{\gamma/h_i}(\omega) \cdot \sigma_{\gamma h_j \to \eta_c h_j}(W^2_{\gamma h_j}) \quad (i \neq j), \qquad (7)$$

where $W^2_{\gamma h} = 2\omega\sqrt{s_{\rm NN}}$ and $s_{\rm NN}$ are the c.m. system energy squared of the photon-hadron and hadron-hadron system, respectively. Moreover, $n_{\gamma/h_i}(\omega)$ is the $\boldsymbol{b}$-integrated photon flux associated with the hadron h_i, which can be obtained considering the requirement that the photon-induced processes are not accompanied by a hadronic interaction (an ultraperipheral collision). An analytic approximation for the equivalent photon flux of a nucleus can be calculated, which is given by [11]

$$\begin{aligned} n_{\gamma/A}(\omega) &= \int_{b_{\rm min}} d^2\boldsymbol{b} N(\omega, \boldsymbol{b}) \\ &= \frac{2Z^2\alpha_{\rm em}}{\pi\omega}\left[\bar\eta K_0(\bar\eta)K_1(\bar\eta) + \frac{\bar\eta^2}{2}\mathcal{U}(\bar\eta)\right] \qquad (8) \end{aligned}$$

where $\bar\eta = \omega b_{\rm min}/\gamma_L$ (with γ_L being the Lorentz boost of a single beam), $b_{\rm min} = R_{h_1} + R_{h_2}$ and $\mathcal{U}(\bar\eta) = K_1^2(\bar\eta) - K_0^2(\bar\eta)$. On the other hand, for proton-proton collisions, we assume that the photon spectrum of a relativistic proton is given by [26]

$$\begin{aligned} n_{\gamma/p}(\omega) &= \frac{\alpha_{\rm em}}{2\pi\omega}\left[1 + \left(1 - \frac{2\omega}{\sqrt{S_{NN}}}\right)^2\right] \\ &\quad \cdot \left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right), \qquad (9) \end{aligned}$$

where $\Omega = 1 + [(0.71\ {\rm GeV}^2)/Q^2_{\rm min}]$ and $Q^2_{\rm min} = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{s_{NN}})] \approx (\omega/\gamma_L)^2$.

The exclusive η_c photoproduction, which is the main input in our calculations [see Eq. (7)] can be obtained using the impact factor representation, proposed by Cheng and Wu [27] many years ago. In this representation, the amplitude for a large-s hard collision process can be factorized in three parts: the two impact factors of the colliding particles and the Green's function for the three interacting Reggeized gluons, which is determined by the BKP equation and is represented by $\mathcal{G}_{\rm BKP}$ hereafter. The differential cross section for the process $\gamma + h \to \eta_c + h$ is given by [9]

$$\frac{d\sigma}{dt} = \frac{1}{32\pi} \sum_{i=1,2} |\mathcal{A}^i|^2, \qquad (10)$$

where $\mathcal{A}^i$ is the amplitude for a given transverse polarization i of the photon, which can be expressed as a convolution of the impact factors for the proton (Φ_p) and for the $\gamma\eta_c$ transition ($\Phi^i_{\gamma\eta_c}$) with the odderon Green's function:

$$\mathcal{A}^i = \frac{5}{1152}\frac{1}{(2\pi)^8}\langle \Phi^i_{\gamma\eta_c}|\mathcal{G}_{\rm BKP}|\Phi_p\rangle. \qquad (11)$$

Different from $\Phi^i_{\gamma\eta_c}$, which can be calculated perturbatively [10], the impact factor Φ_p that describes the coupling of the odderon to the proton is nonperturbative and should be modeled. In our calculations we consider the model used in Refs. [9,10]. Moreover, we assume that the odderon Green's function $\mathcal{G}_{\rm BKP}$ is described in terms of the solution of the BKP equation [7], with the energy dependence being determined by the odderon intercept α_{IO}. In particular, we consider the solution obtained by Bartels, Lipatov and Vacca [28] that have found a solution for the BKP equation with intercept α_{IO} exactly equal to one. For comparison we also consider the solution obtained by Kwiecinski and his collaborators in Ref. [10] (the Czyzewski-Kwiecinski-Motyka-Sadzikowski (CKMS) model hereafter), which has considered a simplified three gluon exchange model for the odderon that implies an energy independent cross section. In our calculations we will use a realistic value for $\alpha_s (= 0.3)$.

III. RESULTS

In what follows we present our predictions for the η_c production in γh and $\gamma\gamma$ interactions considering the kinematical range which will be probed by the AFTER@LHC experiment. Basically, we assume $\sqrt{s_{NN}} = 115/72/72$ GeV for $pp/Pbp/PbPb$ collisions, which implies that $\sqrt{s_{\gamma h}} \le 44/12/9$ GeV, respectively. Similarly, it is possible to obtain that $\sqrt{s_{\gamma\gamma}} \le 17/2.0/1.0$ GeV. Consequently, the η_c production in $\gamma\gamma$ interactions only is present in pp collisions. In other words, the measurement of the exclusive η_c production in Pbp and $PbPb$ collisions can be considered a direct probe of the odderon. Moreover, in our calculations we take into account that the typical rapidity range which is expected to be reachable by the AFTER@LHC experiment is $-3.0 \le Y_{c.m.} \le 0.5$.

In Table I we present our predictions for the total cross sections. We predict cross sections for the η_c production in Pbp and $PbPb$ collisions that are a factor $\gtrsim 10^4$ larger than the pp predictions. This enhancement is directly associated with the nuclear photon flux and the nuclear dependence of the photon-hadron cross section. As the photon flux is proportional to Z^2, because the electromagnetic field surrounding the ion is very much larger than the proton one due to the coherent action of all the protons in the nucleus, the Pbp and $PbPb$ cross sections are amplified by this factor. Moreover, our predictions for the η_c production in $PbPb$ collisions also are amplified by the mass number A, since in our calculations for the nuclear case we are assuming in a first approximation that $\sigma(\gamma A \to \eta_c A) = A.\sigma(\gamma p \to \eta_c p)$. For the exclusive η_c production in pp collisions we predict values of the order of a fraction of a pb, with the Bartels-Braun-Colferai-Vacca (BBVC) prediction being a factor of ≈6 larger than the CKMS one. This enhancement is directly associated with the energy dependence present in the BBVC model, which implies that the γh cross section increases at smaller energies, while the CKMS predicts an energy independent cross section. For the η_c production in Pbp and $PbPb$ collisions, we predict cross sections of the order of a nb for the exclusive η_c photoproduction in $PbPb$ collisions at the AFTER@LHC experiment. Moreover, we predict that the Pbp cross sections are 2 orders of magnitude smaller than those predicted for $PbPb$ collisions.

Let us now estimate the background associated with the η_c production in $\gamma\gamma$ interactions for pp collisions. Assuming that the photon spectrum for the proton is given by Eq. (5), with $R_p = 0.7$ fm, $m_{\eta_c} = 2.983$ GeV and $\Gamma(\eta_c \to \gamma\gamma) = 5.0$ keV, we predict that $\sigma[pp \xrightarrow{(\gamma\gamma)} p \otimes \eta_c \otimes p] = 2.2$ pb, which is a factor $\gtrsim 8$ larger than the predictions for the η_c production in photon-hadron interactions. As both processes generate two rapidity gaps in the final state, the detection of the gaps is not, in the first analysis, an efficient trigger for the separation of the γh production of the η_c. An alternative is the reconstruction of the entire event with a cut on the summed transverse momentum of the event [23]. As the typical photon virtualities are very small, the hadron scattering angles are very low. Consequently, we expect that a different transverse momentum distribution of the scattered hadron, with γh interactions predicting larger p_T values. In contrast, the background is not present in nuclear collisions, since the maximum $\gamma\gamma$ center-of-mass energies in Pbp and $PbPb$ collisions are smaller than the threshold of production.

Considering the design luminosities at the AFTER@LHC for pp ($\mathcal{L}_{\rm pp} = 2 \times 10^4$ pb^{-1} yr^{-1}), Pbp ($\mathcal{L}_{\rm Pbp} = 1.1$ pb^{-1} yr^{-1}) and $PbPb$ collisions ($\mathcal{L}_{\rm PbPb} = 7.0 \times 10^{-3}$ pb^{-1} yr^{-1}) we can calculate the production rates (see Table I). Although the cross section for the exclusive η_c photoproduction in $PbPb$ collisions is much larger than in pp collisions, the event rates are higher in the pp mode due to its larger luminosity. In particular, we predict that the event rates/year for pp collisions at $\sqrt{s} = 115$ GeV should be larger than 1000. On the other hand, for Pbp and $PbPb$ collisions at $\sqrt{s} = 72$ GeV we predict that the event rates/year should be larger than 30. Although smaller than the pp predictions, the observation of the η_c production in nuclear collisions would clearly indicate the existence of the odderon.

TABLE I. Cross sections (event rates/year) for the exclusive η_c photoproduction in $pp/Pbp/PbPb$ collisions at the AFTER@LHC experiment.

h_1h_2	CKMS	BBCV
$pp(\sqrt{s} = 115$ GeV$)$	0.05 pb (1000.0)	0.30 pb (6000.0)
$Pbp(\sqrt{s} = 72$ GeV$)$	28.1 pb (31.0)	356.6 pb (393.0)
$PbPb(\sqrt{s} = 72$ GeV$)$	5870.0 pb (41.0)	74366.0 pb (520.0)

IV. SUMMARY

In recent years, the physics of the odderon has become an increasingly active subject of research, from both theoretical and experimental points of view. On the theoretical side, the investigation of the odderon in pQCD has led to the discovery of relations of high energy QCD to the theory of integrable models [29] and two leading solutions of the BKP evolution equation were obtained [28,30], with the intercept being close to or exactly one, depending on the scattering process (see also Ref. [31]). In contrast, on the experimental side, the current evidence for the odderon is very unsatisfactory.

In Ref. [6] we have proposed the study of the exclusive η_c production in hadronic collisions at LHC energies as a probe of the odderon (for other possibilities see Ref. [32]). In this paper we extend that previous analysis for the kinematical region which would be probed by the AFTER@LHC experiment. As the exclusive η_c photoproduction is only possible if the odderon is exchanged between the vector meson and the hadron, the observation of such processes would clearly indicate the existence of the odderon. We have estimated the η_c cross section considering photon-hadron interactions in $pp/Pbp/PbPb$ collisions. Moreover, the background associated with the η_c production by $\gamma\gamma$ interactions was calculated. We have the background present only in pp collisions, which makes the observation of the exclusive η_c production in Pbp and $PbPb$ a signature of the odderon. We predict total cross sections of an order of pb (nb) for $pp(PbPb)$ collisions and large values for the event rates/year, which makes, in principle, the experimental analysis of this process feasible at the AFTER@LHC experiment.

ACKNOWLEDGMENTS

This work was partially financed by the Brazilian funding agencies CNPq, CAPES and FAPERGS.

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