η_c production in photon-induced interactions at the LHC

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In this paper we investigate the η_c production by photon-photon and photon-hadron interactions in pp and pA collisions at the LHC energies. The inclusive and diffractive contributions for the η_c photoproduction are estimated using the nonrelativistic quantum chromodynamics (NRQCD) formalism. We estimate the rapidity and transverse momentum distributions for the η_c photoproduction in hadronic collisions at the LHC and present our estimate for the total cross sections at the Run 2 energies. A comparison with the predictions for the exclusive η_c photoproduction, which is a direct probe of the odderon, is also presented.

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I. INTRODUCTION

The treatment of quarkonium production have attracted much attention during the last decades, mainly motivated by the possibility to probe the interplay between the long and short distance regimes of the strong interactions [1]. As reviewed in Ref. [1], a number of theoretical approaches have been proposed in the last years for the calculation of the heavy quarkonium production, e.g., the nonrelativistic QCD (NRQCD) approach, the fragmentation approach, the color singlet model, the color evaporation model and the k_T-factorization approach. Despite of the recent theoretical and experimental advances, the underlying mechanism governing heavy quarkonium production is still the subject of intense debate. One of the more successful approaches is the NRQCD formalism [2], in which the cross section for the production of a heavy quarkonium state H factorizes as $\sigma(ab \to H + X) = \sum_n \sigma(ab \to Q\bar{Q}[n] + X)\langle \mathcal{O}^H[n]\rangle$, where the coefficients $\sigma(ab \to Q\bar{Q}[n] + X)$ are perturbatively calculated short distance cross sections for the production of the heavy quark pair $Q\bar{Q}$ in an intermediate Fock state n, which does not have to be color neutral. The $\langle \mathcal{O}^H[n]\rangle$ are nonperturbative long distance matrix elements, which describe the transition of the intermediate $Q\bar{Q}$ in the physical state H via soft gluon radiation. Currently, these elements have to be extracted in a global fit to quarkonium data, as performed, for instance, in Ref. [3].

The quarkonium production at high energies in hadronic colliders is dominated by gluon-gluon interactions, with the final state being characterized by the presence of the quarkonium and a large number of additional tracks associated to fragmentation of the two incident hadrons. The study of these inelastic interactions have been the main focus of recent analyses. A complementary alternative is the study of the quarkonium production in photon-induced interactions at hadronic colliders (See, e.g., [4–8]). During the last years, the study of these interactions in $pp/pA/AA$ collisions [9] became a reality [10–18] and new data associated to the Run 2 of the LHC are expected to be released soon. The basic idea of photon-induced processes is that an ultrarelativistic charged hadron (proton or nucleus) gives rise to strong electromagnetic fields, such that the photon stemming from the electromagnetic field of one of the two incident hadrons can interact with one photon of the other hadron (photon-photon process) or can interact directly with the other hadron (photon-hadron process) [9]. In these processes the total cross section can be factorized in terms of the equivalent flux of photons into the hadron projectile and the photon-photon or photon-target cross section. Differently from the inelastic processes, induced by gluon-gluon interactions, the topology of the final state associated to the quarkonium production by photon-photon interactions will be characterized by two empty regions in pseudorapidity, called rapidity gaps, separating the intact very forward hadrons from the quarkonium [See Fig. 1(a)]. In the case of photon-hadron interactions, one rapidity gap will be present in the final state in the case of an inclusive process [Fig. 1(b)]. On the other hand, in a diffractive γh interaction [Fig. 1(c)], described by a Pomeron exchange in the resolved Pomeron model [19], and for the exclusive η_c photoproduction [Fig. 1(d)], the processes will be characterized by two rapidity gaps and two intact hadrons in the final state. However, in addition to the quarkonium, in the case

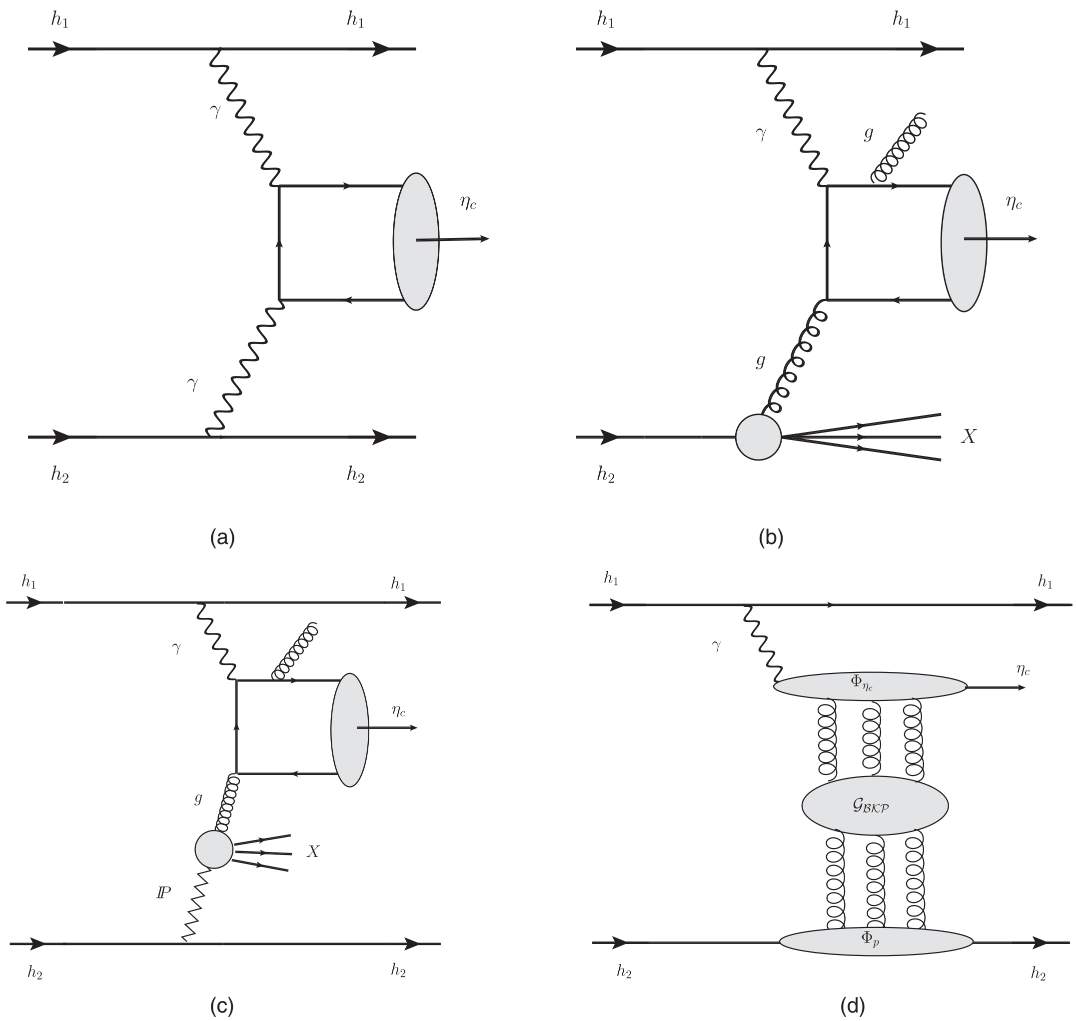

FIG. 1. Schematic view of typical diagrams for the η_c production in hadronic collisions considering (a) photon-photon, (b) inclusive, (c) diffractive and (d) exclusive photon-hadron interactions.

of the diffractive photoproduction, the remnants of the Pomeron also are expected to be present in the final state. These distinct topologies can be used, in principle, to separate the photon-induced processes from the inelastic one [20].

In this paper we will present a comprehensive analysis of the η_c production in photon-induced interactions in pp and pPb collisions at the Run 2 energies of the LHC. Our motivation to perform this study is associated to the fact in the NRQCD formalism, the color singlet contributions to the η_c photoproduction vanish at the leading and next to leading orders in perturbative QCD [21]. Consequently, the analysis of this process is a direct probe of the color-octet production mechanism and the NRQCD formalism. It is important to emphasize that the description of the LHCb data [22] for the η_c production at the LHC by gluon-gluon interactions using the NRQCD formalism still is a theme of intense debate [23–25]. Another motivation is related to the fact the η_c production in photon-photon and diffractive photon-hadron interactions are important backgrounds to the events associated to the exclusive η_c photoproduction, which are events where nothing else is produced except the leading hadrons and the η_c. As demonstrated in Refs. [26,27], the exclusive η_c production in γh interactions is a direct probe of the perturbative odderon, which is the C odd partner of the Pomeron, with C being the charge conjugation, and is described by three reggeized gluons in a color singlet configuration [28] (For a review see [29]). The existence or not of an odderon still is an open question [30,31], which have received a new impulse due to the recent TOTEM data [32,33]. In order to use the exclusive channel as a probe of the odderon, it is fundamental to have control of the backgrounds that will be analyzed in this paper.

This paper is organized as follows. In the next section we will discuss the η_c production in photon-induced interactions at the LHC. In particular, we will present a brief review of the NRQCD formalism for the quarkonium production as well as of the resolved Pomeron model for treatment of diffractive interactions. In Sec. III we present our predictions for the rapidity and transverse momentum distributions and total cross sections considering pp and pA collisions at the Run 2 energies of the LHC. Finally, in Sec. IV we summarize our main conclusions.

II. THE η_c PHOTOPRODUCTION IN HADRONIC COLLISIONS

In this section we will present a brief review of the main concepts needed to describe the η_c production in photon-photon and photon-proton interactions in pp and pA collisions. Our focus will be in ultraperipheral collisions (UPCs), characterized by large impact parameters ($b > R_{h_1} + R_{h_2}$), in which the photon-induced interactions become dominant. Initially, let us consider the η_c production in photon-photon interactions in UPCs between two hadrons, h_1 and h_2, represented in Fig. 1(a). In the equivalent photon approximation [9], the cross section is given by (See, e.g., [9])

$$\sigma(h_1 h_2 \rightarrow h_1 \otimes \eta_c \otimes h_2; s) = \int \hat{\sigma}(\gamma\gamma \rightarrow \eta_c; W) N(\omega_1, \mathbf{b}_1) N(\omega_2, \mathbf{b}_2) S^2_{abs}(\mathbf{b}) \frac{W}{2} \mathrm{d}^2\mathbf{b}_1 \mathrm{d}^2\mathbf{b}_2 \mathrm{d}W \mathrm{d}Y. \quad (1)$$

where $\sqrt{s}$ is the center-of-mass energy for the $h_1 h_2$ collision ($h_i = \mathrm{p, A}$), $\otimes$ characterizes a rapidity gap in the final state and $W = \sqrt{4\omega_1\omega_2}$ is the invariant mass of the $\gamma\gamma$ system. Moreover, Y is the rapidity of the η_c in the final state and $\hat{\sigma}_{\gamma\gamma\rightarrow\eta_c}(\omega_1, \omega_2)$ is the cross section for the η_c production from two real photons with energies ω_1 and ω_2. The functions $N(\omega_i, b_i)$ are the equivalent photon spectra of the hadron (nucleus) i, which are given by

$$N(\omega, b) = \frac{Z^2 \alpha_{em}}{\pi^2} \frac{1}{b^2 \omega} \left[\int u^2 J_1(u) F\left(\sqrt{\frac{(b\omega/\gamma)^2 + u^2}{b^2}} \right) \frac{1}{(b\omega/\gamma)^2 + u^2} \mathrm{d}u \right]^2, \quad (2)$$

where F is the hadronic form factor of the equivalent photon source and ω is the energy of the photon emitted by the hadron at an impact parameter, or distance, b from h. The photon energies are directly related to the rapidity by $\omega_1 = \frac{W}{2} e^{Y}$ and $\omega_2 = \frac{W}{2} e^{-Y}$. The factor $S^2_{abs}(\mathbf{b})$ is the absorption factor, given in what follows by [34]

$$S^2_{abs}(\mathbf{b}) = \Theta(|\mathbf{b}| - R_{h_1} - R_{h_2}) = \Theta(|\mathbf{b}_1 - \mathbf{b}_2| - R_{h_1} - R_{h_2}), \quad (3)$$

where R_{h_i} is the radius of the hadron h_i ($i = 1, 2$). The presence of this factor in Eq. (1) excludes the overlap between the colliding hadrons and allows to take into account only ultraperipheral collisions. Considering the Low formula [35], the cross section $\hat{\sigma}_{\gamma\gamma\rightarrow\eta_c}$ can be written in terms of the two-photon decay width of the η_c ($\Gamma_{\eta_c\rightarrow\gamma\gamma}$) as follows

$$\sigma_{\gamma\gamma\rightarrow\eta_c}(\omega_1, \omega_2) = 8\pi^2 (2J_{\eta_c} + 1) \frac{\Gamma_{\eta_c\rightarrow\gamma\gamma}}{M} \delta(4\omega_1\omega_2 - M^2). \quad (4)$$

Furthermore, M and J_{η_c} are, respectively, the mass and spin of the η_c.

In the case of photon-hadron interactions, the resulting processes can be classified as being inclusive, diffractive or exclusive, depending if the hadron target dissociates or remains intact and if remnants of the Pomeron are present or not in the final state. These three possibilities are represented in Figs. 1(b), 1(c) and 1(d), respectively. The final states will be distinct, with the inclusive processes being characterized by one rapidity gap associated to the photon exchange. On the other hand, in the diffractive and exclusive cases, two rapidity gaps will be present. In the diffractive case we will have one gap associated to the photon exchange and another to the Pomeron ($\mathbb{P}$) one. For the exclusive η_c photoproduction, the two gaps will be associated to the photon exchange and the odderon ($\mathbb{O}$) one, which is represented in perturbative QCD by three reggeized gluons in a C—odd color singlet configuration [28]. We shall start our discussion about the η_c photoproduction considering *inclusive* processes [See Fig. 1(b)]. In this case, the cross section is given by

$$\begin{aligned} \sigma(h_1 + h_2 \rightarrow h_i \otimes \eta_c + X; s) &= \int d\omega n_{h_1}(\omega) \sigma_{\gamma h_2 \rightarrow \eta_c X}(W_{\gamma h_2}) \\ &+ \int d\omega n_{h_2}(\omega) \sigma_{\gamma h_1 \rightarrow \eta_c X}(W_{\gamma h_1}), \end{aligned} \quad (5)$$

where h_i is the hadron that have emitted the photon, $n(\omega)$ is the photon flux integrated over the impact parameter, i.e.,

$$n(\omega) = \int \mathrm{d}^2\mathbf{b} N(\omega, \mathbf{b}), \quad (6)$$

and $W_{\gamma h}$ is the center-of-mass system photon-hadron energy given by $W_{\gamma h} = [2\omega\sqrt{s}]^{1/2}$. In order to describe $\sigma_{\gamma h\rightarrow\eta_c X}$ we will use the NRQCD formalism [2], which takes into account the singlet and octet contributions for the quarkonium production. In the particular case of the η_c photoproduction, the color-singlet contribution at leading order vanishes due to the C (charge) parity conservation [21]. As a consequence, the η_c photoproduction becomes a direct probe of the color octet contribution and the NRQCD formalism. Moreover, at high energies the process is dominated by photon-gluon interactions. Following Ref. [36], we will estimate the cross section for $z < 1$, which suppress the contribution of the $2 \to 1$ subprocess, associated to the $\gamma + g \to \eta_c$ channel. As a consequence, the total cross section for the $\gamma h \to \eta_c + X$ process can be expressed at leading order as follows (See e.g., [21,37])

$$\sigma(\gamma + h \to \eta_c + X) = \int dz dp_T^2 \frac{xg(x, Q^2)}{z(1-z)} \frac{d\sigma}{d\hat{t}}(\gamma + g \to \eta_c + g) \quad (7)$$

where $z \equiv (p_{\eta_c}.p)/(p_\gamma.p)$, with p_{η_c}, p and p_γ being the four momentum of the η_c, hadron and photon, respectively. In the hadron rest frame, z can be interpreted as the fraction of the photon energy carried away by the η_c. Moreover, p_T is the magnitude of the η_c three-momentum normal to the beam axis and $g(x, Q^2)$ is the inclusive gluon distribution, which will be modelled using the CTEQ6LO parametrization [38] assuming that $Q^2 = 4m_c^2$. The $2 \to 2$ subprocess that contribute for the η_c production are the following

$$\gamma + g \to c\bar{c}[^1S_0^{[8]}] + g \quad (8)$$

$$\gamma + g \to c\bar{c}[^3S_1^{[8]}] + g \quad (9)$$

$$\gamma + g \to c\bar{c}[^1P_1^{[8]}] + g. \quad (10)$$

The associated partonic differential cross section $d\sigma/d\hat{t}$ is given by [21]

$$\frac{d\sigma}{d\hat{t}} = \frac{1}{16\pi\hat{s}^2} F(^{2S+1}L_J^{[8]}) \times \langle \mathcal{O}(^{2S+1}L_J^{[8]}) \rangle, \quad (11)$$

with the short distance coefficients F of the subprocesses being given by

$$F(^3S_1^{[8]}) = 20(4\pi)^3 \alpha\alpha_S^2 e_c^2 M \frac{\mathcal{P}^2 - M^2\hat{s}\,\hat{t}\,\hat{u}}{9\mathcal{Q}^2} \quad (12)$$

$$F(^1S_0^{[8]}) = 3(4\pi)^3 \alpha\alpha_S^2 e_c^2 \hat{s}\,\hat{u} \frac{M^8 + \hat{s}^4 + \hat{t}^4 + \hat{u}^4}{M\hat{t}\mathcal{Q}^2} \quad (13)$$

$$F(^1P_1^{[8]}) = \frac{80(4\pi)^3\alpha\alpha_S^2 e_c^2}{9M\mathcal{Q}^3}[M^2\mathcal{Q}(M^6 + 5\hat{s}\,\hat{t}\,\hat{u} - \mathcal{Q}) - 2\hat{s}\,\hat{t}\,\hat{u}\,(\mathcal{P}^2 + 2M^8 - M^2\hat{s}\,\hat{t}\,\hat{u})], \quad (14)$$

with

$$\mathcal{P} = \hat{s}\,\hat{t} + \hat{t}\,\hat{u} + \hat{s}\,\hat{u}, \quad (15)$$

$$\mathcal{Q} = (\hat{s} + \hat{t})(\hat{s} + \hat{u})(\hat{t} + \hat{u}). \quad (16)$$

Moreover, the quantities $\langle \mathcal{O}(^{2S+1}L_J^{[8]}) \rangle$ are the nonperturbative long distance matrix elements (LDMEs), which represent the probability of the $c\bar{c}$ pair in a octet configuration evolving into the physical state η_c.

Similarly to the inclusive case, the cross section for the *diffractive* η_c photoproduction in hadronic collisions, represented in Fig. 1(c), can be expressed as follows

$$\sigma(h_1 + h_2 \to h_1 \otimes \eta_c + X \otimes h_2; s) = \int d\omega n_{h_1}(\omega) \sigma_{\gamma h_2 \to \eta_c X \otimes h_2}(W_{\gamma h_2}) + \int d\omega n_{h_2}(\omega) \sigma_{\gamma h_1 \to \eta_c X \otimes h_1}(W_{\gamma h_1}), \quad (17)$$

where $\sigma_{\gamma h \to \eta_c X \otimes h}$ describes the η_c photoproduction in a diffractive interaction, which keeps the hadron target intact. This quantity can be expressed as in Eq. (7), with the inclusive gluon distribution replaced by the diffractive one (For details see, e.g., Ref. [8]). In the resolved Pomeron model [19], the diffractive gluon distribution, $g_p^D(x, Q^2)$, is defined as a convolution of the Pomeron flux emitted by the proton, $f_{\mathbb{P}}^p(x_{\mathbb{P}})$, and the gluon distribution in the Pomeron, $g_{\mathbb{P}}(\beta, Q^2)$, where β is the momentum fraction carried by the partons inside the Pomeron. The gluon distribution have evolution given by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations and are determined from events with a rapidity gap or a intact hadron. Following Ref. [8], which we refer for a more detailed discussion of the diffractive quarkonium photoproduction, in our analysis we will use the diffractive gluon distribution obtained by the H1 Collaboration at DESY-HERA [39].

Finally, the cross section for the *exclusive* η_c photoproduction in hadronic collisions, represented in Fig. 1(d), can be expressed as follows

$$\sigma(h_1 + h_2 \to h_1 \otimes \eta_c \otimes h_2; s) = \int d\omega n_{h_1}(\omega) \sigma_{\gamma h_2 \to \eta_c \otimes h_2}(W_{\gamma h_2}) + \int d\omega n_{h_2}(\omega) \sigma_{\gamma h_1 \to \eta_c \otimes h_1}(W_{\gamma h_1}), \quad (18)$$

where $\sigma_{\gamma h \to \eta_c \otimes h}$ describes the exclusive η_c photoproduction, which can be estimated taking into account of the odderon exchange [28]. As discussed in detail in Refs. [26,27], the scattering amplitude for this process can be expressed in terms of convolution between the impact factors for the proton (Φ_p) and for the $\gamma \to \eta_c$ transition (Φ_{η_c}) with the odderon Green function $\mathcal{G}_{BKP}$, which is described in terms of the solution of the Bartels-Kwiecinski-Praszalowicz (BKP) equation [28], with the energy dependence being determined by the Odderon intercept $\alpha_{\mathbb{O}}$. In particular, we consider the solution obtained by Bartels, Lipatov and Vacca (BLV) [40] that have found a solution for the BKP equation with intercept $\alpha_{\mathbb{O}}$ exactly equal to one. Differently from Φ_{η_c}, that can be calculated perturbatively [41], 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. [41,42]. It is important to emphasize that distinctly from the diffractive production, where the remnants of Pomeron will be present in the final state, in the exclusive case only the η_c will be present without additional tracks.

In order to estimate the cross sections for the η_c production in photon-induced interactions in pp and pA collisions we should to specify the models used to describe the proton and nuclear photon fluxes. In the nuclear case, it is often used in the literature a monopole form factor given by [43]

$$F(q) = \frac{\Lambda^2}{\Lambda^2 + q^2}, \tag{19}$$

with $\Lambda = 0.088$ GeV. For proton projectiles, the form factor is in general assumed to be

$$F(q) = 1/[1 + q^2/(0.71\ \mathrm{GeV}^2)]^2. \tag{20}$$

These models will be used to estimate the η_c production in photon-photon interactions. Following previous studies of the photon-hadron interactions in hadronic collisions [5,6], we will assume that the equivalent photon flux of a nuclei is given by [9]

$$n_A(\omega) = \frac{2Z^2\alpha_{em}}{\pi\omega}\left[\bar{\eta}K_0(\bar{\eta})K_1(\bar{\eta}) - \frac{\bar{\eta}^2}{2}\mathcal{U}(\bar{\eta})\right] \tag{21}$$

where $K_0(\eta)$ and $K_1(\eta)$ are the modified Bessel functions, $\bar{\eta}=\omega(R_{h_1}+R_{h_2})/\gamma_L$ and $\mathcal{U}(\bar{\eta}) = K_1^2(\bar{\eta}) - K_0^2(\bar{\eta})$. The above expression can be derived assuming a pointlike form factor and considering the requirement that photoproduction is not accompanied by hadronic interaction (ultraperipheral collision). We have verified that our predictions for the η_c production photon-hadron interactions are not modified if a monopole form factor is assumed in the calculations of the nuclear photon flux. For the proton, we will assume that the photon spectrum is given by [44],

$$n_p(\omega) = \frac{\alpha_{\mathrm{em}}}{2\pi\omega}\left[1 + \left(1 - \frac{2\omega}{\sqrt{s}}\right)^2\right] \times \left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right), \tag{22}$$

with the notation $\Omega = 1 + [(0.71\ \mathrm{GeV}^2)/Q^2_{\mathrm{min}}]$ and $Q^2_{\mathrm{min}} = \omega^2/[\gamma_L^2(1 - 2\omega/\sqrt{s})] \approx (\omega/\gamma_L)^2$, where γ_L is the Lorentz boost of a single beam. This expression is derived considering the Weizsäcker-Williams method of virtual photons and using an elastic proton form factor (For more details see Refs. [44,45]).

Before to present our predictions in the next Section, some comments are in order. In our calculations of the photon-hadron interactions in hadronic collisions we will assume that the rapidity gap survival probability S^2 (associated to probability of the scattered proton not to dissociate due to secondary interactions) is equal to the unity. The inclusion of these absorption effects in $\gamma\gamma$ and γh interactions is still a subject of intense debate [46–50]. In particular, the modeling, magnitude and universality of this factor still are open questions. Recent results for the exclusive dimuon production [51] indicate that S^2 can be of the order of 0.9 for $\gamma\gamma$ interactions in the kinematical range covered by the ATLAS Collaboration. In the next section we will estimate the impact of $S^2 = 0.9$ in our predictions for the $\gamma\gamma \to \eta_c$ production. In the case of the exclusive vector meson photoproduction, the results presented in Ref. [6], indicate that the experimental data for this process can be quite well described assuming that $S^2 = 1$. Finally, in the case of diffractive photoproduction, which is described in terms of the diffractive gluon distribution, we also expect that $S^2 \approx 1$. Such expectation is associated to the fact that possible interactions between the proton and partons inside the Pomeron, which could destroy the rapidity gap, in principle already have been included in the parton distributions of the Pomeron when these are fitted to the diffractive HERA data [47]. Finally, it is important to discuss the determination of the long distance matrix elements (LDMEs) $\langle\mathcal{O}^{\eta_c}[^1S_0^{[8]}]\rangle$, $\langle\mathcal{O}^{\eta_c}[^3S_1^{[8]}]\rangle$ and $\langle\mathcal{O}^{\eta_c}[^1P_1^{[8]}]\rangle$, which are one the main inputs to estimate the η_c photoproduction using the NRQCD formalism. As the LDMEs are associated to nonperturbative physics, its values are in general extracted by the comparison of the NRQCD predictions with the corresponding data for a given energy. The resulting LDMEs are then used to predict quarkonium cross sections at other energies. In particular, in Ref. [3] the authors have performed a first NLO analysis of the J/Ψ production in hadron-hadron and photon-hadron interactions and extracted the LDMEs by fitting the world data. With the advent of the LHCb data for the η_c production, the associated LDMEs have been extracted in Refs. [23–25] assuming the heavy-quark spin symmetry to relate the η_c and J/Ψ matrix elements. The LDMEs for η_c extracted by these different authors are distinct, as well its main conclusions about the dominance or not of the color octet contributions. Consequently, the η_c production in hadronic collisions still is a subject of intense debate. In what follows we will use the η_c LDMEs obtained in [24], which describe the LHCb data and are consistent with the set of color octet LDMEs fitted to J/Ψ data. Our predictions will be strongly dependent of these values, which is a shortcoming of the NRQCD formalism. Future experimental data for the η_c production in hadron-hadron collisions at the Run 2 LHC energies will

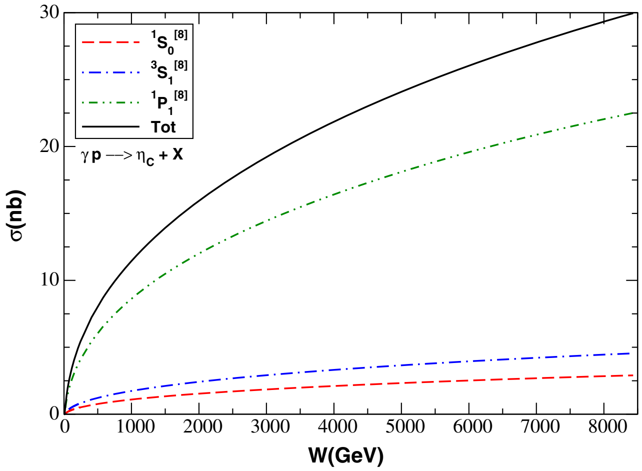

FIG. 2. Predictions for the energy dependence of the cross section for the η_c photoproduction in inclusive γp interactions.

be useful to constrain the associated LDMEs and, as a consequence, to reduce the current theoretical uncertainty.

III. RESULTS

In this section we will present our predictions for the η_c production in photon-photon and photon-hadron interactions in pp and pPb collisions at the LHC energies. In the case of pPb collisions, the cross sections will be dominated by γp interactions, due to the Z^2 enhancement present in the nuclear photon flux. As a consequence, the associated rapidity distributions will be asymmetric. We will assume $m_c = 1.48$ GeV. Moreover, following Ref. [52], we will consider that (in units of GeV^3): $\langle \mathcal{O}^{\eta_c}[^1S_0^{[8]}]\rangle = (1/3)\times(0.0013\pm0.0013)$, $\langle \mathcal{O}^{\eta_c}[^3S_1^{[8]}]\rangle = 0.0180\pm0.0087$ and $\langle \mathcal{O}^{\eta_c}[^1P_1^{[8]}]\rangle = 3\times(0.0180\pm0.0087)m_c^2$. The calculations for the diffractive photoproduction will be performed using the fit A for the diffractive gluon distribution [39]. Following Ref. [36] we will integrate the fraction of the photon energy carried away by the η_c in the range $0.3 \lesssim z \lesssim 0.9$ and we will take the minimum value of the transverse momentum of the meson as being $p_{T,\mathrm{min}} = 1$ GeV. As demonstrated in Ref. [7], the predictions are not strongly dependent on the inferior limit of integration z_{min}.

Initially let us estimate the energy dependence of the cross section for η_c production in γp collisions. It is important to emphasize that in γp interactions at hadronic colliders, the maximum center of mass energy probed ($W_{\gamma h}^{\mathrm{max}}$) is of the order of 8000 (1500) GeV in pp (pPb) collisions [9]. In Fig. 2 we present separately the different color octet contributions, as well as the sum of the three contributions. We have assumed $Q^2 = 4m_c^2$ and the CTEQ6LO parametrization [38] for the inclusive gluon distribution. As demonstrated in Ref. [8], these choices allow to describe the H1 data for the inclusive J/Ψ photoproduction. We have that the η_c photoproduction is dominated by the $^1P_1^{[8]}$ contribution, with the $^3S_1^{[8]}$ and $^1S_0^{[8]}$ contributions being smaller by a factor larger than 6 for $W > 1000$ GeV. In Fig. 2 we only have considered the central values for the matrix elements. In what follows we will take into account the current uncertainty present in the corresponding values. As a consequence, we will present a band of possible values for the associated rapidity and transverse momentum distributions, with the size of the band being mainly determined by the theoretical uncertainty in the $^1P_1^{[8]}$ matrix element.

In Fig. 3 we present our predictions for the rapidity distributions for the *inclusive* η_c photoproduction in pp and pPb collisions at $\sqrt{s} = 13$ and 8.1 TeV, respectively. In pp collisions (left panel), we have a symmetric rapidity distribution, which is directly associated to the fact that both the incident protons are sources of photons with the two terms in Eq. (5) contributing equally at forward and backward rapidities, respectively. In contrast, the rapidity

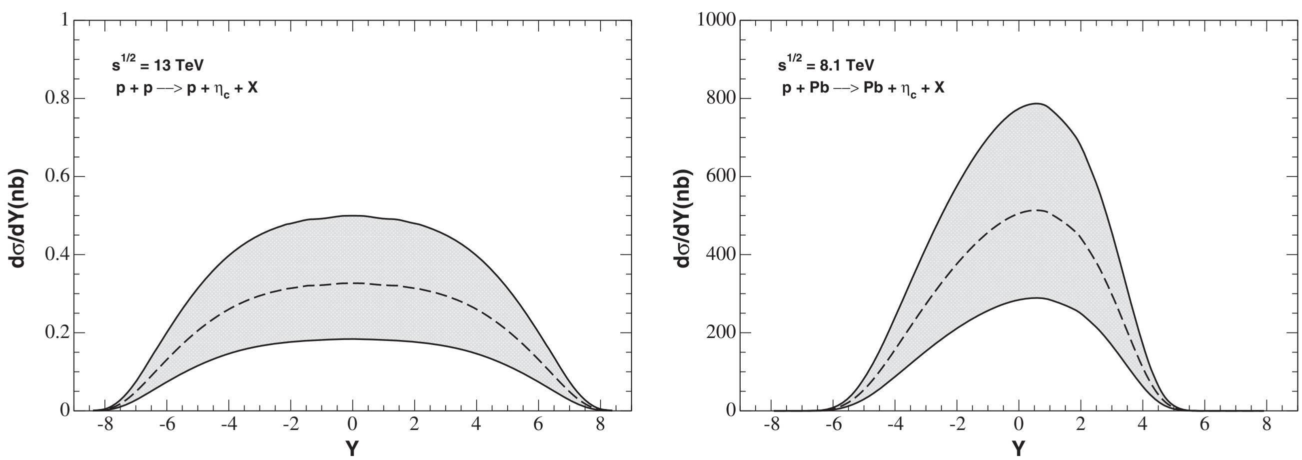

FIG. 3. Rapidity distributions for the inclusive η_c photoproduction in pp (left panel) and pPb (right panel) collisions. The dashed line represents the prediction using the central values of the matrix elements.

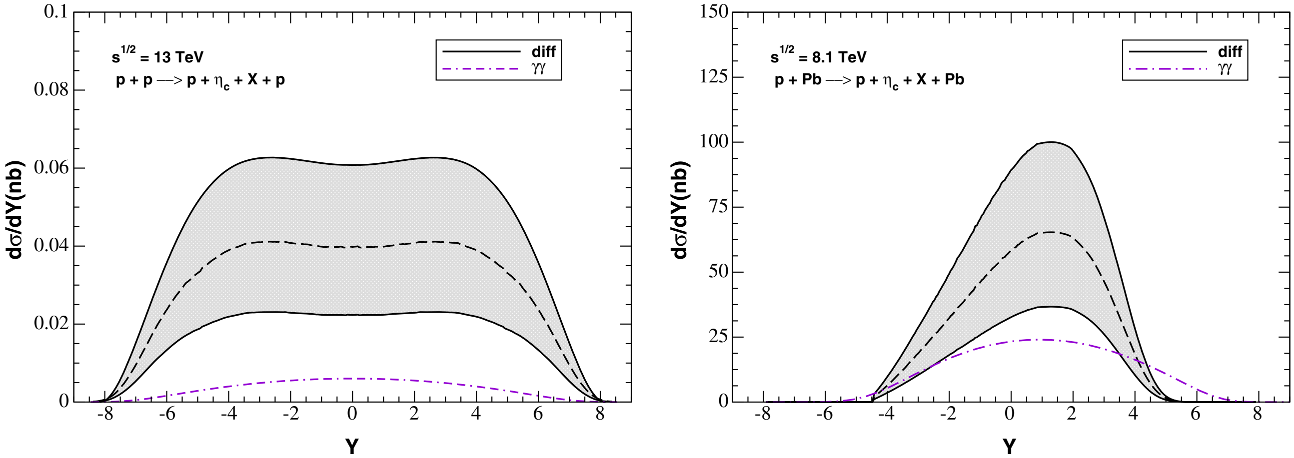

FIG. 4. Rapidity distributions for the diffractive η_c photoproduction in pp (left panel) and pPb (right panel) collisions. The dashed line represents the prediction using the central values of the matrix elements. The predictions for the η_c production by $\gamma\gamma$ interactions is presented by the dot-dashed line.

distribution is asymmetric in pPb collisions due to the Z^2 enhancement on the nuclear photon flux. This enhacement also implies that the pPb predictions for central rapidities are a factor $\approx 10^4$ larger than the pp one.

The predictions for the η_c production in $\gamma\gamma$ and *diffractive* $\gamma\mathbb{P}$ interactions are presented in Fig. 4. As discussed in the Introduction, the final state generated by these two channels are similar: two rapidity gaps and intact hadrons. The basic difference is the presence of the Pomeron remnants in the diffractive case, which should generate additional tracks in the detector. Our results indicate that for central rapidities the contribution associated to $\gamma\gamma$ interactions is a factor $\gtrsim 4(1.2)$ smaller than the diffractive one in pp (pPb) collisions. In the kinematical range probed by the LHCb detector, both contributions are similar in the case of pPb collisions. In comparison to the η_c production in γp interactions, the $\gamma\gamma$ and diffractive channels are suppressed by approximately one order of magnitude. Moreover, the diffractive η_c photoproduction is a factor $\gtrsim 5$ than the predictions for the J/Ψ production in this same channel presented in Ref. [8].

Our predictions for the total cross sections are presented in Table I. For comparison, we also present the predictions associated to the exclusive η_c photoproduction by photon-Odderon ($\gamma\mathbb{O}$) interactions, calculated using the formalism discussed in detail in Ref. [26]. As discussed before, this process is a direct probe of the odderon, which still is an elusive object in perturbative QCD. The results presented in Table I indicate that the contribution of this channel is a factor $\approx 10(4)$ smaller than the $\gamma\mathbb{P}(\gamma\gamma)$ one. In principle, the $\gamma\mathbb{P}$ contribution can be suppressed by requiring the exclusivity of the event, i.e., that nothing else is produced except the leading hadrons and the η_c. On the other hand, in order to suppress the $\gamma\gamma$ contribution, a cutoff in the transverse momentum of the leading hadrons should be considered. 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 hadrons, with exclusive events being characterized by larger values (see below).

In Fig. 5 we present our predictions for the transverse momentum distributions for the inclusive and diffractive η_c photoproduction at central rapidities ($Y = 0$) in pp collisions at $\sqrt{s} = 13$ TeV (left panel) and pPb collisions at $\sqrt{s} = 8.1$ TeV (right panel). We have that the p_T distributions for the inclusive and diffractive production are similar, differing basically in normalization. The distributions decrease with p_T following a power-law behavior $\propto 1/p_T^n$, where the effective power n is energy dependent. Such behavior is expected, since the η_c in the final state in inclusive and diffractive interactions is generated in a $2 \to 2$ subprocess. In contrast, in the exclusive production we have that the typical transverse momentum of the η_c in the final state is determined by the transferred momentum

TABLE I. Total cross sections for the η_c production in $\gamma\gamma$ and inclusive and diffractive $\gamma\mathbb{P}$ interactions in pp and pPb collisions at the Run 2 LHC energies. For comparison the predictions associated to the exclusive η_c photoproduction by photon-odderon ($\gamma\mathbb{O}$) interactions, calculated using the formalism discussed in Ref. [26], are also presented in the last column.

	Inclusive γp interactions	Diffractive $\gamma\mathbb{P}$ interactions	$\gamma\gamma$ interactions	Exclusive $\gamma\mathbb{O}$ interactions
pp ($\sqrt{s} = 13$ TeV)	3.492 nb	0.501 nb	0.059 nb	0.013 nb
pPb ($\sqrt{s} = 8.1$ TeV)	3.194 μb	0.351 μb	0.182 μb	0.032 μb

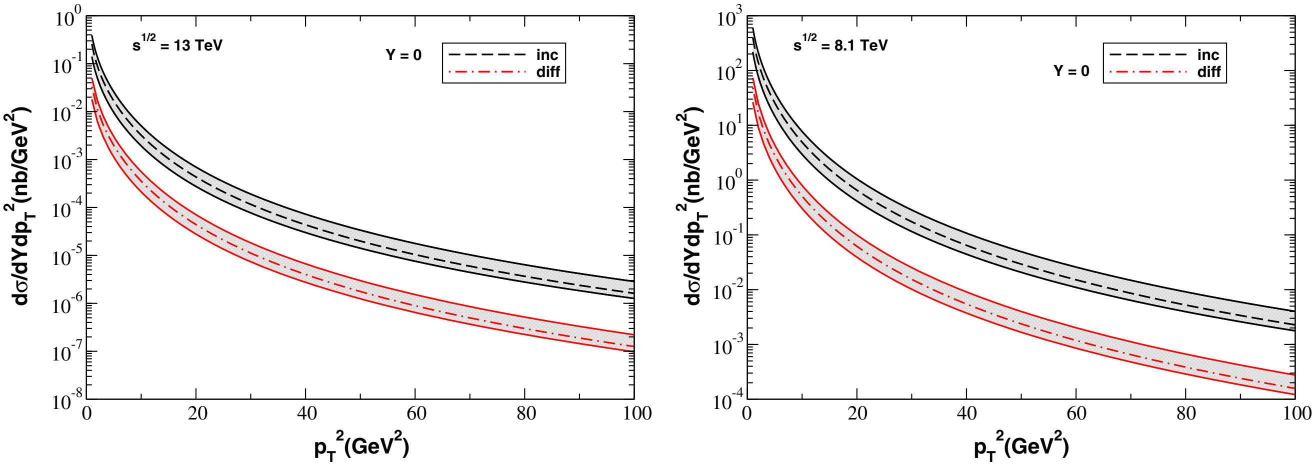

FIG. 5. Transverse momentum distributions for the inclusive and diffractive η_c photoproduction at central rapidities ($Y = 0$) in pp collisions at $\sqrt{s} = 13$ TeV (left panel) and pPb collisions at $\sqrt{s} = 8.1$ TeV (right panel).

in the odderon-proton vertex, which is larger than that present in the photon-proton vertex (See, e.g., Refs. [53–55]). As the exclusive cross section has an $e^{-\beta|t|}$ behavior, where β is the slope parameter associated, the associated p_T distribution decreases exponentially at large transverse momentum. Therefore, it is expected that the production of η_c with a large p_T should be dominated by the inclusive and diffractive mechanisms.

In our analysis of the inclusive η_c photoproduction we have assumed that the standard gluon distribution is given by the CTEQ6LO parametrization [38]. As the behavior of the gluon distribution at small values of x and low virtualities Q^2, which is probed in our calculations, is still poorly constrained due to the lack of direct experimental information, it is important to estimate the impact of a different parametrization in our results. In Fig. 6 (left panel) we estimate the rapidity distribution for the inclusive η_c photoproduction in pPb collisions considering two different parametrizations for the gluon distribution and the central values for the nonperturbative matrix elements. We have that the prediction obtained using the Martin-Stirling-Thorne-Watt (MSTW) parametrization [56] is similar to CTEQ6LO one for large values of $|Y|$. At central rapidities, the MSTW prediction is smaller than the CTEQ6LO one by ≈10%. Similar suppression also is observed in the case of pp collisions. In the case of the diffractive η_c photoproduction we have considered the fit A obtained by the H1 Collaboration for the diffractive gluon distribution. However, this collaboration also have provided an alternative parametrization, denoted fit B, which also is able to describe the HERA data for diffractive processes. These two parametrizations differ in the value for the starting scale Q_0^2 for the DGLAP evolution and the assumption for the β behaviour of the gluon distribution at this scale. While the fit A assumes that $g_{\mathbb{P}}(\beta, Q_0^2 = 1.75\ \mathrm{GeV}^2) \propto (1-\beta)^{C_g}$, the fit B considers that the gluon

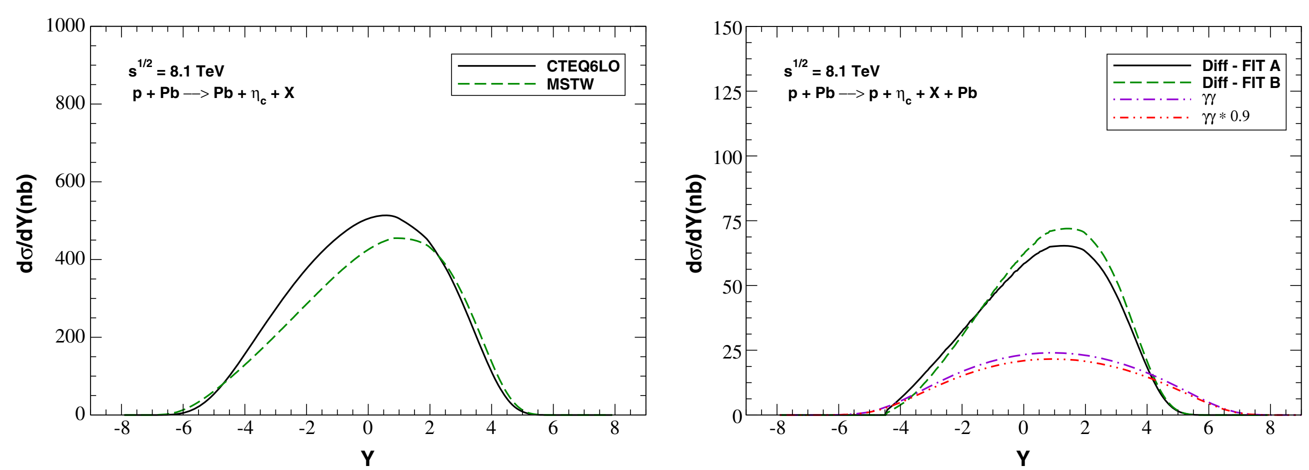

FIG. 6. Rapidity distributions for the inclusive (left panel) and diffractive (right panel) η_c photoproduction in pPb collisions at $\sqrt{s} = 8.1$ TeV considering different parametrizations for the standard and diffractive gluon distributions.

distribution is a simple constant at $Q_0^2 = 2.5\ \mathrm{GeV}^2$. In Fig. 6 (right panel) we estimate the impact of these different parametrizations on our predictions for the diffractive η_c photoproduction in pPb collisions. We have that the predictions are similar for forward and backward rapidities and differ by ≈10% for $Y \approx 2$, with the fit B prediction being larger than the fit A one. We have checked that similar results are obtained for pp collisions. Finally, we also present in Fig. 6 (right panel), the predictions for the η_c production by $\gamma\gamma$ interactions assuming that $S^2 = 0.9$. The comparison between the results presented in Figs. 3 and 4 for pPb collisions with those presented Fig. 6 indicate that the main uncertainty in the predictions for the η_c production is associated to the nonperturbative matrix elements. As a consequence, a future experimental analysis of the inclusive and/or diffractive η_c photoproduction can be useful to constrain these elements, in particular, the $\langle \mathcal{O}^{\eta_c}[^1P_1^{[8]}] \rangle$ one that determines the high energy behaviour of the γp cross section.

IV. SUMMARY

The description of the mechanism underlying the production and decay of quarkonium still is a theme of intense debate in the literature. Significant theoretical improvements have been achieved in recent years and abundant experimental data have been accumulated at the LHC, in particular for the J/Ψ production. The yield and p_T distribution for the J/Ψ production in hadronic collisions, dominated by gluon-gluon interactions, are quite well described by the NRQCD formalism. However, the description of the polarization of prompt J/Ψ using this formalism still remains a theme of dispute. As a consequence, the study of η_c provide an opportunity to further test the NRQCD formalism. Previous studies have focused in the η_c production in hadronic colliders by gluon-gluon interactions. However, this particle also can be produced by photon-induced interactions. During the last years, the experimental results from Tevatron, RHIC and LHC have demonstrated that the study of hadronic physics using photon-induced interactions in $pp/pA/AA$ colliders is feasible and provide important complementary information about the QCD dynamics and quarkonium production. In this paper we have complemented previous studies for the η_c production by considering its production by photon-photon and inclusive and diffractive photon-hadron interactions. Our basic motivation to perform this study was the fact that the η_c photoproduction is dominated by the color-octet process, which implies that this process provide an important test for the color-octet mechanism present in the NRQCD formalism. Moreover, in order to use the exclusive η_c photoproduction as a direct probe of the odderon, it is fundamental to known the magnitude of the $\gamma\gamma$ and diffractive γp channels, which also are characterized by two intact hadrons and two rapidity gaps in the final state. In this paper we have estimated the rapidity distributions for the η_c production by $\gamma\gamma$, γh and $\gamma\mathbb{P}$ interactions in pp and pPb collisions at the Run2 energies of the LHC. We have demonstrated that the inclusive η_c photoproduction is not negligible and its study can be useful to test the NRQCD formalism. In the case of events with two rapidity gaps in the final state, we show that the production of η_c by $\gamma\mathbb{P}$ interactions is dominant. Moreover, our results indicated that the $\gamma\gamma$ channel also dominates the exclusive η_c photoproduction. As a consequence, the probe of odderon in exclusive processes is not an easy task, which will depend of the measurement of the transverse momentum of the hadrons in the final state and the implementation of a strict criteria of exclusivity in the events.

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