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Exclusive photoproduction of J/ψ and $\psi(2S)$ states in proton-proton collisions at the CERN LHC

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In this work we investigate the exclusive photoproduction of J/ψ and the radially excited $\psi(2S)$ state off nucleons in proton-proton collisions. The theoretical framework considered in the analysis is the light-cone dipole formalism and predictions are done for proton-proton collisions at the CERN-LHC energy of 7 TeV. The theoretical uncertainties are investigated and a comparison is made to the recent LHCb Collaboration data for the exclusive charmonium production.

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I. INTRODUCTION

The exclusive vector meson photoproduction, $\gamma + p \rightarrow V + p$, has been investigated both experimentally and theoretically in recent years, as it allows us to test perturbative quantum chromodynamics. The quarkonium masses, m_V, give a perturbative scale for the problem even in the photoproduction limit, $Q^2 = 0$. An important feature of these processes at the high energy regime is the possibility to investigate the Pomeron exchange. For this energy domain, hadrons and photons can be considered color dipoles in the mixed light-cone representation [1], where their transverse size can be considered frozen during the interaction. Therefore, the scattering process is characterized by the color dipole cross section, describing the interaction of those color dipoles with the nucleon target. Dipoles of transverse size $r \approx 1/\sqrt{m_V^2 + Q^2}$ are probed by the $1S$ vector meson production amplitude [1], whereas the diffractive production of the $2S$ radially excited vector mesons presents the so-called node effect [2]. A strong cancellation of dipole size contributions to the production amplitude from the regions above and below the node position in the $2S$ radial wave function [3] takes place and gives origin to a large suppression of the photoproduction $2S$ states compared to the $1S$ states.

In the present work, we focus on the exclusive photoproduction of J/ψ and the radially excited $\psi(2S)$ mesons off nucleons in proton-proton collisions. An important motivation is the recent measurement by the LHCb Collaboration of the cross section at $\sqrt{s} = 7$ TeV of the exclusive dimuon final states, including the $\psi(2S)$ state [4]. Those measurements were performed at forward rapidities $2.0 \leq \eta_{\mu^{\pm}} \leq 4.5$, which correspond to a sufficiently Bjorken-x variable down to $x \approx 5 \times 10^{-6}$. The theoretical framework considered in the current investigation is the light-cone dipole formalism, where the $c\bar{c}$ fluctuation (color dipole) of the incoming quasireal photon interacts with the nucleon target via the dipole cross section and the result is projected in the wave function of the observed hadron. At high energies, it is expected a transition between the regime described by the linear dynamics and a new regime where the physical process of recombination of partons becomes important. Such energy regime is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wave function: the parton saturation phenomenon. The transition is set by saturation scale $Q_{\mathrm{sat}} \propto x^{\lambda}$. For recent reviews on these subjects, we quote Ref. [5]. Therefore, the theoretical investigation of $\psi(1S)$ and $\psi(2S)$ mesons can shed light on the experimental constraints for the dipole-proton cross section and on the phenomenological models based on parton saturation ideas. Along these lines, recently in Ref. [6] we have investigated the photoproduction of radially excited vector mesons off nuclei in heavy ion relativistic collisions. There, the exclusive photoproduction of $\psi(2S)$ off nuclei was analyzed, evaluating the coherent and the incoherent contributions to that process. The approach gives a reasonable description of ALICE Collaboration data for [7,8], J/ψ production at 2.76 TeV in PbPb collisions, and predictions are provided for the $\psi(2S)$ state.

The aim of this work is twofold. First, we show predictions for the photoproduction of $\psi(1S)$ and its excited state in proton-proton collisions at the LHC within the same phenomenological formalism. This fact is completely new, as most predictions in the literature concern only the Psi$(1S)$ state. Second, we investigate the sensitivity of recent LHCb data to the small-x dynamics encoded in our phenomenological model for the dipole cross section. As already mentioned, the $\psi(2S)$ wave function presents nodes compared to the $1S$ state. This fact, in turn, means that the production amplitude is sensitive to large dipole size configurations and, therefore, it is scanning the transition region between the color transparency behavior, $\sigma_{\mathrm{dip}} \propto r^2$, and the soft nonperturbative region. In the saturation models, such a transition is driven by the saturation scale, and this is a clear advantage of the phenomenological model considered here. The analysis presentation is organized as follows. In the next section we present a brief review of the diffractive photoproduction of vector mesons in proton-proton collisions. In Sec. III we present the predictions for the $\psi(1S)$ and $\psi(2S)$ photoproduction cross sections at forward rapidities. We compare the theoretical results to the recent LHCb Collaboration measurements of exclusive J/ψ and $\psi(2S)$ production [4]. In addition, we compare the current results to related approaches available in the literature and discuss the main theoretical uncertainties. Finally, in Sec. IV we summarize our main results and conclusions.

II. EXCLUSIVE MESON PHOTOPRODUCTION IN PROTON-PROTON COLLISIONS

The exclusive vector meson photoproduction is described by the photon-Pomeron process, $\gamma + p(\rightarrow \gamma + IP) \rightarrow V + p$. The corresponding production cross section at photon level is denoted by $\sigma(\gamma p \rightarrow V + p)$. Accordingly, the cross section for the exclusive meson photoproduction in hadron-hadron collisions can be factorized in terms of the equivalent flux of photons of the hadron projectile and photon-target production cross section [9]. The photon energy spectrum, $dN_\gamma/d\omega$, is given by a modified version of the Wiezsäcker-Williams approximation [9]

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

where ω is the photon energy and $\sqrt{s}$ is the hadron-hadron center-of-mass energy. Given the Lorentz factor of a single beam, $\gamma_L = \sqrt{s}/(2m_p)$, one has that $\xi = 1 + (Q_0^2/Q_{\rm min}^2)$ with $Q_0^2 = 0.71\ {\rm GeV}^2$ and $Q_{\rm min}^2 = \omega^2/\gamma_L^2$.

The rapidity distribution y for charmonium photoproduction, i.e., the $\psi(1S)$ and $\psi(2S)$ states, in proton-proton collisions can be written down as

$$\frac{d\sigma}{dy}(pp \rightarrow p \otimes \psi \otimes p) = S_{\rm gap}^2\left[\omega\frac{dN_\gamma}{d\omega}\sigma(\gamma p \rightarrow \psi(nS) + p) + (y \rightarrow -y)\right], \quad (2)$$

where $\otimes$ represents the presence of a rapidity gap. The produced state with mass m_V has rapidity $y \simeq \ln(2\omega/m_V)$ and the square of the γp center-of-mass energy is given by $W_{\gamma p}^2 \simeq 2\omega\sqrt{s}$. The absorptive corrections due to spectator interactions between the two hadrons are represented by the factor $S_{\rm gap}$. We will comment on the effect of absorption in the next section.

The photon-Pomeron interaction will be described within the light-cone dipole frame. In this representation the probing projectile fluctuates into a quark-antiquark pair with transverse separation $\boldsymbol{r}$ long after the interaction, which then scatters off the hadron [1]. The amplitude for vector meson production off nucleons reads [1]

$$\mathcal{A}(x, Q^2, \Delta) = \sum_{h,\bar{h}}\int dz d^2\boldsymbol{r}\Psi^\gamma_{h,\bar{h}}\mathcal{A}_{q\bar{q}}(x, r, \Delta)\Psi^{V*}_{h,\bar{h}}, \quad (3)$$

where $\Psi^\gamma_{h,\bar{h}}(z, \boldsymbol{r}, Q^2)$ and $\Psi^V_{h,\bar{h}}(z, \boldsymbol{r})$ are the light-cone wave function of the photon and of the vector meson, respectively. The quark and antiquark helicities are labeled by h and $\bar{h}$, variable $\boldsymbol{r}$ defines the relative transverse separation of the pair (dipole), $z(1-z)$ is the longitudinal momentum fraction of the quark (antiquark). The quantity Δ denotes the transverse momentum lost by the outgoing proton ($t = -\Delta^2$) and x is the Bjorken variable. Moreover, $\mathcal{A}_{q\bar{q}}$ is the elementary amplitude for the scattering of a dipole of size $\boldsymbol{r}$ on the target. It is related to the dipole cross section at forward limit, $\sigma_{\rm dip}(x, r) = {\rm Im}\mathcal{A}_{q\bar{q}}(x, r, \Delta = 0)$. Assuming the reasonable approximation of the t dependence for the elementary cross section to be $\mathcal{A}_{q\bar{q}} \propto \exp(-B_V|t|/2)$, the total cross section for exclusive production of charmonia off a nucleon target is given by

$$\sigma_{\gamma^* p\rightarrow Vp}(s, Q^2) = \frac{1}{16\pi B_V}|\mathcal{A}(x, Q^2, \Delta = 0)|^2, \quad (4)$$

where B_V is the diffractive slope parameter in the reaction $\gamma^* p \rightarrow Vp$. Here, we consider the energy dependence of the slope using the Regge motivated expression $B_V(W_{\gamma p}) = b_{\rm el}^V + 2\alpha' \log(\frac{W_{\gamma p}}{W_0})^2$ with $\alpha' = 0.25\ {\rm GeV}^{-2}$ and $W_0 = 95$ GeV. The measured slopes are used [10] for $\psi(1S)$ and $\psi(2S)$ at $W_{\gamma p} = 90$ GeV, i.e., $b_{\rm el}^{\psi(1S)} = 4.99 \pm 0.41\ {\rm GeV}^{-2}$ and $b_{\rm el}^{\psi(2S)} = 4.31 \pm 0.73\ {\rm GeV}^{-2}$, respectively. In our numerical evaluations, the corrections related to skewness effect and the real part of the amplitude are properly taken into account [11]. For the charm quark mass, we will use the value $m_c = 1.4$ GeV.

The photon wave functions appearing in Eq. (3) are well known [1]. On the other hand, for the meson wave function we consider the boosted Gaussian wave function:

$$\psi^{nS}_{\lambda,h\bar{h}} = \sqrt{\frac{N_c}{4\pi}}\frac{\sqrt{2}}{z(1-z)}\{\delta_{h,\bar{h}}\delta_{\lambda,2h}m_c + i(2h)\delta_{h,-\bar{h}}e^{i\lambda\phi}[(1-z)\delta_{\lambda,-2h} + z\delta_{\lambda,2h}]\partial_r\} \times \phi_{nS}(z, r), \quad (5)$$

where $\phi(z, r)$ in the mixed (r, z) representation is obtained by boosting a Schrödinger Gaussian wave function in momentum representation, $\Psi(z, \mathbf{k})$. In this case, one obtains the following expression for the $1S$ state [12]:

$$\phi_{1S}(r, z) = N_T^{(1S)}\left\{4z(1-z)\sqrt{2\pi R_{1S}^2}\exp\left[-\frac{m_q^2 R_{1S}^2}{8z(1-z)}\right] \times \exp\left[-\frac{2z(1-z)r^2}{R_{1S}^2}\right]\exp\left[\frac{m_q^2 R_{1S}^2}{2}\right]\right\}, \quad (6)$$

where for the 1S ground state vector mesons one determines the parameters R_{1S}^2 and N_T by considering the normalization property of wave functions and the predicted decay widths.

The radial wave function of the $\psi(2S)$ is obtained by the following modification of the 1S state [2]:

$$\phi_{2S}(r,z) = N_T^{(2S)}\left\{4z(1-z)\sqrt{2\pi R_{2S}^2}\exp\left[-\frac{m_q^2 R_{2S}^2}{8z(1-z)}\right]\right. \times \exp\left[-\frac{2z(1-z)r^2}{R_{2S}^2}\right]\exp\left[\frac{m_q^2 R_{2S}^2}{2}\right] \times\left[1-\alpha\left(1+m_q^2R_{2S}^2-\frac{m_q^2R_{2S}^2}{4z(1-z)}\right.\right. \left.\left.\left. +\frac{4z(1-z)}{R_{2S}^2}r^2\right)\right]\right\}, \quad (7)$$

with a new parameter α. Now, the two parameters α and R_{2S} are constrained from the orthogonality conditions for the meson wave function. The choice of the meson wave function is one of the main sources of theoretical uncertainty, introducing a typical 12%–13% error in theoretical prediction given a specific model for the dipole cross section.

Finally, here we will consider the phenomenological saturation model proposed in Ref. [13] which encodes the main properties of the saturation approaches, with the dipole cross section parametrized as follows:

$$\sigma_{\mathrm{dip}}(x,\boldsymbol{r}) = \sigma_0\begin{cases}\mathcal{N}_0\left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\mathrm{eff}}(x,r)}, & \text{for } \bar{\tau}\le 2,\\ 1-\exp[-a\ln^2(b\bar{\tau})], & \text{for } \bar{\tau}>2,\end{cases}$$

where $\bar{\tau} = \boldsymbol{r}Q_{\mathrm{sat}}(x)$ and the expression for $\bar{\tau}>2$ (saturation region) has the correct functional form, as obtained from the theory of the color glass condensate [5]. For the color transparency region near the saturation border ($\bar{\tau}\le 2$), the behavior is driven by the effective anomalous dimension $\gamma_{\mathrm{eff}}(x,r) = \gamma_{\mathrm{sat}} + \frac{\ln(2/\bar{\tau})}{\kappa\lambda y}$, where $\gamma_{\mathrm{sat}} = 0.63$ is the leading order Balitsky-Fadin-Kuraev-Lipatov anomalous dimension at the saturation limit. In order to account for the threshold region $x\to 1$, we have corrected the dipole cross section by multiplying it by a threshold factor $(1-x)^7$.

III. RESULTS AND DISCUSSIONS

First, we compare the present theoretical approach to the data for the $\psi(1S)$ state measured by the LHCb Collaboration at the energy of 7 TeV in proton-proton collisions at the forward region $2.0 < \eta_{\pm} < 4.5$ [4]. Hereafter, we will assume for the absorption factor the average value $S_{\mathrm{gap}}^2 = 0.8$, despite its dependence on rapidity, as shown in Ref. [14]. The absorptive corrections considering the elastic rescattering have been computed for pp collisions in [14] and have a value of $S_{\mathrm{gap}}^2(y=0) = 0.85$ and $S_{\mathrm{gap}}^2(y=3) = 0.75$, respectively. In Fig. 1 the numerical calculations [labeled Gay Ducati, Griep, and Machado (GGM) and represented by the solid curve] are shown for the rapidity distribution for the $\psi(1S)$ state within the color dipole formalism, Eqs. (2) and (4). The relative normalization and overall behavior on rapidity is quite well reproduced in the forward regime. In Fig. 2, the complete rapidity distribution, including mid-rapidity and the backward region, is presented for J/ψ and $\psi(2S)$ states (solid and dashed curves, respectively). The J/ψ cross section at central rapidity is $\frac{d\sigma}{dy}(y=0) = 5.8$ nb. We obtain $\sigma(pp\to p + J/\psi + p)\times \mathrm{Br}(J/\psi\to\mu^+\mu^-) =$ 698 pb for the meson with a rapidity between 2 and 4.5. After correcting this result by the acceptance factor in order to convert the prediction in terms of muon pseudorapidities we get $\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0<\eta_{\mu^\pm}<4.5) =$ 298 pb. This is in good agreement with the experimental

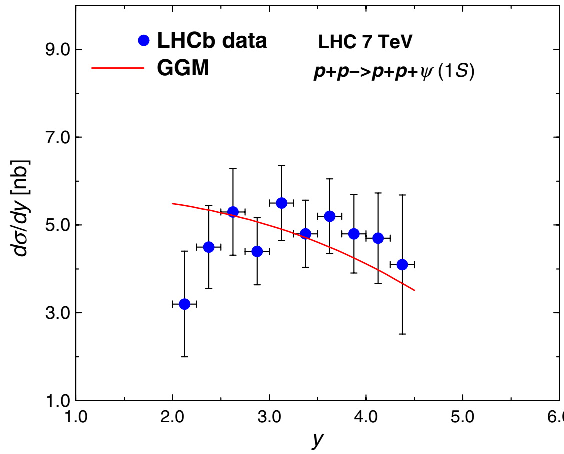

FIG. 1 (color online). The rapidity distribution at forward region of exclusive $\psi(1S)$ meson production at $\sqrt{s} = 7$ TeV in proton-proton collisions at the LHC. The theoretical prediction is labeled by the solid curve (see text). Data from the LHCb Collaboration [4].

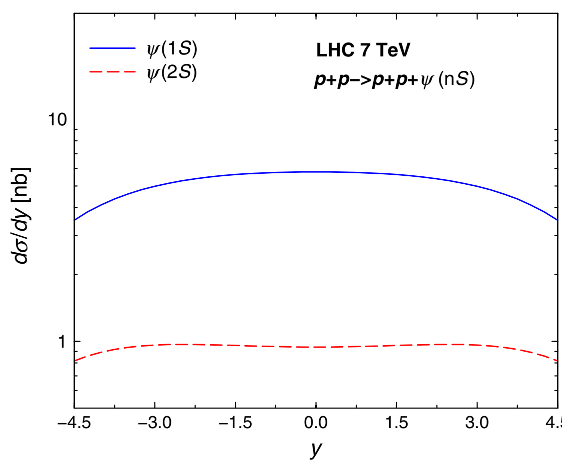

FIG. 2 (color online). The theoretical predictions for the rapidity distribution of exclusive J/ψ (solid curve) and $\psi(2S)$ (dashed curve) meson production at $\sqrt{s} = 7$ TeV in proton-proton collisions at the LHC.

result $\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0<\eta_{\mu^\pm}<4.5)=307\pm42\,\mathrm{pb}$ [4] (summing errors in quadrature).

Now, we analyze the exclusive production of the radially excited $\psi(2S)$ mesons. In Fig. 2, we show the rapidity distribution for that meson state (dashed line), which gives at central rapidity a cross section $\frac{d\sigma}{dy}(y=0)=0.94$ nb. $\sigma(pp\to p+\psi(2S)+p)\times \mathrm{Br}(\psi(2S)\to\mu^+\mu^-)=18\,\mathrm{pb}$ is obtained for rapidities $2.0<y<4.5$. Accordingly, we now predict $\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}(2.0<\eta_{\mu^\pm}<4.5)=$ 7.7 pb compared to $\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}(2.0<\eta_{\mu^\pm}<4.5)=$ $7.8\pm1.6\,\mathrm{pb}$ measured by LHCb [4]. At mid-rapidity we obtain the ratio $[\psi(2S)/\psi(1S)]_{y=0}=0.16$ and, taking the integrated cross section for $2.0<y<4.5$, we have $[\psi(2S)/\psi(1S)]_{2<y<4.5}=0.18$. The latter value of the ratio is strongly consistent with the LHCb determination $[\psi(2S)/\psi(1S)](2.0<\eta_{\mu^\pm}<4.5)=0.19\pm0.04$.

It is timely to compare our results to similar theoretical approaches in the literature. The values obtained for the integrated cross sections for the exclusive J/ψ production are consistent with calculations using the color dipole formalism [11,15] and with the prediction from Starlight [16] and SuperChic [17] generators as well. In the case of the $\psi(2S)$ state, our prediction is in agreement with the Starlight generator result, which gives $\sigma^{\mathrm{STARLIGHT}}_{pp\to\psi(2S)(\to\mu^+\mu^-)}=6.1$ pb. On the other hand, our results are about a factor of 2 lower than the values appearing in Ref. [14], which considers the $k_\perp$-factorization approach.

The complexity of the phenomenological model considered here could make its connection to the QCD dynamics not so clear. Therefore, some comments are in order at this point. The main dependence being probed in the exclusive vector meson production in pp collisions is the energy behavior of the photoproduction cross section (given that the photon flux is well known). The LHCb data cover 1 order of magnitude on photon-proton center-of-mass energy above the typical Deutsches Elektronen-Synchrotron-Hadron Elektron Ring Anlage (DESY-HERA) regime. Such an extrapolation is completely driven by the QCD dynamics at small x and is embedded in the dipole cross section in our analysis. This is directly translated into the rapidity dependence of the pp cross section. The other inputs, such as the paramaters in wave functions, real part and skewness corrections, and absorption effects, only account for the overall normalization. It is worth mentioning that our predictions are parameter free. The inputs in the meson wave function are determined from its normalization condition. The phenomenological parameters in the dipole cross section were determined by a fit to DESY-HERA data for the proton structure function F_2 at small x [13] and were already tested against exclusive processes at DESY-HERA energies at a number of contributions [12,15].

Finally, we perform predictions for the next LHC runs in proton-proton mode. We have found $\frac{d\sigma_{J/\psi}}{dy}=6.2$ nb and 7.9 nb for central rapidities at energies of 8 and 14 TeV, respectively. For the $\psi(2S)$ state, the extrapolation gives $\frac{d\sigma_{\psi(2S)}}{dy}=1.0$ and 1.4 nb for the same energies at central rapidity. We have checked that our values are lower than those predicted by the $k_\perp$-factorization approach [14], which gives $\frac{d\sigma_{\psi(1S)}}{dy}\simeq 11$ nb and $\frac{d\sigma_{\psi(2S)}}{dy}\simeq 2$ nb for energy of 14 TeV and central rapidity.

IV. SUMMARY

We have investigated the exclusive J/ψ and radially excited $\psi(2S)$ photoproduction off nucleons in proton-proton collisions at the LHC. The theoretical framework considered in the analysis is the light-cone dipole formalism and predictions are obtained for center-of-mass energies 7, 8, and 14 TeV. It was found that the coherent exclusive photoproduction of $\psi(2S)$ off nuclei has an upper bound of order 0.71 mb at $y=0$ down to 0.10 mb for backward/forward rapidities $y=\pm3$. The incoherent contribution was also computed and it is a factor 0.2 below the coherent one. Comparison has been done to the recent LHCb Collaboration data for the exclusive $\psi(1S)$ and $\psi(2S)$ production at 7 TeV. The experimental values are fairly described by the present calculation, which gives $\sigma[pp\to J/\psi(\to\mu^+\mu^-)]=298$ pb, $\sigma[pp\to\psi(2S)(\to\mu^+\mu^-)]=7.7$ pb and $R(\frac{\psi(2S)}{\psi(1S)})=$ 0.18 in the pseudorapidity range $2.0<\eta_{\mu^\pm}<4.5$.

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

[2] J. Nemchik, N. N. Nikolaev, E. Predazzi, and B. G. Zakharov, Phys. Lett. B **374**, 199 (1996).

[3] J. Nemchik, Phys. Rev. D **63**, 074007 (2001).

[4] R. Aaij *et al.* (LHCb Collaboration), J. Phys. G **40**, 045001 (2013).

[5] F. Gelis, E. Iancu, J. Jalilian-Marian, and R. Venugopalan, Annu. Rev. Nucl. Part. Sci. **60**, 463 (2010); H. Weigert, Prog. Part. Nucl. Phys. **55**, 461 (2005); J. Jalilian-Marian

and Y. V. Kovchegov, Prog. Part. Nucl. Phys. **56**, 104 (2006).

[6] M. B. Gay Ducati, M. T. Griep, and M. V. T. Machado, arXiv:1305.2407.

[7] B. Abelev *et al.* (ALICE Collaboration), Phys. Lett. B **718**, 1273 (2013).

[8] E. Abbas *et al.* (ALICE Collaboration), arXiv:1305.1467.

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

[10] C. Adloff *et al.* (H1 Collaboration), Phys. Lett. B **541**, 251 (2002).

[11] V. P. Goncalves and M. V. T. Machado, Phys. Rev. C **84**, 011902 (2011).

[12] J. R. Forshaw, R. Sandapen, and G. Shaw, J. High Energy Phys. 11 (2006) 025.

[13] E. Iancu, K. Itakura, and S. Munier, Phys. Lett. B **590**, 199 (2004).

[14] W. Schäfer and A. Szczurek, Phys. Rev. D **76**, 094014 (2007).

[15] H. Kowalski, L. Motyka, and G. Watt, Phys. Rev. D **78**, 014023 (2008).

[16] S. R. Klein and J. Nystrand, Phys. Rev. Lett. **92**, 142003 (2004).

[17] L. A. Harland-Lang, V. A. Khoze, M. G. Ryskin, and W. J. Stirling, Eur. Phys. J C **65**, 433 (2010).