Heavy quark production and gluon saturation in double parton scattering at the LHC

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The production of $c\bar{c}c\bar{c}$, $b\bar{b}b\bar{b}$ and $c\bar{c}b\bar{b}$ pairs considering double parton scattering at LHC energies is investigated. We estimate the contribution of saturation effects to the different final states and predict the energy dependence of the cross sections. Moreover, we estimate the ratio between the double and single parton scattering cross sections for the full rapidity range of the LHC and for the rapidity range of the LHCb experiment. For the full rapidity range we confirm a previous prediction, namely that for charm production the double parton scattering contribution becomes comparable with the single parton scattering one at LHC energies. We also demonstrate that this result remains valid when one introduces saturation effects in the calculations. Finally we show that the production of $c\bar{c}b\bar{b}$ contributes significantly to bottom production. For the LHCb kinematical range the ratio is strongly reduced.

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I. INTRODUCTION

Heavy quark production in hard collisions of hadrons, leptons, and photons has been considered as a clean test of perturbative QCD. This process provides not only many tests of perturbative QCD, but also some of the most important backgrounds to new physics processes, which have motivated comprehensive phenomenological studies carried out at DESY-HERA, Tevatron and LHC. The study of heavy quark production also is motivated by the strong dependence of the cross section on the behavior of the gluon distribution, which determines the QCD dynamics at high energies. The huge density of low-x gluons in the hadron wave functions is expected to modify the usual description of the gluon distribution in terms of the linear DGLAP dynamics [1] by the inclusion of nonlinear corrections associated to the physical process of parton recombination. In particular, it is expected the formation of a color glass condensate (CGC) [2], which is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wave function (parton saturation) and described in the mean-field approximation by the Balitsky-Kovchegov (BK) equation [3]. These saturation effects are expected to contribute significantly at high energies leading to the breakdown of the twist expansion and of the factorization schemes (for recent reviews see Ref. [4]). In Ref. [5] we studied the impact of the saturation effects in the single heavy quark pair production in proton-proton and proton-nucleus collisions at LHC energies considering the color dipole formalism and the solution of the running coupling Balitsky-Kovchegov equation, which is currently the state-of-the-art of the CGC formalism. One of the goals of this paper is to compare our predictions with recent experimental data.

The high density of gluons in the initial state of hadronic collisions at LHC also implies that the probability of multiple gluon-gluon interactions within one proton-proton collision increases. In particular, the probability of having two or more hard interactions in a collision is not significantly suppressed with respect to the single interaction probability. It has motivated a rapid development of the theory of double parton scattering (DPS) processes and several estimates of the cross sections for different processes have been presented in recent years. In particular, the production of two $c\bar{c}$ pairs in double-parton scattering was discussed recently in Ref. [6] (see also Ref. [7]), which obtained the surprising result that at the energies of LHC the contribution of the DPS channel for two $c\bar{c}$ pairs production [see Fig. 1 (right)] becomes of the same order of the single parton scattering (SPS) channel contribution for one pair production [see Fig. 1 (left)], with the production of two $c\bar{c}$ pairs in SPS processes [see Fig. 1 (center)] being strongly suppressed. Another of the goals of this paper is to complement the study performed in Ref. [6] by the inclusion of saturation effects and by the analysis of the two $b\bar{b}$ pairs production. Moreover, we estimate for the first time the cross section for the $c\bar{c}b\bar{b}$ production in DPS processes.

This paper is organized as follows. In the next section (Sec. II) we present a brief review of heavy quark production in SPS and DPS processes. In Sec. III we present the main formulas for the calculation of the one pair $Q\bar{Q}$ production in the color dipole formalism. We also make a brief review of how to include saturation effects in the color dipole formalism and present the models that we will use in the calculations. In Sec. IV we present our predictions for the energy dependence of the $c\bar{c}c\bar{c}$, $b\bar{b}b\bar{b}$ and $c\bar{c}b\bar{b}$ production cross sections. Finally, in Sec. V we summarize our main results and conclusions.

II. HEAVY QUARK PRODUCTION

The calculation of the heavy quark cross section in the standard framework assumes that only one hard interaction

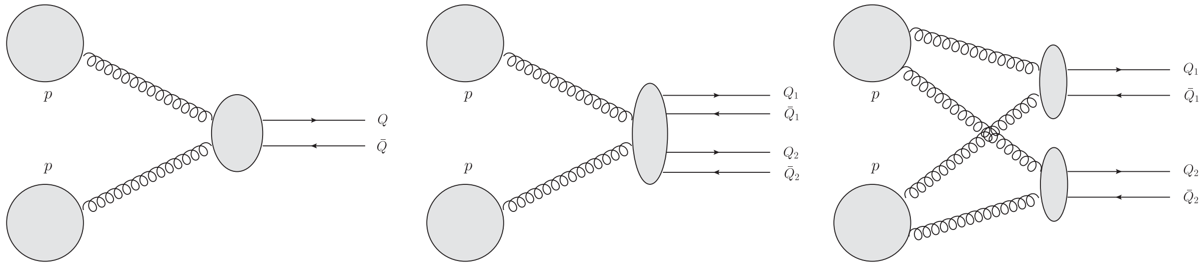

FIG. 1. Left: The $Q\bar{Q}$ pair production in the single parton scattering (SPS) process. Center: The $Q_1\bar{Q}_1Q_2\bar{Q}_2$ pair production in the SPS process. Right: $Q_1\bar{Q}_1Q_2\bar{Q}_2$ pair production in the double parton scattering (DPS) process.

occurs per collision. This mechanism is called single-parton scattering (SPS), since the Feynman diagram contains one gluon from the hadron target and one gluon from the hadron projectile [see Fig. 1 (left)]. The next-to-leading order (NLO) correction for this process was already studied [8–11]. In general, higher order corrections do not change significantly the observables, since the contributions are suppressed by powers of α_s. For example, the $Q_1\bar{Q}_1Q_2\bar{Q}_2$ ($Q_i = c$ or b) production in SPS processes [see Fig. 1 (center)] is suppressed by a factor proportional to α_s^4 (For explicit calculations of two heavy quark pairs production in SPS processes see, e.g., Refs. [12,13]). The basic idea, which justifies the SPS approach, is that the probability of a hard interaction in a collision is very small, which makes the probability of having two or more hard interactions in a collision highly suppressed with respect to the single interaction probability. Such an assumption is reasonable in the kinematical regime in which the flux of incoming partons is not very high. However, as already pointed in Ref. [7], at LHC energies the hadronic cross section appears to be 3 orders of magnitude higher than the cross section of the partonic subprocess. In this condition, there is a high probability of scattering of more than one pair of partons in the same hadron-hadron collision. This expectation has been recently confirmed by the LHCb Collaboration [14], which has observed the production of J/Ψ mesons accompanied by open charm and pairs of open charm hadrons in pp collisions at $\sqrt{s} = 7$ TeV and verified that the SPS predictions are significantly smaller than the observed cross sections. In [15] it was shown that the DPS contribution to differential cross sections of open charm and charmed meson production is rather significant, being of the same order of magnitude of the SPS differential cross sections. Remarkably, the sum of the SPS with the DPS contribution almost describes the experimental data from ATLAS, LHCb and ALICE on transverse momentum distribution of charmed meson production [15]. The contribution of $c\bar{c}c\bar{c}$ production in SPS processes to differential cross sections was shown to be negligible when compared with the production in DPS, reaching at most ≈10% of the magnitude of this last one, but in most cases being 2 orders of magnitude smaller [15].

Following the same factorization approximations assumed for processes with a single hard scattering, it is possible to derive the DPS contribution for the heavy quark cross section considering two independent hard parton subprocesses. It is given by (see, e.g. Ref. [16])

$$\begin{aligned}\sigma^{\rm DPS}_{h_1h_2\to Q_1\bar{Q}_1Q_2\bar{Q}_2} &= \left(\frac{m}{2}\right)\int \Gamma^{gg}_{h_1}(x_1, x_2; \boldsymbol{b}_1, \boldsymbol{b}_2; \mu_1^2, \mu_2^2)\\ &\times \hat{\sigma}^{gg}_{Q_1\bar{Q}_1}(x_1, x_1', \mu_1^2)\hat{\sigma}^{gg}_{Q_2\bar{Q}_2}(x_2, x_2', \mu_2^2)\\ &\times \Gamma^{gg}_{h_2}(x_1', x_2'; \boldsymbol{b}_1 - \boldsymbol{b}, \boldsymbol{b}_2 - \boldsymbol{b}; \mu_1^2, \mu_2^2)\\ &\times dx_1dx_2dx_1'dx_2'd^2b_1d^2b_2d^2b, \end{aligned} \tag{1}$$

where we assume that the quark-induced subprocesses can be disregarded at high energies, $\Gamma^{gg}_{h_1}(x_1, x_2; \boldsymbol{b}_1, \boldsymbol{b}_2; \mu_1^2, \mu_2^2)$ are the two gluon parton distribution functions which depend on the longitudinal momentum fractions x_1 and x_2, and on the transverse position $\boldsymbol{b}_1$ and $\boldsymbol{b}_2$ of the two gluons undergoing the hard processes at the scales μ_1^2 and μ_2^2. The functions $\hat{\sigma}$ are the parton level subprocess cross sections and $\boldsymbol{b}$ is the impact parameter vector connecting the centers of the colliding protons in the transverse plane. Moreover, $m/2$ is a combinatorial factor which accounts for indistinguishable and distinguishable final states. For $Q_1 = Q_2$ one has $m = 1$, while $m = 2$ for $Q_1 \neq Q_2$. In a rigorous calculation several kinds of correlations between the two gluons in the double gluon distribution function $\Gamma^{gg}_{h_1}$ should be taken into account (see, e.g., Ref. [17]), however a precise estimative of the magnitude of the correlations is very difficult, and in practical calculations most of the correlations are disregarded. Moreover, some of these correlations, as the color correlation and the parton-exchange interference, are Sudakov suppressed at high energies, and can be neglected in this kinematical regime [17]. It is common in the literature to assume that the longitudinal and transverse components of the double parton distributions can be decomposed and that the longitudinal components can be expressed in terms of the product of two independent single parton distributions. The proof of these assumptions in the general case is still an open question (see, e.g. Refs. [16,18]). In the particular case of heavy quark production, in Ref. [6] the authors compared the results of this simple factorized Ansatz with those obtained using double parton distributions with QCD evolution and verified that the predictions are similar if we take into account all uncertainties present in the calculations as, for instance, those associated to the choice of the factorization and renormalization scales. In the present study we will also assume the validity of these assumptions and consider that the DPS contribution to the heavy quark cross section can be expressed in a simple generic form given by

$$\sigma^{\rm DPS}_{h_1h_2\to Q_1\bar{Q}_1Q_2\bar{Q}_2} = \left(\frac{m}{2}\right)\frac{\sigma^{\rm SPS}_{h_1h_2\to Q_1\bar{Q}_1}\sigma^{\rm SPS}_{h_1h_2\to Q_2\bar{Q}_2}}{\sigma_{\rm eff}}, \quad (2)$$

where $\sigma_{\rm eff}$ is a normalization cross section representing the effective transverse overlap of partonic interactions that produce the DPS process. As in [6] we assume $\sigma_{\rm eff} = 15$ mb. This formula expresses the DPS cross section as the product of two individual SPS cross sections assuming that the two SPS subprocesses are uncorrelated and do not interfere. An analysis of this hypothesis using a bag model for the proton was done in Ref. [19].

A comment is in order. In what follows we will estimate the DPS cross section using Eq. (2) and taking into account saturation effects in the SPS cross section, which will be discussed in the next section. We are aware that Eq. (2) may not be valid when the saturation effects become important. However, we believe that in the particular case of heavy quark production at LHC energies it allows us to obtain a reasonable first approximation for the magnitude of these effects in the DPS process.

III. SATURATION EFFECTS IN HEAVY QUARK PRODUCTION

Saturation effects can be naturally described in the color dipole formalism. At high energies color dipoles with a defined transverse separation are eigenstates of the interaction. The main quantity in this formalism is the dipole-target cross section, which is universal and determined by QCD dynamics at high energies. In particular, it provides a unified description of inclusive and diffractive observables in ep processes as well as of Drell-Yan pairs, prompt photon and heavy quark production in hadron-hadron collisions.

The description of heavy quark production in the color dipole formalism was proposed in Refs. [20,21] and discussed in detail in Refs. [22,23] (see also Refs. [24–26]). The basic idea is the following. Before interacting with the hadron target h_2 a gluon is emitted by the hadron projectile h_1, which fluctuates into a color octet pair $Q\bar{Q}$. In the low-x regime the time of fluctuation is much larger than the time of interaction, and color dipoles with a defined transverse separation $\vec{\rho}$ are eigenstates of the interaction. Consequently, the total cross section for the process $h_1h_2 \to Q\bar{Q}X$ is then given by [20,21]

$$\sigma(h_1h_2 \to \{Q\bar{Q}\}X) = 2\int_0^{-\ln(2m_Q/\sqrt{s})} dy x_1 G_{h_1}(x_1, \mu_F)\sigma(Gh_2 \to \{Q\bar{Q}\}X), \quad (3)$$

where $x_1G_{h_1}(x_1, \mu_F)$ is the projectile gluon distribution, the cross section $\sigma(Gh_2 \to \{Q\bar{Q}\}X)$ describes the heavy quark production in the gluon-target interaction, y is the rapidity of the pair and μ_F is the factorization scale. The cross section for the process $G + h_2 \to Q\bar{Q}X$ is given by

$$\sigma(Gh_2 \to \{Q\bar{Q}\}X) = \int_0^1 d\alpha \int d^2\rho |\Psi_{G\to Q\bar{Q}}(\alpha, \rho)|^2 \sigma^{h_2}_{Q\bar{Q}G}(\alpha, \rho), \quad (4)$$

where $\sigma^{h_2}_{Q\bar{Q}G}$ is the scattering cross section of a color neutral quark-antiquark-gluon system on the hadron target h_2 [20–23]:

$$\sigma^{h_2}_{Q\bar{Q}G}(\alpha, \rho) = \frac{9}{8}[\sigma_{Q\bar{Q}}(\alpha\rho) + \sigma_{Q\bar{Q}}(\bar{\alpha}\rho)] - \frac{1}{8}\sigma_{Q\bar{Q}}(\rho). \quad (5)$$

The quantity $\sigma_{Q\bar{Q}}$ is the scattering cross section of a color neutral quark-antiquark pair with separation radius ρ on the hadron target and α ($\bar{\alpha} = 1 - \alpha$) is the fractional momentum of quark (antiquark). The light-cone wave function of the transition $G \to Q\bar{Q}$ can be calculated perturbatively, with the squared wave function given by

$$|\Psi_{G\to Q\bar{Q}}(\alpha, \rho)|^2 = \frac{\alpha_s(\mu_R)}{(2\pi)^2}\{m_Q^2 K_0^2(m_Q\rho) + [\alpha^2 + \bar{\alpha}^2]m_Q^2 K_1^2(m_Q\rho)\}, \quad (6)$$

where $\alpha_s(\mu_R)$ is the strong coupling constant. Following Ref. [5] we will assume that $\mu_F = 2m_Q$ and that xG is given in terms of the GRV98 parton distribution [27], but similar predictions are obtained using, e.g., the CTEQ6L parametrization [28].

In order to estimate the heavy quark cross section we need to specify the dipole-target cross section. In the color glass condensate formalism [2] it is given in terms of the dipole-target forward scattering amplitude $\mathcal{N}(x, \rho, \boldsymbol{b})$, which encodes all the information about the hadronic scattering, and thus about the nonlinear and quantum effects in the hadron wave function. It reads

$$\sigma_{Q\bar{Q}}(x, \rho) = 2\int d^2\boldsymbol{b}\mathcal{N}(x, \rho, \boldsymbol{b}). \quad (7)$$

It is useful to assume that the impact parameter dependence of $\mathcal{N}$ can be factorized as $\mathcal{N}(x, \rho, \boldsymbol{b}) = \mathcal{N}(x, \rho)S(\boldsymbol{b})$, so that $\sigma_{Q\bar{Q}}(x, \rho) = \sigma_0\mathcal{N}(x, \rho)$, with σ_0 being a free parameter related to the nonperturbative QCD physics. The Balitsky-JIMWLK hierarchy [2,3] describes the energy evolution of the dipole-target scattering amplitude $\mathcal{N}(x, \rho)$. In the mean-field approximation, the first equation of this hierarchy decouples and becomes the

BK equation [3]. However, an exact analytical solution to the BK equation is unknown. A numerical solution, encoded in a FORTRAN subroutine, which considers running coupling corrections to the kernel of the BK equation, is available in the literature [29]. The calculations using this numerical solution will be denoted as "rcBK" hereafter. Currently, the rcBK model is the most sophisticated saturation model available in the literature. We also present the predictions obtained using the phenomenological saturation model proposed by Golec-Biernat and Wusthoff in Ref. [30] (denoted GBW hereafter), in which the dipole-proton cross section is given by

$$\sigma^{\mathrm{GBW}}_{Q\bar{Q}}(x,\rho) = \sigma_0\left[1 - \exp\left(-\frac{\rho^2 Q_s^2(x)}{4}\right)\right], \quad (8)$$

where the saturation scale is given by $Q_s^2(x) = Q_0^2(x_0/x)^\lambda$, with $Q_0^2 = 1\ \mathrm{GeV}^2$, $x_0 = 3\times 10^{-4}$ and $\lambda = 0.288$. Our motivation to use this model, which has been updated in several aspects in the past years, is that it allows us to easily obtain its linear limit, given by $\sigma^{\mathrm{GBW\ linear}}_{Q\bar{Q}} = \sigma_0\rho^2 Q_s^2(x)/4$. Consequently, it allows one to quantify the contribution of the saturation effects in the observable under analysis.

IV. RESULTS AND DISCUSSION

The heavy quark production in SPS processes considering saturation effects was studied in detail in Ref. [5]. There we predicted the energy dependence of the charm and bottom pair production and compared with data points from UA2, PHENIX and from cosmic rays. All these data can be quite well described using the color dipole formalism and an adequate choice of the heavy quark mass. Recently, the ALICE Collaboration has released its first data for charm production at $\sqrt{s} = 2.76$ TeV [31]. It allows us to compare, for the first time, the color dipole formalism for heavy quark production in hadronic collisions with experimental data at high energies, which is the kinematical range where it is theoretically justified. In Fig. 2 (left) we compare the rcBK, GBW and GBW linear predictions with the ALICE [31] and PHENIX [32,33] data considering $m_c = 1.5$ GeV. We can see that the different models for the dipole-target cross sections are able to describe the experimental data. The rcBK and GBW predictions are almost identical in the whole range of energy. When the GBW linear model is used as input in the calculations, we predict larger values for the charm cross section. In contrast, for bottom production [see Fig. 2 (right)], the GBW and GBW linear predictions are identical in the considered energy range and the rcBK one predicts larger values of the cross section. Unfortunately, up to now, LHC data for bottom production are not available. The distinct behavior observed for charm and bottom production is directly associated to the fact that in the color dipole formalism the contribution of the nonlinear effects is determined by the integrand of the pair separation (ρ) integral [see Eq. (4)], i.e. by the product of the wave function squared and the dipole-target cross section. This integrand has a peak at $\rho \approx 1/m_Q$. Consequently, for bottom production, the integral is dominated by very small pair separations, probing the linear regime of the dipole-target cross section. The rcBK prediction is larger than the GBW and GBW linear ones because its linear regime is associated to the Balitsky-Fadin-Kuraev-Lipatov dynamics, which implies a steep energy dependence. In contrast, for charm production, we probe larger values of the pair separation, where saturation effects cannot be disregarded. The difference between the rcBK and the GBW predictions is associated to the delayed saturation predicted by the rcBK equation.

In Fig. 2 we also present the $c\bar{c}c\bar{c}$ and $b\bar{b}b\bar{b}$ production cross sections in DPS processes considering only the GBW and GBW linear models, for simplicity. For $c\bar{c}c\bar{c}$

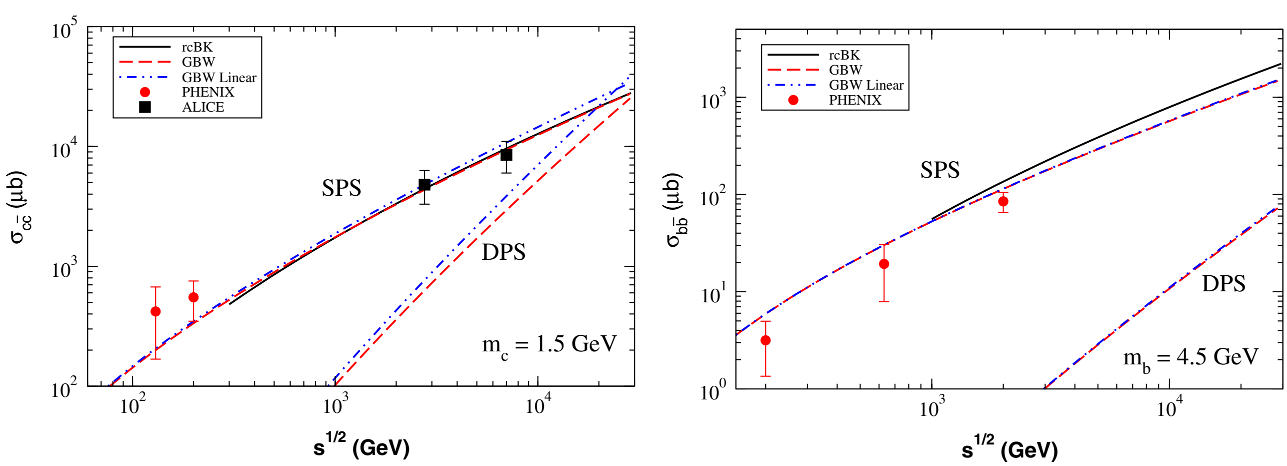

FIG. 2 (color online). Charm (left) and bottom (right) production cross sections in single parton scattering (SPS) and double parton scattering (DPS) as a function of the center of mass system (c.m.s.) energy ($\sqrt{s}$). Data points are from PHENIX [32,33] (circles) and from ALICE [31] (squares).

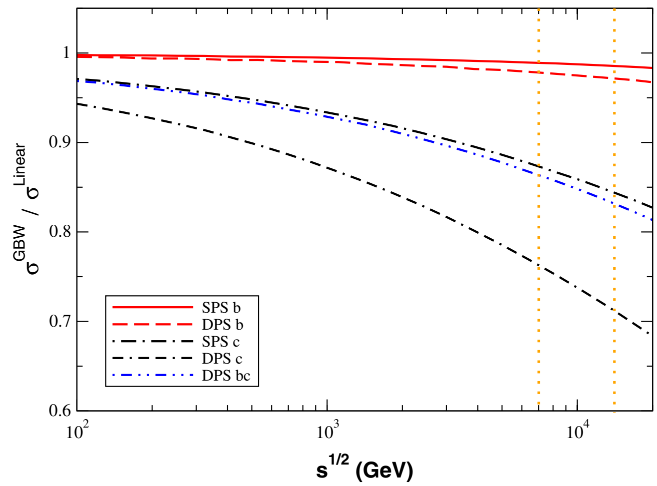

FIG. 3 (color online). The ratio $\sigma^{\mathrm{GBW}}/\sigma^{\mathrm{GBW\ Linear}}$ for charm and bottom production in SPS and DPS processes as a function of the c.m.s. energy ($\sqrt{s}$).

production, we confirm the conclusion from [6], that DPS charm production cross section becomes comparable with the SPS one at LHC energies. This result remains valid when one considers saturation effects in the calculations. On the other hand, the $b\bar{b}b\bar{b}$ production in DPS processes is always negligible when compared to $b\bar{b}$ production in SPS processes. In order to estimate the contribution of the saturation effects in these processes we calculate the ratio between the GBW and GBW linear cross sections. In Fig. 3 we present the energy dependence of this ratio, which is equal to approximately one when the saturation effects are small. The two vertical lines delimit the energy range $7 \leq \sqrt{s} \leq 14$ TeV. For $b\bar{b}$ production (denoted SPS b in the figure) we can see that the magnitude of saturation effects is really very small in the energies of LHC. On the other hand, for $c\bar{c}$ production, the saturation effects decrease the SPS cross section in $\approx 15\%$. In the case of DPS processes, these effects are very small in the bottom case but are $\approx 28\%$ in the $c\bar{c}c\bar{c}$ production. In Fig. 3 we also present the magnitude of the saturation effects for a third type of event: the $c\bar{c}b\bar{b}$ production in DPS processes. In this process, instead of two pairs of the same flavor we have the production of one $c\bar{c}$ pair and one $b\bar{b}$ pair. As we can see, the saturation effects in this type of process (denoted "DPS bc" hereafter) cause almost the same decrease ($\approx 15\%$) that they cause in the SPS $c\bar{c}$ production. This almost identical decrease is a consequence of the fact that the $c\bar{c}b\bar{b}$ production cross section in DPS processes is given by the product of two SPS cross sections, one for $c\bar{c}$ production and one for $b\bar{b}$ production. Since $c\bar{c}$ production is much more sensitive to saturation effects than $b\bar{b}$ production, the saturation effects in $c\bar{c}b\bar{b}$ production come predominantly from the $c\bar{c}$ sector. Having discussed the magnitude of the saturation effects, in the following analysis we will only use the GBW model as input in our calculations.

In Fig. 4 we present our predictions for the energy dependence of the ratio $\sigma^{\mathrm{DPS}}/\sigma^{\mathrm{SPS}}$. We denote by "$bc/b$" the ratio between the cross sections for the $b\bar{b}c\bar{c}$ production in DPS processes and for the $b\bar{b}$ production in SPS processes, and so on. As in previous figures, the vertical lines delimit the energy range probed by the LHC. In the left panel we present the results obtained integrating the cross sections in the full LHC rapidity range, while in the right panel the cross sections have been integrated in the LHCb rapidity range $2 < y < 4.5$. Considering initially the full LHC rapidity range, we have that for $\sqrt{s} = 7$ TeV the DPS charm production cross section is already of the same order of magnitude of the SPS charm production cross section, with the first reaching $\approx 30\%$ of the value of the second. For $\sqrt{s} = 14$ TeV, this value reaches $\approx 60\%$. In contrast, the ratio "bb/b" is almost

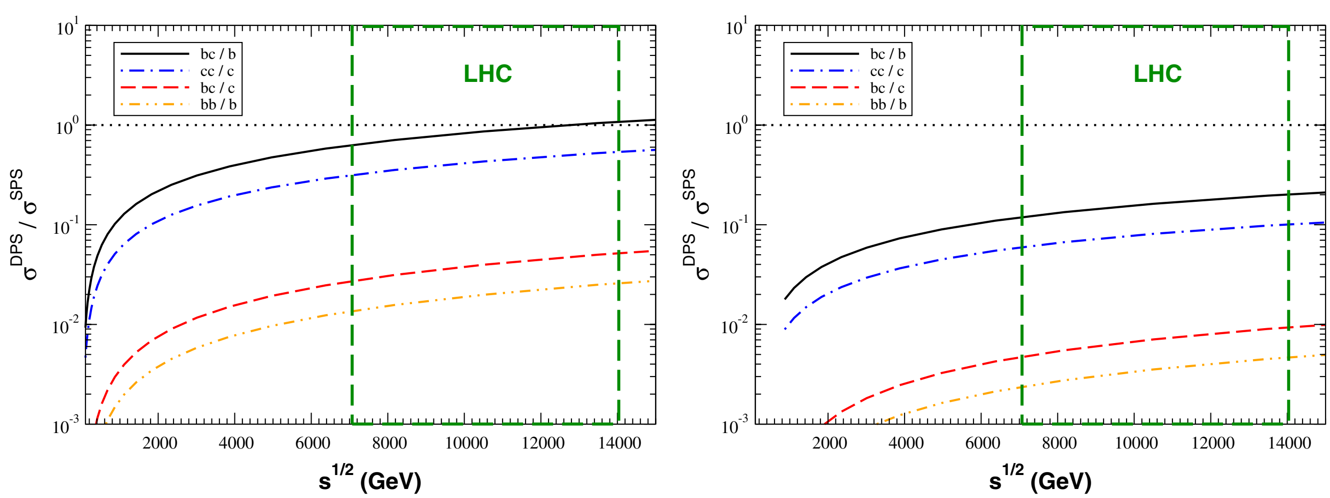

FIG. 4 (color online). The ratio $\sigma^{\mathrm{DPS}}/\sigma^{\mathrm{SPS}}$ as a function of the c.m.s. energy ($\sqrt{s}$) considering the full rapidity range (left) and the LHCb rapidity range (right).

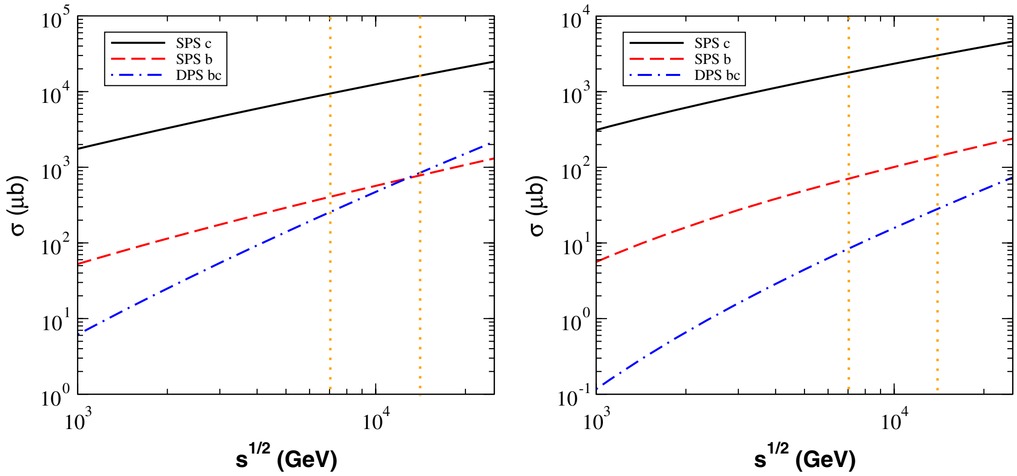

FIG. 5 (color online). $c\bar{c}$ and $b\bar{b}$ production cross sections in SPS events and $c\bar{c}b\bar{b}$ production cross section in DPS events as a function of the c.m.s. energy ($\sqrt{s}$) in the full LHC (left) and LHCb (right) rapidity range.

2% in the LHC energy range. A surprising result is observed when we consider the ratio "bc/b." We obtain that this ratio is ≈ 0.6 for $\sqrt{s} = 7$ TeV and ≈ 1 for $\sqrt{s} = 14$ TeV. It means that in pp collisions at $\sqrt{s} = 14$ TeV half the total amount of $b\bar{b}$ pairs produced in LHC will come from the DPS channel. When we consider the ratio for the restricted rapidity range probed by LHCb, we obtain that all predictions are significantly reduced, being always smaller than 20%. In particular, the ratio "bc/b" in LHCb assumes the value ≈ 0.1 at $\sqrt{s} = 7$ TeV and ≈ 0.2 at $\sqrt{s} = 14$ TeV, indicating a small but non-negligible contribution from the DPS channel to the total amount of $b\bar{b}$ pairs detected in LHCb. For comparison, the ratio "cc/c" assumes the value ≈ 0.06 at $\sqrt{s} = 7$ TeV and ≈ 0.1 at $\sqrt{s} = 14$ TeV.

The behavior of the ratio "bc/b" can be better understood if we compare the energy dependence of the cross sections for the SPS charm and bottom production with that predicted for the $c\bar{c}b\bar{b}$ production (denoted "DPS bc"). In Fig. 5 we present our predictions for these three different processes. As in the previous figure we present in the left panel the results obtained integrating the cross sections in the full LHC rapidity range, while in the right panel the cross sections have been integrated in the LHCb rapidity range $2 < y < 4.5$. In the first case, we can see that the "DPS bc" prediction grows up more rapidly with the energy than those corresponding to the SPS processes. This implies that the "DPS bc" prediction becomes of the same order of the "SPS b" one. In contrast, if we consider the LHCb rapidity range, the energy dependence of the three processes are not very distinct, which implies that the "DPS bc" prediction is always smaller than the "SPS b" one. This conclusion comes from the different rapidity distributions for charm and bottom production, which are presented in Fig. 6, where now the two vertical dotted lines delimit the rapidity interval probed by the LHCb. We observe that by considering the limited interval $2 < y < 4.5$ we are taking only a fraction of the total amount of charm and bottom produced. The product of these cross sections, integrated in the rapidity interval of LHCb, is much smaller than the product of the cross sections integrated in the whole phase space. Moreover, the differential cross section for bottom production falls down suddenly when $y > 6$ while the charm production cross section presents the same behavior only for $y > 7.5$. Therefore, for $y > 6$ the bottom production is negligible when compared with its production in the region $y < 6$. On the other hand, the charm production is still abundant in the interval $6 < y < 7.5$, being negligible only for $y > 7.5$. This extra contribution of charm production in the interval $6 < y < 7.5$, in which the bottom production is very small, is a second factor that makes the total cross section for $c\bar{c}b\bar{b}$ production in DPS much greater than the one obtained in the limited region $2 < y < 4.5$.

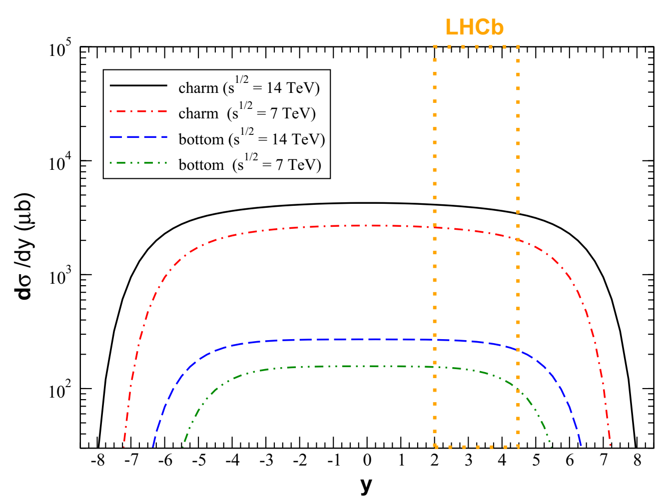

FIG. 6 (color online). Differential cross sections as a function of the rapidity y for SPS production of charm and bottom at the energies of LHC ($\sqrt{s} = 7$ TeV and $\sqrt{s} = 14$ TeV).

V. SUMMARY

The contribution of multiple parton scatterings in the LHC energy range is expected to be non-negligible due to the large number of low-x gluons present in the incident hadrons. The high partonic density should modify the QCD dynamics introducing nonlinear effects (with the possible formation of a color glass condensate) and should enhance the probability of having two or more hard interactions. In this paper we consider the production of double heavy quark pairs taken into account the saturation effects. We estimated the ratio between the double and single parton scattering cross sections for the full rapidity range of the LHC and for the rapidity range of the LHCb experiment. The previous prediction that for the charm production the double parton scattering contribution becomes comparable with the single parton scattering one at LHC energies has been confirmed. Moreover, we demonstrated that this result remains valid when one considers saturation effects in the calculations and that the production of $c\bar{c}b\bar{b}$ contributes significantly for the bottom production. Finally, we obtained that for the LHCb kinematical range the ratio is strongly reduced. We have estimated the DPS contribution considering the simple factorized model, which implies that our predictions should be taken with some caution, especially in the kinematical range when this contribution is large. However, we believe that our predictions can be considered as a reasonable first approximation and our study can motivate the experimental analysis of this particular final state and the theoretical development of more detailed analysis. In particular, the calculation of differential distributions and the inclusion of the hadronization effects, as made in Ref. [15] using the k_T-factorization approach, are important next steps.

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