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Heavy quark production in pA collisions: The double parton scattering contribution

E. R. Cazaroto*, V. P. Gonçalves† and F. S. Navarra*

**Instituto de Física, Universidade de São Paulo, CEP 05315-970 São Paulo, SP, Brazil*
†*Instituto de Física e Matemática, Universidade Federal de Pelotas,*
CEP 96010-900, Pelotas, RS, Brazil
†*victor.goncalves@thep.lu.se*

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In this paper, we estimate the double parton scattering (DPS) contribution for the heavy quark production in pA collisions at the LHC. The cross-sections for the charm and bottom production are estimated using the dipole approach, taking into account the saturation effects, which are important for high energies and for the scattering with a large nucleus. We compare the DPS contribution with the single parton scattering one and demonstrate that in the case of charm production, both are similar in the kinematical range probed by the LHC. Predictions for the rapidity range analyzed by the LHCb Collaboration are also presented. Our results indicate that the study of the DPS contribution for the heavy quark production in pPb collisions at the LHC is feasible and can be useful to probe the main assumptions of the approach.

Keywords: Heavy quark production; double parton scattering; nuclear collisions.

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1. Introduction

In hadronic collisions at high energies, the occurrence of multi-parton interactions (MPI) is a consequence of the high density of partons in the hadron wave functions. In this kinematic regime, the huge number of gluons increases the probability that two or more hard gluon–gluon fusions in a single hadron–hadron collision take place. The single gluon–gluon fusion in this kind of process is usually called Single Parton Scattering (SPS) and its contribution is in general the dominant process in perturbative QCD (pQCD) calculations. Recently, several theoretical and experimental studies have shown that Double Parton Scattering (DPS) processes cannot

†Corresponding author

be neglected at LHC energies (for recent reviews, see e.g. Ref. 1). In particular, the experimental results from the LHCb Collaboration on four D meson production in pp collisions[2] indicate that the DPS contribution is non-negligible in the kinematical range considered. Besides accounting for a significant part of the cross-section, the study of DPS processes is also important for other reasons. It can, for example, help us understand the spatial structure of hadrons,[3] the multi-parton correlations in the hadronic wave function[3–8] and is expected to help in the search for new physics (see, e.g. Ref. 9).

One of the promising processes to probe the DPS mechanism is heavy quark production. At high energies, this process probes the hadron wave function at very small values of the Bjorken-x and its cross-section can be calculated perturbatively. This process is dominated by gluon–gluon scatterings and a large cross-section is predicted at the LHC by the single scattering mechanism. As a consequence of the large luminosity of small-x gluons in the initial state, we expect a significant contribution of the DPS mechanism to heavy quark production. This expectation has been confirmed by the analysis performed in Refs. 10–12 (see also Refs. 7 and 13). In particular, in Ref. 12 we have investigated the impact of saturation effects in DPS production of heavy quarks. The results from Refs. 10 and 12 demonstrated that for charm production in pp collisions at LHC energies, the double parton scattering contribution becomes comparable with the single parton scattering one. Moreover, in Ref. 12 we also demonstrated that the production of $c\bar{c}b\bar{b}$ contributes significantly to bottom production.

Another possibility to probe the DPS mechanism is the analysis of different final states in nuclear collisions. The studies performed in Refs. 5, 14–17 have shown that the DPS mechanism is strongly enhanced in pA and AA collisions. These studies encourage us to extend our previous analysis to pA collisions and investigate the DPS contribution to heavy quark production. In particular, we will estimate the magnitude of the DPS cross-section for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, which can be measured at the LHC. As at small-x and a large nucleus, we expect a large contribution of saturation effects to heavy quark production,[18] we also include these effects in our calculations.

This paper is organized as follows. In Sec. 2, we present the basic assumptions and formulas derived in Refs. 14 and 15, which we use to calculate the DPS cross-sections for the heavy quark production in pA collisions. In Sec. 3, we estimate the total cross-section for the $c\bar{c}c\bar{c}$, $b\bar{b}b\bar{b}$ and $c\bar{c}b\bar{b}$ production for different nuclei and analyze its energy dependence. The DPS and SPS contributions are compared and the magnitude of the DPS contribution for pPb collisions at $\sqrt{s} = 5.02$ TeV is presented. Predictions for the kinematical range probed by the LHCb experiment also are shown. Finally, in Sec. 4, we summarize our main conclusions.

2. The Formalism

Initially, let us present a brief review of the formalism used to treat single and double parton scattering in a generic hadron–hadron collision. In the case of an SPS process, we assume that only one hard interaction occurs per collision. The basic idea, which justifies this 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. As discussed in Refs. 10–12, such assumption is reasonable in the kinematical regime in which the flux of incoming partons is not very high. However, at LHC energies, there is a high probability of scattering of more than one pair of partons in the same hadron–hadron collision. Consequently, it is important to take into account the contribution of the DPS processes. Following the same factorization approximation 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 sub-processes. It is given by (see, e.g. Ref. 3)

$$\begin{aligned}\sigma^{\mathrm{DPS}}_{h_1h_2\to Q_1\bar{Q}_1Q_2\bar{Q}_2} = \left(\frac{m}{2}\right)\int & \Gamma^{gg}_{h_1}(x_1,x_2;\mathbf{b}_1,\mathbf{b}_2;\mu_1^2,\mu_2^2)\\ & \times \hat{\sigma}^{gg}_{Q_1\bar{Q}_1}(x_1,x_1',\mu_1^2)\hat{\sigma}^{gg}_{Q_2\bar{Q}_2}(x_2,x_2',\mu_2^2)\\ & \times \Gamma^{gg}_{h_2}(x_1',x_2';\mathbf{b}_1-\mathbf{b},\mathbf{b}_2-\mathbf{b};\mu_1^2,\mu_2^2)\\ & \times dx_1\,dx_2\,dx_1'\,dx_2'\,d^2b_1\,d^2b_2\,d^2b\,, \end{aligned} \tag{1}$$

where we assume that the quark-induced sub-processes can be disregarded at high energies, $\Gamma^{gg}_{h_i}(x_1,x_2;\mathbf{b}_1,\mathbf{b}_2;\mu_1^2,\mu_2^2)$ are the two-gluon parton distribution functions which depend on the longitudinal momentum fractions x_1 and x_2, and on the transverse positions $\mathbf{b}_1$ and $\mathbf{b}_2$ of the two gluons undergoing hard processes at the scales μ_1^2 and μ_2^2. The functions $\hat{\sigma}$ are the parton level sub-processes cross-sections and $\mathbf{b}$ is the impact parameter vector connecting the centers of the colliding hadrons 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 $Q_1 \neq Q_2$. 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. As in Ref. 12 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

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

where σ_{eff} is a normalization cross-section representing the effective transverse overlap of partonic interactions that produce the DPS process. Disregarding possible correlations between the properties of two partons inside a hadron, e.g. spins, colors, flavors, transverse and longitudinal momenta, it is possible to relate σ_{eff} with the impact parameter integral of the overlap function $t(\mathbf{b})$: $\sigma_{\mathrm{eff}} = [\int d^2b\, t^2(\mathbf{b})]^{-1}$, where $t(\mathbf{b}) = \int f(\mathbf{b}_1)f(\mathbf{b}_1-\mathbf{b})d^2\mathbf{b}_1$ and $f(\mathbf{b})$ describes the transverse parton density in a given hadron. In general, it has been considered as a free parameter to

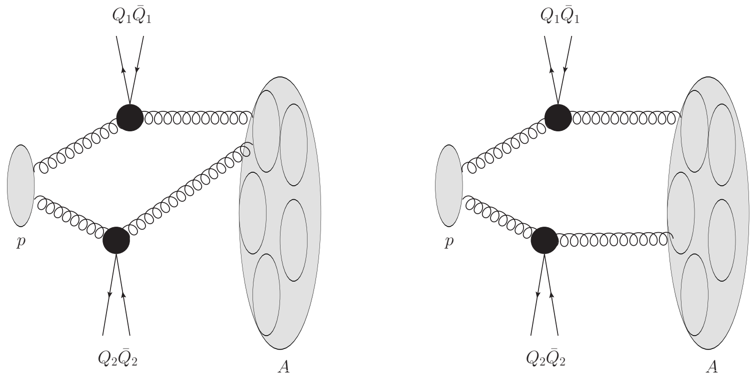

Fig. 1. Heavy quark production through DPS in pA collisions. Left: Two gluons coming from the proton projectile scatter with two gluons coming from the same nucleon in the target nucleus; Right: Two gluons coming from the proton projectile scatter with two gluons coming from different nucleons in the target nucleus.

be determined through fits to experimental $pp/p\bar{p}$ data. Recent results for multiple DPS measurements at Tevatron and LHC indicate that in order to reproduce the data we should have $\sigma_{\text{eff},pp} \approx 15 \pm 5$ mb.[1] Equation (2), usually called "pocket formula", expresses the DPS cross-section as the product of two individual SPS cross-sections assuming that the two SPS sub-processes are uncorrelated and do not interfere. The validity of these strong assumptions at LHC and higher energies is still an open question, which has motivated several theoretical studies (see, e.g. Refs. 3 and 7). However, the phenomenological analysis of different processes indicates that Eq. (2) can be considered a reasonable first approximation for the treatment of DPS processes.

In order to extend the treatment of DPS processes to proton–nucleus collisions we need to take into account that the parton flux associated to the nucleus is enhanced by a factor $\propto A$ and that in the interaction the two gluons associated to the proton can interact with two gluons coming from the same nucleon of the nucleus or with two gluons coming from different nucleons of the nucleus. Both possibilities are represented in the left and right panels of Fig. 1. Hereafter, we will denote the cross-sections associated to these two contributions by $\sigma_{pA}^{\text{DPS},1}$ and $\sigma_{pA}^{\text{DPS},2}$, respectively. A way to treat these contributions was proposed in Ref. 14 and applied in Ref. 15 to the production of same-sign WW in pA collisions, which was suggested to be a signal for DPS. In what follows we extend the framework presented in Refs. 14 and 15 to the calculation of heavy quark production. Following Refs. 14 and 15 we will assume that $\sigma_{pA}^{\text{DPS},1}$ can be estimated scaling the proton–nucleon pN cross-section by the number A of nucleons inside the nucleus, i.e. $\sigma_{pA}^{\text{DPS},1} = A \cdot \sigma_{pN}^{\text{DPS}}$. Moreover, we will consider that $\sigma_{pA}^{\text{DPS},2}$ can be estimated in terms of the DPS proton–nucleon cross-section as follows: $\sigma_{pA}^{\text{DPS},2} = \sigma_{pN}^{\text{DPS}} \cdot \sigma_{\text{eff},pp} \cdot F_{pA}$. The quantity F_{pA} can be expressed in terms of the nuclear thickness function T_{pA} as follows: $F_{pA} = [(A-1)/A] \int T_{pA}^2(\mathbf{r}) d^2r$, where $\mathbf{r}$

is the impact parameter between the colliding proton and nucleus. As discussed in Ref. 15, the factor $(A-1)/A$ was introduced to take into account the difference between the number of nucleon pairs and the number of different nucleon pairs. Consequently, the final formula for the DPS pA cross-section is given by[15]:

$$\sigma^{\rm DPS}_{pA\to ab} = \sigma^{\rm DPS,1}_{pA} + \sigma^{\rm DPS,2}_{pA} = A\sigma^{\rm DPS}_{pN\to ab}\left[1 + \frac{1}{A}\sigma_{{\rm eff},pp}F_{pA}\right] \qquad (3)$$

which implies

$$\sigma^{\rm DPS}_{pA\to ab} = \left(\frac{m}{2}\right)\frac{\sigma^{\rm SPS}_{pN\to a}\cdot\sigma^{\rm SPS}_{pN\to b}}{\sigma_{{\rm eff},pA}}\,, \qquad (4)$$

with the normalization effective cross-section given by

$$\sigma_{{\rm eff},pA} = \frac{\sigma_{{\rm eff},pp}}{A + \sigma_{{\rm eff},pp}F_{pA}}\,. \qquad (5)$$

In the simplest approximation that the nucleus has a spherical form (with uniform nucleon density) of radius $R_A = r_0A^{1/3}$, and $r_0 = 1.25$ fm, the integral of the nuclear thickness factor becomes:

$$F_{pA} = \frac{9A(A-1)}{8\pi R_A^2}\,. \qquad (6)$$

In the above equations one finds that $\sigma_{{\rm eff},pp}/\sigma_{{\rm eff},pA} \approx 3A$ instead of the simple scale factor A that one would naively expect. Moreover, this also implies that the pPb DPS cross-section is enhanced by a factor $3A\,(\approx 600)$ in comparison to the DPS contribution in pp processes.

The main input in the calculation of the DPS pA cross-section, Eq. (4), is the pN cross-section associated to the SPS process. As in our previous study,[12] we will estimate this quantity using the dipole approach, which allows to easily include saturation effects, which are expected to contribute significantly at the small values of x probed in heavy quark production at the LHC. This approach is expected to take into account of leading $\alpha_s\ln(1/x)$ corrections as well of QCD factorization breaking effects predicted to be present at large partonic densities.[19–21] Moreover, the results presented in Ref. 22 demonstrate the equivalence between the color dipole approach and the collinear one at low partonic densities, with the dipole predictions being similar to those obtained at next-to-leading order in the collinear formalism. Finally, as demonstrated in Ref. 12 (see also Ref. 23 for a recent analysis), this approach is able to describe the RHIC and LHC data. In the dipole approach the total cross-section for the process $pN\to Q\bar{Q}X$ is given by[24,25]:

$$\sigma(pN\to\{Q\bar{Q}\}X) = 2\int_0^{-\ln(2m_Q/\sqrt{s})} dy\,x_1g_p(x_1,\mu_F)\sigma(gN\to\{Q\bar{Q}\}X)\,, \qquad (7)$$

where $x_1g_p(x_1,\mu_F)$ is the projectile gluon distribution, the cross-section $\sigma(gN\to\{Q\bar{Q}\}X)$ describes heavy quark production in a gluon–nucleon interaction, y is the rapidity of the pair and μ_F is the factorization scale. The basic idea of this approach is that before interacting with the nucleon target N a gluon is emitted by the projectile p, which fluctuates into a color octet pair $Q\bar{Q}$. As 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 $\boldsymbol{\rho}$ are eigenstates of the interaction. The cross-section for the process $g + N \to Q\bar{Q}X$ is given by

$$\sigma(gN \to \{Q\bar{Q}\}X) = \int_0^1 d\alpha \int d^2\rho |\Psi_{g\to Q\bar{Q}}(\alpha, \rho)|^2 \sigma^N_{Q\bar{Q}g}(\alpha, \rho)\,, \tag{8}$$

where $\Psi_{g\to Q\bar{Q}}$ is the light-cone (LC) wave function of the transition $g \to Q\bar{Q}$ and $\sigma^N_{Q\bar{Q}g}$ is the scattering cross-section of a color neutral quark–antiquark–gluon system on the hadron target N.[19,22,24,25] As discussed in Refs. 12 and 18, this cross-section can be expressed in terms of the dipole–proton cross-section which is determined by the QCD dynamics at high energies and is probed in the deep inelastic scattering ep processes studied at HERA. Equation (7) can be directly generalized to describe the total cross-section of heavy quark production in pA collisions[18] considering the fact that color dipoles are eigenstates of the interaction. Therefore, the $Q\bar{Q}g$-nucleus interaction can be expressed in terms of the cross-section on a nucleon target using the Glauber–Gribov formalism:

$$\sigma^A_{Q\bar{Q}g}(x, \rho) = 2\int d^2\mathbf{b}\left\{1 - \exp\left[-\frac{1}{2}\sigma^N_{Q\bar{Q}g}(x, \rho^2)T_A(\mathbf{b})\right]\right\}, \tag{9}$$

where $T_A(\mathbf{b})$ is the nuclear profile function, which is obtained from a 3-parameter Fermi distribution for the nuclear density normalized to A. As in our previous studies,[12,18] we will assume that the dipole–nucleon cross-section can be described by the phenomenological saturation model proposed by Golec–Biernat and Wusthoff (GBW) in Ref. 26. As demonstrated in Refs. 12 and 18, the predictions for heavy quark production using this simplified model are very similar to those obtained using as input the solution of the running coupling Balitsky–Kovchegov equation,[27] which is the current state of the art of the treatment of the nonlinear and quantum effects in the hadron wave function. Moreover, following Ref. 12 we will assume that $m_c = 1.5$ GeV, $m_b = 4.5$ GeV, $\mu_F = 2m_Q$ and that xg is given in terms of the leading-order CTEQ10 parametrization,[28] which allows to describe the RHIC and LHC data for the total cross-sections. As verified in Refs. 18 and 23, the predictions for the heavy quark production at LHC energies are strongly sensitive to these choices. In particular, for the charm production at $\sqrt{s_{NN}} = 13$ TeV, the upper and lower bound predictions for the total cross-section can be different by $\approx 50\%$ of the central one. Such large uncertainty is similar to that present in the NLO collinear predictions (see Table 2 in Ref. 23). In Sec. 3, we will discuss the implications of this uncertainty on our predictions for the DPS cross-sections.

3. Results and Discussion

In what follows we will present our predictions for the integrated DPS pA cross-section of $c\bar{c}c\bar{c}$, $b\bar{b}b\bar{b}$ and $c\bar{c}b\bar{b}$ production. We will estimate $\sigma^{\rm DPS}_{pA\to Q_1\bar{Q}_1Q_2\bar{Q}_2}$ considering the full rapidity range covered by the LHC as well as the rapidity range probed

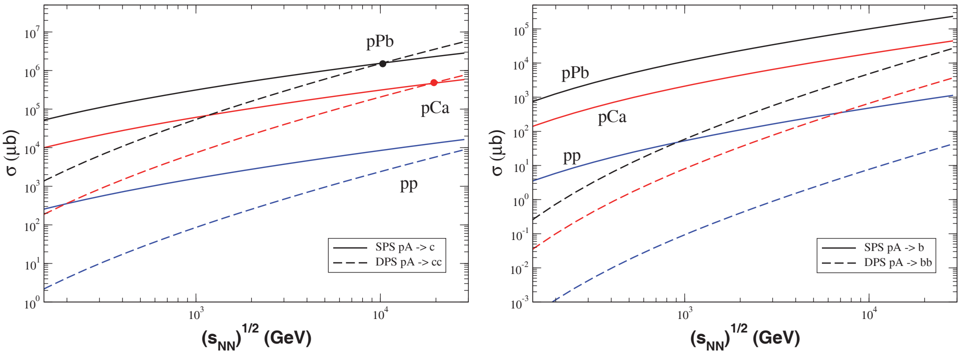

Fig. 2. Central predictions for the energy dependence of the SPS and DPS cross-sections for charm (left panel) and bottom (right panel) production in pp, pCa and pPb collisions. The SPS (DPS) predictions are represented by solid (dashed) lines. The current uncertainty in the predictions at high energies, associated to changes in the factorization and renormalization scales and heavy quark mass, is $\approx 40\,(90)\%$ in the SPS (DPS) case.

by the LHCb experiment ($2.0 < y < 4.5$). The single parton scattering cross-section associated to the process $pN \to Q\bar{Q}X$ will be calculated using Eq. (7). For the case of a nuclear target, we will use Eq. (9) as input in our calculations. Moreover, we will assume that $\sigma_{\text{eff},pp} = 15$ mb. Using Eq. (6) we obtain that $F_{pA} = 3.0\,(28.1)$ mb^{-1} for $A = 40\,(208)$, which implies that $\sigma_{\text{eff},pCa} = 170$ μb and $\sigma_{\text{eff},pPb} = 23.8$ μb. Finally, in our analysis the contribution of the single parton scattering processes associated to the $gg \to Q_1\bar{Q}_1Q_2\bar{Q}_2$ diagram will not be included, since the results presented in Ref. 29 indicate that its magnitude is ≈ 2 orders of magnitude smaller than the DPS contribution in the kinematical range considered.

Initially let us analyze the nuclear dependence of SPS and DPS cross-sections. As emphasized in Sec. 2, the DPS contribution in nuclear collisions is enhanced in comparison to pp collisions. This can be observed in the results presented in Fig. 2, where we show our predictions for charm (left panel) and bottom (right panel) production. In the case of charm production we can see that the energy where the SPS and DPS contributions becomes identical (indicated by a small circle in the figure) decreases at larger values of A. We can see that for $A = 1$ the equality takes place above the considered energy range, whereas $\sigma^{\text{DPS}}_{pA\to c\bar{c}c\bar{c}} = \sigma^{\text{SPS}}_{pA\to c\bar{c}}$ occurs at $\sqrt{s_{NN}} \approx 19.6$ and 10.4 TeV for $A = 40$ and 208, respectively. In the case of bottom production, the SPS and DPS contributions are identical only for energies beyond the range considered in the figure.

In Table 1 we present our predictions for the SPS and DPS cross-sections for pPb collisions at different center-of-mass energies. We present only the results associated to the central predictions, obtained with the set of parameters, gluon PDF and dipole model, that allow us to describe the RHIC and LHC data for the SPS cross-section in pp collisions. Initially, let us discuss the SPS predictions for the charm and bottom production in pPb collisions. We have verified that if the factorization and renormalization scales are modified within a factor of two and heavy

Table 1. Central predictions for the SPS and DPS contributions for charm and bottom production in pPb collisions at different center-of-mass energies considering the full kinematical range covered by the LHC. The current uncertainty in these predictions, associated to changes in the factorization and renormalization scales and heavy quark mass, is $\approx 40\,(90)\%$ in the SPS (DPS) case.

Final state	Mechanism	$\sqrt{s_{NN}} = 2.76$ TeV	$\sqrt{s_{NN}} = 5.02$ TeV	$\sqrt{s_{NN}} = 8.8$ TeV
$c\bar{c}$	SPS	664 mb	994 mb	1420 mb
$c\bar{c}c\bar{c}$	DPS	258 mb	602 mb	1280 mb
$b\bar{b}$	SPS	32 mb	55 mb	90 mb
$b\bar{b}b\bar{b}$	DPS	0.5 mb	1.5 mb	3.9 mb

quark mass are modified by $\pm 20\%$, the resulting predictions differ of the central values by a factor 1.4, which is similar to the uncertainty observed in the pp case. Our predictions can be compared with those presented in Ref. 30, which have estimated the cross-sections using the collinear formalism at next-to-next leading order (NNLO) with the nuclear modifications of the parton distributions being described by the EPS09-NLO parametrization.[31] The results presented in Table 1 are similar to those presented in Ref. 30. In particular, our central predictions are slightly larger than the central results presented in Ref. 30. Such difference is mainly associated to the fact that in our calculations we are assuming a smaller value for the heavy quark mass. As demonstrated in Ref. 18, our predictions are sensitive to the value of m_Q, with larger values reducing the magnitude of the cross-section. It is important to emphasize that saturation effects were not taken into account in Ref. 30. However, they consider the presence of shadowing effects at small-x, which also implies a reduction in the magnitude of the cross-section. The origin of the shadowing effects included in EPS09 parametrization is still an open question, with the saturation physics being one of the possible alternatives (see e.g. Ref. 32).

Let us now discuss the DPS predictions presented in Table 1. As in SPS case, we only present the central results. However, as these predictions were obtained using the pocket formula, Eq. (4), we can estimate the uncertainty present in the results. The results presented in Refs. 18 and 23 indicate that the current uncertainty in the dipole predictions for the charm and bottom production in pp collisions is a factor ≈ 1.5. As a consequence, we can estimate that the uncertainty present in the results shown in Table 1 is of a factor ≈ 2. This factor can be larger by approximately 20% due to current uncertainty in the value of $\sigma_{\text{eff},pp}$. Although the normalization of the SPS and DPS cross-sections can be modified by the current theoretical uncertainty, our results indicate that the DPS contribution for charm production is non-negligible in the range of energies probed by the LHC in pPb collisions, as it already was in pp collisions.[12] In the case of the bottom production, our results indicate that $\sigma^{\text{DPS}}_{pA\to b\bar{b}b\bar{b}} \lesssim 0.05 \times \sigma^{\text{SPS}}_{pA\to b\bar{b}}$ at LHC energies.

Another possible final state that can be produced considering the DPS mechanism is the $b\bar{b}c\bar{c}$ system, which can be generated when one gluon–gluon interaction

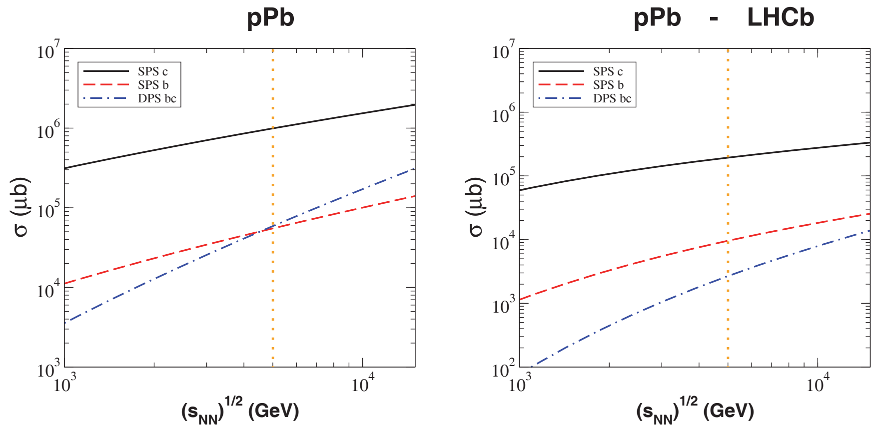

Fig. 3. Comparison between the SPS predictions for charm (solid line) and bottom (dashed line) production and the DPS one for the production of the $b\bar{b}c\bar{c}$ final state (dot-dashed line) in pPb collisions. In the left panel we present our predictions obtained considering the full rapidity range covered by the LHC, while in the right panel the cross-sections were integrated over the rapidity range covered by the LHCb experiment ($2 < y < 4.5$). Only the central predictions are presented, with the uncertainty in the results being similar to that indicated in the previous figures.

creates a $b\bar{b}$ and the other a $c\bar{c}$ pair. As demonstrated in Ref. 12, the DPS production of $b\bar{b}c\bar{c}$ can be responsible for approximately half of the total amount of bottom quarks produced in pp collisions at the LHC. In what follows we will analyze how this conclusion is modified in pPb collisions. In Fig. 3 we compare the SPS production cross-sections of $c\bar{c}$ and $b\bar{b}$ pairs, denoted, respectively, by "SPS c" and "SPS b", with the DPS production cross-section for the $b\bar{b}c\bar{c}$ final state (denoted "DPS bc" in the figure). In the left panel we present our predictions obtained considering the full rapidity range covered by the LHC, while in the right panel the cross-sections were integrated over the rapidity range covered by the LHCb experiment ($2 < y < 4.5$). The vertical dotted-lines indicates the center-of-mass energy of 5.02 TeV. In the case that the cross-sections are integrated over the full rapidity range, one has that the associated production of a $b\bar{b}$ with a $c\bar{c}$ becomes of the same order of the SPS production of a $b\bar{b}$ in pPb collisions for energies of the order of 4 TeV, being dominant at larger energies. As expected, it occurs at smaller energies than in pp collisions, where we have estimated that $b\bar{b}c\bar{c}$ and $b\bar{b}$ cross-sections are similar only at $\sqrt{s_{NN}} \approx 10$ TeV. On the other hand, if the LHCb rapidity range is considered, the $b\bar{b}c\bar{c}$ cross-section is a factor four smaller than the $b\bar{b}$ one.

In order to obtain a more precise estimate of the DPS contributions relative to the SPS ones, in Fig. 4 we present the energy dependence of the ratio $\sigma^{\rm DPS}/\sigma^{\rm SPS}$ for different final states. We denote by "bc/b" the ratio between the DPS production of $b\bar{b}c\bar{c}$ final state and the SPS production of $b\bar{b}$ pair, with analogous notation for the other combinations. In the left panel we present the predictions for the full LHC rapidity range, while in the right panel we integrated over the rapidity range covered by the LHCb experiment. The vertical dashed line indicates $\sqrt{s_{NN}} = 5.02$ TeV.

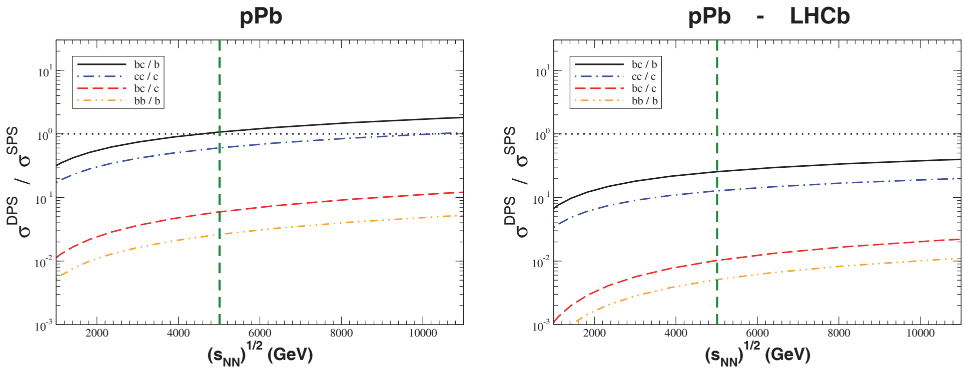

Fig. 4. Energy dependence of the ratio between the DPS and SPS cross-sections for different combinations of final states. Left panel: Cross-sections integrated over the full LHC rapidity range. Right panel: The cross-sections are integrated over the rapidity range of the LHCb experiment $(2 < y < 4.5)$.

Our results for the full rapidity range indicate that the ratios "bc/b" and "cc/c" are of order of unity in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, while the ratios "bc/c" and "bb/b" are smaller than 0.05. In contrast, all ratios are smaller than 0.3 in the LHCb rapidity range. In Ref. 12 we estimated these same ratios for pp collisions. Comparing the above results obtained for pPb collisions with those presented in Fig. 4 of Ref. 12, we have that these are considerably greater. Therefore, even at the rapidity range of the LHCb, heavy quark production in DPS processes is more likely to be experimentally detected in pPb collisions than in pp collisions. As pointed in Ref. 15, this can be useful to constrain the value of $\sigma_{\text{eff},pp}$, since F_{pA} is reasonably well determined from the nuclear geometry [see Eqs. (4) and (5)].

4. Conclusion

Recent experimental and theoretical studies of different final states that can be produced in pp collisions at the LHC have demonstrated that the contribution of double parton scattering processes can be non-negligible and should be taken into account. Such contribution becomes large at high energies due to the large parton luminosity in the initial state and is enhanced in nuclear collisions. In this paper, we have extended our previous study of DPS production of heavy quarks in pp collisions to pA collisions. We have used the dipole approach and we have taken into account the saturation effects which are expected to be important for small x and large nuclei. We estimated the A dependence of the SPS and DPS cross-sections and demonstrated that the DPS contribution for charm production is similar to the SPS one for pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and dominates at larger energies. Additionally, we have shown that the associated production of a $b\bar{b}$ with a $c\bar{c}$ has a cross-section similar to the SPS cross-section for the production of a $b\bar{b}$. Our results indicate that the analysis of the $c\bar{c}c\bar{c}$and $b\bar{b}c\bar{c}$ final states in pPb collisions at the LHC can be useful to constrain the double parton scattering mechanism.

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