Physics Letters B 755 (2016) 24–30

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Production of associated χ_b and open charm at the LHC

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ARTICLE INFO

Article history:
Received 28 November 2015
Received in revised form 22 January 2016
Accepted 25 January 2016
Available online 30 January 2016
Editor: B. Grinstein

ABSTRACT

In the present paper we study the production of $\chi_b + c\bar{c}$ at the LHC within single parton scattering approach. A special attention is paid to the feed-down from χ_b states to the associated $\Upsilon + c\bar{c}$ production, which was recently studied by the LHCb. We have found that this feed-down is about percents of the total cross section seen in the experiment. It is shown that the shapes of the differential distributions are almost the same for single and double parton scattering approaches except for the azimuthal asymmetry, which is the most distinguishing feature of the latter one. We conclude that the precise study of the single parton scattering contributions is necessary for the correct isolation of the double parton scattering role.

1. Introduction

Multiple production of heavy quarks attracted a great interest during recent years, and with the launch of the LHC a huge data sample on these processes became available. Some of such processes, like production of B_c mesons, can certainly be described within standard single parton scattering (SPS) approach. On the contrary, theoretical predictions obtained for the processes like double J/ψ, associated J/ψ + open charm and double open charm production often underestimate experimental cross sections. This is often explained by the fact that other channels, such as double parton scattering (DPS) can give a contribution. While in the case of double J/ψ production it is still possible to reconcile the SPS with the observed cross sections [1–3], in the open charm sector the observed cross sections [4] are significantly larger than the SPS predictions and better fit into the DPS picture [5–8].

It is worth to mention, that the DPS approach is very attractive by its simplicity; the cross section within DPS can be simply obtained via:

$$\sigma^{AB} = \frac{\sigma^A \times \sigma^B}{\sigma_{\text{eff}}},$$

where σ^{AB} is a cross section of paired production of particles A and B, $\sigma^{A,B}$ are the cross sections of single production, and σ_{eff} is some "effective" cross section which is determined experimentally. Despite the simplicity, we cannot say that we fully understand this mechanism, e.g. what is the physical sense of the dimensional non-perturbative parameter σ_{eff} and how it is related to the fundamental parameters of the QCD. Moreover, the experimental value obtained for the σ_{eff} differs significantly from one experiment to another varying in the range $(2.2 \div 20)$ mb [9–14]. Having DPS model as a "badly defined" in some sense, the precise theoretical and experimental input is crucial.

The processes of double production of heavy quarkonia with different flavor i.e. Υ and J/ψ can be extremely helpful in the understanding of the underlying mechanism of heavy quarkonia production. This is because the direct production $pp \to \Upsilon + J/\psi + X$ is forbidden in the leading order $\sim \alpha_s^4$ within the SPS approach, so one can expect that other channels should come to the fore. In the recent paper [15] we have calculated the process of P-wave quarkonia production $pp \to \chi_b + \chi_c + X$ and the corresponding feed-down to the $\Upsilon + J/\psi$, which we have found is about 2% of the DPS prediction for this process. On the other hand, our rough estimations presented ibid. give that the NLO contribution increases the SPS prediction several times, which leaves much less space for the DPS.

Recently the LHCb performed measurement of the associated production of Υ and open charm [11]. The direct production of $\Upsilon + c\bar{c}$ was studied in [16] both within SPS and DPS approach. It was found that the SPS mechanism gives contribution of the order of one percent. Thus, we may expect a significant feed-down contribution from the $\chi_b + c\bar{c}$ and from the NLO $\Upsilon + c\bar{c}$ processes. The

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http://dx.doi.org/10.1016/j.physletb.2016.01.051

results of [11] suggest the DPS approach is valid in both descriptions of total cross sections and cross section distributions.

The rest of our paper is organized as follows. In the next section we consider matrix elements and cross sections of the partonic reaction $gg \to \chi_{bJ} + c\bar{c}$. In Section 3 various distributions and total cross sections of the hadronic reaction $pp \to \chi_{bJ} + D\bar{D} + X$ are presented. Short discussion of the obtained results is given in the last section. Technical details of the calculations can be found in the Appendix.

2. Parton level

The relevant process on the parton level at the LHC energies is gluon fusion:

$$g + g \to \chi_{bJ} + c + \bar{c}. \tag{1}$$

Corresponding Feynman diagrams are shown in Fig. 1. According to the NRQCD factorization theorem [17], the cross section of χ_{bJ} production can be expressed in a series in powers of relative quark-antiquark velocity v:

$$d\hat{\sigma}(\chi_J) = \sum_n O^{\chi_{bJ}}([b\bar{b}]_n) d\hat{\sigma}([b\bar{b}]_n), \tag{2}$$

where n denotes a set of spin S, angular momentum L and color quantum numbers, and parameters $O^{\chi_{bJ}}([b\bar{b}]_n)$ are determined by the non-perturbative matrix elements responsible for $[b\bar{b}]_n$ pair hadronization into observable state with possible emission of soft gluons (so called E1 chromo-electric, M1 chromo-magnetic, E1 × E1 transitions and so on). Since the relative velocity of $b\bar{b}$ pair in bottomonium is small ($v^2 \approx 0.1$), series (2) has a good convergence.

The leading terms in (2) come from color-singlet $[b\bar{b}](^3P_J^{[1]})$ and E1 color-octet $[b\bar{b}](^3S_1^{[8]})$ contributions which are of order $O(v^2)$. Next to leading corrections $O(v^4)$ come from M1 chromo-magnetic $[b\bar{b}](^1P_1^{[8]})$ and E1 × E1 double chromo-electric $[b\bar{b}](^3P_J^{[8]})$ transitions which are of order $O(v^4)$. As it is was shown in our previous works on a single χ_b production [18–20], all color-octet contributions are negligibly small and become important only when considering ratio of cross sections with different total spin (e.g. $\sigma(\chi_{b2})/\sigma(\chi_{b1})$) or at very high p_T region which is not yet accessible in the experiment. Thus, we will take into account only dominant color-singlet contribution in (2). In the latter case, the corresponding non-perturbative matrix element can be expressed in terms of phenomenological non-relativistic wave function of the meson:

$$O^{\chi_{bJ}}([b\bar{b}](^3P_J^{[1]})) = \frac{3}{4\pi}(2J+1)\left|R'(0)\right|^2,$$

where $R(r)$ is a radial part of meson's wave function.

The details of the hard cross sections calculation can be found in Appendix A. Fig. 2 (left) shows the dependence of the hard cross sections for different J-states on the total energy of initial partons. We have also calculated contributions for different quantum numbers of $c\bar{c}$-pair: when $c\bar{c}$ in color singlet (in this case only the last four diagrams from Fig. 1 give a non-zero contribution) with spin $S_{c\bar{c}} = 0$ or 1, and when it is in the color octet combination. Fig. 2 (right) shows these contributions for χ_{b2} in the final state (for other χ_b states pictures are similar). From this figure, it is clear that the dominant part of the cross section comes from colored $c\bar{c}$ combinations.

There is one interesting property of the cross sections. The dependence on the p_T at $p_T \ll M_{\chi_b}$ and $p_T \gg M_{\chi_b}$ is the same as in the case of single χ_b production $gg \to \chi_b + g$. On the one hand, it is clear that at the small values of p_T we have for the ratio:

$$\left.\frac{d\hat{\sigma}(\chi_{b2})/dp_T}{d\hat{\sigma}(\chi_{b0})/dp_T}\right|_{p_T \ll M_{\chi_b}} \to \frac{5}{1} \times \frac{\Gamma(\chi_{b2} \to gg)}{\Gamma(\chi_{b0} \to gg)} = \frac{4}{3},$$

where the first factor comes from $(2J+1)$ factor. On the other hand at the large values of p_T the explicit calculation shows that

$$\left.\frac{d\hat{\sigma}(\chi_{b2})/dp_T}{d\hat{\sigma}(\chi_{b1})/dp_T}\right|_{p_T \gg M_{\chi_b}} \to \frac{1}{3},$$

which is the same behavior as for the single χ_b production (under the assumption that color octet contributions are negligible, see [18] for the details). Fig. 3 (left) shows the dependence of the ratios of hard cross sections on p_T. It is clear, that the same behavior will hold for the hadronic reactions as well (Fig. 3 (right)).

3. Hadron level

The cross section of hadron process within single parton scattering approach can be written as:

$$d\sigma = \int dx_1 dx_2 f_g(x_1; Q^2) f_g(x_2; Q^2) d\hat{\sigma}, \tag{3}$$

where $f_g(x; Q^2)$ are gluon distributions at the scale Q^2. We used CT10 PDF sets [21] with the LHAPDF interface [22]. Both strong coupling and PDFs were taken at $\mu^2 = Q^2 = M_{\chi_b}^2 + 2m_c^2 + p_{T\chi_b}^2$ scale. We have performed calculation of the cross sections with different kinematical cuts; here we present results for the LHCb kinematical region which is $2 < y(\chi_b, \mathrm{D}^{0,+}) < 4.5$ at $\sqrt{s} = 8$ and 13 TeV; results for other kinematical regions (ATLAS, CMS, D0) are available on request.

Since the χ_b mesons are detected via its radiative decays to $\Upsilon(1S)$ state, we have simulated these radiative transitions in our estimations. On the other hand, we have neglected nontrivial fragmentation function of the c-quark $c \to \mathrm{D}^{0,+}$, assuming that all c-quarks hadronize in D mesons with hundred percent probability and that the momentum of the final D-meson is almost the same as for c-quark; account for nontrivial fragmentation will slightly change the numerical values but not the main results.

For the $\sqrt{s} = 8$ TeV we have found the following cross sections:

$$\sigma(\chi_{b0} + c\bar{c})_{\sqrt{s}=8\ \mathrm{TeV}} = 115.7 \pm 7.8\ \mathrm{pb},$$
$$\sigma(\chi_{b1} + c\bar{c})_{\sqrt{s}=8\ \mathrm{TeV}} = 43.5 \pm 0.1\ \mathrm{pb},$$
$$\sigma(\chi_{b2} + c\bar{c})_{\sqrt{s}=8\ \mathrm{TeV}} = 152.6 \pm 18.7\ \mathrm{pb}.$$

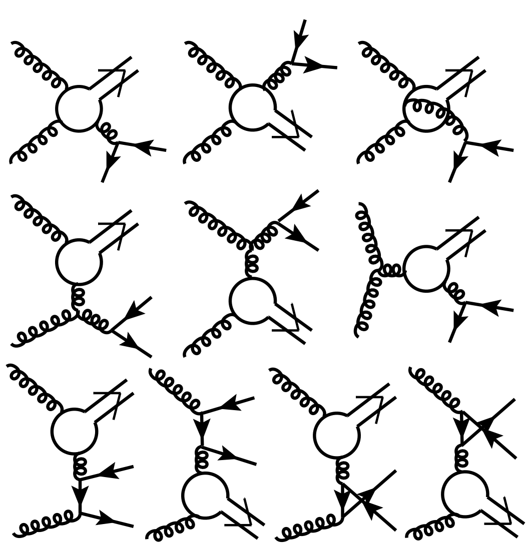

Fig. 1. Feynman diagrams contributing to the process (1) at the leading order.