Associative production of Υ and open charm at LHC.

A. V. Berezhnoy¹,∗ and A. K. Likhoded²,†

¹SINP of Moscow State University, Russia
²Institute for High Energy Physics, Protvino, Russia

The yield of Υ associated with open charm has been estimated with different approaches. The crucial differences between SPS and DPS predictions are discussed.

I. INTRODUCTION

Last years the impressive volume of experimental data on multiple heavy quarks production were obtained by the experiments at LHC. The LHCb experiment has published studies of the $B_c$-meson production [1], of the double $J/\psi$-meson production [2], of the double open charm production, as well as the $J/\psi$ production associated with open charm [3]. The LHCb study of $B_c$ meson is completed by ATLAS, where the candidate to $B_c(2S)$ state has been observed [4]. Also very interesting results on the double $J/\psi$ production have been obtained by the CMS Collaboration [5].

It is worth, to note that the double $J/\psi$ production at LHCb can be satisfactorily described within the standard NRQCD approach [6], as well within the $k_T$-factorization approach [7]. Contrary to this, for other processes of multiple heavy quark production NRQCD underestimates the cross section value by the order of magnitude. This could mean, that in addition to the single parton scattering (SPS), the double parton scattering (DPS) should be taken into account. According DPS, approach heavy quark pairs are produced independently in different partonic interactions inside the same colliding pair of protons. The simplest variant of this model lead to the following formula for the cross section:

$$\sigma_{A_1A_2}^{DPS} = \frac{1}{m} \frac{\sigma_{A_1}^{SPS} \sigma_{A_2}^{SPS}}{\sigma_{eff}},$$

where $\sigma_{A_1}^{SPS}$ and $\sigma_{A_2}^{SPS}$ are the cross section values of the processes $A_1$ and $A_2$ within SPS, $m = 1$ for different $A_1$ and $A_2$, $m = 1/2$ for identical $A_1$ and $A_2$, and $\sigma_{eff}$ is the parameter

∗Electronic address: Alexander.Berezhnoy@cern.ch
†Electronic address: Anatolii.Likhoded@ihep.ru
of DPS model obtained from the experimental data 8, 9.

The formula (1) is surprisingly successful in predicting of the cross section values for the kinematical condition of the LHCb experiment. However, DPS fails in describing of some differential distributions, and therefore in spite of the fact that DPS is recently the most successful model in the discussed field, the problem still exists 3.

Going back to the double $J/\psi$ production at LHCb it worth to mention, that together with SPS, DPS also could contribute to this process, because the predictions within SPS and DPS for this case have the same order of magnitude 10–12.

As a rule it is assumed within the DPS, that both heavy quark production and hadronization processes occur independently for the processes $A_1$ and $A_2$. But in principle one could assume that the soft processes of hardronization occur mutually. In the last case the heavy quark and the heavy antiquark from different pair could join to the heavy meson due to the soft interaction followed by the hard production process (see, for example, 13, where such contribution has been studied for the central exclusive production of $J/\psi$ pair). Therefore it would be very interesting to compare experimentally the process of $J/\psi + c$ production, where quarks in $J/\psi$ can hypothetically origin from different pairs and the process of $\Upsilon + c$ production.

In this paper we discuss some theoretical aspects of the hadronic $\Upsilon + c$ production, as well as its observation prospects.

II. $\Upsilon + c$ PRODUCTION WITHIN SPS

There are 6 LO diagrams, which contribute to the direct gluonic production of the associated $\Upsilon$ and $c$ in SPS (see fig. 1):

$$gg \rightarrow \Upsilon + c\bar{c}. \quad (2)$$

Also 10 diagrams contribute to the indirect production of $\Upsilon$ mesons in $\chi_b$ decays:

$$gg \rightarrow \chi_b + c\bar{c}, \ \chi_b \rightarrow \Upsilon. \quad (3)$$

For rough estimations it is not necessary to take into account the feed-down from the subprocess (3). Indeed, we expect, that within NRQCD $\sigma(\chi_b + c) / \sigma(\Upsilon + c) \sim 10% \div 20%$. Taking into account that $Br(\chi_{b0} \rightarrow \Upsilon) \approx 1.8%$, $Br(\chi_{b1} \rightarrow \Upsilon) \approx 34%$ and $Br(\chi_{b2} \rightarrow \Upsilon) \approx$
19%, we obtain that
\[
\frac{\sigma(gg \rightarrow \chi_b + c\bar{c}, \chi_b \rightarrow \Upsilon)}{\sigma(gg \rightarrow \Upsilon + c\bar{c})} \lesssim 6\%.
\] (4)

It was first shown in [14], that the interaction with heavy sea quark can essentially contribute to the multiple heavy quark production. But in our case the sea charm quark does not contribute essentially to $\Upsilon + c$ production. The subprocess
\[
gc \rightarrow \Upsilon_{\text{direct}} + g + c
\] (5)
is suppressed by the additional order of $\alpha_s$ (see fig. 2), and the contribution of the subprocess
\[
gc \rightarrow \chi_b (\rightarrow \Upsilon) + g + c
\] (6)
by the order of magnitude is comparable with the contribution of (3), and therefore, it also can be neglected within our rough analysis. Therefore, one can conclude that $c\bar{c}$-pair associated with $\Upsilon$ in most cases is produced in gluon splitting.

According our estimations within LO NRQCD for LHCb kinematics
\[
\frac{\sigma_{\Upsilon+c}^{\text{SPS}}}{\sigma_{\Upsilon}^{\text{LHCb}}} \sim 0.2 \div 0.6\%.
\] (7)

It is worth to note, that there is an alternative way to estimate SPS. We could try to use the experimental probability value of the gluon splitting to $c\bar{c}$ pair. According to the LEP data this probability $P_{\text{LEP}}^{g \rightarrow c\bar{c}}$ is about 2.4% [15, 16]. Thus it could be supposed that gluon associated with $\Upsilon$ quarkonium will produce $c$ quark in 2% of events:
\[
\frac{\sigma_{\Upsilon+c}^{\text{SPS}}}{\sigma_{\Upsilon}^{\text{LHCb}}} \approx P_{\text{LEP}}^{g \rightarrow c\bar{c}} \cdot k \sim 2\%,
\] (8)
where $k$ is a geometrical acceptance of the LHCb detector, which can be approximately estimated as

$$k = \frac{\sigma^{LO}(gg \rightarrow \Upsilon_{\text{direct}} + c\bar{c})|_{2.0<y_{\text{charm}}<4.5}}{\sigma^{LO}(gg \rightarrow \Upsilon_{\text{direct}} + c\bar{c})|_{\text{without cuts on charm}}} \approx 0.7. \quad (9)$$

It is useful to mention, that the theoretical predictions of $P^{g\rightarrow c\bar{c}}$ obtained within the leading order calculation ($P^{g\rightarrow c\bar{c}}_{LO} = 0.607\% \ [17]$), as well as within the resummed leading order calculation ($P^{g\rightarrow c\bar{c}}_{RSLO} = 1.35\% \ [18]$) underestimate the LEP data.

### III. DPS AND ACCOUNTING OF CHARM QUARKS FROM PDF

The yield of $\Upsilon$ mesons associated with open charm in DPS can be roughly estimated within formula (1):

$$\frac{\sigma_{\Upsilon+c}^{\text{DPS}}}{\sigma_{\Upsilon}} = \frac{\sigma_{\text{LHCb}}^c}{\sigma_{\text{eff}}} \sim 10\%. \quad (10)$$

Therefore DPS approach predicts ten times larger yield of of $\Upsilon$ mesons associated with open charm than LO SPS.

Also there is another method to estimate the cross section value of $\Upsilon$ and open charm production. We could try to evaluate the number of charm quarks, which "exists" in proton at the scale of order of the $\Upsilon$ mass, as follows:

$$n_{\text{charm}} \sim \int_{x_{\text{min}}}^{x_{\text{max}}} f_{\text{charm}}(x, Q) \, dx, \quad (11)$$

where $x_{\text{min}}$ and $x_{\text{max}}$ are determined by the the LHCb fiducial region.
Figure 3: Accounting of $c$-quarks from PDF at the $\Upsilon$ production scale.

Taking into account that $x \sim \frac{E_T}{\sqrt{s}} \exp(y)$ and assuming that $\langle E_T \rangle \sim 2.5$ GeV and $Q \sim 10$ GeV, one can obtain the following very rough estimation for the LHCb kinematical cuts on charm hadrons ($2.0 < y < 4.5$):

$$\frac{\sigma_{\Upsilon + c}}{\sigma_{\Upsilon}} \sim \int_{0.0026}^{0.032} f_{\text{charm}}(x, 10 \text{ GeV}) \, dx \sim 50\%.$$ (12)

This means that at scale of $\Upsilon$ mass in half of the cases a proton "contains" a charm quark. Therefore one could suppose that this charm quark transforms in the charm hadron during the nonperturbative destruction of the proton.

IV. CONCLUSIONS

We have shown that the predictions of SPS and DPS approaches for the associated production of $\Upsilon$ and a charmed hadron differ from each other by the order of magnitude. According SPS+LO the yield of $\Upsilon + c$ is about of $0.2 \div 2\%$ of $\Upsilon$ production for the LHCb kinematics, whereas DPS or charm quark accounting in pdf predicts about $10\%$.

We think that the LHC experiments will obtain the $\Upsilon + c$ yield, which is close to the predicted in the framework of DPS. This assurance is based on the fact, that the experimental
data on $J/\psi + c$ and double open charm production are in fair agreement with the DPS predictions.

It is known, that the distributions on $p_T$ for the single $J/\psi$ production and for $J/\psi$ associated with open charm are different. This difference cannot be explained within the simplest version of DPS. Maybe it the mutual hadronization of two $c\bar{c}$ pairs could influence the distribution shape. The $\Upsilon + c$ production is more pure case, and $p_T$ distribution of $\Upsilon$ in the single production and in the production associated with open charm should be more close to each other.

We thank I. Belyaev for the fruitful discussion. A. Berezhnoy acknowledges the support from MinES of RF (grant 14.610.21.0002, identification number RFMEFI61014X0002). The work of A. Likhoded is partially supported by Russian Foundation for Basic Research (grant 15-02-03244 A).

[1] R. Aaij et al. (LHCb collaboration) (2014), 1411.2943.
[2] R. Aaij et al. (LHCb Collaboration), Phys.Lett. B707, 52 (2012), 1109.0963.
[3] R. Aaij et al. (LHCb Collaboration), JHEP 1206, 141 (2012), 1205.0975.
[4] G. Aad et al. (ATLAS Collaboration), Phys.Rev.Lett. 113, 212004 (2014), 1407.1032.
[5] C. Collaboration (CMS Collaboration) (2013), CMS-PAS-BPH-11-021.
[6] A. Berezhnoy, A. Likhoded, A. Luchinsky, and A. Novoselov, Phys.Rev. D84, 094023 (2011), 1101.5881.
[7] S. Baranov, Phys.Rev. D84, 054012 (2011).
[8] F. Abe et al. (CDF Collaboration), Phys.Rev. D56, 3811 (1997).
[9] V. Abazov et al. (D0 Collaboration), Phys.Rev. D81, 052012 (2010), 0912.5104.
[10] C. Kom, A. Kulesza, and W. Stirling, Phys.Rev.Lett. 107, 082002 (2011), 1105.4186.
[11] S. Baranov, A. Snigirev, and N. Zotov, Phys.Lett. B705, 116 (2011), 1105.6276.
[12] A. Novoselov (2011), 1106.2184.
[13] L. Harland-Lang, V. Khoze, and M. Ryskin, J.Phys. G42, 055001 (2015), 1409.4785.
[14] S. Baranov, Phys.Rev. D56, 3046 (1997).
[15] R. Akers et al. (OPAL Collaboration), Z.Phys. C67, 27 (1995).
[16] R. Akers et al. (OPAL Collaboration), Phys.Lett. B353, 595 (1995).
[17] M. L. Mangano and P. Nason, Phys.Lett. B285, 160 (1992).

[18] M. Seymour, Nucl.Phys. B436, 163 (1995).