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Enhanced production of Λ_c in proton-proton collisions at the LHC

Rafał Maciuła[*†]
Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland
E-mail: rafal.maciula@ifj.edu.pl

Antoni Szczurek
Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, PL-31-342 Kraków, Poland
E-mail: antoni.szczurek@ifj.edu.pl

We calculate cross section for production of D mesons and Λ_c baryons in proton-proton collisions at the LHC. The cross section for production of $c\bar{c}$ pairs is calculated within k_T-factorization approach with the Kimber-Martin-Ryskin unintegrated gluon distributions. We show that our approach well describes the D^0, D^+ and D_s experimental data. We try to understand recent ALICE and LHCb data for Λ_c production with the $c \to \Lambda_c$ independent parton fragmentation approach. The Peterson fragmentation functions are used. The $f_{c\to\Lambda_c}$ fragmentation fraction and ε_c^{Λ} parameter for $c \to \Lambda_c$ are varied. Although one can agree with the ALICE data using standard estimation of model uncertainties one cannot describe simultaneously the ALICE and the LHCb data with the same set of parameters. The fraction $f_{c\to\Lambda_c}$ neccessary to describe the ALICE data is much larger than the average value obtained from e^+e^- or ep experiments. It seems very difficult, if not impossible, to understand the ALICE data within the considered independent parton fragmentation scheme.

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[*]Speaker.

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1. Introduction

Production of charm ($c\bar{c}$-pairs) belongs in principle to the domain of perturbative physics. The corresponding cross section can be calculated in collinear-factorization approach. Leading-order (LO) calculation is known to give too small cross section and rather next-to-leading order (NLO) calculation must be performed (see *e.g.* Refs. [1, 2]). An effective and efficient alternative is k_T-factorization approach [3, 4, 5]. The k_T-factorization provides a good description of D meson production cross sections at RHIC [6], Tevatron [7] and at the LHC [8, 9].

The production of D mesons and/or nonphotonic leptons requires a nonperturbative information about hadronization process. To describe D meson production fragmentation functions (FFs) for $c \to D$ quark-to-meson transitions are usually included. In the context of heavy-flavour production the Peterson FFs [10] are usually used.

Recently the LHCb [11] and very recently ALICE [12] Collaborations obtained new results for Λ_c production at the highest so far collision energy $\sqrt{s}$ = 7 TeV. We wish to study whether the new LHCb and ALICE data can be described consistently within the chosen scheme of calculation based on $c \to \Lambda_c$ fragmentation. If yes, it would be interesting whether the $f_{c\to\Lambda_c}$ fragmentation fraction is consistent with those found in previous studies of e^+e^-, ep and B meson decays.

2. A sketch of the theoretical formalism

2.1 Parton-level calculations

In the partonic part of our numerical calculations we follow the k_T-factorization approach. This approach is commonly known to be very efficient not only for inclusive particle distributions but also for studies of kinematical correlations. According to this approach, the transverse momenta k_t's (virtualities) of both partons entering the hard process are taken into account and the sum of transverse momenta of the final c and $\bar{c}$ no longer cancels. Then the differential cross section at the tree-level for the $c\bar{c}$-pair production reads:

$$\frac{d\sigma(pp \to c\bar{c}X)}{dy_1 dy_2 d^2p_{1,t} d^2p_{2,t}} = \int \frac{d^2k_{1,t}}{\pi} \frac{d^2k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} \overline{|\mathscr{M}^{\mathrm{off-shell}}_{g^*g^* \to c\bar{c}}|^2} \times \delta^2\left(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}\right) \mathscr{F}_g(x_1, k^2_{1,t})\, \mathscr{F}_g(x_2, k^2_{2,t}) \,, \tag{2.1}$$

where $\mathscr{F}_g(x_1, k^2_{1,t})$ and $\mathscr{F}_g(x_2, k^2_{2,t})$ are the unintegrated gluon distribution functions (UGDFs) for both colliding hadrons and $\mathscr{M}^{\mathrm{off-shell}}_{g^*g^* \to c\bar{c}}$ is the off-shell matrix element for the hard subprocess. The extra integration is over transverse momenta of the initial partons. We keep exact kinematics from the very beginning and additional hard dynamics coming from transverse momenta of incident partons. Explicit treatment of the transverse part of momenta makes the approach very efficient in studies of correlation observables. The two-dimensional Dirac delta function assures momentum conservation. The unintegrated (transverse momentum dependent) gluon distributions must be evaluated at:

$$x_1 = \frac{m_{1,t}}{\sqrt{s}} \exp(y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(y_2), \qquad x_2 = \frac{m_{1,t}}{\sqrt{s}} \exp(-y_1) + \frac{m_{2,t}}{\sqrt{s}} \exp(-y_2), \tag{2.2}$$

where $m_{i,t} = \sqrt{p_{i,t}^2 + m_c^2}$ is the quark/antiquark transverse mass. In the case of charm quark production at the LHC energies, especially in the forward rapidity region, one tests very small gluon longitudinal momentum fractions $x < 10^{-5}$.

The leading-order matrix element squared $gg \to c\bar{c}$ for off-shell gluons is taken here in the analytic form proposed by Catani, Ciafaloni and Hautmann (CCH) [4]. The calculation of higher-order corrections in the k_t-factorization is much more complicated than in the case of collinear approximation. However, the common statement is that actually in the k_t-factorization approach with tree-level off-shell matrix elements some part of real higher-order corrections is effectively included. This is due to possible emission of extra soft (and even hard) gluons encoded in the unintegrated gluon densities. More details of the theoretical formalism adopted here can be found in Ref. [8].

In the numerical calculation below we have applied the Kimber-Martin-Ryskin (KMR) UGDF that is derived from a modified DGLAP-BFKL evolution equation [14] and has been found recently to work very well in the case of charm production at the LHC [8]. As discussed also in Ref. [15] the k_T-factorization approach with the KMR UGDF gives results well consistent with collinear NLO approach. For the calculation of the KMR distribution we used here up-to-date collinear MMHT2014 gluon PDFs [16]. The renormalization and factorization scales $\mu^2 = \mu_R^2 = \mu_F^2 = \frac{m_{1,t}^2 + m_{2,t}^2}{2}$ and charm quark mass $m_c = 1.5$ GeV are used in the present study. The uncertainties related to the choice of these parameters and to the collinear gluon PDFs will be discussed shortly when presenting numerical results.

2.2 From quarks to hadrons

According to the often used independent parton fragmentation picture, the inclusive distributions of charmed hadrons $h = D, \Lambda_c$ are obtained through a convolution of inclusive distributions of charm quarks/antiquarks and $c \to h$ fragmentation functions:

$$\frac{d\sigma(pp \to hX)}{dy_h d^2 p_{t,h}} \approx \int_0^1 \frac{dz}{z^2} D_{c \to h}(z) \frac{d\sigma(pp \to cX)}{dy_c d^2 p_{t,c}} \Bigg|_{\substack{y_c = y_h \\ p_{t,c} = p_{t,h}/z}} , \tag{2.3}$$

where $p_{t,c} = \frac{p_{t,h}}{z}$ and z is the fraction of longitudinal momentum of charm quark c carried by a hadron $h = D, \Lambda_c$. A typical approximation in this formalism assumes that y_c is unchanged in the fragmentation process, i.e. $y_h = y_c$. It was originally motivated for light hadrons but is commonly accepted also in the case of heavy hadrons.

As a default set in all the following numerical calculations the standard Peterson model of fragmentation function [10] with the parameters $\varepsilon_c^D = \varepsilon_c^\Lambda = 0.05$ is applied. The parameter will be varied only in the case of $c \to \Lambda_c$ transition. This choice of fragmentation function and parameters is based on our previous theoretical studies of open charm production at the LHC [8], where detailed analysis of uncertainties related to application of different models of FFs was done.

Finally, the calculated cross sections for D^0, D^+, D_S^+ mesons and Λ_c baryon should be normalized to the relevant fragmentation fractions. For a nice review of the charm fragmentation fractions see Ref. [17].

3. Numerical results

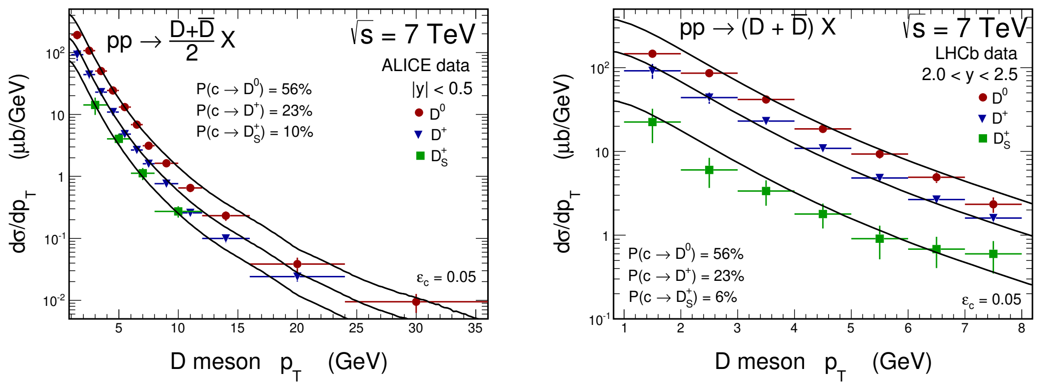

Figure 1: Transverse momentum distribution of D mesons for $\sqrt{s} = 7$ TeV for ALICE (left panel) and LHCb (right panel). The experimental data points are taken from Refs. [**?**] and [11], respectively.

We start our presentation by showing results for D meson production. In Fig. 1 we present transverse momentum distributions of different open charm mesons - D^0, D^+, and D_s for the ALICE (left panel) and the LHCb (right panel) kinematics. Here, and throughout this subsection, the numerical results are obtained within the standard fragmentation procedure with the assumption of unchanged rapidity, *i.e.* $y_c = y_h$, where $h = D, \Lambda_c$. In this calculation we use standard Peterson fragmentation function with $\varepsilon_c^D = 0.05$ for $c \to D$ transition. The fragmentation fractions for charmed mesons are set to be $f_{c\to D^0} = 0.56$ and $f_{c\to D^+} = 0.23$ for both, ALICE and LHCb detector acceptance. In the case of charmed-strange meson two different values of the fragmentation fraction are needed to fit both data sets with the same precision, *i.e.* $f_{c\to D_S} = 0.06$ for LHCb and 0.10 for ALICE. Both values of the fragmentation fraction for $c \to D_S$ transition are consistent with those extracted from combined analysis of charm-quark fragmentation fraction measurements in e^+e^-, ep, and pp collisions [17]. We cannot describe both sets of data with the same $f_{c\to D_S}$. Doing so we would get clear disagreement using, *e.g.* χ^2-criterion. It looks there is a similar effect as for Λ_c, to be discussed below.

Having fixed all parameters of the theoretical approach in the context of open charm meson production we can proceed to the production of Λ_c baryons. In Fig. 2 we present transverse momentum distribution of Λ_c baryons for the ALICE (left panel) and the LHCb (right panel) kinematics. In this calculation we have also used the Peterson FF with the same parameter $\varepsilon_c^\Lambda = 0.05$ (as a default) as for $c \to D$ transition. The three lines correspond to different values of $c \to \Lambda_c$ fragmentation fractions. The dashed curve is for $f_{c\to\Lambda_c} = 0.05$, as typical for pre-LHC results. Clearly this result underpredicts both ALICE and LHCb data. We show also result for increased fragmentation fractions, *i.e.* $f_{c\to\Lambda_c} = 0.10$ (solid line) and 0.20 (dotted line). The agreement between data and the theory predictions with the increased $f_{c\to\Lambda_c}$ becomes better. However, a visible difference appears in the observed agreement for the mid-rapidity ALICE and for forward LHCb regimes. Taking $f_{c\to\Lambda_c} = 0.10$ we are able to describe the LHCb data quite well but we still underestimate the ALICE data by a factor ~ 2 in the whole considered range of transverse momenta. The shapes of the transverse momentum distributions are well reproduced in both ALICE and LHCb cases. In order

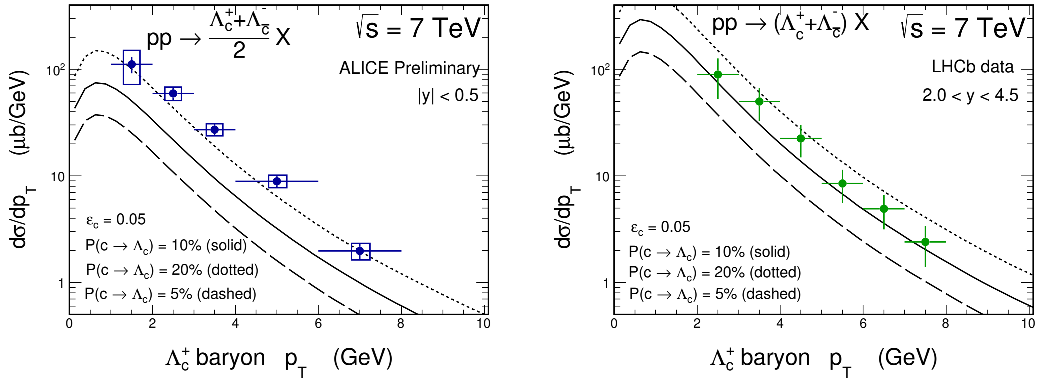

Figure 2: Transverse momentum distribution of Λ_c baryon for $\sqrt{s} = 7$ TeV for ALICE (left panel) and LHCb (right panel). The experimental data points are taken from Refs. [12] and [11], respectively.

to get right normalization in the case of the ALICE measurement we need to take $f_{c\to\Lambda_c} = 0.20$ which is much bigger than the numbers found in previous studies (see *e.g.* a review in Ref. [17]).

4. Conclusions

We find that the fragmentation fraction $f_{c\to\Lambda_c} = 0.1$ - 0.15 describes the recent data of the LHCb collaboration but fails to describe the new ALICE data. Even for LHCb this number is slightly bigger than the values from the compilation of world results [17] obtained from experimental data on e^+e^- and ep and B meson decays. Although we could agree with the ALICE data using standard estimation of model uncertainties related to factorization/renormalization scale, quark mass and PDF we were not able to describe simultaneously the ALICE and the LHCb Λ_c-baryon data as well as data on D-meson production with the same set of parameters.

The interpretation of the increased fragmentation fraction $c \to \Lambda_c$ is at present not clear and requires further studies, both on the theoretical and experimental side.

The independent parton fragmentation approach is only a simplification which has no firm and fundamental grounds and requires tests to be valid approach. At low energies an asymmetry in production of Λ_c^+ and Λ_c^- was observed [18]. This may be related to the charm meson cloud in the nucleon [19] and/or recombination with proton remnants [20]. At high-energy this mechanism is active at large x_F (or η, probably for pseudorapidities larger than available for LHCb). Certainly a study of Λ_c^+/Λ_c^- asymmetry in LHC RunII would be a valueable supplement. This would allow to verify the $c \to \Lambda_c$ "independent" parton hadronization picture. The new data of the ALICE Collaboration suggests a much bigger $f_{c\to\Lambda_c}$ hadronization fraction than those obtained in other processes and LHCb. In principle, it could be even a creation of Λ_c in the quark-gluon plasma due to coalescence mechanism (see *e.g.* Ref. [21]). Such an enhancement was observed in p-Pb and Pb-Pb collisions and interpreted in terms of quark combination/coalescence approach in [22] (for p-Pb) and [23] (for Pb-Pb). Even in the "independent" parton picture the hadronization fractions $f_{c\to D_i}$ or $f_{c\to\Lambda_c}$ do not need to be universal and may depend on partonic sourounding associated with the collision which may be, in principle, reaction and energy dependent. Therefore precise measurements at the LHC will allow to verify the picture and better understand the hadronization mechanism.

To explore experimentally the hypothesis that Λ_c is produced in the mini quark-gluon plasma one could study its production rates as a function of event multiplicity and compare to similar analysis for the production of D^0 mesons.

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