Ω_{ccc} production via fragmentation at LHC

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Abstract

In the framework of the leading order of perturbative QCD and the nonrelativistic quark-diquark model of baryons we have obtained fragmentation function for c-quark to split into Ω_{ccc} baryon. It is shown that at LHC one can expect $3.5 \cdot 10^3$ events with Ω_{ccc} at $p_\perp > 5$ GeV/c and $|y| < 1$ per year.

1. Introduction

During last years the physics of baryons containing heavy quarks was a subject of increasing attention [1]. The new interesting data on heavy baryon production rates and decay widths have been obtained [2]. There are theoretical predictions for doubly heavy baryon production cross sections [3]-[6]. It is expected that Ξ_{cc} and Ξ^*_{cc} baryons, containing two charmed quarks, can be detected already at the Tevatron collider ($\sqrt{s} = 1.8$ TeV), and at LHC ($\sqrt{s} = 14$ TeV) their production rate increase by 10^4 times [7]. The predicted numbers of (bc)- and (bb)-baryons for LHC are 1/3 and 1/100, correspondingly, of the number of (cc)-baryons [8].

The purpose of this paper is to estimate the production rate for Ω_{ccc} baryons at LHC via fragmentation. Most of the fragmentation functions for heavy quarkonia and doubly heavy diquarks have now been calculated [3, 9, 12]. Using the same approach, we calculate here fragmentation function for c-quark to split into Ω_{ccc} baryon which is considered as a nonrelativistic system of c-quark and (cc)-diquark [6, 10, 11].

2. Charmed quark fragmentation into Ω_{ccc}

The fragmentation function is given by the formula [12]:

$$D_{c\to\Omega_{ccc}}(z,\mu_0) = \frac{1}{16\pi^2}\int_{s_{min}}^{\infty} ds \lim_{q_0\to\infty}\frac{|\mathcal{M}|^2}{|\mathcal{M}_o|^2}, \tag{1}$$

where $\mathcal{M}$ is the amplitude for the producing Ω_{ccc} plus $(\bar{c}\bar{c})$-diquark with the total 4-momentum $q = (q_0, 0, 0, q_3)$ and invariant mass $s = q^2$, $\mathcal{M}_o$ is the amplitude to create on-shell c-quark with the same 3-momentum $\vec{q}$ from the same source. The lower limit in the integral is:

$$s_{min} = \frac{M^2}{z} + \frac{m_{cc}^2}{1-z},$$

where

$$z = \frac{p_0 + p_3}{q_0 + q_3},$$

$p = (p_0, 0, 0, p_3)$ is the Ω_{ccc} baryon 4-momentum. In the axial gauge for the gluon propagator associated with four-vector $n = (1, 0, 0, -1)$

$$d_{\mu\nu}(k) = -g_{\mu\nu} + \frac{k_\mu n_\nu + k_\nu n_\mu}{(kn)},$$

the fragmentation contribution comes only from the Feynman diagram shown in Fig.1:

$$\begin{aligned}\mathcal{M} &= \frac{|\Psi_{\Omega_{ccc}}(0)|}{\sqrt{2m_{cc}}}\frac{4\delta^{ij}}{3\sqrt{3}}(4\pi\alpha_s)^2\frac{F_D(k^2)}{k^2(s-m_c^2)}\bar{\Psi}^\beta(p)\gamma_\nu(\hat{q}+m_c)\hat{G} \\ &\quad d^{\mu\nu}(k)V_{\alpha\mu\beta}(q,p_c)\varepsilon^*_\alpha(q'),\end{aligned} \tag{2}$$

where $\hat{G}$ describes the creation of c-quark with the total 4-momentum $q = p + q'$, $4\delta^{ij}/3\sqrt{3}$ is the color factor of the diagram, $F_D(k^2)$ is the vector diquark form factor for the vertex $g^* \to (cc) + (\bar{c}\bar{c})$,$k = q' + p_{cc}$,

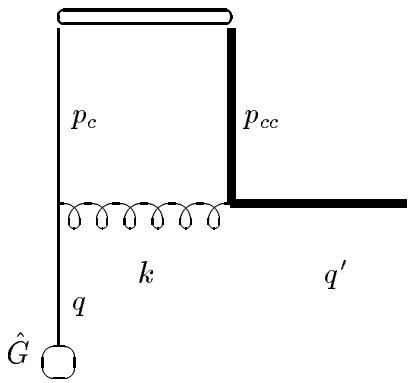

Figure 1: Diagram used for description of the c-quark to split into Ω_{ccc}.

$\bar{\Psi}^{\beta}(p)$ is the spin-vector of the spin-3/2 baryon, $\varepsilon^{*}_{\alpha}(q')$ is the polarization four-vector of $(\bar{c}\bar{c})$-diquark, $\Psi_{\Omega_{ccc}}(0)$ is the nonrelativistic Ω_{ccc} wave function at the origin in the quark-diquark approximation. The vertex $g^{*} \to (cc) + (\bar{c}\bar{c})$ is written as follows

$$-ig_s T^a V_{\alpha\mu\beta}(q', p_{cc}) F_D(k^2), \tag{3}$$

where

$$V_{\alpha\mu\beta}(q', p_{cc}) = -g_{\alpha\beta}(q' - p_{cc})_{\mu} - g_{\beta\mu}(3p_{cc} + 2q')_{\alpha} + g_{\mu\alpha}(3q' + 2p_{cc})_{\beta},$$

$$F_D(k^2) = 128\pi\alpha_s \frac{|\Psi_{cc}(0)|^2}{m_{cc}^3} \left(\frac{m_{cc}^2}{k^2}\right)^2, \tag{4}$$

$\Psi_{cc}(0)$ is the nonrelativistic (cc)-diquark wave function at the origin, m_{cc} is the diquark mass.

In the nonrelativistic approximation one has $p_{cc} = (1-r)p$ and $p_c = rp$, where $r = m_c/M$. Scalar products of k, p and q are presented as follows:

$$k^2 = (1-r)(s - m_c^2), \quad 2(qk) = (2-r)(s - m_c^2),$$

$$2(kp) = s - m_c^2, \quad 2(pq) = s - m_c^2 + 2rM^2.$$

After summation over polarizations of the squared amplitudes and integration over s we have obtained the fragmentation function at the scale $\mu_0 = 4m_c$:

$$D_{c\to\Omega_{ccc}}(z, \mu_0) = \frac{|\Psi_{\Omega_{ccc}}(0)|^2}{M^3} {\alpha_s}^2(\mu_0) F_{D0}^2 \Phi_c(z), \tag{5}$$

$$\begin{aligned}\Phi_c(z) &= \frac{36z^4(1-z)^3}{35(z-3)^{14}}(113519z^8 - 1303182z^7 + 8764206z^6 - 26818758z^5 \\ &\quad +52452396z^4 - 73464138z^3 + 66215394z^2 - 32322402z + 6506325).\end{aligned}$$

The recalculating of the fragmentation function from the starting point μ_0 to $\mu > \mu_0$ may be done using the evolution equation

$$\mu \frac{\partial D}{\partial \mu}(z,\mu) = \int_z^1 \frac{dy}{y} \mathcal{P}_{c\to c}\left(\frac{z}{y},\mu\right) D(y,\mu), \tag{6}$$

where $\mathcal{P}_{c\to c}(x,\mu)$ is the splitting function at the leading order in α_s

$$\mathcal{P}_{c\to c}(x,\mu) = \frac{4\alpha_s(\mu)}{3\pi}\left(\frac{1+x^2}{1-x}\right)_+, \tag{7}$$

$$f(x)_+ = f(x) - \delta(1-x)\int_0^1 f(x')dx'.$$

Fig. 2 shows fragmentation function $D_{c\to\Omega_{ccc}}(z,\mu)$ normalized to unity at the $\mu = \mu_0$ (curve 1) and $\mu = 45$ GeV (curve 2). We have obtained that average fractions of the Ω_{ccc} momentum are equal to $< z >_{\mu_0} = 0.61$ and $< z >_{45} = 0.42$. Since one has at leading order in α_s

$$\int_0^1 \mathcal{P}_{c\to c}(x,\mu)dx = 0,$$

the evolution equation implies that the fragmentation probability $P_{c\to\Omega_{ccc}}$ do not evolve with the scale μ:

$$P_{c\to\Omega_{ccc}} = \int_0^1 D_{c\to\Omega_{ccc}}(z,\mu_0)dz = A_c {\alpha_s}^2(\mu_0) F_{D0}^2 \frac{|\Psi_{\Omega_{ccc}}(0)|^2}{M^3}, \tag{8}$$

where

$$A_c = \frac{263585448}{5}\ln\left(\frac{3}{2}\right) - \frac{1100381933317}{51480} \approx 4.19\cdot 10^{-3}.$$

We used for numerical calculation computer program "schroe" [13] with the power-low quark-quark interaction potential from [14]:

$$V_{Q\bar{Q}}(r) = -A + B(r\cdot 1\ \text{GeV})^n, \quad V_{QQ} = \frac{1}{2}V_{Q\bar{Q}},$$

where $A = -8.064$ GeV, $B = 6.898$ GeV and $n = 0.1$. We have obtained masses of the vector (cc)-diquark, Ω_{ccc} baryon and values of nonrelativistic wave functions of (cc)-diquark and Ω_{ccc} baryon at the origin: $m_{cc} = 3.48$ GeV, $M = 4.70$ GeV, $|\Psi_{cc}(0)|^2 = 0.03$ GeV^3, $|\Psi_{\Omega_{ccc}}(0)|^2 = 0.115$ GeV^3. Using the above set of parameters with α_s=0.3, we have obtained the fragmentation probability

$$P_{c\to\Omega_{ccc}} = 1.15\cdot 10^{-9}. \tag{9}$$

3. Hadronic production of Ω_{ccc} baryons

Accordingly to factorization approach, $p_\perp$-spectrum of Ω_{ccc} baryons in hadronic collisions at high $p_\perp$ may be presented as the convolution of c-quark $p_\perp$-spectrum and fragmentation function $D_{\Omega_{ccc}}(z,\mu)$ at the scale $\mu \approx \sqrt{p_\perp^2 + M^2}$:

$$\frac{d\sigma}{dp_\perp}(p\bar{p}\to\Omega_{ccc}X) = \int_0^1 D_{c\to\Omega_{ccc}}(z,\mu)\frac{d\sigma}{dp_{\perp c}}\left(p\bar{p}\to cX, p_{\perp c} = \frac{p_\perp}{z}\right)dz, \tag{10}$$

$$\begin{aligned}\frac{d\sigma}{dp_\perp}(p\bar{p}\to cX) &= 2p_\perp K\int_{y_{min}}^{y_{max}} dy \int_{x_{1,min}}^1 dx_1 \frac{x_1 x_2 s}{x_1 s + u - m_c^2} \\ &\sum_{i,j} F_i^p(x_1,\mu)F_j^{\bar{p}}(x_2,\mu)\frac{d\hat{\sigma}}{d\hat{t}}(ij\to c\bar{c}),\end{aligned} \tag{11}$$

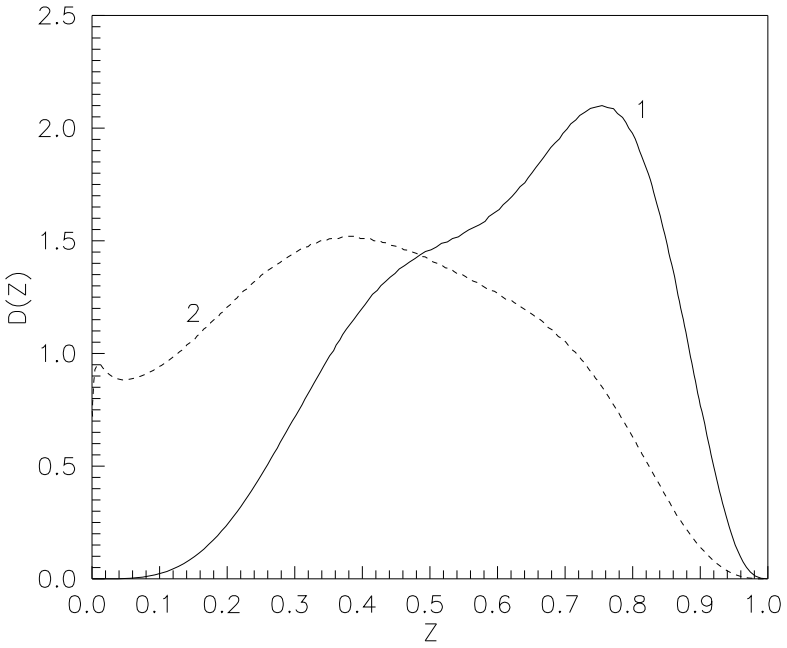

Figure 2: The fragmentation function $D_{c\to\Omega_{ccc}}(z,\mu)$ normalized to unity at $\mu=\mu_0$ (curve 1) and $\mu=45$ GeV (curve 2).

where $F_i^{p,\bar{p}}(x_{1,2},\mu)$ are quark or gluon distribution functions in proton (antiproton), $d\hat{\sigma}/d\hat{t}(ij\to c\bar{c})$ are differential cross sections for partonic subprocesses $gg\to c\bar{c}$, $q\bar{q}\to c\bar{c}$, $K\approx 3$ is a phenomenological factor, which takes into account the next to leading order contribution in α_s. In the calculation we have used CTEQ5 [15] parameterization for distribution functions and K-factor have been fixed using the data for b-quark production in $p\bar{p}$-collisions at $\sqrt{s}=1.8$ TeV.

After numerical integration of (10)-(11) at $p_\perp > 5$ GeV/ and $|y|<1$ we have found:

$$\sigma(p\bar{p}\to\Omega_{ccc},\sqrt{s}=1.8\text{ TeV})=3.6\cdot 10^{-3}\text{ pb}, \tag{12}$$

$$\sigma(p\bar{p}\to\Omega_{ccc},\sqrt{s}=14\text{ TeV})=3.45\cdot 10^{-2}\text{ pb}. \tag{13}$$

For the Tevatron, with an integrated luminosity of $\sim 10^2$ pb$^{-1}/yr$, we predict smaller than one event per year, while the LHC, with luminosity $\sim 10^5$ pb$^{-1}/yr$, should produce of order $3.5\cdot 10^3$ events per year.

In conclusion, the calculation of the production of the hadrons containing heavy quarks in the fragmentation approach gives rather lower result than the exact calculation using total set of Feynman diagrams [7]. This fact also shows that measured number of events should be larger than one predicted here.

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