Doubly charmed baryon production in hadronic experiments

A. V. Berezhnoy, V. V. Kiselev,* A. K. Likhoded, and A. I. Onishchenko
State Research Center of Russia ''Institute for High Energy Physics,'' Protvino, Moscow Region, 142284 Russia
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In the leading order of perturbative QCD we calculate the total and differential cross sections for the hadronic production of doubly charmed baryons Ξ_{cc} and Ξ_{cc}^* in different experiments. The experimental evaluation of the cross sections for the $J/\psi+D+\bar{D}$ production would allow us to decrease the uncertainty in the determination of cross sections for the doubly charmed baryons due to the choice of α_s and m_c. We show that in the HERA-B and E781 experiments with fixed tagets the suppression of the Ξ_{cc} and Ξ_{cc}^* production to the yield of $c\bar{c}$ pairs is a value of the order of $10^{-6}-10^{-5}$, whereas at the Fermilab Tevatron and CERN LHC colliders it is about $10^{-4}-10^{-3}$. In the E781 experiment the observation of Ξ_{cc} and Ξ_{cc}^* is practically impossible. At the HERA-B and Tevatron facilities one can expect 10^5 events with the double charm, and at LHC one has about 10^9 events. [S0556-2821(98)02903-8]

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I. INTRODUCTION

Recent years have been marked by a rapid increase of charmed particles observed in modern experiments. Therefore, the study of about 10^6 charmed particles is expected at the fixed target Fermilab facilities of E831 and E781. An increase of this value by two orders of magnitude is proposed in experiments of the next generation. Along with standard problems of CP violation in the charmed quark sector and a measuring of rare decays, etc., an investigation of processes with more than one $c\bar{c}$-pair production becomes actual. The production of an additional $c\bar{c}$ pair strongly decreases the value of the cross section for such processes. This fact must be especially taken into account in fixed target experiments, where the quark-partonic luminosities are strongly suppressed in the region of heavy mass production.

An interesting process of the above mentioned kind is doubly charmed baryon production. The doubly charmed $\Xi_{cc}^{(*)}$ baryon represents an absolutely new type of object in comparison with ordinary baryons containing light quarks only. The basic state of such a baryon is analogous to a $(\bar{Q}q)$ meson, which contains one heavy antiquark $\bar{Q}$ and one light quark q. In the doubly heavy baryon the role of the heavy antiquark is played by the (cc) diquark, which is in an antitriplet color state [1]. It has a small size in comparison with the scale of light quark confinement.

The spectrum of (ccq)-system states has to differ essentially from the heavy meson spectra, because the composed (cc) diquark has a set of excited states (for example, $2S$ and $2P$) in contrast to the heavy quark. The energy of the diquark excitation is twice less than the excitation energy of the light quark bound with the diquark. So, the representation of the compact diquark can be straightforwardly connected with the level structure of a doubly heavy baryon.[1]

Another interesting aspect of doubly charmed baryon research is the production mechanism. (ccq)-baryon production was discussed in a number of papers [4–7]. The main problem of the calculations is reduced to an evaluation of the production cross section for the diquark in the antitriplet color state. One assumes further that the (cc) diquark nonperturbatively transforms into the (ccq) baryon with a probability close to unity. The hadronic production of the diquark is subdivided into two parts. The first stage is the hard production of two $(c\bar{c})$ pairs in the processes of $gg\to c\bar{c}c\bar{c}$ and $q\bar{q}\to c\bar{c}c\bar{c}$, which are described by Feynman diagrams of fourth order over the α_s coupling constant [8]. The second step is the nonperturbative fusion of two c quarks with a small relative momentum into the (cc) diquark. For the S-wave states, this process is characterized by the radial wave function at the origin $R(0)$.

The main difference between the existing evaluations of the doubly charmed baryon cross section consists in the methods used for the hard subprocess calculation. In [9] the part of the diagrams connected with c fragmentation into the (cc) diquark is used instead of the complete set of diagrams. As was shown in paper [6] this estimation is not absolutely correct, because it becomes true only at $p_T>25-30$ GeV, where the fragmentation mechanism is dominant. In other kinematical regions the application of the fragmentational approximation is not justified and it leads to wrong results,

*Fax: +7-095-2302337. Email address: kiselev@mx.ihep.su

[1]Our estimates of the diquark mass in the Martin [2] potential, with taking into account the color factor for the antitriplet state of the quark pair and using the results of heavy quark effective theory [3], give the value of $M(\Xi_{cc}^{(*)})=3.615\pm 0.035$ GeV (without taking into account a spin dependent interaction). The mass shift of vector diquark is determined by using the formula $\delta M \simeq \frac{1}{2}|R_{cc}(0)|^2/|R_\psi(0)|^2(M_\psi-M_{\eta_c})/4\simeq 5$ MeV. The splitting between Ξ_{cc} and Ξ_{cc}^* is equal to $\Delta M(\Xi_{cc}^{(*)})\simeq \frac{3}{4}\Delta M(D^{(*)})\simeq 108$ MeV, so $M(\Xi_{cc})=3.584\pm 0.035$ GeV, $M(\Xi_{cc}^*)=3.638\pm 0.035$ GeV. The diquark size $r_{cc}\sim 0.5$ fm is close to that of J/ψ.

especially when $\sqrt{\hat{s}}$ is not much greater than $p_T^{\min}$.

In the framework of the fragmentation model the account for the leading logarithm corrections can be performed in a simple way. However, in the framework of calculations for the complete set of diagrams in the α_s^4 order the regime of fragmetation is dominant only in the restricted region of kinematical variables $p_T > p_T^{\min}$, $s > s^{\min}$, wherein the procedure for taking into account the evolution of fragmentation functions does not cause difficulties. But the account for the emission of an additional hard gluon beyond the mentioned region requires calculations in the next α_s^5 order of perturbative QCD so that the number of diagrams increases drastically, and there are no large logs such as $\ln(p_T^2/m^2)$ or $\ln(s/m^2)$ in the dominant kinematical domain. So, following Refs. [4–7], in this paper we are restricted by the Born approximation.

However, even after taking into account the complete set of diagrams, essential uncertainties in the estimations of (ccq)-baryon production remain. The basic parameters determining these uncertainties are the values of α_s, m_c, and $R_{cc}(0)$. In addition, it is not clear to what extent the hypothesis on the hadronization of a (cc) diquark into a (ccq) baryon with the unit probability is correct or not. The problem is that the interaction between the diquark and gluons is not suppressed in contrast to $(c\bar{c})$-pair production in the color singlet state, where the quarkonium dissociation supposes an exchange with the quark-gluonic sea by two hard gluons with virtualities, which are greater than the inverse size of the quarkonium.

A decrease of the uncertainty in the (ccq)-baryon cross section would be possible by means of comparing the process of baryon production with the analogous process of $J/\psi + D\bar{D}$ production.[2] The latter is described by practically the same diagrams of fourth order with the well-known wave function of J/ψ at the origin.[3]

In this way of connection to the $J/\psi + D\bar{D}$ process one could remove the parts of uncertainties which are due to α_s and m_c in the (cc)-diquark production process. In the following sections of the paper the joint cross-section calculations of these processes in $\pi^- p$ and pp interactions are performed.

There are some papers where the fragmentation model for J/ψ production at $p_T > 5$ GeV were constructed taking account of the color-octet contribution (see the review [10]). However, the associated production of $J/\psi + D\bar{D}$ requires the production of an additional $c\bar{c}$ pair, so that the production mechanism is evidently the other one, and the $J/\psi + D\bar{D}$ yield is only a small fraction of the inclusive J/ψ production in pp interactions.

For $B_c + b\bar{c}$ production one has shown that the regime of fragmentation becomes dominant at $p_T > 35$ GeV. The production of $J/\psi + c\bar{c}$ is completely analogous to the associated production of $B_c + b\bar{c}$ (with a careful account for the identity of the charmed quarks). For $B_c + b\bar{c}$, $\Xi_{cc} + \bar{c}\bar{c}$, and $J/\psi + c\bar{c}$ production one finds a common regularity: the fragmentation regime is displaced to the region of $p_T > 25 - 35$ GeV. To convince the reader completely, we present a corresponding figure for the gluon-gluon subprocess of $gg \to J/\psi + c\bar{c}$ at $\sqrt{\hat{s}} = 100$ GeV. Thus, we insist on the statement that for the associated production of $J/\psi + c\bar{c}$ and $\Xi_{cc} + \bar{c}\bar{c}$ the fragmentation works at $p_T \gg m_c$.

Section II is devoted to the description of production models for (ccq) baryons and $J/\psi + D\bar{D}$. In Sec. III we present the calculated results for the production cross section of (ccq) baryons and $J/\psi + D\bar{D}$ in the fixed target experiments E781 and HERA-B.

II. PRODUCTION MECHANISM

As was mentioned in the Introduction, we suppose that the diquark production can be subdivided into two stages. In the first stage the production amplitude of four free quarks is calculated for the following processes:

$$gg \to cc\bar{c}\bar{c}, \tag{1}$$

$$q\bar{q} \to cc\bar{c}\bar{c}. \tag{2}$$

The calculation technique applied in this work is analogous to that for the hadronic production of B_c [11], but in this case the bound state is composed of two quarks [5,6] instead of the quark and antiquark.

We assume that the binding energy in the diquark is much less than the masses of constituent quarks and, therefore, these quarks are on the mass shells. So, the quark four-momenta are related to the (Q_1Q_2) diquark momentum in the following way:

$$p_{Q_1} = \frac{m_{Q_1}}{M_{(Q_1Q_2)}} P_{(Q_1Q_2)}, \quad p_{Q_2} = \frac{m_{Q_2}}{M_{(Q_1Q_2)}} P_{(Q_1Q_2)}, \tag{3}$$

where $M_{(Q_1Q_2)} = m_{Q_1} + m_{Q_2}$ is the diquark mass and m_{Q_1}, m_{Q_2} are the quark masses.

In the given approach the diquark production is described by 36 Feynman diagrams of leading order, corresponding to the production of four free quarks with the combination of two quarks into the color antitriplet diquark with the given quantum numbers over the Lorentz group. The latter procedure is performed by means of the projection operators

$$\mathcal{N}(0,0) = \sqrt{\frac{2M_{(Q_1Q_2)}}{2m_{Q_1}2m_{Q_2}}} \frac{1}{\sqrt{2}} \{ \bar{u}_1(p_{Q_1},+)\bar{u}_2(p_{Q_2},-) - \bar{u}_1(p_{Q_1},-)\bar{u}_2(p_{Q_2},+) \} \tag{4}$$

[2]We calculate the $J/\psi + c\bar{c}$ production and assume that the $c\bar{c}$ pair transforms to $D\bar{D}$+ some light hadrons with the probability very close to unity. So, we neglect the production of charmed baryons as well as bound states of charmonium.

[3]The value of $|R_\Psi(0)|$ is determined by the width of leptonic decay $J/\psi \to l^+ l^-$, taking into account the hard gluonic correction, so, numerically, $|R_\psi(0)| = \sqrt{\pi M/3}\tilde{f}_\psi$, where $\tilde{f}_\psi = 540$ MeV.

for the scalar state of diquark [the corresponding baryon is denoted as $\Xi'_{Q_1Q_2}(J=1/2)$],

$$\mathcal{N}(1,-1)=\sqrt{\frac{2M_{(Q_1Q_2)}}{2m_{Q_1}2m_{Q_2}}}\,\bar{u}_1(p_{Q_1},-)\,\bar{u}_2(p_{Q_2},-),$$

$$\mathcal{N}(1,0)=\sqrt{\frac{2M_{(Q_1Q_2)}}{2m_{Q_1}2m_{Q_2}}}\,\frac{1}{\sqrt{2}}\{\bar{u}_1(p_{Q_1},+)\,\bar{u}_2(p_{Q_2},-)+\bar{u}_1(p_{Q_1},-)\,\bar{u}_2(p_{Q_2},+)\},$$

$$\mathcal{N}(1,+1)=\sqrt{\frac{2M_{(Q_1Q_2)}}{2m_{Q_1}2m_{Q_2}}}\,\bar{u}_1(p_{Q_1},+)\,\bar{u}_2(p_{Q_2},+) \qquad (5)$$

for the vector state of diquark [the baryons are denoted as $\Xi_{Q_1Q_2}(J=1/2)$ and $\Xi^*_{Q_1Q_2}(J=3/2)$]. To produce the quarks, composing the diquark in the $\bar{3}_c$ state, one has to introduce the color wave function as $\varepsilon_{ijk}/\sqrt{2}$, into the diquark production vertex, so that $i=1,2,3$ is the color index of the first quark, j is that of the second one, and k is the color index of diquark.

The diquark production amplitude $A_k^{Ss_z}$ is expressed through the amplitude $T_k^{Ss_z}(p_i)$ for the free quark production in kinematics (3):

$$A_k^{Ss_z}=\frac{R_{Q_1Q_2}(0)}{\sqrt{4\pi}}T_k^{Ss_z}(p_i), \qquad (6)$$

where $R_{Q_1Q_2}(0)$ is the diquark radial wave function at the origin, k is the color state of diquark, and S and s_z are the diquark spin and diquark spin projection on the z axis, respectively.

In the numerical calculation giving the results which will be discussed in the next section, we suppose the following values of parameters:

$$\alpha_s=0.2,$$

$$m_c=1.7\ \text{GeV},$$

$$R_{cc(1S)}(0)=0.601\ \text{GeV}^{3/2}, \qquad (7)$$

where the value of $R_{cc}(0)$ has been calculated by means of the numerical solution of the Schrödinger equation with the Martin potential [12], multiplied by the 1/2 factor caused by the color antitriplet state of quarks instead of the singlet one.

To calculate the production cross section of diquarks composed of two c quarks, one has to account for their identity. One can easily find, that first, the antisymmetrization over the identical fermions leads to the scalar diquark amplitude equal to zero, second, the amplitude of vector (cc)-diquark production is obtained by substituting equal masses in the production amplitude of the vector diquark composed of two quarks with different flavors, and taking the 1/2 factor for identical quarks and antiquarks into account. In this work we suppose that the produced diquark forms a baryon with unit probability by catching the light quark from the quark-antiquark sea at small p_T or having the fragmentation into the baryon at large p_T.

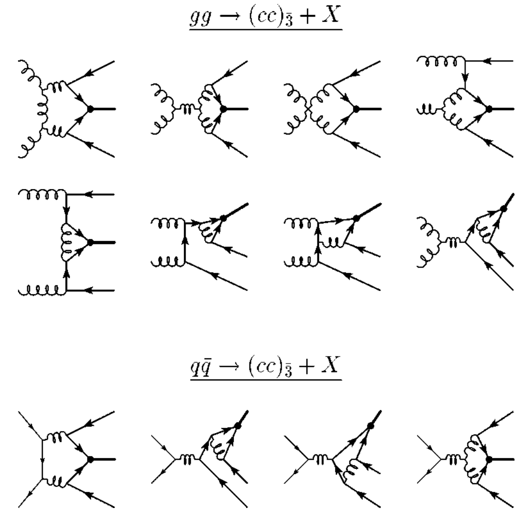

FIG. 1. Examples of the diagrams for gluon-gluon and quark-antiquark production of a (cc) diquark. The initial quarks are denoted by the thin fermion lines, the final quarks are denoted by the bold fermion lines, and the gluons are denoted by the helical lines.

The typical diagrams of fourth order describing the processes (1) and (2) with the binding of the cc pair into the diquark are shown in Fig. 1. One can subdivide them into two groups. The first group contains the diagrams of fragmentation type, wherein the $(c\bar{c})$ pair emits another one. The second group corresponds to the independent dissociation of gluons into $(c\bar{c})$ pairs with the fusion into the diquark. The diagrams of the second group are of recombination type. The authors of some of the papers mentioned above restricted themselves by the consideration of only fragmentation diagrams. In this way they reduced the cross-section formulas to the $(c\bar{c})$-pair production cross section multiplied by the fragmentation function of a c quark into a (cc) diquark. As was shown in [6], the latter approach is correct only under the following two conditions: $M^2_{(cc)} \ll \hat{s}$ and $p_T \gg M_{(cc)}$. In other kinematical regions, the contribution of recombination diagrams dominates.

The typical value of p_T where the fragmentation begins to dominate is $p_T > 25-30$ GeV. It is clear that at realistic p_T one has to take into account all contributions including the recombination one. The complete set of diagrams was taken into account for the first time in [6] and, after that, in [7]. In both papers the calculations were performed only for gluon-gluon production, which is a rather good approximation at collider energies. For the fixed target experiments the value of total energy strongly decreases and, hence, the values of energy in the subprocesses (1) and (2) decrease too.

The contribution of quark-antiquark annihilation becomes essential at fixed target energies, especially for the processes with initial valent antiquarks. In the following consideration

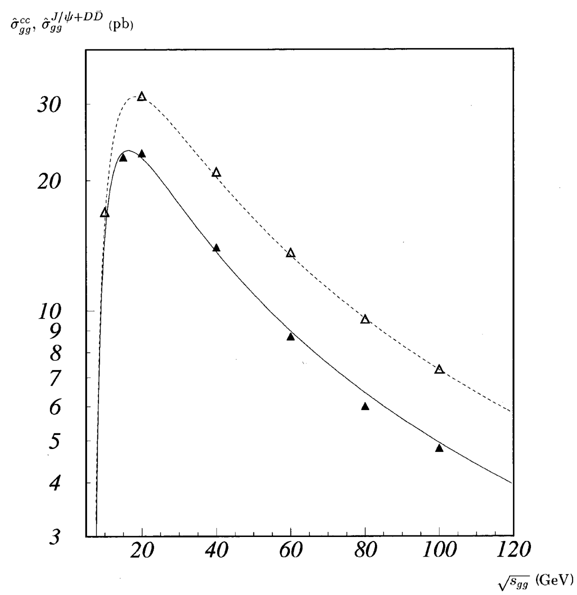

FIG. 2. The total cross section of the gluon-gluon production of the (cc) diquark (solid triangle) and $J/\psi+D\overline{D}$ (empty triangle) in comparison with the approximations of Eqs. (8) and (10) (solid and dashed curves, correspondingly).

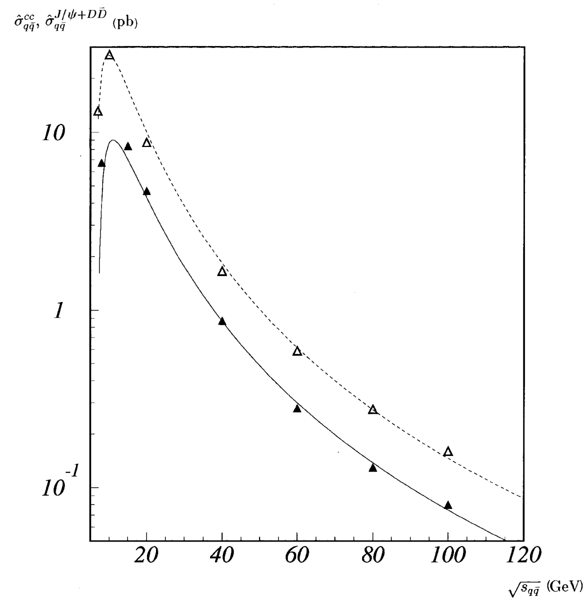

FIG. 3. The total cross section of the quark-antiquark production of the (cc) diquark (solid triangle) and $J/\psi+D\overline{D}$ (empty triangle) in comparison with the approximations of Eqs. (9) and (11) (solid and dashed curves, correspondingly).

we allow for quark-antiquark annihilation into four free charmed quarks in the estimation of the yield for the doubly charmed baryon. To our knowledge, the corresponding calculations for diquark production have not yet been performed.

III. DOUBLY CHARMED BARYON PRODUCTION IN FIXED TARGET EXPERIMENTS

The applied method of calculations is the same as in our previous works [6,11]. We calculate the complete set of diagrams in fourth order over the strong coupling constant for the Born amplitude of the process under consideration.

The calculation results for the total cross section of the diquark-production subprocesses versus the total energy are shown in Figs. 2 and 3 for the given values of α_s, m_c, and $R_{(cc)}(0)$. These dependencies can be approximately described by the following expressions:

$$\hat{\sigma}_{gg}^{(cc)}=213.\left(1-\frac{4m_c}{\sqrt{\hat{s}}}\right)^{1.9}\left(\frac{4m_c}{\sqrt{\hat{s}}}\right)^{1.35}\quad \text{pb}, \tag{8}$$

$$\hat{\sigma}_{q\bar{q}}^{(cc)}=206.\left(1-\frac{4m_c}{\sqrt{\hat{s}}}\right)^{1.8}\left(\frac{4m_c}{\sqrt{\hat{s}}}\right)^{2.9}\quad \text{pb}. \tag{9}$$

We have to mention that the numerical coefficients depend on the model parameters, so that $\hat{\sigma}\sim\alpha_s^4|R(0)|^2/m_c^5$.

As was mentioned in the Introduction, the production of J/ψ in the subprocesses of $gg\to J/\psi+c\bar{c}$ and $q\bar{q}\to J/\psi+c\bar{c}$ is also calculated in this work. The numerical results of such a consideration are shown in Figs. 2 and 3. The parametrization of these results versus the energy $\sqrt{\hat{s}}$ are presented below:

$$\hat{\sigma}_{gg}^{J/\Psi}=518.\left(1-\frac{4m_c}{\sqrt{\hat{s}}}\right)^{3.0}\left(\frac{4m_c}{\sqrt{\hat{s}}}\right)^{1.45}\quad \text{pb}, \tag{10}$$

$$\hat{\sigma}_{q\bar{q}}^{J/\Psi}=699.\left(1-\frac{4m_c}{\sqrt{\hat{s}}}\right)^{1.9}\left(\frac{4m_c}{\sqrt{\hat{s}}}\right)^{2.97}\quad \text{pb}. \tag{11}$$

In addition to $B_c+b\bar{c}$, $\Xi_{cc}+\overline{cc}$ production, we find the following regularity for $J/\psi+c\bar{c}$ production: the fragmentation regime is displaced to the region of $p_T>25-30$ GeV. This fact can be easily observed in the figure for the gluon-gluon subprocess of $gg\to J/\psi+c\bar{c}$ at $\sqrt{\hat{s}}=100$ GeV (Fig. 4). Thus, for the associated production of $J/\psi+c\bar{c}$ and $\Xi_{cc}+\overline{cc}$ the fragmentation works at $p_T\gg m_c$.

These formulas quite accurately reconstruct the results of precise calculations at $\sqrt{\hat{s}}<150$ GeV, which is why they can be used for the approximate estimation of the total hadronic production cross section for the (cc) diquark and J/ψ by means of their convolution with the partonic distributions:

$$\sigma=\sum_{i,j}\int dx_1dx_2f_{i/A}(x_1,\mu)f_{j/B}(x_2,\mu)\hat{\sigma}, \tag{12}$$

where $f_{i/A}(x,\mu)$ is the distribution of an i-type parton in the A hadron. The parton distributions used for the proton are the CTEQ4 parametrizations [12], and those used for the π^-

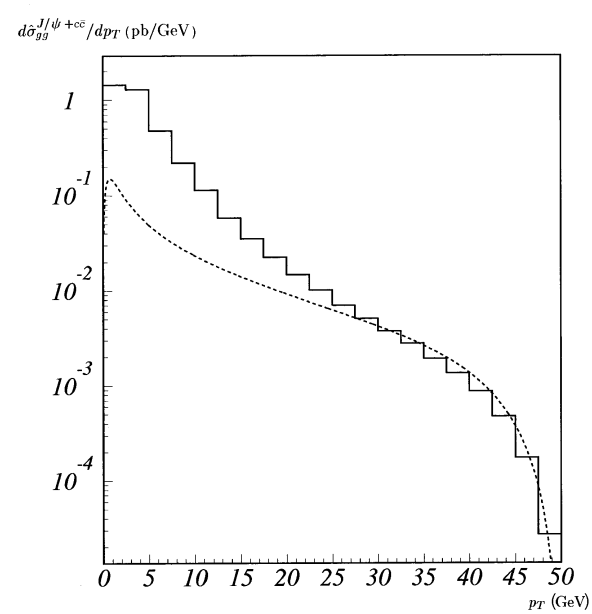

FIG. 4. The differential cross section for the associated production of $J/\psi+c\bar{c}$ in the gluon-gluon subprocess at 100 GeV (solid histogram) in comparison with the prediction of fragmentation model (dashed curve).

meson are the Hpdf ones [13]. In both of these cases the virtuality scale is fixed at 10 GeV. The choice of fixed scale in the structure functions, is caused by the fact that the cross section of subprocesses is integrated in the region of low $\hat{s}$ close to the fixed scale, so that the account of the ''running'' scale weakly changes the estimate of the Ξ_{cc}-baryon yield in comparison with the abovementioned uncertainty of the di-

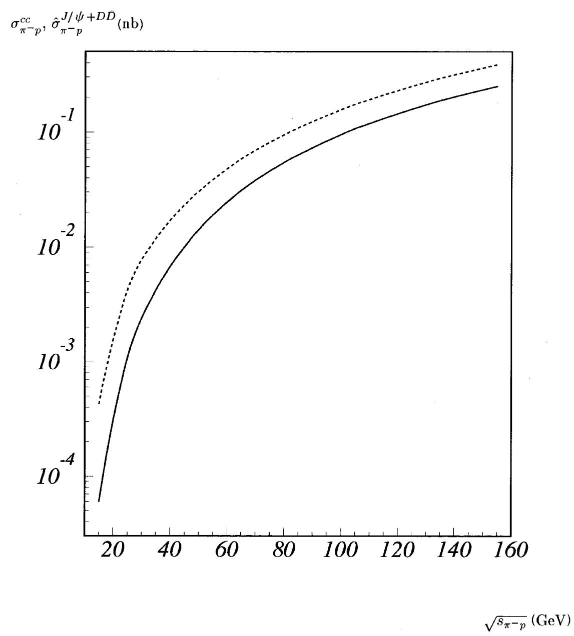

FIG. 5. The total cross section of the pion-proton production of a (cc) diquark and $J/\psi+D\bar{D}$ (solid and dashed curves, respectively).

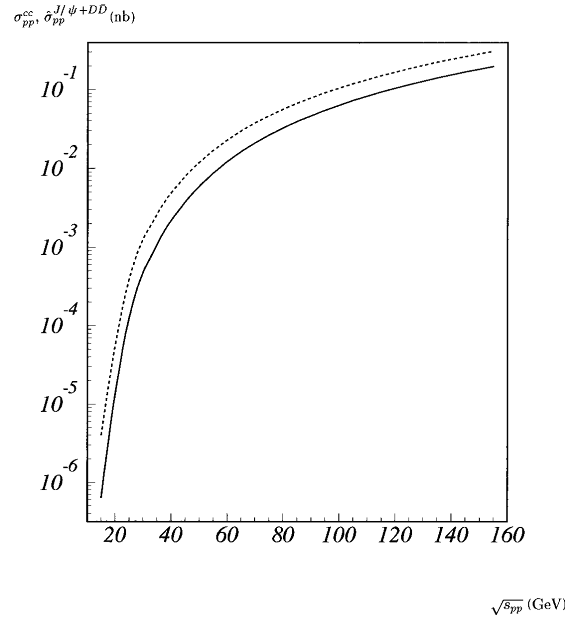

FIG. 6. The total cross section of the proton-proton production of the (cc) diquark and $J/\psi+D\bar{D}$ (solid and dashed curves, respectively).

quark model (we have found the scale-dependent variation to be at the level of $\delta\sigma/\sigma\sim 10\%$).

The total hadronic production cross section for these processes are presented in Figs. 5 and 6 for the $\pi^- p$ and pp interactions, correspondingly. As one can see in Figs. 5 and 6, the cross section of the (cc) diquark as well as the cross section of $J/\psi+c\bar{c}$ are strongly suppressed at low energies in comparison to the values at the collider energies.

The ratio for (cc)-diquark production and total charm production is $\sigma_{(cc)}/\sigma_{\rm charm}\sim 10^{-4}-10^{-3}$ in the collider experiments and $\sim 10^{-6}-10^{-5}$ in the fixed target experiments. The same situation is observed for the hadronic $J/\psi+D\bar{D}$ production. The distributions for (ccq) baryon and $J/\psi+D\bar{D}$ production are shown in Figs. 7–10 for the $\pi^- p$ interaction at 35 GeV and for the pp interaction at 40 GeV, respectively. The rapidity distributions in Figs. 8 and 10 point to the central state of (ccq)-baryon and $J/\psi+D\bar{D}$ production.

The p_T distributions of these processes are also alike [we assume that at given energies the (cc) diquark has no fragmentational transition into the baryon, but it catches the light quark from the quark-antiquark pair sea]. One can see in the latter figures that the process of $J/\psi+D\bar{D}$ production can be used to normalize the estimate of the (ccq)-baryon yield, wherein the following additional uncertainties appear: (1) the unknown value of $|R_{(cc)}(0)|^2$ and (2) uncertainties related to the hadronization of the (cc) diquark.

One can see from the given estimates that in the experiments with the expected number of charmed events at a level of about 10^6 (for example, in the E781 experiment, where $\sqrt{s}=35$ GeV), one has to expect at least one event with a doubly charmed baryon. The situation is more promising for the pp interaction at 800 GeV (HERA-B). The considered

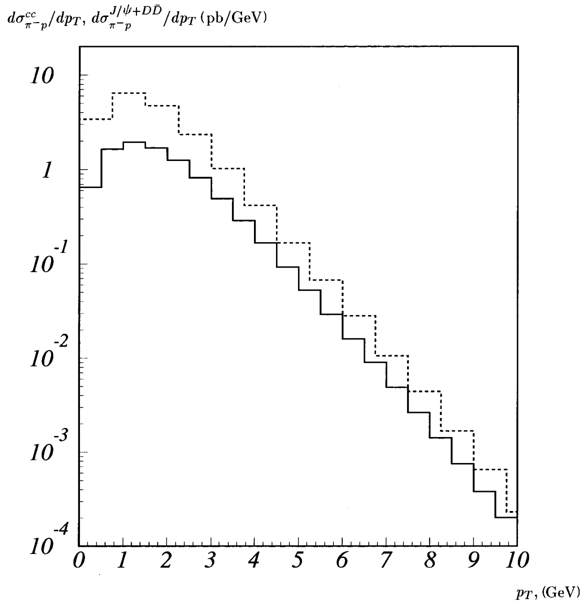

FIG. 7. $d\sigma^{cc}_{\pi^- p}/dp_T$ (solid histogram) and $d\sigma^{J/\psi+D\bar{D}}_{\pi^- p}/dp_T$ (dashed histogram) at a pion-proton interaction energy of 35 GeV.

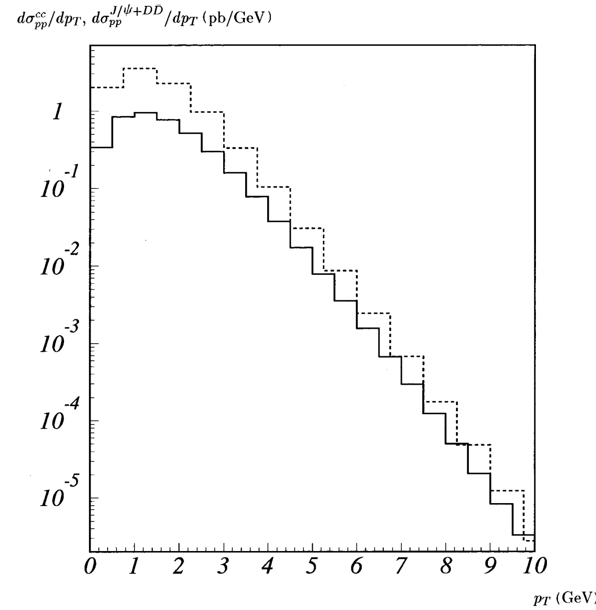

FIG. 9. $d\sigma^{cc}_{pp}/dp_T$ (solid histogram) and $d\sigma^{J/\psi+D\bar{D}}_{pp}/dp_T$ (dashed histogram) at a proton-proton interaction energy of 40 GeV.

processes yield about 10^5 $\Xi^{(*)}_{cc}$ baryons and a close number of $J/\psi+D\bar{D}$'s in the experiment specialized for the detection of about 10^8 events with b quarks.

IV. PRODUCTION OF A (*ccq*) BARYON AT COLLIDERS

As was shown in the previous section, the observation of $\Xi^{(*)}_{cc}$ baryons presents a rather difficult problem in the experiments specialized for the study of charmed particles. As a rule, such experiments are carried out at fixed targets, so that the effective value of the subprocess energy is strongly decreased. Therefore, the relative contribution of doubly charmed baryons into the total charm yield is of the order of $10^{-6}-10^{-5}$. The production of (ccq) baryons at colliders with large p_T is more effective. In this case the cross section is determined by the region of quark-antiquark and gluon-gluonic energies, where the threshold effect becomes negligible and the partonic luminosities are quite large at $x \sim M/\sqrt{s}$. Therefore, the suppression factor in respect to the single production of $c\bar{c}$ pairs is much less and it is in the range of $10^{-4}-10^{-3}$.

The p_T distributions for $\Xi^{(*)}_{cc}$ and J/ψ (which is produced with D and $\bar{D}$) at Fermilab Tevatron and CERN Large Hadron Collider (LHC) are shown in Figs. 11 and 12. The rapidity cut ($|y|<1$) is taken into account. One can easily understand that the presented $\Xi^{(*)}_{cc}$ cross sections are the upper

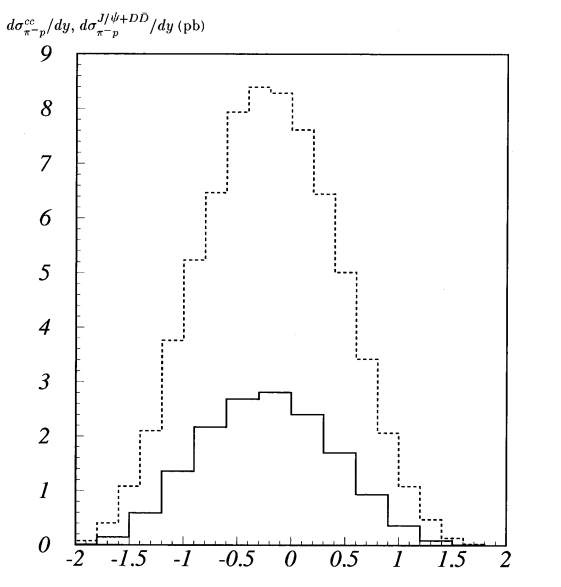

FIG. 8. $d\sigma^{cc}_{\pi^- p}/dy$ (solid histogram) and $d\sigma^{J/\psi+D\bar{D}}_{\pi^- p}/dy$ (dashed histogram) at the pion-proton interaction energy of 35 GeV.

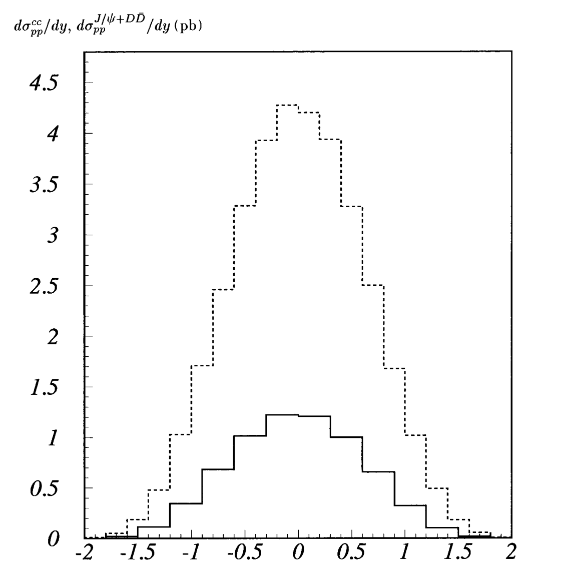

FIG. 10. $d\sigma^{cc}_{\pi^- p}/dy$ (solid histogram) and $d\sigma^{J/\psi+D\bar{D}}_{\pi^- p}/dy$ (dashed histogram) at the proton-proton interaction energy of 40 GeV.

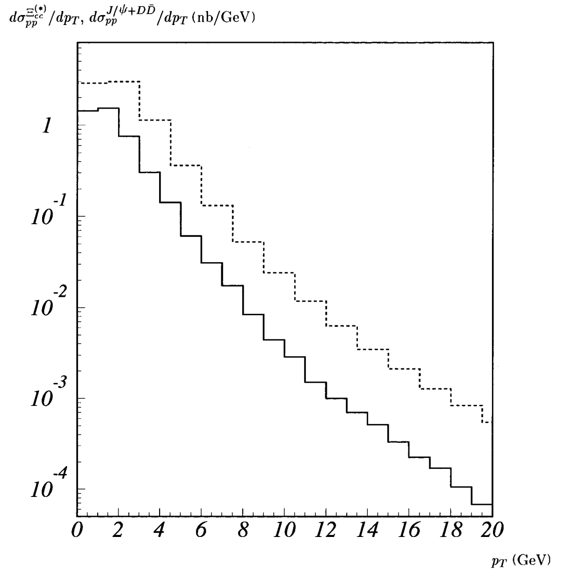

FIG. 11. $d\sigma_{pp}^{\Xi_{cc}^{(*)}}/dp_T$ with taking into account the fragmentation of a cc diquark into a $\Xi_{cc}^{(*)}$ baryon (solid histogram) and $d\sigma_{pp}^{J/\psi+D\bar{D}}/dp_T$ (dashed histogram) at a proton-proton interaction energy of 1.8 TeV.

estimates for the real cross sections because of the possible dissociation of a heavy diquark into a DD pair.

Furthermore, even if the (cc) diquark, being the color object, transforms into the baryon with the unit probability, one has to introduce the fragmentation function describing the hadronization of the diquark into the baryon at quite large p_T values. The simplest form of this function can be chosen by an analogy with that for the heavy quark:

$$D(z) \sim \frac{1}{z} \frac{1}{[m_{cc}^2 - M^2/z - m_q^2/(1-z)]^2}, \quad (13)$$

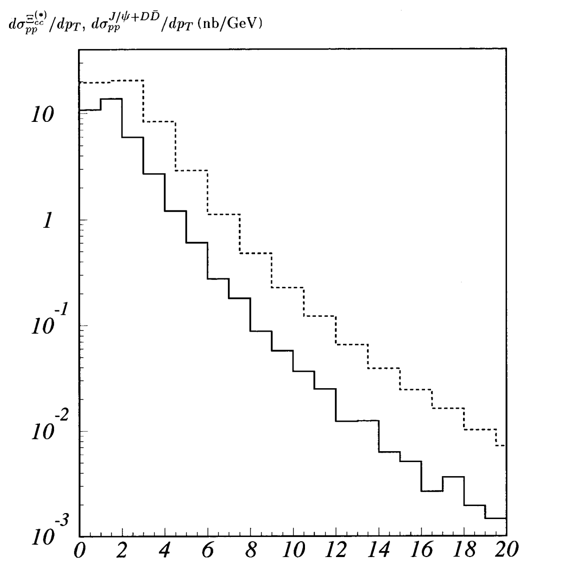

FIG. 12. $d\sigma_{pp}^{\Xi_{cc}^{(*)}}/dp_T$, taking into account the fragmentation of a cc diquark into a $\Xi_{cc}^{(*)}$ baryon (solid histogram) and $d\sigma_{pp}^{J/\psi+D\bar{D}}/dp_T$ (dashed histogram) at a proton-proton interaction energy of 14 TeV.

where M is the mass of baryon $\Xi_{cc}^{(*)}$, m_{cc} is the mass of the diquark, and m_q is the mass of the light quark (we suppose it to be equal to 300 MeV). The p_T distributions of doubly charmed baryon production, are shown in Figs. 11 and 12, calculated with the use of Eq. (13).

We have to mention that in leading order over the inverse heavy quark mass, the relative yields of Ξ_{cc} and Ξ_{cc}^* are determined by the simple counting rule for spin states, and is equal to $\sigma(\Xi_{cc}):\sigma(\Xi_{cc}^*)=1:2$. In this approach one does not take into account a possible difference between the fragmentation functions for baryons with different spins. The corresponding difference is observed in the perturbative fragmentation functions for heavy mesons and quarkonia [14].

V. DISCUSSION

As we have shown with basic perturbative calculations for the hard production of doubly charmed diquark fragmentating in the baryon, the observation of doubly charmed baryons is a difficult problem, because the ratio of $\sigma(\Xi_{cc}^{(*)})/\sigma(\text{charm})$ for these baryons and charmed particles yields the value of $10^{-6}-10^{-3}$ depending on the process energy. The suppression of the doubly charmed baryon yield at low energies is explained by the threshold effect. As one can see in Table I, about 10^5 events with the production of $\Xi_{cc}^{(*)}$ baryons can be expected at HERA-B. Practically the same number of events at $p_T > 5$ GeV and $|y| < 1$ is expected at TEVATRON with an integrated luminosity of 100 pb^{-1}. The large luminosity and large interaction energy allow one to increase the yield of the doubly charmed baryon by 10^4 times at LHC. Under conditions of a large yield of the doubly charmed baryons, the problem of their registration appears.

First of all it is interesting to estimate the lifetimes of the lightest states of Ξ_{cc}^{++} and Ξ_{cc}^{+}. The simple study of quark diagrams shows that in the decay of Ξ_{cc}^{++} baryons the Pauli interference for the decay products of charmed and valent quarks in the initial state takes place as in the case of D^+-meson decay. The exchange of the W boson between the valent quarks plays an important role in the decay of Ξ_{cc}^{+} as well as in the decay of D^0. Therefore we suppose that the mentioned mechanisms give the same ratio for both baryon and D-meson lifetimes:

$$\tau(\Xi_{cc}^{+}) \approx 0.4 \tau(\Xi_{cc}^{++}).$$

The presence of two charmed quark in the initial state results in the expressions

$$\tau(\Xi_{cc}^{++}) \approx \frac{1}{2} \tau(D^+) \simeq 0.53 \ \text{ps},$$

$$\tau(\Xi_{cc}^{+}) \approx \frac{1}{2} \tau(D^0) \simeq 0.21 \ \text{ps}.$$

One can point to the important decay modes of these baryons in analogy to the case of the charmed mesons:

TABLE I. The production cross section of doubly charmed baryons at different facilities.

Facility	HERA-B	E781	TEVATRON	LHC
Total cross section, nb/nucleon	2.0×10^{-3}	4.6×10^{-3}	12	122

$$\mathrm{B}\,(\Xi_{cc}^{++}\to K^{0(*)}\Sigma_c^{++(*)}) \approx \mathrm{B}\,[\Xi_{cc}^{+}\to K^{0(*)}(\Sigma_c^{+(*)}+\Lambda_c^{+})] \approx \mathrm{B}\,(\Lambda_c\to K^{0(*)}p)\simeq 4\times10^{-2}.$$

One can observe 4×10^3 events in these decay modes at HERA-B and TEVATRON without taking a detection efficiency into account. One has to expect a yield of 4×10^7 such decays at LHC. Among other decay modes, $\Xi_{cc}^{++}\to\pi^+\Xi_c^+$ and $\Xi_{cc}^{+}\to\pi^+\Xi_c^0$ taking place with the probability of about 1%, can be essential. The excited Ξ_{cc}^* states always decay into Ξ_{cc} by the emission of γ quanta, so the branching fraction of the transition is equal to 100% since the emission of a π meson is impossible in the Ξ_{cc}^* decay because of the small value of splitting between the basic and excited states, in contrast to the charmed meson decay.

In conclusion we mention another possibility to increase the yield of doubly charmed baryons in fixed target experiments. In the model of an intrinsic charm [15] one assumes that the nonperturbative admixture of exotic hybrid state $|c\bar{c}uud\rangle$ is present in the proton along with the ordinary state $|uud\rangle$ including three light valent quarks. The probability P_{ic} of the $|c\bar{c}uud\rangle$ state is suppressed at the level of 1%. The valent charmed quark from that state can recombine with the charmed quark produced in the hard partonic process of $(c\bar{c})$-pair production. The energy dependence for such doubly charmed baryon production is the same one for single charmed quark production in the framework of perturbative QCD (PQCD) up to the factor of the exotic state suppression and the factor of the fusion of two charmed quarks into the diquark, $K\sim0.1$. This mechanism has no threshold of four quark state production in contrast to the discussed perturbative one. Therefore at low energies of the fixed target experiments, where the threshold suppression of the perturbative mechanism is strong, the model of intrinsic charm would yield the dominant contribution in $\Xi_{cc}^{(*)}$ production. So, the number of events in this model would be increased by three orders of magnitude, and the ratio of $\Xi_{cc}^{(*)}$ and charmed particle yields would equal $\sigma(\Xi_{cc}^{(*)})/\sigma(\mathrm{charm})\sim10^{-3}$. At high energies the perturbative production is comparable with the intrinsic charm contribution. We note that the $|c\bar{c}c\bar{c}uud\rangle$ state suppressed at the level of 3×10^{-4}, could also increase doubly charmed baryon production at low energies of hadron-hadron collisions.

Thus, the observation of Ξ_{cc}^* baryons in hadronic interactions is a quite realistic problem, whose solution opens up new possibilities to research heavy quark interactions. The observation of $\Xi_{cc}^{(*)}$ baryons at fixed target experiments [16] would allow one to investigate the contributions of different mechanisms in doubly charmed baryon production, such as the contribution of the perturbative mechanism and that of the intrinsic charm, which strongly increases the yield of these baryons.

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