

# Resolving the SELEX–LHCb double-charm baryon conflict: the impact of intrinsic heavy-quark hadroproduction and supersymmetric light-front holographic QCD

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**Abstract.** In this paper we review the hadroproduction mechanisms of double-charm baryons for the different experimental environments and reinterpret the SELEX and LHCb results.

## 1 Introduction

The SELEX measurements of the production of the double-charm baryons at large  $x_F$  ( $\langle x_F \rangle \sim 0.33$ ) are among the most intriguing and surprising results in modern baryonic physics [1–3]. The SELEX experiment was a fixed-target experiment utilizing the Fermilab negative charged beam at 600 GeV/c to produce charm particles in a set of thin foil of Cu or in a diamond and was operated in the kinematic region  $x_F > 0.1$ . The negative beam composition was about 80%  $\Sigma^-$  and 20%  $\pi^-$ . The positive beam contained 90% protons. In a first observation using the sample of  $\Lambda_c^+ \rightarrow pK^-\pi^+$  [4, 5], SELEX found a signal of 15.9 events over  $6.1 \pm 0.1$  background events in the channel  $\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^-\pi^+$  [1]. To complement this result, SELEX published an observation of 5.62 signal events over  $1.38 \pm 0.13$  background events for the decay mode  $\Xi_{cc}^+ \rightarrow pDK^-$  from a sample of  $D^+ \rightarrow K^-\pi^+\pi^+$  decays [3].

Two charm quarks at high  $x_F$  cannot be produced from DGLAP evolution [6–8] or perturbative gluon splitting  $g \rightarrow g + g \rightarrow (\bar{c}c) + (\bar{c}c)$  [8–10]. Therefore, the observation of a double-charm baryon  $|qcc\rangle$  at a large mean value for  $x_F$  and a relatively small mean transverse momentum by SELEX can raise skepticism. However,  $\Lambda_c(udc)$  and  $\Lambda_b(udb)$  were both discovered at the ISR at high  $x_F$  [11–13]. In addition, the NA3 experiment measured both the single-quarkonium hadroproduction  $\pi A \rightarrow J/\psi X$  [14] and the double-quarkonium hadroproduction  $\pi A \rightarrow J/\psi J/\psi X$  [15] at high  $x_F$ . In fact, all of the events  $\pi A \rightarrow J/\psi J/\psi X$  were observed by NA3 with a total value of  $x_F > 0.4$ .

Recently, the LHCb collaboration published an observation of  $313 \pm 33$  events of  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^-\pi^+\pi^+$  in a 13 TeV sample at the LHC and  $113 \pm 21$  events in a 8 TeV sample at mass  $3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{sys}) \pm 0.14(\Lambda_c^+) \text{ MeV}/c^2$ , corresponding to  $1.7 \text{ fb}^{-1}$  and  $2 \text{ fb}^{-1}$ , respectively [16]. This result was again complemented by the mode  $\Xi_{cc}^{++} \rightarrow \Xi_c^+\pi^+$  [17]. LHCb reported that the mass difference between the  $\Xi_{cc}^+(dcc)$  candidate reported by SELEX and the  $\Xi_{cc}^{++}(ucc)$  state reported by LHCb was  $103 \text{ MeV}/c^2$ . Therefore, these states cannot be readily interpreted as an isospin doublet since one would expect a mass difference of isospin partners of only a few  $\text{MeV}/c^2$ . Note, though, that the upper limit of the  $x_F$  range at the LHCb

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collider experiment is given by  $x_F \approx 0.15$  and  $x_F \approx 0.09$  for the 8 TeV and 13 TeV analysis, respectively. In contrast to this, the  $x_F$  range at the SELEX fixed-target experiment starts at  $x_F = 0.1$ , nearly complementary to the acceptance for the LHCb. The lifetime of  $\Xi_{cc}^{++}$  state measured by LHCb is  $256_{-22}^{+24} \pm 14$  fs [18]. The upper limit of the lifetime measured by SELEX is given by  $\tau(\Xi_{cc}^+) < 33$  fs. Again, these results are in contradiction,  $\tau(\Xi_{cc}^{++})/\tau(\Xi_{cc}^+) \approx 2.5 - 4$ .

## 2 Production rate and the kinematics of the $\Xi_{cc}^+$ for the SELEX experiment

The SELEX collaboration did not provide the absolute production rate for the double-charm baryon state  $|d_{cc}\rangle$ . Fortunately, this rate can be compared to that of  $\Lambda_c^+$  baryon. The production ratio  $R_{\Lambda_c^+}$  measured by SELEX is given by

$$R_{\Lambda_c^+}^{\text{SELEX}} = \frac{\sigma(\Xi_{cc}^+) \cdot Br(\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} = \frac{N_{\Xi_{cc}^+}}{\epsilon_+} \cdot \frac{\epsilon_{\Lambda_c^+}}{N_{\Lambda_c^+}},$$

where  $N$  is the number of events in the respective sample, and the reconstruction efficiency of  $\Xi_{cc}^+$  is given by  $\epsilon_+ \approx 11\%$  [1]. The central value for the number  $N_{\Lambda_c^+}/\epsilon_{\Lambda_c^+}$  of reconstructed  $\Lambda_c^+$  baryon events reported in [19] lies between 13326 and 10010 according to whether the lowest bin with  $x_F \in [0.125, 0.175]$  is taken into account or not. If we take into account the intrinsic charm mechanism, the reconstruction efficiency of  $\Xi_{cc}^+$  will grow at least by a factor of 2.3 mainly because the  $x_F$  distribution predicted by the intrinsic charm mechanism at large Feynman  $x_F$  is well matched to the acceptance of the SELEX fixed-target experiment [2] (cf. [20]). Therefore, we obtain

$$R_{\Lambda_c^+}^{\text{SELEX}} \sim (0.5 - 0.6) \times 10^{-3}$$

It is clearly of interest to relate the production of the  $\Xi_{cc}^+$  at the SELEX experiment to the production of the double  $J/\psi$  production at the NA3 experiment. Unfortunately, it is not possible to compare the two results directly. However, we are able to compare the following ratios  $R = \sigma(c\bar{c}c\bar{c})/\sigma(c\bar{c})$ :

$$R^{\text{SELEX}} = R_{\Lambda_c^+} \times \frac{f(c \rightarrow \Lambda_c^+)}{f_{\Xi_{cc}^+}} \sim (1 - 4) \times 10^{-3}$$

and

$$R^{\text{NA3}} = \frac{\sigma(\psi\psi)}{\sigma(\psi)} \times \frac{f_\psi}{f_{\psi/\pi}^2} \sim 2 \times 10^{-2},$$

where  $f_{\psi/\pi} \approx 0.03$  is the fragmentation rate of the intrinsic charm state of the pion into  $J/\psi$  [21] and  $f_\psi \approx 0.06$  is the perturbative QCD fragmentation rate into  $J/\psi$  [22].  $f_{\Xi_{cc}^+} \approx 0.25$  [23] represents the fraction of double  $c\bar{c}$  pairs producing the sum of single-charged baryons  $\Xi_{cc}^+$  and double-charged baryons  $\Xi_{cc}^{++}$ , but this fraction cannot be less than the fraction to produce  $J/\psi$ . Therefore,  $R^{\text{SELEX}}$  should not be larger than  $10^{-2}$ . The SELEX production ratio is thus in approximate consistency with the complementary measurement of the double  $J/\psi$  production by the NA3 experiment. It is interesting to note that the intrinsic charm mechanism predicts  $\langle x_F(\Xi_{cc}^+) \rangle = 0.33$ , as shown in Ref. [23]. This is in excellent agreement with the value  $\langle x_F(\Xi_{cc}^+) \rangle \sim 0.33$  measured by the SELEX experiment.

## 3 Mass difference

In order to resolve the discrepancy between the results from SELEX and LHCb we will utilize the predictions of the supersymmetric light front holographic QCD (SUSY LFHQCD).

This approach was developed by imposing the constraints from the superconformal algebraic structure on LFHQCD for massless quarks [24]. As has been shown in Refs. [24, 25], supersymmetry holds to a good approximation, even if conformal symmetry is strongly broken by the heavy quark mass.

Note that the  $3_C + \bar{3}_C$  diquark structure of the  $\Xi_{cc}^+$  can be written explicitly as state  $[[dc]c]$ . The production of the double-charm baryon state  $\Xi_{[dc]c}^+$  with  $[dc]$  in a spin-singlet state is natural in the SELEX fixed target experiment since it has acceptance at high  $x_F$ , i.e., in the realm of intrinsic charm; the  $[dc]c$  configuration can easily re-coalesce from a higher Fock state of the proton such as  $|uudc\bar{c}\bar{c}\bar{c}\rangle$ . In contrast, the production of this state is likely to be suppressed in  $q\bar{q} \rightarrow c\bar{c}c\bar{c}$  or  $gg \rightarrow c\bar{c}c\bar{c}$  reactions at the LHCb. Thus LHCb has most likely observed the double-charm baryon state  $|u(cc)\rangle$ .<sup>1</sup> The mass difference between the  $[[dc]c]$  and the  $|u(cc)\rangle$  states is due to the hyperfine interaction between the quarks.

Supersymmetric light front holographic QCD, if extended to the case of two heavy quarks, predicts that the mass of the spin-1/2 baryon should be the same as the mass of  $h_c(1P)$ (3525) meson [25]. This is well compatible with the SELEX measurement of  $3520.2 \pm 0.7 \text{ MeV}/c^2$  for the  $\Xi_{cc}^+(d[cc])$ , although the uncertainty of SUSY LFHQCD predictions is at least of the order of 100 MeV. Indeed, the mass of the  $|u(cc)\rangle$  state is predicted to be the same as that of the  $\chi_{c2}(1P)$ (3556) meson, which is in turn lower than the LHCb result of  $3621.40 \pm 0.72(\text{stat}) \pm 0.27(\text{sys}) \pm 0.14(\Lambda_c^+) \text{ MeV}/c^2$  for the  $\Xi_{cc}^{++}$ .

Supersymmetric LFHQCD is based on and best tested in the chiral limit of QCD, where all quarks are massless. The mass difference between the  $h_c(1P)$  and the  $\chi_{c2}(1P)$  is mainly due to the hyperfine splitting between the two charm quarks, and hence very small. However, for a baryon there is a spin-spin interaction between the charm quark and a light quark which is larger than the hyperfine splitting. By comparing hadron masses with the masses of light and charm quarks, one can estimate the strength of this additional supersymmetry-breaking interaction to be found in the range  $84 - 136 \text{ MeV}/c^2$  [25, 26], which is well compatible with the mass difference between the SELEX and the LHCb states.

## 4 The $\Xi_{cc}^{++}(3780)$ state

At a few conferences [27, 28] (cf. also the PhD thesis of Mark E. Mattson [2]), the SELEX collaboration presented a decay process  $\Xi_{cc}^{++}(3780) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  for the state  $\Xi_{cc}^{++}(3780)$  with statistical significance of  $6.3\sigma$ . By removing the slower part of the  $\pi^+$ 's, SELEX observed that roughly 50% of the signal events above background decay weakly and 50% decay strongly (to  $\pi^+ \Xi_{cc}^+$ ). However, this is not possible for a single state. As SELEX did not find a plausible explanation for its decay properties, the result was not published.

Assuming  $\Xi_{cc}^{++}(3780)$  to be an excited state  $|ucc^*\rangle$ , we predict the mass of  $|ucc^*\rangle$  by utilizing the predictions of supersymmetric light front holographic QCD (SUSY LFHQCD). The SUSY LFHQCD prediction for the baryon mass spectra is given by the simple formula

$$M^2 \propto \lambda(n + L + 1)$$

where  $\sqrt{\lambda} \approx 0.52 \text{ GeV}$  is the fundamental mass parameter, given by the characteristic mass scale of QCD [26]. Using this simple formula, we can estimate the masses of the states  $[[qc]c]_{3/2}$  ( $n = 1, L = 0$ ) and  $|(qc)c]_{3/2}$  ( $n = 0, L = 1$ ), where  $(qc)$  indicates the spin-1 diquark. These states should have the same mass around  $3730 \text{ MeV}/c^2$ , where the uncertainty of the SUSY LFHQCD predictions is at least of the order of 100 MeV. Obviously, we have good agreement with the data for  $\Xi_{cc}^{++}(3780)$ .

<sup>1</sup>We use square brackets [ ] for spin-0 and round brackets ( ) for spin-1 internal states.

Investigating the decay properties, the  $[[qc]c]_{3/2}$  is more preferable for the weak decay. In contrast to that,  $|(qc)c\rangle_{3/2}$  includes a  $D^*$ -meson-like state, leading to the strong decay  $(qc) \rightarrow [qc] + \pi$ , similar to  $D^* \rightarrow D + \pi$ .

## 5 Isospin splitting of the SELEX states

The analysis of the isospin splitting of the SELEX states implies that double-charm baryons are very compact, i.e. the light quark must be very close to the two heavy quarks [29]. This contradicts the usual wisdom. Indeed, within the heavy-diquark concept, the production of the double-charm baryon can proceed in two steps. In a first step, due to the reactions  $q\bar{q} \rightarrow c\bar{c}c\bar{c}$  or  $gq \rightarrow c\bar{c}c\bar{c}$  the production of two charm quarks with a small relative momentum will take place, followed by the formation of a  $cc$ -diquark in the color-antitriplet state. In a second step, the transition of the produced diquark into the baryon is performed. The normalization of the fragmentation of the  $cc$ -diquark into the double-charm baryons is unknown. However, one is still able to provide some quantitative analysis because the fragmentation function is proportional to the wave function at the origin. The color-antitriplet wave function can be estimated on the basis of information about the color-singlet wave function,  $|R(0)[cc]_3| \sim |R(0)[c\bar{c}]_1|$ . This leads to an atom-like structure where the  $cc$  diquark forms the compact core while the scale of the light quark is given by the nonperturbative confinement scale [30]. In case of the  $S$ -wave solution we have the scale hierarchy

$$r_{cc} : r_{QCD} \approx 0.39 : 1$$

where  $r_{cc} \sim r_{J/\psi} \sim 0.39 \text{ fm} \simeq (0.5 \text{ GeV})^{-1}$  [31] and  $r_{QCD} = 1/(\Lambda_{QCD} \approx 200 \text{ MeV}) \approx 1 \text{ fm}$ .

In contrast to this, the production of the double-charm baryons at the SELEX experiment is supposed to be due to re-coalesce from a higher Fock state of the proton such as [23, 32]

$$|[uu]_3[dc]_3c_3[\bar{c}\bar{c}]_3\rangle$$

which leads to the baryonic state  $[[qc]c]$  in a natural way. Here the scale will be characterized by the size of the spin-0  $[qc]$  diquark, given by the Compton wavelength  $\lambda_{[qc]} \sim 1/m_{[qc]}$  of the diquark. This naturally provides closeness of the light quark to the two heavy quarks. Note that the peculiarities mentioned here are due to the inclusion of two heavy quarks.

It is interesting to estimate the compactness of such a state. The mass  $m_{[qc]}$  can be estimated as the effective diquark mass,  $m_{\Xi_{cc}} - m_c$ , where  $m_{\Xi_{cc}}$  is the double-charm baryon mass and  $m_c$  is the mass of the  $c$  quark. In case of the SELEX 3520 MeV event, one has  $\lambda_{[dc]} \sim 0.5 \text{ fm}$  which is again in the perfect agreement with the compactness of the SELEX state calculated from isospin splitting [29].

## 6 Summary

Using both theoretical and experimental arguments, we have shown that the SELEX and the LHCb results for the production of double-charm baryons can both be correct. We have compared the data for double  $J/\psi$  production observed by the NA3 experiment and the SELEX result for  $\Xi_{cc}^+$  production at high Feynman- $x_F$ . We have found that the NA3 data strongly complement the SELEX production rate for the spin-1/2  $[[dc]c]$  state. In contrast, LHCb has most likely discovered the heavier state  $|u(cc)\rangle$  produced by gluon-gluon fusion  $gg \rightarrow c\bar{c}c\bar{c}$  at  $x_F \sim 0$ . The application of supersymmetric algebra to hadron spectroscopy, together with the intrinsic heavy-quark QCD mechanism for the hadroproduction of heavy hadrons at large  $x_F$ , can thus resolve the apparent conflict between measurements of double-charm baryons

by the SELEX fixed-target experiment and the LHCb experiment at the LHC collider. The mass difference of the two double-charm baryons reflects the distinct spins of the underlying diquarks.

The theoretical estimate for the compactness of the baryon is in good agreement with similar estimates from isospin splitting. In addition, we gave estimates for the mass and the decay properties of  $\Xi_{cc}^{++}(3780) \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$  [33]. The production of the double-charm baryons at AFTER@LHC with the intrinsic charm is investigated in [34].

There is still an unexplained difference in lifetimes. However, it is interesting to note that the LHCb result  $\tau(\Omega_c^0) = 268 \pm 24 \pm 10 \pm 2$  fs [35] for the lifetime is again in disagreement with the respective lifetime measured by fixed-target experiments.

Experiment	lifetime (fs)	Number of events
FOCUS [36]	$72 \pm 11 \pm 11$	64
WA89 [37]	$55^{+13+18}_{-11-23}$	86
E687 [38]	$86^{+27}_{-20} \pm 28$	25
SELEX [39]	$65 \pm 13 \pm 9$	83

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