

Double heavy baryons  
from the theoretical point of view  
Workshop on Heavy Baryons at LHCb, CERN

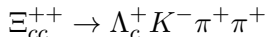
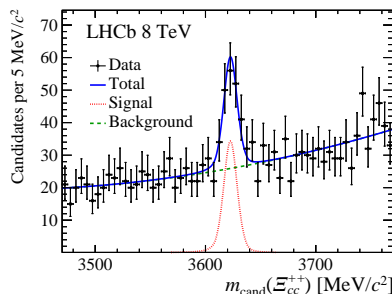
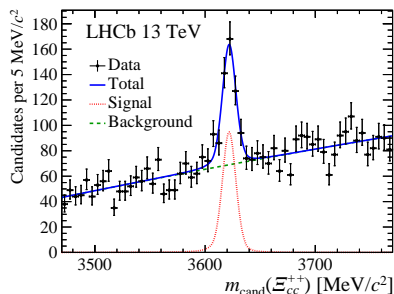
<sup>1</sup>A. Berezhnoy, <sup>2,4</sup>V. Kiselev, <sup>2</sup>A. Likhoded, <sup>1,3,4</sup>A. Onishchenko

<sup>1</sup>SINP MSU, <sup>2</sup>IHEP, <sup>3</sup>JINR, <sup>4</sup>MIPT

17.07.2017

# Congratulations

Our congratulations to the LHCb Collaboration  
on the observation of doubly charmed baryon!!!



[Aaij et al., 2017]

# Contents

- Introduction.
- Spectroscopy of DHB.
- Weak decays of DHB.
- Production.

# Very short introduction into double heavy baryons

- Consisted from two heavy quarks and one light quark:  $(Q_1 Q_2 q)$ .
- Several scales are in game:

$$m_Q \gg m_{Q_1} \cdot v, m_{Q_2} \cdot v \gg m_{Q_1} v^2, m_{Q_2} v^2 \gg \Lambda_{\text{QCD}}$$

(v.s.  $m_Q \gg \Lambda_{\text{QCD}}$  for heavy baryons).

- In the limit  $m_Q \rightarrow \infty$ , the light quark sees the heavy diquark as a local heavy source of a gluon field.
- Two-step calculation are possible:  

diquark in  $\bar{3}_c$

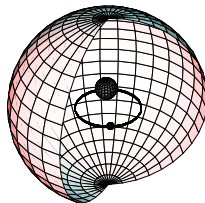
 + 

quark-diquark system

.
- The total spin of the diquark is a good quantum number within this approach.

The alternative way: the solving of three-body problem [Albertus et al., 2007a, Albertus et al., 2007b] and much earlier work [Kerbikov et al., 1990].

Scales for  $\Xi_{bc}$ :



The character of strong interactions in the doubly heavy baryon  $\Xi_{bc}$ : the compton lengths of quarks  $\lambda_Q = 1/m_Q$ , the size of heavy diquark  $r_{bc} \sim 1/(v \cdot m_Q)$  and the scale of nonperturbative confinement of light quark  $r_{QCD} = 1/\Lambda_{\text{QCD}}$  are arranged by  $\lambda_b \approx \frac{1}{3} \lambda_c \approx \frac{1}{9} r_{bc} \approx \frac{1}{27} r_{QCD}$  [Kiselev and Likhoded, 2002a].

# Spectroscopy

We assume that light quark interact with the heavy diquark (and not with heavy quarks separately):



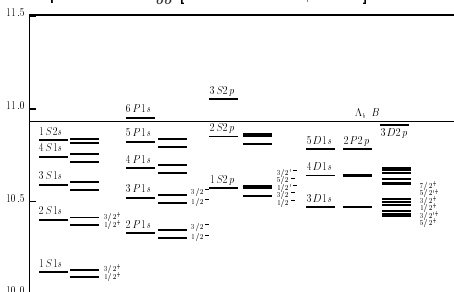
To obtain the spectrum of family of doubly heavy baryons we need:

- to obtain the spectrum of the diquark by analogy with the heavy quarkonium.
- for diquark consisted from equivalent quarks choose the anti-symmetric wave functions.
- to obtain the spectrum of diquark - light quark system by analogy with the heavy-light meson.
- to estimate the mixing between states with the same quantum numbers.

The quark identity simplifies the spectrum:

- $S$ -wave and  $D$ -wave state of  $QQ$  diquark:  $S_{QQ} = 1$
- $P$ -wave state:  $S_{QQ} = 0$

The spectrum of  $\Xi_{bb}$  [Gershtein et al., 1999a]:



See also [Flynn et al., 2003, Brambilla et al., 2005].

# $\Xi_{cc}^{++}$ and $\Xi_{cc}^{+}$ mass spectra

$(n_d L_d n_l L_l), J^P$	mass, GeV	$(n_d L_d n_l L_l), J^P$	mass, GeV
(1S 1s)1/2 <sup>+</sup>	3.478	(3P 1s)1/2 <sup>-</sup>	3.972
(1S 1s)3/2 <sup>+</sup>	3.61	(3D 1s)3/2' <sup>+</sup>	4.007
<b>(2P 1s)1/2<sup>-</sup></b>	3.702	(1S 2p)3/2' <sup>-</sup>	4.034
(3D 1s)5/2 <sup>+</sup>	3.781	(1S 2p)3/2 <sup>-</sup>	4.039
(2S 1s)1/2 <sup>+</sup>	3.812	(1S 2p)5/2 <sup>-</sup>	4.047
(3D 1s)3/2 <sup>+</sup>	3.83	(3D 1s)5/2' <sup>+</sup>	4.05
(2P 1s)3/2 <sup>-</sup>	3.834	(1S 2p)1/2' <sup>-</sup>	4.052
(3D 1s)1/2 <sup>+</sup>	3.875	(3S 1s)1/2 <sup>+</sup>	4.072
(1S 2p)1/2 <sup>-</sup>	3.927	(3D 1s)7/2 <sup>+</sup>	4.089
(2S 1s)3/2 <sup>+</sup>	3.944	(3P 1s)3/2 <sup>-</sup>	4.104

$\Xi_{cc}(2P 1s)$  is metastable, because transition to the ground state requires the angular momentum and the total spin diquark to change simultaneously. So, maybe it is worth to pay attention to the decay  $\Xi_{cc}^{+}(2P 1s) \rightarrow \Xi_{cc}^{++} \pi^{-}$ .

# Mass corrections due to diquark finite size

Taking into account the heavy diquark size increases the baryon masses.

Within the local-diquark approximation

$$m[\Xi_{cc}^{1/2^{++}}] \approx m[\Xi_{cc}^{1/2^+}] = 3478 \pm 30 \text{ MeV},$$

and

$$m[\Xi_{cc}^{3/2^{++}}] \approx m[\Xi_{cc}^{3/2^+}] = 3610 \pm 30 \text{ MeV}.$$

However, the actual sizes of doubly charmed diquarks are not negligible. As we have found in [Gershtein et al., 2000, Gershtein et al., 1999b], the sizes of basic vector  $1S$ -diquarks:

$$\langle r^2 \rangle_{cc}^{1/2} = 0.58 \text{ fm}$$

$$\langle r^2 \rangle_{bb}^{1/2} = 0.33 \text{ fm}$$

Accounting of diquark size within two different approaches increases the mass values:

- form factor:  $\delta M(\Xi_{cc}) \approx 80 \text{ MeV}$  [Ebert et al., 2002];
- longer string inside non-local diquark:  $\delta M(\Xi_{cc}) \approx 80 \text{ MeV}$  [Kiselev et al., 2017].

Therefore:

$$m[\Xi_{cc}^{1/2^{++}}] \approx m[\Xi_{cc}^{1/2^+}] = 3615 \pm 55 \text{ MeV},$$

$$m[\Xi_{cc}^{3/2^{++}}] \approx m[\Xi_{cc}^{3/2^+}] = 3747 \pm 55 \text{ MeV}.$$

# Taking into account the diquark form factor

Mass spectrum of  $\Xi_{cc}$  baryons in GeV.

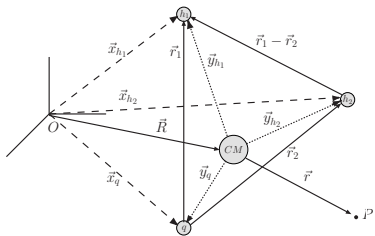
State $(n_d L n_q l) J^P$	Mass		State $(n_d L n_q l) J^P$	Mass	
	EFGM	our		EFGM	our
$(1S1s)1/2^+$	3.620	3.478	$(1P1s)1/2^-$	3.838	3.702
$(1S1s)3/2^+$	3.727	3.61	$(1P1s)3/2^-$	3.959	3.834
$(1S1p)1/2^-$	4.053	3.927	$(2S1s)1/2^+$	3.910	3.812
$(1S1p)3/2^-$	4.101	4.039	$(2S1s)3/2^+$	4.027	3.944
$(1S1p)1/2'^-$	4.136	4.052	$(2P1s)1/2^-$	4.085	3.972
$(1S1p)5/2^-$	4.155	4.047	$(2P1s)3/2^-$	4.197	4.104
$(1S1p)3/2'^-$	4.196	4.034	$(3S1s)1/2^+$	4.154	4.072

EFGM: D. Ebert, R. N. Faustov, V. O. Galkin, A. P. Martynenko [Ebert et al., 2002]



# Alternative way: to solve the three-body problem

C. Albertus, E. Hernandez, J. Nieves, J.M. Verde-Velasco [Albertus et al., 2007a, Albertus et al., 2007b]



Masses of ground states in GeV

$\Xi_{cc}$	$3612^{+17}$
$\Xi_{cc}^*$	$3706^{+23}$
$\Xi_{bb}$	$10197^{+10}_{-17}$
$\Xi_{bb}^*$	$10236^{+9}_{-17}$
$\Xi_{bc}$	$6919^{+17}_{-7}$
$\Xi'_{bc}$	$6948^{+17}_{-6}$
$\Xi_{bc}^*$	$6986^{+14}_{-5}$

Much earlier work of B. Kerbikov, M. Polikarpov and L. Shevchenko [Kerbikov et al., 1990]

Masses of centers of gravity  $M_{i,j}^{(a)}$  and the expectation values  $\delta_{ij}$  and  $\langle r_{ij}^2 \rangle^{1/2}$  for baryons

System	$M_{i,j}$ (MeV)	$10^3 \delta_{ij}$ (GeV <sup>3</sup> )	$\langle r_{ij}^2 \rangle^{1/2}$ (GeV <sup>-1</sup> )
udu	$1087.8 \pm 0.3$	$\delta_{12} = \delta_{13} = \delta_{23}$ $= 4.98 \pm 0.61$	$\langle r_{12}^2 \rangle^{1/2} = \langle r_{13}^2 \rangle^{1/2}$ $= \langle r_{23}^2 \rangle^{1/2} = 4.480 \pm 0.009$
uds	$1271.7 \pm 0.4$	$\delta_{12} = 4.07 \pm 0.41$ $\delta_{13} = \delta_{23}$ $= 6.85 \pm 0.72$	$\langle r_{12}^2 \rangle^{1/2} = 4.421 \pm 0.014$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 4.087 \pm 0.019$
udc	$2413.9 \pm 1.3$	$\delta_{12} = 5.24 \pm 0.85$ $\delta_{13} = \delta_{23}$ $= 8.51 \pm 1.10$	$\langle r_{12}^2 \rangle^{1/2} = 4.295 \pm 0.024$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 3.631 \pm 0.037$
udb	$5768.7 \pm 2.0$	$\delta_{12} = 5.21 \pm 1.03$ $\delta_{13} = \delta_{23}$ $= 12.22 \pm 1.21$	$\langle r_{12}^2 \rangle^{1/2} = 4.269 \pm 0.042$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 3.461 \pm 0.039$
usc	$2562.2 \pm 1.7$	$\delta_{12} = 7.49 \pm 1.08$ $\delta_{13} = 9.87 \pm 1.44$ $\delta_{23} = 17.99 \pm 1.99$	$\langle r_{12}^2 \rangle^{1/2} = 3.935 \pm 0.036$ $\langle r_{13}^2 \rangle^{1/2} = 3.582 \pm 0.021$ $\langle r_{23}^2 \rangle^{1/2} = 3.072 \pm 0.021$
sss	$1604.9 \pm 1.3$	$\delta_{12} = \delta_{13} = \delta_{23}$ $= 9.91 \pm 0.89$	$\langle r_{12}^2 \rangle^{1/2} = \langle r_{13}^2 \rangle^{1/2}$ $\langle r_{23}^2 \rangle^{1/2} = 3.557 \pm 0.026$
ssu	$1444.9 \pm 0.7$	$\delta_{12} = 9.97 \pm 0.85$ $\delta_{13} = \delta_{23}$ $= 6.34 \pm 0.80$	$\langle r_{12}^2 \rangle^{1/2} = 3.587 \pm 0.020$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 3.996 \pm 0.033$
ssc	$2704.8 \pm 1.8$	$\delta_{12} = 10.88 \pm 1.28$ $\delta_{13} = \delta_{23}$ $= 17.66 \pm 1.61$	$\langle r_{12}^2 \rangle^{1/2} = 3.458 \pm 0.033$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 2.996 \pm 0.030$
ssb	$6040.9 \pm 2.4$	$\delta_{12} = 11.51 \pm 1.58$ $\delta_{13} = \delta_{23}$ $= 24.16 \pm 2.40$	$\langle r_{12}^2 \rangle^{1/2} = 3.367 \pm 0.020$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 2.770 \pm 0.026$
ccc	$4776.1 \pm 6.2$	$\delta_{12} = \delta_{13} = \delta_{23}$ $= 63.47 \pm 8.60$	$\langle r_{12}^2 \rangle^{1/2} = \langle r_{13}^2 \rangle^{1/2}$ $\langle r_{23}^2 \rangle^{1/2} = 2.118 \pm 0.034$
ccu	$3632.8 \pm 2.4$	$\delta_{12} = 45.25 \pm 2.90$ $\delta_{13} = \delta_{23}$ $= 11.28 \pm 1.94$	$\langle r_{12}^2 \rangle^{1/2} = 2.322 \pm 0.024$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 3.407 \pm 0.035$
ccs	$3760.7 \pm 2.4$	$\delta_{12} = 50.30 \pm 2.53$ $\delta_{13} = \delta_{23}$ $= 18.63 \pm 1.22$	$\langle r_{12}^2 \rangle^{1/2} = 2.238 \pm 0.044$ $\langle r_{13}^2 \rangle^{1/2} = \langle r_{23}^2 \rangle^{1/2}$ $= 2.842 \pm 0.030$

# Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (I)

Reference	Value (MeV)	Method
[Karliner and Rosner, 2014]	$3627 \pm 12$	
[De Rujula et al., 1975]	$3550 - 3760$	QCD-motivated quark model
J. Bjorken (unpublished draft, 1986)	$3668 \pm 62$	QCD-motivated quark model
[Anikeev et al., 2001]	3651	QCD-motivated quark model
[Fleck and Richard, 1989]	3613	Potential and bag models
[Richard, 1994]	3630	Potential model
[Korner et al., 1994]	3610	Heavy quark effective theory
[Roncaglia et al., 1995]	$3660 \pm 70$	Feynman-Hellmann + semi-empirical
[Lichtenberg et al., 1996]	3676	Mass sum rules
[Ebert et al., 1997]	3660	Relativistic quasipotential quark model
[Silvestre-Brac, 1996]	3607	Three-body Faddeev equations.
[Gerasyuta and Ivanov, 1999]	3527	Bootstrap quark model + Faddeev eqs.
[Itoh et al., 2000]	$ucc: 3649 \pm 12,$ $dcc: 3644 \pm 12$	Quark model
[Kiselev and Likhoded, 2002a]	$3480 \pm 50$	Potential approach + QCD sum rules
[Narodetskii and Trusov, 2002]	3690	Nonperturbative string
[Ebert et al., 2002]	3620	Relativistic quark-diquark

# Comparison of predictions for $M(\Xi_{cc})$ from [Karliner and Rosner, 2014] (II)

Reference	Value (MeV)	Method
[He et al., 2004]	3520	Bag model
[Richard and Stancu, 2005]	3643	Potential model
[Migura et al., 2006]	3642	Relativistic quark model + Bethe-Salpeter
[Albertus et al., 2007b]	$3612^{+17}$	Variational
[Roberts and Pervin, 2008]	3678	Quark model
[Weng et al., 2011]	$3540 \pm 20$	Instantaneous approx. + Bethe-Salpeter
[Zhang and Huang, 2008]	$4260 \pm 190$	QCD sum rules
[Lewis et al., 2001]	$3608(15)_{(35)}^{(13)},$ $3595(12)_{(22)}^{(21)}$	Quenched lattice
[Flynn et al., 2003]	$3549(13)(19)(92)$	Quenched lattice
[Liu et al., 2010]	$3665 \pm 17 \pm 14_{-78}^{+0}$	Lattice, domain-wall + KS fermions
[Namekawa, 2012]	$3603(15)(16)$	Lattice, $N_f = 2 + 1$
[Alexandrou et al., 2012]	$3513(23)(14)$	LGT, twisted mass ferm., $m_\pi = 260$ MeV
[Briceno et al., 2012]	$3595(39)(20)(6)$	LGT, $N_f = 2 + 1$ , $m_\pi = 200$ MeV
[Alexandrou et al., 2014]	$3568(14)(19)(1)$	LGT, $N_f = 2 + 1$ , $m_\pi = 210$ MeV

# Conclusions on spectroscopy

- Potential model heavy diquark-light quark allows to predict the DHB spectrum including high excitations.
- The corrections on finite diquark size improve an agreement with experiment.
- Three-body description with two body Cornell type potential is in an good agreement with the experiment for the ground state. However, within this model it is quite difficult to predict the masses of excited states.
- Maybe, maybe there is a more simple way to obtain the DHB spectrum (KR).

# Total width within OPE

$$\Gamma_{\Xi_{cc}} = \frac{1}{2M_{\Xi_{cc}}} \langle \Xi_{cc}^{\diamond} | \mathcal{T} | \Xi_{cc}^{\diamond} \rangle$$

$$\langle \Xi_{cc} | \Xi_{cc} \rangle = 2EV$$

$$\mathcal{T} = \Im m \int d^4x \{ \mathcal{T} H_{eff}(x) H_{eff}(0) \}$$

where  $H_{eff}$  is the standard effective hamiltonian describing the low energy weak interactions of initial quarks with the decay products. For the transition of  $c$ -quark,  $u$ -quark and the quarks  $q_{1,2}$  with the charge  $-1/3$ , the lagrangian has the form

$$H_{eff} = \frac{G_F}{2\sqrt{2}} V_{uq_1} V_{cq_1}^* [C_+(\mu)O_+ + C_-(\mu)O_-] + \text{h.c.}$$

where  $V$  is the matrix of mixing between the charged currents, and

$$O_{\pm} = [\bar{q}_{1\alpha} \gamma_{\nu} (1 - \gamma_5) c_{\beta}] [\bar{u}_{\gamma} \gamma^{\nu} (1 - \gamma_5) q_{2\delta}] (\delta_{\alpha\beta} \delta_{\gamma\delta} \pm \delta_{\alpha\delta} \delta_{\gamma\beta}),$$

$\alpha, \beta$  are color states of quarks and

$$C_+ = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{\frac{6}{33-2n_f}}, \quad C_- = \left[ \frac{\alpha_s(M_W)}{\alpha_s(\mu)} \right]^{\frac{-12}{33-2n_f}}$$

where  $n_f$  is the number of flavors.

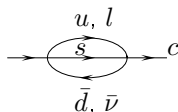
# OPE for the transition operator $\mathcal{T}$

$$\mathcal{T} = C_1(\mu)\bar{c}c + \frac{1}{m_c^2}C_2(\mu)\bar{c}g\sigma_{\mu\nu}G^{\mu\nu}c + \frac{1}{m_c^3}O(1).$$

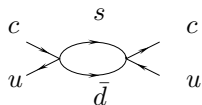
Main features:

- $\bar{c}c$  — spectator decays of  $c$ -quarks;
- no operators of dimension 4 contribute;
- the only operator of dimension 5 ;
- Pauli interference (operators of dimension 6) essentially contribute to  $\Xi_{cc}^{++}$  life time;
- weak scattering (operators of dimension 6) essentially contribute to  $\Xi_{cc}^+$  life time.

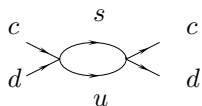
Spectator contribution:



Pauli interference:



Weak scattering:



# Model parameters and life time estimation

$$m_c, m_q, M(\Xi_{cc}^{++}), M(\Xi_{cc}^+), T \text{ and } \psi_{dd}(0)$$

- $m_c = 1.6 \text{ GeV}$  — the pole  $c$ -quark mass (lifetime and semileptonic decays of  $D^0$  meson).
- $T = 0.4 \text{ GeV}$  — the kinetic energy of diquark and light quark (potential models).
- $M(\Xi_{cc}^{++}) \approx M(\Xi_{cc}^+) \approx 3.56 \text{ GeV}$  — mean values (PM and SR).
- $\psi_{dd}(0) = 0.17 \text{ GeV}^{3/2}$

$$\tau(\Xi_{cc}^{++}) = 0.48 \text{ ps} \quad \tau(\Xi_{cc}^+) = 0.12 \text{ ps}$$

# Dependence on parameters values

The lifetime and inclusive widths of  $\Xi_{cc}^{++}$  baryon

Parameters, GeV	$\sum c \rightarrow s, \text{ps}^{-1}$	PI, $\text{ps}^{-1}$	$\tau_{\Xi_{cc}^{++}}, \text{ps}$
$m_c = 1.35, m_s = 0.15$	1.638	-0.616	0.99
$m_c = 1.6, m_s = 0.45$	2.397	-0.560	0.56
$m_c = 1.55, m_s = 0.2$	3.104	-0.874	0.45

The lifetime and inclusive widths of  $\Xi_{cc}^+$  baryon.

Parameters, GeV	$\sum c \rightarrow s, \text{ps}^{-1}$	WS, $\text{ps}^{-1}$	$\tau_{\Xi_{cc}^+}, \text{ps}$
$m_c = 1.35, m_s = 0.15$	1.638	1.297	0.34
$m_c = 1.6, m_s = 0.45$	2.397	2.563	0.20
$m_c = 1.55, m_s = 0.2$	3.104	1.776	0.20

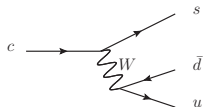
The lifetime and inclusive widths of  $\Omega_{cc}^+$  baryon.

Parameters, GeV	$\sum c \rightarrow s, \text{ps}^{-1}$	PI, $\text{ps}^{-1}$	$\tau_{\Omega_{cc}^+}, \text{ps}$
$m_c = 1.35, m_s = 0.15$	1.638	1.780	0.30
$m_c = 1.6, m_s = 0.45$	2.397	0.506	0.34
$m_c = 1.55, m_s = 0.2$	3.104	1.077	0.24

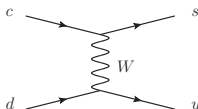


# Double heavy baryons decays

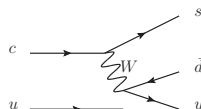
Spectator mechanism



Weak scattering



Pauli interference



The spectator mechanism does not work.

Mode or decay mechanism	Width, $ps^{-1}$	Contribution, % ( $\Xi_{cc}^{++}$ )	Contribution, % ( $\Xi_{cc}^+$ )
$c \rightarrow sdu$	2.648	127	31
$c \rightarrow se^+\nu$	0.380	18	4.2
PI	-1.317	-63	-
WS	5.254	-	60.6
$\Gamma_{\Xi_{cc}^{++}}$	2.089	100	-
$\Gamma_{\Xi_{cc}^+}$	8.660	-	100

$$\tau(\Xi_{cc}^{++}) = 0.48 \text{ ps} \quad \tau(\Xi_{cc}^+) = 0.12 \text{ ps}$$

# Why lifetimes are very important

The contributions of different terms to the life time essentially depend on baryon composition (40-50%).

The lifetimes of doubly heavy baryons [Kiselev and Likhoded, 2002a, Kiselev et al., 2000, Kiselev et al., 1999].

baryon	$\tau$ , ps	baryon	$\tau$ , ps	baryon	$\tau$ , ps
$\Xi_{cc}^{++}$	$0.46 \pm 0.05$	$\Xi_{bc}^+$	$0.30 \pm 0.04$	$\Xi_{bb}^0$	$0.79 \pm 0.02$
$\Xi_{cc}^+$	$0.16 \pm 0.05$	$\Xi_{bc}^0$	$0.27 \pm 0.03$	$\Xi_{bb}^-$	$0.80 \pm 0.02$
$\Omega_{cc}^+$	$0.27 \pm 0.06$	$\Omega_{bc}^0$	$0.22 \pm 0.04$	$\Omega_{bb}^-$	$0.80 \pm 0.02$

The strong splitting of lifetimes contributions of nonspectator terms, especially in the presence of charmed quark:

$$\begin{aligned}
 \tau[\Xi_{cc}^{++}] &> \tau[\Omega_{cc}^+] &> \tau[\Xi_{cc}^+], \\
 \tau[\Xi_{bc}^+] &> \tau[\Xi_{bc}^0] &> \tau[\Omega_{bc}^0], \\
 \tau[\Xi_{bb}^-] &\approx \tau[\Omega_{bb}^-] &> \tau[\Xi_{bb}^0].
 \end{aligned}$$

The measurements of doubly heavy baryons would be the crucial test of the OPE approach.

# Exclusive decays

The formfactor of decay for the baryon with the spin  $\frac{1}{2}$  into the baryon with the spin  $\frac{1}{2}$  is expressed in the general form as follows:

$$\langle H_F(p_F) | J_\mu | H_I(p_I) \rangle = \bar{u}(p_F) \{ \gamma_\mu G_1^V + v_\mu^I G_2^V + v_\mu^F G_3^V + \gamma_5 (\gamma_\mu G_1^A + v_\mu^I G_2^A + v_\mu^F G_3^A) \} u(p_I).$$

At small recoils  $v^i \sim v^f$  and  $v^i \cdot v^f = w \sim 1$ . This is why only two of six form factors are not suppressed by heavy quark mass, namely

$$G_1^V = G_1^A = \xi(w),$$

where  $\xi(w)$  is so-called Isgur-Wise form factor. CVC gives  $\xi(1) = 1$ .

$$\xi(w) = \frac{\xi(1)}{1 - q^2/m_{\text{pol}}^2}$$

$$m_{\text{pol}}(b \rightarrow c) = 6.3 \text{ GeV}$$

$$m_{\text{pol}}(c \rightarrow s) = 1.85 \text{ GeV}$$

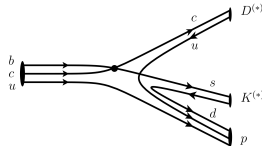
# Examples of exclusive decays

Estimation within SR [Gershtein et al., 1999a]

Mode	Br (%)	Mode	Br (%)
$\Xi_{bb}^{\diamond} \rightarrow \Xi_{bc}^{\diamond} l \bar{\nu}_l$	14.9	$\Xi_{bc}^{++} \rightarrow \Xi_{cc}^{++} l \bar{\nu}_l$	4.9
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^{+} l \bar{\nu}_l$	4.6	$\Xi_{bc}^{+} \rightarrow \Xi_b^0 l \bar{\nu}_l$	4.4
$\Xi_{bc}^0 \rightarrow \Xi_b^{-} l \bar{\nu}_l$	4.1	$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} l \bar{\nu}_l$	16.8
$\Xi_{cc}^{+} \rightarrow \Xi_c^0 l \bar{\nu}_l$	7.5	$\Xi_{bb}^{\diamond} \rightarrow \Xi_{bc}^{\diamond} \pi^{-}$	2.2
$\Xi_{bb}^{\diamond} \rightarrow \Xi_{bc}^{\diamond} \rho^{-}$	5.7	$\Xi_{bc}^{+} \rightarrow \Xi_{cc}^{++} \pi^{-}$	0.7
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^{+} \pi^{-}$	0.7	$\Xi_{bc}^{+} \rightarrow \Xi_{cc}^{+} \rho^{-}$	1.9
$\Xi_{bc}^0 \rightarrow \Xi_{cc}^{\rho} \rho^{-}$	1.7	$\Xi_{bc}^{+} \rightarrow \Xi_b^0 \pi^{+}$	7.7
$\Xi_{bc}^0 \rightarrow \Xi_b^{-} \pi^{+}$	7.1	$\Xi_{bc}^{+} \rightarrow \Xi_b^0 \rho^{+}$	21.7
$\Xi_{bc}^0 \rightarrow \Xi_b^{-} \rho^{+}$	20.1	$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} \pi^{+}$	15.7
$\Xi_{cc}^{+} \rightarrow \Xi_c^0 \pi^{+}$	11.2	$\Xi_{cc}^{++} \rightarrow \Xi_c^{+} \rho^{+}$	46.8
$\Xi_{cc}^{+} \rightarrow \Xi_c^0 \rho^{+}$	33.6		

This decay could be observed:

$$\Xi_{bc} \rightarrow D^{(*)} K^{(*)} p \quad (Br \sim 0.1\%)$$



More better than

$$\Xi_{bc} \rightarrow \Xi_{cc} + X \rightarrow \Xi_c + X \rightarrow \Xi + X.$$

It is very difficult to find the "golden decay mode" for doubly heavy baryons.

# How to produce doubly heavy baryons

Two steps:

- To produce doubly heavy diquark in a hard process in the color triplet state.
- To transform it into the baryon.

The strategy is analogous to the used one for estimation of  $J/\psi$  or  $B_c$  production cross section:

$$(Q_1 \bar{Q}_2)_{1_c} \Rightarrow [Q_1 Q_2]_{\bar{3}_c}$$

$$|R_{1_c}(0)|^2 \Rightarrow |R_{\bar{3}_c}(0)|^2$$

Quarks in  $\bar{3}_c$  attract each other and

$$|R(0)_{\bar{3}_c}^{Q_1 Q_2}|^2 \approx \frac{|R(0)_{1_c}^{Q_1 \bar{Q}_2}|^2}{4}$$

*Some research groups also use  $[QQ]_{6_c}$  as a baryon pattern. Seems, not good idea, because quarks in  $6_c$  repulse each other.*

$[QQ]_{\bar{3}_c}$  looks like a "heavy antiquark", and therefore we could try to use a fragmentation model to transform it to the doubly heavy baryon:

$$[QQ]_{\bar{3}_c}(\vec{p}) \xrightarrow{D(z)dz} H(z\vec{p})$$

Several important problems:

- Why  $[Q_1 Q_2]_{\bar{3}_c}$  do not dissociate to mesons?
- What is the probability value for  $(QQ)_{\bar{3}_c}$  to create the doubly heavy baryon?
- What is the shape of fragmentation function  $[Q_1 Q_2]_{\bar{3}_c} \rightarrow (Q_1 Q_2 q)$ ?

# $bc$ -diquark production amplitude

$$A^{S J j_z} = \int T_{b\bar{b}c\bar{c}}^{S s_z}(p_i, k(\vec{q})) \cdot \left( \Psi_{[bc]_{\bar{3}_c}}^{L l_z}(\vec{q}) \right)^* \cdot C_{s_z l_z}^{J j_z} \frac{d^3 \vec{q}}{(2\pi)^3},$$

where  $T_{b\bar{b}c\bar{c}}^{S s_z}$  is an amplitude of the hard production of two heavy quark pairs;

$\Psi_{\bar{b}c}^{L l_z}$  is the diquark wave function (color antitriplet);

$J$  and  $j_z$  are the total angular momentum and its projection on  $z$ -axis in the  $[bc]_{\bar{3}_c}$  rest frame;

$L$  and  $l_z$  are the orbital angular momentum of  $bc$ -diquark and its projection on  $z$ -axis;

$S$  and  $s_z$  are  $bc$ -diquark spin and its projection;

$C_{s_z l_z}^{J j_z}$  are Clebsh-Gordon coefficients;

$p_i$  are four momenta of diquark,  $\bar{b}$  quark and  $\bar{c}$  quark;

$\vec{q}$  is three momentum of  $b$ -quark in the  $bc$ -diquark rest frame (in this frame  $(0, \vec{q}) = k(\vec{q})$ ).

Under assumption of small dependence of  $T_{b\bar{b}c\bar{c}}^{S s_z}$  on  $k(\vec{q})$

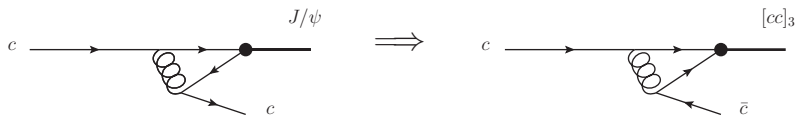
$$A \sim \int d^3 q \Psi^*(\vec{q}) \left\{ T(p_i, \vec{q})|_{\vec{q}=0} + \vec{q} \frac{\partial}{\partial \vec{q}} T(p_i, \vec{q})|_{\vec{q}=0} + \dots \right\}$$

and, particularly, for the  $S$ -wave states

$$A \sim R_S(0) \cdot T_{b\bar{b}c\bar{c}}(p_i)|_{\vec{q}=0},$$

where  $R_S(0)$  is a value of radial wave function at origin.

# Fragmentation to diquark



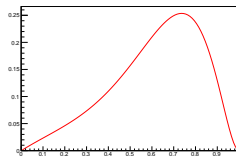
For  $e^+e^-$ -annihilation at  $4m_c^2/s \ll 1$  the fragmentation model can be applied:

$$Q(\vec{p}) \xrightarrow{D(z)dz} [QQ]_{\bar{3}_c}(z\vec{p})$$

$$D_{c \rightarrow cc}(z) = \frac{2}{9\pi} \frac{|R_{cc}(0)|^2}{m_c^3} \times \\ \times \alpha_s^2(4m_c^2) \frac{z(1-z)^2}{(2-z)^6} (16 - 32z + 72z^2 - 32z^3 + 5z^4),$$

An absolute analog of the fragmentation function for  $c \rightarrow J/\psi + c$ . [Falk et al., 1994]

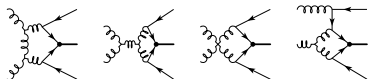
$D_{c \rightarrow cc}(z)$  has a common "Peterson-like" shape:



# Diquark production in the hadronic interaction

Many non-fragmentational diagrams contribute to the hadronic production:

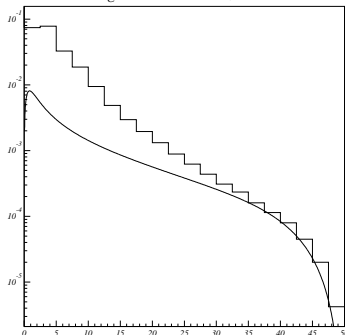
$$gg \rightarrow (cc)\bar{3}_c + X$$



$$q\bar{q} \rightarrow (cc)\bar{3}_c + X$$



$d\sigma(gg \rightarrow [cc]\bar{3}_c + X)/dp_T, \sqrt{s_{gg}} = 100 \text{ GeV}, \text{ pb/GeV}$



GeV

Histogram: full set of diagrams  
Curve: fragmentation approach



# Diquark *Rightarrow* baryon

Diquark production ( $k \sim 0.2 \div 0.3$ ):

- $\sigma([bc]_{\bar{3}_c}) \sim k \cdot \sigma(B_c)$
- $\sigma([cc]_{\bar{3}_c}) \sim k \cdot \sigma^{\text{SPS}}(J/\psi + c)$
- $\sigma([bb]_{\bar{3}_c}) \sim k \cdot \sigma^{\text{SPS}}(\Upsilon + b)$
- Seems, DPS does not contribute to the double heavy diquark production.

The Peterson-like FF can be used to simulate the transformation of diquark to baryon [Peterson et al., 1983]:

$$D(z) \sim \frac{1}{z \left(1 - \frac{1}{z} - \frac{\epsilon}{1-z}\right)^2},$$

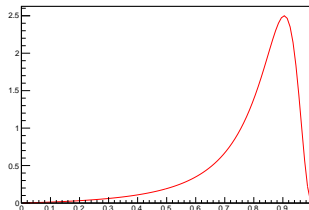
where  $\epsilon \sim \frac{m_q^2}{M_{QQ}^2}$ ,  $m_q \sim \Lambda_{\text{QCD}}$

The normalization is unknown:

$$P([QQ]_{\bar{3}_c} \rightarrow \Xi_{QQ}) \leq 1$$

[Baranov, 1997, Berezhnoy et al., 1996, Berezhnoy et al., 1998, Chang et al., 2006, Chang et al., 2007, Zhang et al., 2011, Chen et al., 2014]

Quite sharp even for  $\Xi_{cc}$ :



What we could expect:

- $\sigma(\Xi_{QQ}) \lesssim 0.3 \cdot \sigma^{\text{SPS}}((Q\bar{Q}) + Q)$ .
- $\sigma(\Xi_{bc}) \lesssim 0.3 \cdot \sigma(B_c)$ .
- $p_T$ -distribution for  $\Xi_{bc}$  softer than for  $B_c$ -meson.

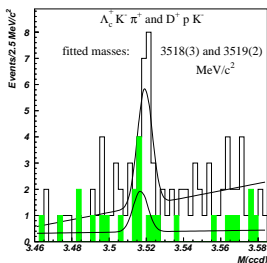
# SELEX results

Peak interpreted as  $\Xi_{cc}^+$  is seen at fixed target experiment SELEX for baryon beams only ( $\Sigma^-$  and  $p$ , not  $\pi^-$ ) in modes  $\Xi_{cc}^+ \rightarrow \Lambda_c K^- \pi^+$  and  $\Xi_{cc}^+ \rightarrow p D^+ K^-$  [Ocherashvili et al., 2005].

$$\frac{\Gamma(p D^+ K^-)}{\Gamma(\Lambda_c K^- \pi^+)} = 0.36 \pm 0.21 \quad \tau(\Xi_{cc}^+) < 0.033 \text{ ps}$$

$$N(\Xi_{cc}^+)/N(\Lambda_c) \approx 20\%$$

No confirmation from other experiments.



The resonance observed by SELEX and interpreted as  $\Xi_{cc}$  have an extremely short lifetime and an extremely large cross-section.

For first time these problems were discussed in [Kiselev and Likhoded, 2002b].

# Conclusions

- There are two main approaches to predict HDB masses: quark-diquark potential models and the three-body model with Cornell pair potentials. Both approaches successfully predicted the mass of  $\Xi_{cc}$  ground state. The quark-diquark models allow also to obtain the full particle spectrum including high excitations. Maybe the more simple way exists [KR].
- It would be very interesting to observe  $\Xi_{cc}^+$  and to compare the life times of  $\Xi_{cc}^{++}$  and  $\Xi_{cc}^+$ , because it would be the crucial test of the OPE method.
- The  $\Xi_{bc}$  production cross section should be comparable to the cross section of  $B_c$ -meson production. This is why we hope, that  $\Xi_{bc}$  baryon will also be observed at LHC.

Many thanks for your attention!

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