Inclusive search for Ξ_{bc}

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The 3rd Workshop of Heavy Flavor Physics and QCD (May 1-3, 2021)



• It is important to study Ξ_{bc}

• We will show it is reachable at LHCb

Contents

• We propose a inclusive strategy to find Ξ_{bc}

The quark model

- Old myth
- New life





Murry Gell-Mann 1969 Nobel Prize for physics

Three new milestones

Observation of tetraquarks \bullet

[BESIII, *Phys.Rev.Lett.* 110 (2013) 252001]

Observation of pentaguarks \bullet

[LHCb, *Phys.Rev.Lett.* 115 (2015) 072001]

Observation of a double-charm baryon Ξ_{cc}^{++} lacksquare[LHCb, *Phys.Rev.Lett.* 119 (2017) 112001]

The *Physics* 2013 "Highlights of the Year" (rank 1st)

The *Physics World* 2015 "top-10 breakthroughs"

国家科技部"2017年度中国科学十大进展"

"Periodic table of the hadrons"

Periodic Table of the Elements										2 Helium 4.003							
3 Li Lithium 6.941	4 Beryllium 9.012		5 B Boron 10.811 Boron 12.011 Boron 12.011 Boron 14.007 Boron 14.007 Boron 14.007 Boron 15.999 Boron 15.999 Boron 18.998 Boron 18.									10 Neon 20.180					
11 Na Sodium 22.990	12 Magnesium 24.305											13 Aluminum 26.982	14 Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Manganese 54.938	26 Fe Iron 55.845	27 Cobalt 58.933	28 Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Gallium 69.723	32 Germanium 72.631	33 Assenic 74.922	34 Selenium 78.972	35 Br Bromine 79.904	36 Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Niobium 92.906	42 Molybdenum 95.95	43 TC Technetium 98.907	44 Ru Ruthenium 101.07	45 Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 Indium 114.818	50 Sn 118.711	51 Sb Antimony 121.760	52 Tellurium 127.6	53 Iodine 126.904	54 Xenon 131.294
55 Cs Cesium 132.905	56 Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Osmium 190.23	77 Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 TI Thallium 204.383	82 Pb Lead 207.2	83 Bismuth 208.980	84 PO Polonium [208.982]	85 At Astatine 209.987	86 Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 HS Hassium [269]	109 Meitnerium [268]	110 DS Darmstadtium [269]	111 Rg Roentgenium [272]	112 Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Moscovium unknown	116 LV Livermorium [298]	117 TS Tennessine unknown	118 Oganesson unknown
	57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 Lanthanum 138,995 Cerium 140,116 Promethium 140,216 Ndd Promethium 144,242 63 64 65 66 67 68 69 70 71 Lanthanum 138,995 Lanthanum 144,242 Neodymium 144,242 Neodymium 144,242 Neodymium 150,36 Samarium 151,964 157,255 158,925 66 67 68 69 70 71 Lutetium 144,913																
89 90 91 92 93 94 94 95 96 97 98 99 100 101 102 103										.r encium 62]							
	Alkali Metal Alkaline Basic Metal Semimetal Nonmetal Halogen Gas Lanthanide Actinide																

$\pi, K,$	D	В	η_c	B _c	η_b			
p, n, 	Λ_c	Λ_b				Ecc	Ξ_{bc}	Ξ
	X (2900)		Z_c			T _{cc}	T_{bc}	T
			(P_c)					

 Z_c, P_c : a new period

 Ξ_{cc} : a new main group



Beyond stamp collecting

 \bullet hadrons

 \bullet and also electroweak dynamics

> e.g., doubly-heavy baryons have a unique structure, a bound state of a heavy 'diquark' and a light quark

analogous to a heavy meson, but also different: bosonic, sizable heavy element

threshold and thus decay weakly

Because of color confinement, properties of quarks are studied via

See Prof. Xiang Liu's talk

b c

Different types of hadrons provide different visual angles into QCD q

e.g., the double-bottom tetraquark $T^{\{bb\}}_{[qq']}$ is expected to be below [Eichten,Quigg,1707.09575]



Who is to be shot next?

$\pi, K,$	D	В	η_c	B _c	η_b			
p, n, 	Λ_c	Λ_b				Ξ_{cc}	Ξ_{bc}	Ξ_{bb}
	X (2900)		Z_{c}			T_{cc}	T_{bc}	T _{bb}
			P_c					

T_{cc}: [QQ, F.S.Yu,2008.08026]

 Ξ_{bc} : this talk

$\sigma(\Xi_{bc}) = 37 \text{ nb} \text{ at } 14 \text{ TeV LHCb}$

[X.G.Wu, et al 1101.1130]

	2011	2012	2018	2023	2029	2035
LHCb	Ru	ın I	Run II	Run III	Run IV	Run V
Integrated Iuminosity	1 fb ⁻¹	3 fb ⁻¹	9 fb ⁻¹	23 fb ⁻¹	50 fb ⁻¹	300 fb

Trillions of Ξ_{bc} will be produced @ LHCb Run3.







Difficulties in experimental searches

- Production rate lacksquare
- Detection efficiency -- small exclusive branching ratios \bullet

channels	$\Gamma/~{\rm GeV}$	\mathcal{B}	channels	$\Gamma/~{ m GeV}$	B
$\Xi_{bc}^+ \to \Lambda_b^0 \pi^+$	5.74×10^{-15}	2.13×10^{-3}	$\Xi_{bc}^+ \to \Lambda_b^0 \rho^+$	1.55×10^{-14}	$5.77 imes 10^{-3}$
$\Xi_{bc}^+ \to \Lambda_b^0 a_1^+$	5.85×10^{-15}	$2.17 imes 10^{-3}$	$\Xi_{bc}^+ \to \Lambda_b^0 K^+$	5.21×10^{-16}	$1.93 imes 10^{-4}$
$\Xi_{bc}^+ \to \Lambda_b^0 K^{*+}$	7.32×10^{-16}	2.71×10^{-4}			
$\Xi_{bc}^{+} \to \Sigma_{b}^{0} \pi^{+}$	3.08×10^{-15}	1.14×10^{-3}	$\Xi_{bc}^+ \to \Sigma_b^0 \rho^+$	1.30×10^{-14}	$4.81 imes 10^{-3}$
$\Xi_{bc}^+\to \Sigma_b^0 K^{*+}$	6.50×10^{-16}	2.41×10^{-4}	$\Xi_{bc}^+ \to \Sigma_b^0 K^+$	2.32×10^{-16}	$8.62 imes 10^{-5}$
$\Xi_{bc}^+\to \Xi_b^0\pi^+$	9.42×10^{-14}	3.49×10^{-2}	$\Xi_{bc}^+ \to \Xi_b^0 \rho^+$	1.91×10^{-13}	$7.09 imes 10^{-2}$
$\Xi_{bc}^+\to \Xi_b^0 K^{*+}$	7.55×10^{-15}	2.80×10^{-3}	$\Xi_{bc}^+ \to \Xi_b^0 K^+$	8.16×10^{-15}	$3.03 imes 10^{-3}$
$\Xi_{bc}^+\to \Xi_b^{\prime 0}\pi^+$	5.47×10^{-14}	2.03×10^{-2}	$\Xi_{bc}^+\to \Xi_b^{\prime 0}\rho^+$	2.01×10^{-13}	7.44×10^{-2}
$\Xi_{bc}^+\to \Xi_b^{\prime 0}K^{*+}$	8.53×10^{-15}	3.16×10^{-3}	$\Xi_{bc}^+ \to \Xi_b^{\prime 0} K^+$	3.82×10^{-15}	1.42×10^{-3}

[W. Wang, F.S. Yu, Z.X. Zhao, 1707.02834]

• First experimental attempt

$$\frac{\sigma(\Xi_{bc}^{0})}{\sigma(\Lambda_{b}^{0})} \frac{B(\Xi_{bc}^{0} \to \Lambda_{c}^{+}\pi^{-})}{B(\Lambda_{b}^{0} \to \Lambda_{c}^{+}\pi^{-})} < [0.5, 2.5] \times 10^{-4}$$
$$\frac{\sigma(\Xi_{bc}^{0})}{\sigma(\Lambda_{b}^{0})} \frac{B(\Xi_{bc}^{0} \to \Xi_{c}^{+}\pi^{-})}{B(\Lambda_{b}^{0} \to \Xi_{c}^{+}\pi^{-})} < [1.4, 6.9] \times 10^{-3}$$

[LHCb, 2104.04759]

See Prof. Yuehong Xie's talk



Generally, inclusive decays have (1) larger branching ratios but (2) lower detection efficiencies

Basically impossible at hadron colliders

• However, for $\Xi_{bc} \to \Xi_{cc} + X$, the efficiency can be large by making use of the inform of displaced vertex, because Ξ_{bc} can only decay weakly

Inspired by the proposal to search for Ξ_{bb} via $\Xi_{bb} \rightarrow B_c + X$ [Gershon, Poluektov, 1810.06657]

- Ξ_{bc} is (almost) the only source for displaced Ξ_{cc} 's
- The $B_c \rightarrow \Xi_{cc} + X$ decay is highly suppressed

A novel approach — — inclusive Ξ_{bc} search

See Prof. Xiaolong Wang's talk



- First important fact: $\Xi_{bc} \to \Xi_{cc} + X = \Xi_{bc} \to X_{cc}$ X_{cc} include excited states of Ξ_{cc} , which still decay into Ξ_{cc}
- If we regard the heavy diquarks χ_{bc} and χ_{cc} as elementary objects, the decay at the quark-diquark diquark level is

$$\chi_{bc} \to \chi_{cc} + \ell^- \bar{\nu}, \chi_{cc} +$$

It is reasonable because $r_{OO'} \sim 1/(m_O v) \ll 1/\Lambda_{QCD}$ [e.g., Brodsky, Guo, Hanhart, Meissner, 1101.1983]

- By making use of OPE, the inclusive decay width can be expanded by powers of $1/M_{OO'}$ within the Heavy Diquark Effective Theory
- At the leading power

$$B(\Xi_{bc} \to X_{cc}) = B(\chi_{bc} \to \chi_{cc} + \ell)$$

Calculation of $\Xi_{bc} \rightarrow \Xi_{cc} + X$



 $+ \bar{q}q'$

[Y.J.Shi, W.Wang, Z.X.Zhao, Meissner, 2002.02785]

 $\gamma^{-}\bar{\nu}, \chi_{cc} + \bar{q}q') + \mathcal{O}(1/M_{OO'})$

Calculation of $\Xi_{bc} \rightarrow \Xi_{cc} + X$

- The key issue is the 2-diquark-2-fermion interaction vertex, i.e. the $\chi_{bc} \rightarrow \chi_{cc}$ diquark current
- Assuming the heavy quark symmetry, the diquark current is matched from the quark current to be $\Gamma^{\mu}_{\rho\sigma} = \left[i \left(g_{\rho\sigma} \overleftarrow{\partial^{\mu}} - g^{\mu}_{\rho} \overleftarrow{\partial}_{\sigma} - g_{\rho\sigma} \partial^{\mu} + \partial_{\rho} g^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu} + g^{\mu}_{\rho\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} + g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\nu\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\rho\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\rho\sigma} \left(\overleftarrow{\partial}_{\sigma} - g^{\mu}_{\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_{\sigma} \left(\overleftarrow{\partial}_{\sigma} \partial^{\mu}_{\sigma} \right) + \epsilon^{\mu}_$

with
$$\mathcal{I}(\ldots) \equiv 1$$

- If we consider the heavy quark mass effects, the structure is more complicated, and $\mathcal{I}(\ldots)$ is given by the right curve
- The model matching is to be improved

$$\left(\overleftarrow{\partial^{\nu}} - \partial^{\nu} \right) \right] \sqrt{\frac{1}{2}} \mathscr{I} \left(m_c |\mathbf{v}' - \mathbf{v}| \right)$$



 \mathcal{X}_{bc}





 \mathcal{X}_{cc}

Calculation of $\Xi_{bc} \to \Xi_{cc} + X$ (Preliminary)

Numerical result for the decay width

$$\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (3.9 \pm 0.1 \pm$$

Uncertainties from Quark mass, model independence, power correction

• The branching ratio is

$$B(\Xi_{bc} \to \Xi_{cc} + X) \approx 12\%$$

• Ξ_{cc}^{++} fragmentation suffers a factor of 1/2 (Assuming the u and d quark saturate the fragmentation)

$$B(\Xi_{bc} \to \Xi_{cc}^{++} + X) = 6\% \times \frac{1}{2} \left(\frac{\tau_{\Xi_{bc}^{+}}}{200 \text{fs}} + \frac{\tau_{\Xi_{bc}^{0}}}{200 \text{fs}} \right) = 6\% \times \left(\frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^{0}}}{400 \text{fs}} \right)$$

Lifetime [H.Y.Cheng, F.R.Xu, 1903.08148] ullet

93fs < $\tau(\Xi_{bc}^{0})$ < 108 fs, 409 fs <

- $1.0 \pm 1.2) \times 10^{-13}$ GeV

$$\frac{\tau_{\Xi_{bc}}}{200 \mathrm{fs}}$$

<
$$\tau(\Xi_{bc}^+)$$
 < 607 fs

Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

- Estimated of signal signal events
 - $N(\Xi_{hc} \rightarrow \Xi_{cc}^{++} + X) =$

Three ingredients:

1. Number of signals of Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

3. Branching fraction of inclusive decay of $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$

$$= N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X)$$

(Both Ξ_{bc}^{0} and Ξ_{bc}^{+} decay equally to Ξ_{cc}^{++} and thus Identical detection efficiency)



1.Number of signals of Ξ_{cc}^{++}



	2011	2012	2018	2023	2029	2035
LHCb	Ru	in I	Run II	Run III	Run IV	Run V
Integrated Iuminosity	1 fb ⁻¹	3 fb ⁻¹	9 fb ⁻¹	23 fb ⁻¹	50 fb ⁻¹	300 fb-

		LHCb	
Decay mode	$23\mathrm{fb}^{-1}$	$50\mathrm{fb}^{-1}$	$300\mathrm{fb}^{-1}$
$\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$	7k	15k	90k
$\Xi_{bc}^+ \to J/\psi \Xi_c^+$	50	100	600

Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

J.B.He

• Data of 9 fb^{-1} Run 1+2



00 fb⁻¹

Belle II $50 \,\mathrm{ab}^{-1}$ <6k Z.W.Yang _____

• Events estimated for 23 fb^{-1} (Run III) 7000 $\times (1600 + 600) \approx 10000$ 1600



Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced Ξ_{cc}^{++}

2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$

[X.G.Wu et al, 1101.1130]

respectively. In the calculations, we adopt $p_T > 4$ GeV and |y| < 1.5.

	Ē	cc	Έ	Ξ_{bc}	Ξ_{bb}		
	$\sqrt{S} = 7.0 \text{ TeV}$	$\sqrt{S} = 14.0 \text{ TeV}$	$\sqrt{S} = 7.0 \text{ TeV}$	$\sqrt{S} = 14.0 \text{ TeV}$	$\sqrt{S} = 7.0 \text{ TeV}$	$\sqrt{S} = 14.0 \text{ TeV}$	
$[{}^{3}S_{1}]$	38.11	69.40	16.7	28.55	0.503	1.137	
$[{}^{1}S_{0}]$	9.362	17.05	3.72	6.315	0.100	0.226	
Total	47.47	86.45	20.42	34.87	0.603	1.363	

 $\sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \approx 40\%$

TABLE VI. Comparison of the total cross section (in units nb) for the hadronic production of Ξ_{cc} , Ξ_{bc} , and Ξ_{bb} at $\sqrt{S} = 7.0$ TeV and $\sqrt{S} = 14.0$ TeV, where $[{}^{3}S_{1}]$ and $[{}^{1}S_{0}]$ stand for the combined results for the diquark in spin-triplet and spin-singlet states,

Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++}$

• Final number of estimated signal events @ LHCb Run3

$$\begin{split} N(\Xi_{bc} \to \Xi_{cc}^{++} + X) &= N(\Xi_{cc}^{++}) \cdot \frac{2\sigma(\Xi_{bc})}{\sigma(\Xi_{cc})} \cdot B(\Xi_{bc} \to \Xi_{cc}^{++} + X) \\ &= 10^4 \cdot \frac{N(\Xi_{cc}^{++})}{10^4} \times 40\% \cdot \frac{2\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\%} \times 6\% \cdot \left(\frac{\tau_{\Xi_{bc}^+} + \tau_{\Xi_{bc}^0}}{400 \text{ fs}}\right) \\ &= 480 \times \frac{N(\Xi_{cc}^{++})}{10^4} \cdot \frac{\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\%} \cdot \left(\frac{\tau_{\Xi_{bc}^+} + \tau_{\Xi_{bc}^0}}{400 \text{ fs}}\right) \end{split}$$

$$E_{c}^{+} + X$$
 with displaced Ξ_{cc}^{++} (Preliminary)

Small possibility from B_c decays

- The small phase space (0.18 GeV for $\Xi_{cc}\Xi_{c}$) only allows the processes of $B_c \to \Xi_{cc} \Xi_c$, or $\Xi_{cc} \Xi_c \pi$, or $\Xi_{cc} \Xi_c$, or $\Xi_{cc} \Xi_c$
- Similar process but with a light spectator quark:
 - $Br(B^0 \to \Xi_c^- \Lambda_c^+) = (1.2 \pm 0.8) \times 10^{-3}$ $Br(B^- \to \Xi_c^0 \Lambda_c^-) = (0.95 \pm 0.23) \times 10^{-3}$







Conclusion

• We calculate $\Gamma(\Xi_{bc} \to \Xi_{cc} + X) = (3.9 \pm 0.1 \pm 1.0 \pm 1.2) \times 10^{-13}$ GeV.

• We estimate about 480 signal events to be observed @ LHC Run 3.

• We hope it is useful.

• We propose to search for Ξ_{bc} via inclusive $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with a displaced Ξ_{cc}^{++} .

Thank you!