Double-heavy baryons

Fu-Sheng Yu
Lanzhou University

LHCb implications, 19.10.2021
Key points of observations:

1. productions
2. branching fractions
3. lifetimes
Why double-heavy baryons?

• Double-charm baryons are predicted in SU(4) quark model
  De Rujula, Georgi and Glashow, 1975;
  Jaffe, J. E. Kiskis, 1976; Ponce, 1979

• A heavy ‘double-star’ system with an attached light ‘planet’, much different from light baryons

• Open a new window for QCD properties
Role of Decay in the observation

• Two problems in the exp searches: Production and Decay

\[ N \propto \sigma \cdot BR \]

• Production problem was solved at the beginning of LHC running

\[ \sigma(pp \to \Xi_{cc}) \sim \sigma(pp \to B_c) \]


• Decay properties are the key problem in the LHCb searches of doubly charmed baryons.

FSY, Sci.China.PMA, 2020

• Statistics requires: largest branching ratios and easily detected
Lifetime is important

1. Longer lifetime ⇒ Larger branching ratios
   \[ BR_i = \Gamma_i \cdot \tau \]

2. Longer lifetime ⇒ Higher efficiency to reject backgrounds in hadron colliders

- Large ambiguity in predictions
- But less ambiguity in the ratio
  \[ \tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^{+}) \]
- Recommend $\Xi_{cc}^{++}$ rather than $\Xi_{cc}^{+}$

<table>
<thead>
<tr>
<th>Literatures</th>
<th>$\Xi_{cc}^{++}$ (fs)</th>
<th>$\Xi_{cc}^{+}$ (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karliner, Rosner, 2014</td>
<td>185</td>
<td>53</td>
</tr>
<tr>
<td>Kiselev, Likhoded, 2002</td>
<td>460±50</td>
<td>160±50</td>
</tr>
<tr>
<td>Chang, Li, Li, Wang, 2007</td>
<td>670</td>
<td>250</td>
</tr>
<tr>
<td>Cheng, Shi, 2018</td>
<td>250</td>
<td>45</td>
</tr>
</tbody>
</table>
Decay amplitudes

- Short-distance contributions: factorization
- Long-distance contributions: FSI rescattering

Topologies:
- **C** quark exchange
- hadron triangle

Theoretical uncertainty is under control in the ratio of branching fractions of different processes

1703.09086
2102.00961
Discovery potentials of doubly charmed baryons*

Fu-Sheng Yu(于福升)\textsuperscript{1,2(1)}  Hua-Yu Jiang(蒋华玉)\textsuperscript{1,2}  Run-Hui Li(李润辉)\textsuperscript{3}  Cai-Dian Lü(吕才典)\textsuperscript{4,5(2)}  Wei Wang(王伟)\textsuperscript{6,3}  Zhen-Xing Zhao(赵振兴)\textsuperscript{6}

$\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ and $\Xi_{cc}^+ \pi^+$ are the most favorable decay modes

\begin{align*}
\Xi_{cc}^{++} &\rightarrow \Lambda_c^+ K^- \pi^+ \pi^+\text{ July 2017} \\
\Xi_{cc}^+ &\rightarrow \Xi_c^+ \pi^+\text{ July 2018}
\end{align*}
Double-charm baryons: $\Xi_{cc}^+, \Omega_{cc}^+$

- Decaying processes for $\Xi_{cc}^+$ and $\Omega_{cc}^+$

$$B_{cc} \rightarrow B_cP, B_cV, B_8D^{(*)}$$

$$B^R(\Xi_{cc}^+ \rightarrow \Xi_c^+\rho^0) \in [0.4\%, 2.5\%] \quad B^R(\Omega_{cc}^+ \rightarrow \Xi_c^+\bar{K}^*0) \in [0.5\%, 3.3\%]$$

- Suggestion for measurements

$\Xi_{cc}^+ \rightarrow \Lambda_c^+K^-\pi^+ \; , \; \Xi_c^+\pi^+\pi^-$

$\Omega_{cc}^+ \rightarrow \Xi_c^+K^-\pi^+$

Lifetimes:

$$\tau(\Xi_{cc}^{++}) > \tau(\Omega_{cc}^+) > \tau(\Xi_{cc}^+)$$

298fs, 200fs, 45fs

Cheng, Shi, 2018

To be observed

Run-Hui Li, 2017, 2018
**Discovery of $T_{cc}$**

\[ N_s = 117 \pm 16 \]

**Discovery potentials of double-charm tetraquarks**

We find that their production cross sections at the LHCb with $\sqrt{s} = 13$ TeV reach $O(10^4)$ pb, which indicate that the LHCb has collected $O(10^8)$ such particles. Through the decay channels of $T_{[ud]}^{(cc)} \to D^+ K^- \pi^+$ or $D^0 D^+ \gamma$ (if stable) or $T_{[ud]}^{(cc)} \to D^0 D^{*+}$ (if unstable), it is highly hopeful that they get discovered at the LHCb in the near future. We also discuss the productions and decays of the double-charm tetraquarks at future Tera-Z factories.

branching fractions of $T_{[ud]}^{(cc)}$ decays is the same as the observed $\Xi_{cc}^{++}$. Comparing with the production rates between double-charm tetraquarks and baryons, and considering around $2 \times 10^3$ events of $\Xi_{cc}^{++}$ with the current LHCb data, the signal yields of $T_{[ud]}^{(cc)}$ would be $O(10^2)$ at LHCb, and will reach $O(10^3)$ at LHCb Run III. Thus it is hopefully expected that the double-charm tetraquark will be observed in the near future. Although the production rates are smaller at the future $Z$ factories, it is also expected to be observed at the Tera-Z factories due to the smaller backgrounds.

- Correct discovery channel
- Correct signal yields

Qin, Shen, **FSY**, 2008.08026

"Highlights from the LHCb Experiment" —— Franz Muheim
"Recent LHCb results on exotic meson candidates" —— Ivan Polyakov

@ European Physical Society Conference on high energy physics 2021
**Fully reconstructed:** \( T_{cc}^+ \rightarrow D^0 D^{*+} \)

<table>
<thead>
<tr>
<th>Compared with</th>
<th>( \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ )</th>
<th>( u \leftrightarrow \bar{u}d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>( f_{\Lambda_b} / f_{B_u} \sim 0.5 )</td>
<td>( f_{T_{cc}} / f_{\Xi_{cc}} \sim 1/4 )</td>
</tr>
<tr>
<td></td>
<td>( f_{\Sigma^{(*)}<em>b} / f</em>{\Lambda_b} \sim 1 )</td>
<td></td>
</tr>
<tr>
<td>Decay</td>
<td>( Br(\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+) \mid Br(\Lambda_c^+ \rightarrow pK^- \pi^+) \mid Br(T_{cc} \rightarrow D^0 D^{<em>+}) \mid Br(D^{</em>+} \rightarrow D^0 \pi^+) \mid Br(D^0 \rightarrow K^- \pi^+)^2 )</td>
<td>one track more</td>
</tr>
<tr>
<td></td>
<td>( 10% \mid 6% \mid 1/2 \mid 2/3 \mid (4%)^2 )</td>
<td>( 1/3 )</td>
</tr>
</tbody>
</table>
|                | \( 
\rightarrow Br(T_{cc})/Br(\Xi_{cc}^{++}) \sim 1/4 
\) |

1500 events of \( \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \) \( \rightarrow \) 100 events of \( T_{cc} \)

Qin, Shen, FSY, 2008.08026
Fragmentation

- Different from ordinary heavy mesons and baryons with excited states decaying into the ground states,
- The excited cc-tetraquarks would directly decay into DD mesons, but not the ground states
- Primarily production \( \text{v.s.} \) final production
- The ground-state fragmentation fraction is

\[
\frac{f_{T_{cc}}}{f_{\Xi_{cc}}} \approx \frac{f_{ud}(\text{primary})}{f_{ud}(\text{final})} \times \frac{f_{ud}(\text{final})}{f_u} \]

\[
\frac{f_{\Lambda_c}}{f_{\Lambda_c + \Sigma_c + \Lambda_c^*}} = 0.48 \pm 0.08
\]

\[
\frac{f_{\Lambda_b^0}}{f_u + f_d}(p_T) = (1 \pm 0.061) \left[ (0.0793 \pm 0.0141) + e^{(-1.022 \pm 0.047) + (-0.107 \pm 0.002) \times p_T} \right]
\]

Belle, arXiv:1706.06791

LHCb, 1902.06794
Difficulties in experimental searches for $\Xi_{bc}$

- Detection efficiency — small exclusive branching ratios

\[
\begin{array}{cccc|cccc}
\text{channels} & \Gamma / \text{GeV} & B & \text{channels} & \Gamma / \text{GeV} & B \\
\Xi_{bc}^0 \to \Lambda_c^+ \pi^- & 1.13 \times 10^{-18} & 1.60 \times 10^{-7} & \Xi_{bc}^0 \to \Lambda_c^+ \rho^- & 3.31 \times 10^{-18} & 4.68 \times 10^{-7} \\
\Xi_{bc}^0 \to \Lambda_c^+ a_1 & 4.42 \times 10^{-18} & 6.24 \times 10^{-7} & \Xi_{bc}^0 \to \Lambda_c^+ K^- & 9.36 \times 10^{-20} & 1.32 \times 10^{-8} \\
\Xi_{bc}^0 \to \Lambda_c^+ K^+ & 1.70 \times 10^{-19} & 2.41 \times 10^{-8} & \Xi_{bc}^0 \to \Lambda_c^+ D^- & 2.27 \times 10^{-19} & 3.21 \times 10^{-8} \\
\Xi_{bc}^0 \to \Lambda_c^+ D_s^- & 2.42 \times 10^{-19} & 3.42 \times 10^{-8} & \Xi_{bc}^0 \to \Lambda_c^+ D_s^- & 6.23 \times 10^{-18} & 8.80 \times 10^{-7} \\
\Xi_{bc}^0 \to \Sigma_c^+ \pi^- & 5.82 \times 10^{-18} & 8.22 \times 10^{-7} & \Xi_{bc}^0 \to \Sigma_c^+ \rho^- & 3.53 \times 10^{-18} & 4.99 \times 10^{-7} \\
\Xi_{bc}^0 \to \Sigma_c^+ a_1 & 5.24 \times 10^{-18} & 7.41 \times 10^{-7} & \Xi_{bc}^0 \to \Sigma_c^+ K^- & 9.16 \times 10^{-20} & 1.29 \times 10^{-8} \\
\Xi_{bc}^0 \to \Sigma_c^+ K^+ & 1.86 \times 10^{-19} & 2.63 \times 10^{-8} & \Xi_{bc}^0 \to \Sigma_c^+ D^- & 1.96 \times 10^{-19} & 2.77 \times 10^{-8} \\
\Xi_{bc}^0 \to \Sigma_c^+ D_s^- & 3.85 \times 10^{-19} & 5.44 \times 10^{-8} & \Xi_{bc}^0 \to \Sigma_c^+ D_s^- & 5.34 \times 10^{-18} & 7.55 \times 10^{-7} \\
\Xi_{bc}^0 \to \Sigma_c^+ D_{s}^+ & 9.73 \times 10^{-18} & 1.38 \times 10^{-6} & \\
\end{array}
\]

- First experimental attempts

\[
\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to D^0 p K^-)}{B(\Lambda_b^0 \to D^0 p K^-)} < [1.7, 3.0] \% \\
\text{[LHCb, 2009.02481]}
\]

\[
\frac{\sigma(\Xi_{bc}^0)}{\sigma(\Lambda_b^0)} \frac{B(\Xi_{bc}^0 \to \Xi_c^+ \pi^-)}{B(\Lambda_b^0 \to \Xi_c^+ \pi^-)} < [0.6, 3] \times 10^{-4} \\
\text{[LHCb, 2104.04759]}
\]

\[
B(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = 4.9 \times 10^{-3}, \sigma(\Lambda_b^0) \sim 10 \mu b, \sigma(\Xi_{bc}^0) \sim 40 nb
\]

Wang, FSY, Zhao, 1707.02834
Han, Zhang, Jiang, Xiao, FSY, 2102.00961
Proposal: inclusive $\Xi_{bc}$ search

- Generally, inclusive decays have (1) larger branching ratios but (2) lower detection efficiencies
  
  Basically impossible at hadron colliders

- However, for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$, the efficiency can be large by making use of the inform of displaced vertex

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

- $\Xi_{bc}$ is (almost) the only source for displaced $\Xi_{cc}$’s

- The $B_{c} \rightarrow \Xi_{cc}^{++} + X$ decay is highly suppressed
Calculation of $\Xi_{bc} \rightarrow \Xi_{cc} + X$

- First important fact: $\Xi_{bc} \rightarrow \Xi_{cc} + X = \Xi_{bc} \rightarrow X_{cc}$

  $X_{cc}$ include excited states of $\Xi_{cc}$, which still decay into $\Xi_{cc}$

- Regarding the heavy diquarks $\chi_{bc}$ and $\chi_{cc}$ as point-like particles, the decay at the quark-diquark diquark level is

  $$\chi_{bc} \rightarrow \chi_{cc} + \ell^- \bar{\nu}, \chi_{cc} + \bar{q}q'$$

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

- By making use of OPE, the inclusive decay rate is expanded by powers of $1/M_{QQ'}$ within the Heavy Diquark Effective Theory


- At the leading power

  $$B(\Xi_{bc} \rightarrow X_{cc}) = B(\chi_{bc} \rightarrow \chi_{cc} + \ell^- \bar{\nu}, \chi_{cc} + \bar{q}q') + O(1/M_{QQ'})$$
Calculation of $\Xi_{bc} \rightarrow \Xi_{cc} + X$

- Numerical result for the decay width

$$\Gamma(\Xi_{bc} \rightarrow \Xi_{cc} + X) = (1.9 \pm 0.1 \pm 0.3 \pm 0.4) \times 10^{-13} \text{ GeV}$$

Uncertainties from model dependence, scale dependence, power correction

- The branching ratio is

$$B(\Xi_{bc}^+ \rightarrow \Xi_{cc}^{++} + X) \approx 6\% \times \frac{\tau_{\Xi_{bc}^+}}{400\text{fs}}$$

Qin, Shi, Wang, Yang, FSY, Zhu, 2108.06716

- Lifetimes

$93\text{fs} < \tau(\Xi_{bc}^0) < 108 \text{ fs}$, $409 \text{fs} < \tau(\Xi_{bc}^+) < 607 \text{ fs}$

Cheng, Xu, 1903.08148
Still difficult at Run3
Summary

• The observation of double-charm baryon, $\Xi_{cc}^{++}$, opens a new window on the study of strong interaction.

• The decay properties, including the branching fractions and lifetimes, are very important in the experimental searches, as well as productions.

• Collaborations between experimentalists and theorists are helpful.

• Some suggestions are given to search for other double-heavy baryons.

Thank you!
Backups
Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced $\Xi_{cc}^{++}$

- Estimated of signal signal events

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

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

Three ingredients:

1. Number of signals of $\Xi_{cc}^{++}$
2. Production ratio $\sigma(\Xi_{bc})/\sigma(\Xi_{cc})$
3. Branching fraction of inclusive decay of $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$
Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced $\Xi_{cc}^{++}$

1. Number of signals of $\Xi_{cc}^{++}$

- Data of 9 fb$^{-1}$ Run 1+2
- Events estimated for 23 fb$^{-1}$ (Run III)

$$\frac{7000}{1600} \times (1600 + 600) \approx 10000$$
Search for $\Xi_{bc} \rightarrow \Xi_{cc}^{++} + X$ with displaced $\Xi_{cc}^{++}$

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

[X.G.Wu et al, 1101.1130]

TABLE VI. Comparison of the total cross section (in units nb) for the hadronic production of $\Xi_{cc}$, $\Xi_{bc}$, and $\Xi_{bb}$ at $\sqrt{s} = 7.0$ TeV and $\sqrt{s} = 14.0$ TeV, where $[^3S_1]$ and $[^1S_0]$ stand for the combined results for the diquark in spin-triplet and spin-singlet states, respectively. In the calculations, we adopt $p_T > 4$ GeV and $|y| < 1.5$.

<table>
<thead>
<tr>
<th></th>
<th>$\Xi_{cc}$ $\sqrt{s} = 7.0$ TeV</th>
<th>$\Xi_{cc}$ $\sqrt{s} = 14.0$ TeV</th>
<th>$\Xi_{bc}$ $\sqrt{s} = 7.0$ TeV</th>
<th>$\Xi_{bc}$ $\sqrt{s} = 14.0$ TeV</th>
<th>$\Xi_{bb}$ $\sqrt{s} = 7.0$ TeV</th>
<th>$\Xi_{bb}$ $\sqrt{s} = 14.0$ TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$[^3S_1]$</td>
<td>38.11</td>
<td>69.40</td>
<td>16.7</td>
<td>28.55</td>
<td>0.503</td>
<td>1.137</td>
</tr>
<tr>
<td>$[^1S_0]$</td>
<td>9.362</td>
<td>17.05</td>
<td>3.72</td>
<td>6.315</td>
<td>0.100</td>
<td>0.226</td>
</tr>
<tr>
<td>Total</td>
<td>47.47</td>
<td>86.45</td>
<td>20.42</td>
<td>34.87</td>
<td>0.603</td>
<td>1.363</td>
</tr>
</tbody>
</table>

$\sigma(\Xi_{bc})/\sigma(\Xi_{cc}) \approx 40\%$
Search for $\Xi_{bc} \to \Xi_{cc}^{++} + X$ with displaced $\Xi_{cc}^{++}$

- Final number of estimated signal events @ LHCb Run3

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

$$= 10^4 \cdot \frac{N(\Xi_{cc}^{++})}{10^4} \times 40\% \cdot \frac{2\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\%} \times 6\% \cdot \left( \frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^0}}{400\text{fs}} \right)$$

$$= 240 \times \frac{N(\Xi_{cc}^{++})}{10^4} \cdot \frac{\sigma(\Xi_{bc})/\sigma(\Xi_{cc})}{40\%} \cdot \left( \frac{\tau_{\Xi_{bc}^{+}} + \tau_{\Xi_{bc}^0}}{400\text{fs}} \right)$$
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 $\Xi_{cc}\Xi_c\gamma$, or $\Xi_{cc}\Xi_c\pi$, or $\Xi_{cc}\Xi_{cc}$, or $\Xi_{cc}\Xi_{cc}$.

- Similar process but with a light spectator quark:

$$Br(B^0 \to \Xi_c^-\Lambda_c^+) = (1.2 \pm 0.8) \times 10^{-3}$$

$$Br(B^- \to \Xi_{cc}^0\Lambda_c^-) = (0.95 \pm 0.23) \times 10^{-3}$$

(0.5 GeV phase space)
\[ \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \ v.s. \ \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \]

SELEX’s discovery channel, LHCb measured

<table>
<thead>
<tr>
<th>Baryons</th>
<th>Modes</th>
<th>( B_{LD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi_{cc}^{++}(ccu) )</td>
<td>( \Sigma_c^{++}(2455) \bar{K}^{*0} )</td>
<td>defined as 1</td>
</tr>
<tr>
<td></td>
<td>( pD^{*+} )</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>( pD^+ )</td>
<td>0.0008</td>
</tr>
<tr>
<td>( \Xi_{cc}^{+}(ccd) )</td>
<td>( \Lambda_c^+ \bar{K}^{*0} )</td>
<td>( (R_\tau/0.3) \times 0.22 )</td>
</tr>
<tr>
<td></td>
<td>( \Sigma_c^{++}(2455)K^- )</td>
<td>( (R_\tau/0.3) \times 0.008 )</td>
</tr>
<tr>
<td></td>
<td>( \Xi_c^{+} \rho^0 )</td>
<td>( (R_\tau/0.3) \times 0.04 )</td>
</tr>
<tr>
<td></td>
<td>( \Lambda D^+ )</td>
<td>( (R_\tau/0.3) \times 0.004 )</td>
</tr>
<tr>
<td></td>
<td>( pD^0 )</td>
<td>( (R_\tau/0.3) \times 0.002 )</td>
</tr>
</tbody>
</table>

\[ \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \] has more signal yields around one more order than

\[ \Xi_{cc}^{+} \rightarrow \Lambda_c^+ K^- \pi^+ \]