Search for doubly heavy baryon via weak decays

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Outline

1. Motivation and Introduction to doubly heavy baryons
   masses, lifetimes and productions
2. Semi-leptonic decays
   form factors in the light-front quark model
3. Non-leptonic decays
   topologies and hierarchy
4. Suggestions on the discovery channels

Summary
The Doubly charm baryons

- Two SU(4) baryon 20-plets with $J^P = \frac{1}{2}^+$ and $J^P = \frac{3}{2}^+$, each contains a SU(3) triplet with two charm quarks: $\Xi_{cc}^+(ccd), \Xi_{cc}^{++}(ccu), \Omega_{cc}^+(ccs)$

- $J^P = \frac{3}{2}^+$ expected to decay to $\frac{1}{2}^+$ states via strong/electromagnetic interaction

- $J^P = \frac{1}{2}^+$ states decay weakly with a $c$ quark transformed to lighter quarks
Motivations

- Doubly heavy baryons are predicted in quark model and QCD

<table>
<thead>
<tr>
<th>Baryons</th>
<th>quarks</th>
<th>$I(J^P)$</th>
<th>Baryons</th>
<th>quarks</th>
<th>$I(J^P)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_{cc}^{++}$</td>
<td>ucc</td>
<td>$\frac{1}{2}(\frac{1}{2}^+)$</td>
<td>$\Xi_{cb}^+$</td>
<td>ucb</td>
<td>$\frac{1}{2}(\frac{1}{2}^+)$</td>
</tr>
<tr>
<td>$\Xi_{cc}^+$</td>
<td>dcc</td>
<td>$\frac{1}{2}(\frac{1}{2}^+)$</td>
<td>$\Xi_{cb}^0$</td>
<td>dcb</td>
<td>$\frac{1}{2}(\frac{1}{2}^+)$</td>
</tr>
<tr>
<td>$\Omega_{cc}^+$</td>
<td>scc</td>
<td>$0(\frac{1}{2}^+)$</td>
<td>$\Omega_{cb}^0$</td>
<td>scb</td>
<td>$0(\frac{1}{2}^+)$</td>
</tr>
</tbody>
</table>

- But not established until 2017 (by LHCb)
  - The only evidence was found for $\Xi_{cc}^+$ by SELEX
    \[ \Xi_{cc}^+ \rightarrow \Lambda_c^+ K^- \pi^+ \quad \Xi_{cc}^+ \rightarrow pD^+ K^- \]  
    [SELEX, 02’; 04’]
  - But not confirmed by other experiments
    [Babar, 06’; Belle, 13’; LHCb, 13’]
  - Searching for them is one of the most important purposes of particle physics, to understand the hadron spectroscopy, the perturbative and non-perturbative QCD dynamics of the productions and decays.
    LHCb asked us for help
Lifetimes

\[ \tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^+) \sim \tau(\Omega_{cc}^+) \]

Priority to search for \( \Xi_{cc}^{++} \)

<table>
<thead>
<tr>
<th>Literatures</th>
<th>( \Xi_{cc}^{++} )</th>
<th>( \Xi_{cc}^+ )</th>
<th>( \Omega_{cc}^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Karliner, Rosner, 2014</td>
<td>185</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Kiselev, Likhoded, 1998</td>
<td>430±100</td>
<td>110±10</td>
<td></td>
</tr>
<tr>
<td>Kiselev, Likhoded, 2002</td>
<td>460±50</td>
<td>160±50</td>
<td>270±60</td>
</tr>
<tr>
<td>Guberina, Melic, Stefancic, 1998</td>
<td>1550</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Chang, Li, Li, Wang, 2007</td>
<td>670</td>
<td>250</td>
<td>210</td>
</tr>
</tbody>
</table>

SELEX collaboration: \( \tau(\Xi_{cc}^+) < 33 \) fs @ 90% confidence

Large ambiguity of lifetimes

Compared to

\[ \tau(\Lambda_c^+) = (200 \pm 6) \times 10^{-15} \text{s}, \]
\[ \tau(\Xi_c^0) = (112^{+13}_{-10}) \times 10^{-15} \text{s}, \]
\[ \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} \text{s}, \]
\[ \tau(\Omega_c^0) = (69 \pm 12) \times 10^{-15} \text{s}. \]
2. Semi-leptonic decays

Key point is to calculate form factors
First try in the light-front quark model

Wei Wang, Fu-Sheng Yu, Zhen-Xing Zhao, EPJC77 (2017) 781
Form factors with di-quark assumption

- \(Q_1 Q_2 q \rightarrow q' Q_2 q\)

- weak decays of \(Q_1 \rightarrow q'\)

- diquark assumption: spectators \([Q_2 q]\)

- diquark is dominated by \(J^P = 0^+\)

\[
\langle B'(P', S'_z)|(V - A)_{\mu}|B(P, S_z)\rangle = \bar{u}(P', S'_z) \left[ \frac{q^\nu}{M} f_2(q^2) + \frac{q_\mu}{M} f_3(q^2) \right] u(P, S_z) \\
- \bar{u}(P', S'_z) \left[ \frac{q^\nu}{M} g_2(q^2) + \frac{q_\mu}{M} g_3(q^2) \right] \gamma_5 u(P, S_z)
\]
Form factors in light-front quark model

\[ |B(P, S, S_z)\rangle = \int \{d^3p_1\}\{d^3p_2\} 2(2\pi)^3 \delta^3(\tilde{P} - \tilde{p}_1 - \tilde{p}_2) \times \sum_{\lambda_1} \Psi^{SS_z}(\tilde{p}_1, \tilde{p}_2, \lambda_1)|q_\alpha(p_1, \lambda_1)[di](p_2)\rangle \]

- LRQM: all particles are on-shell

\[
\begin{array}{cccccc}
 m_u & m_d & m_s & m_c & m_b & m_{[cu]} & m_{[cd]} \\
 0.25 & 0.25 & 0.37 & 1.4 & 4.8 & 1.4 + 0.25 & 1.4 + 0.25 \\
\end{array}
\]
Form factors in LFQM

\[ F(q^2) = \frac{F(0)}{1 - \frac{q^2}{m_{pole}^2}} \]

<table>
<thead>
<tr>
<th>channels</th>
<th>( f_1(0) )</th>
<th>( f_2(0) )</th>
<th>( g_1(0) )</th>
<th>( g_2(0) )</th>
<th>( m_{pole} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Xi^{++}_{cc} \to \Lambda^+_c )</td>
<td>0.653</td>
<td>-0.739</td>
<td>0.533</td>
<td>-0.053</td>
<td>( D^* )</td>
</tr>
<tr>
<td>( \Xi^{++}_{cc} \to \Sigma^+_c )</td>
<td>0.653</td>
<td>-0.739</td>
<td>0.533</td>
<td>-0.053</td>
<td>( D^* )</td>
</tr>
<tr>
<td>( \Xi^{++}_{cc} \to \Xi^+_c )</td>
<td>0.754</td>
<td>-0.783</td>
<td>0.620</td>
<td>-0.080</td>
<td>( D_s^* )</td>
</tr>
<tr>
<td>( \Xi^{+}_{cc} \to \Sigma^0_c )</td>
<td>0.653</td>
<td>-0.739</td>
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</tr>
<tr>
<td>( \Xi^{+}_{bc} \to \Sigma^{++}_c )</td>
<td>0.136</td>
<td>-0.081</td>
<td>0.130</td>
<td>-0.009</td>
<td>( B^* )</td>
</tr>
<tr>
<td>( \Xi^{0}_{bc} \to \Lambda^+_c )</td>
<td>0.136</td>
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<td>-0.009</td>
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<td>0.136</td>
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<td>0.130</td>
<td>-0.009</td>
<td>( B^* )</td>
</tr>
<tr>
<td>( \Xi^{+}_{bc} \to \Lambda^0_b )</td>
<td>0.639</td>
<td>-1.707</td>
<td>0.499</td>
<td>-0.232</td>
<td>( D^* )</td>
</tr>
<tr>
<td>( \Xi^{+}_{bc} \to \Xi^0_b )</td>
<td>0.725</td>
<td>-1.801</td>
<td>0.571</td>
<td>-0.269</td>
<td>( D_{s}^* )</td>
</tr>
<tr>
<td>( \Xi^{0}_{bc} \to \Xi^-_b )</td>
<td>0.725</td>
<td>-1.801</td>
<td>0.571</td>
<td>-0.269</td>
<td>( D_{s}^* )</td>
</tr>
</tbody>
</table>

**c decay**

**b decay**

**c decay**
## Semi-leptonic decays

| channels         | $\mathcal{B}$       | $|V_{cd}|^2 \sim \lambda^2 \sim 0.05$ | $|V_{cs}|^2 \sim 1$ |
|------------------|----------------------|--------------------------------------|---------------------|
| $\Xi_{cc}^{++} \to \Lambda_c^+$ | $5.16 \times 10^{-3}$ |                       |                     |
| $\Xi_{cc}^{++} \to \Sigma_c^+$  | $2.50 \times 10^{-3}$ |                       |                     |
| $\Xi_{cc}^{++} \to \Xi_c^+$       | $5.58 \times 10^{-2}$ |                       |                     |
| $\Xi_{cc}^+ \to \Sigma_c^0$     | $7.13 \times 10^{-4}$ |                       |                     |
| $\Xi_{cc}^+ \to \Xi_c^0$         | $1.58 \times 10^{-2}$ |                       |                     |
| $\Xi_{bc}^+ \to \Sigma_c^{++}$   | $3.11 \times 10^{-5}$ |                       |                     |
| $\Xi_{bc}^0 \to \Lambda_c^+$     | $1.53 \times 10^{-5}$ |                       |                     |
| $\Xi_{bc}^0 \to \Sigma_c^+$      | $1.19 \times 10^{-5}$ |                       |                     |
| $\Xi_{bc}^+ \to \Lambda_b^0$     | $6.53 \times 10^{-3}$ |                       |                     |
| $\Xi_{bc}^+ \to \Xi_b^0$         | $6.79 \times 10^{-2}$ |                       |                     |
| $\Xi_{bc}^0 \to \Xi_b^-$         | $2.56 \times 10^{-2}$ |                       |                     |

**b decay**

**Phase space**

$$\left(\frac{m_b}{m_c}\right)^5 \sim 300$$

$|V_{ub}|^2 \sim \lambda^6 \sim 10^{-5}$

**c decay**

$|V_{cd}|^2 \sim \lambda^2 \sim 0.05$

$|V_{cs}|^2 \sim 1$
### Semi-leptonic decays are not competitive with missing energy 😨😢😢

<table>
<thead>
<tr>
<th>Channels</th>
<th>$\mathcal{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi^{++}_{cc} \rightarrow \Lambda^+_c$</td>
<td>$5.16 \times 10^{-3}$</td>
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</tr>
<tr>
<td>$\Xi^{++}_{cc} \rightarrow \Xi^+_c$</td>
<td>$5.58 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\Xi^+_c \rightarrow \Sigma^0_c$</td>
<td>$7.13 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Xi^+_c \rightarrow \Xi^0_c$</td>
<td>$1.58 \times 10^{-2}$</td>
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<tr>
<td>$\Xi^{++}_{bc} \rightarrow \Sigma^{++}_c$</td>
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<tr>
<td>$\Xi^0_{bc} \rightarrow \Xi^-_b$</td>
<td>$2.56 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Non-leptonic: $10^{-3} \sim 10^{-4}$

Non-leptonic: $10^{-6} \sim 10^{-8}$

Non-leptonic: $10^{-6} \sim 10^{-8}$
Non-leptonic decays

- Only **two-body** decays are available in theory
- Estimate branching fractions using **topological diagrammatic approach**
Difficulties in theory

- It is always difficult to understand the dynamics of charm decays, due to large non-perturbative contributions.

- Heavy quark effective theory does not work for $1/m_c$.

- Topological diagrammatic approach works well in D decays. $\Delta A_{CP}$ was predicted to be (-0.06 ~ -0.19)\% in 2012 [Li, Lu, Yu, PRD86,036012], and confirmed by recent LHCb measurements.

- But it does not work in charmed baryon decays so far, due to less data to fix parameters.
Hierarchy in heavy quark expansion

SCET: $|C/T| \sim |C'/T| \sim |E/T| \sim O(\Lambda_{QCD}/m_Q)$, $|B/E| \sim O(\Lambda_{QCD}/m_Q)$,

[Leibovich, Ligeti, Stewart, Wise, 04’]

$b$ decay: $|C/T| \sim |C'/T| \sim |E/T| \sim |P/T| \sim O(\Lambda_{QCD}/m_Q) \sim 0.3$

$|B/E| \sim |P/E| \sim O(\Lambda_{QCD}/m_Q) \sim 0.3$

<table>
<thead>
<tr>
<th>PQCD approach</th>
<th>$A$</th>
<th>$B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b \rightarrow p\pi$</td>
<td>$-2.42 \times 10^{-9}$</td>
<td>$-1.74 \times 10^{-9}$</td>
</tr>
<tr>
<td>$T$</td>
<td>$-2.42 \times 10^{-9}$</td>
<td>$-1.74 \times 10^{-9}$</td>
</tr>
<tr>
<td>$C'$</td>
<td>$2.05 \times 10^{-10}$</td>
<td>$-2.35 \times 10^{-10}$</td>
</tr>
<tr>
<td>$B$</td>
<td>$2.89 \times 10^{-11}$</td>
<td>$1.11 \times 10^{-11}$</td>
</tr>
<tr>
<td>$E$</td>
<td>$-7.00 \times 10^{-11}$</td>
<td>$2.21 \times 10^{-10}$</td>
</tr>
<tr>
<td>$PE$</td>
<td>$-6.84 \times 10^{-12}$</td>
<td>$7.00 \times 10^{-12}$</td>
</tr>
<tr>
<td>$P$</td>
<td>$1.37 \times 10^{-10}$</td>
<td>$-1.60 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Hierarchy in heavy quark expansion

SCET: $IC/\overline{TI} \sim IC'/\overline{TI} \sim IE/\overline{TI} \sim O(\Lambda_{QCD}/m_Q)$, $IB/\overline{EI} \sim O(\Lambda_{QCD}/m_Q)$,

[Leibovich, Ligeti, Stewart, Wise, 04’]

c decay: $IC/\overline{TI} \sim IC'/\overline{TI} \sim IE/\overline{TI} \sim O(\Lambda_{QCD}/m_Q) \sim 1$

$IB/\overline{EI} \sim O(\Lambda_{QCD}/m_Q) \sim 1$

$|P| \sim 0$

$\Lambda_c^+ \equiv V_{cs}^* V_{ud}$

<table>
<thead>
<tr>
<th>Modes</th>
<th>Representation</th>
<th>$B_{exp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p\overline{K}^0$</td>
<td>$\lambda_{sd}(C + E)$</td>
<td>$(3.04 \pm 0.17)%$</td>
</tr>
<tr>
<td>$\Lambda^0\pi^+$</td>
<td>$\lambda_{sd}(T - C' + B - E)/\sqrt{2}$</td>
<td>$(1.24 \pm 0.08)%$</td>
</tr>
<tr>
<td>$\Delta^{++}K^-$</td>
<td>$\lambda_{sd}E$</td>
<td>$(1.18 \pm 0.27)%$</td>
</tr>
</tbody>
</table>

$\Lambda_c$ decay would help to understand dynamics
Example of Two body decays

\begin{align*}
\Xi_{cc}^+ & \rightarrow (\Lambda_c^+ \pi^+) K^- \\
\Sigma_c^{++}(2520) & \approx (3/2^+) \\
\Lambda_c^+ & \rightarrow \Delta^{++} K^- \\
\Delta^{++} & \approx (3/2^+)
\end{align*}

- pure W-exchange process
- possible discovery channel
- measured \text{ [PDG]}  

$$ Br(\Lambda_c^+ \rightarrow \Delta^{++} K^-) = (1.09 \pm 0.25)\% $$

Experimentally, \( \Sigma_c^{++}(2520) \) is found to decay into \( \Lambda_c^+ \pi^+ \) with branching ratio 100%.

\[ BR(\Xi_{cc}^+ \rightarrow \Sigma_c^{++}(2520) K^-) \approx BR(\Lambda_c^+ \rightarrow \Delta^{++} K^-) \times 0.66 \times 4 \times \frac{1}{2} \times \frac{\tau_{\Xi_{cc}^+}}{\tau_{\Lambda_c^+}} \in [0.36\%, 1.80\%] \]

[Li, Lu, Wang, Yu, Zou, PLB767,232(2017), 1701.03284]
Topologies of two-body non-leptonic charmed baryon decays

(T) color-favored tree emitted

(E₁) W-exchange 1

d,s

W

c

(C) color-suppressed emitted

(E₂) W-exchange 2

d,s

W

c

(C’) color-commensurate

(B) Bow tie
Theoretical Framework

1. tree emitted (T) diagrams, dominated by factorizable contributions
   - form factor times decay constant
     • Form factors calculated in light-front quark model

2. all other diagrams dominated by non-factorizable contributions, which is non-perturbative through final-state interacting
   • Calculate rescattering effects by triangle diagrams
\[ \Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+ \]

\[ V_{cs} V_{ud} (T + C') \]

\[ \Xi_{cc}^{++} \rightarrow \Xi_{cc}^+ \Xi_c^+ + \Xi_{cc}^{+++} \Xi_c^+ \]

\[ \Xi_{cc}^{++} \rightarrow \Xi_{cc}^{+++} \Xi_{cc}^{++} + \Xi_{cc}^{+++} \Xi_{cc}^{+++} \]

\[ \Xi_{cc}^{+++} \rightarrow \Xi_{cc}^{+++} \Xi_{cc}^{+++} + \Xi_{cc}^{+++} \Xi_{cc}^{+++} \]

\[ \Xi_{cc}^{+++} \rightarrow \Xi_{cc}^{+++} \Xi_{cc}^{+++} + \Xi_{cc}^{+++} \Xi_{cc}^{+++} \]

\[ \Xi_{cc}^{+++} \rightarrow \Xi_{cc}^{+++} \Xi_{cc}^{+++} + \Xi_{cc}^{+++} \Xi_{cc}^{+++} \]
$$\Xi_{cc}^{++} \rightarrow \Sigma_{c}^{++} \bar{K}^{*0} \rightarrow \Lambda_{c}^{+} K^{-} \pi^{+} \pi^{+}$$

$V_{cs} V_{ud} C$

- $\Xi_{cc}^{++} \rightarrow \Sigma_{c}^{++} \bar{K}^{*0}$
- $\Xi_{c}^{+}/\Xi_{c}^{'+} \rightarrow \Sigma_{c}^{++}$
- $\Xi_{c}^{+}/\Xi_{c}^{'+} \rightarrow \Lambda_{c}^{+}$
- $\Xi_{c}^{+}/\Xi_{c}^{'+} \rightarrow \bar{K}^{*0}$

**FSI**

e.g.

$$\Xi_{cc}^{++} \overset{\pi^{+}}{\rightarrow} \bar{K}^{*0} \Xi_{c}^{+}/\Xi_{c}^{'+} \overset{K^{\pm}}{\rightarrow} \Sigma_{c}^{++} \Xi_{c}^{+}/\Xi_{c}^{'+} \overset{\rho^{+}}{\rightarrow} \bar{K}^{*0}$$

$$\Xi_{c}^{+}/\Xi_{c}^{'+} \overset{\pi^{+}/\rho^{+}}{\rightarrow} \Lambda_{c}^{+} \bar{K}^{*0} \Xi_{c}^{+}/\Xi_{c}^{'+} \overset{\Sigma^{+}}{\rightarrow} \Xi_{c}^{++} \bar{K}^{*0}$$

$$\Xi_{c}^{+}/\Xi_{c}^{'+} \overset{\pi^{+}/\rho^{+}}{\rightarrow} \Sigma_{c}^{++} \bar{K}^{*0}$$
\[ \Xi_{cc}^{++} \rightarrow \Lambda_c^+ \pi^+ \]

\[ V_{cd} V_{ud} (T + C') \]

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

\[ \Xi_{cc}^{++} \rightarrow \Xi_{cc}^{++} \pi^+ \rightarrow \rho^0 \Xi_{cc}^{++} \rightarrow \Sigma_c^+ \Lambda_c^+ \]

\[ + \Xi_{cc}^{++} \rightarrow \rho^+ \Xi_{cc}^{++} \rightarrow \Sigma_c^0 \Lambda_c^+ \rightarrow \pi^+ \]

\[ + \Xi_{cc}^{++} \rightarrow \Sigma_c^+ \Lambda_c^+ \rightarrow \pi^+ \]
$$\Xi_{cc}^+ \rightarrow \Lambda_c^+ K^{*0} \rightarrow \Lambda_c^+ K^- \pi^+$$

\[ V_{cs} V_{ud} (C + E_1) \]

SELEX exp. ever found evidence in this channel
$V_{cs}V_{ud}E_1 = \Xi_{cc}^+ \rightarrow \Sigma_{c}^{++} K^- \rightarrow \Lambda_c^+ K^- \pi^+$

SELEX exp. ever found evidence in this channel
## Results of Branching Fractions

<table>
<thead>
<tr>
<th>Baryons</th>
<th>Modes</th>
<th>Representation</th>
<th>$Br$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_{cc}^{++}$</td>
<td>$\Sigma_{c}^{++} K^{*0}$</td>
<td>$V_{cs} V_{ud} C$</td>
<td>$(1.6 \sim 11%)$</td>
</tr>
<tr>
<td></td>
<td>$\Xi_{c}^{+} \pi^{+}$</td>
<td>$V_{cs} V_{ud} (T + C')$</td>
<td>$(9.0 \sim 9.4%)$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_{c}^{+} \pi^{+}$</td>
<td>$V_{cd} V_{ud} (T + C')$</td>
<td>$(0.6 \sim 1.3%)$</td>
</tr>
<tr>
<td></td>
<td>$pD_{c}^{+}$</td>
<td>$V_{cd} V_{ud} C'$</td>
<td>$(0.01 \sim 0.08%)$</td>
</tr>
<tr>
<td></td>
<td>$pD_{c}^{*+}$</td>
<td>$V_{cd} V_{ud} C'$</td>
<td>$(0.3 \sim 2.8%)$</td>
</tr>
<tr>
<td>$\Xi_{cc}^{+}$</td>
<td>$\Xi_{c}^{0} \pi^{+}$</td>
<td>$V_{cs} V_{ud} (T + E_2)$</td>
<td>$(2.9 \sim 3.8%)$</td>
</tr>
<tr>
<td></td>
<td>$\Xi_{c}^{+} \rho^{0}$</td>
<td>$\frac{1}{\sqrt{2}} V_{cs} V_{ud} (C' - E_2)$</td>
<td>$(0.2 \sim 1.8%)$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_{c}^{+} \overline{K}^{*0}$</td>
<td>$V_{cs} V_{ud} (C + E_1)$</td>
<td>$(0.14 \sim 0.5%)$</td>
</tr>
<tr>
<td>$\Sigma_{c}^{++} K^{-}$</td>
<td>$V_{cs} V_{ud} E_1$</td>
<td>$(0.02 \sim 0.1%)$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\Lambda D_{c}^{+}$</td>
<td>$V_{cs} V_{ud} (C' + B)$</td>
<td>$(0.1 \sim 0.7%)$</td>
</tr>
<tr>
<td></td>
<td>$pD_{c}^{0}$</td>
<td>$V_{cd} V_{ud} B$</td>
<td>$(0.0002 \sim 0.001%)$</td>
</tr>
</tbody>
</table>
Theoretical Uncertainties

- **Strong couplings between hadrons**
  - Large ambiguities in literatures
- **Off-shell effects of intermediate states**

\[
F(t, m) = \left( \frac{\Lambda^2 - m^2}{\Lambda^2 - t} \right)^n
\]

\[
t \equiv (p_1 - p_3)^2 \quad n = 1
\]

\[
\Lambda = m_{\text{exc}} + \eta \Lambda_{\text{QCD}}
\]

[Cheng, Chua, Soni, PRD 71, 014030 (2005)]

Results are very sensitive to the value of $\eta$

No first-principle calculations for $\eta$

We take $\eta$ from 1.0 to 2.0
Checked with $\Lambda_c^+ \rightarrow p\phi$

$$V_{cd}^* V_{ud} C =$$

$$\Lambda_c^+ \rightarrow p\phi$$

$$\Rightarrow$$

$$\Lambda_c^+ \rightarrow K^+ K^\pm \phi$$

$$\Lambda_c^+ \rightarrow K^{*+} K^{*\pm} \phi$$

$$\Lambda_c^+ \rightarrow K^+/K^{*+} \phi$$

PDG \hspace{1cm} \mathcal{B}(\Lambda_c^+ \rightarrow p\phi) = (1.04 \pm 0.21) \times 10^{-3}

$$\eta \sim 1.3$$

26
Relative importance of various decay modes (theoretical uncertainties mostly canceled)

### TABLE II: Branching fractions of $\Xi_{cc}^{++}$ and $\Xi_{cc}^+$ decays with the long-distance contributions, relative to that of $\Xi_{cc}^{++} \rightarrow \Sigma_{c}^{++} (2455) \overline{K}^{*0}$.

<table>
<thead>
<tr>
<th>Baryons</th>
<th>Modes</th>
<th>$\mathcal{B}_{LD}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_{cc}^{++} (ccu)$</td>
<td>$\Sigma_{c}^{++} (2455) \overline{K}^{*0}$</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>$\Lambda_c^{+} \overline{K}^{*0}$</td>
<td>$(\mathcal{R}_{\tau}/0.3) \times 0.22$</td>
</tr>
<tr>
<td></td>
<td>$\Sigma_{c}^{++} (2455) K^-$</td>
<td>$(\mathcal{R}_{\tau}/0.3) \times 0.008$</td>
</tr>
<tr>
<td></td>
<td>$\Xi_c \rho^0$</td>
<td>$(\mathcal{R}_{\tau}/0.3) \times 0.04$</td>
</tr>
<tr>
<td></td>
<td>$\Lambda D^+$</td>
<td>$(\mathcal{R}_{\tau}/0.3) \times 0.004$</td>
</tr>
<tr>
<td></td>
<td>$pD^0$</td>
<td>$(\mathcal{R}_{\tau}/0.3) \times 0.002$</td>
</tr>
</tbody>
</table>
\[ \Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+ \]

1. Many resonances

\[ Br(\Sigma_c^{++} K^0) = (1.6 \sim 11)\% \]

2. Large non-resonant contributions

\[ Br(\Lambda_c^+ \rightarrow pK^- \pi^+ \pi^0) = (4.9 \pm 0.4)\% \]

\[ Br(\Lambda_c^+ \rightarrow p(K^- \pi^+)_{\text{nonresonant}} \pi^0) = (4.6 \pm 0.9)\% \]

\[ Br(\Lambda_c^+ \rightarrow \Lambda \pi^+) = (1.30 \pm 0.07)\% \]

multi-body > two-body

It would be expected to be as large as \( O(10\%) \)
**Prediction on Br of** \( \Xi_c^+ \rightarrow pK^-\pi^+ \)

\( \Xi_c^+ \) detecting mode, Br not directly measured

Under U-spin symmetry

\[ \mathcal{A}(\Xi_c^+ \rightarrow pK^*0) = -\mathcal{A}(\Lambda_c^+ \rightarrow \Sigma^+K^*0) \]

PDG

\( \Lambda_c^+ \rightarrow \Sigma^+K^*0 \) saturates

\[ Br(\Lambda_c^+ \rightarrow \Sigma^+K^-\pi^+) = (0.21 \pm 0.06)\% \]

\[ Br(\Xi_c^+ \rightarrow pK^*0)/Br(\Xi_c^+ \rightarrow pK^-\pi^+) = 0.54 \pm 0.10 \]

Averaged:

\[ Br(\Xi_c^+ \rightarrow pK^-\pi^+) = (1.6 \pm 0.5)\% \]

It can be widely used

\[ \tau(\Xi_c^+) = (442 \pm 26) \times 10^{-15} \text{s} \]

Precision can be improved by measurements of \( \Lambda_c^+ \) and \( \Xi_c^+ \) decays.
Priorities to measure

1. $E_{cc}^{++} > E_{cc}^+$, due to $\tau(\Xi_{cc}^{++}) \gg \tau(\Xi_{cc}^+)$

2. $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$ has the largest branching fraction in $E_{cc}^{++}$ decays. And large $Br(\Lambda_c^+ \rightarrow pK^- \pi^+)$
   But suffer 6 tracks. LHCb, *PRL 119 (2017) 112001*

3. $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+$ has only 4 tracks. Its $Br(\Xi_c^+ \rightarrow pK^- \pi^+)$ fraction has large ambiguity. Small

4. For $E_{cc}^+$, $\Lambda_c^+ K^- \pi^+$ has the largest priority.
Summary

• We estimate the branching fractions of many channels of doubly heavy baryon weak decays

• We suggest to measure the following processes with the largest possibilities to be observed.

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

• \[ \Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+ \]

• \( \Xi_{cc} \) has been discovered by LHCb, through the first channel

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