$\Lambda_c$ physics at BESIII

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Hadron2017, Salamanca, Spain
Overview

- BEPCII and BESIII
- Physics of $\Lambda_c$
- BESIII Data Taken Near $\Lambda_c^+\bar{\Lambda}_c^-$ Threshold
- Analysis Method
  - Tagging Technique
  - $\Delta E$ and $M_{BC}$
- $\Lambda_c$ Decays at BESIII
  - $\Lambda_c$ hadronic decays
  - $\Lambda_c$ semi-leptonic decays

Summary
Beijing Electron and Positron Collider (BEPCII)

beam energy: 1.0 – 2.3 GeV

2004: start BEPCII upgrade
2008: test run of BEPCII
2009-now: BESIII data taking
Achieved the design luminosity in 2016:

\[ L_{\text{peak}} = 1.0 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \]
The new BESIII detector is hermetic for neutral and charged particle with excellent resolution, PID and large coverage.
Physics of \( \Lambda_c \)

- The lightest and most common charmed baryon, \( \Lambda_c \), most of the charmed baryons will eventually decay into \( \Lambda_c \).
  😊 Important to know the decay properties of \( \Lambda_c \).

- The golden mode, \( \Lambda_c^+ \to pK^-\pi^+ \), often used to normalize BFs.
  😊 Very important to determine the absolute BF.

- Total known measured BF is \( \sim 60\% \).
In 2014, BESIII collected $\Lambda_c$ data with excellent performance near the pair-production threshold.

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Luminosity (pb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.5745</td>
<td>47.67</td>
</tr>
<tr>
<td>4.5800</td>
<td>8.545</td>
</tr>
<tr>
<td>4.5900</td>
<td>8.162</td>
</tr>
<tr>
<td>4.5995</td>
<td>566.9</td>
</tr>
</tbody>
</table>

Advantages of $\Lambda_c^+ \Lambda_c^-$ pair production near threshold:
- Double Tag technique: access to absolute BFIs and dynamics
- With clean background
- Most systematic uncertainties in tag side can be cancelled

Presented results use this sample.

Charm Production @ Mass Threshold

- Around $E_{cm} \sim 4.6$ GeV,
  Pair production:
  $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^+ \bar{\Lambda}_c^-$

- Two ways to obtain the $\Lambda_c$ yields:
  - **Single Tag (ST):** Reconstruct only one of the $\Lambda_c$-pair.
    - Larger backgrounds
    - Higher efficiencies
  - **Double Tag (DT):** Find both of them.
    - Smaller backgrounds
    - Lower efficiencies.
Analysis Method

- In ST studies frequently used variables:
  - **Beam-Constrained Mass:**
    
    \[
    M_{BC} = \sqrt{\frac{E_{beam}^2}{c^4} - \frac{p^2}{c^2}}
    \]
    
    \( p \) is the reconstructed \( \Lambda_c \) 3-momentum
  
    - Asymmetric shape due the ISR
    - Resolution dominated by the energy spread of the beam (independently from the final states)

- **Energy Difference (\( \Delta E \))**
  
  \[ \Delta E = E - E_{beam} \]

- In DT Studies:
  - **\( U_{\text{miss}} \) (usually in semi-leptonic decay)**
    
    \[ U_{\text{miss}} = E_{\text{miss}} - c |\vec{p}_{\text{miss}}| \]
First direct measurement of $\Lambda_c$ BF

- First absolute BF measurement of the $\Lambda_c$
- Very clean event environment!
- In the above DT case, summed over the 12 tag modes
- A least square global fit: Simultaneous fit to all the tag modes, while constraining the total $\Lambda_c^+\Lambda_c^-$ pair number, taking into account the correlations.

\[
N_{ij}^{ST} = N_{\Lambda_c^+\Lambda_c^-} B_j \varepsilon_j
\]
\[
N_{ij}^{DT} = N_{\Lambda_c^+\Lambda_c^-} B_i B_j \varepsilon_{ij}
\]
First direct measurement of $\Lambda_c$ BF

<table>
<thead>
<tr>
<th>Mode</th>
<th>This work (%)</th>
<th>PDG (%)</th>
<th>BELLE $B$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$pK_S^0$</td>
<td>1.52 ± 0.08 ± 0.03</td>
<td>1.15 ± 0.30</td>
<td></td>
</tr>
<tr>
<td>$pK^-\pi^+$</td>
<td>5.84 ± 0.27 ± 0.23</td>
<td>5.0 ± 1.3</td>
<td>6.84 ± 0.24$^{+0.21}_{-0.27}$</td>
</tr>
<tr>
<td>$pK_S^0\pi^0$</td>
<td>1.87 ± 0.13 ± 0.05</td>
<td>1.65 ± 0.50</td>
<td></td>
</tr>
<tr>
<td>$pK_S^0\pi^+\pi^-$</td>
<td>1.53 ± 0.11 ± 0.09</td>
<td>1.30 ± 0.35</td>
<td></td>
</tr>
<tr>
<td>$pK^-\pi^+\pi^0$</td>
<td>4.53 ± 0.23 ± 0.30</td>
<td>3.4 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>$\Lambda\pi^+$</td>
<td>1.24 ± 0.07 ± 0.03</td>
<td>1.07 ± 0.28</td>
<td></td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^0$</td>
<td>7.01 ± 0.37 ± 0.19</td>
<td>3.6 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>$\Lambda\pi^+\pi^-\pi^+$</td>
<td>3.81 ± 0.24 ± 0.18</td>
<td>2.6 ± 0.7</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^0\pi^+$</td>
<td>1.27 ± 0.08 ± 0.03</td>
<td>1.05 ± 0.28</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\pi^0$</td>
<td>1.18 ± 0.10 ± 0.03</td>
<td>1.00 ± 0.34</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\pi^+\pi^-$</td>
<td>4.25 ± 0.24 ± 0.20</td>
<td>3.6 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>$\Sigma^+\omega$</td>
<td>1.56 ± 0.20 ± 0.07</td>
<td>2.7 ± 1.0</td>
<td></td>
</tr>
</tbody>
</table>

- BF for $pK^-\pi^+$ is consistent with PDG2014 within 2$\sigma$.
- The precision of absolute BFs of 12 modes are improved significantly.
- Also obtained $N_{\Lambda_c\Lambda_c} = (105.9 ± 4.8 ± 0.5) \times 10^3$
Observation of $\Lambda_c^+ \rightarrow nK_S\pi^+$

- First direct measurement in a final state involving a neutron
- Test if Isospin symmetry holds in charmed baryon decay (after it fails in charmed meson)

First Observation!

Simultaneous 2D fit

\[ \Sigma(n\pi)\pi\pi \]

\[
B(\Lambda_c^+ \rightarrow nK^0\pi^+) = (1.82 \pm 0.23 \pm 0.11)\%
\]

\[
B(\Lambda_c^+ \rightarrow n\bar{K}^0\pi^+)/B(\Lambda_c^+ \rightarrow p\bar{K}^-\pi^+) = 0.62 \pm 0.09
\]

\[
B(\Lambda_c^+ \rightarrow n\bar{K}^0\pi^+)/B(\Lambda_c^+ \rightarrow p\bar{K}^0\pi^0) = 0.97 \pm 0.16
\]

PRL 118, 112001 (2017)
$\Lambda_c^+ \to p\pi^+\pi^-$ and $pK^+K^-$

- ST method relative BF w.r.t. the $pK\pi$ mode
- First observation of Singly Cabibbo Suppressed (SCS) decay $\Lambda_c^+ \to p\pi^+\pi^-$
- Improved measurements on the SCS decays, $\Lambda_c^+ \to p\Phi$ and $\Lambda_c^+ \to pK^+K^-$ (non-$\Phi$)

### Decay modes

<table>
<thead>
<tr>
<th>Decay modes</th>
<th>$B_{\text{mode}}/B_{\text{ref}}$ (This work)</th>
<th>$B_{\text{mode}}/B_{\text{ref}}$ (PDG average)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c^+ \to p\pi^+\pi^-$</td>
<td>$(6.70 \pm 0.48 \pm 0.25) \times 10^{-2}$</td>
<td>$(6.9 \pm 3.6) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p\phi$</td>
<td>$(1.81 \pm 0.33 \pm 0.13) \times 10^{-2}$</td>
<td>$(1.64 \pm 0.32) \times 10^{-2}$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to pK^+K^-$ (non-$\Phi$)</td>
<td>$(9.36 \pm 2.22 \pm 0.71) \times 10^{-3}$</td>
<td>$(7 \pm 2 \pm 2) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p\pi^+\pi^-$</td>
<td>$B_{\text{mode}}$ (This work)</td>
<td>$B_{\text{mode}}$ (PDG average)</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p\phi$</td>
<td>$(3.91 \pm 0.28 \pm 0.15 \pm 0.24) \times 10^{-3}$</td>
<td>$(3.5 \pm 2.0) \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to p\phi$</td>
<td>$(1.06 \pm 0.19 \pm 0.08 \pm 0.06) \times 10^{-3}$</td>
<td>$(8.2 \pm 2.7) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Lambda_c^+ \to pK^+K^-$ (non-$\Phi$)</td>
<td>$(5.47 \pm 1.30 \pm 0.41 \pm 0.33) \times 10^{-4}$</td>
<td>$(3.5 \pm 1.7) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

*PRL 117, 232002 (2016)*
$\Lambda_c^+ \to p\eta$ and $p\pi^0$

- First evidence of the SCS decay, $\Lambda_c^+ \to p\eta$ (4.2σ stat. significance)
- No signals seen in $\Lambda_c^+ \to p\pi^0$
- Predicted BFs vary under different theoretical models (SU(3) symmetry and FSI)

**PRD 95, 111102(R) (2017)**

<table>
<thead>
<tr>
<th>$\Lambda_c^+ \to p\eta$</th>
<th>$\Lambda_c^+ \to p\pi^0$</th>
<th>$\frac{B_{\Lambda_c^+ \to p\pi^0}}{B_{\Lambda_c^+ \to p\eta}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESIII</td>
<td>$1.24 \pm 0.29$</td>
<td>$&lt;0.27$</td>
</tr>
<tr>
<td>Sharma et al. [3]</td>
<td>$0.2^{+0.2}_{-0.1}$</td>
<td>$0.2$</td>
</tr>
<tr>
<td>Uppal et al. [4]</td>
<td>$0.3$</td>
<td>$0.1$–$0.2$</td>
</tr>
<tr>
<td>S. L. Chen et al. [12]</td>
<td>$0.11$–$0.36^*$</td>
<td>$0.3$–$0.7$</td>
</tr>
<tr>
<td>Cai-Dian Lü et al. [13]</td>
<td>$0.45$</td>
<td>$&lt;0.24$</td>
</tr>
</tbody>
</table>

*a Assumed to have a positive sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.

*b Assumed to have a negative sign for the p-wave amplitude of $\Lambda_c^+ \to \Xi^0 K^+$.

*c Calculated relying on different values of parameters b and α.
\[ \Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+ \pi^0 \]

- **First observation** of CF decay, \( \Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+ \pi^0 \)
- **Improved BF** on \( \Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+ \)
- \( \Sigma^- \rightarrow n\pi^- \) is reconstructed.

Fit to \( M_{n\pi^-} - M_n \) to extract the signal yield

\[
M_{n\pi^-} = \sqrt{(E_{\text{beam}} - E_{\pi^+\pi^+})^2 - | \vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+} |^2}
\]

\[
M_n = \sqrt{(E_{\text{beam}} - E_{\pi^+\pi^+\pi^-})^2 - | \vec{p}_{\Lambda_c^+} - \vec{p}_{\pi^+\pi^+\pi^-} |^2}
\]

\[
\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+ \pi^0) = (2.11 \pm 0.33 \pm 0.14)\% \\
\mathcal{B}(\Lambda_c^+ \rightarrow \Sigma^- \pi^+ \pi^+) = (1.81 \pm 0.17 \pm 0.09)\%
\]

*PLB 772, 388 (2017)*
\[ \Lambda_c^+ \rightarrow \Lambda + X \]

- Currently PDG: \( \text{BF}(\Lambda_c^+ \rightarrow \Lambda + X) = (35 \pm 11)\% \)
  - Large rate, but also with large uncertainty...
- DT method: ST with \( pK\pi \) and \( pK_S \)
- Extract yields from 2D distributions in bins of \( p_{\pi\pi} \) and \( |\cos \theta| \)
  where \( \theta \) is the polar angle w.r.t. the beam pipe.

\[ \text{BF}(\Lambda_c^+ \rightarrow \Lambda + X) = (36.98 \pm 2.18)\% \]

\[ A_{CP} = +0.02 \pm 0.06 \]
\[ \Lambda_c^+ \to \Lambda l^+ v_l \]

- \( \Lambda_c^+ \to \Lambda l^+ v_l \) is a \( c \to s l^+ v_l \) dominated process
- First **absolute BF of semi-leptonic mode**
- First measurement of its **muonic mode**!
- Useful for calibrating the Lattice-QCD calculations

PRL 115, 221805 (2015)

PLB 747, 42 (2017)

\[ B(\Lambda_c^+ \to \Lambda e^+ v_e) = (3.63 \pm 0.38 \pm 0.20)\% \]

\[ B(\Lambda_c^+ \to \Lambda \mu^+ v_\mu) = (3.49 \pm 0.46\text{(stat)} \pm 0.27\text{(syst)})\% \]

\[ \frac{B(\Lambda_c^+ \to \Lambda \mu^+ v_\mu)}{B(\Lambda_c^+ \to \Lambda e^+ v_e)} = 0.96 \pm 0.16\text{(stat)} \pm 0.04\text{(syst)} \]
The Born Cross Section of $e^+e^- \rightarrow \gamma^* \rightarrow B\bar{B}$ can be parameterized in terms of electromagnetic form factors:

$$
\sigma_{BB}(q) = \frac{4\pi \alpha^2 C \beta}{3q^2} \left[ |G_M(q)|^2 + \frac{1}{2\tau} |G_E(q)|^2 \right]
$$

- Baryon velocity: $\beta = \sqrt{1 - 4m_B^2c^4/q^2}$, $\tau = q^2/(4m_B^2c^4)$

- For charged Baryon, the Coulomb factor $C$ will result in a non-zero cross section at threshold.

**Coulomb enhanced factor in $e^+e^- \rightarrow \gamma^* \rightarrow \Lambda_c^+\bar{\Lambda}_c^-$?**
Summary

- BESIII took a data set of 567 pb$^{-1}$ and improved various $\Lambda_c$ BFs significantly
- Measured some new decay modes
- Continue to study on precise measurement of $\Lambda_c$ decays by the near-threshold data

More potentials

- A larger data set
  - BESIII will keep collecting data in the next ~ decade
  - The current plan is to accumulate 1M $\Lambda_c$ in total

Thank you!