Measurement of masses and widths of $\Sigma_c$ baryons at Belle

Lake Louise Winter Institute, Feb 19, 2015
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On behalf of the Belle Collaboration
**Σc Baryons**

- Σc baryons have very short lifetime → finite decay widths
  - Decays into Λc⁺π⁻ (≈100%)
    - Σc⁰ → Λc⁺π⁻ / Σc⁺⁺ → Λc⁺π⁺ with Λc⁺ → pK⁻π⁺

- The uncertainties of the current world average values are a bit large
  - e.g. ≈10% for widths

<table>
<thead>
<tr>
<th></th>
<th>Σc(2455)⁰</th>
<th>Σc(2455)⁺⁺</th>
<th>Σc(2520)⁰</th>
<th>Σc(2520)⁺⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>2453.74 ± 0.16</td>
<td>2453.98 ± 0.16</td>
<td>2518.8 ± 0.6</td>
<td>2517.9 ± 0.6</td>
</tr>
<tr>
<td>Mass Difference</td>
<td>167.27 ± 0.08</td>
<td>167.52 ± 0.08</td>
<td>232.3 ± 0.5</td>
<td>231.4 ± 0.6</td>
</tr>
<tr>
<td>Decay Widths</td>
<td>2.16 ± 0.26</td>
<td>2.26 ± 0.25</td>
<td>14.5 ± 1.5</td>
<td>14.9 ± 1.5</td>
</tr>
</tbody>
</table>

* Large uncertainties
\[ \Sigma_c \text{ Baryons} \]

- **Isospin mass splittings**
  - Since u and d quarks have a bit different masses, their compositions may have different masses, therefore, one may expect that
  \[ m(u) < m(d) \rightarrow m(\Sigma_c^{++}) \text{(uuc)} < m(\Sigma_c^0) \text{(ddc)} \]
  - Experimental measurements show opposite results
    \[ m(\Sigma_c(2455)^{++}) - m(\Sigma_c(2455)^0) = 0.24 \pm 0.09 \quad \text{(PDG 2014)} \]

- **Theoretical models calculate the mass splittings with considering various contributions**
  - e.g. electromagnetic potential, hyperfine interaction, ...
  - Precise measurements of the masses of \( \Sigma_c \) baryons will test the models

<table>
<thead>
<tr>
<th>Theoretical Expectations</th>
<th>( m(\Sigma_c(2455)^{++}) - m(\Sigma_c(2455)^0) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chan, <em>Phys. Rev. D</em> 31, 204 (1985)</td>
<td>0.18</td>
</tr>
<tr>
<td>Cutkosky and Geiger, <em>Phys. Rev. D</em> 48, 1315 (1993)</td>
<td>0.84</td>
</tr>
<tr>
<td>Silvestre-Brac <em>et al.</em>, <em>J. Phys. G</em> 29, 2685 (2003)</td>
<td>0.27 ± 0.11</td>
</tr>
</tbody>
</table>
Data Samples and Backgrounds

- Belle data of 711 fb⁻¹ taken at Υ(4S) used for the study
- Mass differences after event selections

• Backgrounds are classified as:
  - Feed-down backgrounds from excited Λ⁺ states
  - Reflection backgrounds from D⁺⁺ decays
  - Contribution from Ξ⁺⁺⁰ decay
  - Random background due to wrong combinations
Feed-down Backgrounds from $\Lambda_c^{*+}$ Decays

- $\Lambda_c^{*+}$ decays can be either signal or background, e.g.:
  - $\Lambda_c^{*+} \rightarrow \Sigma_c^0 \pi^+$ is signal for $\Sigma_c^0$ measurement, but background for $\Sigma_c^{++}$ measurement
- In order to extract the backgrounds, a tagging method is used
  - By appending an additional $h^\pm$, and test the mass with defined $\Lambda_c^{*+}$ signal region, the candidates are tagged
- Obtained feed-down backgrounds are corrected with detection efficiency of the additional charged hadrons as a function of their momenta

**Graphical Content:**
- Plots showing the distribution of events with and without feed-down subtraction for $\Sigma_c^0$ and $\Sigma_c^{++}$ candidates.
- Heatmaps illustrating the distribution of masses for $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ with and without feed-down subtraction.

**Legend:**
- Red: Signal region of $\Lambda_c(2595)^+$
- Blue: Signal region of $\Lambda_c(2625)^+$

**Data:**
- [302, 312] MeV/c^2 for $\Lambda_c(2595)^+$
- [336, 347] MeV/c^2 for $\Lambda_c(2625)^+$
Reflection Backgrounds from $D^{*+}$ Decays

- $D^{*+}$ decays may contribute as a background source
  - e.g. $D^{*+} \rightarrow D^0 \Xi^{+}_s$ with $D^0 \rightarrow K^- \pi^+ \pi^+ \pi^-$

  Background contribution of $pK^- \pi^+ \pi^+$ is possible

- The background contribution from $D^{*+}$ decays are confirmed with MC
  - It appears only in $m(pK^- \pi^+ \pi^-) - m(pK^- \pi^+)$
Random Backgrounds

- Random backgrounds are classified by true and fake $\Lambda_c^+$
  - Associated with fake $\Lambda_c^+$: Extractable by using $\Lambda_c^+$ sideband (sideband subtraction)
  - Since the reflection backgrounds from $D^{*+}$ decays is also a random background associated with fake $\Lambda_c^+$, it appears here as well $\rightarrow$ no explicit description of the reflection background needed

\[
\begin{align*}
&\text{[2278.07, 2295.27] MeV/c}^2 \\
&\text{[2305.58, 2314.18] MeV/c}^2 \\
&\text{[2259.16, 2267.76] MeV/c}^2
\end{align*}
\]
Random Backgrounds

• Random backgrounds are classified by true and fake $\Lambda_c^+$
  - Associated with true $\Lambda_c^+$: No way to extract from data
  - Modeled with:
    \[ (\Delta m - m_{\pi})^{c_0} e^{-c_1(\Delta m - m_\pi)} \]
  - The modeling is confirmed by fitting to MC samples

[Graphs showing data and fit for $\Sigma_c^0$ and $\Sigma_c^{++}$ candidates]
Contribution from $\Xi_c^0$ Decays

- Small peak is found in $m(pK^-\pi^+\pi^-)-m(pK^-\pi^+)$

  ![Small peak is shown only here](image)

- The peak position is $\sim 185 \text{ MeV}/c^2$
  - If a nominal mass of $\Lambda_c^+$ is added, it is compatible with $\Xi_c^0$ mass
    - $m(\text{peak}) + m(\Lambda_c^+) = 185 + 2286.46$ (PDG 2013) = $2471.46 \text{ MeV}/c^2$
    - $m(\Xi_c^0) = 2470.88$ (PDG 2013)

- Because of the charge conservation, it makes a sense that the peak only appears in the neutral mode (there is no $\Xi_c^{++}$)
Contribution from $\Xi_c^0$ Decays

- From MC and data, this background contribution is confirmed
  - $\Xi_c^0 \to \Lambda_c^+ \pi^-$ is dominant, $\Xi_c^0 \to p K^- \pi^+ \pi^-$ is negligible
**Fit Procedure**

- Because of the finite decay width, it should be considered with a detector resolution simultaneously by the convolution theorem

\[ M(m; m_0, \Gamma) = T(m; m_0, \Gamma) \otimes R(m) \]

\[ = \int_{-\infty}^{+\infty} T(m; m_0, \Gamma) R(m - m') dm' \]

- Detector response functions are obtained from MC with no \( \Sigma_c \) widths

![Graph 1](image1)

![Graph 2](image2)

- For \( \Sigma_c(2455)^{0/++} \)
  
  1.012 ± 0.001 MeV/c^2 on average

- For \( \Sigma_c(2520)^{0/++} \)
  
  1.578 ± 0.013 MeV/c^2 on average
Results

• Binned ML fit done with necessary components
  \((\Xi_c^0\) contribution is modeled by a Gaussian; mean=184.08 ± 0.15, width=1.21 ± 0.18 in MeV/c^2\)

\[
\begin{array}{cccc}
\text{(MeV/c}^2\text{)} & \Sigma_c(2455)^0 & \Sigma_c(2455)^{++} & \Sigma_c(2520)^0 & \Sigma_c(2520)^{++} \\
m(\Sigma_c)-m(\Lambda_c^+) & 167.29 \pm 0.01 & 167.51 \pm 0.01 & 231.98 \pm 0.11 & 231.99 \pm 0.10 \\
\text{Decay Widths} & 1.76 \pm 0.04 & 1.84 \pm 0.04 & 15.41 \pm 0.41 & 14.77 \pm 0.25 \\
m(\Sigma_c)^* & 2453.75 \pm 0.01 & 2453.97 \pm 0.01 & 2518.44 \pm 0.11 & 2518.45 \pm 0.10 \\
\end{array}
\]

* Mass is calculated by adding a nominal \(\Lambda_c^+\) mass to \(m(\Sigma_c)-m(\Lambda_c^+)\)
Systematic Uncertainties

- Major contributions of the systematic uncertainties:
  - Resolution model
    ‣ Discrepancy between data and MC
    ‣ Statistical fluctuation of the resolution model
  - Momentum scale
  - Fit model
    ‣ Bias by the fitter
    ‣ Binning effect
    ‣ Effect of the fit ranges
  - Background model
    ‣ Feed-down correction
    ‣ Statistical fluctuation of the random backgrounds with fake \( \Lambda_c^+ \)
    ‣ Various modeling of the random background with true \( \Lambda_c^+ \)
Systematics: Resolution Model

- Discrepancy between data and MC
  - Studied by using a control sample, \( D^{*+} \rightarrow D^0 \pi_s^+ \)
  - By comparing the resolution of \( m(D^{*+}) - m(D^0) \) between data and MC, a (single-sided) systematic uncertainties are assigned for the decay widths
    - -0.19 MeV/c^2 for \( \Gamma(\Sigma_c(2455)^{0/++}) \)
    - -0.25 MeV/c^2 for \( \Gamma(\Sigma_c(2520)^0) \)
    - -0.24 MeV/c^2 for \( \Gamma(\Sigma_c(2520)^{++}) \)

- Statistical fluctuation of the resolutions by ±1\( \sigma \)
  - Small uncertainties are found for the decay widths
    - 0.01 and 0.04 MeV/c^2 for \( \Gamma(\Sigma_c(2455)^{0/++}) \) and \( \Gamma(\Sigma_c(2520)^{0/++}) \), respectively
Systematics: Momentum Scale

• Possible bias in the measurements of charged particle momenta
  - Wrong momentum scale of the detector
  - The effect is studied with the control sample of $D^{*+}$ decay
  - By comparing $m(D^{*+}) - m(D^0)$ with the world average, the uncertainty is assigned to be $0.02$ MeV/$c^2$ for the mass difference
Systematic Uncertainties

- Major contributions of the systematic uncertainties:
  - Resolution model
    ‣ Discrepancy between data and MC
    ‣ Statistical fluctuation of the resolution model
  - Momentum scale
  - Fit model
    ‣ Bias by the fitter
    ‣ Binning effect
    ‣ Effect of the fit ranges
  - Background model (all negligible)
    ‣ Feed-down correction
    ‣ Statistical fluctuation of the random backgrounds with fake $\Lambda_c^\pm$
    ‣ Various modeling of the random background with true $\Lambda_c^\pm$

<table>
<thead>
<tr>
<th>(MeV/c$^2$)</th>
<th>$\Sigma_c(2455)^0$</th>
<th>$\Sigma_c(2455)^{++}$</th>
<th>$\Sigma_c(2520)^0$</th>
<th>$\Sigma_c(2520)^{++}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta m$</td>
<td>$\Gamma$</td>
<td>$\Delta m$</td>
<td>$\Gamma$</td>
</tr>
<tr>
<td>Resolution model</td>
<td>—</td>
<td>$^{+0.01}_{-0.19}$</td>
<td>—</td>
<td>$^{+0.01}_{-0.19}$</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>$\pm 0.02$</td>
<td>—</td>
<td>$\pm 0.02$</td>
<td>—</td>
</tr>
<tr>
<td>Fit model</td>
<td>$\pm 0.01$</td>
<td>$\pm 0.09$</td>
<td>$\pm 0.03$</td>
<td>$\pm 0.20$</td>
</tr>
<tr>
<td>Total</td>
<td>$\pm 0.02$</td>
<td>$^{+0.09}_{-0.21}$</td>
<td>$\pm 0.04$</td>
<td>$^{+0.20}_{-0.32}$</td>
</tr>
</tbody>
</table>
Results

• The results are the most precise to date
  • \( m(\Sigma_c) \)'s are calculated by adding a nominal \( \Lambda_c^+ \) mass to the mass difference
    • The most systematic uncertainties cancels (e.g. momentum scale)

<table>
<thead>
<tr>
<th>( (\text{MeV}/c^2) )</th>
<th>( m(\Sigma_c) - m(\Lambda_c^+) )</th>
<th>Decay widths (( \Gamma ))</th>
<th>( m(\Sigma_c) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Sigma_c(2455)^0 )</td>
<td>( 167.29 \pm 0.01 \pm 0.02 )</td>
<td>( 1.76 \pm 0.04 \pm 0.09 \pm 0.21 )</td>
<td>( 2453.75 \pm 0.01 \pm 0.02 \pm 0.14 )</td>
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<tr>
<td>( \Sigma_c(2455)^{++} )</td>
<td>( 167.51 \pm 0.01 \pm 0.02 )</td>
<td>( 1.84 \pm 0.04 \pm 0.07 \pm 0.20 )</td>
<td>( 2453.97 \pm 0.01 \pm 0.02 \pm 0.14 )</td>
</tr>
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<td>( \Sigma_c(2520)^0 )</td>
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<td>( 2518.45 \pm 0.10 \pm 0.02 \pm 0.14 )</td>
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Summary

• Charmed baryons are an interesting testbed to test QCD models
  • Properties of $\Sigma_c$ baryons are not well established
  • Isospin mass splitting contradicts a naive expectation
  • Precise measurements will be helpful to develop theoretical models

• Measurements of masses and decay widths of the $\Sigma_c(2455)^{0/++}$ and $\Sigma_c(2520)^{0/++}$ baryons have been performed at Belle
  • Various sources of the backgrounds are analyzed
  • Systematic uncertainties reduces significantly
  • The results are most precise to date
Backup Slides
Data Samples and Selection Criteria

- Integrated luminosity of 711 fb^{-1} collected at \( \Upsilon(4S) \) resonance
  - \( \Lambda_c^+ \) decay chain is chosen to be \( \Lambda_c^+ \rightarrow pK^-\pi^+ \) (BR \( \sim \) 5%)

- Track selection for all charged tracks
  - Impact parameters
    - |dr| < 1 cm (radial position from the interaction point (IP))
    - |dz| < 3 cm (z-position from IP)
  - SVD hit requirements
    - > 1 hits both r-\( \phi \) and z direction

- Particle identification
  - \( P(K:\pi) > 0.6 \) for K / \( P(\pi:K) > 0.6 \) for \( \pi \) / \( P(p:h) > 0.9 \) for p (h={K,\( \pi \)})
  - PID efficiencies (\( \varepsilon: \) efficiency / f: fake rate)
    - \( \varepsilon(K:\pi) = (90.58 \pm 0.53)\% \), \( f(K:\pi) = (9.77 \pm 0.33)\% \)
    - \( \varepsilon(\pi:K) = (92.63 \pm 0.69)\% \), \( f(\pi:K) = (7.84 \pm 0.33)\% \)
    - \( \varepsilon(\pi_s:K) = (99.18 \pm 0.89)\% \), \( f(\pi_s:K) = (5.93 \pm 0.52)\% \)
Data Samples and Selection Criteria

- **$\Lambda_c^+$ reconstruction**
  - Using $p, K^-, \pi^+$ tracks, $\Lambda_c^+$ candidates are reconstructed
  - Daughter tracks are refit to a common vertex ($\Lambda_c^+$ decay vertex)

- **$\Sigma_c$ reconstruction**
  - Attaching $\pi_s$ track to $\Lambda_c^+$ candidate, $\Sigma_c$ candidates are reconstructed
  - $\Lambda_c^+$ production vertex is found by fitting $\Lambda_c^+$ trajectory to IP
  - $\pi_s$ track is refit to the $\Lambda_c^+$ production vertex

- **$\Sigma_c$ selection**
  - $m(\Lambda_c^+) \in [2278.07, 2295.79] \text{ MeV/c}^2$
    (±2.1σ around $m(\Lambda_c^+$))
  - $p(\Sigma_c) > 2.0 \text{ GeV/c}$
  - (Confidence level of $\pi_s$ vertex fit) > 0.1%
Feed-down Backgrounds from $\Lambda_c^{*+}$ Decays

- Decays of the excited states of $\Lambda_c^+$ baryon can make contributions

<table>
<thead>
<tr>
<th>Mass (MeV/c²)</th>
<th>Decay modes</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_c(2595)^+$</td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-$</td>
<td>~ 67%</td>
</tr>
<tr>
<td>2592.25 ± 0.28</td>
<td>$\Sigma_c(2455)^{++}\pi^-\pi^-$</td>
<td>(24 ± 7)%</td>
</tr>
<tr>
<td></td>
<td>$\Sigma_c(2455)^0\pi^+\pi^-$</td>
<td>(24 ± 7)%</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-_{3\text{-body}}$</td>
<td>(18 ± 10)%</td>
</tr>
<tr>
<td>$\Lambda_c(2625)^+$</td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-$</td>
<td>~ 67%</td>
</tr>
<tr>
<td>2628.11 ± 0.19</td>
<td>$\Sigma_c(2455)^{++}\pi^-\pi^-$</td>
<td>&lt; 5 @ 90% C.L.</td>
</tr>
<tr>
<td></td>
<td>$\Sigma_c(2455)^0\pi^+\pi^-$</td>
<td>&lt; 5 @ 90% C.L.</td>
</tr>
<tr>
<td></td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-_{3\text{-body}}$</td>
<td>Large</td>
</tr>
<tr>
<td>$\Lambda_c(2765)^+$</td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-_{3\text{-body}}$</td>
<td>seen</td>
</tr>
<tr>
<td>2766.6 ± 2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c(2880)^+$</td>
<td>$\Lambda_c^{+}\pi^+\pi^-\pi^-_{3\text{-body}}$</td>
<td>seen</td>
</tr>
<tr>
<td>2881.53 ± 0.35</td>
<td>$\Sigma_c(2455)^{0/+/-}\pi^+\pi^-\pi^-$</td>
<td>seen</td>
</tr>
<tr>
<td></td>
<td>$\Sigma_c(2520)^{0/+/-}\pi^+\pi^-\pi^-$</td>
<td>seen</td>
</tr>
</tbody>
</table>

- Those contributions can be either signal or background events
  - $\Lambda_c(2625)^+\rightarrow\Sigma_c(2455)^{0}\pi^+\pi^-$ (final state: $pK^-\pi^+\pi^-\pi^+\pi^+$): Signal events for $\Sigma_c(2455)^0$ but background events for $\Sigma_c(2455)^{++}$
  - $\Lambda_c(2625)^+\rightarrow\Sigma_c(2455)^{++}\pi^-$: Background events for $\Sigma_c(2455)^0$ but signal events for $\Sigma_c(2455)^{++}$
  - $\Lambda_c(2625)^+\rightarrow\Lambda_c^{+}\pi^+\pi^-\pi^-_{3\text{-body}}$: Background events for both
Feed-down Backgrounds from $\Lambda_c^{*+}$ Decays

- The contributions from $\Lambda_c(2765)^+$ and $\Lambda_c(2880)^+$ are kinematically negligible

From MC simulations (1M events generated for each channels)

* Branching fractions are not accounted
Feed-down Backgrounds from $\Lambda_c^*$ Decays

- The contributions from $\Lambda_c(2595)^+$ and $\Lambda_c(2625)^+$ are found to be dominant
Feed-down Backgrounds from $\Lambda_c^{*+}$ Decays

- **Feed-down corrections**
  - Partial reconstruction of $pK^{-}\pi^+\pi^+\pi^-$ events
    $\rightarrow$ no efficiency involves
  - Tagging by attaching an additional charged track
    $\rightarrow$ efficiency involves
  - Since the feed-down obtained by the tagging method reflects the detector efficiency, it should be corrected to get real feed-down normalization
    \[
    N_{\text{corrected}}(\text{Feed-down}) = \frac{N_{\text{uncorrected}}(\text{Feed-down})}{\epsilon_{\text{tracking}}(h^\pm) \cdot \epsilon_{\text{acceptance}}(h^\pm)}
    \]
    $\sim$74% on average

- **The feed-down shape depends on charged track momentum**
  - The efficiencies are obtained as a function of charged track momentum
  - The correction is applied as a function of charged track momentum
Feed-down Backgrounds from $\Lambda_c^{*-}$ Decays

- Before and after the feed-down subtraction

![Graphs showing feed-down backgrounds from $\Lambda_c^{*-}$ decays with and without subtraction.](image-url)
Backgrounds from $\Xi_c^0$ Decays

- From MC and data, this background contribution is confirmed
  - Data also shows that the peak is related to $\Lambda_c^+$ and $\Xi_c^0$ simultaneously
• However, there is no known decays of $\Xi_c^0 \rightarrow \Lambda_c^+ \pi^-$ or $\Xi_c^0 \rightarrow pK^- \pi^+ \pi^-$
  - Theoretically possible (Cabibbo-suppressed) but no experimental observation to date
  - No such an observation of which charmed baryon decays into charmed baryon through weak decay
  - The observation of this will be addressed in a separate study

\[ \Xi_c^0 \rightarrow pK^- \pi^+ \pi^- \]

\[ \Xi_c^0 \rightarrow \Lambda_c^+ \pi^- \]
Fit Procedure

• Since the $\Sigma_c$ baryons have finite decay widths, the decay widths and detector resolutions should be considered simultaneously in the modeling

$$M(\Delta m; \Delta m_0, \Gamma) = T(\Delta m; \Delta m_0, \Gamma) \otimes R(\Delta m)$$

$$= \int_{-\infty}^{+\infty} T(\Delta m; \Delta m_0, \Gamma) R(\Delta m - \Delta m') d(\Delta m')$$

• Relativistic Breit-Wigner function is employed for the theoretical model

$$\frac{dN}{dm} \propto m \cdot \Gamma(m) \left(\frac{m^2 - m_0^2}{(m_0^2 - m^2)^2 + m_0^2 \cdot \Gamma^2(m)}\right)$$

where

$$\Gamma(m) = \Gamma_0 \frac{m_0}{m} \left(\frac{q}{q_0}\right)^{2L+1} \frac{F(Rq) \Gamma_0}{F(Rq_0)}$$

$$q = \sqrt{(m^2 - (m_{\Sigma_c}^+ + m_{\pi}^2)^2)(m^2 - (m_{\Sigma_c}^+ - m_{\pi})^2)}$$

$$2m$$

• Since $L=0$ for the $\Sigma_c$ baryons in SM, that is, the width reduces and Blatt-Weisskopf form factor $F(Rq)=1$, therefore,

$$\frac{dN}{dm} \propto \frac{m \cdot \left(\Gamma_0 \frac{m_0}{m} \frac{q}{q_0}\right)}{(m_0^2 - m^2)^2 + m_0^2 \cdot \left(\Gamma_0 \frac{m_0}{m} \frac{q}{q_0}\right)^2}$$
Systematics: Fit Model

- Fit bias from the fitter is estimated with pseudo-experiments
  - Each pseudo-experiment has the same input values obtained from data
  - Only small uncertainties of 0.02 and 0.04 MeV/c² for \( \Sigma_c(2455)^0/++ \) and \( \Sigma_c(2520)^0/++ \) widths

- Binning effect
  - Fits are tested with various bin size from 0.1 to 1.0 MeV/c²
  - Uncertainties:
    - For \( m(\Sigma_c)-m(\Lambda_c^+) \): negligible
    - For \( \Gamma(\Sigma_c) \): 0.09, 0.06, 0.04, and 0.05 MeV/c² for \( \Sigma_c(2455)^0 \), \( \Sigma_c(2455)^++ \), \( \Sigma_c(2520)^0 \), \( \Sigma_c(2520)^++ \), respectively

- Fit ranges
  - Fits are tested with various fit ranges
  - Uncertainties:
    - For \( m(\Sigma_c)-m(\Lambda_c^+) \): 0.03 and 0.01 MeV/c² for \( \Sigma_c(2520)^0 \) and \( \Sigma_c(2520)^++ \)
    - For \( \Gamma(\Sigma_c) \): 0.19 and 0.17 MeV/c² for \( \Sigma_c(2520)^0 \) and \( \Sigma_c(2520)^++ \)

10,000 pseudo-experiments are performed
Systematics: Background Model

- Feed-down correction

\[
\frac{\delta N_{\text{corrected}}(\text{Feed-down})}{N_{\text{corrected}}(\text{Feed-down})} = \left( \frac{\delta N_{\text{uncorrected}}(\text{Feed-down})}{N_{\text{uncorrected}}(\text{Feed-down})} \right)^2 + \left( \frac{\delta \epsilon_{\text{tracking}}(h^\pm)}{\epsilon_{\text{tracking}}(h^\pm)} \right)^2 + \left( \frac{\delta \epsilon_{\text{acceptance}}(h^\pm)}{\epsilon_{\text{acceptance}}(h^\pm)} \right)^2 \right]^{1/2}
\]

\begin{align*}
0.46 \% & \quad 1.80\% & \quad 0.17\%
\end{align*}

- Total uncertainty is estimated to be \(1.87\%\) - negligible

- Statistical fluctuation of the random background with fake \(\Lambda_c^+\)
  - Normalizations of fake \(\Lambda_c^+\) backgrounds by \(\pm 1\sigma\)
  - No uncertainties are found

- Various modeling of the random background with true \(\Lambda_c^+\)
  - e.g.
    \[c_0(\Delta m - m_\pi)^{1/2} + c_1(\Delta m - m_\pi)^{3/2}\]
    \[c_0(\Delta m - m_\pi)^{1/2} + c_1(\Delta m - m_\pi)^{3/2} + c_2(\Delta m - m_\pi)^{5/2}\]

- No uncertainties are found