Measurements of charm lifetimes at Belle II

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(for the Belle II collaboration)
7 July 2022
Motivation and status

- Heavy Quark Expansion (HQE) predict beauty and charm hadron lifetimes
  - Charm hadron lifetime prediction is challenging: significant higher order correction+QCD contributions
  - Charm lifetime measurements allow for HQE validation and refinement increasing reliability and precision of SM predictions in flavor dynamics
- The best measurements of charm-meson lifetimes date back to FOCUS; LHCb recently reported precise relative measurements of charm-baryon lifetimes
- The LHCb measurements changed the lifetime hierarchy of singly charmed baryons:
  \[ \tau(\Omega_c^0) < \tau(\Xi_c^-) < \tau(\Lambda_c^+) \Rightarrow \tau(\Xi_c^-) < \tau(\Lambda_c^+) < \tau(\Omega_c^0) < \tau(\Xi_c^+) \]
- Possible reasons why HQE has initially failed are being debated (Science Bulletin 67 (2022) 445-447, arXiv:2204.11935)
- No other experimental confirmation of the LHCb results
SuperKEKB and Belle II

- SuperKEKB: asymmetric energy $e^+e^-$ collider
  - Squeeze the beam at collision point: $(x=10, y=0.2, z=250) \, \mu m$ compared to $(100, 1, 6000) \, \mu m$ at Belle.
  - Charm hadrons produced in $e^+e^- \rightarrow c\bar{c}$ with large boost; large center-of-mass momentum ($\gtrsim 2.5 \, \text{GeV}/c$) required to select promptly produced charm hadrons
- Belle II detector capabilities:
  - Good vertex resolution ($\sim15 \, \mu m$): 2x better than Belle
  - Precise alignment of vertex detector
  - Precise calibration of final state particle momenta
- Belle II can measure absolute lifetimes

424 fb$^{-1}$ data collected so far

World record instantaneous luminosity: $4.7 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$ (June 2022)
**Lifetime fit**

- Proper decay time calculated from flight length between production and decay vertices and momentum as:
  \[ t = \frac{m}{p} (\vec{L} \cdot \hat{p}) \quad m - \text{known mass of the charm hadron} \]
- Lifetime (\(\tau\)): unbinned maximum-likelihood fit to \((t, \sigma_t)\)
  - simultaneous fit to signal and sideband regions to constrain background
  - background fraction (\(f_b\)) is constrained from mass fit

  \[
  \text{PDF}(t, \sigma_t) = (1 - f_b) \int_0^\infty e^{-t_{\text{true}}/\tau} R(t - t_{\text{true}} | b, s\sigma_t) dt_{\text{true}} \text{PDF}_{\text{sig}}(\sigma_t) + f_b \text{PDF}_{\text{bkg}}(t, \sigma_t)
  \]

- All measurements are done in blind fashion, receive no input from simulation, and are absolute

- \(b\)-bias
- \(s\)-scale
- \(R\) - resolution function
  - Gaussian: for \(D^+, \Lambda_c^+\) and \(\Omega_c^0\)
  - Double Gaussian: for \(D^0\)
\section*{D lifetime}

- 171k and 59k signal candidates are reconstructed for 
  $D^{*+} \rightarrow (D^0 \rightarrow K^-\pi^+)\pi^+$ and $D^{*+} \rightarrow (D^+ \rightarrow K^-\pi^+\pi^+)\pi^0$ decays

- Remove $D$ from $B$ decays with $p^{CMS}(D^{*+}) > 2.5(2.6)$ GeV/$c$ for $D^0(D^+)$
  - Avoid possible bias in the lifetime measurement

- Neglected 0.2\% background in $D^0$ signal region (systematics assigned)

- 9\% background in $D^+$ signal regions is included in the fit
  - Background: zero-lifetime + two non-zero lifetime components

- Dominant systematics: vertex detector alignment and background modeling

<table>
<thead>
<tr>
<th>Source</th>
<th>$\tau(D^0)$ [fs]</th>
<th>$\tau(D^+)$ [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution model</td>
<td>0.16</td>
<td>0.39</td>
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<tr>
<td>Backgrounds</td>
<td>0.24</td>
<td>2.52</td>
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<tr>
<td>Detector alignment</td>
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<td>1.70</td>
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<td>Momentum scale</td>
<td>0.19</td>
<td>0.48</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>0.80</strong></td>
<td><strong>3.10</strong></td>
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</tbody>
</table>
$D$ lifetime

$\tau(D^0) = 410.5 \pm 1.1\,(\text{stat.}) \pm 0.8\,(\text{syst.}) \text{ fs}$  
$\tau(D^+) = 1030.4 \pm 4.7\,(\text{stat.}) \pm 3.1\,(\text{syst.}) \text{ fs}$


- More precise than and consistent with previous measurements
- Sub-1% accuracy establishes excellent detector performance
- Paves the way for additional lifetime measurements
$\Lambda_c^+$ lifetime

- Low-background sample of $\Lambda_c^+ \rightarrow pK^-\pi^+$
  - 116k signal with 7.5% background in the signal region
- Potential bias due to $\Xi_c^{0/+} \rightarrow \Lambda_c^+\pi^-/0$
  - veto applied and corrected for remaining contamination
- Resolution modeling and vertex detector alignment are dominant source of systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [fs]</th>
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<tbody>
<tr>
<td>$\Xi_c$ contamination</td>
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<tr>
<td>Resolution model</td>
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<td>Detector alignment</td>
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<td>Momentum scale</td>
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<td><strong>Total</strong></td>
<td><strong>0.77</strong></td>
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</table>
$\Lambda_c^+$ lifetime

*Belle II* preliminary result

$\tau(\Lambda_c^+) = 203.2 \pm 0.9\text{(stat.)} \pm 0.8\text{(syst.)} \text{ fs}$

arXiv: 2206.15227[hep-ex]

- World’s best measurement of the $\Lambda_c^+$ lifetime
- Consistent with current world averages
- Slight tension with CLEO measurement remains
- Benchmark for future baryon lifetime measurements
**Ω^0_c lifetime**

- ~90 signal candidates are reconstructed in the decay:
  \[ Ω^0_c → Ω^-π^+; Ω^- → Λ^0K^-; Λ^0 → pπ^- \]
  
- Background contamination in signal region: 33%

- Background: zero-lifetime + non-zero lifetime components

- First Belle II lifetime measurement with complex decay topology
  - Two secondary decay vertices

- Dominant systematics: Modeling of background and resolution

<table>
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<th>Source</th>
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<td>Fit bias</td>
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<td>Input charm masses</td>
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<td>Total</td>
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Ω^0_c lifetime

*Belle II* preliminary result, new at ICHEP2022

\[ \tau(\Omega^0_c) = 243 \pm 48 \text{(stat.)} \pm 11 \text{(syst.)} \text{ fs} \]

- \( \Omega^0_c \) is not the shortest lived singly charmed baryon
  - consistent with LHCb average
  - inconsistent with pre-LHCb world average at 3.4σ
- Demonstrate the capabilities of the Belle II detector for vertexing complex decay topologies
  - Benchmark for future measurements with complex decay topology
- Limited by statistics and can improve with larger samples and additional decay modes
Conclusion

- Absolute lifetime measurements of charm hadrons from Belle II:
  - Improved knowledge of $D$ lifetimes, with world-best measurements, after ~20 years
    \[
    \tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs} \\
    \tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs}
    \]
  - World’s best $\Lambda_c^+$ lifetime measurement
    \[
    \tau(\Lambda_c^+) = 203.2 \pm 0.9 \pm 0.8 \text{ fs}
    \]
    \textit{Belle II preliminary, arXiv: 2206.15227[hep-ex]}
  - Independent confirmation of LHCb's finding that $\Omega_c^0$ is not the shortest-lived weakly decaying charm baryon
    \[
    \tau(\Omega_c^0) = 243 \pm 48 \pm 11 \text{ fs}
    \]
    \textit{Belle II preliminary, new at ICHEP2022}
Backup
Belle II luminosity

![Belle II Online luminosity chart](image)

- Integrated luminosity
  - Recorded Weekly
- $\int L_{\text{Recorded}} dt = 427.79 \text{[fb}^{-1}]$

- $\Lambda_c^+ & \Omega_c^0$ lifetimes
- $D$ lifetimes

Updated on 2022/06/22 18:14 JST
**SuperKEKB and Belle II**

**Belle II:** general purpose detector situated at the interaction point of SuperKEKB.

**SuperKEKB:** asymmetric $e^+ - e^-$ collider operating at $\Upsilon(4S)$ resonance.

**Operation:**
- Recorded $\approx 430$ fb$^{-1}$;
- Achieved world record: $\mathcal{L} = 4.7 \cdot 10^{34}$ cm$^{-2}$/s (more than twice of KEKB/Belle).
## Weak modes of vertex detector misalignment

<table>
<thead>
<tr>
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<th>$\Delta r$</th>
<th>$r\Delta \phi$</th>
<th>$\Delta z$</th>
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<tbody>
<tr>
<td>$r$</td>
<td><strong>Radial expansion</strong></td>
<td><strong>Curl</strong></td>
<td><strong>Telescope</strong></td>
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<tr>
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<td>$\Delta r = c_{scale} \cdot r$</td>
<td>$r\Delta \phi = c_{scale} \cdot r + c_0$</td>
<td>$\Delta z = c_{scale} \cdot r$</td>
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<tr>
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<td><strong>Clamshell</strong></td>
<td><strong>Skew</strong></td>
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<td>$\Delta \phi = c_{scale} \cdot \cos(\phi)$</td>
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<td>$z$</td>
<td><strong>Bowling</strong></td>
<td><strong>Twist</strong></td>
<td><strong>Z expansion</strong></td>
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<td></td>
<td>$\Delta r = c_{scale} \cdot</td>
<td>z</td>
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