Measurements of Charmed Meson Lifetimes and Search for $D^0$-$\bar{D}^0$ Mixing with Belle

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Outline

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Introduction

- Lifetime Physics
  - Theoretical inputs to understand non-perturbative QCD in the heavy quark decay.
    - Annihilation process, W-exchange
  - Theoretical challenge to explain $\frac{\tau(D_s^+)}{\tau(D^0)} \sim 1.21 \pm 0.02$

- Mixing
  - Difference of lifetime between flavor specific mode and CP mode gives mixing parameter, $\gamma_{\text{CP}}$.
    $$\gamma_{\text{CP}} = \frac{\Gamma(CP_{\text{even}}) - \Gamma(CP_{\text{odd}})}{\Gamma(CP_{\text{even}}) + \Gamma(CP_{\text{odd}})} = \frac{\tau(K\pi)}{\tau(KK)} - 1$$
  - FOCUS: $\gamma_{\text{CP}} = 3.42 \pm 1.39 \pm 0.74\% \rightarrow$ inconsistent with 0 at 2.2$\sigma$
  - E791: $\gamma_{\text{CP}} = 0.8 \pm 2.9 \pm 1\% \rightarrow$ consistent with 0
  - CLEO: $-5.8\% < \gamma' < 1\% \ (95\% \text{ CL}) \rightarrow$ consistent with 0
    $$\gamma_{\text{CP}} = -1.1 \pm 2.5 \pm 1.4\% \rightarrow$$ consistent with 0

- Analysis is based on 11/ fb. All results are preliminary.
Reconstruction

- Reconstruct specific D decay modes.
  - $D^0 \rightarrow K\pi^+, KK^+$
  - $D_s^+ \rightarrow \phi(KK^+)\pi^+, \overline{K^*0}(K\pi^+)K^+$
  - $D^+ \rightarrow K\pi^+\pi^+, \phi(KK^+)\pi^+$
  - $p^*(D) > 2.5\text{GeV} \rightarrow \text{from } e^+e^- \rightarrow c\bar{c}$
  - Obtain decay vertex point (3D).

- Reconstruct D production point.
  - Extrapolate pseudo D flight path to interaction point (IP) profile.

- Calculate proper-time.
  - $\tau = Lm(D) / \alpha p_D$
Lifetime Fit

\[ L(t_i, \sigma_i^2, f_{SIG}^i) = f_{SIG}^i \int_0^{t_i} dt' \frac{1}{\tau_{SIG}} e^{-t'/\tau_{SIG}} R_{SIG}(t_i - t', \sigma_i^2) \]

\[ + \left(1 - f_{SIG}^i\right) \int_{t_i}^{\infty} dt' \left[ f_{BG}^i \frac{1}{\tau_{BG}} e^{-t'/\tau_{BG}} + \left(1 - f_{BG}^i\right) g(t') \right] R_{BG}(t_i - t', \sigma_i^2) \]

\[ R(x, \sigma_x) = \left(1 - f_{tail}\right) \frac{1}{\sqrt{2\pi\sigma_x^2}} e^{-x^2/(2\sigma_x^2)} + f_{tail} \frac{1}{\sqrt{2\pi\sigma_x^2}} e^{-x^2/(2\sigma_x^2)} \]

Unbinned Maximum Likelihood Fit

- \(\tau_{SIG}\): D lifetime
- \(f_{SIG} = f_{SIG}(D\ mass)\): Signal probability calculated event by event.
- \(\tau_{BG}\): Lifetime of BG component.
- \(f_{BG}\): Fraction of BG with lifetime.

Resolution Function

- \(\sigma_t\): Proper-time error (event by event)
- \(S\): Global scaling factor.
- \(S_{tail}\): Global scaling factor for poorly-measured events.
  - Hard scattering, mis-association of SVD hits.
- \(f_{tail}\): Fraction of poorly-measured events.

Fitting Parameters: \(\tau_{SIG}, \tau_{BG}, f_{BG}, S, S_{tail}, f_{tail}, (S, S_{tail}, f_{tail})_{BG}\)

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$D^0 \rightarrow K^- \pi^+$ Lifetime Fit

$\sigma = 5.4\text{MeV}$
$90601\pm387\text{ events}$
$M = 1865.0\text{MeV}$

$\tau_{\text{SIG}} = 414.5\pm1.7(\text{stat})\text{fs}$

($\tau = 412.6 \pm 2.8\text{ fs} : \text{PDG2k}$)

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$D^0 \rightarrow K^-K^+$ Lifetime Fit

$\sigma = 6.5\text{MeV}$

7451±118 events

$M = 1865.0\text{MeV}$

$\tau_{\text{SIG}} = 409.8\pm6.3(\text{stat})\text{fs}$

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$D_s^+ \rightarrow \phi (K^-K^+)\pi^+$ Lifetime Fit

$\sigma = 4.6\text{MeV}$

3757$\pm$54 events

$M = 1968.6\text{MeV}$

$\tau_{\text{SIG}} = 482.4 \pm 9.2(\text{stat})\text{fs}$

($\tau = 496 \pm 10 \text{fs} : \text{PDG2k}$)

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$D^+ \rightarrow K^+ \pi^+ \pi^+(D^{*+} \rightarrow D^+ \pi^0)$ Lifetime Fit

$\sigma = 0.79\text{MeV}$

6953$\pm$99 events
$M = 1870.1\text{MeV}$

$\tau_{\text{SIG}} = 1021 \pm 13(\text{stat})\text{fs}$

($\tau = 1051 \pm 13\text{ fs} : \text{PDG2k}$)

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Combined Lifetime/$y_{cp}$ Fit

A likelihood is combined to obtain $y_{cp}$ and lifetimes of $D^+$ and $D_s^+$ since these measurements are obtained from two decay chains.

- $D^+, D_s^+$: use a common lifetime value.
- $y_{cp}$: $\tau (D^0 \rightarrow KK) = y_{cp}$ and $\tau (D^0 \rightarrow K\pi)$

$\tau_{D^0 \rightarrow KK} = \tau_{D^0 \rightarrow K\pi} / (1 + y_{cp})$

<table>
<thead>
<tr>
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<th>Combined fit</th>
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</thead>
<tbody>
<tr>
<td>$D^+$</td>
<td>$1029 \pm 12$ fs</td>
</tr>
<tr>
<td>$D_s^+$</td>
<td>$488.4^{+7.8}_{-7.7}$ fs</td>
</tr>
<tr>
<td>$y_{cp}$</td>
<td>$1.16^{+1.67}_{-1.65}$ %</td>
</tr>
</tbody>
</table>
Systematic Error

We consider the following items as systematic uncertainties.

- Due to reconstruction
  - Interaction point.
  - Reconstruction efficiency.
  - Decay vertex bias by $2\gamma \rightarrow 4\pi$ which has a "zero" lifetime.
  - Mass dependence of proper-time.

- Due to fitting
  - Signal probability.
  - Mass peak shift.
  - Fitting bias.
  - Used mass region.

**They are not quoted since our study does not finish yet.**
DCSD and $D^0$-$\overline{D^0}$ Mixing Search

We are studying "wrong sign" decays $D^0 \rightarrow K^+\pi^-$.  

When BG is understood, we will perform a fit to decay time to extract DCSD rate and mixing parameters $x'$, $y'$.  

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### Summary

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\tau(D^0)$ fs</th>
<th>$\tau(D^+)$ fs</th>
<th>$\tau(D_s^+)$ fs</th>
<th>$\gamma_{CP}$ %</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDG2000</td>
<td>$412.6 \pm 2.8$</td>
<td>$1051 \pm 13$</td>
<td>$496^{+10}_{-9}$</td>
<td>$-$</td>
</tr>
<tr>
<td>E791</td>
<td>$(413 \pm 3 \pm 4)^i$</td>
<td>$-$</td>
<td>$(518 \pm 14 \pm 7)^i$</td>
<td>$0.8 \pm 2.9 \pm 1.0$</td>
</tr>
<tr>
<td>CLEO</td>
<td>$(408.5 \pm 4.1 \pm 3.0)^i$</td>
<td>$(1034 \pm 22 \pm 18)^i$</td>
<td>$(486 \pm 15 \pm 5)^i$</td>
<td>$-1.1 \pm 2.5 \pm 1.4$</td>
</tr>
<tr>
<td>FOCUS</td>
<td>$409.2 \pm 1.3^i$</td>
<td>$-$</td>
<td>$506 \pm 8^i$</td>
<td>$3.42 \pm 1.39 \pm 0.74$</td>
</tr>
<tr>
<td>Belle</td>
<td>$414.5 \pm 1.7$(stat.)</td>
<td>$1029 \pm 12$(stat.)</td>
<td>$488.4^{+7.8}_{-6.7}$(stat.)</td>
<td>$1.16^{+1.67}_{-1.65}$(stat.)</td>
</tr>
</tbody>
</table>

*This result is included in the PDG2000 world average.

*No systematic error is given.

- Our statistical uncertainties on the lifetimes are better than those of the best published measurements.
- After our systematic study is done, we will publish these lifetimes and $\gamma_{CP}$.  

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