Recent results and prospects for charm mixing and CPV at Threshold

Xiao-Rui Lyu
(E-mail: xiaorui@ucas.ac.cn)
University of Chinese Academy of Sciences (UCAS), Beijing

The International Workshop on the CKM Unitarity Triangle (CKM2014)
8-12 September, 2014, Vienna University of Technology
Outline

• Introduction
• Recent results from charm threshold data
  • mixing parameter $y_{\text{CP}}$
  • strong phase $\delta_{K\pi}$
    *(see Roy Briere’s talk for $\delta_{Ks\pi^+\pi^-}$ measurement at BESIII)*
  • CP asymmetries
• Prospects on future (dedicated) charm facility
• Summary
Neutral $D$ meson oscillation

$D^0$ and $\bar{D}^0$ can transfer into each other, like $K$, $B$ and $B_s$ mesons

- The mass eigenstates are

$$\left|D_1\right> = p \left|D^0\right> + q \left|\bar{D}^0\right>$$
$$\left|D_2\right> = p \left|D^0\right> - q \left|\bar{D}^0\right>$$

- With eigenvalues

$$\mu_1 = m_1 - \frac{i}{2} \Gamma_1$$
$$\mu_2 = m_2 - \frac{i}{2} \Gamma_2$$

$x$ mixing: Channel for New Physics.

$y$ (long-distance) mixing: SM background.

$$m = \frac{m_1 + m_2}{2}, \quad \Delta m = m_2 - m_1$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}, \quad \Delta \Gamma = \Gamma_2 - \Gamma_1$$

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta \Gamma}{2 \Gamma}$$

CKM suppression: $b$
GIM suppression: $d$, $s$
D meson oscillation

✓ short distance is highly suppressed by the GIM mechanism and by the CKM matrix elements within the SM: \(x \sim O(10^{-5}); \ y \sim O(10^{-7})\)
- new physics might manifest in the loop, such as FCNC processes with up-type quark, complementary to those with down quarks (K or B mesons, already studied with observed CPV)

✓ long distance is dominant: \((x, y) \sim O(10^{-3})\)
- but theoretical uncertainty is large

✓ Observation of D\(\bar{D}\) oscillation by CDF and LHCb
  \[
  \begin{align*}
  y' &\equiv y \cos \delta_{K\pi} - x \sin \delta_{K\pi} \\
  x' &\equiv x \cos \delta_{K\pi} + y \sin \delta_{K\pi}
  \end{align*}
  \]

✓ Improving the constraints on the charm mixing parameters is important for testing the SM, such as long-distance effect

✓ At charm threshold, strong phase is a unique contribution:
  - to extract the mixing parameter \((x, y)\) from \((x', y')\)
  - to (over-)constrain the CKM unitarity triangle, which is crucial for searching for new physics
Charm facilities

- Hadron colliders (huge cross-section, energy boost)
  - Tevatron (CDF, D0)
  - LHC (LHCb, CMS, ATLAS)
- $e^+e^-$ Colliders (more kinematic constraints, clean environment, ~100% trigger efficiency)
  - B-factories (Belle, BaBar)
  - Threshold production (CLEOc, BESIII)
    - Quantum Correlations (QC) and CP-tagging are unique
    - Only D meson pairs, no extra CM Energy for pions: clean backgrounds
    - Lots of systematic uncertainties cancellation while applying double tag technique
Data samples at charm threshold

- CLEO-c: 818 pb\(^{-1}\) \(\psi(3770)\)
- BESIII: 2.9 fb\(^{-1}\) (~3.5 x CLEO-c data) \(\psi(3770)\)

In the future, in total BESIII will accumulate \(\approx 10/fb\) data \(\psi(3770)\)
The decay rate of a correlated state

For a physical process producing $D^0 \bar{D}^0$ such as

$$e^+ e^- \rightarrow \psi'' \rightarrow D^0 \bar{D}^0$$

The $D^0 \bar{D}^0$ pair will be a quantum-correlated state.

The quantum number of $\psi''$ is $J^{PC} = 1^{--}$

The $C$ number of $D^0 \bar{D}^0$ pair in this process is $C = -$.

Taking advantage the quantum coherence of $D\bar{D}$ pairs, we can study the $D$ mixing and CPV in a unique way

- strong phase in $D$ decays
- $D$ mixing parameters
- direct CP violation
- ...

...
Time-integrated decay rates

- **No time dependent information at Charm threshold**
- **Anti-symmetric wavefunction:**
  \[ \Gamma_{ij}^2 = |\langle i | D^0 \rangle \langle j | \overline{D}^0 \rangle - \langle j | D^0 \rangle \langle i | \overline{D}^0 \rangle|^2 \]
- **Double tag rates:**
  \[ A_i^2 A_j^2 \left[ 1 + r_i^2 r_j^2 - 2 r_i r_j \cos(\delta_i + \delta_j) \right] \]
- **CP tag:** \( r=1, \delta=0 \) or \( \pi \); \( l^\pm \) tag: \( r=0 \)
- **Single and Double tag rates**

\[ z_f \equiv 2 \cos \delta_f, r_f \equiv \frac{A_{DCS}}{A_{CF}}, R_M \approx \frac{x^2+y^2}{2} \]

<table>
<thead>
<tr>
<th>C-odd</th>
<th>( f )</th>
<th>( \bar{f} )</th>
<th>( t^+ )</th>
<th>( t )</th>
<th>( CP^+ )</th>
<th>( CP^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td>( R_M[1 + r_f^2(2 - z_f^2) + r_f^4] )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \bar{f} )</td>
<td>( 1 + r_f^2(2 - z_f^2) + r_f^4 )</td>
<td>( R_M[1 + r_f^2(2 - z_f^2) + r_f^4] )</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t^+ )</td>
<td>( r_f^2 )</td>
<td>( 1 )</td>
<td>( R_M )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t )</td>
<td>( 1 )</td>
<td>( r_f^2 )</td>
<td>( 1 )</td>
<td>( R_M )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( CP^+ )</td>
<td>( 1 + r_f(r_f + z_f) )</td>
<td>( 1 + r_f(r_f + z_f) )</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>( 0 )</td>
<td></td>
</tr>
<tr>
<td>( CP^- )</td>
<td>( 1 + r_f(r_f - z_f) )</td>
<td>( 1 + r_f(r_f - z_f) )</td>
<td>( 1 )</td>
<td>( 1 )</td>
<td>( 4 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td><strong>Single Tag</strong></td>
<td>( 1 + r_f^2 + r_f z_f y )</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 ( (1 \mp y) )</td>
</tr>
</tbody>
</table>
Analysis techniques

Quantum Correlated topics

- **Mixing** \((x^2+y^2) \rightarrow (K^-l^+\nu)^2, (K^-\pi^+)^2\)
- **Strong phase** cos\(\delta\): Double Tag Events: \(K^-\pi^+\) vs CP\(\pm\)
- **Charm Mixing** \((y_{CP})\): Flavor Tag vs CP\(\pm\)
- **DCS**: Wrong sign decays \(K^-\pi^+\) vs \(K^-l^+\nu\)
- **Strong phase** \(c_i, s_i\) (Dalitz): \(K_S\pi^+\pi^-\) vs CP\(\pm\); \(K_S\pi^+\pi^-\) vs Flavor Tag; \(K_S\pi^+\pi^-\) vs \(K_{S,L}\pi^+\pi^-\)
- **Typical Kinematic variables for full reconstruction**
  - Energy difference & Beam Constrained mass
    \[
    \Delta E = E_D - E_{Beam}
    \]
    \[
    M_{BC} = \sqrt{E_{Beam}^2 - \vec{p}_D^2}
    \]

Global fit method

- Combined analysis to extract mixing parameters, DCS, strong phase plus charm hadronic branching fractions
Global Analysis at CLEO-c (818 pb\(^{-1}\))

- Updated analysis from the one in 2008:
  \[ \cos \delta = 1.03^{+0.31}_{-0.17} \pm 0.06 \]

- [PRL100, 221801 (2008); PRD78, 012001 (2008)]
- Included more modes
  - more ST and DT modes
  - \(K_{s}\pi^{+}\pi^{-}\) strong phase bins
- [PRD80, 032002 (2008)]
- 251 yield measurements!

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fit: no ext. meas. (standard)</th>
<th>Fit: w/ ext. y, x, y' (extended)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(y) (10^{-2})</td>
<td>4.2 ± 2.0 ± 1.0</td>
<td>0.636 ± 0.114</td>
</tr>
<tr>
<td>(x^{2}) (10^{-3})</td>
<td>0.6 ± 2.3 ± 1.1</td>
<td>0.022 ± 0.023</td>
</tr>
<tr>
<td>(r_{K\pi}^{2}) (10^{-3})</td>
<td>5.33 ± 1.07 ± 0.45</td>
<td>3.33 ± 0.08</td>
</tr>
<tr>
<td>(\cos \delta_{K\pi})</td>
<td>0.81 ±0.22+0.07 -0.18 -0.05</td>
<td>1.15 +0.19 +0.17 -0.17 -0.08</td>
</tr>
<tr>
<td>(\sin \delta_{K\pi})</td>
<td>-0.01 ± 0.41 ± 0.04</td>
<td>0.56 +0.32 +0.21 -0.31 -0.20</td>
</tr>
<tr>
<td>(\delta_{K\pi}) (°) [derived]</td>
<td>10 ±28 ±13 -53 -0</td>
<td>18 +11 -17</td>
</tr>
</tbody>
</table>

\[ \cos \delta_{K\pi} \rightarrow y \]
\[ \sin \delta_{K\pi} \rightarrow r_{K\pi}^{2} \]
\[ \sim 3500 CP\text{-tagged } Kl\nu \]
\[ \sim 30 \text{ WS } Kl\nu \text{ vs. } K\pi \]
We measure the $y_{CP}$ using $CP$-tagged semi-leptonic $D$ decays, which allows to access $CP$ asymmetry in mixing and decays.

★ Single tag decay rate (CP tags)
$$\mathcal{B}_{CP\pm} \propto 2|A_{CP\pm}|^2(1 \mp y)$$

★ Double tag decay rates (flavor tags + CP tags)
$$\mathcal{B}_{l;CP\pm} \propto |A_l|^2|A_{CP\pm}|^2$$

★ Neglect term $y^2$ or high order

$$y_{CP} = \frac{1}{4} \left( \frac{\mathcal{B}_{l;CP+} - \mathcal{B}_{l;CP-}}{\mathcal{B}_{l;CP+} + \mathcal{B}_{l;CP-}} \right)$$

✦ Reconstructed modes:
 ✦ Flavor tags: $K\nu_e$, $K\mu\nu_\mu$
 ✦ CP+ tags (3 modes): $K^-K^+$, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$,
 ✦ CP- tags (3 modes): $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$
signals to determine $y_{CP}$

(BESIII: $2.92 \text{ fb}^{-1}$)

- **Single tag yields extraction:**
  - Singal shape: $\sigma \otimes \text{MC-truth}$
  - Background: ARGUS function
  - Kinematic variable: $M_{BC}$

- **Double tag yields extraction:**
  - Singal shape: $\sigma \otimes \text{MC-truth}$
  - Background: Polynomial
  - $K\pi\pi^0$ background shape from data
  - Kinematic variable:
    
    \[ U_{\text{miss}} = E_{\text{miss}} - |\vec{P}_{\text{miss}}| \approx 0 \text{ for signals} \]

DTs of $Ke\nu$ mode

DTs of $K\mu\nu$ mode

- Peaking bkg. from $K\pi\pi^0$
$K\pi\pi^0$ backgrounds in $K\mu\nu$ modes

define $E_{\text{extra}}$ as total energy of the remaining showers other than those being used

take $E_{\text{extra}} > 0.5\text{GeV}$ as control sample to estimate the shape and size of $K\pi\pi^0$ backgrounds

shape: MC shape smeared by a Gaussian, whose parameters are obtained from fit to the control sample

calculate $E_{\text{extra}} > 0.5\text{GeV}$

size: scale the MC-determined size in the signal region with the ratio of the number of $K\pi\pi^0$ events in data to that in MC in the control sample
**$y_{CP}$ preliminary result**

(BESIII: 2.92 fb$^{-1}$)

- **CLEOc 2012:**
  - [PRD 86 (2012) 112001]
  - \( y_{CP} = (4.2 \pm 2.0 \pm 1.0)\% \)

**BESIII preliminary result:**

\[
y_{CP} = -1.6\% \pm 1.3\%(\text{stat.}) \pm 0.6\%(\text{syst.})
\]

- result is statistically limited
- systematic uncertainty is relatively small
- most precise measurement with QC D mesons
- in the limit of no CPV, \( y_{CP} = y \)

*Paper is close to be submitted to journal.*
Strong Phase $\delta_{K\pi}$ (BESIII: 2.92 fb$^{-1}$)

Strong phase:

$$\frac{\langle K^-\pi^+ | D^0 \rangle^{DCS}}{\langle K^-\pi^+ | D^0 \rangle^{CF}} \equiv -r_{K\pi} e^{-i\delta_{K\pi}}$$

Quantum correlation $\rightarrow$ Interference $\rightarrow$ access strong phase!

$$\langle K\pi | D_{CP\pm} \rangle = \left( \langle K\pi | D^0 \rangle \pm \langle K\pi | \bar{D}^0 \rangle \right) / \sqrt{2} \Rightarrow \sqrt{2} A_{CP\pm} = A_{K\pi} \pm A_{\bar{K}\pi}$$

$\Rightarrow 2r_{K\pi} \cdot \cos \delta_{K\pi} \approx A_{CP \rightarrow K\pi} \equiv \frac{|A_{CP-}|^2 - |A_{CP+}|^2}{|A_{CP-}|^2 + |A_{CP+}|^2}$

$$= \frac{Br(D_{CP- \rightarrow K\pi}) - Br(D_{CP+ \rightarrow K\pi})}{Br(D_{CP- \rightarrow K\pi}) + Br(D_{CP+ \rightarrow K\pi})}$$

✧ Measuring $\delta_{K\pi}$ from rate differences if using external $r_{K\pi}$

✧ Reconstructed modes:

✧ Flavor tags: $K^-\pi^+$, $K^+\pi$

✧ CP+ tags (5 modes): $K^-K^+$, $\pi^+\pi^-$, $K_S^0\pi^0\pi^0$, $\pi^0\pi^0$, $\rho^0\pi^0$

✧ CP- tags (3 modes): $K_S^0\pi^0$, $K_S^0\eta$, $K_S^0\omega$
Strong Phase $\delta_{K\pi}$

(BESIII: 2.92 fb$^{-1}$)

- **Signal reconstruction:**
  - Single Tag (ST): CP tags
  - Double Tag (DT): $K\pi +$ CP Tag
  - Kinematic variable: Beam Constrained Mass ($M_{BC}$)
  - Singal shape: $\sigma\otimes$MC-truth
  - Background shape: ARGUS function

- $Br(D_{CP\pm} \rightarrow K\pi) = \frac{n_{K\pi,CP\pm}}{n_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{K\pi,CP\pm}}$

- $n_{K\pi,CP\pm}$ and $n_{CP\pm}$ are event yields for DT and ST from $M_{BC}$ fit
- $\varepsilon_{K\pi,CP\pm}$ and $\varepsilon_{CP\pm}$ are detection efficiencies of DT and ST from MC simulation
- Most systematics cancelled for ratio $\varepsilon_{CP\pm}/\varepsilon_{K\pi,CP\pm}$

**BESIII direct product of results:**

$$A_{CP\rightarrow K\pi} = (12.7 \pm 1.3 \pm 0.7) \times 10^{-2}$$

Improvement from previous results and inputs for world average fit!
\[ \delta_{K\pi} \text{ in } D \rightarrow K\pi \]

If we don’t ignore the mixing effect:

\[ 2r_{K\pi} \cos \delta_{K\pi} + y = (1 + R_{WS}) \cdot A_{CP\rightarrow K\pi} \]

\[ R_{WS} = \frac{\Gamma(D^0 \rightarrow K^+\pi^-)}{\Gamma(D^0 \rightarrow K^-\pi^+)} = r_{K\pi}^2 + r_{K\pi}y' + \frac{(x^2 + y^2)}{2} \]

with external inputs from HFAG2014 and PDG:

\[ r_{K\pi}^2 = (3.50 \pm 0.04) \times 10^{-3}; \quad y_{CP} = (6.7 \pm 0.9) \times 10^{-3}; \quad R_{WS} = (3.80 \pm 0.05) \times 10^{-3} \]

**BESIII results:** \[ \cos \delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01 \]

- The third error is due to the input parameters
- The statistical errors dominant the precision
- World best precision


\[ \cos \delta_{K\pi} = 0.81^{+0.22}_{-0.18} \pm 0.07 \]

\[ \cos \delta_{K\pi} = 1.15_{-0.17}^{+0.19} + 0.00 (\text{global fit}) \]

In the next 5 years, BESIII will in total accumulate about 10 fb on-threshold \( D \) data:

- precision of \( \cos \delta_{K\pi} \) will reach \( \sim 0.06 \): level of syst. err.
CPV in charm factory

**CP asymmetry:** \( A_{CP}(f) = \frac{\Gamma(f) - \Gamma(f)}{\Gamma(f) + \Gamma(f)} \)

★ CPV in charm:
- SM: <= a few %
- NP: >~ 1%
★ World precision: ~0.1%
★ CLEO-c measured \( A_{CP} \) based on single tag events
  - at the order 1% for all modes
  - no evidence of CPV
  - systematics dominant

<table>
<thead>
<tr>
<th>Mode</th>
<th>CP Asymmetry (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^0 \to K^-\pi^+ )</td>
<td>0.3 ± 0.3 ± 0.6</td>
</tr>
<tr>
<td>( D^0 \to K^-\pi^+\pi^0 )</td>
<td>0.1 ± 0.3 ± 0.4</td>
</tr>
<tr>
<td>( D^0 \to K^-\pi^+\pi^+\pi^- )</td>
<td>0.2 ± 0.3 ± 0.4</td>
</tr>
<tr>
<td>( D^+ \to K^-\pi^+\pi^+ )</td>
<td>-0.3 ± 0.2 ± 0.4</td>
</tr>
<tr>
<td>( D^+ \to K^-\pi^+\pi^+\pi^0 )</td>
<td>-0.3 ± 0.6 ± 0.4</td>
</tr>
<tr>
<td>( D^+ \to K_S^0\pi^+ )</td>
<td>-1.1 ± 0.6 ± 0.2</td>
</tr>
<tr>
<td>( D^+ \to K_S^0\pi^+\pi^0 )</td>
<td>-0.1 ± 0.7 ± 0.2</td>
</tr>
<tr>
<td>( D^+ \to K_S^0\pi^+\pi^+\pi^- )</td>
<td>0.0 ± 1.2 ± 0.3</td>
</tr>
<tr>
<td>( D^+ \to K^+K^-\pi^+ )</td>
<td>-0.1 ± 0.9 ± 0.4</td>
</tr>
</tbody>
</table>

★ CLEO-c: 818 pb\(^{-1}\)

PRD89, 072002 (2014)

- With the LHCb’s updates (~0.1%), CPV test becomes not sensitive in charm factory
- In future charm factory, it is important to reduce the systematic uncertainty by using a large D threshold sample
High Intensity Electron Positron Accelerator (HIEPA)

- China is proposing a future **super-tau-charm factory: HIEPA**
- Providing peak luminosity about \(1 \times 10^{35} \, \text{cm}^{-2}\text{s}^{-1}\) at 4 GeV for physics at **tau charm** sector, covering \(E_{\text{cm}} = 2\text{-}7 \, \text{GeV} \).

**with 1ab\(^{-1}\) data @HIEPA**

- Direct CP violation in \(D^+ \rightarrow hh\) sensitivity: \(10^{-3}\sim 10^{-4}\)
- \(\Delta(\cos \delta_{K\pi}) \sim 0.007; \Delta(\delta_{K\pi}) \sim 2^\circ\)
- \(R_M = (x^2+y^2)/2 \sim 10^{-5}\) in \(K\pi\) and Ke\(\nu\) channels
- Probe \(y\): \(\Delta y_{CP} < 0.1\%\)

by 2016: CDR & TDR

Clean background and better systematic control in threshold production would be complementary to the future \(B\) factory results
Summary

✦ Data at charm threshold provide unique ingredient on identifying $D\bar{D}$ oscillations and CPV in charm sector
✦ CLEO-c have made great progress and paved a way for subsequent precision experiment
✦ BESIII has been involved in the world campaign
  ‣ Many more QC analyses are undergoing.
  ‣ The global fit package has been developed to measure strong phases and mixing parameters.
  ‣ Precision required more stringent systematic control
✦ A super-tau-charm factory in China is being proposed:
  ✦ Complementary to precision measurements at BELLEII and upgraded LHCb
AIM to explore possible future collider project post BEPCII/BESIII. HIEPA is one of the options.

online registration: Sep. 8 — Dec. 08, 2014
Thank you!
Danke!
谢谢！
Charm tagging at the $\psi(3770)$

$e^+e^- \rightarrow \psi(3770) \rightarrow D\bar{D}$

- Pure $D\bar{D}$ final state, no additional particles ($E_D = E_{\text{beam}}$).
- Low multiplicity ~ 5-6 charged particles / event
- More kinematical constraints to reconstruct decay channels with $\nu$
- Single Tag (ST)
  - Reconstruct one $D$ meson
- Double Tag (DT)
  - Tag one $D$ meson in a selected tag mode. Study the other $D$ (signal $D$).
- Flavor Tag
  - Tag the flavor of $D^0$ or $\bar{D}^0$
- CP tag (CP$\pm$)
  - Tag the CP eigenstate: $D_{\text{CP}+}$ or $D_{\text{CP}-}$
least squares fitter: used for extracting expected physics parameters from the correlated experimental data

Monte Carlo validation of the fitter

MC study corresponding to 3.0 /fb data

input parameters:

\[
\begin{align*}
\delta_{K\pi} &= 22.1^{+9.7}_{-11.1}(^o), \\
y_D &= 0.75 \pm 0.12(\%) 
\end{align*}
\]

output after constrains:

\[
\begin{align*}
\delta_{K\pi} &\approx \pm 8.3(\^o), \\
y_D &\approx \pm 0.10(\%)
\end{align*}
\]

\(~15\%~ improvement~ on~ the~ parameters\)

\(\text{We expect larger improvements on the strong phase and mixing parameters based on 10 /fb data at BESIII}\)