D-mixing and indirect CPV at Belle, and prospects for Belle II

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- motivation
- $D^0(t) \rightarrow K^+\pi$
- $D^0(t) \rightarrow K_S \pi^+\pi$
- $D^0(t) \rightarrow K^+K^-, \pi^+\pi$
- HFAG fit results
- Belle II prospects
Why study...

... CP Violation in D Decays?

• SM rates are very low ⇒ a good place to search for new physics [Most promising: singly Cabibbo-suppressed decays, see Grossman, Kagan, Nir, PRD 75, 036008 (2007) ]

• Now established that $D^0/D^0\bar{b}$ar mesons mix ⇒ is there CPV in the mixing? or CPV due to interference between mixed and direct decay amplitudes?

... CPV in D Decays at an $e^+e^-$ machine (Belle/BaBar/Belle II)?

• Final states with neutral particles ($\gamma$, $K_S$, $\pi^0$) can be reconstructed that are difficult/impractical to reconstruct at a hadron machine

• Low backgrounds, high trigger/reconstruction efficiencies, minimal decay time bias, roughly flat acceptance over Dalitz plots, several control samples
Belle CPV in mixing or interference

“Wrong-sign” $D^0(t) \rightarrow K^+\pi^-$
[Ko et al., PRL 112, 111801 (2014);
Zhang et al., PRL 96, 151801 (2006);
Li et al., PRL 94, 071801 (2005)]
Fit for $x^2$, $y'$, $|q/p|$, $\phi = \text{Arg}(q/p)$
$[x' = x\cos\delta + y\sin\delta, y' = y\cos\delta - x\sin\delta]$

$D^0(t) \rightarrow K^0 \pi^+\pi^-$ Dalitz plot analysis
[Peng et al., PRD 89, 091103(R) (2014);
Zhang et al., PRL 99, 131803 (2007)]
Fit for $x$, $y$, $|q/p|$, $\phi = \text{Arg}(q/p)$

Time-dependent $D^0(t) \rightarrow K^+K^-, \pi^+\pi^-$
[Staric arXiv:1212.3478 (2012);
Staric et al., PRL 98, 211803 (2007);
Abe et al., hep-ex/0308034 (2003)]
Fit for $y_{CP}$, $A_{\Gamma}$
$2 \ y_{CP} = \left( |q/p| + |p/q| \right) y \cos \phi - \left( |q/p| - |p/q| \right) x \sin \phi$
$2 \ A_{\Gamma} = \left( |q/p| - |p/q| \right) y \cos \phi - \left( |q/p| + |p/q| \right) x \sin \phi$

3 features in common:

a) flavor is tagged via $D^* \rightarrow D^0\pi_{slow}$ or $D^{*+} \rightarrow D^0\pi_{slow}$

b) dominant background is typically “random $\pi_{slow}$” – include PDF for this in fits

c) decay time $t$ calculated via

$$t = \left( \frac{m_D}{p_D} \right) \vec{l} \cdot \hat{p}_D$$

A. J. Schwartz Mixing and Indirect CPV from Belle CKM 2014 Workshop
976 fb⁻¹, full data set

double mis-ID background reduced with tight PID cuts if |
M_{\text{swapped}} - M_D < 25 \text{ MeV/c}^2

Method (opposite the usual):

a) WS and RS samples are selected: |
M_{K\pi} - M_D < 20 \text{ MeV/c}^2

b) Divide samples into 10 bins of decay time. For each bin,
determine event yields by fitting 
\Delta M = M_{K\pi\pi} - M_{K\pi} distribution

c) plot ratio of event yields, fit this distribution for \( R_D, x'^2, y' \)

Advantage: as one fits to ratios of event yields, less sensitive to resolution function
**Time-dependent $D^0(t) \rightarrow K^+\pi^-$**

Ko et al., PRL 112, 111801 (2014)

![Graph showing mixing and no mixing](image)

**Test hypothesis (χ²/d.o.f.)** | **Parameters** | **Fit results (10⁻³)**
--- | --- | ---
Mixing (4.2/7) | $R_D$ | 3.53 ± 0.13
 | $y'$ | 4.6 ± 3.4
 | $x'^2$ | 0.09 ± 0.22
No Mixing (33.5/9) | $R_D$ | 3.864 ± 0.059

Most precise results from $e^+e^-$ experiments, But LHCb obtains:

- $R_D = 3.568 ± 0.066$
- $y' = 4.8 ± 1.0$
- $x'^2 = 0.055 ± 0.049$

$\Delta \chi^2 = 29.3$, CL = 4.3 x 10⁻⁷ (5.1σ)
Fitting the time-dependent Dalitz plot yields x, y, |q/p| and φ = Arg(q/p)

- 976 fb⁻¹, full data set
- Signal yield determined from 2-dim. fit to $M_{K_{s}\pi\pi}$ and $\Delta M = M_{K_{s}\pi\pi} - M_{K_{s}\pi\pi}$. Yield is $1.2 \times 10^6$ events with a purity of 96%.
- Select events in signal region $|M_{K_{s}\pi\pi} - M_D| < 15$ MeV/c² and $\Delta M = (5.75, 5.95)$ MeV.
- For events in signal region, do unbinned ML fit to $m^+ = M(K\pi^+)^2$, $m^- = M(K\pi^-)^2$, and decay time t. Fit parameters are x, y, τ, resolution function parameters (2-3 Gaussians), and decay model: magnitudes and phases of 13 intermediate resonances.
- Do fit separately (+ simultaneously) for $D^0$ and $D^0\bar{\text{bar}}$ samples to obtain |q/p|, φ parameters.

\[
R_{D^0} = \frac{e^{-\Gamma t}}{2} \left\{ \left( |A_f|^2 + \frac{q^2}{p^2} |\bar{A}_f|^2 \right) \cosh(yt) + \left( |A_f|^2 - \frac{q^2}{p^2} |\bar{A}_f|^2 \right) \cos(xt) \\
+ 2 \text{Re} \left( \frac{q}{p} A_f \bar{A}_f^* \right) \sinh(yt) - 2 \text{Im} \left( \frac{q}{p} A_f \bar{A}_f^* \right) \sin(xt) \right\}
\]

\[
R_{D^0} = \frac{e^{-\Gamma t}}{2} \left\{ \left( |\bar{A}_f|^2 + \frac{q^2}{p^2} |A_f|^2 \right) \cosh(yt) + \left( |\bar{A}_f|^2 - \frac{p^2}{q^2} |A_f|^2 \right) \cos(xt) \\
+ 2 \text{Re} \left( \frac{p}{q} A_f \bar{A}_f^* \right) \sinh(yt) - 2 \text{Im} \left( \frac{p}{q} A_f \bar{A}_f^* \right) \sin(xt) \right\}
\]

If no CPV: $A_f(m^2_+, m^2_-) = \bar{A}_f(m^2_-, m^2_+)$
**D^0(t) → K_S π^+π^−**: time-dependent Dalitz plot fit

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>K^*(892)^−</td>
<td>1.590 ± 0.003</td>
<td>131.8 ± 0.2</td>
<td>0.6045</td>
</tr>
<tr>
<td>K_0^*(1430)^−</td>
<td>2.059 ± 0.010</td>
<td>−194.6 ± 1.7</td>
<td>0.0702</td>
</tr>
<tr>
<td>K^*_2(1430)^−</td>
<td>1.150 ± 0.009</td>
<td>−41.5 ± 0.4</td>
<td>0.0221</td>
</tr>
<tr>
<td>K^*(1410)^−</td>
<td>0.496 ± 0.011</td>
<td>83.4 ± 0.9</td>
<td>0.0026</td>
</tr>
<tr>
<td>K^*(1680)^−</td>
<td>1.556 ± 0.097</td>
<td>−83.2 ± 1.2</td>
<td>0.0016</td>
</tr>
<tr>
<td>K^*(892)^+</td>
<td>0.139 ± 0.002</td>
<td>−42.1 ± 0.7</td>
<td>0.0046</td>
</tr>
<tr>
<td>K^*_0(1430)^+</td>
<td>0.176 ± 0.007</td>
<td>−102.3 ± 2.1</td>
<td>0.0005</td>
</tr>
<tr>
<td>K^*_2(1430)^+</td>
<td>0.077 ± 0.007</td>
<td>−32.2 ± 4.7</td>
<td>0.0001</td>
</tr>
<tr>
<td>K^*(1410)^+</td>
<td>0.248 ± 0.010</td>
<td>−145.7 ± 2.9</td>
<td>0.0007</td>
</tr>
<tr>
<td>K^*(1680)^+</td>
<td>1.407 ± 0.053</td>
<td>86.1 ± 2.7</td>
<td>0.0013</td>
</tr>
<tr>
<td>ρ(770)</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td>0.2000</td>
</tr>
<tr>
<td>ω(782)</td>
<td>0.0370 ± 0.0004</td>
<td>114.9 ± 0.6</td>
<td>0.0057</td>
</tr>
<tr>
<td>f_2(1270)</td>
<td>1.300 ± 0.013</td>
<td>−31.6 ± 0.5</td>
<td>0.0141</td>
</tr>
<tr>
<td>ρ(1450)</td>
<td>0.532 ± 0.027</td>
<td>80.8 ± 2.1</td>
<td>0.0012</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ππ S-wave</td>
<td>4.23 ± 0.02</td>
<td>164.0 ± 0.2</td>
</tr>
<tr>
<td>β_1</td>
<td>10.90 ± 0.02</td>
<td>15.6 ± 0.2</td>
</tr>
<tr>
<td>β_2</td>
<td>37.4 ± 0.3</td>
<td>3.3 ± 0.4</td>
</tr>
<tr>
<td>β_3</td>
<td>14.7 ± 0.1</td>
<td>−8.9 ± 0.3</td>
</tr>
<tr>
<td>f_{11}^{prod}</td>
<td>12.76 ± 0.05</td>
<td>−161.1 ± 0.0</td>
</tr>
<tr>
<td>f_{12}^{prod}</td>
<td>14.2 ± 0.2</td>
<td>−176.2 ± 0.0</td>
</tr>
<tr>
<td>f_{13}^{prod}</td>
<td>10.0 ± 0.5</td>
<td>−124.7 ± 2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kπ S-wave</td>
<td>M(MeV/c^2)</td>
</tr>
<tr>
<td></td>
<td>Γ(MeV/c^2)</td>
</tr>
<tr>
<td></td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>φ_F(rad)</td>
</tr>
<tr>
<td></td>
<td>R</td>
</tr>
</tbody>
</table>

*Fit projections: (fitted function describes the data well)*
**$D^0(t) \rightarrow K_S \pi^+\pi^+$: results**

Peng et al., PRD 89, 091103(R) (2014)

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**Fit type | Parameter | Fit result**

| No CPV     | $x$ (%) | $0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$ |
|            | $y$ (%) | $0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$ |

| CPV        | $x$ (%) | $0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$ |
|            | $y$ (%) | $0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$ |
|            | $|q/p|$  | $0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$ |
|            | arg($q/p$) (°) | $-6 \pm 11\pm3_{-4}$ |

**$\tau = (410.3 \pm 0.6)$ fs**

---

$\Delta\chi^2 \Rightarrow$ mixing significance = 2.5σ but no evidence for indirect or direct CPV
**Systematics due to decay model:**

\[ D^0(t) \rightarrow K_S \pi^+ \pi : \text{systematic errors} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>No CPV</th>
<th>CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta x / 10^{-4} )</td>
<td>( \Delta y / 10^{-4} )</td>
</tr>
<tr>
<td>Best candidate selection</td>
<td>+1.0</td>
<td>+1.9</td>
</tr>
<tr>
<td>Signal and background yields</td>
<td>±0.3</td>
<td>±0.3</td>
</tr>
<tr>
<td>Fraction of wrong tagged events</td>
<td>−0.7</td>
<td>−0.4</td>
</tr>
<tr>
<td>Time resolution of signal</td>
<td>−1.4</td>
<td>−0.9</td>
</tr>
<tr>
<td>Efficiency</td>
<td>−1.1</td>
<td>−2.1</td>
</tr>
<tr>
<td>Combinatorial PDF</td>
<td>+1.9</td>
<td>+2.3</td>
</tr>
<tr>
<td>( K^*(892) ) DCS/CF reduced by 5%</td>
<td>−7.3</td>
<td>+2.3</td>
</tr>
<tr>
<td>( K^*_2(1430) ) DCS/CF reduced by 5%</td>
<td>+1.7</td>
<td>−0.7</td>
</tr>
<tr>
<td>Total</td>
<td>+2.8</td>
<td>+3.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>No CPV</th>
<th>CPV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta x / 10^{-4} )</td>
<td>( \Delta y / 10^{-4} )</td>
</tr>
<tr>
<td>Resonance M &amp; ( \Gamma )</td>
<td>±1.4</td>
<td>±1.2</td>
</tr>
<tr>
<td>( K^*(1680)^+ ) removal</td>
<td>−1.8</td>
<td>−3.0</td>
</tr>
<tr>
<td>( K^*(1410)^\pm ) removal</td>
<td>−1.2</td>
<td>−3.6</td>
</tr>
<tr>
<td>( \rho(1450) ) removal</td>
<td>+2.1</td>
<td>+0.3</td>
</tr>
<tr>
<td>Form factors</td>
<td>+4.0</td>
<td>+2.4</td>
</tr>
<tr>
<td>( \Gamma(q^2) = \text{constant} )</td>
<td>+3.3</td>
<td>−1.6</td>
</tr>
<tr>
<td>Angular dependence</td>
<td>−8.5</td>
<td>−3.9</td>
</tr>
<tr>
<td>K-matrix formalism</td>
<td>−2.2</td>
<td>+1.8</td>
</tr>
<tr>
<td>Total</td>
<td>+5.8</td>
<td>+3.2</td>
</tr>
</tbody>
</table>

\[ 091103(R) \text{ (2014)} \]

**A. J. Schwartz**  
**Mixing and Indirect CPV from Belle**
Belle time-dependent $D^0(t) \rightarrow K^+K^-, \pi^+\pi^-$

presented by Staric at CHARM 2012 (arXiv:1212.3478); update of Staric et al., PRL 98, 211803 (2007)

\[ y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1 \]
\[ A_{\Gamma} = \frac{\tau(D^0 \rightarrow K^+K^-) - \tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^+K^-) + \tau(D^0 \rightarrow K^+K^-)} \]

\[ = \left( |q/p| + |p/q| \right) y \cos \phi - \left( |q/p| - |p/q| \right) x \sin \phi \]
\[ = \left( |q/p| - |p/q| \right) y \cos \phi - \left( |q/p| + |p/q| \right) x \sin \phi \]
\[ = -a_{int} - a_{indirect} \text{ contribution to } A_{CP} \]

**Method:**
1) tag flavor via $D^{*+} \rightarrow D^0\pi^+$
2) determine resolution function from MC/data studies
3) do simultaneous binned fit to $K^+K^-, K^+\pi^-, \pi^+\pi^-$ samples

\[ \chi^2/\text{ndf} = 792.9/684 \text{ (CL = 0.2\%)} \]
Belle time-dependent $D^0(t) \rightarrow K^+K^-, \pi^+\pi^-$ (cont’d)

Note: as resolution function depends on $D^0$ CMS angle ($\theta^*$), fit is performed in bins of $\cos \theta^*$

977 fb$^{-1}$ preliminary:

$y_{CP} = 1.06 \pm 0.23\%$

$A_\Gamma = -0.03 \pm 0.21\%$

$\tau = 408.2 \pm 0.6$ fs

$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$

$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$

Note: as resolution function depends on $D^0$ CMS angle ($\theta^*$), fit is performed in bins of $\cos \theta^*$

HFAG World Averages

www.slac.stanford.edu/xorg/hfag/charm/index.html

A. J. Schwartz  Mixing and Indirect CPV from Belle  CKM 2014 Workshop
HFAG global fit to all available data

45 measured observables, 10 theoretical fitted parameters: $x$, $y$, $\delta$, $\delta_{K\pi\pi}$, $R_D$, $A_D$, $|q/p|$, $\phi$, $A_K$, $A_{\pi}$
(for details see Marco Gersabeck’s talk & www.slac.stanford.edu/xorg/hfag/charm/index.html)

$\Delta \chi^2$ at no mixing point $(x,y) = (0,0) > 420$ (>12\sigma)  [$x: > 2.4\sigma$, $y: > 9.4\sigma$]
No CPV $(|q/p|, \phi) = (1,0)$ point:  $\Delta \chi^2 = 1.32$,  $CL = 0.48$, consistent with no CPV
## Belle II expectations for $D^0$-$D^0$ mixing and CPV

**Expected Uncertainties** (M. Staric, KEK FFW14):

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Observable</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^0_S\pi^+\pi^-$</td>
<td>$x$</td>
<td>0.19 0.08</td>
</tr>
<tr>
<td></td>
<td>$y$</td>
<td>0.15 0.05</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>q/p</td>
</tr>
<tr>
<td></td>
<td>$\phi$</td>
<td>11° 4°</td>
</tr>
<tr>
<td>$\pi^+\pi^-$, $K^+K^-$</td>
<td>$y_{CP}$</td>
<td>0.22 0.04</td>
</tr>
<tr>
<td></td>
<td>$A_\Gamma$</td>
<td>0.20 0.03</td>
</tr>
<tr>
<td>$K^+\pi^-$</td>
<td>$x'$</td>
<td>0.022 0.003</td>
</tr>
<tr>
<td></td>
<td>$y'$</td>
<td>0.34 0.04</td>
</tr>
<tr>
<td></td>
<td>$</td>
<td>q/p</td>
</tr>
<tr>
<td></td>
<td>$\phi$</td>
<td>25° 2.3°</td>
</tr>
</tbody>
</table>

**Note:** statistical error and some systematics scale by luminosity, but other systematics do not.

- factor of ~3 better
- factor of ~6 better
- factor of 8-10 better
Belle II expectations for $\bar{D}^0-D^0$ mixing

Now:

50 ab$^{-1}$:

Current measurements of $x$, $y$ give many constraints on NP models
[see Golowich et al., PRD76, 095009 (2007); 21 models considered, e.g., 2-Higgs doublets, left-right models, little Higgs, extra dimensions, of which 17 give constraints]

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Belle II expectations for $D^0 - D^0$ CPV

Now:

Note: LHCb will dominate most of these measurements, but Belle II should be competitive in $y_{CP}$ and possibly in $x^2$, $y'$, $|q/p|$, $\phi$ (see Staric, KEK FFW14). If LHCb sees new physics, it would be important for Belle II to independently confirm.
Summary

**time-dependent** $D^0(t) \rightarrow K^+\pi^-$
976 fb$^{-1}$ published:

\[
R_D = (3.53 \pm 0.13) \times 10^{-3}
\]
\[
x'^2 = (0.09 \pm 0.22) \times 10^{-3}
\]
\[
y' = (0.46 \pm 0.34)\%
\]

**time-dependent** $D^0(t) \rightarrow K_S \pi^+\pi^-$
921 fb$^{-1}$ published:

\[
x = (0.56^{+0.20}_{-0.22})\%
\]
\[
y = (0.30^{+0.16}_{-0.17})\%
\]
\[
|q/p| = (0.90^{+0.18}_{-0.16})\%
\]
\[
\phi = (-6 \pm 12)^\circ
\]

**time-dependent** $D^0(t) \rightarrow K^+K^-, \pi^+\pi^-$
977 fb$^{-1}$ preliminary:

\[
y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%
\]
\[
A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%
\]

Evidence for mixing is unequivocal: $K^+\pi$ alone is 5.1$\sigma$; combined with all other world data is $>12\sigma$. No sign yet of indirect CPV. However, the sensitivity of these searches will greatly improve (factor of $\sim$50 statistics) at Belle II
Extra/Backup
B factory performance – final tally:

World integrated luminosity on $\Upsilon(4S)$:
- CLEO: $11 \text{ fb}^{-1}$
- KEKB
- PEP-II

$Luminosity$ (fb$^{-1}$):
- 2000
- 2002
- 2004
- 2006
- 2008
- 2010
- 2012

$> 1 \text{ ab}^{-1}$
- On resonance:
  - $\Upsilon(5S)$: $121 \text{ fb}^{-1}$
  - $\Upsilon(4S)$: $711 \text{ fb}^{-1}$
  - $\Upsilon(3S)$: $3 \text{ fb}^{-1}$
  - $\Upsilon(2S)$: $25 \text{ fb}^{-1}$
  - $\Upsilon(1S)$: $6 \text{ fb}^{-1}$
- Off resonance/scan:
  - $\sim 100 \text{ fb}^{-1}$

$\sim 550 \text{ fb}^{-1}$
- On resonance:
  - $\Upsilon(4S)$: $433 \text{ fb}^{-1}$
  - $\Upsilon(3S)$: $30 \text{ fb}^{-1}$
  - $\Upsilon(2S)$: $14 \text{ fb}^{-1}$
- Off resonance:
  - $\sim 54 \text{ fb}^{-1}$