CP violation in charm and tau

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Introduction

- **CP violation in D meson decays**
  - Very small effect in SM; \( A_{\text{CP}} \leq O(10^{-3}) \).
    - Highly suppressed by the Cabibbo factors \( O(\lambda^5) \).
  - CP violation at \( O(1\%) \) level can be a clean signal for NP.
  - Recent measurement by LHCb stimulates an interest.

\[
\Delta A_{\text{CP}} = A_{K^+K^-} - A_{\pi^+\pi^-} = -(0.82 \pm 0.21 \pm 0.11)\%, \ 3.5\sigma
\]

- **CP violation in \( \tau \) lepton decays**
  - No KM type mechanism exists in charged leptons.
  - Tau is the only lepton that can decay to hadrons, which provides an opportunity for observing non-SM type CP violation.

  - CP violation in charm and tau lepton provides a unique possibility to search for New Physics.
Outline

- **Introduction**
  - $D^0 \overline{D}^0$ Mixing and $t$-dependent CPV measurements
    - Updated results for $D^0 \rightarrow \pi^+\pi^-, K^+K^-$ (Belle)
  - $t$-integrated CPV measurements
    - CP violation in $D^+ \rightarrow \phi\pi^+$ (Belle)
    - CP violation in $D^+ \rightarrow K_S\pi^+$ (Belle)
    - CP violation in $D^0 \rightarrow K_S P^0 (P^0=\pi^0, \eta, \eta')$ (Belle)

- **CP violation in tau lepton decays.**
  - Rate asymmetry for $\tau^- \rightarrow K_S\pi^- (\geq 0 \pi^0)\nu_\tau$ (BaBar)
  - CP asymmetry in angular distribution for $\tau^- \rightarrow K_S\pi^- \nu_\tau$ (Belle)
Mass eigenstate ≠ Flavor eigenstate

\[ |D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle, \quad |D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle \]

By solving the Schrödinger Eq.,

\[ i\frac{\partial}{\partial t} \begin{pmatrix} |D^0\rangle \\ |\bar{D}^0\rangle \end{pmatrix} = \left( M - i\frac{\Gamma}{2} \right) \begin{pmatrix} |D^0\rangle \\ |\bar{D}^0\rangle \end{pmatrix} \]

time evolution of a \( D^0 - \bar{D}^0 \) system is given by

\[ |D^0_{phys}(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p} g_-(t)|\bar{D}^0\rangle \]
\[ |\bar{D}^0_{phys}(t)\rangle = \frac{p}{q} g_-(t)|D^0\rangle + g_+(t)|\bar{D}^0\rangle \]

We define mixing parameters \( x \) and \( y \) as

\[ x = \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma} \]

\[ m = \frac{m_1 + m_2}{2}, \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \]

where state 2 is chosen as heavier mass state.

\[ \Delta m = m_2 - m_1 > 0 \]
\[ \Delta \Gamma = \Gamma_2 - \Gamma_1 \]
Master formula for t–dependent decay rates

**Time–dependent decay rates for** \( D^0 \rightarrow f \)

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

**Time–dependent decay rates for** \( \bar{D}^0 \rightarrow f \)

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

**Three classes of CP violation**

- CP violation in decay; \( |\bar{A}_f| \neq |A_f| \)
- CP violation in mixing;
- CP violation in interference btw a decay and mixing

\[
\text{Im}(\lambda_f) \neq 0 \text{ or } \pi, \quad \lambda_f = \frac{q \bar{A}_f}{p A_f}
\]

\( |D_1\rangle = p |D^0\rangle + q |\bar{D}^0\rangle, \quad |D_2\rangle = p |D^0\rangle - q |\bar{D}^0\rangle \)

\[
x = \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma}
\]

Since $D^0$ mixing is small ($|x|, |y|<<1$)

\[ \Gamma(D^0(t) \rightarrow f) = N_f e^{-\gamma t} |A_f|^2 \left\{ 1 + \text{Re} \left( \frac{q}{p} \frac{A_f}{A_r} \right) \Gamma y t - \text{Im} \left( \frac{q}{p} \frac{A_f}{A_r} \right) \Gamma x t \right\} \]

\[ \Gamma(\bar{D}^0(t) \rightarrow f) = N_f e^{-\gamma t} |\bar{A}_f|^2 \left\{ 1 + \text{Re} \left( \frac{p}{q} \frac{\bar{A}_f}{A_r} \right) \Gamma y t - \text{Im} \left( \frac{p}{q} \frac{\bar{A}_f}{A_r} \right) \Gamma x t \right\} \]

- Exponential decay modulates with $x$ and $y$.
  - $x$, $y$, $|p/q|$, $\varphi$ can be obtained from time dependence $dN/dt$
    \[ \varphi = \arg \left( \frac{q}{p} \frac{A_f}{A_r} \right) \]

- Need a tag of $D^0$ flavor
- Different final states sensitive to different combinations of $x$, $y$, $|p/q|$ and $\varphi$
D^0 mixing
and
time–dependent CPV measurements
Experimental method

- Use \( D^*+ \rightarrow \pi_S^+ D^0 \)
  - Tagging \( D^0 \) flavor from \( \pi_S \) charge.
  - Background suppression

- \( D^0 \) proper decay time measurement:
  \[
  t = \frac{l_{\text{dec}}}{c \beta \gamma}, \quad \beta \gamma = \frac{p_{D^0}}{M_{D^0}}
  \]

- Reject \( D^*+ \) from B decays:
  \( \rho_{D^*+}^{CM} \geq 2.5(3.1) \text{GeV} \) for \( Y(4S) \) (\( Y(5S) \)) data

- Observables
  
  \[
  m(K\pi) \\
  q = M(K\pi\pi_S) - m(K\pi) - m_\pi
  \]
Decays to CP–even eigenstate $D^0 \to K^+K^-, \pi^+\pi^-$

- Measurement of lifetime difference btw. $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-, \pi^+\pi^-$ decays
  
  \[ \Gamma(D^0, \bar{D}^0 \to K^-\pi^+) \propto e^{-\frac{t}{\tau_{K\pi}}} \]
  
  \[ \Gamma(D^0, \bar{D}^0 \to K^+K^-, \pi^+\pi^-) \propto e^{-(1+Y_{CP})\frac{t}{\tau_{K\pi}}} \]

- Ratio of lifetime
  
  \[ Y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1 \]

  In the limit of no CPV  $Y_{CP} = y$

- CP Violation
  
  \[ A_\tau = \frac{\tau(D^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(D^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} \]

  In the limit of no CPV  $A_\tau = 0$

- Relation with mixing and CP violating parameters
  
  \[ Y_{CP} = \frac{1}{2} \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) x \sin \phi \]

  \[ A_\tau = \frac{1}{2} \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - \frac{1}{2} \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi \]

  where  \( \phi = \text{arg} \left( \frac{q}{p} \right) \)

(S.Bergmann et al., PLB 486,418(2000)

D⁰ → K⁺K⁻, π⁺π⁻ (update with 976 fb⁻¹)

- Signal yield (purities)
<table>
<thead>
<tr>
<th>Item</th>
<th>KK</th>
<th>Kπ</th>
<th>πππ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield</td>
<td>242k</td>
<td>2.61M</td>
<td>114k</td>
</tr>
<tr>
<td>Purity</td>
<td>98.0%</td>
<td>99.7%</td>
<td>92.9%</td>
</tr>
</tbody>
</table>

- Background estimated from sidebands
- Fitting Proper decay time distribution

\[ f(t) = \frac{N}{\tau} \int e^{-t/\tau(y_{cp}\Gamma)} R(t - t') + B(t) \]

Free parameters: \( N, \tau, y_{cp}, \Gamma \) + parameters for \( R(t) \).

- Resolution function is prepared for each bin of timing resolution (\( \sigma_t \)).
- PDF parameters (\( N, \tau, y_{cp}, \Gamma \) etc) are determined in each polar bin of \( D^* \) production (cos\( \theta^* \))
Fitting results

<table>
<thead>
<tr>
<th>Tagging</th>
<th>$D^0$</th>
<th>$\bar{D}^0$</th>
<th>$D^0$</th>
<th>$\bar{D}^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2/\text{ndf} = 545.0/542$ (CL = 45.6%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Data1

3-layer SVD
153 fb$^{-1}$

Data2

4-layer SVD
823 fb$^{-1}$

The fits after integrating over $\cos\theta^*$ bins.
**Results (preliminary)**

\( \gamma_{cp} = (+1.11 \pm 0.22 \pm 0.11)\% \)

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

- \( \gamma_{cp} \) is at 4.5\( \sigma \) from zero when both errors are combined and at 5.1\( \sigma \) if only statistical error is considered.
- \( A_\Gamma \) is consistent with no indirect CP violation.
Comparison with previous exp. (hfag March 2012)

This analysis

\[ \gamma_{CP} = (+1.11 \pm 0.22 \pm 0.11\%) \]

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

Most precise measurement to date.
Time–integrated CPV measurements
Classification of Charmed meson decays
- Cabibbo Favored (CF)
- Singly Cabibbo Suppressed (SCS)
- Doubly Cabibbo Suppressed (DCS)

SCS decays are sensitive to new contribution from QCD penguin operators, which can yield direct CP violation effects of O(1%), while SM predict O(0.1%) direct CP in SCS decays.


Belle made searches for CP violation in following SCS modes.
\[ D^0 \rightarrow K^+K^-, \pi^+\pi^- , \quad D_S^+ \rightarrow Ks^0\pi^+, \quad D^+ \rightarrow Ks^0K^+, \quad \phi\pi^+, \quad \eta\pi^+, \quad \eta'\pi^+ \]

We report here \( \phi\pi^+ \) results that are based on 955 \( fb^{-1} \) Belle data. The diagrams contributing are very similar to the ones for \( K^+K^- \).
D^+ \rightarrow \phi \pi^+

- **Event selection**
  - Decay and production vertex fits
  - P_{D^+}^* > 2.5(3.1) GeV to reject D from B
  - |M_{KK} - m_\phi| < 1.6 MeV
  - P_\pi > 0.38 GeV
  - |\cos \theta_{hel}| > 0.28
- Found 238x10^3 D^+ and 723x10^3 Ds^+
- Measured decay asymmetry A_{rec}
  \[ A_{rec} = A_{cp} + A_{FB}(\cos \theta^*) + A_{\pi\varepsilon}(p_{\pi}, \cos \theta_{\pi}) \]
  - A_{FB}(\cos \theta^*): FB asymmetry, odd function of \cos \theta^*
  - A_{\pi\varepsilon}(p_{\pi}, \cos \theta_{\pi}): asymmetry in the reconstruction efficiency of pion.
- The effect of FB is subtracted by taking the sum of N(\cos \theta^*) and N(-\cos \theta^*)
To cancel $A_{\pi_e}(p_\pi, \cos\theta_\pi)$ effects, we take a difference btw $D^+$ and CF mode ($D_s^+\to \phi\pi^+$), in bins of $(\cos\theta^*, p_\pi, \cos\theta_\pi)$.

Assuming no CPV in CF mode ($D_s^+\to \phi\pi^+$), we obtain $A_{cp}$ for $D^+\to \phi\pi^+$

$$A_{cp}(D^+ \to \phi\pi^+) = \frac{\Gamma(D^+ \to \phi\pi^+) - \Gamma(D^+ \to \phi\pi^+)}{\Gamma(D^+ \to \phi\pi^+) + \Gamma(D^+ \to \phi\pi^+)} = (+0.51 \pm 0.28 \pm 0.05)\%$$

- No CP violation within 1.8 $\sigma$
- Precision improved by 5X compared to previous results (CLEO, Babar).
Belle measurements of Acp in SCS modes

- CP violation in various SCS modes has been searched with a sensitivity of 0.30–1% in Acp.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Data (fb⁻¹)</th>
<th>Process type</th>
<th>CP eigen state</th>
<th>Acp (%)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>D⁰→K⁺K⁻</td>
<td>540</td>
<td>SCS</td>
<td>Yes</td>
<td>−0.43±0.30±0.11</td>
<td>PL B670,190(2008)</td>
</tr>
<tr>
<td>D⁰→π⁺π⁻</td>
<td>540</td>
<td>SCS</td>
<td>Yes</td>
<td>+0.43±0.52±0.11</td>
<td>PL B670,190(2008)</td>
</tr>
<tr>
<td>D⁺→K⁺K⁻</td>
<td>540</td>
<td>SCS</td>
<td>Yes</td>
<td>±5.45±2.50±0.33</td>
<td>PRL 104,181602(2010)</td>
</tr>
<tr>
<td>D⁺→π⁺π⁻</td>
<td>540</td>
<td>SCS</td>
<td>Yes</td>
<td>±0.16±0.58±0.25</td>
<td>PRL 104,181602(2010)</td>
</tr>
<tr>
<td>D⁺→π⁺π⁻</td>
<td>540</td>
<td>SCS</td>
<td>Yes</td>
<td>±0.51±0.28±0.05</td>
<td>PRL 108,071801(2012)</td>
</tr>
<tr>
<td>D⁺→η⁻π⁺</td>
<td>791</td>
<td>SCS</td>
<td>Yes</td>
<td>±1.74±1.13±0.19</td>
<td>PRL 107,221801(2010)</td>
</tr>
<tr>
<td>D⁺→η⁻π⁺</td>
<td>791</td>
<td>SCS</td>
<td>Yes</td>
<td>±0.12±1.12±0.17</td>
<td>PRL 107,221801(2010)</td>
</tr>
</tbody>
</table>

c.f.:

\[ \Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = -(0.82 \pm 0.21 \pm 0.11)\% \] (LHCb) 3.5σ, Phys. Rev. lett.108,111602 (2012)

\[ \Delta A_{CP} = A_{K^+K^-} - A_{\pi^+\pi^-} = -(0.62 \pm 0.21 \pm 0.10)\% \] (CDF) 2.7σ, arxiv: 1205.3899
Two sources of CPV in $D^+ \rightarrow K_s^0 \pi^+$
- Interference btw CF($D^+ \rightarrow K^0\pi^+$) and DCS($D^+ \rightarrow K^0\pi^+$) modes: $A_{CP}^{A\Delta}$
- CP violation in $K^0$ system: $A_{CP}^{K^0} = (-0.332 \pm 0.006)\%$

\[
A_{CP}^{D^+ \rightarrow K_s^0 \pi^+} = \frac{\Gamma(D^+ \rightarrow K_s^0\pi^+) - \Gamma(D^- \rightarrow K_s^0\pi^-)}{\Gamma(D^+ \rightarrow K_s^0\pi^+) - \Gamma(D^- \rightarrow K_s^0\pi^-)} = A_{CP}^{A\Delta} + A_{CP}^{K^0}
\]

Data
- Signal yield is obtained by a simultaneous fit of $D^+, D^-$
  - $D^+, D^-$ yield 1.74 M events
  - Measured asymmetry $A_{rec}$
    \[
    A_{rec} = (-0.146 \pm 0.094)\%
    \]
D\(^+\) \rightarrow K_S\(^0\)\(\pi^+\)

Asymmetry extraction

\[ A_{\text{rec}} = A_{\text{cp}} + A_{\text{FB}}(\cos\theta^*) + A_{\pi e}(p_\pi, \cos\theta_\pi) + A_D \]

- \(A_{\text{FB}}(\cos\theta^*)\): FB asymmetry, odd function of \(\cos\theta^*\)
- Cancelled by taking the sum of \(N(\cos\theta^*)\) and \(N(-\cos\theta^*)\)
- \(A_{\pi e}(p_\pi, \cos\theta_\pi)\)
- Determined from CF decays \(D^+ \rightarrow K^-\pi^+\pi^+\) and \(D^+ \rightarrow K^-\pi^+\pi^0\) in each bin of \(p_\pi, \cos\theta_\pi\)

See red triangles

- Average over phase space
  \[ A_{\pi e} = (0.08 \pm 0.04)\% \]
- \(A_D\): differences in the interaction of \(K^0\) and \(K^0\) with material in the detector.

Dilution factor is obtained from \(\sigma(K^0 N)\) and \(\sigma(K^0 N)\) \(\text{Phys.Rev. D 84, 111501 (2011)}\)

\[ A_D = (0.10 \pm 0.02)\% \]
Results

\[ A_{cp} = (-0.46 \pm 0.09 \pm 0.07)\% \]

- SM prediction for \( A_{cp}^{K^0} \)
  
  Need to take into account acceptance effects as a function of \( K_s^0 \) decay time.
  
  (Grossman, Nir, arxiv: 1110.3709)
  
  \[ A_{cp}^{K^0} = (-0.345 \pm 0.008)\% \leftarrow (-0.332 \pm 0.006)\% \times 1.04 \]

- Observed \( A_{cp} \) is 3.2\( \sigma \) deviations away from zero, which is consistent with the expected CP violation due to the neutral kaon.
t–integrated rate asymmetry (CF/DCS)

- Cabibbo favored and DCS modes (Belle)

<table>
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<tr>
<th>Mode</th>
<th>Data (fb⁻¹)</th>
<th>Process type</th>
<th>CP eigen state</th>
<th>Acp (%)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>( D^+ \to K_S^0 \pi^+ )</td>
<td>977</td>
<td>CF/DCS</td>
<td></td>
<td>(-0.36\pm0.09\pm0.07)</td>
<td>arxiv. 1203.6409</td>
</tr>
<tr>
<td>( D_S^+ \to K_S^0 K^+ )</td>
<td>673</td>
<td>CF/DCS</td>
<td></td>
<td>+0.12\pm0.36\pm0.22</td>
<td>PRL 104,181602(2010)</td>
</tr>
<tr>
<td>( D^0 \to K_S^0 \pi^0 )</td>
<td>791</td>
<td>CF/DCS</td>
<td>Yes</td>
<td>(-0.28\pm0.19\pm0.10)</td>
<td>PRL 106,211801(2011)</td>
</tr>
<tr>
<td>( D^0 \to K_S^0 \eta )</td>
<td>* 791</td>
<td>CF/DCS</td>
<td>Yes</td>
<td>(-0.54\pm0.51\pm0.16)</td>
<td>PRL 106,211801(2011)</td>
</tr>
<tr>
<td>( D^0 \to K_S^0 \eta' )</td>
<td>* 791</td>
<td>CF/DCS</td>
<td>Yes</td>
<td>(-0.98\pm0.67\pm0.14)</td>
<td>PRL 106,211801(2011)</td>
</tr>
</tbody>
</table>

- \( D^0 \to K_S^0 \eta, K_S^0 \eta' \) first measurement
- Asymmetries for \( D^0 \to K_S^0 \pi^0, K_S^0 \eta, K_S^0 \eta' \) are also consistent with (-0.33%), the value due to CPV in neutral kaon.
CP violation in tau lepton decays.
CP Violation in $\tau^- \rightarrow \pi^- K_s (\geq 0\pi^0) \nu_\tau$ (BaBar)

- **Motivation**
  - CP violation is not yet observed in the lepton sector
  - Bigi and Sanda predict a decay rate asymmetry in $\tau^- \rightarrow \pi^- K_s \nu_\tau$ due to CPV in $K^0$ system.

$$A_\tau \equiv \frac{\Gamma(\tau^+ \rightarrow \pi^K_0 \nu_\tau) - \Gamma(\tau^- \rightarrow \pi^- K^0_0 \nu_\tau)}{\Gamma(\tau^+ \rightarrow \pi^+ K^0_0 \nu_\tau) + \Gamma(\tau^- \rightarrow \pi^- K^0_0 \nu_\tau)} = +0.33\%$$

- **Note:**
  - $\tau^+ \rightarrow K^0 \pi^- \nu_\tau, \tau^- \rightarrow K^0 \pi^- \nu_\tau$
  - $D^+ \rightarrow \bar{K}^0 \pi^+, D^- \rightarrow K^0 \pi^-$

- **Event selection**
  - **Signal side.**
    - 1$K_s^0$
    - 1–prong (not identified as kaon)
    - Any number of $\pi^0$
  - **Tag–side**
    - Electron or muon
  - Likelihood cuts to reduce qq background and select good Ks

Number of yield
- 169,455 event for $\tau^-$
- 170,211 event for $\tau^+$

Background(15%) is dominated by $\pi^- K^0 \bar{K}^0 \nu_\tau$
Efficiency as a function of Ks decay time.

2.8 $\sigma$ deviation from the SM prediction.

Asymmetry measurements

$A_{ec} = (\pm 0.19 \pm 0.21)\%$

$A_{ec} = A_{cp} + A_{e} + A_{D} + A_{back}$

- **$A_{e}$**: Asymmetry of pion efficiency
  checked by $\tau^{-} \rightarrow h^{-}h^{+}h^{-}\nu_{\tau}$, included in systematic

- **$A_{D}$**: Asymmetry $K^{0}$ and $\bar{K}^{0}$ interaction
  with material in the detector.
  $A_{D} = (0.07 \pm 0.01)\%$

- **$A_{back}$**: Asymmetry from background

  $\tau^{-} \rightarrow K^{+}K^{0}(\geq 0\pi^{0})\nu_{\tau}$
  $\tau^{-} \rightarrow K^{0}\bar{K}_{s}^{0}(\geq 0\pi^{0})\nu_{\tau}$

  $A_{back} = 0.11\%$

- **Results**

  $A_{cp} = (-0.36 \pm 0.23 \pm 0.11)\%$

  c.f. SM prediction

  $A_{SM} = (0.36 \pm 0.01)\%$ (due to CPV in $K^{0}$ system)

  (Ks efficiency effect is taken into account.)
Search for the decay angle CPV asymmetry by Belle.

Motivation

CP violation in $\tau$ decay is possible generally if there is an interference between the SM diagram and the CP violating scalar boson exchange diagrams. (Kuhn, Mirkes 1993)

Data

- With 699 fb$^{-1}$ data, signal yield is
  
  \[ \tau^+ \rightarrow K_S \pi^+ \nu_\tau : (162.2 \pm 0.4) \cdot 10^3 \text{ events} \]
  
  \[ \tau^- \rightarrow K_S \pi^- \nu_\tau : (162.0 \pm 0.4) \cdot 10^3 \text{ events} \]

Background: total 23%

- $\tau^- \rightarrow K_S K_L \pi \nu_\tau$: 9.5%
- $\tau^- \rightarrow K_S \pi \pi^0 \nu_\tau$: 3.7%
- $e^+ e^- \rightarrow qq$: 3.5%

PRL 107, 131801(2011)
Decay angle asymmetry in $\tau^{-} \rightarrow \pi^{-}K_{s}\nu_{\tau}$

- Differential decay rate
  \[
  \frac{d\Gamma(\tau^{-})}{dQ^{2}d\cos\theta d\cos\beta} = \left[ A(Q^{2}) - B(Q^{2})(3\cos^{2}\Psi - 1)(3\cos^{2}\beta - 1) \right] \cdot |F|^{2} + m_{\tau}^{2} |F_s|^{2} - C(Q^{2}) \cos\Psi \cos\beta \cdot \text{Re}(FF^{\dagger}(\eta_{s}))
  \]

- $F$: spin 1 Form Factor, $F_s$: spin 0 Form Factor
- $A(Q^{2}), B(Q^{2}), C(Q^{2})$: known functions of $Q^{2} = M^{2}(K_{\pi})$
- The last term proportional to $\cos\beta \cos\Psi$ changes the sign for the CP transformation (i.e. CP odd term).

- In order to extract this CP violation, we define the observable $A_{\text{cp}}$
  \[
  A^{\text{CP}}(M) = \frac{\int \left( \frac{d\Gamma_{\tau^{-}}}{d\omega} \cdot \cos\beta \cos\Psi - \frac{d\Gamma_{\tau^{+}}}{d\omega} \cdot \cos\beta \cos\Psi \right) d\omega}{\int \left( \frac{d\Gamma_{\tau^{-}}}{d\omega} + \frac{d\Gamma_{\tau^{+}}}{d\omega} \right) d\omega}
  \]
  where $d\omega = dQ^{2}d\cos\beta d\cos\Psi$

- $A_{\text{cp}}$ is the difference between the mean values of $\cos\beta\cos\Psi$ for $\tau^{-}$ and $\tau^{+}$.
After applying small corrections for $A_{FB}$ and $A_\pi$, we obtain

$$A_{\text{cp}} = (1.8 \pm 2.1(\text{stat}) \pm 1.4(\text{sys})) \times 10^{-3}$$

for $0.89 \leq M_{K\pi} \leq 1.11\text{GeV}$

No CP violation is observed.

Extraction of CP violating parameter $\eta_s$

$$F_s(Q^2) = F_s(Q^2) + \frac{\eta_s}{m_s} F_H(Q^2)$$

$$A'^{i}_{\text{cp}} = \text{Im}(\eta_s) \frac{N_s}{n_i} \int_{Q^2_{i}}^{Q^2_{2,i}} C(Q^2) \frac{\text{Im}(F_H^*)}{m_\tau} dQ^2, \quad C(Q^2); \text{known function} + \text{efficiency}$$

Use the measured mass spectrum to obtain the form factor $F$, $F_H$

- $|\text{Im}(\eta_s)| < (0.012 - 0.026)$ at 90 %C.L.
- limit depending on the resonance model.
- One order of magnitude more restrictive than the previous CLEO results.
Summary

- Updated measurements are presented with full Belle data of \( \approx 1 \text{ab}^{-1} \)
  - \( y_{\text{cp}}(K^+K^-,\pi^+\pi^-) = (+1.11 \pm 0.22 \pm 0.11)\% \)
  - \( A_{\tau}(K^+K^-,\pi^+\pi^-) = (-0.03 \pm 0.20 \pm 0.08)\% \)
    - 4.5\( \sigma \) from zero by a single exp.
    - no indirect CPV.
  - \( A_{\text{cp}}(D^+\to \phi \pi^+) = (+0.51 \pm 0.28 \pm 0.05)\% \)
  - \( A_{\text{cp}}(D^+\to K_s \pi^+) = (-0.36 \pm 0.09 \pm 0.07)\% \)
    - no direct CPV in SCS mode.
    - consistent w SM expectation from CPV in \( K^0 \).

- The sensitivity is achieving \( O(0.3-0.2)\% \)
- No CP violation is observed yet in charmed mesons in any experiments, except for 3.5 \( \sigma \) significance reported by LHC\( _b \)

- Tau leptons
  - BaBar reports \( A_{\text{cp}}(\tau^- \to K_s \pi^-\nu_t) = (-0.36 \pm 0.23 \pm 0.11)\% \), which is
    - 2.5\( \sigma \) away from SM expectation.
  - While Belle shows no indication of CP asymmetry in the angular distribution of \( \tau^- \to K_s \pi^-\nu_t \)
Backup
Systematics

<table>
<thead>
<tr>
<th>source</th>
<th>$\Delta y_{CP}$ (%)</th>
<th>$\Delta A_{\Gamma}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>acceptance</td>
<td>0.050</td>
<td>0.044</td>
</tr>
<tr>
<td>SVD misalignments</td>
<td>0.060</td>
<td>0.041</td>
</tr>
<tr>
<td>mass window position</td>
<td>0.007</td>
<td>0.009</td>
</tr>
<tr>
<td>background</td>
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<td>0.050</td>
</tr>
<tr>
<td>resolution function</td>
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<td>0.002</td>
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<tr>
<td>binning</td>
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<td>0.010</td>
</tr>
<tr>
<td>sum in quadrature</td>
<td>0.11</td>
<td>0.08</td>
</tr>
</tbody>
</table>

SVD misalignments:

- Studied with misaligned signal MC:
  - different local and different global misalignments simulated
- Found to affect resolution function considerably (especially $t_0$)
- Effect very similar for $KK$, $K\pi$ and $\pi\pi$
  - small impact on $y_{CP}$, $A_\Gamma$, large impact on $\tau_{K\pi}$
### TABLE I: Summary of systematic uncertainties in $A_{CP}^{D^+ \rightarrow \phi\pi^+}$

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_\epsilon^{KK}$ corrections</td>
<td>0.025</td>
</tr>
<tr>
<td>3D binning</td>
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</tr>
<tr>
<td>Invariant mass binning</td>
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</tr>
<tr>
<td>Fitting procedure</td>
<td>0.018</td>
</tr>
<tr>
<td>Selection of fit results</td>
<td>0.020</td>
</tr>
<tr>
<td>Sum in quadrature</td>
<td>0.050</td>
</tr>
</tbody>
</table>
Heavy Flavor Averaging Group performs an average of 10 physics parameters (including direct CP parameters, from observables reported until end-of-2011.

\[
x = (0.62 \pm 0.19) \%
\]
\[
y = (0.75 \pm 0.10)\%
\]
\[
(x, y = 0 \text{ is excluded at } 10.2 \sigma)
\]
\[
|q/p| = 0.88 \pm 0.18
\]
\[
\phi = (-10.1 \pm 9.5)^\circ
\]

No indirect CP violation
Check on the potential source of artificial CPV
- $\gamma-Z$ interference effect.
  (measure as a function of Lab. $3\pi$ system)
- Asymmetries induced by detector
  (measure as a function of $p$ and $\theta$ of particle in lab. system.)

Apply correction in event–by–event basis.

The Net effect of corrections to Acp is
- $\gamma-Z$: $O(10^{-4})$
- Detector: $O(10^{-3})$

Small since the Acp is measured as a function of angle relative to $\tau$ direction not in Lab. angles.
5–1. Extraction of limit for $\text{Im} \eta_s$

- **Relation between $A_{cp}$ and $\text{Im}(\eta_s)$**

$$A^i_{cp} = \text{Im}(\eta_s) \frac{N_s^{Q^2_i}}{\eta^i_{Q^2_i}} \int C(Q^2) \frac{\text{Im}(FF^*_H)}{m_c} dQ^2,$$

- Use our previous results of Form Factor $F$ and $F_s$ obtained a fit to the $K_s \pi$ mass spectrum.
- Float the relative const. phase $\phi_s$ btw $F$ and $F_s$, which cannot be determined only from mass spectrum.
Time dependent decay rates, D meson

- Approximation \((x, y \ll 1)\)
- Cabibbo favored, Flavor specific decay \(A_f = 0\)
  \[
  \Gamma(D^0(t) \rightarrow K^-\pi^+) = N_f |A_{K^-\pi^+}|^2 e^{-\Gamma t}
  \]
  \[
  \Gamma(\bar{D}^0(t) \rightarrow K^+\pi^-) = N_f |\bar{A}_{K^+\pi^-}|^2 e^{-\Gamma t}
  \]
- Singly Cabibbo suppressed, Decay to CP eigenstate
  \[
  \Gamma(D^0 \rightarrow K^+K^- / \pi^+\pi^-) = N_f |A_{KK / \pi\pi}|^2 e^{-\Gamma t} \left\{ 1 + \text{Re}(\lambda_{KK / \pi\pi})y \Gamma t - \text{Im}(\lambda_{KK / \pi\pi})x \Gamma t \right\}
  \]
  \[
  \Gamma(\bar{D}^0 \rightarrow K^+K^- / \pi^+\pi^-) = N_f |\bar{A}_{KK / \pi\pi}|^2 e^{-\Gamma t} \left\{ 1 + \text{Re}\left(\frac{1}{\lambda_{KK / \pi\pi}}\right)y \Gamma t - \text{Im}\left(\frac{1}{\lambda_{KK / \pi\pi}}\right)x \Gamma t \right\}
  \]
  \[
  \lambda_{KK} = \frac{q}{p} \lambda_{K\pi}, \quad \lambda_{\pi\pi} = \frac{q}{p} \lambda_{\pi\pi}
  \]
- Doubly Cabibbo suppressed
  \[
  \Gamma(D^0 \rightarrow K^+\pi^-) = N_f \left|A_{K^+\pi^-}\right|^2 \frac{|q|^2}{p} e^{-\Gamma t} \left\{ \left|\lambda_{K^+\pi^-}\right|^2 + \text{Re}\left(\frac{1}{\lambda_{K^+\pi^-}}\right)y \Gamma t + \text{Im}\left(\frac{1}{\lambda_{K^+\pi^-}}\right)x \Gamma t + \frac{1}{4} (y^2 + x^2)(\Gamma t)^2 \right\}
  \]

Cabibbo singly suppressed decay

\[ \lambda_{kk} = \frac{q}{p} \frac{\overline{A}_{kk}}{A_{kk}} = \left| \frac{q}{p} \right| e^{i\phi} \langle \overline{KK} | H | D^0 \rangle = \left| \frac{q}{p} \right| e^{i\phi} \frac{\langle \overline{KK} | (\text{CP})^{-1} HCP | D^0 \rangle}{\langle \overline{KK} | H | D^0 \rangle} = - \left| \frac{q}{p} \right| e^{i\phi} \implies \text{CP} | D^0 \rangle = - | D^0 \rangle \]

By substituting to the master equation, one get

\[ \Gamma(D^0 \to K^+ K^-) = N_r |A_{kk}|^2 e^{-\Gamma t} \{1 + \text{Re}(\lambda_{kk}) \gamma t - \text{Im}(\lambda_{kk}) x \gamma t\} \]
\[ = N_r |A_{kk}|^2 e^{-\Gamma t} \left\{1 - \left| \frac{q}{p} \right| (y \cos \phi - x \sin \phi) \gamma t \right\} \]
\[ \Gamma(D^0 \to \overline{K}^+ K^-) = N_r |A_{kk}|^2 e^{-\Gamma t} \{1 + \text{Re}(\lambda_{kk}^{-1}) \gamma t - \text{Im}(\lambda_{kk}^{-1}) x \gamma t\} \]
\[ = N_r |A_{kk}|^2 e^{-\Gamma t} \left\{1 - \left| \frac{p}{q} \right| (y \cos \phi + x \sin \phi) \gamma t \right\} \]

Since, for small \( z \), \( e^{-\Gamma t} (1 - z \gamma t) \approx e^{-\Gamma t} e^{-z \gamma t} = e^{-\Gamma(1+z)t} \), the effective decay width \( \Gamma = \Gamma(1+z) \) is given by

\[ \Gamma(D^0 \to K^+ K^-) = \Gamma(1 + \left| \frac{q}{p} \right| (y \cos \phi - x \sin \phi) \]
\[ \Gamma(D^0 \to \overline{K}^+ K^-) = \Gamma(1 + \left| \frac{p}{q} \right| (y \cos \phi + x \sin \phi) \]
\[ \Gamma(D^0 \to K^- \pi^+) = \Gamma(D^0 \to K^+ \pi^-) = \Gamma \]