Latest results on mixing and CPV in the charm decays at the $B$-Factories

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IISER Mohali
Outline

- Study $D$ at $B$ factory

- $D$ mixing
  - Wrong sign decay of $D^0 \rightarrow K\pi$
  - $D \rightarrow K_S^0 h h$ decay
  - $D \rightarrow \pi^+ \pi^- \pi^0$ decay

- Direct $CPV$ in $D$ decays
  - Radiative $D$ decays
  - $D^0 \rightarrow K_S K_S$ decays

- Summary of mixing and $CPV$ at $B$ factories
Why study $D$ at $B$ factory?

- General purpose detectors, built to test Standard Model mechanism for CP violation in $B$ decays.

Strength:
- Excellent particle identification.
- $\gamma$, $\pi^0$, and $K_S$ reconstruction can be done easily.
- Good background reduction and high signal efficiency (5-10%)

Based on which one can also call $B$ factory to be a charm factory!

$\sigma(b\bar{b}) \sim 1.05$ nb and $\sigma(c\bar{c}) \sim 1.3$ nb
**$D^0 - D^0$ mixing**

Mass : $(1864.83 \pm 0.05)$ MeV  \( \tau_{D^0} = (410.1 \pm 1.5) \times 10^{-15} \) s

Phenomenon of mixing can be described as a decaying two-component quantum state.

Mass eigenstates \((D_1, D_2) \neq \text{Flavor eigenstates} (D^0, \bar{D}^0)\).

Time evolution : \(|D_{1,2}(t)\rangle = e^{-im_{1,2}t} e^{-\frac{\Gamma_{1,2}t}{2}} |D_{1,2}(t = 0)\rangle\)

\(m_1(m_2)\) and \(\Gamma_1(\Gamma_2)\) are the mass and decay width of \(D_1(D_2)\)

Flavor states

\(|D^0(t)\rangle = \frac{1}{2p} \left[ |D_1(t)\rangle + |D_2(t)\rangle \right] \text{ and } |\bar{D}^0(t)\rangle = \frac{1}{2q} \left[ |D_1(t)\rangle - |D_2(t)\rangle \right]\)

At \(t=0\), states are produced as pure \(D^0\) or \(\bar{D}^0\)

\(|D_0(t)\rangle = \left[ |D_0\rangle \cosh \left( \frac{ix+y}{2} \bar{\Gamma} t \right) - \frac{q}{p} |\bar{D}_0\rangle \sinh \left( \frac{ix+y}{2} \bar{\Gamma} t \right) \right] e^{-imt-\frac{\bar{\Gamma}t}{2}} \quad |\bar{D}_0(t)\rangle = \left[ |\bar{D}_0\rangle \cosh \left( \frac{ix+y}{2} \bar{\Gamma} t \right) - \frac{q}{p} |D_0\rangle \sinh \left( \frac{ix+y}{2} \bar{\Gamma} t \right) \right] e^{-imt-\frac{\bar{\Gamma}t}{2}}

At later time can be \(\bar{D}_0\) or \(D_0\), depending on the value of mixing parameter \(x, y\):

\[x \equiv \frac{m_1 - m_2}{\bar{\Gamma}}; \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\bar{\Gamma}}; \quad \bar{\Gamma} \equiv \frac{\Gamma_1 + \Gamma_2}{2}; \quad \bar{m} \equiv \frac{m_1 + m_2}{2}\]

* under CPT conservation assumption: \(|p|^2 + |q|^2 = 1\)
In SM, $D^0$ meson can change to $\bar{D}^0$ via Double weak boson exchange (Short distance effects)

$$c \xrightarrow{W^+} d,s,b \xrightarrow{u} \bar{c}$$

Intermediate state common to both (Long distance effects)

$$\bar{c} \xrightarrow{W^-} u \xrightarrow{d,s,b} c$$

SM predictions for $x$ and $y$ suffers from larger uncertainties.
Generally, Mixing in charm system strongly suppressed : $|x|, |y| \sim 1\%$

Sensitive to New Physics effects : $|x| \gg |y|$

Observables at $B$ factories :

$$\frac{dN(D^0 \rightarrow f)}{dt} \propto e^{-\Gamma t} \left| A_f + \frac{q}{p} i x + y \bar{A}_f \bar{\Gamma} t \right|^2$$

$$\frac{dN(\bar{D}^0 \rightarrow f)}{dt} \propto e^{-\Gamma t} \left| \bar{A}_f + \frac{q}{p} i x + y A_f \bar{\Gamma} t \right|^2$$

$A_f = \langle f | D^0 \rangle$, $\bar{A}_f = \langle f | \bar{D}^0 \rangle$

Decay time distribution of accessible states $D^0, \bar{D}^0$ are sensitive to mixing parameters ($x$ and $y$), depending on the final state.

$dN(D^0 \rightarrow f)/dt$ is different function of $x$, $y$ (and $q$, $p$) for different $A_f^5 A_f$
CP violation in charmed mesons

Direct CPV (neutral and charged, mode dependent)

CP violation in decay appears on the amplitude level. Occurs if two different amplitude contribute to a single decay

\[ \left| \frac{A(D \rightarrow f)}{A(D \rightarrow f')} \right| \neq 1 \]

Indirect CPV (neutral, common for all decay modes)

In Mixing:

CP violation in mixing occurs if a particle \( D^0 \) can’t decay into a final state \( \bar{f} \) buts CP-conjugate \( \bar{D}^0 \) can.

\[ D^0 \rightarrow \bar{D}^0 \rightarrow Y^+X^- \leftrightarrow D^0 \quad \bar{D}^0 \rightarrow D^0 \rightarrow Y^-X^+ \leftrightarrow \bar{D}^0 \]

\( r_m = |q/p| \neq 1 \)

In interference of decays with and without mixing:

If mixing followed by decay and direct decay interfere. Final state must be common to \( D^0 \) and \( D^0 \).

Two conditions:

\[ x = \frac{\Delta M}{\Gamma} \neq 0 \]

\[ \text{arg} \left( \frac{q\bar{A}_f}{pA_f} \right) \neq 0 \]
D$^0 \to K^+\pi^-$ wrong sign analysis

Doubly Cabibbo Suppressed (DCS)

\[ \bar{u} \quad \bar{d} \quad \text{W}^+ \quad \text{V}^*_{us} \]
\[ \text{D}^0 \quad \text{c} \quad \text{V}_{cd} \quad \text{d} \quad \pi^- \]
\[ \text{u} \quad \text{c} \quad \text{s} \quad \text{K}^+ \]

Cabibbo Flavored (CF)

\[ \bar{u} \quad \bar{c} \quad \text{W}^- \quad \text{V}^*_{ud} \]
\[ \text{D}^0 \quad \text{c} \quad \text{V}_{cs} \quad \text{d} \quad \pi^- \]
\[ \text{u} \quad \text{d} \quad \text{s} \quad \text{K}^+ \]

Same initial-and final state
Interference between the two amplitude will occur

In the limit of CP conservation

Normalize wrong sign rate to the right sign to obtain

\[ R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = RD + \sqrt{R_D} y' \Gamma_{D^0} t + \frac{x'^2 + y'^2}{4} (\Gamma_{D^0} t)^2 \]

\[ R_D = \left| \frac{A_{DCS}}{A_{CF}} \right|^2 \quad x' = x \cos \delta + y \sin \delta \quad y' = -x \sin \delta + y \cos \delta \]

\[ \delta = \arg \left( \frac{A_{DCS}}{A_{CF}} \right) \quad x = \frac{\Delta m_{D^0}}{\Gamma_{D^0}} \quad y = \frac{\Delta \Gamma_{D^0}}{2 \Gamma_{D^0}} \]

\( \delta \) → strong phase not directly measurable at B-factories

\( y' \) and \( x'^2 \) accessible
**D⁰-D̄⁰ mixing at B factories**

**Experimental method**

- **Tag and suppress background**
  - $D^{*+} \rightarrow D^0\pi^+_{\text{slow}}$
  - Flavor of $D^0$ using charge of $\pi^+_{\text{slow}}$
  - $p_{\text{CMS}}(D^*) > 2.5 \text{ GeV/c}$ to eliminate $D^0$ from B decay

- **Measure $D^0$ proper time $t$, its error $\sigma_t$ by reconstructing $D^0$ momentum and flight length $l$**
  
  \[
  t = \frac{l_{\text{dec}}}{c\beta\gamma}, \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}
  \]
  
  $\sigma_t$ calculated from vtx error matrices

- **Mixing parameters ($x'², y'$) extracted by the fit to the time-dependent ratio of wrong sign to right sign decays**

  \[
  R\left(\frac{t}{\tau_{D^0}}\right) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS} \left(\frac{t'}{\tau_{D^0}}\right) R\left(\frac{t}{\tau_{D^0}} - \frac{t'}{\tau_{D^0}}\right) d\left(\frac{t'}{\tau_{D^0}}\right)}{\int_{-\infty}^{+\infty} \Gamma_{RS} \left(\frac{t'}{\tau_{D^0}}\right) R\left(\frac{t}{\tau_{D^0}} - \frac{t'}{\tau_{D^0}}\right) d\left(\frac{t'}{\tau_{D^0}}\right)}
  \]

  $R\left(\frac{t}{\tau_{D^0}} - \frac{t'}{\tau_{D^0}}\right)$ is resolution function of the real decay time $t'$. 

$D^0 \rightarrow K^+\pi^-$
WS decay $D^0 \rightarrow K^+\pi^-$

$\Delta M = M(D^{*+} \rightarrow D^0 \rightarrow K\pi)\pi^+_s$ - $M(D^0 \rightarrow K\pi)$

Gaussian + Johnson $S_U$

$R_{WS} : (0.385 \pm 0.006) \%$

Divide sample into $N$ bins of decay time and fit $\Delta M$

Fitting ratios less sensitive to resolution function

$\tau = 1/\Gamma_{D^0}$ Belle, PRL 112, 111801(2014)
WS decay $D^0 \rightarrow K^+\pi^-$: Results

Belle, PRL 112, 111801 (2014)

<table>
<thead>
<tr>
<th>Test hypothesis (χ²/DOF)</th>
<th>Parameters</th>
<th>Fit results (10⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing (4.2/7)</td>
<td>$R_D$</td>
<td>3.53 ± 0.13</td>
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<tr>
<td></td>
<td>$y'$</td>
<td>4.6 ± 3.4</td>
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<tr>
<td></td>
<td>$x'^2$</td>
<td>0.09 ± 0.22</td>
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<tr>
<td>No mixing (33.5/9)</td>
<td>$R_D$</td>
<td>3.864 ± 0.059</td>
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</tbody>
</table>

No CP Violation hypothesis

No-mixing hypothesis is excluded at 5.1σ

BaBar, PRD 98, 211802 (2007)

<table>
<thead>
<tr>
<th>Test hypothesis</th>
<th>Parameters</th>
<th>Fit results (10⁻³)</th>
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<tbody>
<tr>
<td>Mixing</td>
<td>$R_D$</td>
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<tr>
<td>with CPV</td>
<td>$y'^+$</td>
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<td></td>
<td>$x'^2+$</td>
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<tr>
<td>No CPV</td>
<td>$y'$</td>
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<tr>
<td></td>
<td>$x'^2$</td>
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<tr>
<td>No mixing</td>
<td>$R_D$</td>
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</table>

No-mixing hypothesis is excluded at 3.9σ

<table>
<thead>
<tr>
<th>Expt</th>
<th>$R_D$ (x10⁻³)</th>
<th>$y'$ (x10⁻³)</th>
<th>$x'^2$ (x10⁻³)</th>
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</thead>
<tbody>
<tr>
<td>Belle</td>
<td>3.53 ± 0.13</td>
<td>4.6 ± 3.4</td>
<td>0.09 ± 0.22</td>
</tr>
<tr>
<td>BaBar</td>
<td>3.03 ± 0.19</td>
<td>9.7 ± 5.4</td>
<td>-0.22 ± 0.37</td>
</tr>
<tr>
<td>CDF</td>
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<td>4.3 ± 4.3</td>
<td>0.08 ± 0.18</td>
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<tr>
<td>LHCb</td>
<td>3.533 ± 0.054</td>
<td>5.23 ± 0.84</td>
<td>3.6 ± 4.3</td>
</tr>
</tbody>
</table>

B factories results are competitive to that of Hadron colliders!
Mixing in $D^0$ decays to CP eigenstates, give rise to an effective lifetime $\tau$ that differs from that in the decays to flavor eigenstates such as $D \rightarrow K^\pm \pi^\mp$.

Observables

$$y_{CP} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow K^-K^+)} - 1$$

$y_{CP}$ is equal to the mixing parameter $y$ if CP is conserved. Otherwise, effective lifetimes of $\bar{D}^0$ and $D^0$ decaying to the same CP eigenstate differ and the asymmetry

$$A_\Gamma = \frac{\tau(\bar{D}^0 \rightarrow K^-K^+) - \tau(D^0 \rightarrow K^+K^-)}{\tau(\bar{D}^0 \rightarrow K^-K^+) + \tau(D^0 \rightarrow K^+K^-)} \neq 0$$

In absence of direct CP violation, $y_{CP}$ and $A_\Gamma$ are related to $x$ and $y$ as

$$y_{CP} = \frac{1}{2} \left( \frac{|q|}{|p|} + \frac{|p|}{|q|} \right) y \cos \phi - \frac{1}{2} \left( \frac{|q|}{|p|} - \frac{|p|}{|q|} \right) x \sin \phi$$

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

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

We measure:

Difference in proper decay time distributions of $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow \bar{f}$
CP eigenstates decays $D^0 \rightarrow K^+K^- / \pi^+\pi^-$

Tag $D^0$ flavor by charge of $\pi_S$ from $D^*$

Proper decay time distribution summed over $\cos\theta^*$

where $\theta^*$ polar angle of $D^0$ in CMS with respect to the direction of $e^+$

Measure $\gamma_{CP}$ and $A_\Gamma$ in bins of $\cos\theta^*$

Least Square fit

Fitted $D^0$ Lifetime:
(408.46±0.54)fs (stat only)

World Average:
(410.1±1.5) fs

$$\gamma_{CP} = [+1.11 \pm 0.22(\text{stat}) \pm 0.09(\text{syst})]\% (4.7\sigma)$$

$$A_\Gamma = [-0.03 \pm 0.20(\text{stat}) \pm 0.07(\text{syst})]\%$$
CP eigenstates decays $D^0 \to K^+K^- / \pi^+\pi^-$

Measure the lifetimes

$\tau^+: D^0 \to K^- K^+, \pi^- \pi^+$

$\bar{\tau}^+: \bar{D}^0 \to K^- K^+, \pi^- \pi^+$

Use their inverse to compute

$\gamma_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$ and

$\Delta Y = -\frac{A\Gamma}{2} = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$

$p_{CMS}(D^0)> 2.5 \text{ GeV/c}$

Only tagged for $D^0 \to \pi\pi$ due to poor S/N in untagged

$\gamma_{CP} = [0.72 \pm 0.18 \pm 0.12] \% (3.3\sigma)$

$\Delta Y = -\frac{A\Gamma}{2} = [0.09 \pm 0.26 \pm 0.06] \%$

*I roughly subtract combinatorial background*
Mixing in three body $D^0 \to K_S^0 \pi^+ \pi^-$

Powerful decay mode for flavor-tagged time-dependent $D^0$-$D^0$ studies

Quasi two body intermediate state
- **CF**: $D^0 \to K^{*-} \pi^+$
- **DCS**: $D^0 \to K^{*+} \pi^-$
- **CP**: $D^0 \to \rho K_S^0$

- Interference between intermediate resonance provide sensitivity to both magnitude and sign of the mixing parameters.
- Allows for probes for indirect CP violation

$$
\mathcal{M}(m_{-}^2, m_{+}^2, t) = \mathcal{A}(m_{-}^2, m_{+}^2) \frac{e_1(t) + e_2(t)}{2} + \frac{q}{p} \mathcal{A}^*(m_{-}^2, m_{+}^2) \frac{e_1(t) - e_2(t)}{2}
$$

$$
\overline{\mathcal{M}}(m_{-}^2, m_{+}^2, t) = \mathcal{A}^*(m_{-}^2, m_{+}^2) \frac{e_1(t) + e_2(t)}{2} + \frac{p}{q} \mathcal{A}(m_{-}^2, m_{+}^2) \frac{e_1(t) - e_2(t)}{2}
$$

- $\mathcal{A}$ amplitude for $|D^0\rangle$
- $\mathcal{A}^*$ amplitude for $|\overline{D}^0\rangle$
- $m_{\pm}^2 \equiv m^2(KS^0\pi^\pm)$

Sum of intermediates states

$$
\mathcal{A}(m_{-}^2, m_{+}^2) = \sum a_r e^{i\phi_r} \mathcal{A}_r(m_{-}^2, m_{+}^2) + aNRe^{i\phi}
$$

$$
\mathcal{A}^*(m_{-}^2, m_{+}^2) = \sum a_{\overline{a}} e^{i\phi_{\overline{a}}} \overline{\mathcal{A}_r}(m_{-}^2, m_{+}^2) + aNRe^{i\phi}
$$

Time dependence contained in terms $e_{1,2}(t) = \exp[-i(m_{1,2} - i\Gamma_{1,2}/2)t]$

Simultaneous determination of $x$ and $y$ via t-dependent amplitude analysis
**Signal selected:**

\[ M(K_S^0\pi^+\pi^-) \text{ and } Q = M(K_S^0\pi^+\pi^-\pi_s) - M(K_S^0\pi^+\pi^-) - m(\pi_s) \]

\[ |M - m_{D^0}| < 15 \text{ MeV} \]

\[ 5.75 \text{ MeV} < Q < 5.95 \text{ MeV} \]

**1231731±1633 signal events with purity of 95.5%**

**Dalitz model**

- For P- and D-wave decays, include 12 relativistic BW
- Blatt-Weisskopf penetration factors as form factors
- Zemach tensors for the angular dependence.
- \( \pi\pi \) S-wave dynamics: K-matrix formalism with P-vector approximation
- \( K_S^0\pi \) S-wave: LASS parameterization

\[ \chi^2/\text{ndf} = 1.207 \text{ for 14264-42 degrees of freedom} \]
Measurement of $x$, $y$ and $q/p$

Fit projection for CP conserved fit

$D^0$ mean lifetime = $(410.3 \pm 0.6)$fs
Consistent with PDG: $(410.1 \pm 1.5)$fs

Also search for CPV in $D^0/D^0 \rightarrow K_S^0 \pi^+ \pi^-$

$|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
$\text{arg}(q/p) = (-6 \pm 11^{+3+3}_{-3-4})^\circ$

Value of $x$ and $y$ consistent with CP conserved fit

$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$
$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$

No hint for indirect CP violation
Using $D^0 \rightarrow K_S \pi\pi$ and $D^0 \rightarrow K_S K K$ decays

BaBar, PRL 105 081803 (2010)

$469 fb^{-1}$

<table>
<thead>
<tr>
<th>Fit type</th>
<th>$x/10^{-3}$</th>
<th>$y/10^{-3}$</th>
</tr>
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<tbody>
<tr>
<td>Nominal</td>
<td>$1.6 \pm 2.3 \pm 1.2 \pm 0.8$</td>
<td>$5.7 \pm 2.0 \pm 1.3 \pm 0.7$</td>
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<tr>
<td>$K_S^0 \pi^+ \pi^-$</td>
<td>$2.6 \pm 2.4$</td>
<td>$6.0 \pm 2.1$</td>
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<tr>
<td>$K_S^0 K^+ K^-$</td>
<td>$-13.6 \pm 9.2$</td>
<td>$4.4 \pm 5.7$</td>
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<tr>
<td>$D^0$</td>
<td>$0.0 \pm 3.3$</td>
<td>$5.5 \pm 2.8$</td>
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<tr>
<td>$\bar{D}^0$</td>
<td>$3.3 \pm 3.3$</td>
<td>$5.9 \pm 2.8$</td>
</tr>
</tbody>
</table>

Disfavor non-mixing hypothesis with C.L. equivalent to 1.9σ
Using $D^0 \rightarrow \pi^+\pi^-\pi^0$ decay

First measurement of mixing parameter of time dependent amplitude analysis.

Signal identified as:

$$\Delta m \equiv m(\pi^+\pi^-\pi^0) - m(\pi^+\pi^-\pi^0)$$

$p_{\pi^0} > 350$ MeV

$p^*(D^0) > 2.8$ GeV

$\sim 138000$ events

<table>
<thead>
<tr>
<th>State</th>
<th>$J^{PC}$</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>$m(\pi^+\pi^-\pi^0)$</th>
<th>Phase (°)</th>
<th>Fraction $f_\tau$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho(770)^+$</td>
<td>1--</td>
<td>775.8</td>
<td>150.3</td>
<td>1.05±0.01</td>
<td>16.1±0.4</td>
<td>23.9±0.3</td>
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<tr>
<td>$\rho(770)^0$</td>
<td>1--</td>
<td>775.8</td>
<td>150.3</td>
<td>0.73±0.01</td>
<td>-1.6±0.5</td>
<td>35.6±0.4</td>
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<td>$\rho(770)^-$</td>
<td>1--</td>
<td>1465</td>
<td>400</td>
<td>0.55±0.07</td>
<td>-7.7±8.2</td>
<td>1.1±0.3</td>
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<tr>
<td>$\rho(1450)^+$</td>
<td>1--</td>
<td>1465</td>
<td>400</td>
<td>0.19±0.07</td>
<td>-7.0±15.9</td>
<td>0.1±0.1</td>
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<tr>
<td>$\rho(1450)^0$</td>
<td>1--</td>
<td>1465</td>
<td>400</td>
<td>0.53±0.06</td>
<td>8.2±6.7</td>
<td>1.0±0.2</td>
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<tr>
<td>$\rho(1700)^+$</td>
<td>1--</td>
<td>1720</td>
<td>250</td>
<td>0.91±0.15</td>
<td>-23.3±10.3</td>
<td>1.5±0.5</td>
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<td>$\rho(1700)^0$</td>
<td>1--</td>
<td>1720</td>
<td>250</td>
<td>0.60±0.13</td>
<td>-56.3±16.0</td>
<td>0.7±0.3</td>
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<td>$\rho(1700)^-$</td>
<td>1--</td>
<td>1720</td>
<td>250</td>
<td>0.98±0.17</td>
<td>78.9±8.5</td>
<td>1.7±0.6</td>
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<tr>
<td>$f_0(980)^+$</td>
<td>0++</td>
<td>980</td>
<td>44</td>
<td>0.06±0.01</td>
<td>-58.8±2.9</td>
<td>0.3±0.1</td>
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<td>$f_0(1370)^+$</td>
<td>0++</td>
<td>1434</td>
<td>173</td>
<td>0.20±0.03</td>
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<td>$f_0(1500)^+$</td>
<td>0++</td>
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<td>109</td>
<td>0.18±0.02</td>
<td>7.4±7.4</td>
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<td>$f_0(1710)^+$</td>
<td>0++</td>
<td>1714</td>
<td>140</td>
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<td>$f_0(1270)^+$</td>
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<td>0.25±0.01</td>
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<tr>
<td>$f_0(500)$</td>
<td>0++</td>
<td>500</td>
<td>400</td>
<td>0.26±0.01</td>
<td>-4.1±3.7</td>
<td>0.9±0.1</td>
</tr>
</tbody>
</table>

$D^0$ mean lifetime = $(410.2±3.8)$fs

Consistent with PDG: $(410.1±1.5)$fs

No CPV

$x = (1.5 \pm 1.2 \pm 0.6)\%$

$y = (0.2 \pm 0.9 \pm 0.5)\%$
$D^0$-$D^0$ Mixing: Summary

No mixing $(x, y) = (0,0)$

$\Delta \chi^2 = 450$, excluded at $> 11.5 \sigma$

$B$ factories results quite competent with hadron machines
Time integrated CPV measurements

Asymmetry of time-integrated decay rates:

\[ A_{\text{CP}} = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} \approx a_{\text{dir}} + \frac{\langle t \rangle}{\tau_D} a_{\text{ind}} \]

Charged D meson: \( A_{\text{CP}} = a_{\text{dir}} \)

Neutral D meson: \( A_{\text{CP}} = a_{\text{dir}} + a_{\text{ind}} \)

Indirect CPV is universal

\[ a_{\text{ind}} = (0.056 \pm 0.040)\% \]

\[ \Delta A_{\text{CP}} = A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi) \]

\[ \approx A_{\text{dir}}^{KK} - A_{\text{dir}}^{\pi\pi} + \frac{\Delta \langle t \rangle}{\tau_D} a_{\text{ind}} \]

This way, one can cancel the indirect component and experimental systematics to large extent.

SM estimate

\[ \Delta A_{\text{CP}}^{\text{SM}} \sim \frac{\alpha_s}{\pi} \frac{V_{ub} V_{cb}^*}{V_{us} V_{cs}} \sim 10^{-4} \]

But can also be as large as

\[ \Delta A_{\text{CP}}^{\text{SM}} \sim \text{few} - \text{several} \times 10^{-3} \]

Latest HFAG average

\[ \Delta A_{\text{CP}}^{\text{EXP}} \sim (-0.137 \pm 0.070)\% \]

Agreement with no CP violation CL = 6.5 x 10^{-2}

Belle and Babar provide competitive results.

Further, neutral modes not easy for LHCb.

Only limited results from CLEO.

\[ A_{\text{CP}} (D^0 \to \pi^0\pi^0) = [-0.03 \pm 0.64 \pm 0.10]\% \]

\[ A_{\text{CP}} (D^0 \to K_S^0\pi^0) = [-0.21 \pm 0.16 \pm 0.07]\% \]

Belle, PRL 112, 211601 (2014)
Search for \( CP \) violation in FCNC \( D^0 \to V\gamma, \ V=\phi, \ K^*0, \ \rho^0 \)

Radiative charm decays are dominated by long-range non-perturbative processes

- enhance B.F. up to \( 10^{-4} \), \( \text{PRD 52, 6383 (1995)} \)
- whereas short-range interactions are predicted to yield rates at the level \( 10^{-8} \).

<table>
<thead>
<tr>
<th>Expt.</th>
<th>Lumi., ( fb^{-1} )</th>
<th>Decay</th>
<th>B.F., ( \times 10^{-5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>78</td>
<td>( D^0 \to \phi \gamma )</td>
<td>( 2.67^{+0.70+0.15}_{-0.61-0.17} )</td>
</tr>
<tr>
<td>BaBar</td>
<td>387</td>
<td>( D^0 \to \phi \gamma )</td>
<td>( 2.73 \pm 0.30 \pm 0.26 )</td>
</tr>
<tr>
<td>BaBar</td>
<td>387</td>
<td>( D^0 \to K^*0 \gamma )</td>
<td>( 32.2 \pm 2.0 \pm 2.7 )</td>
</tr>
</tbody>
</table>

- Decay \( D^0 \to \rho \gamma \) has not been observed
- No \( A_{CP} \) measurement in \( D^0 \to V\gamma \)

In some SM extensions sizeable \( CP \) asymmetry expected in radiative charm decays:

- \( A_{CP}^{V\gamma} > 3 \% \) signal of New Physics \( \text{PRL 109, 171801 (2012)}, \text{arXiv:1210.6546} \)

Decay chain

\[
\begin{align*}
D^0 &\to \phi \gamma \to K^+ K^- \gamma \\
D^0 &\to K^*0 \gamma \to K^- \pi^+ \gamma \\
D^0 &\to \rho^0 \gamma \to \pi^+ \pi^- \gamma \\
D^0 &\to \rho^0 \gamma \to \pi^+ \pi^- \gamma
\end{align*}
\]

Normalization mode

\[
\begin{align*}
D^0 &\to K^+ K^- \\
D^0 &\to K^- \pi^+ \\
D^0 &\to \pi^+ \pi^- \\
D^0 &\to K^+ \pi^-
\end{align*}
\]

Signal extraction: Simultaneous 2D fit of \( M_{D^0} \) and \( \cos(\theta_H) \)

\[
A_{raw} = \frac{N(D \to V\gamma) - N(\bar{D} \to V\gamma)}{N(D \to V\gamma) + N(\bar{D} \to V\gamma)} = A_{CP} + A_{FB} + A_{\pi_s}^{\pi_s}
\]

\( A_{FB}, A_{\pi_s}^{\pi_s} \) eliminated through relative measurement of \( A_{CP} \).

\[
A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + A_{CP}^{norm}
\]
Search for CP violation in FCNC $D^0 \to V\gamma$, $V=\phi$, $K^{*0}$, $\rho^0$

First measurement of $\mathcal{A}_{CP}$.

Results consistent with no CPV
Search for CP violation in $D^0 \rightarrow K_S K_S$

- SM limit $\leq 1.1\%$ (95 C.L.) for direct CPV in $D^0 \rightarrow K_S^0 K_S^0$
- SCS decays (such as $D^0 \rightarrow K_S^0 K_S^0$) are special interest: possible interference with NP amplitude could lead to larger nonzero CPV

Previous measured $A_{CP} (D^0 \rightarrow K_S^0 K_S^0)$ by:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$A_{CP}$</th>
<th>Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$(-23 \pm 19)%$</td>
<td>$13.7 \text{ fb}^{-1}$</td>
</tr>
<tr>
<td>LHCb</td>
<td>$(-2.9 \pm 5.2 \pm 2.2)%$</td>
<td>$3 \text{ fb}^{-1}$</td>
</tr>
</tbody>
</table>

CLEO, PRD 63, 071101 (2001)
LHCb, JHEP 10, 055 (2015)

Method:

$A_{CP} (D^0 \rightarrow K_S K_S) = A_{raw} (D^0 \rightarrow K_S K_S) - A_{raw} (D^0 \rightarrow K_S \pi^0) + A_{CP} (D^0 \rightarrow K_S \pi^0) + A_{K^0/\bar{K}^0}$

$A_{K^0/\bar{K}^0}$: Asymmetry originating from the different strong interaction of $K^0$ and $\bar{K}^0$ mesons with nucleons of the detector material $= (-0.11 \pm 0.01)\%$

Ko et al PRD 84, 111501 (2011)

$A_{CP} (D^0 \rightarrow K_S^0 \pi^0) = (-0.20 \pm 0.17)\%$ [PDG]

Peaking background $D^0 \rightarrow K_S^0 \pi \pi$ ($D^0 \rightarrow \pi \pi \pi^0$) in $D^0 \rightarrow K_S K_S$ ($D^0 \rightarrow K_S \pi^0$) estimated in the $K_S$ mass sideband.

$0.470 < M_{\pi \pi} < 0.478 \text{ GeV}/c^2$ and $0.516 < M_{\pi \pi} < 0.536 \text{ GeV}/c^2$

$A_{raw}$ extraction: Simultaneous fit of $\Delta M$ for $D^0$ and $D^0$
Search for CP violation in $D^0 \rightarrow K_S K_S$

$D^0 \rightarrow K_S^0 K_S^0$ decay mode
Efficiency = (11.04±0.02)%
Signal Yield = 5399±87
$A_{raw} = (0.45±1.53)%$

$D^0 \rightarrow K_S^0 \pi^0$ decay mode
Efficiency = (12.60±0.02)%
Signal Yield = 531807±796
$A_{raw} = (0.16±0.14)%$

$A_{CP} (D^0 \rightarrow K_S^0 K_S^0) = (-0.02±1.53±0.17)\%$

- Consistent with no CPV.
- Improve precision of previous best measurement (LHCb) by more than a factor 3 !

arXiv:1609.06393
Mixing in $D^0 - D^0$ system is established with high confidence. Belle (BaBar) measured mixing parameters:

- $x'^2$ and $y'$ in WS decay of $D^0 \rightarrow K^+\pi^-$ with $5.1\sigma$ ($3.3\sigma$)
- $y_{CP}$ and $A_r$ in $D^0 \rightarrow h^+ h^-$ with $4.7\sigma$ ($3.3\sigma$)
- $x, y (D \rightarrow \pi^+\pi^0\pi^0), |q/p|, \arg(q/p)$ using $D \rightarrow \pi\pi\pi$ and $D \rightarrow K_s h h$

$B$ factory results comparable to the LHCb!

No significant $CP$ violation been observed so far in the search carried out in variety of $D$ mesons decays.

$A_{CP}$ measurement in $B$ factories →

✓ Strength lies in $\gamma, \pi^0$ reconstruction and clean environment.

CPV in $D$ decays challenge for the LHCb and Belle II.

Both provide competitive and complementary results.

For more details regarding charm prospects in Belle II, please look at

- Belle II Prospects for Time-Dependent CPV and Mixing by Alan Schwartz
- Belle II Prospects for Time-Integrated CPV by Seema Bahinipati
Thank you