Charm physics at the B-factories

Minnie-review

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IISER Mohali
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Saving us!
[up, down, bottom, top]
nothing matches their
[ strange, charm]
A series of fortunate events

Strange 1964

- CPV in Kaon system
  \[ K_L \rightarrow \pi^+\pi^-, \text{ 45 events} \]
  \[ 23 \times 10^3 \text{ in } K_L \rightarrow \pi^+\pi^\pi^0 \]

Beauty 2001

- CPV in Beauty system
- Large CPV in \( B^0 \) system
  \[ B^0 \rightarrow J/\psi K_S \sim 700 \text{ events} \]

Charm 2019

- CPV in Charm system
  \[ D^0 \rightarrow \pi\pi \sim 14000000 \text{ events} \]

As one can see, CPV in charm requires large data sample along with good control of systematic uncertainty.

Beauty is the new strange

Charm is the new strange.

Charm is really strange!
CP violation in the Standard Model

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix}
= 
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

\[
\left( egin{array}{ccc}
1 - \lambda^2/2 - \lambda^4/8 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda + A^2\lambda^5[1 - 2(\rho + i\eta)]/2 & 1 - \lambda^2/2 - \lambda^4(1 + 4A^2)/8 & A\lambda^2 \\
A\lambda^3[1 - (\rho + i\eta)(1 - \lambda^2/2)] & -A\lambda^2 + A\lambda^4[1 - 2(\rho + i\eta)]/2 & 1 - A^2\lambda^4/2
\end{array} \right) + O(\lambda^6)
\]

Here \( \lambda = \sin(\theta_c) \), and \( A, \rho, \eta \) are all real.

This representation is easy for relating CP violation to specific decay rates.

\( \eta \) is the only CPV source in the Standard Model.

Unitarity condition \( V^\dagger V = 1 \) gives six relations between the CKM matrix elements.

\[
\begin{align*}
V_{ud}^*V_{us} + V_{cd}^*V_{cs} + V_{td}^*V_{ts} &= 0 \\
V_{ud}^*V_{cd} + V_{us}^*V_{cs} + V_{ub}^*V_{cb} &= 0 \\
V_{us}^*V_{ub} + V_{cs}^*V_{cb} + V_{ts}^*V_{tb} &= 0 \\
V_{us}^*V_{cs} + V_{tc}^*V_{ts} + V_{cb}^*V_{tb} &= 0 \\
V_{td}^*V_{ud} + V_{ts}^*V_{us} + V_{tb}^*V_{ub} &= 0 \\
V_{ub}^*V_{ud} + V_{cb}^*V_{cd} + V_{tb}^*V_{td} &= 0
\end{align*}
\]

Each of these relations can be visualized as triangle in the complex plane. 
relating elements which appear in **strange and charmed particles**, are flat (despite having same area), so that one of the angles representing the relative phases of the CKM matrix elements is tiny.

**Related to K & D meson system**

One side is still small, angles not that large. Related to physics in \( B_S \) system.

All sides almost equal. Angles (relative phases) are large. Related to physics in \( B_d \) system.
Why the Charm?

• SM larger CP violation effects are expected with heavy quarks, in which complex phase of CKM matrix can appear directly rather through virtual transitions.

• *$D^0$* dominated by first two quarks families, and therefore large CP-violating effects are not expected.
• Top quark loops which provide largest effects in $K$ and $B$ decays are absent for $D$.
• Many channels are possible for *$D$* mesons, which are not suppressed by small mixing angles.
• Leading to large decay widths making observation of small effects a bit difficult.
• SM actually predicts very small mixing and CP violation.
  • 0.1% CP violation in decays can be searched in single cabibbo suppressed as SM predicts small asymmetries.

❖ Decays of charmed mesons are currently the only way to probe flavor violation in the up-quark sector.
  ➢ Non SM effects might show different patterns for the *$u$* and *$d$*.

Within SM, CP violation is expected to be small in charm sector. But, it is promising to study single Cabibbo-suppressed decays where direct CP asymmetry may be large enough to be detected. First evidence of CP violation in charm sector is observed in SCS decays $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ at LHCb.
$D^0 - \bar{D}^0$ mixing

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

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

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

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

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

Flavor states

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

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

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

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

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: \(|p|^2 + |q|^2 = 1\)
\( D^0 - \bar{D}^0 \) mixing

In SM, \( D^0 \) meson can change to \( \bar{D}^0 \) via

\[
\begin{align*}
\text{Double weak boson exchange} & \quad \text{(Short distance effects)} \\
\text{Intermediate state common to both} & \quad \text{(Long distance effects)}
\end{align*}
\]

Doubly Cabibbo Suppression vanishes in exact \( SU(3)_{FLAVOR} \)

\( |x|, |y| \sim 1\% \)

Observables at \( B \) factories:

\[
\frac{dN(D^0 \to f)}{dt} \propto e^{-\Gamma t} \left| A_f + \frac{q}{p} \frac{ix+y}{2} \bar{A}_f \bar{\Gamma} t \right|^2 \quad \frac{dN(\bar{D}^0 \to f)}{dt} \propto e^{-\bar{\Gamma} t} \left| \bar{A}_f + \frac{p}{q} \frac{ix+y}{2} A_f \bar{\Gamma} t \right|^2
\]

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

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

\( dN(D^0 \to f)/dt \) is different function of \( x, y (\text{and } q, p) \) for different \( A_f, \bar{A}_f \)
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
\[
\frac{|A(D \rightarrow f)|}{|A(\bar{D} \rightarrow f)|} \neq 1
\]

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.
\[
D^0 \rightarrow \bar{D}^0 \rightarrow Y^+X^- \leftrightarrow D^0 \quad \bar{D}^0 \rightarrow D^0 \rightarrow Y^-X^+ \leftrightarrow \bar{D}^0
\]
\[
r_m = \frac{|q/p|}{|q/p|} \neq 1
\]

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 $\bar{D}^0$.
Two conditions:
\[
x = \frac{\Delta M}{\Gamma} \neq 0
\]
\[
arg \left( \frac{qA_f}{pA_f} \right) \neq 0
\]
### Where one can study charm?

#### Clean environment

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Charm Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO (3.77, 4.17 GeV)</td>
<td>$3.5 \times 10^6 (D), 2.3 \times 10^6 (D^+)$</td>
</tr>
<tr>
<td>BESIII (3.77, 4.18, 4.6 GeV)</td>
<td>$10.5 \times 10^6 (D), 8.4 \times 10^6 (D^+), 3\times10^6 (D_{s+}), 1\times10^5 (\Lambda_c^+)$</td>
</tr>
<tr>
<td>BaBar 0.5 $ab^{-1}$</td>
<td>$6.5 \times 10^8 (D)$</td>
</tr>
<tr>
<td>Belle (1 $ab^{-1}$),</td>
<td>$1.3 \times 10^9 (D), 1.5 \times 10^8 (\Lambda_c^+)$</td>
</tr>
<tr>
<td>Belle II (0.08 $ab^{-1}$),</td>
<td>$\sim 1.0 \times 10^8 (D)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Efficiency ($\varepsilon$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLEO</td>
<td>$\varepsilon \sim 10 - 30%$</td>
<td>Pure sample with no background. Quantum Coherence. No T-dependent analyses.</td>
</tr>
<tr>
<td>BaBar</td>
<td>$\varepsilon \sim 5 - 10%$</td>
<td>High efficiency detection of neutral. Time-dependent analysis. High statistics control sample. Higher trigger event.</td>
</tr>
<tr>
<td>Belle</td>
<td>$\varepsilon &lt; 0.5%$</td>
<td>Large production cross-section. Large boost. Excellent time resolution. Dedicated trigger required.</td>
</tr>
</tbody>
</table>

#### Large production

<table>
<thead>
<tr>
<th>Collider</th>
<th>Charm Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (1.96 TeV)</td>
<td>$1.3 \times 10^{11}$</td>
</tr>
<tr>
<td>LHCb (7 TeV, 8 TeV)</td>
<td>$5 \times 10^{12}$</td>
</tr>
</tbody>
</table>

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</table>
Some results from BESIII

Test on Lepton flavor universality

Recently, lot of hints of LFU violation has emerged in semileptonic B- decays. One can also expect to have similar in $c \rightarrow s$ transitions.

\[
R_{D_s^+} = \frac{\Gamma(D_s^+ \rightarrow \tau^+ \nu_\tau)}{\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)} = \frac{m_{\tau^+}^2 \left(1 - \frac{m_{\tau^+}^2}{m_{D_s^+}^2}\right)^2}{m_{\mu^+}^2 \left(1 - \frac{m_{\mu^+}^2}{m_{D_s^+}^2}\right)^2}.
\]

Results agree with the SM prediction (but still statistically limited).

\[
\frac{B(D^0 \rightarrow \pi^- \mu^+ \nu_\mu)}{B(D^0 \rightarrow \pi^- e^+ \nu_e)} = 0.922 \pm 0.030 \pm 0.022 \quad 1.7\sigma \text{ consistent}
\]

\[
\frac{B(D^+ \rightarrow \pi^0 \mu^+ \nu_\mu)}{B(D^+ \rightarrow \pi^0 e^+ \nu_e)} = 0.964 \pm 0.037 \pm 0.026 \quad 0.5\sigma \text{ consistent}
\]
Quantum correlated measurement of $D^0$ hadronic decays.

Quantum correlation of the $D^0\bar{D}^0$ meson pair produced at $\psi(3770)$ provides a unique way to probe amplitude of the $D$ decays.

**Determination of the strong-phase difference between the CF and DCS amplitudes in decay of quantum-correlated $D$ pairs**

- Essential inputs to extract the angle $\phi_3/\gamma$ of the CKM unitarity triangle.
- Relating measured mixing parameters in hadronic decay $(x', y')$ to the mass and width difference parameters $(x, y)$.

<table>
<thead>
<tr>
<th>Runs</th>
<th>Collected / Expected integrated luminosity</th>
<th>Year</th>
<th>$\gamma/\phi_3$ sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb Run-1 [7, 8 TeV]</td>
<td>3 fb$^{-1}$</td>
<td>2012</td>
<td>8°</td>
</tr>
<tr>
<td>LHCb Run-2 [13 TeV]</td>
<td>6 fb$^{-1}$</td>
<td>2018</td>
<td>4°</td>
</tr>
<tr>
<td>Belle II Run</td>
<td>50 ab$^{-1}$</td>
<td>2025</td>
<td>1.5°</td>
</tr>
<tr>
<td>LHCb upgrade I [14 TeV]</td>
<td>50 fb$^{-1}$</td>
<td>2030</td>
<td>$&lt; 1^\circ$</td>
</tr>
<tr>
<td>LHCb upgrade II [14 TeV]</td>
<td>300 fb$^{-1}$</td>
<td>(&gt;2035)</td>
<td>$&lt; 0.4^\circ$</td>
</tr>
</tbody>
</table>

Recently, BESIII has presented measurement of the strong-phase difference in $K_{S,L}^0\pi^+\pi^-$ and $K_{S,L}^0K^+K^-$ decays.

✓ *Expected uncertainty on $\phi_3/\gamma$ to be 0.8°.*
Different ways of identifying $D^0$

**Belle (II), LHCb**

$D^{*+} \rightarrow D^0 \pi^+_{slow}$

Charged slow $\pi$ tell the flavor of $D$

For signal extraction and background reduction

$$\Delta M = M(D^0 \pi^+_{slow}) - M(D^0)$$

or

$$q = \Delta M - m(\pi^+_{slow})$$

$\varepsilon(D^*) \sim 80\%$, $\omega(D^*) \sim 0.2\%$

**Belle II (Rest of Events)**

$\varepsilon(D^*) \sim 27\%$, $\omega(D^*) \sim 13\%$

3 × more produced $D^0$

Increase sample by \sim 40\% \sigma(A_{CP}) reduced by \sim 15\%

**LHCb (Semileptonic B decays)**

$b \rightarrow c \mu^- \bar{\nu}_\mu$

20% of the prompt tagging

$\varepsilon$: Efficiency $\omega$: Mistagging

\[\text{Daughter particles:}\]

- $D^0(c\bar{u})$
- $K$
- $\pi^+$
- $\pi^-$
- $\pi^0$
- $\bar{c}$
- $e^+$
- $e^-$
- $K^+$
- $\bar{\nu}$
- $\bar{\nu}$
First observation of CP violation in charm

Measurement of time-integrated CP asymmetries in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ decays

![Graphs showing distributions of mass squared ($m(D^0\pi^+)$) for different decay modes and associated data counts.](image-url)
\[
A_{CP} = \frac{\Gamma(D \rightarrow f) - \Gamma(\bar{D} \rightarrow \bar{f})}{\Gamma(D \rightarrow f) + \Gamma(\bar{D} \rightarrow \bar{f})}
\]

\[
A_{raw} = A_{CP} + A_{prod} + A_{det}
\]

\[
A_{raw} = N_{D^0} - N_{\bar{D}^0}
\]

\[
A_{raw} = \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}}
\]

If the kinematics are similar then one can expect same to cancel.

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

Not simple, one need to perform reweighting procedure to match kinematics of \(D^0 \rightarrow K^+K^-\) and \(D^0 \rightarrow \pi^+\pi^-\)

Run2 result:

\[
\Delta A_{CP} = (-18.2 \pm 3.2 \text{ (stat.)} \pm 0.9 \text{ (syst.)}) \times 10^{-4}
\]

PRL 122, 211803 (2019)

Run1 result:

\[
\Delta A_{CP} = (-10 \pm 8 \text{ (stat.)} \pm 3 \text{ (syst.)}) \times 10^{-4}
\]

PRL 116, 191601 (2016)

\[
\Delta A_{CP} = (-14 \pm 16 \text{ (stat.)} \pm 8 \text{ (syst.)}) \times 10^{-4}
\]

Combining the two modes + Run1 measurement:

\[
\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}
\]

First observation of charm CPV at 5.3\(\sigma\)
How one might interpret CPV?

\[ \Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \quad \text{First observation of charm CPV at 5.3\sigma} \]

Difficult to estimate in SM.

In SM, need to estimate size of penguin vs tree!

SM prediction for desired CP asymmetry

\[ A_{CP}^f \propto \text{Im} \left( \frac{2V_{cb}^* V_{ub}}{V_{cs}^* V_{us} - V_{cd}^* V_{ud}} \right) \sim -6 \times 10^{-4} \]

Within \( SU(3)_{\text{Flavor}} \): \( A_{CP}^{KK} \sim -A_{CP}^{\pi\pi} \quad \Delta a_{CP}^{SU(3) \text{ limit}} = 2a_{CP}^{\text{dir}}(D^0 \rightarrow K^+ K^-). \) 

A. Petrov, PLB 774, 295 (2017)

But then data shows \( \mathcal{O}(30\%) \) in amplitudes

\[ \Delta A_{CP} \sim (2.0 \pm 0.3) \times 10^{-4} \quad \text{Smaller than experimental value by a factor of 7} \]

Physics beyond SM may well affect \( \Delta A_{CP} \)

QCD dynamics enhancing \( P \) and \( PA \) ?

In order to pin-point the reason for this, one need to measure precise CP asymmetries in other charm decays.

\[ |a_{CP}^{\text{dir}}(D^0 \rightarrow \bar{K}^* 0 K_S)| \leq 0.003, \quad |a_{CP}^{\text{dir}}(D^0 \rightarrow K_S K_S)| \leq 1.1\% \quad \text{@95\% C.L.} \]

QCD dynamics enhancing \( P \) and \( PA \) by factor of 7 can’t enhance \( |A_{CP}^{\text{dir}}(D^0 \rightarrow K_S K_S)| \) or \( |A_{CP}^{\text{dir}}(D^0 \rightarrow \bar{K}^* 0 K_S)| \) by same factor of 7.
Search for CP violation in $D^0 \rightarrow K_S K_S$

- SM limit 1% 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

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 = $(-0.11 \pm 0.01)\%$

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

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

In Belle II, we expect to reach sensitivity of $\pm 0.23\%$ with 50 ab$^{-1}$.

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)
### $A_{CP}$ sensitivity

**Belle II compliment LHCb in neutrals**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\mathcal{L}$ (fb$^{-1}$)</th>
<th>$A_{CP}$ (%)</th>
<th>Belle II 50 ab$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^+ K^-$</td>
<td>976</td>
<td>$-0.32 \pm 0.21 \pm 0.09$</td>
<td>±0.03</td>
</tr>
<tr>
<td>$D^0 \to \pi^+ \pi^-$</td>
<td>976</td>
<td>$+0.55 \pm 0.36 \pm 0.09$</td>
<td>±0.05</td>
</tr>
<tr>
<td>$D^0 \to \pi^0 \pi^0$</td>
<td>966</td>
<td>$-0.03 \pm 0.64 \pm 0.10$</td>
<td>±0.09</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 \pi^0$</td>
<td>966</td>
<td>$-0.21 \pm 0.16 \pm 0.07$</td>
<td>±0.02</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 K_S^0$</td>
<td>921</td>
<td>$-0.02 \pm 1.53 \pm 0.02 \pm 0.17$</td>
<td>±0.23</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 \eta$</td>
<td>791</td>
<td>$+0.54 \pm 0.51 \pm 0.16$</td>
<td>±0.07</td>
</tr>
<tr>
<td>$D^0 \to K_S^0 \eta'$</td>
<td>791</td>
<td>$+0.98 \pm 0.67 \pm 0.14$</td>
<td>±0.09</td>
</tr>
<tr>
<td>$D^0 \to \pi^+ \pi^- \pi^0$</td>
<td>532</td>
<td>$+0.43 \pm 1.30$</td>
<td>±0.13</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^- \pi^0$</td>
<td>281</td>
<td>$-0.60 \pm 5.30$</td>
<td>±0.40</td>
</tr>
<tr>
<td>$D^0 \to K^+ \pi^- \pi^+ \pi^-$</td>
<td>281</td>
<td>$-1.80 \pm 4.40$</td>
<td>±0.33</td>
</tr>
<tr>
<td>$D^+ \to \phi \pi^+$</td>
<td>955</td>
<td>$+0.51 \pm 0.28 \pm 0.05$</td>
<td>±0.04</td>
</tr>
<tr>
<td>$D^+ \to \pi^+ \pi^0$</td>
<td>921</td>
<td>$+2.31 \pm 1.24 \pm 0.23$</td>
<td>±0.17</td>
</tr>
<tr>
<td>$D^+ \to \eta \pi^+$</td>
<td>791</td>
<td>$+1.74 \pm 1.13 \pm 0.19$</td>
<td>±0.14</td>
</tr>
<tr>
<td>$D^+ \to \eta' \pi^+$</td>
<td>791</td>
<td>$-0.12 \pm 1.12 \pm 0.17$</td>
<td>±0.14</td>
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<tr>
<td>$D^+ \to K_S^0 \pi^+$</td>
<td>977</td>
<td>$-0.36 \pm 0.09 \pm 0.07$</td>
<td>±0.02</td>
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<tr>
<td>$D^+ \to K_S^0 K^+$</td>
<td>977</td>
<td>$-0.25 \pm 0.28 \pm 0.14$</td>
<td>±0.04</td>
</tr>
<tr>
<td>$D_S^+ \to K_S^0 \pi^+$</td>
<td>673</td>
<td>$+5.45 \pm 2.50 \pm 0.33$</td>
<td>±0.29</td>
</tr>
<tr>
<td>$D_S^+ \to K_S^0 K^+$</td>
<td>673</td>
<td>$+0.12 \pm 0.36 \pm 0.22$</td>
<td>±0.05</td>
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</tbody>
</table>

LHCb, PRL 122,191803 (2019).
Search for CP violation in FCNC $D^0 \rightarrow V\gamma$, $V=\phi, K^{*0}, \rho^0$

Radiative charm decays are dominated by long-range non-perturbative processes
- enhance B.F. up to $10^{-4}$, PRD 52, 6383 (1995)
- whereas short-range interactions are predicted to yield rates at the level $10^{-8}$.

In some SM extensions sizeable CP asymmetry expected in radiative charm decays:
- $A_{CP}^{V\gamma} > 3\%$ signal of New Physics

\[
A_{raw} = \frac{N(D \rightarrow V\gamma) - N(\bar{D} \rightarrow V\gamma)}{N(D \rightarrow V\gamma) + N(\bar{D} \rightarrow V\gamma)} = A_{CP} + A_{FB} + A_{\pi s} 
\]

$A_{FB}, A_{\pi s}$ eliminated through relative measurement of $A_{CP}$.

\[
A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + A_{CP}^{norm}
\]

$A_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$

$A_{CP}^{K^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$

$A_{CP}^{\rho^0\gamma} = +0.056 \pm 0.152 \pm 0.006$

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)
Rare $D$ decays

➢ In case, the believed enhancement of CPV in charm decay is due to the New Physics.
   ➢ One expect it to have effect in other charm decays.
➢ Rare charm decays seems to be the other way to confirm this.
   ➢ Forbidden at tree level in SM and CKM suppressed.
➢ Expected to be dominated by long distance tree-level contributions
➢ Potential for enhancements from BSM physics

PRD101,115006 (2020)
Search for rare decay $D^0 \rightarrow \gamma \gamma$

Decay is sensitive to search for new Physics:
mediated by FCNC ($c \rightarrow u$), forbidden in the tree level and highly suppressed due to GIM in SM

SM Prediction: $B \sim 10^{-8}$ PRD 66, 014009 (2002)

In MSSM $B \sim 10^{-6}$ with gluinos exchange

Set world’s best limit at $8.5 \times 10^{-7}$ in absence of a signal

In Belle II, with 50 ab$^{-1}$, one might expect to reach: $10^{-7}$-$10^{-8}$.

More in Latika’s talk

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)
Search for $D \rightarrow$ invisible decay

In the Standard Model (SM), $D$ meson decay to $\nu \bar{\nu}$ helicity suppressed by a factor of

$$\left(\frac{m_\nu}{m_D}\right)^2 \cdot \mathcal{B}(D^0 \to \nu \bar{\nu})_{SM} = 1.1 \times 10^{-30}$$

NP contributions such as scalar Dark matter, right-handed neutrino or Majorana fermion could substantially enhance the value up to $10^{-15}$

DM search associated with $D$ meson: alternative way for search for DM.

Method is based on the Belle previous techniques for $D_S$ leptonic decay.

$$e^+ e^- \rightarrow c \bar{c} \rightarrow D_{tag}^{(*)} X_{frag} D_{sig}^{*-}\text{ with } D_{sig}^{*-} \rightarrow D_{sig} D_{sig}^{0} \pi_s^-$$

$D_{tag}^{(*)}$: tag side, product of one $c$-jet

$X_{frag}$: fragmentation up to three $\pi$ at most one $\pi^0$

$\pi_s^-$: Slow pion decay from $D_{sig}^{*-}$

Signal side information:

Missing momentum against $D_{tag}^{(*)}, X_{frag}$ and $\pi^-$

PRD 82, 034005 (2010)

PLB 651, 374 (2007)

PR 117, 75 (1985)

JHEP 09, 139 (2013)
Reconstruct $D_{tag}^{(*)}, X_{frag}$ and $\pi^-$. Get $M_{miss}$ to get inclusive $D^0$ sample.

$$e^+e^- \rightarrow c\bar{c} \rightarrow D_{tag}^{(*)}X_{frag}\bar{D}^*_{sig} \text{ with } \bar{D}^*_{sig} \rightarrow \bar{D}^0_{sig}\pi^-$$

$$B(D^0 \rightarrow f) = \frac{N_{sig}(D^0 \rightarrow f)}{\varepsilon \times N_{D^0}^{intrinsic}}$$

90% CL upper limit at $9.4 \times 10^{-5}$

<table>
<thead>
<tr>
<th></th>
<th>Luminosity, ab$^{-1}$</th>
<th>Inclusive D yield, in 10$^6$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Belle II</td>
<td>50</td>
<td>38</td>
</tr>
</tbody>
</table>

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)
**D^0 \rightarrow K^+\pi^-** wrong sign analysis

**Doubly Cabibbo Suppressed (DCS)**

\[
\begin{array}{c}
\bar{u} \\
\uparrow D^0 \\
\downarrow c \\
V_{cd} \\
\downarrow W^+ \\
\uparrow V^*_{us} \\
\downarrow u \\
\downarrow \pi^- \\
\uparrow \bar{u} \\
\end{array}
\]

**Cabibbo Flavored (CF)**

\[
\begin{array}{c}
c \\
\uparrow D^0 \\
\downarrow u \\
V_{cs} \\
\downarrow W^- \\
\uparrow V^*_{ud} \\
\downarrow \bar{u} \\
\downarrow \pi^- \\
\uparrow \bar{c} \\
\end{array}
\]

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

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

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

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

\(\delta \rightarrow \text{strong phase not directly measurable at B-factories}\)

*Right sign CF dominates the Right Sign decay amplitude*

*y' and x'^2 accessible*
$D^0 - \bar{D}^0$ mixing at B factories

Experimental method

Tag and suppress background

- $D^{*+} \rightarrow D^0\pi^+_{\text{slow}}$
- Flavor of $D^0 \rightarrow$ 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 $(x', y')$ extracted by the fit to the time-dependent ratio of wrong sign to right sign decays

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

$R \left( t/\tau_{D^0} - t'/\tau_{D^0} \right)$ is resolution function of the real decay time $t'$. 
WS decay $D^0 \to K^+\pi^-$

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

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)
Most precise measurement by LHCb

TABLE I. Results of fits for different CP-violation hypotheses. The first contribution to the uncertainties is statistical and the second systematic. Correlations include both statistical and systematic contributions.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Direct and indirect CP violation $R_D$</th>
<th>$y'$</th>
<th>$(x')^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_D^{D}$</td>
<td>$3.454 \pm 0.040 \pm 0.020$</td>
<td>$1.000$</td>
<td>$-0.935$</td>
<td>$0.843$</td>
</tr>
<tr>
<td>$y'$</td>
<td>$5.01 \pm 0.64 \pm 0.38$</td>
<td>$1.000$</td>
<td>$-0.963$</td>
<td>$1.000$</td>
</tr>
<tr>
<td>$(x')^2$</td>
<td>$0.061 \pm 0.032 \pm 0.019$</td>
<td>$1.000$</td>
<td>$-0.963$</td>
<td>$1.000$</td>
</tr>
<tr>
<td>$R_D^{D}$</td>
<td>$3.454 \pm 0.040 \pm 0.020$</td>
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</tr>
<tr>
<td>$y'$</td>
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<td>$1.000$</td>
<td>$-0.963$</td>
<td>$1.000$</td>
</tr>
<tr>
<td>$(x')^2$</td>
<td>$0.016 \pm 0.033 \pm 0.020$</td>
<td>$1.000$</td>
<td>$-0.963$</td>
<td>$1.000$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$R_D (\times 10^{-3})$</th>
<th>$y' (\times 10^{-3})$</th>
<th>$x'^2 (\times 10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle [18]</td>
<td>$3.64 \pm 0.17$</td>
<td>$0.6_{-3.9}^{+4.9}$</td>
<td>$0.18_{-0.23}^{+0.37}$</td>
</tr>
<tr>
<td>BaBar [7]</td>
<td>$3.03 \pm 0.19$</td>
<td>$9.7 \pm 5.4$</td>
<td>$-0.22 \pm 0.37$</td>
</tr>
<tr>
<td>CDF [5]</td>
<td>$3.51 \pm 0.35$</td>
<td>$4.3 \pm 4.3$</td>
<td>$0.08 \pm 0.18$</td>
</tr>
<tr>
<td>LHCb [17]</td>
<td>$3.568 \pm 0.066$</td>
<td>$4.8 \pm 1.0$</td>
<td>$0.055 \pm 0.049$</td>
</tr>
<tr>
<td>Belle (this work)</td>
<td>$3.53 \pm 0.13$</td>
<td>$4.6 \pm 3.4$</td>
<td>$0.09 \pm 0.22$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Belle II $976 / fb$</th>
<th>Belle II $5 / ab$</th>
<th>Belle II $20 / ab$</th>
<th>Belle II $50 / ab$</th>
</tr>
</thead>
<tbody>
<tr>
<td>no $\sigma(x'^2) (10^{-5})$</td>
<td>$22$</td>
<td>$7.5$</td>
<td>$3.7$</td>
<td>$2.3$</td>
<td></td>
</tr>
<tr>
<td>CPV $\sigma(y') (%)$</td>
<td>$0.34$</td>
<td>$0.11$</td>
<td>$0.056$</td>
<td>$0.035$</td>
<td></td>
</tr>
<tr>
<td>no $\sigma(x'^2)$</td>
<td>$0.37$</td>
<td>$0.23$</td>
<td>$0.15$</td>
<td>$0.10$</td>
<td></td>
</tr>
<tr>
<td>$\sigma(y') (%)$</td>
<td>$0.26$</td>
<td>$0.17$</td>
<td>$0.10$</td>
<td>$0.051$</td>
<td></td>
</tr>
<tr>
<td>no CPV allowed $\sigma(q/p)$</td>
<td>$0.197$</td>
<td>$0.089$</td>
<td>$0.051$</td>
<td>$5.7$</td>
<td></td>
</tr>
<tr>
<td>$\sigma(\phi^0)$</td>
<td>$15.5$</td>
<td>$9.2$</td>
<td>$5.7$</td>
<td>$5.7$</td>
<td></td>
</tr>
</tbody>
</table>

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)
CP eigenstates decays $D^0 \to K^+K^- / \pi^+\pi^-$

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 $D \to K^{\pm}\pi^\mp$.

Observables

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

$y_{CP}$ 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

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

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

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

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

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

We measure:

Difference in proper decay time distributions of $D^0 \to f$ and $D^0 \to \bar{f}$
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: $(408.46\pm0.54)\text{fs}$ (stat only)
World Average: $(410.1\pm1.5)\text{ fs}$

\[
\begin{align*}
\gamma_{CP} &= [+1.11 \pm 0.22(stat) \pm 0.09(syst)]\% \quad (4.7\sigma) \\
A_\Gamma &= [-0.03 \pm 0.20(stat) \pm 0.07(syst)]\%
\end{align*}
\]
CP eigenstates decays $D^0 \to K^+K^- / \pi^+\pi^-$

\[
\gamma_{CP} = [0.63 \pm 0.15 \pm 0.11]\% \quad D^0 \to K^+K^- \\
\gamma_{CP} = [0.38 \pm 0.28 \pm 0.15]\% \quad D^0 \to \pi^+\pi^- \\
\gamma_{CP} = [0.57 \pm 0.13 \pm 0.09]\% 
\]

Result is consistent with the known value of the mixing parameter $y = (0.62 \pm 0.07)\%$

Showing no evidence for CP violation in $D^0 - \overline{D}^0$ mixing.

Prospectus in Belle II

The Belle II Physics Book, PTEP2019, 12, 123C01 (2019)

<table>
<thead>
<tr>
<th>Observable</th>
<th>Stats</th>
<th>Systematic</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma_{CP}(%)$</td>
<td>Reducible</td>
<td>Irreduc.</td>
<td></td>
</tr>
<tr>
<td>976 fb-1</td>
<td>0.22</td>
<td>0.07</td>
<td>0.24</td>
</tr>
<tr>
<td>5 ab-1</td>
<td>0.10</td>
<td>0.03-0.04</td>
<td>0.11-0.12</td>
</tr>
<tr>
<td>50 ab-1</td>
<td>0.03</td>
<td>0.01</td>
<td>0.05-0.08</td>
</tr>
</tbody>
</table>

Source $\Delta \gamma_{CP}(10^{-2})$

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>0.050</td>
</tr>
<tr>
<td>SVD misalignments</td>
<td>0.060</td>
</tr>
<tr>
<td>Mass window position</td>
<td>0.007</td>
</tr>
<tr>
<td>Background</td>
<td>0.059</td>
</tr>
<tr>
<td>Resolution function</td>
<td>0.030</td>
</tr>
<tr>
<td>Binning</td>
<td>0.021</td>
</tr>
<tr>
<td>Total syst. Error</td>
<td>0.220</td>
</tr>
</tbody>
</table>
$\mathcal{B}(D^0 \rightarrow K_s \omega) = 5 \times \mathcal{B}(D^0 \rightarrow K_s \phi)$ in PDG

Measure $\mathcal{Y}_{CP}$ in $D^0 \rightarrow K_s \omega$ for the first time.

Utilizes the full Belle data set.

Parameter $\mathcal{Y}_{CP}$ is determined by

$$\mathcal{Y}_{CP} = 1 - \frac{\tau(D^0 \rightarrow K^- \pi^+)}{\tau(D^0 \rightarrow K_s \omega)}$$

Lifetime fitting is performed with resolution (triple Gaussians) and background (with nonzero- and zero-lifetime components),

We get

$$\mathcal{Y}_{CP} = (0.96 \pm 0.91 \pm 0.62^{+0.17}_{-0.00})\%$$

Statistical, systematic, and from possible CP-even decays in the final state.
Mixing in three body $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

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

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

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

\[
\mathcal{M}(m_-, m_+, t) = \mathcal{A}(m_-, m_+) \frac{e_1(t) + e_2(t)}{2} + \begin{pmatrix} q \bar{\mathcal{A}}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2} \\
-p \mathcal{A}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2}
\end{pmatrix}
\]

\[
\bar{\mathcal{M}}(m_-, m_+, t) = \bar{\mathcal{A}}(m_-, m_+) \frac{e_1(t) + e_2(t)}{2} + \begin{pmatrix} p \bar{\mathcal{A}}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2} \\
-q \mathcal{A}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2}
\end{pmatrix}
\]

\[\mathcal{A}\text{ amplitude for } |D^0\rangle \quad \bar{\mathcal{A}}\text{ amplitude for } |\bar{D}^0\rangle \quad m_+^2 \equiv m^2(KS^0\pi^+)\]

Sum of intermediates states
\[\mathcal{A}(m_-, m_+) = \sum a_r e^{i \phi_r} \mathcal{A}_r(m_-, m_+) + aNRe^{i \phi_r} \quad \bar{\mathcal{A}}(m_-, m_+) = \sum a\bar{a}_r e^{i \phi_r} \bar{\mathcal{A}}_r(m_-, m_+) + aNRe^{i \phi_r}\]

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
Measurement of $x$, $y$ and $q/p$

1231731±1633 signal events with purity of 95.5%  

**Fit projection for CP conserved fit**

\[
\begin{align*}
&D^0 \text{ mean lifetime } = (410.3\pm0.6)\text{fs} \\
&\text{Consistent with PDG: } (410.1\pm1.5)\text{fs}
\end{align*}
\]

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

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

No hint for indirect CP violation

$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$  

$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$
Mixing parameters using $D^0 \rightarrow K_S\pi^+\pi^-$

\[
x_{CP} = \frac{1}{2} \left[ x \cos \varphi \left( \frac{|q|}{|p|} + \frac{|p|}{|q|} \right) + y \sin \varphi \left( \frac{|q|}{|p|} - \frac{|p|}{|q|} \right) \right]
\]

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

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

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

If no CPV:

\[
x_{CP} = x
\]

\[
\varphi = \arg \left( \frac{q A_f}{p A_f} \right) \quad \Delta x = 0
\]

\[
\frac{|q|}{|p|} = 1 \quad y_{CP} = y \quad \Delta y = 0
\]

Mixing is well established.

No evidence of CPV in mixing.
$D^0 \rightarrow K_S \pi^+ \pi^-$  

**Belle II prospectus**

*Uncertainty due to Dalitz model*

$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$$  
$$y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$$  
$$|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$$  
$$\arg(q/p) = (-6 \pm 11^{+3+3}_{-3-4})^\circ$$

<table>
<thead>
<tr>
<th>Data</th>
<th>stat.</th>
<th>syst.</th>
<th>Total</th>
<th>stat.</th>
<th>syst.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>red.</td>
<td>irred.</td>
<td></td>
<td>red.</td>
<td>irred.</td>
<td></td>
</tr>
<tr>
<td>$\sigma_x (10^{-2})$</td>
<td></td>
<td></td>
<td>$0.20$</td>
<td>$0.15$</td>
<td>$0.06$</td>
<td>$0.04$</td>
</tr>
<tr>
<td>$\sigma_y (10^{-2})$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0.16$</td>
</tr>
<tr>
<td>$\phi (^\circ)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$12.2$</td>
</tr>
</tbody>
</table>

Systematic uncertainty start dominating at $\sim 5 \text{ ab}^{-1}$.  
Can this be avoided?  
Measuring strong phase variation across Dalitz plane using coherent $D^0\overline{D}^0$ pairs (BESIII).
$D^0 \rightarrow K_s \pi^+ \pi^-$ bin flip method

Bin-flip method → Relies on ratios between charm decays reconstructed in similar kinematic and decay-time conditions, thus avoiding the need for an accurate modelling of the efficiency variation across phase space and decay time.

Data is binned in Dalitz coordinates where the binning scheme is chosen to have approximately constant strong-phase differences.

$m_\pm^2$ is squared invariant mass $m^2(K_s \pi^\pm)$ for $D^0 \rightarrow K_s \pi^+ \pi^-$ and $m^2(K_s \pi^{\mp})$ for $\bar{D}^0 \rightarrow K_s \pi^+ \pi^-$.

Two sets of eight bins are formed and organized symmetrically about principal bisector $m_+^2 = m_-^2$.

Bins labelled with indices $\pm b$. $+b$ refer to $m_+^2 > m_-^2$ (unmixed CF $D^0 \rightarrow K^{*-} \pi^+$ dominate)

$-b$ refer to symmetric $m_+^2 < m_-^2$ (receives larger contribution from decays following oscillation)

J. Libby et al PRD 82, 112006 (2010)
LHCb measure ratio $R_i^+ (R_i^-)$ between initially produced $D^0 (\bar{D}^0)$ meson in $i$ bin

$$R_b(t_j) = \frac{N_{-b}(t_j)}{N_b(t_j)} \quad \bar{R}_b(t_j) = \frac{\bar{N}_{-b}(t_j)}{\bar{N}_b(t_j)}$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value $[10^{-3}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{CP}$</td>
<td>$2.7 \pm 1.6 \pm 0.4$</td>
</tr>
<tr>
<td>$y_{CP}$</td>
<td>$7.4 \pm 3.6 \pm 1.1$</td>
</tr>
<tr>
<td>$\Delta x$</td>
<td>$-0.53 \pm 0.70 \pm 0.22$</td>
</tr>
<tr>
<td>$\Delta y$</td>
<td>$0.6 \pm 1.6 \pm 0.3$</td>
</tr>
</tbody>
</table>

$x_{CP} = (2.7^{+0.17}_{-0.15}) \times 10^{-2} \quad |q/p| = 1.05^{+0.22}_{-0.17}$

$y_{CP} = (7.4 \pm 0.37) \times 10^{-3} \quad \phi = -0.09^{+0.11}_{-0.16}$

Combining the world average value: $x = 3.9^{+1.1}_{-1.2} \times 10^{-3}$

Evidence of positive mass difference b/w the $D^0$ mass eigenstates.
$$a_{CP}^{ind} = (0.028 \pm 0.026 \%)$$

$$\Delta a_{CP}^{dir} = (-0.164 \pm 0.028 \%)$$
CPV is observed in Charm after Mixing.
Need to measure CPV in different models in order to really prove that the CPV is due to SM or NP.
Exciting and difficult times ahead.
Stats limitation is going to over soon.
We will soon start getting limited by Syst.
Need to be more smart. Pretty sure that next generation will be.
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Thank you
Using $D^0 \to K_S \pi\pi$ and $D^0 \to K_S K K$ decays

BaBar, PRL 105 081803 (2010)

469 fb$^{-1}$

Disfavor non-mixing hypothesis with C.L. equivalent to 1.9σ
CP eigenstates decays $D^0 \rightarrow K^+ K^- \, / \, \pi^+ \pi^-$

Measure the lifetimes

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

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

$\tau_{K\pi} : D^0 (\bar{D}^0) \rightarrow K^\mp \pi^\pm$

Use their inverse to compute $\gamma_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$ and $\Delta Y = -\frac{A\Gamma}{2} = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$

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

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

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

Uncertainty on $\gamma_{CP}$ is impressive
Using $D^0 \rightarrow \pi^+\pi^-\pi^0$ decay

First measurement of mixing parameter of time dependent amplitude analysis.

Signal identified as:

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

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

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

~138000 events

No CPV

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

$y = (0.2 \pm 0.9 \pm 0.5)\%$

$D^0$ mean lifetime = $(410.2 \pm 3.8)$fs

Consistent with PDG: $(410.1 \pm 1.5)$fs

Background from:

$D \rightarrow K^-\pi^+, D \rightarrow K^-\pi^+\pi^0,$

$D \rightarrow K_S\pi^+\pi^-$ and $D \rightarrow K_S(\rightarrow \pi^+\pi^-)\pi^0$

Fit with isobar model of relativistic BW line shape