Observation of CP violation in charm decays with the LHCb experiment

Angelo Carbone
INFN and University of Bologna
On behalf of the LHCb Collaboration
CP violation key dates

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Parity violation
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C. N. Yang and
C. S. Wu et al.
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2019
Charm particles: CP violation in $D^0$
meson decays
LHCb collaboration

TODAY
Outline

• CP violation in charm
• LHC as charm factory and the LHCb detector
• Recent LHCb results in the charm sector
  • Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ decay
  • Observation of CP violation in charm decays ($\Delta A_{CP}$ with $D^0 \rightarrow \pi^- \pi^+$ and $D^0 \rightarrow K^- K^+$)
• HFLAV update on CP violation searches
• Conclusions
CP violation
**CP violation**

A CP transformation has the effect of:
- changing the sign of the phase due to **weak** interactions ($\theta$)
- leaving unchanged the phase due to **strong** interactions ($\delta$)
CP violation

Tree level

\[ A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1} \]

\[ \overline{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1} \]

Loop level

\[ A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2} \]

\[ \overline{A}_2 = \rho_2 e^{i\delta_2} e^{-i\theta_2} \]

\[ |\overline{A}_1 + \overline{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2) \]
CP violation

\[ |\tilde{A}_1 + \tilde{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2) \]

It differs from zero if \( \delta_1 \neq \delta_2 \) and \( \theta_1 \neq \theta_2 \)

To observe CP violation in the decay it is necessary to have two distinct paths with amplitudes of different phases
$D^0$ mixing

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

\[
{i \frac{\partial}{\partial t} \left( \frac{D^0(t)}{\bar{D}^0(t)} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{D^0(t)}{\bar{D}^0(t)} \right)}
\]
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Mixing occurs because $D^0$ and $\bar{D}^0$ are linear combinations of mass eigenstates

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$
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$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
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The mass eigenstates develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$
$$e_{1,2}(t) = \exp \left[ -i \left( M_{1,2} - \frac{i}{2} \Gamma_{1,2} \right) t \right]$$
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Two parameters characterize the $D^0$ and $\bar{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$
$$y \equiv \frac{\Delta \Gamma}{2\Gamma}, \quad \Delta \Gamma \equiv \Gamma_1 - \Gamma_2$$
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If either $x$ or $y$ are different from zero, mixing occurs

$$|\langle \bar{D}^0|D^0(t)\rangle|^2 = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left[ \cosh(y \Gamma t) - \cos(x \Gamma t) \right]$$
$$|\langle D^0|\bar{D}^0(t)\rangle|^2 = \frac{1}{2} \left| \frac{p}{q} \right|^2 e^{-\Gamma t} \left[ \cosh(y \Gamma t) - \cos(x \Gamma t) \right]$$
$D^0$ mixing

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

$$i \frac{\partial}{\partial t} \left( \frac{D^0(t)}{\bar{D}^0(t)} \right) = \left( M - i \frac{\Gamma}{2} \right) \left( \frac{D^0(t)}{\bar{D}^0(t)} \right)$$

Mixing occurs because $D^0$ and $\bar{D}^0$ eigenstates develop in time.

Mixing is well established. Charm mixing parameters are small $< 10^{-2}$

$$x = (0.36^{+0.21}_{-0.16})\% \quad y = (0.67^{+0.06}_{-0.13})\% \text{ [HFLAV]}$$

Two parameters characterize the $D^0$ and $\bar{D}^0$ mixing:

$$x \equiv \frac{\Delta M}{\Gamma}, \quad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta \Gamma}{2 \Gamma}, \quad \Delta \Gamma \equiv \Gamma_1 - \Gamma_2$$

If either $x$ or $y$ are different from zero, mixing occurs:

$$|\langle \bar{D}^0 | D^0 (t) \rangle |^2 = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} [\cosh(y \Gamma t) - \cos(x \Gamma t)]$$

$$|\langle D^0 | \bar{D}^0 (t) \rangle |^2 = \frac{1}{2} \left| \frac{p}{q} \right|^2 e^{-\Gamma t} [\cosh(y \Gamma t) - \cos(x \Gamma t)]$$
CP violation in $D^0$ mixing

If $|q/p| \neq 1$
CP violation occurs in $D^0$ mixing
Current experimental status on $D^0$ mixing
CP violation in the interference

Starting from a given $D^0$ or $\bar{D}^0$ meson there are two different quantum paths to get the same final state $\rightarrow$ interference!

In case that $|D^0 \rightarrow \bar{D}^0 \rightarrow f|^2 \neq |\bar{D}^0 \rightarrow D^0 \rightarrow f|^2$, there is CP violation in the interference.
Why charm is charming?

- CP violation in charm sector (was) **not observed**
- Only way to probe CP violation in **up-type** mesons
- Complementary to K and B mesons
- SM expectation lie in the range $10^{-3} - 10^{-4}$
- Intense theoretical activities since several years on this topic

(Not a complete) List of recent theoretical papers on charm physics

Golden et. al., PLB 222 (1989) 501
Buccella et. al., PRD 51 (1995) 3478
Grossman et al., PRD 75 (2007) 036008
Artuso et. al., AR Nucl. Part. Sci. 58 (2008) 249
Khodjamirian et. al., PLB 774 (2017) 235
Pirtskhalava et al., PLB 712 (2012) 81
Cheng et al., PRD 85 (2012) 034036
Feldmann et al., JHEP 06 (2012) 007
Li et al., PRD 86 (2012) 036012
Franco et al., JHEP 05 (2012) 140
Brod et al., JHEP 10 (2012) 161
Atwood et al., PTEP 2013 (2013) 093B05
Hiller et al., PRD 87 (2013) 014024
Grossman et al., JHEP 04 (2013) 067
Müller et al., PRL 115 (2015) 251802
Today results are on those observables

CP violation in the decay can be observed if the asymmetry

\[ A_{CP}^{dir} (D^0 \to f) = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} \]

is different from zero

Direct CP violation

By defining:

\[ z_{CP} \pm \Delta z = -(q/p)^{\pm 1} (y \pm ix) \]
\[ x_{CP} = -\text{Im}(z_{CP}), \quad y_{CP} = -\text{Re}(z_{CP}) \]
\[ \Delta x = -\text{Im}(\Delta z), \quad \Delta y = -\text{Re}(\Delta z) \]

CP violation in mixing

\[ x_{CP} = x, \quad y_{CP} = y \]
\[ \Delta x = \Delta y = 0 \]
if CP conserved

\[ \Delta y \] is more often referred to as \( A_\Gamma \)


Angelo Carbone
LHC: a charm factory

- At the LHC, the production cross-section of charm is ~20 times larger than the beauty one

\[
\sigma(pp \to c\bar{c}X) = 1419 \pm 134 \, \mu b \quad @ \quad \sqrt{s} = 7 \, TeV^* \\
\sigma(pp \to c\bar{c}X) = 2840 \pm 226 \, \mu b \quad @ \quad \sqrt{s} = 13 \, TeV^{**}
\]

More than 1 billion of \( D^0 \to K^-\pi^+ \) events reconstructed with the full LHCb data sample

FORWARD-PEAKED PRODUCTION

- LHCb designed as forward spectrometer (operating in collider mode) covering the pseudorapidity range $2 < \eta < 5$

PYTHIA

10-300 mrad

VELO PRECISION VERTEXING

- 20 $\mu m$ impact parameter resolution, corresponding to $\sim 0.1 \times \tau(D^0)$ decay-time resolution for a 2-body charm decay.
The LHCb detector

TRACKING SYSTEM

- \( \Delta p/p = 0.4-0.6\% \) at 5–100 GeV/c, corresponding to \(~8\) MeV/c of mass resolution for a 2-body charm decay
RICH DETECTORS

• Provide discrimination between kaons, pions and protons between 5 and 100 GeV/c. Typical kaon ID ~ 95 % for ~ 5 % $\pi \rightarrow K$ mis-ID probability
The LHCb detector

CALORIMETERS

- Preshower + SPD + electromagnetic + hadronic calorimeters
- Vital for hardware-level hadron triggering
MUON STATIONS

- Five stations, used also in hardware trigger
- Excellent muon/pion separation (single hadron mis-ID rate 0.7% Phys. Lett. B699 (2011) 330)
Integrated recorded luminosity

The full LHCb data set is about $9 \text{ fb}^{-1}$

THANKS LHC!!
D⁰ production exploits in the analysis presented today

Two mechanisms of $D⁰$ production

Independent data sample

$D^{*+} \rightarrow D⁰ K^-$

$D⁰ \rightarrow K^+ \pi^+$

$IP \sim 0$

$K^-$

$\pi^+$

$PV$

$\mu^-$

$K^+$

$B$

$D⁰$

$PV$

Large $IP$

$X$
D⁰ production exploits in the analysis presented today

Experimentally we can tag $D⁰$ flavour at production by means of the charge of the muon and the soft pion.
Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay

Run 1 $[3 \, fb^{-1}]$

LHCB-PAPER-2019-001
[arXiv:1903.03074]
Measurement of $x_{CP}$ and $\Delta x$

- $D^0 \rightarrow K_s^0 \pi^+ \pi^-$ has a rich resonance substructure
- The analysis is performed by means of a model independent approach (bin-flip method)
  - avoids accurate modelling of the efficiency
- Binning scheme chosen to have almost constant strong phase differences
- Measure yield ratio $R_{bj}^{\pm}$ between $-b$ and $b$ in bins ($j$) of decay time
- $D^0$ flavour identified with the charge of $\pi$ and $\mu$
- $R_{bj}^{\pm}$ is function of $x_{CP}$, $y_{CP}$, $\Delta x$ and $\Delta y$

\[ m_{\pm} = \begin{cases} m^2(K_s^0 \pi^\pm) & \text{for } D^0 \rightarrow K_s^0 \pi^+ \pi^- \\ m^2(K_s^0 \pi^\mp) & \text{for } \bar{D}^0 \rightarrow K_s^0 \pi^+ \pi^- \end{cases} \]
Search for CP Violation in Mixing

Results

\[ y_{CP} = [0.74 \pm 0.36 \text{ (stat)} \pm 0.11 \text{ (syst)}] \%
\]

\[ \Delta y = [-0.06 \pm 0.16 \text{ (stat)} \pm 0.03 \text{ (syst)}] \%
\]

\[ x_{CP} = [0.27 \pm 0.16 \text{ (stat)} \pm 0.04 \text{ (syst)}] \%
\]

\[ \Delta x = [-0.053 \pm 0.070 \text{ (stat)} \pm 0.022 \text{ (syst)}] \%
\]

Most precise determination of \( x \) from a single experiment

Combination with current global knowledge gives \( x > 0 \) at more than 3\( \sigma \)

This brings to the first evidence that the masses of the neutral charm-meson eigenstates differ

no CP violation observed

LHCb

Prompt Semileptonic

Fit

LHCb

Prompt Semileptonic

Fit

LHCb-PAPER-2019-001

[arXiv:1903.03074]
Search for CP Violation in Mixing

Impact on the current world average
Search for Direct $CP$ Violation with $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays

+ Run 1 combination

LHCb-PAPER-2019-006
Paper submitted today

Paper link: http://cds.cern.ch/record/2668357/
Time-integrated CP asymmetry

CP asymmetry is defined as

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(D^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(D^0 \rightarrow f)}$$

with \( f = K^-K^+ \) and \( f = \pi^-\pi^+ \)

The flavour of the initial state \((D^0 \text{ or } D^0)\) is tagged by the charge of the slow pion from \(D^{*\pm} \rightarrow D^0\pi^+\) or muon from \(B \rightarrow D^0 (\rightarrow f) \mu^- X\)

The raw asymmetry for tagged \(D^0\) decays to a final state \(f\) is given by

$$A_{raw}(f) = \frac{N(D^0 \rightarrow f) - N(D^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(D^0 \rightarrow f)}$$

where \(N\) refers to the number of reconstructed events of decay after background subtraction
What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

\[ A_{\text{raw}}(f) = A_{\text{CP}}(f) + A_D(f) + A_D(\pi^+) + A_P(D^{*+}) \]

- No detection asymmetry for \( D^0 \) decays to \( K^-K^+ \) or \( \pi^-\pi^+ \)
- ... if we take the raw asymmetry difference

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

- the \( D^{*+} \) production and the slow pion detection asymmetries will cancel
What we measure is the physical asymmetry plus asymmetries due both to production and detector effects

\[ A_{\text{raw}}(f) = A_{CP}(f) + A_{D}(f) + A_{D}(\mu^-) + A_{P,\text{eff}}(D^0) \]

- No detection asymmetry for \(D^0\) decays to \(K^-K^+\) or \(\pi^+\pi^-\)
- ...if we take the raw asymmetry difference

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

- The \(D^0\) effective production and the muon detection asymmetries will cancel
**Current experimental status**

- Both CPV in decay (dir) and in the interference between mixing/decay (ind) can contribute

\[ \Delta A_{CP} = \left[ a_{CP}^{\text{dir}}(K^-K^+) - a_{CP}^{\text{dir}}(\pi^-\pi^+) \right] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{\text{ind}} \]

Relative difference of average proper time between \( D^0 \rightarrow K^-K^+ \) and \( D^0 \rightarrow \pi^-\pi^+ \)

In BaBar and Belle this quantity is zero

HFLAV combination

\[ a_{CP}^{\text{ind}} = (0.030 \pm 0.026)\% \]

\[ \Delta A_{CP}^{\text{dir}} = (-0.134 \pm 0.070)\% \]

Consistency with NO CPV hypothesis: 9.3%
LHCb $\Delta A_{CP}$ history [2012-2016]

- $\pi$-tagged (3 fb$^{-1}$)
- $\mu$-tagged (3 fb$^{-1}$)
- $\mu$-tagged (1 fb$^{-1}$)
- $\pi$-tagged (0.62 fb$^{-1}$)

JHEP 07 041 (2014)
$\Delta A_{CP}$ experimental status (before today)

- $\pi$-tagged (3 fb$^{-1}$)

- $\mu$-tagged (3 fb$^{-1}$)
  - LHCb [JHEP 07 041 (2014)]

- 385.8 fb$^{-1}$ $\Upsilon(4S)$

- 9.7 fb$^{-1}$ $\sqrt{s} = 1.96$ TeV $p\bar{p}$

- 976 fb$^{-1}$ $\Upsilon(4S)$
Data sample selection

- Reconstruction performed online
  - Turbo stream
- Requirements placed on:
  - Quality and PID information of tracks
  - $p_T$ of tracks and $D^0$
  - $D^0$ vertex quality
  - IP of $D^0$

![Diagram showing mass distributions](image)

**LHCb-PAPER-2019-006**

for $\pi$-tagged

$$m(D^0) \in [1844,1887] \text{ MeV}/c^2$$
Data sample selection

- Additional requirements placed on for $\mu$-tagged candidates:
  - $m_{corr} = \sqrt{m(D^0\mu) + p_T'(D^0\mu) + p_T'(D^0\mu)}$
  - $m(D^0)$ for prompt and $m(D^0\mu)$ for

- $\mu$-tagged candidates are further filtered with a MVA using as input the quality of the vertices, the $D^0$ flight distance, the IP and $p_T$ of the particles
For some regions of phase space, the soft pion of a specific charge is kicked out from the detector acceptance by the magnetic field.

This breaks the assumption that the raw asymmetries are small.
Fiducial Selection

- For some regions of phase space, the soft pion of a specific charge is kicked out from the detector acceptance by the magnetic field.
- This breaks the assumption that the raw asymmetries are small.
Fiducial Selection

- There are regions of phase space where only $D^{*+}$ or only $D^{*-}$ is kinematically possible.
  - this causes large value of $A_{raw}$ up to 100% in the edge regions where only $D^{*+}$ or $D^{*-}$ is reconstructed
  - this asymmetry is independent of the $D^0$ decay modes but it breaks the assumption that the raw asymmetries are small

Magnetic field $\uparrow$

| $p_y/p_z$ | $< 0.02$ |

LHCb-PAPER-2019-006
• There are regions of phase space where only $D^*$ or only $D^*$ is kinematically possible.

  • this causes large value of $A_{\text{raw}}$ up to 100% in the edge regions where only $D^*$ or $D^*$ is reconstructed

• this asymmetry is independent of the $D^0$ decay modes but it breaks the assumption that the raw asymmetries are small

**Fiducial Selection**

- **Magnetic field ↓**

![Graphical representation of Fiducial Selection](image-url)
Kinematic weighting

- Detection and production asymmetries are expected to depend on the kinematics of the reconstructed particles
  - the cancellation of nuisance asymmetries may be incomplete if the kinematic distributions of reconstructed $D^{*\pm}$ or $B$ candidates
  - a small correction to the $K^-K^+$ sample is applied by means of a weighting procedure.

- $\pi$-tagged: $p_T(D^*)$, $p(D^*)$, $\phi(D^*)$

Very small effect on $\Delta A_{CP}$ below $10^{-4}$
Kinematic weighting

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Very small effect on $\Delta A_{CP}$ below $10^{-4}$
$A_{\text{raw}}$ measurements [$\pi$-tagged]

- Fit $m(D^0\pi)$ distribution
- $A_{\text{raw}}$ measured from a simultaneous fit between $D^{*+}$ and $D^{*-}$

![Graph 1](image1.png)
![Graph 2](image2.png)

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

Comb. bkg.
$A_{\text{raw}}$ measurements [µ-tagged]

- Fit $m(D^0)$ distribution
- $A_{\text{raw}}$ measured from a simultaneous fit between $D^0$ and $\bar{D}^0$
Systematic uncertainties [$\pi$-tagged]

- Fit model: evaluated by fitting pseudoexperiments with alternative models $\rightarrow 0.6 \times 10^{-4}$
Systematic uncertainties [π-tagged]

- Fit model: evaluated by fitting pseudoexperiments with alternative models $\Rightarrow 0.6 \times 10^{-4}$
- Weighting procedure: considered the statistical knowledge of the weights $\Rightarrow 0.2 \times 10^{-4}$
Systematic uncertainties \([\pi\text{-tagged}]\)

- **Fit model:** evaluated by fitting pseudoexperiments with alternative models \(\rightarrow 0.6 \times 10^{-4}\)
- **Weighting procedure:** considered the statistical knowledge of the weights \(\rightarrow 0.2 \times 10^{-4}\)
- **Secondaries decays:** evaluated the presence of \(D^0\) decaying from \(B \rightarrow 0.3 \times 10^{-4}\)
Systematic uncertainties [π-tagged]

- Misreconstructed background: e.g. $D^0 \rightarrow K^-\pi^+\pi^0$, $D^0 \rightarrow \pi^-l^+\nu_l$ peaking in $m(D^0\pi)$ estimated by measuring the yields and asymmetries of backgrounds on the $m(D^0)$ distributions $\rightarrow 0.5 \times 10^{-4}$

yields and raw asymmetries of peaking background measured and extrapolated to the signal region [1844,1887] MeV/c²
Systematic uncertainties [$\mu$-tagged]

- Fit model: evaluated by fitting pseudoexperiments with alternative models $\Rightarrow 2 \times 10^{-4}$
- $\mu$-tagged dominated by mistag (wrong muon) evaluated on the $B \rightarrow D^0(\rightarrow K^-\pi^+)\mu^-X$ control sample $\Rightarrow 4 \times 10^{-4}$
Angularly,$\text{uncertainties}$

• Fit model: evaluated by fitting pseudoexperiments with alternative models $\rightarrow 2 \times 10^{-4}$

• $\mu$-tagged dominated by mistag (wrong muon) evaluated on the $B \rightarrow D^0 (\rightarrow K^- \pi^+) \mu^- X$ control sample $\rightarrow 4 \times 10^{-4}$

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- $\mu$-tagged dominated by mistag (wrong muon) evaluated on the $B \rightarrow D^0 (\rightarrow K^-\pi^+)\mu^-X$ control sample $\rightarrow 4 \times 10^{-4}$
- Weighting procedure: considered the statistical knowledge of the weights $\rightarrow 10^{-4}$
- $B^0$ fraction: reconstructed $B^0$ and $B^+$ decays can be slightly different between the $K^-K^+$ and $\pi^-\pi^+$ decay modes $\rightarrow 10^{-4}$
Systematic uncertainties $[\mu\text{-tagged}]$

- Fit model: evaluated by fitting pseudoexperiments with alternative models $\rightarrow 2 \times 10^{-4}$
- $\mu$-tagged dominated by mistag (wrong muon) evaluated on the $B \rightarrow D^0 (\rightarrow K^- \pi^+) \mu^- X$ control sample $\rightarrow 4 \times 10^{-4}$
- Weighting procedure: considered the statistical knowledge of the weights $\rightarrow 10^{-4}$
- $B^0$ fraction: reconstructed $B^0$ and $B^+$ decays can be slightly different between the $K^- K^+$ and $\pi^- \pi^+$ decay modes $\rightarrow 10^{-4}$
- $B^0$ reconstruction efficiency: difference ($K^- K^+$ and $\pi^- \pi^+$ modes) $B^0$ in reconstruction efficiency as function of decay time and $B^0$ oscillation $\rightarrow 2 \times 10^{-4}$
### Systematic uncertainties summary

<table>
<thead>
<tr>
<th>Source</th>
<th>$\pi$-tagged $[10^{-4}]$</th>
<th>$\mu$-tagged $[10^{-4}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit model</td>
<td>0.6</td>
<td>2</td>
</tr>
<tr>
<td>Mistag</td>
<td>–</td>
<td>4</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>Secondary decays</td>
<td>0.3</td>
<td>–</td>
</tr>
<tr>
<td>$B^0$ fraction</td>
<td>–</td>
<td>1</td>
</tr>
<tr>
<td>$B$ reco. efficiency</td>
<td>–</td>
<td>2</td>
</tr>
<tr>
<td>Peaking background</td>
<td>0.5</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>0.9</td>
<td>5</td>
</tr>
</tbody>
</table>

$\pi$-tagged systematic uncertainty below $10^{-4}$!
Robustness checks

- Sample split according to year and magnet polarity $\rightarrow \Delta A_{CP}$ consistent among the subsamples
- Sample split according to data taking period $\rightarrow \Delta A_{CP}$ consistent among the subsamples
- Analysis repeated with tighter PID and looser fiducial requirements $\rightarrow \Delta A_{CP}$ compatible with statistical fluctuations
- (Only $\pi$-tagged) measurement of $\Delta A_{bkg}$ (the difference between the background raw asymmetries of $K^-K^+$ and $\pi^-$-$\pi^+$ modes
  - the prompt background is mainly composed of genuine $D^0$ and unrelated pions originating from PV
  - $\Delta A_{bkg}$ is expected to be compatible with zero
  - $\Delta A_{bkg} = (-2 \pm 4) \times 10^{-4}$
Additional robustness checks

Measured value of $\Delta A_{CP}$ is studied as a function of several variables \(\rightarrow\) data taking period

No evidence for unexpected dependences
Additional robustness checks

- Measured value of $\Delta A_{CP}$ is studied as a function of several variables $\rightarrow D^0$ impact parameter and decay time

No evidence for unexpected dependences
Additional robustness checks

- Measured value of $\Delta A_{CP}$ is studied as a function of several variables $\rightarrow \pi/\mu$ impact parameter and transverse momentum

No evidence for unexpected dependences
Results with Run-2 [6 fb$^{-1}$]

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

\[
\Delta A_{CP}^{\mu\text{-tagged}} = [-9 \pm 8 \text{ (stat.)} \pm 5 \text{ (syst.)}] \times 10^{-4}
\]

Compatible with previous LHCb results and the WA

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

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

$\mu$-tagged Run 1 (3 fb$^{-1}$)


$\pi$-tagged Run 1 (3 fb$^{-1}$)

JHEP 07 041 (2014)
Results with full LHCb data sample [9 fb⁻¹]

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

5.3 standard deviations from zero

This is the first observation of CP violation in the decay of charm hadrons
Interpretation

\[ \Delta A_{CP} \approx \Delta a_{CP}^{\text{dir}} \left( 1 + \frac{\langle t \rangle}{\tau(D^0)} y_{CP} \right) + \frac{\Delta \langle t \rangle}{\tau(D^0)} a_{CP}^{\text{ind}} \]

\[ \langle t \rangle = \frac{\langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}}{2} \]

\[ \Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi} \]

\[ \langle t \rangle_f \] is the reconstructed decay time of a given decay

assuming universal contribution from mixing/decay interference in KK and \pi\pi
For the full LHCb data set (9 fb$^{-1}$):

$$\Delta \langle t \rangle / \tau(D^0) = 0.115 \pm 0.002$$

$$\langle t \rangle / \tau(D^0) = 1.71 \pm 0.10$$

Using the LHCb averages:

$$\gamma_{CP} = (5.7 \pm 1.5) \times 10^{-3}$$

$$A_\Gamma = (-2.8 \pm 2.8) \times 10^{-4} \approx -a_{CP}^{\text{ind}}$$

$$\Delta a_{CP}^{\text{dir}} = (-15.6 \pm 2.9) \times 10^{-4}$$

$\Delta A_{CP}$ mostly sensitive to direct $CP$ violation
$\Delta A_{CP}$ history in LHCb [2012-2019]

- $\pi$-tagged (6 fb$^{-1}$)
  - LHCb-PAPER-2019-006
- $\mu$-tagged (6 fb$^{-1}$)
  - LHCb-PAPER-2019-006
- $\pi$-tagged (3 fb$^{-1}$)
- $\mu$-tagged (3 fb$^{-1}$)
  - JHEP 07 041 (2014)
- $\mu$-tagged (1 fb$^{-1}$)
- $\pi$-tagged (0.62 fb$^{-1}$)
$\Delta A_{CP}$ experimental status (today)

9 fb\(^{-1}\) $\sqrt{s} = 7.13$ TeV $pp$

385.8 fb\(^{-1}\) $\Upsilon(4S)$

9.7 fb\(^{-1}\) $\sqrt{s} = 1.96$ TeV $p\bar{p}$

976 fb\(^{-1}\) fb\(^{-1}\) $\Upsilon(4S)$

LHCb [LHCb-PAPER-2019-006]


Belle Preliminary [arXiv:1212.1975]
HFLAV update

HFLAV combination

\[ a_{CP}^{\text{ind}} = (0.028 \pm 0.026)\% \]

\[ \Delta a_{CP}^{\text{dir}} = (-0.164 \pm 0.028)\% \]

Consistency with NO CPV hypothesis: \( 5 \times 10^{-8} \)

World average dominated by LHCb results

provided by the courtesy of M. Gersabeck
Conclusions

The LHCb Collaboration observes for the first time CP violation in charm decays with a significance of 5.3 standard deviations.
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Present theoretical predictions have large uncertainties due to low-energy strong-interaction effects which are difficult to compute.

Several other searches for CP violation in charm are carried out with different decay modes and new updates with full data set will be available soon → Stay tuned!
Backup
Search for Direct CP Violation

• $A_{CP}$ in $D_s^+ \to K_S^0 \pi^+$, $D^+ \to K_S^0 K^+$, $D^+ \to \phi \pi^+$:

\[
A_{CP}(D_s^+ \to K_S^0 \pi^+) = (1.3 \pm 1.9 \text{ (stat)} \pm 0.5 \text{ (syst)}) \times 10^{-3}
\]
\[
A_{CP}(D^+ \to K_S^0 K^+) = (-0.09 \pm 0.65 \text{ (stat)} \pm 0.48 \text{ (syst)}) \times 10^{-3}
\]
\[
A_{CP}(D^+ \to \phi \pi^+) = (0.05 \pm 0.42 \text{ (stat)} \pm 0.29 \text{ (syst)}) \times 10^{-3}
\]

No CP violation observed
Measurement of the mass difference between neutral charm-meson eigenstates with $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay

Table 5: Updated global combinations of charm-mixing measurements.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>68.3% CL</th>
<th>95.5% CL</th>
<th>99.7% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x [10^{-2}]$</td>
<td>$0.38 \pm 0.12$</td>
<td>[0.26, 0.50]</td>
<td>[0.14, 0.61]</td>
<td>[0.02, 0.71]</td>
</tr>
<tr>
<td>$y [10^{-2}]$</td>
<td>$0.655 \pm 0.062$</td>
<td>[0.588, 0.717]</td>
<td>[0.52, 0.78]</td>
<td>[0.44, 0.84]</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
<td>$0.967 \pm 0.050$</td>
<td>[0.922, 1.017]</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$-0.070 \pm 0.079$</td>
<td>[-0.151, 0.009]</td>
<td>[-0.24, 0.09]</td>
<td>[-0.33, 0.19]</td>
</tr>
</tbody>
</table>
$\Delta A_{CP}$ vs data taking period Run 1

LHCb

$\chi^2 / \text{ndf}$

48.8 / 52

$p$-value

0.56

2011

2012

Run block

$A_{CP}(KK)$ and $A_{CP}(\pi\pi)$

Systematic uncertainties $[\pi$-tagged$]$

\[ \Delta_{\text{sec}} = \frac{f_{\text{sec}}^{K^+K^-} - f_{\text{sec}}^{\pi^+\pi^-}}{2} \left[ A_{\text{raw}}^{\text{sec}}(KK) + A_{\text{raw}}^{\text{sec}}(\pi\pi) - A_{\text{raw}}^{\text{prompt}}(KK) - A_{\text{raw}}^{\text{prompt}}(\pi\pi) \right] \]

- Measure fraction of secondary $D^0$ by fitting the distribution of the $D^0$ IP in the plane transverse to the beam (TIP)

- Study performed in bins of $t/\tau(D^0)$ to have a better control on the resolution
Further cross-checks

- [Diagram 1]: LHCb $\Delta A_{CP} [%]$, $\chi^2 / ndf = 9.002 / 9$, $p$-value = 0.437
- [Diagram 2]: LHCb $\Delta A_{CP} [%]$, $\chi^2 / ndf = 12.034 / 14$, $p$-value = 0.604
- [Diagram 3]: LHCb $\Delta A_{CP} [%]$, $\chi^2 / ndf = 6.418 / 9$, $p$-value = 0.697
- [Diagram 4]: LHCb $\Delta A_{CP} [%]$, $\chi^2 / ndf = 16.364 / 14$, $p$-value = 0.292
Δ\( A_{CP} \) – Fit model systematic

- Choose 6 alternative fit models
- 1000 toys for each subsample → generate with baseline → fit with baseline and alternative → calculate \( \Delta A_{CP,alt} - \Delta A_{CP,nom} \)
- Sum in quadrature mean and \( \sigma \) of \( \Delta A_{CP,alt} - \Delta A_{CP,nom} \) distribution for each model
- As a conservative choice, take the maximum as systematic uncertainty
  - \( 0.6 \times 10^{-4} \) for π-tagged
  - \( 2 \times 10^{-4} \) for μ-tagged
$\Delta A_{CP}$ – Weighting systematic

- Uncertainty on weighting function due to limited statistics
- Gaussian extraction of alternative weight event by event $\rightarrow$ fit to get $\Delta A_{CP,\text{alt}}$
- Perform 300 tests
- Uncertainty is the sum in quadrature of mean and $\sigma$ of $\Delta A_{CP,\text{alt}} - \Delta A_{CP,\text{nom}}$
  \[ \rightarrow 0.2 \times 10^{-4} \text{ for } \pi\text{-tagged} \]
  \[ \rightarrow 10^{-4} \text{ for } \mu\text{-tagged} \]
\( \Delta A_{CP} \) – Difference in \( B^0 \) fraction (\( \mu \)-tagged)

- Effective \( D^0 \) production asymmetry in \( \mu \)-tagged \( B \) decays:
  \[
  A_{P,\text{eff}}(D^0) = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]
  \]

- In Run 1 analysis: difference in \( f(B^0) \) is \( (0.34 \pm 0.18)\% \) between \( KK \) and \( \pi\pi \) due to difference in \( B^0 \) and \( B^+ \) reconstruction efficiencies

- \( A_P(B^0) \) and \( A_P(B^+) \) measured by LHCb

  Conservative assumption \( \Rightarrow f(B^0) \) difference is 1%

  \( \Rightarrow \) difference in \( A_{P,\text{eff}}(D^0) \) is \( (-0.0001 \pm 0.0058)\% \)

  \( \Rightarrow \) take \( 10^{-4} \) as systematic uncertainty
\( \Delta A_{CP} \) – Difference in \( \tau \) acceptance (\( \mu \)-tagged)

- Effective \( D^0 \) production asymmetry in SL \( B \) decays:
  \[
  A_{P,eff}(D^0) = A_P(B^+) + f(B^0)[A_P(B^0) \cdot D - A_P(B^+)]
  \]

- That depends also on \( D = 1 - 2P_{osc} \), so also on lifetime acceptance (slightly different between \( KK \) and \( \pi\pi \))

\[
P_{osc} = \frac{\Gamma_d}{2} \int_{t_0}^{\infty} e^{-\Gamma_d t}(1 - \cos(\Delta m_d t)) dt
\]

- Syst uncertainty taken unchanged from Run 1 analysis ➔ estimated to be maximum \( 2 \times 10^{-4} \)
Mistag rate (μ-tagged)

\[ \delta_\omega = \Delta A_{CP} - \Delta A_{\text{raw}} = 2\omega_{KK} A_{CP}(K^-K^+) - 2\omega_{\pi\pi}[A_{CP}(K^-K^+) - \Delta A_{CP}] \\
+ 2A_{P,\text{eff}}(D^0)(\omega_{KK} - \omega_{\pi\pi}) + \Delta\omega_{KK} - \Delta\omega_{\pi\pi}, \]

- Measure mistag on \( D^0 \rightarrow K\pi \) sample
- Take into account also mixed \( D^0 \rightarrow K\pi \)
- Use \( A_{CP}(KK) \) and \( \Delta A_{CP} \) from Run 1 μ-tagged
- Assume conservatively \( A_{P,\text{eff}}(D^0) = 3\% \)
- Systematic uncertainty is \( 4 \times 10^{-4} \)