Measurements of CP violation and mixing in two body charm decays

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Mixing:


CP Violation:

- CP violation in charm not yet observed.

- LHCb has collected very large samples of charm decays to look for CP violation in mixing and decay.
Introduction

Charm mixing:

\[ |D_{1,2}\rangle = p |D^0\rangle \mp q |\bar{D}^0\rangle \]

\[ x = \frac{\Delta m}{\Gamma} \quad y = \frac{\Delta \Gamma}{2\Gamma} \]

CP violation:

\[ \left| \frac{q}{p} \right| \neq 1 \quad \left| \frac{q}{p} \right|^{\pm 2} \approx 1 \pm A_m \]

CPV in mixing

\[ a_{CP}^{ind} = -\frac{A_m}{2} y \cos \phi + x \sin \phi \]

CPV in decay

\[ \left| \frac{\bar{A}_f}{A_f} \right|^{\pm 2} \approx 1 \pm A_d \neq 1 \quad a_{CP}^{dir} \approx -\frac{1}{2} A_d \]

CPV in interference

\[ \lambda_f = \left| \frac{q}{p} \right| \left| \frac{\bar{A}_f}{A_f} \right| e^{i\phi} \]

- In the Standard Model CP violation in charm is expected to be small.
- Significant enhancements are an indication of New Physics.
We can tag the initial $D^0$ flavour in two ways:

- **Prompt:**
  - $D^{*+}$ produced at the interaction point.
  - Look for the decay $D^{*+} \rightarrow D^0 \pi^+_s$.
  - Background from $B$ decays.
  - Fit difference between $D^{*+}$ and $D^0$ mass, $\Delta m$, to ascertain correctly tagged candidates.
  - LHCb primarily used prompt decays thus far.

- **Semi-leptonic:**
  - Search for the decay $\bar{B} \rightarrow D^0 \mu^- X$.
  - Negligible mis-tag.
Forward spectrometer.
Acceptance $2 < \eta < 5$

3 level trigger:
- L0 hardware selects events with high $p_T$ particles.
- Two layers of software triggers.
- Charm output at $\sim 2\text{kHz}$

Data set
- 2011: $1\text{fb}^{-1}$ at 7TeV
- 2012: $2\text{fb}^{-1}$ at 8TeV

Charm

$$\sigma_{b\bar{b},\text{acc}} = 75.3 \pm 14.1\mu\text{b at 7TeV}$$

$$\sigma_{c\bar{c},\text{acc}} = 1419 \pm 134\mu\text{b at 7TeV}$$
Nucl. Phys. B871, 1-20
Wrong sign I

Study the time dependence of the ratio of $D^0 \rightarrow K^-\pi^+$ (right-sign) and $D^0 \rightarrow K^+\pi^-$ (wrong-sign) decays.

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} = R_D + \sqrt{R_D} y' t + \frac{x'^2 + y'^2}{4} t$$

$$x' = x \cos \delta + y \sin \delta \quad y' = y \cos \delta - x \sin \delta$$

$\delta$ is the strong phase between CF and DCS decays, $R_D$ is the ratio of the decay amplitude magnitudes.

Analysis of 2011 data: PRL 110, 101802 (2013)

No mixing hypothesis excluded at 9.1$\sigma$.

Update with full 3fb$^{-1}$ data set. PRL 111, 251801 (2013)

Measure $D^0 (R_D^+)$ and $\bar{D}^0 (R_D^-)$ to look for CP violation in mixing and in the decay amplitude:

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$
Fit $R^+$, $R^-$ and plot the difference.

Fit to $3 \text{fb}^{-1}$ of 2011 + 2012 data.

Consistent with no CP violation.

$A_D = (-1.3 \pm 1.9)\%$

$0.75 < \left| \frac{q}{p} \right| < 1.24$ at 68.3% confidence level.

$\sim$ factor 2.5 improvement on previous mixing measurement (no CPV).

$y' = (4.81 \pm 0.85 \pm 0.53) \times 10^{-3}$  
$x'^2 = (5.5 \pm 4.2 \pm 2.6) \times 10^{-5}$
Asymmetry of $D^0$ and $\bar{D}^0$ decay rates to a $CP$ eigenstate, $K^+K^-$ or $\pi^+\pi^-$:

$$A^\Gamma(KK) = \frac{\hat{\Gamma}(D^0 \rightarrow K^+K^-) - \hat{\Gamma}(\bar{D}^0 \rightarrow K^+K^-)}{\hat{\Gamma}(D^0 \rightarrow K^+K^-) + \hat{\Gamma}(\bar{D}^0 \rightarrow K^+K^-)} \approx \frac{A_m + A_d}{2} y \cos \phi - x \sin \phi$$

In the SM:

- Roughly final state independent

$$\Delta A^\Gamma = A^\Gamma(KK) - A^\Gamma(\pi\pi) \approx \Delta A_d y \cos \phi + (A_m + A_d) y \Delta \cos \phi - x \Delta \sin \phi$$

Large $A^\Gamma$ or final state dependence is indicative of New Physics.
1 fb$^{-1}$ of $pp$ collisions collected in 2011.

Measure effective lifetime of $D^0$ decaying to $K^-K^+$ and $\pi^+\pi^-$.  

Fit to $D^0$ mass and $\Delta m$ to determine signal and backgrounds.

Simultaneous fit to $D^0$ decay time and $\ln(IP\chi^2)$ to extract the prompt signal mean lifetime.

$D^0 \rightarrow K^+K^-$
$A_{\Gamma} (KK) = (-0.35 \pm 0.62_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$

$A_{\Gamma} (\pi\pi) = (0.33 \pm 1.06_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-3}$

PRL 112 (2014) 041801
$A_F$ - HFAG average

HFAG-charm

CHARM 2013

Belle 2012
-0.030 ± 0.200 ± 0.080 %

BaBar 2012
0.088 ± 0.255 ± 0.058 %

LHCb 2013 KK
-0.035 ± 0.062 ± 0.012 %

LHCb 2013 $\pi\pi$
0.033 ± 0.106 ± 0.014 %

World average
-0.014 ± 0.052 %

ICHEP 2014
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HFAG fit results

HFAG-charm
April 2013
no CPV

HFAG-charm
FPCP 2014
no CPV
Time-integrated asymmetries for final states $f$: $K^+K^-$ and $\pi^+\pi^-$. 

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

Measured asymmetry:

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

The measured quantity includes production and measurement asymmetries:

$$A_{raw} = A_{CP} + A^{prod} + A^{det}$$

- Taking the difference cancels detection and production asymmetries.
- To a good approximation this is a measure of direct CP violation.

$$\Delta A_{CP} = A_{KK} - A_{\pi\pi} \approx \Delta a_{CP}^{dir} \left(1 + y_{CP} \frac{\langle t \rangle}{\tau}\right) + a_{CP}^{ind} \frac{\Delta \langle t \rangle}{\tau}$$

LHCb has both prompt and semi-leptonic analyses - they are completely independent.
Full 1fb\(^{-1}\) 2011 data set.

Fit $\Delta m$ to extract signal yield; $K^+ K^-$ on left, $\pi^+ \pi^-$ on right.

$\Delta A_{CP} = (-0.34 \pm 0.15_{stat} \pm 0.10_{syst})\%$

Preliminary
Tag the initial $D^0$ flavour from the charge of the muon in the decay of a $B$ meson.

\[ A_{raw} = A_{CP} + A_{prod}(\bar{B}) + A_{det}(\mu) \]

- Full 3 fb$^{-1}$ data set - this result supersedes the previous semi-leptonic analysis on 1 fb$^{-1}$.

Make two measurements:
- Measure $\Delta A_{CP}$.
- Extract the individual asymmetries $A_{CP}(KK)$ and $A_{CP}(\pi^+\pi^-)$ using CF control channels.
Fit mass distributions to ascertain yields of each decay mode:

\[ \Delta A_{CP} - \text{semi-leptonic analysis II} \]

Submitted to JHEP: arXiv:1405.2797

Consistent with CP conservation. First individual charm asymmetry measurement at LHCb; most precise to date.
HFAG fit results

\[ a_{\text{CP}}^{\text{ind}} = (0.010 \pm 0.162)\% \]
\[ \Delta a_{\text{CP}}^{\text{dir}} = (0.329 \pm 0.121)\% \]
HFAG fit results

\[ a^\text{ind}_{CP} = (0.013 \pm 0.052)\% \]
\[ \Delta a^{\text{dir}}_{CP} = (0.253 \pm 0.104)\% \]
$D^\pm \rightarrow K_S^0 h^\pm$  

Submitted to JHEP: arXiv:1406.2624

Look for CP violation in the SCS decays $D^\pm \rightarrow K_S^0 K^\pm$ and $D_s^\pm \rightarrow K_S^0 \pi^\pm$.

$$A^D_{CP} \equiv \frac{\Gamma(D^+_{(s)} \rightarrow K_S^0 h^+) - \Gamma(D^-_{(s)} \rightarrow K_S^0 h^-)}{\Gamma(D^+_{(s)} \rightarrow K_S^0 h^+) + \Gamma(D^-_{(s)} \rightarrow K_S^0 h^-)}$$

The measurement includes nuisance asymmetries:

$$A_{meas}^{D^\pm \rightarrow K_S^0 h^\pm} \approx A_{CP} + A_{prod}^{D_{(s)}} + A_{det}^{h^\pm} + A_{K^0/\bar{K}^0}$$

Use CF modes $D^\pm \rightarrow K_S^0 \pi^\pm$ and $D_s^\pm \rightarrow K_S^0 K^\pm$ and construct the double difference:

$$A^{DD}_{CP} = \left[A_{meas}^{D^\pm \rightarrow K_S^0 \pi^\pm} - A_{meas}^{D^\pm \rightarrow K_S^0 K^\pm}\right] - \left[A_{meas}^{D^\pm \rightarrow K_S^0 \pi^\pm} - A_{meas}^{D^\pm \rightarrow K_S^0 K^\pm}\right] - 2A_{K^0}$$

$$= A_{CP}^{D^\pm \rightarrow K_S^0 K^\pm} + A_{CP}^{D^\pm \rightarrow K_S^0 \pi^\pm}$$

Then use a combination of CF modes to extract the individual asymmetries.
Extract yields from fit to invariant mass:

\[ D_{(s)}^{\pm} \rightarrow K_S^0 h^{\pm} \]

\[ A_{CP}^{D_{(s)}^{\pm} \rightarrow K_S^0 K^{\pm}} = +0.03 \pm 0.17 \pm 0.14 \quad \text{NEW!} \]

\[ A_{CP}^{D_{(s)}^{\pm} \rightarrow K_S^0 \pi^{\pm}} = +0.38 \pm 0.46 \pm 0.17 \]

Consistent with CP conservation.
LHCb made the first individual measurement of charm mixing. More data has improved the precision further.

Presented the most accurate measurement of $A_R$.

- Analysis of 2012 data set is to follow.
- Semi-leptonic analysis is to follow.

Presented the most precise measurements of the time-integrated CP asymmetries $A_{CP}(K^-K^+)$ and $A_{CP}(\pi^+\pi^-)$.

- First measurement of the individual asymmetries at LHCb.

Improved the constraints on charm CP violation parameters.

Presented most precise measurement of CP violation in $D^{+}_{(s)} \rightarrow K^0_S h^{\pm}$ decays.

Expect further improvements in precision with data from run 2.

All results so far are consistent with CP conservation in charm.
Wrong sign - CP violation

The ratio of DCS to CF decays is:

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

with

\[ x' = x \cos \delta + y \sin \delta \quad y' = y \cos \delta - x \sin \delta \]

where \( \delta \) is the strong phase between CF and DCS decays.

If we include CP violation in the mixing and consider \( D^0 \) \((R^+)\) and \( \bar{D}^0 \) \((R^-)\) separately the ratio becomes:

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

with

\[ x'^\pm = \left( \frac{1 \pm A_M}{1 \mp A_M} \right)^{\frac{1}{4}} (x' \cos \phi \pm y' \sin \phi) \]

\[ y'^\pm = \left( \frac{1 \pm A_M}{1 \mp A_M} \right)^{\frac{1}{4}} (y' \cos \phi \mp x' \sin \phi) \]
Perform the mixing measurements for $D^0$ and $\bar{D}^0$, extract $R_D^{\pm}$, $x^\prime 2^{\pm}$ and $y^\prime 2^{\pm}$ and look for differences to find CP violation in mixing.

Can extract the direct CP violation in the decay amplitude:

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$
Extracting CP asymmetries

The raw asymmetry measured using semi-leptonic decays is:

\[ A_{\text{raw}} = A_{CP} + A_{\text{prod}}(\bar{B}) + A_{\text{det}}(\mu) \]

- Remove \( A_{\text{prod}}(\bar{B}) + A_{\text{det}}(\mu) \) via:

\[ A_{\text{raw}}(B \to D^0(K^-\pi^+)\mu X) = A_{\text{prod}}(B) + A_{\text{det}}(\mu) + A_{\text{det}}(K^-\pi^+) \]

- Use \( D^+ \to K^-\pi^+\pi^+ \) and \( D^+ \to K^0\pi^+ \) with \( A_{CP}(K^0) \) to deal with \( A_{\text{det}}(K^-\pi^+) \).

\[ A_{\text{det}}(K^-\pi^+) = A_{\text{raw}}(K^-\pi^+\pi^+) - A_{\text{raw}}(K^0\pi^+) - A_D(K^0) \]

Then:

\[ A_{CP}(K^-K^+) = A_{\text{raw}}(K^-K^+) - A_{\text{raw}}(K^-\pi^+) + A_{\text{det}}(K^-\pi^+) \]
The double difference:

\[ A_{DD}^{CP} = \left( A_{D_{s}^{±}\to K_{S}^{0}\pi^{±}}^{meas} - A_{D_{s}^{±}\to K_{S}^{0}K^{±}}^{meas} \right) - \left( A_{meas}^{D^{±}\to K_{S}^{0}\pi^{±}} - A_{meas}^{D^{±}\to K_{S}^{0}K^{±}} \right) - 2A_{K^{0}} \]

Because of the cancellation this is the sum of the CP asymmetries:

\[ A_{DD}^{CP} = A_{D_{s}^{±}\to K_{S}^{0}K^{±}}^{CP} + A_{D_{s}^{±}\to K_{S}^{0}\pi^{±}}^{CP} \]

Using the CF decay \( D_{s}^{±} \to \phi\pi^{±} \) the individual asymmetries are extracted:

\[ A_{CP}^{(D_{s}^{±}\to K_{S}^{0}K^{±})} = \left( A_{meas}^{D^{±}\to K_{S}^{0}K^{±}} - A_{meas}^{D_{s}^{±}\to K_{S}^{0}K^{±}} \right) - \left( A_{meas}^{D^{±}\to K_{S}^{0}\pi^{±}} - A_{meas}^{D_{s}^{±}\to \phi\pi^{±}} \right) - A_{K^{0}} \]

\[ A_{CP}^{(D_{s}^{±}\to K_{S}^{0}\pi^{±})} = A_{meas}^{D_{s}^{±}\to K_{S}^{0}\pi^{±}} - A_{meas}^{D_{s}^{±}\to \phi\pi^{±}} - A_{K^{0}} \]