Direct CPV studies at LHCb

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on behalf of the LHCb collaboration

BESIII-LHCb joint workshop, Beijing, February 2018
Outline

- CP violation basics and charm
- Direct CPV searches in
  - two-body $D^0 \rightarrow h^+h^-$ charm decays
  - other two- or three-body charm decays
  - multi-body charm decays
- Conclusions and prospects
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CP violation in the up and down sectors

• CP symmetry applies to processes invariant under the combined transformation of
  • charge conjugation (C): exchange of particle and anti-particle
  • and parity (P): spatial inversion
• CP symmetry conserved in the strong and the EM interaction
• CPV discovered in weak decays of strange and beauty mesons containing quarks from the down sector
• What about the up-sector?
Charm

- Charm is unique: only bound up-type quark system where mixing and CP violation can occur

\[
V_{\text{CKM}} = \begin{pmatrix}
1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda - iA^2\lambda^5\eta & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
A\lambda^3(1 - \hat{\rho} - i\hat{\eta}) & -A\lambda^2 - iA\lambda^4\eta & 1
\end{pmatrix}
\]

- Making precise SM predictions in the D-meson sector is difficult
  - Perturbative QCD valid at energies $\gg 1$ GeV
  - Chiral perturbation theory valid between 0.1 GeV and 1 GeV
  - $D^0$ mass $= 1.864$ GeV
Types of CPV

The symmetry under CP transformation can be violated in different ways: Present if $\lambda_f$ is not equal to 1

$$\lambda_f \equiv \frac{q\bar{A}_f}{pA_f} = -\eta_{\text{CP}} \left| \frac{q}{p} \right| \left| \frac{\bar{A}_f}{A_f} \right| e^{i\phi}$$

| $|\bar{A}_f/A_f| \neq 1$ |
|------------------------|
| direct CPV depends on the decay mode |

| $|q/p| \neq 1$ |
|----------------|
| CPV in mixing |

The transition probability of particles to anti-particles compared to the reverse process differs.

<table>
<thead>
<tr>
<th>CPV in the interference</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi$, the CP-violating relative phase between $q/p$ and $\bar{A}_f/A_f$, is non-zero</td>
</tr>
</tbody>
</table>

The indirect CP violation is independent of the decay mode.

It involves neutral particles
Flavour tagging at LHCb

Prompt charm:
D points to primary vertex
Daughters of D don’t in general

Secondary charm:
D doesn’t point to PV

If $B \rightarrow D^{* \pm} (\rightarrow D^0 \pi^\pm) \mu^{\mp} \nu$:
doubly-tagged decays

The flavour of the initial state $(D^0, \bar{D}^0)$
is tagged by the charge of the soft pion or the muon
Prompt vs secondary decays

- **prompt charm:**
  - high yield (3x)
  - access only to high $D^0$ decay times
  - small impact parameter
  - smaller flight distance
- **secondary charm:**
  - high trigger efficiency
  - access to all $D^0$ decay times
  - large impact parameter
  - larger flight distance

Most direct CPV searches presented today use prompt decays, full Run 1 data sample (3 fb$^{-1}$), unless specified.
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The CP asymmetries

Measure the time integrated asymmetry in the SCS decays $D^0 \rightarrow hh$ decays ($h=K$ or $\pi$)

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

But $A_{CP}$ this is not what we measure. We measure

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

where $N(X)$ refers to the number of reconstructed events of decay $X$ after background subtraction.

We measure the physical CP asymmetry plus asymmetries due to detection effects and production

$$A_{raw} = A_{CP} + A_{production} + A_{detection}$$
The observable $\Delta A_{CP}$

Main experimental challenge: separate the CP asymmetry from the nuisance asymmetries $\sim O(1\%)$

$$A_{\text{raw}} = A_{CP} + A_{\text{production}} + A_{\text{detection}}$$

if we take the raw asymmetry difference: experimentally more robust and enhanced sensitivity to CP violation

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

$\Delta A_{CP}$ muon-tagged $= (+0.14 \pm 0.16 \pm 0.08)\%$

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$\Delta A_{CP}$ prompt $= (-0.10 \pm 0.08 \pm 0.03) \%$

Theoretical expectations for the asymmetries

- $a_{CP}^{dir} < 10^{-2}$ within the SM
- Enhancements up to 1 order of magnitude possible in some BSM models
- Sum rules link several experimental observables
- Branching ratios are essential for the CP asymmetry sum rules:
  - the sum rule coefficients in front of the CP asymmetries are topologies which are constrained by the branching ratios

Global fit of $D \to hh$ branching ratios to topological amplitudes including linear SU(3)$_F$ breaking and $1/N_c$-counting

Theoretical expectations

- The SM prediction for the CP asymmetries based on the sum rule with current data is shown in blue.
- The SM prediction for the CP asymmetries based on the sum rule with future data is shown in green (all errors scaled by a factor 1/sqrt(50)).
- For the green ellipse no improvement in the CP asymmetries is assumed, in order to show the effect of improved branching ratios only.
- With better branching ratios one can eliminate one of the two overlapping solutions.
Experimental strategy for measuring the individual asymmetries: use CF decay control channels

\[ A_{raw}(K^+K^-) = A_{cp}(K^+K^-) + A_{D}(\pi_s) + A_{P}(D^{*+}) \]

Combination with the prompt \( \Delta A_{CP} \) measurement

\[ \Delta A_{CP} = A_{CP}(K\cdotK^+) - A_{CP}(\pi\cdot\pi^+) \approx \Delta a_{CP}^{dir}(1 + y_{CP}(t)/\tau) + a_{CP}^{ind}\Delta(t)/\tau \]
$A_{CP}(h^- h^+) \text{ results with LHCb Run 1 data}$

Combination of the prompt and secondary results

$A_{CP}^{\text{comb}}(K^- K^+) = (0.04 \pm 0.12\text{(stat)} \pm 0.10\text{(syst)})\%$

$A_{CP}^{\text{comb}}(\pi^- \pi^+) = (0.07 \pm 0.14\text{(stat)} \pm 0.11\text{(syst)})\%$

Most precise measurement of charm time-integrated CP asymmetry

Desirable input from BESIII

- Improved $D \to h h$ branching fraction ratios for improving the theory predictions
  - $\Gamma(D^0 \to K^+ K^-)/\Gamma(D^0 \to \pi^+ \pi^-) = 2.760 \pm 0.040 \pm 0.034$ (CDF, 7334 events): LHCb can do this
  - $\Gamma(D^0 \to K^+ K^-)/\Gamma_{total} = 4.08 \pm 0.08 \pm 0.09$ (CLEO, 4746 events)
  - $\Gamma(D^0 \to \pi^0 \pi^0)/\Gamma_{total} = 8.24 \pm 0.21 \pm 0.30$ (BESIII, 6k)

BESIII BR preliminary results @CHARM’16

- CP violation in SCS $D^0 \to h h^+$ decays:
  - $A_{CP}$ measurements assume that CP violation in the Cabibbo-favoured decays is negligible
  - How precise can BESIII measure the $A_{CP}$ in CF decays?
  - $A_{CP}(D^0 \to K^+ \pi^-) = (0.3 \pm 0.3 \pm 0.6)\%$ (CLEO)
  - $A_{CP}(D^+ \to K_S \pi^+) = (-1.1 \pm 0.6 \pm 0.2)\%$ (CLEO), = (-0.363 ± 0.094 ± 0.067)%* (BELLE)
    (neutral kaon contribution not subtracted)
  - $A_{CP}(D^0 \to K^- \pi^0 \pi^+) = (-0.16 \pm 0.15 \pm 0.09)\%$ (D0), = (-0.3±0.2±0.4)% (CLEO)

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{net}$ signal</th>
<th>$\epsilon$ (%)</th>
<th>$B(\text{stat}) \pm B(\text{sys})$</th>
<th>$B_{PDG}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^-$</td>
<td>21105 ± 249</td>
<td>66.03 ± 0.25</td>
<td>(1.505 ± 0.018 ± 0.031) \times 10^{-3}</td>
<td>(1.421 ± 0.025) \times 10^{-3}</td>
</tr>
<tr>
<td>$K^+ K^-$</td>
<td>56438 ± 273</td>
<td>62.82 ± 0.32</td>
<td>(4.229 ± 0.020 ± 0.087) \times 10^{-3}</td>
<td>(4.01 ± 0.07) \times 10^{-3}</td>
</tr>
<tr>
<td>$K^- \pi^+$</td>
<td>537745 ± 767</td>
<td>64.98 ± 0.09</td>
<td>(3.996 ± 0.006 ± 0.073) %</td>
<td>(3.93 ± 0.04) %</td>
</tr>
<tr>
<td>$K_0^0 \pi^0$</td>
<td>66539 ± 302</td>
<td>36.06 ± 0.17</td>
<td>(1.236 ± 0.006 ± 0.032) %</td>
<td>(1.20 ± 0.04) %</td>
</tr>
<tr>
<td>$K_0^0 \eta'$</td>
<td>9532 ± 126</td>
<td>31.96 ± 0.14</td>
<td>(5.149 ± 0.068 ± 0.134) \times 10^{-3}</td>
<td>(4.85 ± 0.30) \times 10^{-3}</td>
</tr>
<tr>
<td>$K_0^0 \eta'$</td>
<td>3007 ± 61</td>
<td>12.66 ± 0.08</td>
<td>(9.562 ± 0.197 ± 0.379) \times 10^{-3}</td>
<td>(9.5 ± 0.5) \times 10^{-3}</td>
</tr>
<tr>
<td>$\pi^0 \pi^+$</td>
<td>10108 ± 267</td>
<td>48.98 ± 0.34</td>
<td>(1.259 ± 0.033 ± 0.025) \times 10^{-3}</td>
<td>(1.24 ± 0.06) \times 10^{-3}</td>
</tr>
<tr>
<td>$\pi^0 K^+$</td>
<td>1834 ± 168</td>
<td>51.52 ± 0.42</td>
<td>(2.171 ± 0.198 ± 0.060) \times 10^{-4}</td>
<td>(1.89 ± 0.25) \times 10^{-4}</td>
</tr>
<tr>
<td>$\eta \pi^+$</td>
<td>11636 ± 215</td>
<td>46.96 ± 0.25</td>
<td>(3.790 ± 0.070 ± 0.075) \times 10^{-3}</td>
<td>(3.66 ± 0.22) \times 10^{-3}</td>
</tr>
<tr>
<td>$\eta K^+$</td>
<td>439 ± 72</td>
<td>48.21 ± 0.31</td>
<td>(1.393 ± 0.228 ± 0.124) \times 10^{-4}</td>
<td>(1.12 ± 0.18) \times 10^{-4}</td>
</tr>
<tr>
<td>$\eta' \pi^+$</td>
<td>3088 ± 83</td>
<td>21.49 ± 0.18</td>
<td>(5.122 ± 0.140 ± 0.210) \times 10^{-3}</td>
<td>(4.84 ± 0.31) \times 10^{-3}</td>
</tr>
<tr>
<td>$\eta' K^+$</td>
<td>87 ± 25</td>
<td>22.39 ± 0.22</td>
<td>(1.377 ± 0.428 ± 0.202) \times 10^{-4}</td>
<td>(1.83 ± 0.23) \times 10^{-4}</td>
</tr>
<tr>
<td>$K_0^0 \pi^+$</td>
<td>93884 ± 352</td>
<td>51.38 ± 0.18</td>
<td>(1.591 ± 0.006 ± 0.033) \times 10^{-2}</td>
<td>(1.53 ± 0.06) \times 10^{-2}</td>
</tr>
<tr>
<td>$K_0^0 K^+$</td>
<td>17704 ± 151</td>
<td>48.45 ± 0.14</td>
<td>(3.183 ± 0.028 ± 0.065) \times 10^{-3}</td>
<td>(2.95 ± 0.15) \times 10^{-3}</td>
</tr>
</tbody>
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CP asymmetries in $D^0 \to h^+h^-$ from theoretical point of view

• Many other SCS decay modes involving penguins suggested:
  $D^+ \to K + \bar{K}^0, K^+ + \bar{K}^0$; $D^+ \to \phi \pi^+$, $\rho^0 \pi^+$, $\pi^+ \pi^0(\eta')$; $Ds^+ \to \phi K^+(\eta')$, $K^0(\bar{K}^0)^+$ and many more.
  ‣ same operators in the weak effective Hamiltonian as $D^0 \to \pi^+\pi^-, K^+K^-$

• Could be expected to yield direct CP asymmetries of similar magnitude.

• One can constrain direct CP violation in tree-level decays such as $D^+ \to \bar{K}^0(\bar{K}^0)^+\pi^+$, $Ds^+ \to \phi \pi^+$, $D^+ \to \eta' \pi^+$ etc. in order to test against NP contributions in charged flavour transitions.
CP violation in SCS $D^+ \rightarrow K_SK^+$ and $D_s^+ \rightarrow K_S \pi^+$ decays

$$A_{\text{raw}}(f) = A_{CP}(f) + A_{CP/\text{int}}(K^0/\bar{K}^0) + A_D(h^+) + A_P(D^{+}_{(s)})$$

$h^+ = K^+$ or $\pi^+$

Cancel production and detection asymmetries:
- control channel CF $D_S^+ \rightarrow \Phi \pi^+$, $D_S^+ \rightarrow K_S K^+$ and $D^+ \rightarrow K_S \pi^+$ decays
- $A_{CP/\text{int}}(K^0)$: small effect from CPV
- Only $K^0$ decays with short times used

$JHEP$ 1410 (2014) 25

\[
\mathcal{A}_{CP}^{D^+ \rightarrow K_s^0 K^\pm} = (+0.03 \pm 0.17 \pm 0.14)\% \\
\mathcal{A}_{CP}^{D_s^+ \rightarrow K_s^0 \pi^\pm} = (+0.38 \pm 0.46 \pm 0.17)\%. \\
\mathcal{A}_{CP}^{D^+ \rightarrow K_s^0 K^\pm} + \mathcal{A}_{CP}^{D_s^+ \rightarrow K_s^0 \pi^\pm} = (+0.41 \pm 0.49 \pm 0.26)\%.
\]

PV $D^{*+}$  $D^0$

Most precise measurement of these quantities

No indication for CPV
CP violation in $D^0 \to K_S K_S$


\[
\frac{a_{CP}^{dir}(D^0 \to K^0 \bar{K}^0)}{a_{CP}^{dir}(D^0 \to K^+ K^-)} \sim \sqrt{\frac{BR(D^0 \to K^+ K^-)}{BR(D^0 \to K^0 \bar{K}^0)}} \sim 3,
\]

\[A_{CP} = (-2.9 \pm 5.2 \pm 2.2)\% \text{ no CPV}\]


\[|a_{CP}^{dir}(D^0 \to K_S K_S)| \leq 1.1\% (95\% \text{ C.L.})\]

Belle’s result is more precise
\[A_{CP} = (-0.02 \pm 1.53 \pm 0.17)\%\]

CONF-1609 ArXiv 1609.06393

\[\sim 600 \text{ events}\]
**Direct CPV search in D_{(s)}^{+} \rightarrow \eta'\pi^+**

**Consistent with CP conservation**

**Most precise measurements to date of these variables**

**Usual strategy:** Subtract detector asymmetries using control channels

**Signal** \( D_{(s)}^{+} \rightarrow \eta'\pi^+ \) with \( \eta' \rightarrow \pi^+\pi^+\gamma \)

**Control** \( D^{+} \rightarrow K_S\pi^+ \) with \( K_S \rightarrow \pi^+\pi^- \)

or \( D^{+}_{s} \rightarrow \phi\pi \) with \( \phi \rightarrow K^+K^- \)

63k \( D^\pm \) and 152k \( D^\pm_s \)


**Fit** \( m(\eta'\pi^\pm) \) to extract raw asymmetry

**Control channel asymmetry**

**External input** (D0, Belle)

**More precise input from BESIII?**
First measurement of CPV parameters in three-body $\Lambda_c$ decays

- Little theoretical understanding of the dynamics of $\Lambda_c \rightarrow p h h$ decays; no CPV prediction
- Run I (2011-2012, 3 fb\(^{-1}\)) data used
- Reconstructed as part of $\Lambda_b \rightarrow \Lambda_c \mu X$ decays in order to reduce prompt background
- Measurement of $\Delta A_{CP}$ in order to cancel production and detection asymmetry $\Lambda_c \rightarrow p KK$
- 6 dimensional kinematical reweighting ($\Lambda_b$, $p$, $\mu$)
- $\Delta A_{CP} \approx A_{CP}(\Lambda_c \rightarrow p K^- K^+) - A_{CP}(\Lambda_c \rightarrow p \pi^- \pi^+)$ = $(0.30 \pm 0.91 \pm 0.61)$ %
Desirable input from BESIII

- Improved $D \to K_S K_S$ branching fraction ratios,
  - $\Gamma(D^0 \to K^0 K^0)/\Gamma_{\text{total}} = 1.67 \pm 0.11 \pm 0.11$ (BESIII, 576 events)
  - ($^*$theory paper 2013; BESIII paper 2017)
- CP violation in SCS $D^{+}_{(s)} \to K^0_{s} h^+$ decays:
  - Assuming that CP violation in the Cabibbo-favoured decays is negligible
  - How precise can BESIII measure the $A_{CP}$ in CF decays?
    - $A_{CP}(D^+ \to K^0 S \pi^+) = (-1.1 \pm 0.6 \pm 0.2)\%$ (CLEO),
    - $A_{CP}(D_{s}^+ \to K^0 S \pi^+) = (-0.38 \pm 0.26 \pm 0.08)\%$ (D0)
- CP violation in $D^{+}_{(s)} \to \eta' \pi^+$
  - How precise can BESIII measure the $A_{CP}$ in CF decays?
    - $A_{CP}(D^+ \to K_S \pi^+), A_{CP}(D_{s}^+ \to \phi \pi^+)$
- Further sum rules input:
  - $\Gamma(D^+ \to K_S K^+) / \Gamma_{\text{total}} = 3.14 \pm 0.09 \pm 0.08$ (CLEO, 1971 events); (CHARM’16 $= 3.06 \pm 0.09 \pm 0.10$ BESIII)
  - $\Gamma(D_{s}^+ \to K_S \pi^+) / \Gamma_{\text{total}} = 8.5 \pm 0.7 \pm 0.2$ (CLEO, 393 events);
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Multi-body decays and local asymmetries

- Many ways to reach multi-body final states through intermediate resonances
- Local asymmetries potentially larger than the phase space integrated ones
- Model-independent:
  Look for asymmetries in regions of phase space by “counting”
  - binned ($\chi^2$ difference method)
  - unbinned (Energy test, kNN)

- Model-dependent:
  Fit all contributing amplitudes and look for differences in fit parameters

Discover CPV

Origin of CPV

Binned method ($\chi^2$ difference method)

\[ S_{CP}^i = \frac{N^i(D^+)-\alpha N^i(D^-)}{\sqrt{N^i(D^+)+\alpha^2 N^i(D^-)}} \]

\[ \chi^2 = \sum (S_{CP}^i)^2 \]

removes sensitivity to global asymmetries

p-value for no CPV hypothesis

- $D^+ \rightarrow \pi^+\pi^+\pi^+$ decays (1 fb$^{-1}$): sensitive to 1$^\circ$-10$^\circ$ differences in phase and 1-10% in magnitude
  - p-values for no-CPV hypothesis $> 50$
- $D^0 \rightarrow 4\pi/KK\pi\pi$ decays (1 fb$^{-1}$): sensitive to 10$^\circ$ differences in phase and 10% in magnitude
  - p-values for no-CPV hypothesis are 9.1% for KK$\pi\pi$ and 41% for 4$\pi$
Unbinned method: Energy test

**Energy test:** unbinned sample comparison used to assign p-value for hypothesis of identical distributions (= no CPV)

Test statistic \( T \approx \frac{1}{n(n-1)} \sum_{i,j>i} \psi(\Delta \bar{x}_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i} \psi(\Delta \bar{x}_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j} \psi(\Delta \bar{x}_{ij}). \)

- Compare average pair-wise distance in Dalitz plot between: all \( D^0 \) events; all \( \bar{D}^0 \) events; all \( D^0 \) to \( \bar{D}^0 \) events
  - no CP violation \( \rightarrow T \approx 0 \)
  - CP asymmetry \( \rightarrow T > 0 \)
- For 4-body decays, introduce triple product \( C_T \) as parity sensitive variable
- Analyse different flavours and signs of \( C_T \) regions

\[
C_T = \vec{p}(\pi_3) \cdot [\vec{p}(\pi_1) \times \vec{p}(\pi_2)]
\]
Energy test at LHCb

- $D^0 \rightarrow \pi\pi^+\pi^0$ decays (2 $fb^{-1}$) $\sim 660k$

<table>
<thead>
<tr>
<th>Resonance $(A, \phi)$</th>
<th>$p$-value (fit)</th>
<th>upper limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0$ (+3%, +0°)</td>
<td>$1.1^{+2.4}_{-1.1} \times 10^{-2}$</td>
<td>$4.0 \times 10^{-2}$</td>
</tr>
<tr>
<td>$\rho^0$ (+0%, +3°)</td>
<td>$1.5^{+1.7}_{-1.4} \times 10^{-3}$</td>
<td>$3.8 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^+$ (+2%, +0°)</td>
<td>$5.0^{+8.8}_{-3.8} \times 10^{-6}$</td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\rho^+$ (+0%, +1°)</td>
<td>$6.3^{+5.5}_{-3.3} \times 10^{-4}$</td>
<td>$1.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^-$ (+2%, +0°)</td>
<td>$2.0^{+1.3}_{-0.9} \times 10^{-3}$</td>
<td>$3.9 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^-$ (+0%, +1.5°)</td>
<td>$8.9^{+22}_{-6.7} \times 10^{-7}$</td>
<td>$4.2 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

- $D^0 \rightarrow \pi\pi^+\pi^+\pi^-$ decays (3 $fb^{-1}$) $\sim 1M$

$p$-value = $(2.6 \pm 0.5)\%$
Results consistent with no CP violation
Direct CPV searches in $D^0 \rightarrow \pi^+\pi^-\pi^+\pi^-$ decays

$P$-even

$p$-value: 
(4.6±0.5)%

$P$-even test consistent with $CP$ symmetry

$P$-odd

$p$-value: 
(0.6±0.2)%

2.7σ

$P$-odd test only marginally consistent with no-$CPV$ hypothesis
Model dependent searches

Searches for time-integrated CPV effects in the resonant structure of $D^0 \to K_S K \pi$

- $116k \ D^0 \to K_S K^+ \pi^+$; $76k \ D^0 \to K_S K^+ \pi^- (2011+2012)$
- Full amplitude analysis
- Fit the amplitudes separately for $D^0$ and $\bar{D}^0$ events
- CPV in the resonance amplitude $a_R \to a_R (1 \pm \Delta a_R)$; the phase $\Phi_R \to \Phi_R \pm \Delta \Phi_R$
- Results consistent with no CP violation

Multibody decays (phase-space integrated approach)

CP violation in $D^0 \rightarrow \Lambda \pi \pi$ (3 fb$^{-1}$)

Using triple product of final state particle momenta

\[ C_T \equiv \vec{p}_{K+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \quad \quad \overline{C}_T \equiv \vec{p}_{K-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \]

Define triple product asymmetries

\[ A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)}, \quad \quad \overline{A}_T \equiv \frac{\Gamma_{D^0}(\overline{C}_T > 0) - \Gamma_{D^0}(\overline{C}_T < 0)}{\Gamma_{D^0}(\overline{C}_T > 0) + \Gamma_{D^0}(\overline{C}_T < 0)}, \]

\[ a_{T-odd}^{CP} \equiv \frac{1}{2}(A_T - \overline{A}_T) \]

Triple product asymmetries $\sim \sin \phi \cos \delta$

More careful consideration given in Durieux, Grossman


JHEP 1410 (2014) 005

All production and detection effects cancel
All final states interactions cancel

\[ a_{T-odd}^{CP} = (0.18 \pm 0.29 \pm 0.04)\% \]

No indication of CPV
Desirable input from BESIII

• Improved amplitude models for multibody decays:
  • used to test the sensitivity of the model independent techniques
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Conclusions

• Latest precision direct CP violation searches in the charm sector at LHCb presented
• CPV in charm not yet observed: All searches consistent with no direct CPV - some only marginally
• Sub-permille precision reached in direct CPV searches
• The key measurements are still statistically limited; systematics reduces with statistics
• BESIII measurements can help improve some SM theoretical expectations
• A precise measurement of the $A_{\text{CP}}$ in CF channels could be used as external input instead of assumptions
• Improved models of multibody decays with BESIII data can be used to test sensitivities for model independent direct CPV searches
What comes next?

- LHCb Run II analyses ongoing
- **Factor two gain** in statistics seen with Run II LHCb data due to trigger optimisation and the higher cross-sections @13TeV
- and even more with the upgraded LHCb experiment is expected

<table>
<thead>
<tr>
<th>Run</th>
<th>Run2</th>
<th>Run3</th>
<th>Run4</th>
<th>Run5</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 fb⁻¹</td>
<td>8 fb⁻¹</td>
<td>23 fb⁻¹</td>
<td>46 fb⁻¹</td>
<td>100 fb⁻¹</td>
</tr>
</tbody>
</table>

Δ\(a_{\text{CP}}\): uncertainty 10⁻⁴ at 50 fb⁻¹

upgrade; gain more data by removing the L0 thresholds
HFLAV averages including the latest results

Mostly a measure of direct CPV

\[ \Delta A_{\text{CP}} \equiv A_{\text{CP}}(KK) - A_{\text{CP}}(\pi\pi) \]
\[ \approx \Delta a_{\text{CP}}^{\text{dir}} (1 + y_{\text{CP}} \frac{\langle t \rangle}{\tau}) + a_{\text{CP}}^{\text{ind}} \Delta \frac{\langle t \rangle}{\tau} \]

Compatible with no-CPV in the charm sector at 9.3% CL

\[ a_{\text{CP}}^{\text{ind}} = (0.030 \pm 0.026)\% \]
\[ \Delta a_{\text{CP}}^{\text{dir}} = (-0.134 \pm 0.070)\% \]
CP violation

CP symmetry applies to processes invariant under the combined transformation of

charge conjugation (C): exchange of particle and anti-particle
and parity (P): spatial inversion

CP violation discovered in 1964 in weak interactions of neutral Kaon decays by Cronin and Fitch

CP symmetry conserved in the strong and the EM interaction

The symmetry under CP transformation can be violated in different ways
Direct CPV

• Condition for direct CPV: $|A/\bar{A}| \neq 1$
• Need $A$ and $\bar{A}$ to consist of (at least) two parts: with different weak ($\phi$) and strong ($\delta$) phases
• Divide amplitudes into leading and sub-leading parts:
  • $C$ is the leading amplitude
  • $r$ is the ratio of sub-leading over leading amplitude

$$A(D \rightarrow f) = C(1+re^{i(\delta+\phi)})$$
$$\bar{A}(\bar{D} \rightarrow \bar{f}) = C(1+re^{i(\delta-\phi)})$$

• CP violation requires difference in strong ($\delta$) and weak phase ($\phi$):
  $$a_{CP} \equiv \frac{(|A|^2-|\bar{A}|^2)}{(|A|^2+|\bar{A}|^2)} = 2r \sin(\delta) \sin(\phi)$$
CPV in decay: SCS $D^0 \rightarrow h^+h^-$ decays

Often realised by “tree” and “penguin” diagrams

Tree-level weak decay amplitude.
- involves the CKM matrix elements
  - $V_{us}$ and $V_{cs}$ for $D^0 \rightarrow K^+K^-$
  - $V_{ud}$ and $V_{cd}$ for $D^0 \rightarrow \pi^+\pi^-$

One-loop amplitude (“penguin”)
- $b$-loop involves $V_{ub}V_{cb}^*$: tiny
- $s$ and $d$ loops: similar magnitude, opposite sign

$V_{us} \approx -V_{cd} \approx 0.22$ gives the Cabbibo suppression
The observable $\Delta A_{CP}$

$$A_{CP}(f) \approx a^{\text{dir}}_{CP}(f) \left(1 + \frac{\langle t(f) \rangle}{\tau} y_{CP}\right) + \frac{\langle t(f) \rangle}{\tau} a^{\text{ind}}_{CP}$$

where $y_{CP} \equiv \frac{\Gamma_{CP^\pm}}{\Gamma} - 1$

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

$$\approx \Delta a^{\text{dir}}_{CP} \left(1 + \frac{\langle t \rangle}{\tau} y_{CP}\right) + \frac{\Delta \langle t \rangle}{\tau} a^{\text{ind}}_{CP}$$

- Mostly a measure of direct CPV
- The indirect CPV is expected to cancel but a small amount could be present due to the different decay time acceptance of the two decays
- $\Delta A_{CP}$ is more sensitive to direct CPV but if non-zero, the individual asymmetries are needed to find the source of direct CPV
What to expect?

Individual asymmetries are expected to have opposite sign due to CKM structure

\[ A(\bar{D}^0 \to \pi^+\pi^-, K^+K^-) = \mp \frac{1}{2} (V_{cs}V_{us}^* - V_{cd}V_{ud}^*) (T \pm \delta S) - V_{cb}V_{ub}^* (P \mp \frac{1}{2} \delta P), \]

Direct CP violation depends on the decay mode: can be different for different final states

Expect non-zero \( \Delta A_{CP} = A_{CP}(KK) - A_{CP}(\pi\pi) \) result in presence of direct CP violation
Production asymmetries

Production rates of $B^0$ and $\bar{B}^0$ (or $D^0$ and $\bar{D}^0$) are not the same.

gluon fusion, quarks combine with valence quark from the beam protons, valence quark scattering, etc.

Example mechanism

Expected to be around 1%

$$a_P = \frac{\sigma(pp \to \bar{B}) - \sigma(pp \to B)}{\sigma(pp \to \bar{B}) + \sigma(pp \to B)}$$
Detection asymmetries (1)

- Detector asymmetries

\[ A_D = \frac{\varepsilon(f) - \varepsilon(\bar{f})}{\varepsilon(f) + \varepsilon(\bar{f})} \]

- Cancel left-right asymmetries by swapping dipole field
- But do not rely only on it (detectors move, alignment changes etc.)
Detection asymmetries (2)

- Interaction asymmetries: e.g. $K^+$ cross-section for interaction with matter differs from $K^-$ cross-section.

![Graph showing cross section vs. lab momentum for different interactions]
Cancelling nuisance asymmetries

The detection asymmetries as well as the production asymmetries depend on the kinematics of the decay $A_D, A_P$ ($\sim 1\%$) cancel to 1st order but if the decays are kinematically very different there would be a residual nuisance asymmetry: equalise the KK and $\pi\pi$ kinematical distributions by re-weighting.
Direct CPV search in $D^+_{(s)} \rightarrow \eta'\pi^+$

- **Main challenge**: Background modelling. Main physics BG from $D(s)^+ \rightarrow \pi^+(\phi \rightarrow \pi^+\pi^-\pi^0)$
- Also gives largest systematic uncertainty
- Statistically limited
- Additional uncertainty from external $A_{CP}$ (control) inputs

\[
A_{CP}(D^{\pm} \rightarrow \eta'\pi^{\pm}) = (-0.61 \pm 0.72 \pm 0.55 \pm 0.12) \%
\]
\[
A_{CP}(D^{s\pm} \rightarrow \eta'\pi^{\pm}) = (-0.82 \pm 0.36 \pm 0.24 \pm 0.27) \%
\]

Consistent with CP conservation

Most precise measurements to date of these variables

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta[\Delta A_{CP}(D^{\pm})]$</th>
<th>$\delta[\Delta A_{CP}(D^{s\pm})]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-prompt charm</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Background model</td>
<td>0.50</td>
<td>0.19</td>
</tr>
<tr>
<td>Fit procedure</td>
<td>0.16</td>
<td>0.09</td>
</tr>
<tr>
<td>Sideband subtraction</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$K^0$ asymmetry</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>$D^{\pm}_{(s)}$ production asymmetry</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>Total</td>
<td>0.55</td>
<td>0.24</td>
</tr>
</tbody>
</table>

arXiv:1701.01871 submitted to PLB
Multi-body decays and local asymmetries

- Many ways to reach multi-body final states through intermediate resonances
- Resonances interfere and can carry different strong phases: Superb playground for CP violation

Local asymmetries

- potentially larger than the phase space integrated ones
- may change sign across the phase space
- additional information about the dynamics
Energy test

• Compare two distributions statistically
• Idea comes from the calculation of electric potential energy

\[ +q \text{ and } -q \text{ equally distributed, } \]
\[ \text{electric potential energy } = 0 \]
Energy test

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy

$q^+$ and $q^-$ equally distributed, electric potential energy $= 0$

$q^+$ and $q^-$ distributions different, electric potential energy $> 0$
Energy test

System $\rightarrow$ phase space
$+q / -q$ $\rightarrow$ opposite flavoured decays

$\psi(d_{ij}) = e^{-d_{ij}/\delta^2}$: interaction potential

$n, \bar{n}$: number of $D^0, \bar{D}^0$ candidates

d$_{ij}$: distance in phase space

$\delta$: tunable parameter:
effectively, radius in the phase space in which a local asymmetry is measured

Test statistic: $T = \frac{1}{n(n-1)} \sum_{i,j>i}^{n} \psi(d_{ij}) + \frac{1}{\bar{n}(\bar{n}-1)} \sum_{i,j>i}^{\bar{n}} \psi(d_{ij}) - \frac{1}{nn} \sum_{i,j}^{n,\bar{n}} \psi(d_{ij})$
Energy test p-value

- Calculate p-value for no CPV hypothesis
- Compare T-value from tested sample ($T_0$) with T-values from no-CPV samples
- No-CPV sample from permutation of data: randomly assign flavour tags
- p-value: fraction of permutation T-values above $T_0$

New $P$-odd observables

- In decays to four or more pseudo-scalars, there is the possibility of using $P$-parity-odd observables for $CP$ violation searches.
- Four-body-decay kinematics cannot be described unambiguously using only invariant-mass-squared variables, as these are all parity even.
- Introduce triple product $C_T$ as parity sensitive variable
  \[ C_T = p(\pi_3) \cdot [p(\pi_1) \times p(\pi_2)] \]
- Analyse different flavours and signs of $C_T$ regions.
Detection / tracking / production asymmetries

- Cancellations occur due to method
- Verified with a control sample of Cabibbo-favoured $D^0 \rightarrow K\pi^+\pi^+\pi^-$ decays
  - Split into ten sub-samples equal in size to signal mode
  - Sensitive with neither $P$-even nor $P$-odd tests
- $p$-value distributions for reference sample
Sensitivity tests with Monte Carlo

- Performed for both $P$-even and $P$-odd tests
- Insert $CP$ violation to simulated samples*, apply energy test, determine the sensitivity
- Visualise significance of asymmetries by assigning per-event T-values
- Highlight those $>1,2,3\sigma$ positive in pink, negative in blue

<table>
<thead>
<tr>
<th>$R$ (partial wave) $\Delta A$, $\Delta \phi$</th>
<th>$p$-value (fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1 \to \rho^0 \pi^0$ (S) (5%, 0\°)</td>
<td>$2.6^{+3.4}_{-1.7} \times 10^{-4}$</td>
</tr>
<tr>
<td>$a_1 \to \rho^0 \pi^0$ (S) (0%, 3\°)</td>
<td>$1.2^{+3.6}_{-1.2} \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho^0 \rho^0$ (D) (5%, 0\°)</td>
<td>$3.8^{+2.9}_{-1.9} \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^0 \rho^0$ (D) (0%, 4\°)</td>
<td>$9.6^{+24}_{-7.2} \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho^0 \rho^0$ (P) (4%, 0\°)</td>
<td>$3.0^{+1.2}_{-0.9} \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^0 \rho^0$ (P) (0%, 3\°)</td>
<td>$9.8^{+4.4}_{-3.8} \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Example:
3° phase difference in $D^0 \to a_1(1260)^+\pi^-$ Amplitude

*Amplitude model taken from P. d’Argent, N. Skidmore ... E.Gersabeck et al. arXiv:1703.08505
Results for CPV searches in the $D^0 \rightarrow K_s K \pi \pi$

- In the CPV searches the resonance amplitude $a_R \rightarrow a_R(1 \pm \Delta a_R)$; the phase $\Phi_R \rightarrow \Phi_R \pm \Delta \Phi_R$

<table>
<thead>
<tr>
<th></th>
<th>$\Delta a_R$</th>
<th>$\Delta \Phi_R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^+$</td>
<td>0.0 (fixed)</td>
<td>0.0 (fixed)</td>
</tr>
<tr>
<td>$K^*(1410)^+$</td>
<td>$0.07 \pm 0.06 \pm 0.04$</td>
<td>$3.9 \pm 3.5 \pm 1.9$</td>
</tr>
<tr>
<td>$(K^0_s \pi)^+_\text{S-wave}$</td>
<td>$0.02 \pm 0.08 \pm 0.07$</td>
<td>$2.0 \pm 1.7 \pm 0.0$</td>
</tr>
<tr>
<td>$K^*(892)^0$</td>
<td>$-0.046 \pm 0.031 \pm 0.005$</td>
<td>$1.2 \pm 1.6 \pm 0.3$</td>
</tr>
<tr>
<td>$K^*(1410)^0$</td>
<td>$0.006 \pm 0.034 \pm 0.017$</td>
<td>$2 \pm 5 \pm 5$</td>
</tr>
<tr>
<td>$(K\pi)^0\text{S-wave}$</td>
<td>$0.05 \pm 0.04 \pm 0.02$</td>
<td>$0.4 \pm 1.6 \pm 0.6$</td>
</tr>
<tr>
<td>$a_2(1320)^-$</td>
<td>$-0.25 \pm 0.14 \pm 0.01$</td>
<td>$2 \pm 9 \pm 3$</td>
</tr>
<tr>
<td>$a_0(1450)^-$</td>
<td>$-0.01 \pm 0.14 \pm 0.12$</td>
<td>$0 \pm 5 \pm 4$</td>
</tr>
<tr>
<td>$\rho(1450)^-$</td>
<td>$0.06 \pm 0.13 \pm 0.11$</td>
<td>$-13 \pm 10 \pm 9$</td>
</tr>
</tbody>
</table>

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

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

No CPV

*Phys. Rev. D 93, 052018 (2016)*
Triple product observables in multi-body decays
Triple product observables in theory

Different sensitivity to CPV

\[ \text{CP asymmetries} \sim \sin \varphi \sin \delta \]
\[ \text{Triple product asymmetries} \sim \sin \varphi \cos \delta \]

More careful consideration given in Durieux, Grossman

Unlike total rate asymmetries between CP-conjugate processes, their sensitivity to small differences in CP-violating phases is not conditioned by the presence of CP-conserving strong phase differences.
CP violation in $D^0 \rightarrow KK\pi\pi$

Analysis based on the full Run 1 statistics
Using secondary charm

Using triple product of final state particle momenta

$$C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$
$$\overline{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+})$$

Define triple product asymmetries

$$A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)},$$
$$\overline{A}_T \equiv \frac{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) - \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)}{\Gamma_{\overline{D}^0}(-\overline{C}_T > 0) + \Gamma_{\overline{D}^0}(-\overline{C}_T < 0)},$$
$$a_{CP}^{T-odd} \equiv \frac{1}{2} (A_T - \overline{A}_T)$$

All final states interactions cancel
All production and detection effects cancel
CP violation in $D^0 \rightarrow KK\pi\pi$

Integrated over the phase-space

$\alpha_{T-\text{odd}}^{CP} = (0.18 \pm 0.29 \pm 0.04)\%$

additionally: measurements in bins of decay time and phase space regions

No indication of CPV

Previous measurements by
FOCUS: $(1.0 \pm 5.7 \pm 3.7)\%$ PLB622 (2005) 239-248
BaBar: $(0.10 \pm 0.51 \pm 0.44)\%$ PRD81 (2010) 111103

~171k decays
Improved trigger strategies for Run11

- **Turbo stream of the trigger:**
  - Data are ready for analysis directly after the trigger
  - Smaller size of raw events: reduce pre-scaling
- **More efficient exclusive charm triggers**
  - Split high level trigger in 2 stages: gain CPU power
  - Events from lower trigger levels can be buffered on disk while performing **real-time alignment and calibration**
  - Improved speed of the algorithms
E.Gersabeck, Overview of the CP violation and mixing in the charm sector
Forward spectrometer at LHC

LHCb is optimised for heavy flavour physics

- Forward acceptance $2<\eta<5$
- Precise vertex reconstruction
- Precise & efficient tracking
- Excellent decay time resolution $\sim 0.1 \tau_D$
- Hadron identification: RICHeS
- Dipole magnet with reversible polarity

$b\bar{b}$ (and $c\bar{c}$) production angles strongly correlated: heavily boosted in the forward or backward direction
Run 1 performance

Luminosity levelling unlike ATLAS and CMS: uniform operating conditions

Instantaneous Luminosity $[10^{32}$ cm$^{-2}$s$^{-1}]$:

- **2010**: 37 pb$^{-1}$ at 7 TeV
- **2011**: 1 fb$^{-1}$ at 7 TeV
- **2012**: 2 fb$^{-1}$ at 8 TeV

**LHCb**
- Displacement of beams to optimize luminosity

**ATLAS & CMS**
Charm production cross-sections @ 7TeV in LHCb acceptance

All c species produced at LHCb

\[
\begin{align*}
\sigma(D^0) &= 1661 \pm 129 \text{ \( \mu \text{b} \)} \\
\sigma(D^+) &= 645 \pm 74 \text{ \( \mu \text{b} \)} \\
\sigma(D^{*+}) &= 677 \pm 83 \text{ \( \mu \text{b} \)} \\
\sigma(D_s^+) &= 197 \pm 31 \text{ \( \mu \text{b} \)} \\
\sigma(\Lambda_c^+) &= 233 \pm 77 \text{ \( \mu \text{b} \)}
\end{align*}
\]

- Cross section for \( c\bar{c} \) in LHCb acceptance
  \[
  \sigma(c\bar{c})_{p_T<8 \text{ GeV/c}, 2.0<y<4.5} = 1419 \pm 12 \text{ (stat)} \pm 116 \text{ (syst)} \pm 65 \text{ (frag) \( \mu \text{b} \)}
  \]
- \( \sim 5 \times 10^{12} \) \( D^0 \) mesons produced in LHCb acceptance in run1
- Huge statistics of prompt and secondary charm: worlds’ best sensitivity to very small CP asymmetries

2010 data