Charm mixing and CP violation at LHCb

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on behalf of the LHCb Collaboration
Outline

• Introduction
  ✷ Why are we interested in charm physics?
    ✓ phenomenology of $D^0$ – anti-$D^0$ mixing and CPV
    ✓ SM predictions

• Measurements of mixing and CPV in charm sector at LHCb
  ✷ observation of $D^0$ – anti-$D^0$ mixing
  ✷ $A_\Gamma$ asymmetry from $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$
  ✷ $\Delta A_{CP}$ in $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ from $B \rightarrow D^0\mu X$
  ✷ Search for CPV in:
    ✓ $D^+_{(s)} \rightarrow K^0_{(s)}h^+$
    ✓ $D^+ \rightarrow \pi\pi\pi$
    ✓ $D^0 \rightarrow KK\pi\pi$

• Summary and prospects
Mixing of neutral mesons

Neutral mesons can oscillate between matter and anti-matter, mass eigenstates are different from flavour eigenstates

\[ i \frac{d}{dt} \left( |D^0_0\rangle \right) = \left[ \left( \begin{array}{cc} M_{11} & M_{12} \\ M^*_{12} & M_{22} \end{array} \right) - \frac{i}{2} \left( \begin{array}{cc} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22} \end{array} \right) \right] \left( |D^0_0\rangle \right) \]

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

Two parameters describe mixing \((x,y)\):

- mass difference \(\Delta m\):
  \[ x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma} \]

  - experiment
  - theory
  \[ \Delta m = M_H - M_L = 2|M_{12}|(1 + \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi + ...) \]
  \[ \Delta \Gamma = \Gamma_H - \Gamma_L = 2|\Gamma_{12}| \cos \phi(1 - \frac{1}{8} \frac{|\Gamma_{12}|^2}{|M_{12}|^2} \sin^2 \phi + ...) \]

- weak phase: \(\phi \equiv \text{arg}(-M_{12}/\Gamma_{12})\)

\(\Delta m, \Delta \Gamma, \phi\) – measured experimentally

For charm: \(x\) and \(y\) are small
- Mixing is very slow
- Very precise measurements needed

Motivation

- Oscillations in \(K\): mass eigenstates are different from flavour eigenstates
- Mixing is very slow
- What about charm?
- Established and provide precision tests of the standard model CKM parameters
- Oscillations in \(K\) and anti-matter: mass eigenstates are different

Low standard model rate, potentially a powerful probe for new physics

\[ m \equiv (m_1 + m_2)/2 \]
\[ \Gamma \equiv (\Gamma_1 + \Gamma_2)/2 \]

\((D^0 – \text{as an example, the same for } B^0, B^0_s)\)
• In SM:
  ✷ the charm mixing rate is expected to be small: $|x|, |y| \lesssim 10^{-2}$
  ✷ expected CPV in charm sector is small $\lesssim 10^{-3}$ (much smaller than in the beauty sector)
  ✷ SM predictions vary widely
  ✷ New Physics contributions can enhance CPV up to $10^{-2}$


• Perfect place for New Physics searching (small background from SM)

Mixing via box-diagram, short range

Mixing via hadronic intermediate states, long range (difficult to calculate)
The tagging of $D^0$ flavour

LHCb uses two **statistically independent** methods to identify $D^0$ flavour

✧ **pion-tagged method (exclusive)**
  
  the sign of slow pion from $D^*$ decays is used to tag the initial $D^0$ flavour
  
  $D^{*+} \rightarrow D^0 \pi^+_s$
  
  $D^{*-} \rightarrow \text{anti-}D^0 \pi^-_s$

✧ **muon-tagged method (inclusive)**
  
  the sign of muon from semileptonic $B$ decays is used to tag $D^0$ flavour
  
  $B \rightarrow D^0 \mu^- \nu_\mu X$
  
  $B \rightarrow \text{anti-}D^0 \mu^+ \nu_\mu X$
**D⁰ – anti-D⁰ mixing**

Measure the time-dependent ratio of D⁰ decays with Wrong Sign to Right Sign

\[ R(t) = \frac{N(D^0 \rightarrow K^+\pi^-)}{N(D^0 \rightarrow K^-\pi^+)} \]

In the limit of small mixing |x|,|y| << 1 and for no CPV:

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

- DCS – double Cabibbo suppressed
- CF – Cabibbo favoured

If CPV not negligible

\[ R^+(t) \neq R^-(t) \]

(for D⁰) (for anti-D⁰)

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

δ is a strong phase difference between DCS and CF amplitudes
Results for \( D^0 \) – anti-\( D^0 \) mixing

We determine the time-dependent WS/RS ratios in thirteen \( D^0 \) decay time bins

\[
\begin{align*}
R^+ & \quad \text{for} \quad D^{*+} \to D^0 \pi^+_s \\
R^- & \quad \text{for} \quad D^{*-} \to \text{anti-}D^0 \pi^-_s
\end{align*}
\]


- 0.23M WS decays \( D^0 \to K^+\pi^- \)
- 54M RS decays \( D^0 \to K^-\pi^+ \)

\( R^+ \) for \( D^{*+} \to D^0 \pi^+_s \)
\( R^- \) for \( D^{*-} \to \text{anti-}D^0 \pi^-_s \)

D\(^0\) – anti-D\(^0\) mixing is observed

<table>
<thead>
<tr>
<th>PRL 111 (2013) 251801</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct and indirect CP violation</td>
</tr>
<tr>
<td>( R^+_D ) [10^{-3}] &amp; 3.545 ± 0.082 ± 0.048</td>
</tr>
<tr>
<td>( y'^+_T ) [10^{-3}] &amp; 5.1 ± 1.2 ± 0.7</td>
</tr>
<tr>
<td>( x'^{2+}_T ) [10^{-5}] &amp; 4.9 ± 6.0 ± 3.6</td>
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<tr>
<td>( R^-_D ) [10^{-3}] &amp; 3.591 ± 0.081 ± 0.048</td>
</tr>
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<td>( y'^-_T ) [10^{-3}] &amp; 4.5 ± 1.2 ± 0.7</td>
</tr>
<tr>
<td>( x'^{2-}_T ) [10^{-5}] &amp; 6.0 ± 5.8 ± 3.6</td>
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<td>( \chi^2/\text{ndf} ) &amp; 85.9/98</td>
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<td>( R^+_D ) [10^{-3}] &amp; 3.568 ± 0.058 ± 0.033</td>
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Translation into $D^0$ – anti-$D^0$ mixing parameters

Estimated confidence-level (CL) regions

**LHCb**
(a) *CPV allowed*

(b) *No direct CPV*

(c) *No CPV*

---

$D^0$ – anti-$D^0$ mixing is observed

Results assuming CP conservation:

\[ x'^2 = (5.5 \pm 4.9) \times 10^{-5} \]

\[ y' = (4.8 \pm 1.0) \times 10^{-3} \]

\[ R_D = (3.568 \pm 0.066) \times 10^{-3} \]

$x'^2$ is very small

Measurement is more sensitive to $y'$

---

CP-violating parameters:

1. CPV in mixing
   \[ 0.75 < |q/p| < 1.24 \quad (68.3\% \text{ CL}) \]

2. Direct CPV
   \[ A_D = \frac{R^+_D - R^-_D}{R^+_D + R^-_D} = (-0.7 \pm 1.9)\% \]

---

No indication of direct or indirect CPV
AΓ asymmetry

The asymmetry of the inverse of effective lifetimes in decays of D0 and anti-D0 to CP eigenstate: K-K+ and π-π+

\[ A_\Gamma \equiv \frac{\Gamma(D^0 \rightarrow K^+ K^-) - \Gamma(D^0 \rightarrow K^+ K^-)}{\Gamma(D^0 \rightarrow K^+ K^-) + \Gamma(D^0 \rightarrow K^+ K^-)} \approx \frac{1}{2} (A_m + A_d) y \cos \phi - x \sin \phi \]

\[ A_m \equiv \frac{|q_p|^2 - |p_q'|^2}{|q_p|^2 + |p_q'|^2} \quad A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} \]

AΓ makes a measurement of indirect CPV, as the contributions from direct CPV are measured to be small compared to the current precision


• We measure the ratio of D0 / anti-D0 yields as a function of decay time
• The time dependence of this ratio allows the calculation of AΓ from a simple linear χ2 minimization with

\[ R(t) \approx \frac{N_D^0}{N_{D^0}} \left( 1 + \frac{2A_\Gamma}{\tau_{KK}} t \right) \frac{1 - e^{-\Delta t/\tau_{D^0}}}{1 - e^{-\Delta t/\tau_{D^0}}} \]

\[ \tau_{KK} = \tau_{K\pi} / (1 + y_{CP}) \quad \text{used from an external input based on world averages} \]
\[ N_{\text{anti-D}^0} / N_{D^0} \quad \text{is the signal yield ratio integrated over all decay times} \]
\[ \Delta t \quad \text{is the bin width} \]

PRL 112 (2014) 041801
$A_{\Gamma}$ asymmetry

LHCb 1/fb (2011), we use $D^*$ to identify $D^0$ flavour

$D^0, \text{anti-}D^0 \rightarrow K^-K^+, 3.11\text{M events}$

$D^0, \text{anti-}D^0 \rightarrow \pi^-\pi^+, 1.03\text{M events}$

$A_{\Gamma}(K^-K^+) = (-0.35 \pm 0.62 \pm 0.12) \times 10^{-3}$

$A_{\Gamma}(\pi^-\pi^+) = (-0.33 \pm 1.06 \pm 0.14) \times 10^{-3}$

The world’s best measurements up to now (2012 (2/fb) data is being studied)

1) No significant difference between the two final states

2) No evidence for indirect CPV within 1 per mil
   Expected value of CPV in SM is small $\lesssim 10^{-3}$, predictions vary widely
We want to measure asymmetry between particles and antiparticles:

\[
A_{CP} = \frac{N(D^0 \rightarrow h^- h^+) - N(\bar{D}^0 \rightarrow h^- h^+)}{N(D^0 \rightarrow h^- h^+) + N(D^0 \rightarrow h^- h^+)}
\]

We use two methods:

1) pion-tagged: \( D^{*+} \rightarrow D^0 \pi^+_s \), \( D^{*-} \rightarrow \text{anti-D}^0 \pi^-_s \)
2) muon-tagged: \( B \rightarrow D^0 \mu^- \nu_\mu X \), \( B \rightarrow \text{anti-D}^0 \mu^+ \nu_\mu X \)

Measured raw asymmetry \( A_{RAW} \) includes physics and detector effects:

\[
A_{RAW}(f) = A_{CP}(f) + A_{det} + A_{prod}
\]

- taking the difference cancels detection and production asymmetries
- to a good approximation this is a measure of direct CP violation

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

[JHEP 1106 (2011) 089]
**Time-integrated CPV in $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$ decays**

Using 3/fb (2011+2012) semileptonic $B \rightarrow D^0 \mu^-\nu_\mu X$ decays

Extract yields from fit

\[ \Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\% \]

Extract individual CP asymmetries using a combination of CF modes where CP asymmetry is not expected

\[ A_{CP}(K^+K^-) = (-0.06 \pm 0.15 \pm 0.10)\% \]
\[ A_{CP}(\pi^+\pi^-) = (-0.20 \pm 0.19 \pm 0.10)\% \]

No CP Violation is observed
Search for direct CPV in $D^+ \rightarrow K^0_s K^+$ and $D^+_s \rightarrow K^0_s \pi^+$

The goal is to measure the CP asymmetry for SCS decays $D^+ (s) \rightarrow K^0_s h^+ (h=K,\pi)$

\[
A_{CP} \equiv \frac{\Gamma(D^+_s \rightarrow K^0_s h^+) - \Gamma(D^-_s \rightarrow K^0_s h^-)}{\Gamma(D^+_s \rightarrow K^0_s h^+) + \Gamma(D^-_s \rightarrow K^0_s h^-)}
\]

Measured raw asymmetry $A_{RAW}$ includes pollution asymmetries:

\[
A_{RAW} = \frac{N^+ - N^-}{N^+ + N^-} \approx A_{CP} + A_{det}(h) + A_{prod}(D^-_s) + A_{K^0/\bar{K}^0}
\]

The contribution from the neutral kaon asymmetries (arXiv:1405.2797):

\[
A_{K^0} \equiv (N_{K^0} - N_{\bar{K}^0})/(N_{K^0} + N_{\bar{K}^0}) = -A_{\bar{K}^0} = (+0.07 \pm 0.02)\%
\]

We use CF modes $D^+ \rightarrow K^0_s \pi^+$ and $D^+_s \rightarrow K^0_s K^+$ and construct the double difference to cancel detection and production asymmetries

\[
A_{DD}^{CP} = [A_{RAW}(D^+_s \rightarrow K^0_s \pi^+) - A_{RAW}(D^-_s \rightarrow K^0_s K^+)] - [A_{RAW}(D^+_s \rightarrow K^0_s \pi^+) - A_{RAW}(D^-_s \rightarrow K^0_s K^+)] - 2A_{K^0}
\]

\[
\approx A_{CP}(D^+_s \rightarrow K^0_s K^+) + A_{CP}(D^-_s \rightarrow K^0_s \pi^+)
\]

We use a combination with CF mode $D^+_s \rightarrow \phi \pi^+$ to extract the individual asymmetries.
Search for direct CPV in $D^+ \to K^0_s K^+$ and $D^+_s \to K^0_s \pi^+$

LHCb 3/fb (2011+2012), extract yields from fit

$$A_{CP}(D^\pm \to K^0_s K^\pm) = (+0.03 \pm 0.17 \pm 0.14\%)$$

$$A_{CP}(D_s^\pm \to K^0_s \pi^\pm) = (+0.38 \pm 0.46 \pm 0.17\%)$$

$$A_{CP}^{DD} = A_{CP}(D^\pm \to K^0_s K^\pm) + A_{CP}(D_s^\pm \to K^0_s \pi^\pm) = (+0.41 \pm 0.49 \pm 0.26\%)$$

The results show no evidence for CP violation
Searches for CPV in multi-body charm decays

- Decay products form many resonance states visible in Dalitz plot
  ⇒ strong phases vary from region to region

\[ A_{CP} \propto \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2) \]

weak phases \hspace{1cm} strong phases

- The charge asymmetry can be measured locally in the regions of Dalitz plots
- No clear indications where CPV would appear
- To find asymmetries we compare locally Dalitz plots for \( D^+ \) and \( D^- \) (we perform here searches based on techniques that are model-independent)
Searches for CPV in multi-body charm decays

**Binned method**

- In each bin we calculate a significance of a difference between $D^+$ and $D^-$

$$S_{CP}^i \equiv \frac{N^i(D^+)-\alpha N^i(D^-)}{\sqrt{N^i(D^+)+\alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N(D^+)}{N(D^-)}$$

- To cancel global asymmetries (production asymmetry, etc.) we normalize Dalitz plots

- If no CPV (only statistical fluctuations) then $S_{CP}$ is Gauss distributed ($\mu=0$, $\sigma=1$)

**Unbinned (k-nearest neighbour) method**

- To compare $D^+$ and $D^-$ we define a test statistic $T$ which is based on the counting particles with the same sign to each event for a given number of the nearest neighbour event

- $T$ is the mean fraction of like pairs in the pooled sample of the two datasets
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

**Binned method**

100 adaptive bins

LHCb 2011, 1/fb $\sim$3.1M $D^+ \rightarrow \pi^-\pi^+\pi^+$
PLB 728 (2014) 585

We tested uniform and adaptive binning schemes with different bin numbers

$S_{CP}$ distributions agree with the normal Gaussian function

**Unbinned method**

To increase the sensitivity of the method we divide the Dalitz plot into regions

Two different divisions: 7 and 3 regions defined around resonances

All p-values are above 30%

No evidence for CP asymmetry using binned and unbinned methods and both methods provide similar sensitivities for CPV searches
We measure CP-violating observable $A_T$ which is built using triple products of final state particle momenta in the $D^0$ center-of-mass frame.

For $D^0$:
\[ C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) \quad A_T \equiv \frac{\Gamma_{D^0}(C_T > 0) - \Gamma_{D^0}(C_T < 0)}{\Gamma_{D^0}(C_T > 0) + \Gamma_{D^0}(C_T < 0)} \]

For anti-$D^0$:
\[ \bar{C}_T \equiv \vec{p}_{K^-} \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}) \quad \bar{A}_T \equiv \frac{\Gamma_{\bar{D}^0}(\bar{C}_T > 0) - \Gamma_{\bar{D}^0}(\bar{C}_T < 0)}{\Gamma_{\bar{D}^0}(\bar{C}_T > 0) + \Gamma_{\bar{D}^0}(\bar{C}_T < 0)} \]

But $A_T$ and anti-$A_T$ can be non zero if there are final state interactions:
\[ A_T \equiv \frac{1}{2}(A_T - \bar{A}_T) \]

In the first case,
- CPV vanishes when strong phase of two interfering amplitudes ($\delta_1 - \delta_2$) is zero
- while $A_T$ is maximal

\[ A_{CP} \propto \sin(\phi_1 - \phi_2) \sin(\delta_1 - \delta_2) \quad \text{weak phases} \]
\[ A_T \propto \sin(\phi_1 - \phi_2) \cos(\delta_1 - \delta_2) \quad \text{strong phases} \]
Search for CPV in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

To probe direct and indirect CPV, $A_T$ is measured:

1) in **integrated** the phase space
   - for $D^0$: $A_T = (-7.18 \pm 0.41 \pm 0.13)\%$
   - for anti-$D^0$: $\text{anti-}A_T = (-7.55 \pm 0.41 \pm 0.12)\%$
   - $A_T = (0.18 \pm 0.29 \pm 0.04)\%$

Large asymmetries due to final state interaction effects

2) in **different regions** of the phase space done by dividing the sample using variables $m^2(K^+K^-)$, $m^2(\pi^+\pi^-)$, $\cos(\theta(K^+))$, $\cos(\theta(\pi^+))$, $\phi$

3) as a function of $D^0$ proper time

No evidence for CP asymmetry

Measurements have small syst. uncertainties (larger datasets will improve result)
Summary and prospects

- LHCb experiment has broad and important beauty and charm physics program
- Many world’s most sensitive measurements
- first observation of charm mixing in a single measurement
- so far, all results are consistent with CP conservation in charm
- we are within 1 per mil sensitivity (very close to the SM expectations)
- many more…

Prospects:
- We enhance discovery potential during 2015-17 >5/fb at √s=14TeV
- LHCb upgrade (starting 2019) plans to collect ~50/fb data and will have huge statistics for charm decays
Backup
### LHCb upgrade

**Table 16:** Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with 50 fb\(^{-1}\) by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>Current precision</th>
<th>LHCb 2018</th>
<th>Upgrade (50 fb(^{-1}))</th>
<th>Theory uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-handed</td>
<td>2(\beta_s) ((B_s^0 \rightarrow J/\psi \phi))</td>
<td>0.10 [138]</td>
<td>0.025</td>
<td>0.008</td>
<td>~ 0.003</td>
</tr>
<tr>
<td></td>
<td>2(\beta_s) ((B_s^0 \rightarrow J/\psi f_0(980)))</td>
<td>0.17 [214]</td>
<td>0.045</td>
<td>0.014</td>
<td>~ 0.01</td>
</tr>
<tr>
<td></td>
<td>(a_{sL}^s)</td>
<td>6.4 \times 10^{-3} [43]</td>
<td>0.6 \times 10^{-3}</td>
<td>0.2 \times 10^{-3}</td>
<td>0.03 \times 10^{-3}</td>
</tr>
<tr>
<td>Gluonic</td>
<td>2(\beta_s^{\text{eff}}) ((B_s^0 \rightarrow \phi \phi))</td>
<td>–</td>
<td>0.17</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>penguins</td>
<td>2(\beta_s^{\text{eff}}) ((B_s^0 \rightarrow K^{*0} \bar{K}^{*0}))</td>
<td>–</td>
<td>0.13</td>
<td>0.02</td>
<td>&lt; 0.02</td>
</tr>
<tr>
<td></td>
<td>2(\beta_s^{\text{eff}}) ((B_s^0 \rightarrow \phi K_s^0))</td>
<td>0.17 [43]</td>
<td>0.30</td>
<td>0.05</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed</td>
<td>2(\beta_s^{\text{eff}}) ((B_s^0 \rightarrow \phi \gamma))</td>
<td>–</td>
<td>0.09</td>
<td>0.02</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>currents</td>
<td>(\tau^{\text{eff}}) ((B_s^0 \rightarrow \phi \gamma)/\tau_{B_s^0})</td>
<td>–</td>
<td>5%</td>
<td>1%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>(S_3(B^0 \rightarrow K^{*0} \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.08 [67]</td>
<td>0.025</td>
<td>0.008</td>
<td>0.02</td>
</tr>
<tr>
<td>penguins</td>
<td>(s_0 A_{FB}(B^0 \rightarrow K^{*0} \mu^+ \mu^-))</td>
<td>25% [67]</td>
<td>6%</td>
<td>2%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>(A_1(K \mu^+ \mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/\text{c}^4))</td>
<td>0.25 [76]</td>
<td>0.08</td>
<td>0.025</td>
<td>~ 0.02</td>
</tr>
<tr>
<td></td>
<td>(B(B^+ \rightarrow \pi^+ \mu^+ \mu^-)/B(B^+ \rightarrow K^+ \mu^+ \mu^-))</td>
<td>25% [85]</td>
<td>8%</td>
<td>2.5%</td>
<td>~ 10%</td>
</tr>
<tr>
<td>Higgs</td>
<td>(B(B_s^0 \rightarrow \mu^+ \mu^-))</td>
<td>1.5 \times 10^{-9} [13]</td>
<td>0.5 \times 10^{-9}</td>
<td>0.15 \times 10^{-9}</td>
<td>0.3 \times 10^{-9}</td>
</tr>
<tr>
<td>penguins</td>
<td>(B(B^0 \rightarrow \mu^+ \mu^-)/B(B_s^0 \rightarrow \mu^+ \mu^-))</td>
<td>–</td>
<td>~ 100%</td>
<td>~ 35%</td>
<td>~ 5%</td>
</tr>
<tr>
<td>Unitarity</td>
<td>(\gamma (B \rightarrow D^{(<em>)} K^{(</em>)}))</td>
<td>~ 10–12(^\circ) [244, 258]</td>
<td>4(^\circ)</td>
<td>0.9(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle angles</td>
<td>(\gamma (B_s^0 \rightarrow D_s K))</td>
<td>–</td>
<td>11(^\circ)</td>
<td>2.0(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td></td>
<td>(\beta (B^0 \rightarrow J/\psi K_s^0))</td>
<td>0.8(^\circ) [43]</td>
<td>0.6(^\circ)</td>
<td>0.2(^\circ)</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>(A_T)</td>
<td>2.3 \times 10^{-3} [43]</td>
<td>0.40 \times 10^{-3}</td>
<td>0.07 \times 10^{-3}</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>(\Delta A_{CP})</td>
<td>2.1 \times 10^{-3} [18]</td>
<td>0.65 \times 10^{-3}</td>
<td>0.12 \times 10^{-3}</td>
<td>–</td>
</tr>
</tbody>
</table>

A.Ukleja

Charm mixing and CPV at LHCb

25/07/2014
Three ways of CP violation

1. in mixing (indirect)
   \[ D^0 \rightarrow \text{anti-D}^0 \neq \text{anti-D}^0 \rightarrow D^0 \]

2. in decay amplitudes (direct)
   \[ D \rightarrow f \neq \text{anti-D} \rightarrow \text{anti-f} \]

3. in interference (indirect)
   between direct decays and decays with mixing

- CPV in mixing does not depend on final state (universal)
- Direct CPV depends on final states and it has to be searched everywhere it is possible: \( D \rightarrow hh, hhh, hhhh, \ldots \)
Two production types of charm:

- **prompt** – produced directly in the primary vertex (PV)
  
  \[ \text{IP}(D^0) \sim 0 \]

- **secondary** – produced in B decays (>50% of B → DX)
  
  \[ \text{IP}(D^0) > \sim 0 \]

To separate prompt charm and secondary charm decays we use the cut on \( \chi^2(\text{IP}) \) parameter.

- **Prompt** charm more abundant
- **Secondary** can have higher purity

**Using D impact parameter**

Chris Parkes
Consequences for CPV from $D^0$ – anti-$D^0$ mixing

1. CPV in mixing

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

if $|q/p| \neq 1$ then CPV

The relations could be used to calculate constraints for $|q/p|$

$$x'^\pm = |q/p|^{\pm1}(x' \cos \phi \pm y' \sin \phi)$$

$$y'^\pm = |q/p|^{\pm1}(y' \cos \phi \mp x' \sin \phi)$$

Result: $0.75 < |q/p| < 1.24$ (68.3% CL)

Consistent with no CPV in mixing

2. Direct CPV is measured by the asymmetry

$$A_D = \frac{R^+_D - R^-_D}{R^+_D + R^-_D} = (-0.7 \pm 1.9)\%$$

Direct CP asymmetry is consistent with zero

No indication of direct or indirect CPV
Search for CPV in $D^+ \rightarrow \pi^+\pi^+\pi^+$

$D^+ \rightarrow \pi^+\pi^+\pi^+$ is singly-Cabibbo Suppressed (SCS) and gets contribution from penguin diagram

- If tree and penguin amplitudes interfere with different phases then CP symmetry is broken

$$A_{sym CP} \sim |A_1||A_2|\sin(\phi_1 - \phi_2)\sin(\delta_1 - \delta_2)$$

- Only CP violation in decay amplitudes (direct) since there is no mixing
- Penguin diagram opens possibilities for finding New Physics
Searches for CPV in multi-body charm decays

To find asymmetries we compare locally Dalitz plots for $D^+$ and $D^-$

We perform searches based on techniques that are model-independent: binned and unbinned methods

**Binned method**

- In each bin we calculate a significance of a difference between $D^+$ and $D^-$
  \[ S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}} \]

- To cancel global asymmetries (production asymmetry, etc.) we normalize Dalitz plots for $D^+$ and $D^-$
  \[ \alpha = \frac{N(D^+)}{N(D^-)} \]

- If no CPV (only statistical fluctuations) then $S_{CP}$ is Gauss distributed ($\mu=0$, $\sigma=1$)

- We calculate $\chi^2 = \sum S_{CP}^i$ to obtain p-value for the null hypothesis to test if $D^+$ and $D^-$ distributions are statistically compatible
  \[ p\text{-value} \ll 1 \text{ in case of CPV} \]

---

**Figure 9:**

- Top row: $D_P S_{CP}$ for the bins in Fig. 8b that pass the statistical cut, fit to a centred Gaussian with unit width for model $f_0$. $P_1$ is the normalization parameter.

- Bottom two rows: Distribution of top row divided into the regions shown in Fig. 5. $P_1$ is the normalization parameter.

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A.Ukleja

Charm mixing and CPV at LHCb

25/07/2014
Search for CPV in $D^+ \rightarrow \pi^\pi^\pi^+$

Results for binned method

To increase the sensitivity of the method we use uniform and adaptive binning schemes with different bin numbers

<table>
<thead>
<tr>
<th>Number of bins</th>
<th>$\chi^2$</th>
<th>p-value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>14.0</td>
<td>78.1</td>
</tr>
<tr>
<td>30</td>
<td>28.2</td>
<td>50.6</td>
</tr>
<tr>
<td>40</td>
<td>28.5</td>
<td>89.2</td>
</tr>
<tr>
<td>49</td>
<td>26.7</td>
<td>99.5</td>
</tr>
<tr>
<td>100</td>
<td>89.1</td>
<td>75.1</td>
</tr>
</tbody>
</table>

All p-values for null CPV hypothesis are above 50%

$S_{CP}$ distributions agree with the standard normal Gaussian function

No evidence for CP asymmetry using binned and unbinned methods
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

To find asymmetries we compare locally Dalitz plots for $D^+$ and $D^-$

We perform searches based on techniques that are model-independent: binned and unbinned (k-nearest neighbour) methods

- To compare $D^+$ and $D^-$ we define a test statistic $T$ which is calculated for a pooled sample of $D^+$ and $D^-$:

$$T = \frac{1}{n_k(n_+ + n_-)} \sum_{i=1}^{n_+ + n_-} \sum_{k=1}^{n_k} I(i, k)$$

- $I(i, k) = 1$ if $i^{th}$ event and its $k^{th}$ nearest neighbor have the same charge ($D^+ - D^+$, $D^- - D^-$)
- $I(i, k) = 0$ if pair has opposite charge ($D^+ - D^-$)

- $T$ is the mean fraction of like pairs in the pooled sample of the two datasets

- We calculate p-value for case of no CPV by comparing $T$ with expected mean

$$\mu_T = \frac{n_+(n_+ - 1) + n_-(n_- - 1)}{n(n-1)}$$

$$\lim_{n, n_k, D \rightarrow \infty} \sigma_T^2 = \frac{1}{nn_k} \left( \frac{n_+n_-}{n^2} + 4 \frac{n_+^2n_-^2}{n^4} \right)$$

If $n_+ = n_-$ then $\mu_T \approx 1/2$ (mean value) and $\sigma_T^2 = \frac{1}{nn_k} (0.25 + 0.25)$
Searches for CPV in $D^+ \rightarrow \pi^-\pi^+\pi^+$

To increase the sensitivity of the method we divide the Dalitz plot into regions

LHCb 2011, 1/fb
\sim 3.1M $D^+ \rightarrow \pi^-\pi^+\pi^+$

Two different divisions
• 7 and 3 regions defined around resonances

LHCb results for $B \rightarrow hhh$ show large CPV in the regions not associated to resonances

• All p-values are above 30%, no evidence for CP asymmetry in $D^+ \rightarrow \pi^-\pi^+\pi^+$
• Consistent results we obtained with the binned analysis
Search for CPV in $D^0 \rightarrow K\cdot K^+\pi^-\pi^+$ and $D^0 \rightarrow \pi^-\pi^+\pi^-\pi^+$

While three-body decay kinematics can be described completely in 2D Dalitz plot, a four-body decay has 5 dimensions phase space to fully describe the decay.

Here we divide 5D phase space into bins and in each $i^{th}$ bin we calculate $S_{CP}$

$$S_{CP}^i \equiv \frac{N^i(D^0) - \alpha N^i(D^0)}{\sqrt{N^i(D^0) + \alpha^2 N^i(D^0)}}$$

$$\alpha = \frac{N(D^0)}{N(D^0)}$$

LHCb 2011, 1/fb

32 bins, ~1800 events in each

57k $D^0 \rightarrow K\cdot K^+\pi^-\pi^+$ decays

128 bins, ~2500 events in each

330k $D^0 \rightarrow \pi^-\pi^+\pi^-\pi^+$ decays

$S_{CP}$ distributions agree with normal Gauss distributions

All results are consistent with CP conservation at the current sensitivity (a phase difference of $10^0$ or a magnitude difference of 10%)
LHCb – precision detector

Single-arm forward spectrometer covering range: $2<\eta<5$


For each 1/fb:

$\sim 7k \ B^0_s \rightarrow J/\psi(\mu\mu) \ f_0(\pi^+\pi^-)$

$\sim 28k \ B^0_s \rightarrow J/\psi(\mu\mu) \ \phi(K^+K^-)$

$\sim 2M \ D^{*\pm} \rightarrow D^0(\rightarrow K^{-}K^{+})\pi^{\pm}$

- **VELO** – resolution of IP: 20 $\mu$m, decay lifetime resolution $\sim 45$ fs: $0.1 \ \tau(D^0)$
- Excellent tracking resolution: $\Delta p/p = 0.4\%$ at 5 GeV to 0.6$\%$ at 100 GeV
- **RICH** – very good particle identification for $\pi$ and $K$
- Dedicated trigger lines for beauty and charm with high efficiency
- The polarity of the magnet is reversed repeatedly during data taking
- **LHCb** has possibilities of precise measurements of beauty and charm particles