Measurements of Mixing and Indirect CPV in multi-body Charm decays at LHCb

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Outline

• Mixing and Indirect CP Violation in Charm decays
• Mixing and Coherence Factor in $D^0 \rightarrow K^{\pm} \pi^\pm \pi^+ \pi^-$
• Mixing in $D^0 \rightarrow K^0_S \pi^+ \pi^-$
• LHCb Prospects for Run2
Mixing in Charm Decays

Mixing of Neutral Mesons

- Pure Quantum Mechanics effect

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

- By labelling the mass eigenstates

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

- The mixing parameters can be defined

\[ x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta M}{\Gamma}, \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma} \]
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- The mixing parameters can be defined
  \[ x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta M}{\Gamma} \quad \text{and} \quad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma} \]

- Established!
CPV and Mixing

- CPV can arise from mixing
  \[ \left| \frac{q}{p} \right| \neq 1 \]

- or from interference of decay with and without mixing \( D^0 \to f; \overline{D^0} \to \bar{f} \)
  \[ \arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0 \]
  \[ \lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} \]

- Still consistent with no CPV
Indirect Searches

- Charm mixing sets the second stringent bounds on NP from $\Delta F=2$ processes
- Not as much powerful on other models (NMFV), but still worth considering

Up-sector

- Charm probes up-sector quark mixing
  Alternative path to NP
- Very small SM expectations
Multi-Body Decays

Cons

- Lower efficiency than two-body
- Long-range dynamics more difficult to predict
- May need understanding the resonant structure of the decay

Pros

- Large number of intermediate states
  offer many possible interference patterns
- More observables exploiting the underlying resonant structure
- Useful for $\gamma$ measurement using $B \to D^0K$
$D^0 \rightarrow K\pi\pi\pi$

Mixing and Coherence Factor
WS/RS Ratio

- Exploits mixing by measuring the time-dependent ratio of $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ (WS) decays to $D^0 \rightarrow K^-\pi^+\pi^+\pi^-$ (RS) decays (assuming CP symmetry)

$$R(t) \approx \left( r_D^{K3\pi} \right)^2 - r_D^{K3\pi} R_D^{K3\pi} y'_{K3\pi} \frac{t}{\tau} + \frac{x^2 + y^2}{4} \left( \frac{t}{\tau} \right)^2$$

- $r_D^{K3\pi}$: phase space averaged ratio of DCS/CF amplitudes
- $R_D^{K3\pi}$: coherence factor: $R_D^{K3\pi} e^{-i\delta_D^{K3\pi}} \equiv \langle \cos \delta \rangle + i \langle \sin \delta \rangle$
- $y'_{K3\pi}$: interference term: $y'_{K3\pi} \equiv y \cos \delta_D^{K3\pi} - x \sin \delta_D^{K3\pi}$

All the three parameters are needed for measuring $\gamma$ with $B \rightarrow D^0(K\pi\pi\pi)K$. 

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D$^0 \rightarrow K\pi\pi\pi$ - Mixing and Coherence Factor
Dataset

- Prompt $D^+ \rightarrow D^0 \pi^+$ decays
- Run1: 3fb$^{-1}$ at 7 and 8 TeV

\[ N_{RS} = 11.4 \times 10^6 \]

\[ N_{WS} = 42.5 \times 10^3 \]
D^0 → Kπππ - Run1 Analysis

Ratios Fit

- The WS/RS ratio measured in 10 decay time bins in [0.5,12.0]τ_D

\[ R = \sqrt{N_{WS}^D N_{WS}^\bar{D} / N_{RS}^D N_{RS}^\bar{D}} \] to cancel production or π_s± detection asymmetries

- Uncertainties in the plot include systematics
  - double mis-id (K^+π^- → K^-π^+)
  - D^0 → K^+π^-K^0_S
  - contribution from secondary decays (bin-by-bin)
  - trigger efficiency

- A few hypotheses are tested
  - Mixing
  - No Mixing (excluded at 8.2σ)
  - WA Mixing (compatible at 1.8σ)

### Fit Table

<table>
<thead>
<tr>
<th>Fit Type</th>
<th>Parameter</th>
<th>Fit result</th>
<th>Correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unconstrained</td>
<td>( r_D^{K3\pi} )</td>
<td>( (5.67 \pm 0.12) \times 10^{-2} )</td>
<td>1</td>
</tr>
<tr>
<td>7.8/7 (0.35)</td>
<td>( R_D^{K3\pi} \cdot y'_{K3\pi} )</td>
<td>( (0.3 \pm 1.8) \times 10^{-3} )</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>( \frac{1}{4}(x^2 + y^2) )</td>
<td>( (4.8 \pm 1.8) \times 10^{-5} )</td>
<td>0.80</td>
</tr>
</tbody>
</table>
D⁰ → Kπππ - Coherence Factor

The Constrained Fit

- Allows to determine a line of solutions in the (δ_D^{K3π}, R_D^{K3π}) plane
  - Uncertainties on r_D^{K3π} and R_D^{K3π} y'_{K3π} are greatly reduced
- Improves constraints previously produced by CLEO-c
  - But a combination would require a combined fit
- Will increase the sensitivity to γ in B → D⁰(Kπππ)K

OSS: \[ y'_{K3π} \equiv y \cos \delta_D^{K3π} - x \sin \delta_D^{K3π} \]

<table>
<thead>
<tr>
<th></th>
<th>τ_D^{K3π}</th>
<th>R_D^{K3π} \cdot y'_{K3π}</th>
<th>x</th>
<th>y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing-constrained</td>
<td>(5.50 ± 0.07) × 10^{-2}</td>
<td>1</td>
<td>0.83</td>
<td>0.17</td>
</tr>
<tr>
<td>11.2/8 (0.19)</td>
<td>(−3.0 ± 0.7) × 10^{-3}</td>
<td>1</td>
<td>0.34</td>
<td>0.20</td>
</tr>
<tr>
<td>x</td>
<td>(4.1 ± 1.7) × 10^{-3}</td>
<td>1</td>
<td></td>
<td>-0.40</td>
</tr>
<tr>
<td>y</td>
<td>(6.7 ± 0.8) × 10^{-3}</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Combination with CLEO-c

\[
\begin{align*}
\Delta \chi^2 &= 1 \\
\Delta \chi^2 &= 4 \\
\Delta \chi^2 &= 9
\end{align*}
\]
$D^0 \rightarrow K^0_S \pi^+ \pi^-$

Mixing
A Golden Mode for Mixing and CPV

- Both CF and DCS components are present in the same final state
- It gives direct access to all the mixing parameters $x, y, q/p, \text{arg}(q/p)$
- Thanks to the various contributions in the Dalitz plot, whose time dependance is modified by mixing parameters

All that Glitters is not Gold…

- Amplitude structure
- Time dependance of the Amplitude structure
  Time-dependent Dalitz-plot Analysis
- Presence of varying strong phases across the DP need to be treated with care
  It is fixed in two-body decays
- A time-dependent amplitude analysis approach has been pioneered by CLEO and later followed by BaBar and Belle
- At LHCb this approach is more challenging
  Run1 trigger has decay-time dependent selections $\rightarrow$ need to model that bias
  (Things should be better in Run2…)
**External Input**

- In reality one does not need to know perfectly the Amplitude structure.
- Just how the strong phases vary along the Dalitz plot.
- External input can be used.

**Strong Phases Measurement**

- Quantum coherence of $D^0 - \bar{D}^0$ needed to separate $D^0$ and $\bar{D}^0$ decays.
- Assuming an amplitude model as a reference, the difference of strong phase between bin $-i$ and $i$ is measured.
Formalism

- Fraction of events in a bin
\[ T_i = \int_i |A| dm^2_1 dm^2_3 \]

- Interference terms
\[ c_i = \frac{1}{\sqrt{T_i T_{-i}}} \int_i |A^*_D||A_{\bar{D}}| \cos \Delta \delta_i dm^2_+ dm^2_- \]
\[ s_i = \frac{1}{\sqrt{T_i T_{-i}}} \int_i |A^*_D||A_{\bar{D}}| \sin \Delta \delta_i dm^2_+ dm^2_- \]

- Time-dependent decay rate
\[ \mathcal{P}_{D^0}(i; t) \approx e^{\Gamma t} \left( T_i - \Gamma t \sqrt{T_i T_{-i}} (yc_i + xs_i) \right) \]
\[ \mathcal{P}_{\bar{D}^0}(i; t) \approx e^{\Gamma t} \left( T_{-i} - \Gamma t \sqrt{T_i T_{-i}} (yc_i - xs_i) \right) \]

x, y can be measured from the decay-time distribution of events in the DP bins
**Dataset**
- Prompt $D^* \to D^0 \pi^+$ decays
- 2011 data: $1 fb^{-1}$

**Challenges**
- Per-event decay-time acceptance
  Data-driven (swimming$^1$)
- Secondary ($B \to D^* X$) candidates rejection

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**Graphs**
- Candidates per 1.7 MeV/$c^2$
- $N_D = 178k$
- S/B~97%

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**Equations**
- $D^0 \to K^0_S \pi^+ \pi^-$ at LHCb: 2011 Analysis
Analysis

- The distributions of $D^0$ mass, $D^0 \log IPx^2$ and $D^0$ decay time are fit separately in various steps and finally simultaneously to measure the mixing parameter.
- Systematic uncertainties studying by measuring the impact on final result:
  - external input ($T_i$)
  - mass resolution
  - decay time resolution
  - combinatorial background
  - efficiency over PS
  - per-event decay time acceptance

$$x = (-0.86 \pm 0.53 \pm 0.17) \times 10^{-2},$$
$$y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}.$$
Synergy with BESIII

External Inputs

- Quantum coherence of $D^0$-$\bar{D}^0$ mesons produced at $c$ factories allows complementary measurements to LHCb
- A proposal is out describing where branching fraction and strong phases measurements could help (LHCb-PUB-2016-025)
- Focused on the determination of $\gamma$ at LHCb, but applies also to mixing and CPV in Charm

Synergy of BESIII and LHCb physics programmes

LHCb Collaboration
LHCb Run2 Prospects

**Much Larger Yields**

- $c\bar{c}$ cross-section almost doubled
- Extensive work during LS1 on Charm triggers (Turbo)
  - Larger efficiency
  - Improved acceptance
- Online Alignment and Calibration

**Alternative Techniques**

- Amplitude analyses in Charm are gaining momentum
- Useful for measuring Mixing and CPV
D⁰→K⁰_sπ⁺π⁻ Run2 Preview

K⁰_s vtx inside VELO

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ 2 \text{ fb}^{-1} \]

LHCb preliminary

\[ m(D^{*+}) - m(D^0) \ [\text{MeV/c}^2] \]

N_D ≈ 3.2 \times 10^6 \ (1.6 \text{ M/fb})

Run1: 0.3 \text{ M/fb}

K⁰_s vtx outside VELO

\[ \sqrt{s} = 13 \text{ TeV} \]
\[ 2 \text{ fb}^{-1} \]

LHCb preliminary

\[ m(D^{*+}) - m(D^0) \ [\text{MeV/c}^2] \]

N_D ≈ 5.0 \times 10^6 \ (2.5 \text{ M/fb})

Run1: 0.4 \text{ M/fb}
Run2 Prospects

$D^0 \rightarrow K\pi\pi\pi$ Run2 Preview

$LHCb$ Preliminary

$\sqrt{s} = 13$ TeV

2 fb$^{-1}$

$N_D \approx 3 \times 10^6$ (16 M/fb)

Run1: 3.7 M/fb
Summary

Just Started

- The study of Mixing and CPV in Charm multi-body decays at LHCb has just started
- Many more analysis are in the pipeline
- More experience with the detector will favour amplitude analyses

The Best is Yet to Come

- Run2 data are very promising
- Improved trigger provides us unprecedented yields of Charm decays
Spares
Two Ways of Selecting and Tagging Charm Hadrons at LHCb

- Charm hadrons can be promptly produced in pp collisions or as product of B decays.

**Prompt**

- Prompt production of charm hadrons can be observed directly in pp collisions.

**Muon-tagged**

- Muon-tagged charm hadrons can be identified by the decay of \( D^0 \) into \( \mu^- \) and a hadronic system.

**Doubly-tagged**

- Doubly-tagged charm hadrons involve the decay of both \( D^0 \) and \( B \) mesons into a muon pair and a hadronic system.
Comparison with other meson mixing

<table>
<thead>
<tr>
<th>Λ (TeV)</th>
<th>K</th>
<th>D</th>
<th>B_d</th>
<th>B_s</th>
</tr>
</thead>
<tbody>
<tr>
<td>FC~1</td>
<td>5x10^5</td>
<td>3.5x10^4</td>
<td>3.3x10^3</td>
<td>880</td>
</tr>
<tr>
<td>FC~SM</td>
<td>113</td>
<td>8.5</td>
<td>21</td>
<td>27</td>
</tr>
</tbody>
</table>

Graphical representations of NP scales for various CKM parameters (Re C_K, Im C_K, Im C_D, C_{Bd}, C_{Bs}) for FC~1 and FC~SM cases.
Table 1: Systematic uncertainties on $x$ and $y$. The statistical uncertainties, which include the uncertainties associated with the CLEO parameters $(c_i, s_i)$, are shown for comparison.

<table>
<thead>
<tr>
<th>Source</th>
<th>$x \times 10^{-2}$</th>
<th>$y \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit bias</td>
<td>0.021</td>
<td>0.020</td>
</tr>
<tr>
<td>Decay time resolution</td>
<td>0.065</td>
<td>0.039</td>
</tr>
<tr>
<td>Turning point (TP) resolution</td>
<td>0.020</td>
<td>0.022</td>
</tr>
<tr>
<td>Invariant mass resolution</td>
<td>0.073</td>
<td>0.028</td>
</tr>
<tr>
<td>Prompt/secondary TP distributions</td>
<td>0.051</td>
<td>0.023</td>
</tr>
<tr>
<td>Efficiency over phase space</td>
<td>0.057</td>
<td>0.071</td>
</tr>
<tr>
<td>Tracking efficiency parameterisation</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td>Kinematic boundary</td>
<td>0.012</td>
<td>0.006</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.061</td>
<td>0.052</td>
</tr>
<tr>
<td>Treatment of secondary $D$ decays</td>
<td>0.046</td>
<td>0.025</td>
</tr>
<tr>
<td>Uncertainty from $T_i$</td>
<td>0.079</td>
<td>0.056</td>
</tr>
<tr>
<td>Uncertainties from $(m_D, \Delta m)$ fits</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Uncertainties from lifetime fit</td>
<td>0.020</td>
<td>0.043</td>
</tr>
<tr>
<td>$D^0$ background</td>
<td>0.001</td>
<td>0.006</td>
</tr>
<tr>
<td>Variation of signal components across the phase space</td>
<td>0.013</td>
<td>0.017</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.171</td>
<td>0.134</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.527</td>
<td>0.463</td>
</tr>
</tbody>
</table>