Measurements of CPV and mixing in charm decays
Rencontres de Physique de la Vallée d’Aoste

Andrea Contu on behalf of the LHCb collaboration

INFN Cagliari - CERN

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Outline

1. Introduction
2. Measurement of $A_{\Gamma}$ in $D^0 \rightarrow hh$
3. Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$
4. Conclusions
Why study charm physics?

- Up-type quark: unique probe of NP in the flavour sector, complementary to studies in K and B systems
- Precision CKM physics in the B sectors needs input from charm
- Small mixing and CPV in the SM due to GIM mechanism and CKM suppression

Long-distance contributions are non-negligible, precise theoretical predictions are difficult, charm is more a discovery tool (but lattice QCD may one day help?)
Neutral $D$ mesons

Produced as flavour $D^0$ and $\bar{D}^0$ eigenstates, decay as mass eigenstates $D_1$ and $D_2$

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma & 0 \\ 0 & M + \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

$$|D_1\rangle = p |D^0\rangle + q |\bar{D}^0\rangle$$

$$|D_2\rangle = p |D^0\rangle - q |\bar{D}^0\rangle$$

$$(q/p)^2 = \frac{M^*_{12} - \frac{i}{2} \Gamma^*_{12}}{M^*_{12} - \frac{i}{2} \Gamma^*_{12}}$$

Mixing occurs if $\Delta M = M_1 - M_2 \neq 0$ or $\Delta \Gamma = \Gamma_1 - \Gamma_2 \neq 0$

Mixing parameters

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2 \Gamma}, \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

DIRECT CPV

Different decay amplitudes for $D^0$ and $\bar{D}^0$

$$A_f = \langle f|H|D^0\rangle, \quad \bar{A}_f = \langle \bar{f}|H|\bar{D}^0\rangle$$

$$\frac{A_f}{\bar{A}_f} \neq 1$$

CPV IN MIXING

Different mixing rates

$D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$

$$|q/p| \neq 1$$

CPV IN INTERFERENCE

between mixing and decay

$$\phi = \arg\left(\frac{q\bar{A}_f}{pA_f}\right)$$

Precision on $q/p$ and $\phi$ is driven by the knowledge of $x$ and $y$
Charm physics at LHCb

- Unprecedented charm yields at LHC produced world best measurements:
  - Mixing and CPV in $D^0 \rightarrow K\pi$ [PRL 111 (2013) 251801]
  - Direct CPV with $\Delta A_{CP}$ [JHEP 07 (2014) 041, LHCb-CONF-2013-003]
  - Indirect CPV in $A_\Gamma$ [PRL 112 (2014) 041801] (only 2011 data!)

- Still statistically dominated in core measurements
- Experimentally we can tag $D$ flavour at production:

![Diagram of Charm Physics](Image)

- Independent samples
Introduction

Current LHCb detector [JINST 3 (2008) S080005]

LHCb proved itself to be a forward general purpose detector at the LHC:

- **Vertexing**
- **PID**
- **Tracking**
- **Calorimeters**
- **Muon**

**Performance:**
- \( \Delta p/p = 0.35\% - 0.55\% \)
- Mass resolution = 10 - 25 MeV/c^2
- Impact parameter resolution: 20 \( \mu \)m for high-\( p_T \) tracks
- ECAL \( \sigma(E)/E = 10\%(E/\text{GeV})^{-1/2} \oplus 1\% \)
- Excellent particle ID thanks with RICH detectors (2-100 GeV/c^2)
Measurement of $A_\Gamma$ in $D^0 \to hh$ [PRL 112 (2014) 041801]

- Asymmetry in the effective lifetime between $D^0$ and $\bar{D}^0$

$$A_\Gamma = \frac{\tau_{\text{eff}}^{\bar{D}^0} - \tau_{\text{eff}}^{D^0}}{\tau_{\text{eff}}^{\bar{D}^0} + \tau_{\text{eff}}^{D^0}} \approx \left( \left| \frac{q}{p} \right| - \left| \frac{p}{q} \right| \right) y \cos \phi - \left( \left| \frac{q}{p} \right| + \left| \frac{p}{q} \right| \right) x \sin \phi$$

- Almost clean measurement of indirect CPV
- World best determination from LHCb using prompt sample with $1\text{fb}^{-1}$

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

$$A_\Gamma(KK) = (-0.035 \pm 0.062_{\text{stat}} \pm 0.012_{\text{syst}})\%$$

$$A_\Gamma(\pi \pi) = (0.033 \pm 0.106_{\text{stat}} \pm 0.014_{\text{syst}})\%$$
Measurement of $A_\Gamma$ in $D^0 \rightarrow hh$ [arXiv:1501.06777, sub. to JHEP]

- Latest LHCb measurement using $D^0$ from semi-leptonic B decays
- Full Run1 dataset, 3 fb$^{-1}$
- Mistag asymmetry dominant systematic, $D^0 \rightarrow K^-\pi^+$ used as control channel

![Graphs showing data and fits for signal and background](image)

- Signal: $2.34 \times 10^6$ events
- Signal: $0.79 \times 10^6$ events
Measurement of $A_{\Gamma}$ in $D^0 \rightarrow hh$

- Fit the time evolution of the asymmetry
  
  $$A_{CP}(t) \approx A_0 - A_{\Gamma} \frac{t}{\tau}$$

  $$A_{\Gamma}(KK) = (-0.134 \pm 0.077_{\text{stat}}^{+0.026}_{-0.034})\%$$

  $$A_{\Gamma}(\pi\pi) = (-0.092 \pm 0.145_{\text{stat}}^{+0.025}_{-0.033})\%$$

- Assuming indirect CPV is universal
  
  $$A_{\Gamma} = (-0.125 \pm 0.073)\%$$

- In agreement with previous measurements and consistent with no indirect CPV in $D^0$ decays
Combining LHCb prompt and semileptonic results

\[ A_\Gamma(KK) = (-0.072 \pm 0.050)\% \]

\[ A_\Gamma(\pi\pi) = (-0.010 \pm 0.087)\% \]

If universal indirect CPV:

\[ A_\Gamma = (-0.056 \pm 0.044)\% \]

Combining also with

Belle [arXiv:1212.3478],
BaBar [PRD87 (2013) 012004],
and CDF [PRD90 (2014) 111103]

\[ A_\Gamma = (-0.058 \pm 0.040)\% \]
Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ [Phys. Lett. B 740 (2015) 158]

Time integrated CP asymmetry search in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ using the “energy test” method [Phys. Rev. D, 84 (2011), p. 054015]

- First CPV analysis with $\pi^0$s in LHCb

Resolved $\pi^0$, two ECAL clusters, better mass resolution, low $p_T$
416 x $10^3$ events, purity: 82%

Merged $\pi^0$, single ECAL cluster, worse mass resolution, high $p_T$
247 x $10^3$ events, purity: 91%

Define test statistic $T$, which depends on the distance between pair of events in the Dalitz plane $\Delta x_{ij}$

$$T = \frac{1}{n(n-1)} \sum_{i,j>i} \psi(\Delta x_{ij}) + \frac{1}{n(n-1)} \sum_{i,j>i} \psi(\Delta x_{ij}) - \frac{1}{n\bar{n}} \sum_{i,j} \psi(\Delta x_{ij})$$

- $\Delta x_{ij} = (m_{12}^j - m_{12}^i, m_{23}^j - m_{23}^i, m_{13}^j - m_{13}^i )$, does not depend on the choice of axes in the Dalitz plane
- $\psi(\Delta x_{ij}) = \exp \Delta x_{ij}^2 / 2\sigma^2$ is the metric used in the analysis
Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ [Phys. Lett. B 740 (2015) 158]

- Distribution of $T$ for no-CPV hypothesis is determined by doing permutations randomly assigning the $D^0$ flavour.
- It can be verified that the $T$ distribution follows the Generalised Extreme Value (GEV) function:
  \[ f(T; \mu, \delta, \xi) = N \left[ 1 + \xi \left( \frac{T-\mu}{\delta} \right) \right]^{(-1/\xi)-1} \exp \left[ 1 + \xi \left( \frac{T-\mu}{\delta} \right) \right]^{-1/\xi} \]
- Local asymmetries can be looked at by defining for each event in the Dalitz plane:
  \[ T_i = \frac{1}{2n(n-1)} \sum_{j \neq i}^n \psi_{ij} - \frac{1}{n\bar{n}} \sum_{j \neq i} \psi_{ij} \]
Search for CPV in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ [Phys. Lett. B 740 (2015) 158]

Consistent with CP conservation

\[ p\text{-value : } (2.6 \pm 0.5) \times 10^{-2} \]

Local positive asymmetry exceeding 1σ significance in the region dominated by the $\rho^+$
Prospects for CP violation in charm at LHCb

courtesy of M. Gersabeck

contours hold 68%, 95% CL
Conclusions

- Charm physics is a unique probe of NP
- Precious input to charm physics from LHCb
- Precision measurements thanks to $\mathcal{O}(1M)$ samples
- Still more to come in Run 1
- Excellent prospects for Run2 and Upgrade
- Stay tuned!