Status of Direct CPV searches in Charm at LHCb

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Outline

- Introduction
- Charm CP violation observation in $\Delta A_{CP}$
- Search for CP violation in $D_{(s)}^+ \rightarrow h^+\pi^0$ and $D_{(s)}^+ \rightarrow h^+\eta$ decays
- Search for CP violation in $D^0 \rightarrow K_S^0 K_S^0$ decays
- Search for CP violation in $D^0 \rightarrow h^+h^-\mu^+\mu^-$ decays
Introduction
Introduction to CPV in charm

- *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)
- New Physics may be hidden in the loops, but these are very suppressed in charm. CPV is expected to be small: $O(10^{-3} - 10^{-4})$
- Moreover, long-distance contributions are non-negligible and precise theoretical predictions are difficult
- CPV classification:

  - **DIRECT CPV**
    - Different decay amplitudes for $D$ and $\bar{D}$
    - Only CPV possible for charged hadrons

  - **CPV IN MIXING**
    - Different mixing rates
    - $D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$

  - **TIME DEPENDENT CPV**
    - Between mixing and decay
Charm production at LHCb

- LHCb detector: excellent particle identification, IP and momentum resolution ($\sim 13 \, \mu\text{m}$ on the transverse plane and $\Delta p/p \sim 0.5\% - 0.8\%$, respectively.)
- Huge charm production $\sigma(pp \rightarrow c\bar{c}X)_{p_T < 8 \, \text{GeV/c}, 2.0 < y < 4.5} = 2369 \pm 3 \pm 152 \pm 118 \, \mu\text{b}$.

\[
\begin{align*}
\sigma(pp \rightarrow D^0 X) &= 2072 \pm 2 \pm 124 \, \mu\text{b}, \\
\sigma(pp \rightarrow D^+ X) &= 834 \pm 2 \pm 78 \, \mu\text{b}, \\
\sigma(pp \rightarrow D^+_s X) &= 353 \pm 9 \pm 76 \, \mu\text{b}, \\
\sigma(pp \rightarrow D^{*+} X) &= 784 \pm 4 \pm 87 \, \mu\text{b},
\end{align*}
\]

$>10^{12} \ c\bar{c} \ \text{pairs per year!}$

[JHEP 05 (2017) 074]

[JINST 3 S08005 (2008)]
Flavour tagging

- Whether the decaying D meson is produced as $D^0$ or $\bar{D}^0$ needs to be determined to perform mixing and CPV measurements
- There are two possible tagging methods
- Both samples used by LHCb, independent and complementary in lifetime coverage
Measuring the CP asymmetry

- We want to measure the time integrated asymmetries

\[ A_{CP}(f) = \frac{\Gamma(M \rightarrow f) - \Gamma(M \rightarrow \bar{f})}{\Gamma(M \rightarrow f) + \Gamma(M \rightarrow \bar{f})} = 1 - \frac{|\bar{A}_f/A_f|^2}{1 + |\bar{A}_f/A_f|^2} \]

- However the observable is the yield asymmetry, which must be corrected to extract the physical asymmetry

\[ A_{raw} = \frac{N(D \rightarrow f) - N(\bar{D} \rightarrow \bar{f})}{N(D \rightarrow f) + N(\bar{D} \rightarrow \bar{f})} = A_{CP} + A_P + A_D \]

- \( A_P \) is the production asymmetry in pp collisions
- \( A_D \) is the detection asymmetry due to the detector
- \( A_P \) and \( A_D \) are determined and corrected for using calibration samples

In general for \( D^0 \) SCS decays

\[ A_{CP}(f) = A_{CP}^{dir}(f) + A_{CP}^{mix} + A_{CP}^{int} \]

In the studies presented today, time dependent CPV is negligible
Observation of CPV in charm
Observation of CPV in charm with $\Delta A_{CP}$

- Full Run1 + Run2 dataset, $D^*$ and semileptonic tag
- Observable is mainly sensitive to direct CPV
  
  $\Delta A_{CP} = A_{CP}(D^0 \rightarrow K^+ K^-) - A_{CP}(D^0 \rightarrow \pi^+ \pi^-)$
  
  assuming universal $a_{cp}^{ind}$
  
  $\approx \Delta a_{CP}^{dir} + \frac{\Delta \langle t \rangle}{T_D} a_{CP}^{ind}$
  
  $\Delta \langle t \rangle = \langle t \rangle_{KK} - \langle t \rangle_{\pi\pi}$

- Experimentally robust as production and detection asymmetries cancel to first order
- Not clear is NP or not, additional measurements are needed!

$\Delta a_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

CP violation observed at 5.3σ!
Search for CP violation in $D_{(s)}^{+} \rightarrow h^+ \pi^0$ and $D_{(s)}^{+} \rightarrow h^+ \eta$ decays
Overview

- Measurement of direct CP asymmetries
- \( h^+ = \pi^+ \) or \( K^+ \), these are in fact 8 decays with a Golden channel: \( A_{CP}(D^+ \to \pi^+\pi^0) = 0 \) in SM since it is driven by a single isospin amplitude (no penguin contributions)
- Challenging to reconstruct in LHCb:
  - Large combinatorial background from neutral reconstruction
  - Cannot reconstruct a displaced vertex with a single charged track
- Exploit \( e^+e^-\gamma \) final state to recover mass resolution (at the price of a lower BF):
  - \( h^0 \to \gamma (\to e^+e^-) \gamma \), with converted photon (86%)
  - \( h^0 \to \gamma e^+e^- \) (14%)
- \( D_{(s)}^+ \to h^+\pi^0 \) Run 1 and Run 2 (9 fb-1)
- \( D_{(s)}^+ \to h^+\eta \) Run 2 (6 fb-1)
Signal selection and control samples

- Main background is combinatorial: rejected with track/vertex quality and displacement and transverse momentum
- Raw asymmetry and signal yields determined from 2D fits to $m(h^+h^0)$ and $m(\gamma^+\gamma^-)$

$D_{(s)}^+ \rightarrow K_s^0 h^+$ as control samples to subtract production and detection asymmetries, $A_{CP}$ measured with high precision [PRL 122 (2019) 191803]
Results

\[ A_{CP}(D^+ \to \pi^+\pi^0) = (-1.3 \pm 0.9 \pm 0.6)\% \]
\[ A_{CP}(D^+ \to K^+\pi^0) = (-3.2 \pm 4.7 \pm 2.1)\% \]
\[ A_{CP}(D^+ \to \pi^+\eta) = (-0.2 \pm 0.8 \pm 0.4)\% \]
\[ A_{CP}(D^+ \to K^+\eta) = (-6 \pm 10 \pm 4)\% \]
\[ A_{CP}(D_s^+ \to K^+\pi^0) = (-0.8 \pm 3.9 \pm 1.2)\% \]
\[ A_{CP}(D_s^+ \to \pi^+\eta) = (0.8 \pm 0.7 \pm 0.5)\% \]
\[ A_{CP}(D_s^+ \to K^+\eta) = (0.9 \pm 3.7 \pm 1.1)\% \]

First five results are world best, the rest are slightly worse w.r.t. very recent Belle publication \([\text{PRD 103, 112005 (2021)}]\)

Update for \(D_s^{+} \to \eta'\pi^{+}\) \([\text{PLB771 (2017) 21]}\) is in the pipeline

Main systematics:

- Fit model
- Control mode for \(D_s^+ \to \pi^+\eta\)
  \((D_s^+ \to K_s^0 h^+ \text{ has the lowest stat})\)
Search for CP asymmetry in $D^0 \rightarrow K^0_S K^0_S$
Overview

- $A_{CP}$ in $D^0 \rightarrow K_S^0 K_S^0$ is SM is predicted to sizeable \cite{PRD 92, 054036 (2015)}, \cite{PRD 86, 036012 (2012)}, \cite{PRD 100, 093002 (2019)}, \cite{PRD 99, 113001 (2019)}.
- Challenging at LHCb, due to the long $K_S^0$ lifetime.
- Three samples are analysed separately:
  - LL $\rightarrow$ both $K_S^0$ are reconstructed with long tracks
  - LD $\rightarrow$ one $K_S^0$ is reconstructed with long and the other with downstream tracks
  - DD $\rightarrow$ both $K_S^0$ are reconstructed with downstream tracks
- This analysis exploits the full run 2 sample (6 fb$^{-1}$)
Signal selection and control samples

- Main backgrounds are:
  - $D^0 \to K_S^0 \pi^+\pi^-$: reduced with a cut on the $D^0 - K_S^0$ vertices distance and then statistically separated with a simultaneous fit to the distributions of $\Delta m = m(D^*) - m(D^0)$ and $m(K_S^0)$
  - Combinatorial: reduced with a multivariate discriminant and accounted for in the fit

- $A_P$ and $A_D$ are corrected for using a $D^0 \to K^+K^-$ calibration sample, $A_{CP}(KK)$ is taken from [PLB 767 (2017) 177-187]. Selections equalized between signal and calibration sample

- Separate measurements are performed by splitting in:
  - LL, LD and DD categories:
  - 2015-2016, 2017-2018 (different trigger selections)
  - purity level (determined using a kNN classifier)
  - compatibility for $D^*$ to come from PV
Results

Combining all categories:

$$A_{CP}(D^0 \rightarrow K_S^0 K_S^0) = (-3.1 \pm 1.2 \text{ (stat.)} \pm 0.4 \text{ (syst.)} \pm 0.2 \text{ (}A_{CP}(D^0 \rightarrow KK)) \%)$$

Most precise to date, compatible with no CPV at 2.4σ
Search for CP asymmetry in $D^0 \rightarrow h^+h^-\mu^+\mu^-$
Overview

- Rarest observed charm meson decay \([\text{PRL 119, 181805 (2017)}]\), dominated by vector meson intermediate resonances
- \(A_{\text{CP}}\) is predicted to be up to \(O(1\%)\) in NP models \([\text{PRD 101 (2020) 115006}]\) ...
- First LHCb measurements (which includes angular observables) available at \([\text{PRL 121, 091801 (2018)}]\)
- **Now:** update with the full Run1+Run2 dataset (more details and full angular analysis shown in D. Brundu’s talk (WP3))
- \(D^0 \to K^+K^-\) used as control sample
Results

Measurement in the full phase space and in bins of $m(\mu\mu)$

No CPV observed (yet)
Conclusion

- LHCb collected the largest charm sample to date
- After the observation of non-zero direct CPV, the hunt continues in other channels (even in rare decays!)
- Significant improvements may come in the upgrade, not only for the additional luminosity, but from higher efficiency thanks to our fully software trigger

STAY TUNED