Time-integrated CP violation in Charm decays

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On behalf of LHCb collaboration
(including results also from CLEO-c, Belle and CDF)
Covered experiments

- Very large sample of HF hadrons in pp collisions at LHC:
  - $\sigma_{c\bar{c}} = 1419 \pm 134 \mu\text{b} @ 7 \text{ TeV}$ [Nucl. Phys. B871, 1-20]
  - 1 fb$^{-1}$ @ 7 TeV + 2 fb$^{-1}$ @ 8 TeV
  - $\sim 2$ kHz of charm events stored on disk

- Exploiting final statistics collected after 10 years at TeVatron
  - general purpose experiment
  - $\sim 10^{13}$ p$p$ collisions @ 1.96 TeV
  - $\sim 1\%$ of collisions yields a D meson

- Collected $e^+e^-$ asymmetric collisions at KEKB:
  - More than 1 ab$^{-1}$ of integrated luminosity at various Y resonances
  - $\sigma_{c\bar{c}} \approx 1.3 \text{ nb} @ Y(4S)$ resonance

- Collected $e^+e^-$ collisions at $\Psi(3770)$ resonance:
  - Full sample is 818 pb$^{-1}$
  - very clean environment
Experimental observable

- Quintessential observable in time-integrated CPV is

\[ A_{\text{RAW}} = \frac{N(D \to f) - N(\bar{D} \to \bar{f})}{N(D \to f) + N(\bar{D} \to \bar{f})} \]

- \( A_{\text{RAW}} \) is related to CPV parameters by

\[ A_{\text{RAW}} \approx A_{\text{CP}} + A_P + A_D + A_T \]

- Asymmetry in determination of D flavour

\[ A_{\text{CP}} = \frac{\Gamma(D \to f) - \Gamma(D \to \bar{f})}{\Gamma(D \to f) + \Gamma(D \to \bar{f})} \]

CP asymmetry related to CKM parameters

Different production rates between D and \( \bar{D} \)

Different detection efficiencies between f and \( \bar{f} \)

- Experimental issues
  - determine the corrections to \( A_{\text{RAW}} \)
  - general strategy is to measure \( A_{\text{RAW}} \) in Cabibbo-favoured decays where CPV is very unlikely
Tag asymmetry

- Correction peculiar of neutral D\(^0\) mesons
- Two strategies:
  - D\(^*\)-prompt:
    - reconstruct D\(^*+\)→D\(^0\)\(\pi^+_s\) decays
    - \(\pi^+_s\) charge denotes D\(^0\) flavour
    - \(A_T\) comes from \(\pi^+_s\) detection asymmetry
    - used by all the experiments
  - Semi-leptonic:
    - reconstruct B→D\(^0\)\(\mu^\pm X\) decays
    - \(\mu^\pm\) charge denotes D\(^0\) flavour
    - \(A_T\) comes from m detection asymmetry
    - completely independent of the D\(^*\)-prompt sample
    - peculiar of LHCb
Production asymmetry

• Depends on several factors
• Tag of $D^0$:
  – $D^*$-prompt $\rightarrow A_P$ of $D^*$
  – Semi-leptonic $\rightarrow A_P$ of $B$ mesons
• Environment
  – p-p collisions:
    • initial imbalance between $q$ and $\bar{q}$
    • different hadronization probabilities for $D$ and $\bar{D}$
    • may depend on kinematic
  – p-$\bar{p}$ collisions:
    • expect $A_P$ to vary as a function of $\eta$
    • $D$ ($\bar{D}$) production may be favourite in the direction of $\bar{p}$ (p)
  – $e^+$-$e^-$ collisions:
    • function of CMS polar angle
      \[ A_P \equiv A_{FB} \left( \cos \theta^* \right) \]
    • can be easily disentangled
      \[
      A_{CP} = \frac{A_{raw}^{cor}(\cos \theta^*) + A_{raw}^{cor}(-\cos \theta^*)}{2} \\
      A_{FB} = \frac{A_{raw}^{cor}(\cos \theta^*) - A_{raw}^{cor}(-\cos \theta^*)}{2}
      \]

$A_{FB} \equiv A_{FB} \cos \theta^*$

arXiv:1212.1975
Detection asymmetry

- Charge conjugate final states can have different detection efficiency
- Asymmetry in particle interaction with material
  - e.g.: $K^-$ has larger inelastic cross-section with detector material with respect to $K^+$
- Asymmetry in detector response
  - e.g.: different efficiency with respect to bending direction of charged tracks
  - regularly revert magnet polarity

Data from K.A. Olive et al. (PDG), CPC 38 (2014) 090001

$A_{\mu}/\Lambda_{\mu}[\%]$ vs. Kaon $p$ [GeV/c]
CP asymmetries in $D^0$ and $D^{\pm}$ decays

PRD 89 (2014) 072002
CP asymmetries in $D^0$ and $D^\pm$ decays

[PRD 89 (2014) 072002]

- D-$\bar{D}$ pairs produced in the decay of $\Psi(3770)$ resonance:
  - very clean environment
- Detection asymmetries are estimated using partially reconstruction of D decays
  - fits of missing mass in regions of the kinematic of missing track

No evidence for CPV
Search for CP violation in the decay
$D^+ \rightarrow \pi^- \pi^+ \pi^+$

PLB 728 (2014) 585-595
Search for CP violation in the decay $D^+ \rightarrow \pi^- \pi^+ \pi^+$

(PLB 728 (2014) 585-595)

- Model independent Dalitz Plot analysis to look for local CP asymmetries
  - define a test statistic
    - binned method
      \[ S_{CP}^i = \frac{N_i^+ - \alpha N_i^-}{\sqrt{\alpha (N_i^+ + N_i^-)}} \]
      \[ \alpha = \frac{N^+}{N^-} \]
    - unbinned method (k-nearest neighbour, kNN)
      \[ T = \frac{1}{n_k(N_+ + N_-)} \sum_{i=1}^{N_+ + N_-} \sum_{k=1}^{n_k} I(i, k) \]
  - both $S_{CP}$ and $T$ have well defined distributions in the no-CPV hypothesis
    \[ f(S_{CP}) = G(0,1) \]
    \[ f(T) = G(\mu_T, \sigma_T) \]

$1 \text{ fb}^{-1} @ 7 \text{ TeV}$

- parameter used to remove global asymmetries ($A_p, A_d$ or $A_{CP}$)

- computed in different regions of DP to take into account resonance structure

$\sim 3M D^\pm$
Search for CP violation in the decay $D^+ \rightarrow \pi^- \pi^+ \pi^+$
(PLB 728 (2014) 585-595)

Binned method
- p-value for no-CPV always > 50% for different binning schemes

Unbinned method
- p-value for no-CPV always > 30% in different regions of DP

No evidence of CP violation is observed
Search for CP violation in $D^0 \to \pi^- \pi^+ \pi^0$ decays with the energy test

Search for CP violation in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays with the energy test


• Model independent Dalitz Plot analysis to look for CPV
  – method is unbinned and is based on test statistic $T = \sum_i (T_i + \bar{T}_i)$
  
  \begin{align*}
  T_i &= \frac{1}{2n(n-1)} \sum_{j \neq i}^n \psi_{ij} - \frac{1}{2n^2} \sum_j^n \psi_{ij}, \rightarrow \text{contribute of a single } D^0 \\
  \bar{T}_i &= \frac{1}{2n(n-1)} \sum_{j \neq i}^n \bar{\psi}_{ij} - \frac{1}{2n^2} \sum_j^n \bar{\psi}_{ij}, \rightarrow \text{contribute of a single } \bar{D}^0 
  \end{align*}

$\Psi_{ij}$: gaussian metric decreasing with ij-distance in the DP

\[
T = 0 \rightarrow \text{no-CPV} \\
T > 0 \rightarrow \text{CPV}
\]

Examples from simulation

introducing 2% direct CPV in $\rho^+$ resonance

introducing 1° CPV phase in $\rho^+$ resonance
Search for CP violation in $D^0 \rightarrow \pi^- \pi^+ \pi^0$ decays with the energy test


- $D^0$ flavour determined using $D^*$-prompt
- Two different reconstruction of $\pi^0$
  - merged: worse mass resolution but larger $p_T$
  - resolved: better mass resolution but lower $p_T$
- Reference distribution of $T$ for no-CPV case is obtained using permutation with randomly assigned flavour
  - p-value is the fraction of permutations above nominal $T$ value

Consistent with no-CPV

p-value = $(2.6 \pm 0.5)\%$
Search for direct CPV in $D^+ \rightarrow K_S^0 K^+$ and $D_s^+ \rightarrow K_S^0 \pi^+$ decays

JHEP 10 (2014) 025
Search for direct CPV in $D_{(s)}^+ \rightarrow K_S^0 h^+$

$[\text{JHEP} 10 (2014) 025]$ 

• CPV observable is

$$A_{\text{meas}}^{D_{(s)}^\pm \rightarrow K_S^0 h^\pm} \approx A_{CP}^{D_{(s)}^\pm \rightarrow K_S^0 h^\pm} + A_{\text{prod}}^{D_{(s)}^\pm} + A_{\text{det}}^{h^\pm} + A_{K^0 / \bar{K}^0}$$

• Two sources of asymmetry
  - interaction asymmetry of $K^0 / \bar{K}^0$
  - presence of mixing and CPV in the $K^0 - \bar{K}^0$ system

$$A_{K / \bar{K}} = (+0.07 \pm 0.02)\%$$

• Assuming negligible CPV in CF decays

$$A_{CP}^{D_{(s)}^\pm \rightarrow K_S^0 \pi^\pm} = A_{\text{meas}}^{D_{(s)}^\pm \rightarrow K_S^0 \pi^\pm} - A_{\text{meas}}^{D_{s}^\pm \rightarrow \phi \pi^+} - A_{K^0}$$

$$A_{CP}^{D_{(s)}^\pm \rightarrow K_S^0 K^\pm} = \left[ A_{\text{meas}}^{D_{(s)}^\pm \rightarrow K_S^0 K^\pm} - A_{\text{meas}}^{D_{s}^\pm \rightarrow K_S^0 K^\pm} \right] - \left[ A_{\text{meas}}^{D_{(s)}^\pm \rightarrow K_S^0 \pi^\pm} - A_{\text{meas}}^{D_{s}^\pm \rightarrow \pi^+} \right] - A_{K^0}$$

Detection and production asymmetries cancel in the difference of raw asymmetries
Search for direct CPV in $D_{(s)}^{+} \rightarrow K_{S}^{0} h^{+}$
(JHEP 10 (2014) 025)

- Sample divided by charge and magnet polarity
- Simultaneous fit of all subsamples
- $p_T$ and $\eta$ distributions of $D$ in the various channels are equalized using a weighting procedure

\[ A_{CP}^{D^{\pm} \rightarrow K_{S}^{0} K^{\pm}} = (+0.03 \pm 0.17 \pm 0.14)\% \]
\[ A_{CP}^{D_{s}^{\pm} \rightarrow K_{S}^{0} \pi^{\pm}} = (+0.38 \pm 0.46 \pm 0.17)\% \]

1 fb$^{-1}$ @ 7 TeV + 2 fb$^{-1}$ @ 8 TeV

No evidence of CPV
Search for CP Violation in $D^0 \rightarrow \pi^0 \pi^0$
and $D^0 \rightarrow K_S^0 \pi^0$ decays

[Belle [PRL 112 (2014) 211601]]
Search for CP Violation in $D^0 \rightarrow \pi^0 \pi^0$ and $D^0 \rightarrow K_S^0 \pi^0$ decays

[PRL 112 (2014) 211601]

- Initial flavour of the $D^0$ tagged with $D^*$-prompt
  - introduce detection asymmetry of $\pi^+_S$
  - studied using tagged and untagged samples of $D^0 \rightarrow K \pi^+$ decays as a function of $p_T$ and $\cos \theta$ of $\pi^+_S$

- $A_{FB}$ can be subtracted thanks to its dependence on $\cos \theta^*$

$$A_{CP} = \frac{A_{\text{raw}}^{\cos \theta^*} + A_{\text{raw}}^{-\cos \theta^*}}{2}$$

$$A_{FB} = \frac{A_{\text{raw}}^{\cos \theta^*} - A_{\text{raw}}^{-\cos \theta^*}}{2}$$

- For $D^0 \rightarrow K_S^0 \pi^0$ decays need to take into account
  - $K^0/\bar{K}^0$ interaction asymmetry: $A_{K/\bar{K}} = -0.11\%$ [PRD 84, 111501 (2011)]
  - CPV in $K^0-\bar{K}^0$ mixing: $(-0.339 \pm 0.007)\%$ [PRL 109, 021601 (2012); 109, 119903(E) (2012)]
Search for CP Violation in $D^0 \rightarrow \pi^0\pi^0$ and $D^0 \rightarrow K_S^0\pi^0$ decays

[PRl 112 (2014) 211601]

- Using a luminosity of 996 fb$^{-1}$
  - $\sim 345k \ D^0 \rightarrow \pi^0\pi^0$
  - $\sim 470k \ D^0 \rightarrow K_S^0\pi^0$

- In order to take into account all the corrections to $A_{RAW}$ fits are performed in bins of $(\cos\theta^*, p_T, \cos\theta) \rightarrow 10 \times 7 \times 8$

$$A_{CP}^{\pi^0\pi^0} = (-0.03 \pm 0.64 \pm 0.10)\%$$
$$A_{CP}^{K_S^0\pi^0} = (-0.21 \pm 0.16 \pm 0.07)\%$$

Correcting for $K^0$-mixing
$$A_{CP}^{K_S^0\pi^0} = (+0.12 \pm 0.16 \pm 0.07)\%$$

No evidence for CPV
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

JHEP 07 (2014) 041
Measurement of CP asymmetry in \( D^0 \rightarrow K^-K^+ \) and \( D^0 \rightarrow \pi^-\pi^+ \) decays

[JHEP 07 (2014) 041]

- Use semi-leptonic B decays to tag \( D^0 \) flavour
  - reconstruct \( B \rightarrow D^0 \mu^\pm X \) decays
  - reconstruct \( D^0 \rightarrow K^-K^+ \) and \( D^0 \rightarrow \pi^-\pi^+ \)
  - corrections to \( A_{RAW} \) are \( A_P(B) \) and \( A_D(\mu) \)
- Measuring \( \Delta A_{CP} \) corrections cancel in the difference:
  \[
  \Delta A_{CP} = A_{RAW}(K^+K^-) - A_{RAW}(\pi^+\pi^-) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)
  \]
  - re-weight of events is used to equalize kinematical distributions
  - sample is separated by magnet polarity to further check removal of corrections
- Experimental challenge is to measure single \( A_{CP} \):
  - need to determine corrections
  - help from CF decays where CPV \( \approx 0 \)
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

$A_{RAW}(K^+ K^-) = A_{CP}(K^+ K^-) + A_P(B) + A_D(\mu)$

$A_{CP}(K^- \pi^+) + A_P(B) + A_D(\mu) + A_D(K^- \pi^+) = A_{RAW}(K^- \pi^+)$

$cM(K^- \pi^+) [\text{MeV}/c^2]$
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

$$A_{RAW}(K^+ K^-) = A_{CP}(K^+ K^-) + A_P(B) + A_D(\mu)$$
$$A_{CP}(K^- \pi^+) + A_P(B) + A_D(\mu) + A_D(K^- \pi^+) = A_{RAW}(K^- \pi^+)$$

$$A_{RAW}(D^+ \rightarrow K^- \pi^+ \pi^+) = A_{CP}(D^+ \rightarrow K^- \pi^+ \pi^+) + A_D(K^- \pi^+) + A_P(D^+) + A_D(\pi^+)$$

(c) $D^0 \rightarrow K^- \pi^+$ from $B$ ~9M

(d) Prompt $D^+ \rightarrow K^- \pi^+ \pi^+$ ~40M
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

$$A_{\text{RAW}}(K^+ K^-) = A_{\text{CP}}(K^+ K^-) + A_P(B) + A_D(\mu)$$

$$A_{\text{CP}}(K^- \pi^+) + A_P(B) + A_D(\mu) + A_D(K^- \pi^+) = A_{\text{RAW}}(K^- \pi^+)$$

$$A_{\text{RAW}}(D^+ \rightarrow K^- \pi^+ \pi^+) = A_{\text{CP}}(D^+ \rightarrow K^- \pi^+ \pi^+) + A_D(K^- \pi^+) + A_P(D^+) + A_D(\pi^+)$$

$$A(K_S^0) + A_{\text{CP}}(D^+ \rightarrow K_S^0 \pi^+) + A_P(D^+) + A_D(\pi^+) = A_{\text{RAW}}(D^+ \rightarrow K_S^0 \pi^+)$$

$$A_{\text{CP}}(K^- K^+) = A_{\text{raw}}(K^- K^+) - A_{\text{raw}}(K^- \pi^+) + A_D(K^- \pi^+)$$
Measurement of CP asymmetry in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

Ignoring contribution from indirect CPV

\[ A_{CP}(K^- K^+) = (-0.06 \pm 0.15 \text{ (stat)} \pm 0.10 \text{ (syst)})\% \]
\[ A_{CP}(\pi^- \pi^+) = (-0.20 \pm 0.19 \text{ (stat)} \pm 0.10 \text{ (syst)})\% \]
Direct and indirect CPV in $\Delta A_{CP}$

- In $D^0$ decays one should take into account indirect CPV coming from mixing and interference between mixing and decay
  - $\Delta A_{CP}$ does not measure pure direct CPV
    \[
    \Delta A_{CP} \approx \Delta a_{CP}^{dir} - \frac{\Delta \langle t \rangle}{\tau} A_{\tau}
    \]
    \[
    A_{\tau} = \frac{\tau(D^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(D^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)}
    \]

- Two recent measurements of $A_{\Gamma}$:
  - LHCb [JHEP 04 (2015) 043]:
    - use of $D^0$ from semi-leptonic $B$ decays
  - CDF [PRD 90 (2014) 111103]:
    - use of $D^0$ tagged with $D^*$-prompt
  - Same technique
    - measure $A_{RAW}$ in bins of $t/\tau$
      \[
      A_{\tau}^{CP}(t) \approx A_0 - A_{\tau} \frac{t}{\tau}
      \]
    - $A_0$ contains $A_D$, $A_P$ and $A_{CP}^{dir}$ → no effect on the determination of $A_{\tau}$
    - independence of $A_0$ from decay time is controlled using CF $D^0 \to K^-\pi^+$ decays
Measurements of $A_{\Gamma}$

$9.7 \text{ fb}^{-1}$

$D^0 \rightarrow K^+ K^-$ from $D^*$ ~1.2M

$D^0 \rightarrow \pi^+ \pi^+$ from $D^*$ ~0.6M

$A_{\Gamma}(K^+ K^-) = (-0.19 \pm 0.15 \text{(stat)} \pm 0.04 \text{(syst)})\%$

$A_{\Gamma}(\pi^+ \pi^-) = (-0.01 \pm 0.18 \text{(stat)} \pm 0.03 \text{(syst)})\%$

No evidence of CPV
Measurements of $A_\Gamma$

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

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

No evidence of CPV
Direct and indirect CPV

Data are consistent with no-CPV at 1.8% CL
Conclusions

• Several measurements of time-integrated CPV in charm decays have been presented
  – model independent search for CPV in Dalitz Plot of multibody D decays
    • $D^\pm \rightarrow \pi^-\pi^0\pi^+$, $D^0 \rightarrow \pi^-\pi^+\pi^0$
    • model-dependent measurements will be the next step to extract all the information from resonance structure
  – Measurements of CPV asymmetries in several $D^0$ and $D^\pm$ decays
    • $D^0$ and $D^\pm$ to several modes including $\pi^0$ and $K_S^0$
    • $D^+_S \rightarrow K_S^0\pi^\pm$, $D^- \rightarrow K_S^0K^\pm$
    • $D^0 \rightarrow \pi^0\pi^0$ and $D^0 \rightarrow K_S^0\pi^0$
    • $D^0 \rightarrow K^-K^+$ and $D^0 \rightarrow \pi^-\pi^+$
    • Measurements entered the regime of $O(10^{-3})$ precision
Conclusions

• No evidence of CPV yet...

• More results will arrive in the near future
  – LHCb still have to exploit the full potential of Run1
  – more data will come from Run2 of LHC → LHCb
    trigger rate will double
  – Belle II will start to take data soon
  – for longer term prospects see Umberto Marconi’s
    and Matt Barrett’s talks on Friday