CP-violating triple product asymmetries in Charm decays

Maurizio Martinelli (EPFL) on behalf of the LHCb and BaBar Collaborations
Theoretical Introduction

- CPV and $T$-odd correlations

Search at LHCb

- CPV search using $T$-odd correlations in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays

More observables

- The study of further triple-product correlations has been recently suggested

Search at Babar

- Extraction of TP correlation asymmetries with BaBar data
  
  $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$, $D_{(s)}^+ \rightarrow K^+ K^0_S \pi^+ \pi^-$

Conclusions
Small CKM contribution

- CPV is expected to be small in the charm sector due to small CKM amplitude

New Physics

- May enhance this amplitude through the introduction of new processes and particles

Recently

- Mixing in charm is established within SM expectation
- Experiments have recorded enough statistics to probe CPV with sensitivities approaching $10^{-3}$
- If any NP effect is out there we should start to be able to see it
**CP Violation**

**CPV in decay**

\[ \mathcal{A}_f \equiv \frac{\Gamma(M^- \to f^-) - \Gamma(M^+ \to f^+)}{\Gamma(M^- \to f^-) + \Gamma(M^+ \to f^+)} \]

- **CPV** is measured as the asymmetry between the decay rate of a meson and charge-conjugate state

\[ \mathcal{A}_{f\pm} = - \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\phi_2 - \phi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1) \cos(\phi_2 - \phi_1)} \]

**CPV in mixing**

\[ \frac{q}{p} \neq 1, \quad \mathcal{A}_{SL}(t) \equiv \frac{d\Gamma/dt(M^0_{\text{phys}}(t) \to l^+X) - d\Gamma/dt(M^0_{\text{phys}}(t) \to l^-X)}{d\Gamma/dt(M^0_{\text{phys}}(t) \to l^+X) + d\Gamma/dt(M^0_{\text{phys}}(t) \to l^-X)} \]

- **CPV** measured from the mixing parameters

\[ \mathcal{A}_{SL} = - \left| \frac{\Gamma_{12}}{M_{12}} \right| \sin(\phi_M - \phi_F) \]

**CPV in interference between decay and mixing**

\[ \text{Im}(\lambda_f) \neq 0, \quad \lambda_f \equiv \frac{q}{p} \frac{\mathcal{A}_f}{\mathcal{A}_f}, \quad \mathcal{A}_{f_{CP}}(t) \equiv \frac{\frac{d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP}) - d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP})}{d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP}) + d\Gamma/dt(M^0_{\text{phys}}(t) \to f_{CP})}} \]

- **CPV asymmetry is modified by mixing effects**

\[ \mathcal{A}_{f_{CP}}(t) = \eta_f \sin(\phi_M + 2\phi_f) \sin(\Delta m t) \]

\( \phi \): weak phases, from CKM  
\( \delta \): unitarity (strong) phases
T-odd Observables

A different point of view

• Describe invariant matrix element in the most general way (quasi two-body) $B(p) \to V_1(k, \epsilon_1)V_2(q, \epsilon_2)$

\[
M = a\epsilon_1 \cdot \epsilon_2 + \frac{b}{m_1 m_2} (p \cdot \epsilon_1)(p \cdot \epsilon_2) + \frac{c}{m_1 m_2} \epsilon_\alpha \mu \nu \epsilon_1 \alpha \epsilon_2 \beta k_\mu p_\nu
\]

\[
a = \sum |a_j| e^{i(\delta_{sj} + \phi_{sj})}
\]

\[
b = \sum |b_j| e^{i(\delta_{dj} + \phi_{dj})}
\]

\[
c = \sum |c_j| e^{i(\delta_{pj} + \phi_{pj})}
\]

\[
\bar{a} = \sum |a_j| e^{i(\delta_{sj} - \phi_{sj})}
\]

\[
\bar{b} = \sum |b_j| e^{i(\delta_{dj} - \phi_{dj})}
\]

\[
\bar{c} = \sum |c_j| e^{i(\delta_{pj} - \phi_{pj})}
\]

• A triple-product correlation arises in $|M|^2$ from terms involving the $c$ amplitude (Im[ac*], Im[bc*]) wrt $\vec{k} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2)$

\[
A_B = \frac{\Gamma(k \cdot \epsilon_1 \times \epsilon_2 > 0) - \Gamma(k \cdot \epsilon_1 \times \epsilon_2 < 0)}{N_B}
\]

\[
\approx \Im(ac^*) = |ac| e^{i(\delta_s - \delta_p)} e^{i(\phi_s - \phi_p)} = |ac| \sin(\Delta \delta + \Delta \phi)
\]

• The same observable on the charge-conjugate decay gives

\[
A_B \approx |ac| e^{i(\delta_s - \delta_p)} e^{-i(\phi_s - \phi_p)} = |ac| \sin(\Delta \delta - \Delta \phi)
\]

• That allows the definition of the $CPV$ observable

\[
a_{CP}^{T=odd} = A_B + \bar{A}_B \approx \cos \Delta \delta \sin \Delta \phi
\]
Comparison to Direct CPV

They are complementary

- The only difference is in the unitarity phases that enter differently in the game

\[ a_{CP} \propto \sin \Delta \delta \sin \Delta \phi \]
\[ a_{CP}^{T-odd} \propto \cos \Delta \delta \sin \Delta \phi \] (*)

- \( a_{CP} \) is more sensitive to CPV when the difference in the strong phases is large

- \( a_{CP}^{T-odd} \) is more sensitive to CPV when the difference in the strong phases between the interfering amplitudes is small

- Datta and London demonstrated that a TP asymmetry can be also built with interference between decay and mixing, but it is proportional to \( \sin \Delta \delta \) as well.

(*) **Caveat:** in \( a_{CP} \) the two phases are from different diagrams, in \( a_{CP}^{Todd} \) from different spin contributions
Defining a $T$-odd observable

- One needs at least 3 independent momentum or spin variables

**4-body decay**

\[
C_T = (\vec{p}_1 \times \vec{p}_2) \cdot \vec{p}_3
\]

- Momenta can be also used to define angles

\[
\sin \phi = (\hat{n}_{ab} \times \hat{n}_{cd}) \cdot \hat{z}
\]
T-odd Correlation Asymmetry

Asymmetries

- Two asymmetries are measured separately on the particle and charge-conjugate decays

\[
A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma}
\]

\[
\bar{A}_T = \frac{\bar{\Gamma}(-\bar{C}_T > 0) - \bar{\Gamma}(-\bar{C}_T < 0)}{\bar{\Gamma}}
\]

- The CP-violating asymmetry is

\[
a_{CP}^{T-odd} = \frac{1}{2}(A_T - \bar{A}_T)
\]
Charm Mesons Decays

Four-body decays

- So far: \( D^0 \rightarrow K^+ K^- \pi^+ \pi^- \), \( D^+ \rightarrow K^+ K^0_S \pi^+ \pi^- \), \( D_s^+ \rightarrow K^+ K^0_S \pi^+ \pi^- \)

T-odd observable

- \( C_T = \vec{p}(K^+) \cdot \vec{p}(\pi^+) \times \vec{p}(\pi^-) \)

Analysis

- Split data sample in 4 depending on \( D^0 \) flavour and \( C_T \) sign
- Extract the number of signal events for each sample
- Calculate the asymmetry

\[
a_{CP}^{T-\text{odd}} = \frac{1}{2} \left( A_T - \overline{A}_T \right)
\]
Results From Previous Experiments

Used prompt $D^0$ and $D_{(s)}^+$ decays

- **FOCUS (2005) $N_{ev} \sim 1k$**
  
  \[
  a_{CP}^{T - \text{odd}}(D^0) = (1.0 \pm 5.7\,(\text{stat}) \pm 3.7\,(\text{syst}))\% \\
  a_{CP}^{T - \text{odd}}(D^+ ) = (2.3 \pm 6.2\,(\text{stat}) \pm 2.2\,(\text{syst}))\% \\
  a_{CP}^{T - \text{odd}}(D_s^+ ) = ( -3.6 \pm 6.7\,(\text{stat}) \pm 2.3\,(\text{syst}))\%
  \]


- **BaBar (2010-2011) $N_{ev} \sim 50k$**
  
  \[
  a_{CP}^{T - \text{odd}}(D^0) = (1.0 \pm 5.1\,(\text{stat}) \pm 4.4\,(\text{syst})) \times 10^{-3} \\
  a_{CP}^{T - \text{odd}}(D^+ ) = (-12.0 \pm 10.0\,(\text{stat}) \pm 4.6\,(\text{syst})) \times 10^{-3} \\
  a_{CP}^{T - \text{odd}}(D_s^+ ) = (-13.6 \pm 7.7\,(\text{stat}) \pm 3.4\,(\text{syst})) \times 10^{-3}
  \]


- **BaBar provided significant statistical improvement (x10)**
Results From LHCb - $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

Semileptonic B decay

- $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ from semileptonic B decays, tagged from muon charge
  $B \rightarrow D^0 \mu^- X$, $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$
- Clean sample

Data Sample

- 2011+2012: $3\text{fb}^{-1}$

Fit Model

- Samples simultaneously fit to a model of two Gaussian distributions over an exponential shape
- Asymmetry parameters extracted from the fit

$B \rightarrow D^0 \mu^- X$, $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

LHCb Results

$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

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3fb$^{-1}$: $N_{ev} \sim 170k$
Three Measurements

1. Integrated

\[ a_{CP}^{T-\text{odd}}(D^0) = (1.8 \pm 2.9\,\text{(stat)} \pm 0.4\,\text{(syst)}) \times 10^{-3} \]

2. Bins of phase-space

No significant deviation from 0 observed

\[ CP \text{ conservation tested with } P(\chi^2)=74\% \]

3. Bins of proper time

No significant deviation from 0 observed

\[ CP \text{ conservation tested with } P(\chi^2)=83\% \]
Results From LHCb - $A_T$ and $\bar{A}_T$

**FSI Effects?**

- It’s possible that FSI are producing effects in all the three measurements
- Significant differences in bins of phase space
- Average consistent wrt $D^0$ decay time
- Wide spectrum of resonances and rescattering among the final state particles

\[ A_T(D^0) = (-71.8 \pm 4.1\text{(stat)} \pm 1.3\text{(syst)}) \times 10^{-3} \]
\[ \bar{A}_T(D^0) = (-75.5 \pm 4.1\text{(stat)} \pm 1.2\text{(syst)}) \times 10^{-3} \]
A Rich Resonant Structure

Resonant structure in $D^0 \rightarrow K^+K^-\pi^+\pi^-$

- Clear evidence for $\phi$ and $\rho$ resonances
- Significant difference in the distributions vs $C_T$
- Visible effects in angular variables as well
- $D^0 \rightarrow K^0_S K^+K^-$ removed by $\pi^+\pi^-$ invariant mass cut

hep-ex/1408.1299, submitted to JHEP
An Almost Systematic Free Measurement

Reconstruction Efficiency ☺
- Does not affect at all the result: $A_T$ and $\bar{A}_T$ asymmetries are calculated separately on the same final state.

Particle Identification ☺
- The same considerations apply to particle identification.

$C_T$ Resolution ✝
- Estimated accurately from Monte Carlo, almost cancels in $a_{CP}^{T_{odd}}$.

Peaking Backgrounds under $D^0/\bar{D}^0$ signal ✝
- Any contamination affects the asymmetry as $A \rightarrow A(1 - f) + f A^d$.
  
  $f$ - contamination fraction; $A^d$ - asymmetry of the contamination sample.

Flavour Mistag ✝
- Considering the events with flavour mistag as a contamination $a_{CP}^{T_{odd}} \rightarrow a_{CP}^{T_{odd}} - \Delta\omega/2(A_T + \bar{A}_T)$.
  
  $\Delta\omega = \omega^+ - \omega^-$ — difference among the mistag probabilities, measured from control samples $B \rightarrow D^+ \mu^X$, $(D^+ \rightarrow D^0\pi^+, D^0 \rightarrow K^+\pi^+\pi^-)$; $B \rightarrow D^0 \mu^X$ ($D^0 \rightarrow K^-\pi^+\pi^+\pi^-$).

Detector bias ✝
- Conservative estimate from control sample of $CF D^0 \rightarrow K^-\pi^+\pi^+\pi^-$. 

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**Systematic uncertainty estimates**

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\Delta A_T(%)$</th>
<th>$\Delta \bar{A}_T(%)$</th>
<th>$\Delta a_{CP}^{T_{odd}}(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt background</td>
<td>±0.09</td>
<td>±0.08</td>
<td>±0.00</td>
</tr>
<tr>
<td>Detector bias</td>
<td>±0.04</td>
<td>±0.04</td>
<td>±0.04</td>
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<tr>
<td>$C_T$ resolution</td>
<td>±0.02</td>
<td>±0.03</td>
<td>±0.01</td>
</tr>
<tr>
<td>Fit Model</td>
<td>±0.01</td>
<td>±0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>Flavor misidentification</td>
<td>±0.08</td>
<td>±0.07</td>
<td>±0.00</td>
</tr>
<tr>
<td>Total</td>
<td>±0.13</td>
<td>±0.12</td>
<td>±0.04</td>
</tr>
</tbody>
</table>

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Three approaches

• *CPV* is searched for in \( D^0 \rightarrow K^+K^-\pi^+\pi^- \) using:
  1. A measurement integrated over the phase space
  2. Measurements in different regions of the phase space
  3. Measurements as a function of the \( D^0 \) decay time

Results

• No *CPV* found
• Nevertheless, a lot of interesting information in the phase space of the decay, with local *A_T* asymmetries up to 30%

These results are interpreted as possible effects of FSI produced by the rich resonant structure of the decay
• \( a_{CP}^{Todd} \) measured for the first time in bins of \( D^0 \) decay time

Remarks

• Systematic uncertainties are found to be very small (as expected) in these observables
  High statistics control samples, toy studies
More Asymmetries

Theoretical reinterpretation

• A recent paper by A. Bevan reinterprets the asymmetries outlined before and suggests describing them as $C$, $P$, and $CP$ asymmetries

• $A_T$ interpreted as a $P$-odd ($A_P$) rather than $T$-odd observable since time-reversal test is not possible

$$P(C_T) = P(p_{K+} \cdot p_{\pi^+} \times p_{\pi^-}) = -p_{K+} \cdot p_{\pi^+} \times p_{\pi^-} = -C_T$$

• Assuming

$$\Gamma_+ = \Gamma(C_T > 0) \quad \Gamma_+ = \Gamma(\overline{C_T} > 0)$$

$$\Gamma_- = \Gamma(C_T < 0) \quad \Gamma_- = \Gamma(\overline{C_T} < 0)$$

• One gets

$$A_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}; \quad \overline{A}_P = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}$$

• Considering that $C(A_P) = \overline{A}_P$ and $CP(A_P) = -\overline{A}_P$ the following asymmetries testing $C$ and $CP$ can be extracted

$$a^P_C = \frac{1}{2} (A_P - \overline{A}_P) \quad a^P_{CP} = \frac{1}{2} (A_P + \overline{A}_P) = a^{T-\text{odd}}_{CP}$$
Same exercise for C operator

- One observes that $C(C_T) = \bar{C}_T$

\[
C(C_T) = C(\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) = \vec{p}_{K^-} \cdot \vec{p}_{\pi^-} \times \vec{p}_{\pi^+} = \bar{C}_T
\]

\[
A_C = \frac{\Gamma_- - \Gamma_-}{\Gamma_- + \Gamma_-}; \quad \bar{A}_C = \frac{\Gamma_+ - \Gamma_+}{\Gamma_+ + \Gamma_-}
\]

\[
P(A_C) = \bar{A}_C
\]

\[
a_P^C = \frac{1}{2} (A_C - \bar{A}_C) \quad a_{CP}^C = \frac{1}{2} (A_C + \bar{A}_C)
\]

...and for CP

\[
CP(C_T) = CP(\vec{p}_{K^+} \cdot \vec{p}_{\pi^+} \times \vec{p}_{\pi^-}) = -\vec{p}_{K^-} \cdot \vec{p}_{\pi^-} \times \vec{p}_{\pi^+} = -\bar{C}_T
\]

\[
A_{CP} = \frac{\Gamma_+ - \Gamma_-}{\Gamma_+ + \Gamma_-}; \quad \bar{A}_{CP} = \frac{\Gamma_- - \Gamma_+}{\Gamma_- + \Gamma_+}
\]

\[
P(A_{CP}) = \bar{A}_{CP}
\]

\[
a_P^{CP} = \frac{1}{2} (A_{CP} - \bar{A}_{CP}) \quad a_{CP}^{CP} = \frac{1}{2} (A_{CP} + \bar{A}_{CP}) \quad C(A_{CP}) = -\bar{A}_{CP}
\]
Reanalysis of BaBar data

Extraction of the asymmetries

• BaBar data from $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$, $D_{(s)}^+ \rightarrow K^0 \pi^+ \pi^+ \pi^-$ used to extract all the asymmetries

  Lees et al., Phys. Rev. D84 (2011) 031103(R)

• $A_T$ and $\bar{A}_T$ translated to yields

  $$\Gamma_+ = N_{D^0} \left( 1 + A_P \right) \quad \bar{\Gamma}_+ = N_{\bar{D}^0} \left( 1 - \bar{A}_P \right)$$
  $$\Gamma_- = N_{D^0} \left( 1 - A_P \right) \quad \bar{\Gamma}_- = N_{\bar{D}^0} \left( 1 + \bar{A}_P \right)$$

• Systematic uncertainties propagated by assuming them to be Gaussian-distributed
The 2010 analysis

- Prompt $D^+\to D^0\pi^+$ decays
- 2D fit to $m(K^+K^-\pi^+\pi^-)$ and
  $\Delta m = m(K^+K^-\pi^+\pi^-\pi^+) - m(K^+K^-\pi^+\pi^-)$
- $N_{ev} = 47k$
- Most important systematic uncertainties from particle identification and selection criteria in general

Asymmetries:

$A_T(D^0) = (-68.5 \pm 7.3_{stat} \pm 5.8_{syst}) \times 10^{-3}$

$\bar{A}_T(D^0) = (-70.5 \pm 7.3_{stat} \pm 3.9_{syst}) \times 10^{-3}$

$a_T^{odd}(D^0) = (1.0 \pm 5.1_{stat} \pm 4.4_{syst}) \times 10^{-3}$
Analysis of BaBar $D_{(s)}^+ \rightarrow K^0_S K^+ \pi^+ \pi^-$

Original analysis

- About 20(30)$k D_{(s)}^+$ decays reconstructed
- One-dimensional fit
- Main systematics from PID and selection criteria

$A_T(D^+) = (+11.2 \pm 14.1_{\text{stat}} \pm 5.7_{\text{syst}}) \times 10^{-3}$

$\bar{A}_T(D^-) = (+35.1 \pm 14.3_{\text{stat}} \pm 7.2_{\text{syst}}) \times 10^{-3}$

$A_T(D_s^+) = (-99.2 \pm 10.7_{\text{stat}} \pm 8.3_{\text{syst}}) \times 10^{-3}$

$\bar{A}_T(D_s^-) = (-72.1 \pm 10.9_{\text{stat}} \pm 10.7_{\text{syst}}) \times 10^{-3}$

$a_{CP}^{T-\text{odd}}(D^+) = (-12.0 \pm 10.0_{\text{stat}} \pm 4.6_{\text{syst}}) \times 10^{-3}$

$a_{CP}^{T-\text{odd}}(D_s^+) = (-13.6 \pm 7.7_{\text{stat}} \pm 3.4_{\text{syst}}) \times 10^{-3}$
Event Rates

- Event rates exacted from the fit results on the asymmetries

\[
\begin{array}{|c|ccc|}
\hline
\text{Event rate} & D^0 & D^+ & D_s^+ \\
\hline
\Gamma_+ & 10974 \pm 117 & 5406 \pm 136 & 6792 \pm 135 \\
\Gamma_- & 12587 \pm 125 & 5287 \pm 131 & 8287 \pm 153 \\
\tilde{\Gamma}_+ & 12380 \pm 124 & 5073 \pm 104 & 7886 \pm 121 \\
\tilde{\Gamma}_- & 10749 \pm 116 & 5443 \pm 111 & 6826 \pm 107 \\
\hline
\end{array}
\]

Extraction of the systematic uncertainties

- Systematic uncertainties assumed to be Gaussian
- The uncertainty on the event rates are then extracted from the ones on the asymmetries
- In addition three other sources of uncertainty have been considered:
  - Slow-pion tag asymmetry (for \(A_C\) and \(A_{CP}\) - negligible) \([D^0]\]
  - Neutral Kaon regeneration and interference (5-6x10^{-4} from \(D^+ \rightarrow K^0_s h^+\)) \([D(s)^+]\]
  - \(K^+/K^-\) interaction with detector material (affects \(A_C\) and \(A_{CP}\), 5x10^{-3}) \([D(s)^+]\]
Results of the Reanalysis

All the asymmetries

- Possible effects of FSI
- Observation of $P$ and $C$ violation
- No CPV

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>$D^0 \rightarrow K^+ K^- \pi^+ \pi^-$</th>
<th>$D^+ \rightarrow K^{0}_S K^+ \pi^+ \pi^-$</th>
<th>$D^+_s \rightarrow K^{0}_S K^+ \pi^+ \pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{FSI}$</td>
<td>$A_P$</td>
<td>$-0.069 \pm 0.007 \pm 0.006 (7.5)$</td>
<td>$0.011 \pm 0.014 \pm 0.006 (0.7)$</td>
</tr>
<tr>
<td></td>
<td>$A_P$</td>
<td>$0.071 \pm 0.007 \pm 0.004 (8.8)$</td>
<td>$-0.035 \pm 0.014 \pm 0.007 (2.2)$</td>
</tr>
<tr>
<td>$C_{FSI}$</td>
<td>$a^P_C$</td>
<td>$-0.070 \pm 0.005 \pm 0.001 (13.5)$</td>
<td>$0.023 \pm 0.011 \pm 0.002 (2.1)$</td>
</tr>
<tr>
<td></td>
<td>$a^P_C$</td>
<td>$0.001 \pm 0.005 \pm 0.004 (0.2)$</td>
<td>$-0.012 \pm 0.010 \pm 0.005 (1.1)$</td>
</tr>
<tr>
<td>$C$</td>
<td>$A_C$</td>
<td>$0.060 \pm 0.007 \pm 0.001 (8.3)$</td>
<td>$-0.026 \pm 0.016 \pm 0.005 (1.6)$</td>
</tr>
<tr>
<td></td>
<td>$A_C$</td>
<td>$-0.079 \pm 0.007 \pm 0.001 (10.8)$</td>
<td>$0.020 \pm 0.016 \pm 0.005 (1.2)$</td>
</tr>
<tr>
<td>$P$</td>
<td>$a^P_P$</td>
<td>$0.070 \pm 0.005 \pm 0.001 (13.5)$</td>
<td>$-0.023 \pm 0.011 \pm 0.002 (2.1)$</td>
</tr>
<tr>
<td></td>
<td>$a^P_P$</td>
<td>$-0.009 \pm 0.005 \pm 0.000 (1.8)$</td>
<td>$-0.004 \pm 0.011 \pm 0.010 (0.3)$</td>
</tr>
<tr>
<td>$ACP$</td>
<td>$A_{CP}$</td>
<td>$-0.008 \pm 0.007 \pm 0.004 (1.0)$</td>
<td>$-0.016 \pm 0.016 \pm 0.008 (0.9)$</td>
</tr>
<tr>
<td></td>
<td>$A_{CP}$</td>
<td>$-0.010 \pm 0.008 \pm 0.004 (1.1)$</td>
<td>$0.008 \pm 0.016 \pm 0.008 (0.5)$</td>
</tr>
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<td>$a^P_{CP}$</td>
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<td>$-0.004 \pm 0.011 \pm 0.010 (0.3)$</td>
</tr>
</tbody>
</table>
Tests of $C$, $P$ and $CP$ violation

- Exploited all the information from $T$-odd correlations in 4-body $D_{(s)}$ decays
- $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ (CS), $D^+ \rightarrow K^+ K^0_S \pi^+ \pi^-$ (CS), $D_{s}^+ \rightarrow K^+ K^0_S \pi^+ \pi^-$ (CF) decays are studied
- No evidence of $CP$ violation from the tests performed
- No evidence of $C$ or $P$ violation from the tests performed on $D^+$
- Significant deviation from 0 is found for some tests in $D^0$ and $D_{s}^+$
- These results are interpreted as observation of $C$ and $P$ violation in $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ and $D_{s}^+ \rightarrow K^+ K^0_S \pi^+ \pi^-$ decays
Conclusions

Alternative and Complementary Tests

- Searches for CPV through asymmetries in $T$-odd moments are alternative and complementary to “standard” CPV measurements
- $T$-odd moments can be used for studying $P$ and $C$ symmetries as well
- Applicable to many possible particle decays

Low Systematics

- Previous analysis have demonstrated that the systematic uncertainties are very small

Outlook

- Given the very low systematic uncertainties, such measurements could become extremely competitive at LHCb (10fb$^{-1}$) or future experiments (Belle-II, LHCb Upgrade,...)