Searches for CPV in $D^0$ decays at LHCb

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Outline

• Physics motivations
• Time-integrated CPV in two body decays
  • $A_{CP}$ in $D^0 \rightarrow K^+K^-$ \textcolor{red}{New for ICHEP}
• Time-integrated CPV in multi-body decays
  • $D^0 \rightarrow \pi^+\pi^+\pi^-\pi^-$ \textcolor{red}{New for CHARM}
• Summary & conclusions
Physics motivations

- $CP$ violation found in kaon and $B$ sectors, **not in charm**
- Charm hadron is the **only up-type sector** that could search for $CP$ violation
- $CP$ violation in charm
  - Expected to be $\sim 10^{-3}$ by Standard Model
  - Interfering tree and penguin amplitudes
  - **New physics contributions may enhance $CPV$ up to $\sim 10^{-2}$** *
- There are two ways to $CP$ violation
  - In decay amplitude (time-integrated) ← this talk
  - In mixing or interference (time-dependent) ← see S. Reichert and P. Marino’s talks

**$D^0$ tagging**

- To get the initial flavour of $D^0$, two techniques are used:
  - $D^{*+} \rightarrow D^0 \pi^+$, pion tagged
  - $B^- \rightarrow D^0 \mu^- X$, muon tagged
Measurement of $CP$ asymmetry in $D^0 \rightarrow K^- K^+$ decays

LHCb-PAPER-2016-035 (in preparation)
\[ A_{CP}(D^0 \rightarrow K^-K^+) \] Method

- Define \[ A_{raw}(D^0 \rightarrow f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow \bar{f})}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow \bar{f})} \]

- Measure \[ A_{CP}(D^0 \rightarrow K^-K^+) \], using pion tagged \( D^{*+} \rightarrow D^0 \pi_s^+ \)

\[ A_{CP}(D^0 \rightarrow K^-K^+) = A_{raw}(D^0 \rightarrow K^-K^+) - A_{prod}(D^{*+}) - A_{det}(\pi_s^+) \]

- Eliminate detection / production asymmetries using control channels

- \( K^0 \) asymmetry determined using known material interaction asymmetry
Signal, control samples and results

Samples are weighted to cancel production and detection asymmetries

Extract yields with binned maximum likelihood fit to $\delta m$ in $D^0$ mass region for $D^*$ modes, or $m(D^*)$

Result:

$$A_{CP}^{\pi-tag}(K^-K^+) = [0.14 \pm 0.15(stat) \pm 0.10(syst)]\%$$
Combination with previous results

\[ A_{CP}^{\pi-\text{tag}}(K^-K^+) = [0.14 \pm 0.15(\text{stat}) \pm 0.10(\text{syst})] \%
\]

Combined with pion tagged \( \Delta A_{CP} \) measurement [PRL 116.191601]

\[ \Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \]
\[ A_{CP}^{\pi-\text{tag}}(\pi^-\pi^+) = [0.24 \pm 0.15(\text{stat}) \pm 0.11(\text{syst})] \%
\]

Combined with muon tagged measurement [JHEP (2014) 2014: 41]

\[ A_{CP}^{\text{comb}}(K^-K^+) = [0.04 \pm 0.12(\text{stat}) \pm 0.10(\text{syst})] \%
\]
\[ A_{CP}^{\text{comb}}(\pi^-\pi^+) = [0.07 \pm 0.14(\text{stat}) \pm 0.11(\text{syst})] \%
\]

Results consistent with no CPV

See E.Gersabeck’s poster!
Search for \( CP \) asymmetry in \( D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^- \) decays

LHCb-PAPER-2016-044 (in preparation)
CPV in $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$

- Multi-body decays
  - Rich resonant structures in decay phase space
    - Variation of strong phase difference among the Dalitz plot may enhance local CPV sensitivity
- Four-body decays CPV
  - Standard $P$-parity-even observables compare $D^0 - \bar{D}^0$
  - Novel $P$-parity–odd observables
- Analysis method: energy test
  - Model-independent, unbinned method to search for local CPV in the decay phase space
Signal sample

- Pion tagged $D^0$ decays
  - $D^{*+} \rightarrow D^0 \pi_s^+$
- ~1M signal candidates
- Purity ~96%
- Use all LHCb Run 1 sample
  - 2011+2012

- Previous LHCb $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ analysis using 2011 data, with binned approach, and $P$-even observables [PLB726 (2013) 623]
Energy test

- Compare two distributions statistically
- Idea comes from the calculation of electric potential energy

$+q$ and $-q$ equally distributed, electric potential energy $= 0$
Energy test

• Compare two distributions statistically
• Idea comes from the calculation of electric potential energy

$+q$ and $-q$ equally distributed, electric potential energy $= 0$

$+q$ and $-q$ distributions different, electric potential energy $> 0$
Energy test

System → phase space
+q /−q → opposite flavoured decays

\[ \psi(d_{ij}) = e^{-d_{ij}/2\delta^2} : \text{interaction potential} \]

\( n, \bar{n} : \text{number of } D^0, \bar{D}^0 \text{ candidates} \)

\( d_{ij} : \text{distance in phase space} \)

Test statistic: \( T = \frac{1}{n(n-1)} \sum_{i,j>i}^n \psi(d_{ij}) + \frac{1}{n(n-1)} \sum_{i,j>i}^\bar{n} \psi(d_{ij}) - \frac{1}{nn} \sum_{i,j}^{n,\bar{n}} \psi(d_{ij}) \)
Energy test

- Compare T-value from tested sample ($T_0$) with T-values from no-CPV samples
- No-CPV sample from permutation of data: randomly assign flavour tags
- $p$-value: fraction of permutation T-values above $T_0$

Large $p$-value, no-CPV
Energy test

- Compare T-value from tested sample ($T_0$) with T-values from no-CPV samples
- No-CPV sample from permutation of data: randomly assign flavour tags
- $p$-value: fraction of permutation T-values above $T_0$

Small $p$-value, evidence of CPV!
Energy test

• First application in LHCb $D^0 \rightarrow \pi^- \pi^+ \pi^0$ analysis
  
  PLB740 (2015) 158-167

• This time, extend method to four body decays
New $P$-odd observables

- Standard test compare $D^0 - \bar{D}^0$, sensitive to only $P$-parity-even
- In decays to four or more pseudo-scalars, there is the possibility of using $P$-parity-odd observables for $CP$ violation searches
- Four-body-decay kinematics cannot be described unambiguously using only invariant-mass-squared variables, as these are all parity even
- In $D^0 \rightarrow \pi^+ \pi^- \pi^+ \pi^-$ decay, there is $P$-odd amplitude
- Introduce triple product $C_T$ as parity sensitive variable

$$C_T = \vec{p}(\pi_3) \cdot \left[ \vec{p}(\pi_1) \times \vec{p}(\pi_2) \right]$$

$$CP(C_T) = -C(C_T) = -\bar{C}_T$$
New $P$-odd observables

- The total sample could be divided into four sub-samples according to the particle/antiparticle flavour and the triple product sign:

- Asymmetries may be measured in the $C_T$ regions using the number of events populating the four samples

$$A_{CP}(C_T > 0) = \frac{N(I) - N(III)}{N(I) + N(III)}, \quad A_{CP}(C_T < 0) = \frac{N(II) - N(IV)}{N(II) + N(IV)}$$
New $P$-odd observables

- $CP$ asymmetries can be extracted from these samples that are $P$-even or $P$-odd simply by adding or subtracting the asymmetries measured in $C_T$ regions:

\[ A_{CP}^{P-even} = \frac{A_{CP}(C_T > 0) + A_{CP}(C_T < 0)}{2}, \quad A_{CP}^{P-odd} = \frac{A_{CP}(C_T > 0) - A_{CP}(C_T < 0)}{2} \]

- $P$-even : I+II vs. III+IV
  - Integral over $C_T$, not sensitive to $P$-odd amplitude

- $P$-odd : I+IV vs. II+III
  - Mix of flavours, $P$-even contribution cancels out
Sensitivity tests with Monte Carlo

- Performed for both $P$-even and $P$-odd tests
- Insert $CP$ violation to simulated samples*, apply energy test, determine the sensitivity
- Visualise significance of asymmetries by assigning per-event T-values
- Highlight those $>1,2,3\sigma$ positive in red, negative in blue

<table>
<thead>
<tr>
<th>$R(\Delta A, \Delta \phi)$</th>
<th>$p$-value (fit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_1 \rightarrow \rho^0\pi$ (S) (5%, 0°)</td>
<td>$2.6^{+3.4}_{-1.7} \times 10^{-4}$</td>
</tr>
<tr>
<td>$a_1 \rightarrow \rho^0\pi$ (S) (0%, 3°)</td>
<td>$1.2^{+3.6}_{-1.2} \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho^0\rho^0$ (D) (5%, 0°)</td>
<td>$3.8^{+2.9}_{-1.9} \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^0\rho^0$ (D) (0%, 4°)</td>
<td>$9.6^{+2.4}_{-7.2} \times 10^{-6}$</td>
</tr>
<tr>
<td>$\rho^0\rho^0$ (P) (4%, 0°)</td>
<td>$3.0^{+1.2}_{-0.9} \times 10^{-3}$</td>
</tr>
<tr>
<td>$\rho^0\rho^0$ (P) (0%, 3°)</td>
<td>$9.8^{+4.4}_{-3.8} \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Example: $3°$ phase difference in $D^0 \rightarrow a_1(1260)^+\pi$ Amplitude

(P-even test)

*Prelim. amplitude model from CLEO-c measurement, see P. D’Argent’s talk
Detection / tracking / production asymmetries

- Cancellations occur due to method
- Verified with a control sample of Cabibbo-favoured $D^0 \rightarrow K^{-}\pi^+\pi^+\pi^-$ decays
  - Split into ten sub-samples equal in size to signal mode
  - Sensitive with neither $P$-even nor $P$-odd tests
- $p$-value distributions for reference sample

![Graphs showing $p$-value distributions for LHCb preliminary $P$-even and $P$-odd tests.](image)
Results (Preliminary)

$LHCb$ preliminary

$P$-even
$p$-value: $(4.3\pm0.6)\%$
$2.0\sigma$

$P$-odd
$p$-value: $(0.6\pm0.2)\%$
$2.8\sigma$

$P$-odd test only marginally consistent with no-CPV hypothesis
Conclusions

- The LHCb has performed very well in Run 1 (2011+2012, 3/fb)
- LHCb makes many interesting charm measurements, today:
  - Measurement of \( CP \) asymmetry in \( D^0 \rightarrow K^-K^+ \) decays
    - LHCb-PAPER-2016-035 (in preparation)
    - \( A_{\text{CP}}^{\pi^{-}\text{tag}}(K^-K^+) = [0.14 \pm 0.15(\text{stat}) \pm 0.10(\text{syst})]\% \)
  - Search for \( CP \) asymmetry in \( D^0 \rightarrow \pi^+\pi^-\pi^+\pi^- \) decays
    - LHCb-PAPER-2016-044 (in preparation)
    - \( \rho \)-value=2.0\( \sigma \) for \( P \)-even test, \( \rho \)-value=2.8\( \sigma \) for \( P \)-odd test
    - \( P \)-odd test only marginally consistent with no \( CPV \)
    - Will repeat analysis with Run 2 data

Future:

- LHC is running very efficiently
- Data are being recorded (Run 2): 2015-18 > 8/fb at \( \sqrt{s}=13 \) TeV
- Many new and updated results will come soon!
Backup
List of LHCb $D^0$ direct CPV paper

- Measurement of the difference of time-integrated CP asymmetries in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays  
  *Phys. Rev. Lett. 116 (2016) 191601*
- Measurement of the time-integrated CP asymmetry in $D^0 \to K_S^0K_S^0$ decays  
  *JHEP 10 (2015) 055*
- Search for CP violation in $D^0 \to \pi^-\pi^+\pi^0$ decays with the energy test  
- Search for CP violation using T-odd correlations in $D^0 \to K^+K^-\pi^+\pi^-$ decays  
  *JHEP 10 (2014) 005*
- Measurement of CP asymmetry in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays  
  *JHEP 07 (2014) 041*
- Model-independent search for CP violation in $D^0 \to K^-K^+\pi^-\pi^+$ and $D^0 \to \pi^-\pi^+\pi^+\pi^-$ decays  
- Search for direct CP violation in $D^0 \to h^-h^+$ modes using semileptonic B decays  
  *Phys. Lett. B723 (2013) 33*
- Evidence for CP violation in time-integrated $D^0 \to h^-h^+$ decay rates  
Phase space for $4\pi$ energy test

- Four-body decays have 5 degrees of freedom
- 6 two-body invariant masses, 4 of them are physically meaningful
- 4 three-body invariant masses

- Fix the charge order of the four pions: $1234=+---$
- $m^2(\pi^+\pi^-)$: $s_{12}$ $s_{14}$ $s_{23}$ $s_{34}$ are all possible combinations
- $m^2(\pi^+\pi^-\pi^+)$: $s_{123}$ $s_{134}$
- $m^2(\pi^+\pi^-\pi^-)$: $s_{124}$ $s_{234}$
- Find the largest $m^2(\pi^+\pi^-)$, and let it be $s_{34}$, the order is fully determined
- The dominating resonances are not with very high mass, so reject highest two-body mass combinations $s_{34}$ and three-body combinations including it: $s_{134}$, $s_{234}$
- 5 coordinates left: $s_{12}$ $s_{14}$ $s_{23}$ $s_{123}$ $s_{124}$
P-odd MC vs data

**P-odd**

Monte Carlo

\[ p\text{-value: 9.8X10^{-4}} \]

\[ P\text{-odd data} \]

\[ p\text{-value: (0.6\pm0.2)\% 2.8\sigma} \]
Reference sample $p$-value ranges

$P$-even: from 3% to 87%
$P$-odd: from 8% to 74%
Results with other metric parameters

\[ \psi(d_{ij}) = e^{-d_{ij}/2\delta^2} \]

- Metric parameter \( \delta \) affects the interaction range in phase space, plays the role of bin size in binned approaches.
- Default \( \delta \) was chosen to be the 0.5 GeV\(^2/c^4\) before unblinding of data. This is the value that gives best sensitivity in most of the simulated CPV scenarios.

- Results with other \( \delta \)'s:
  - \( \delta = 0.3 \), \( P \)-even \( p \)-value = (1.1 \( \pm \) 0.4)\%
  - \( \delta = 0.3 \), \( P \)-odd \( p \)-value = (0.4 \( \pm \) 0.2)\%
  - \( \delta = 0.7 \), \( P \)-even \( p \)-value = (15.8 \( \pm \) 1.9)\%
  - \( \delta = 0.7 \), \( P \)-odd \( p \)-value = (0.8 \( \pm \) 0.5)\%