EXPERIMENTAL OVERVIEW OF RECENT MIXING AND CPV RESULTS IN CHARM DECAYS

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on behalf of the LHCb collaboration

Implications of LHCb measurements and future prospects
CERN
3 November 2015
OUTLINE

› Introduction

› Charm mixing and indirect CPV searches

› Direct CPV searches

› Summary and conclusion
CHARM MIXING

• Mass eigenstates $|D_{1,2}\rangle$ with mass $m_{1,2}$ and width $\Gamma_{1,2}$
  → mixing occurs if $\Delta m \equiv m_2 - m_1 \neq 0$ or $\Delta \Gamma \equiv \Gamma_2 - \Gamma_1 \neq 0$

• $|D_{1,2}\rangle$ are linear combination of flavour states $|D^0\rangle$ and $|\overline{D}^0\rangle$
  $$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$
  with $q, p \in \mathbb{C}$ satisfying $|q|^2 + |p|^2 = 1$

• Mixing parameters $x \equiv \Delta m / \Gamma$ and $y \equiv \Delta \Gamma / (2\Gamma)$
  $$P(D^0 \rightarrow \overline{D}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left\{ - \cos(x \Gamma t) + \cosh(y \Gamma t) \right\}$$
CP VIOLATION

- CP violation searches in charm provide probe for new physics
- In SM, CPV expected to be small $\rightarrow$ enhancement hints at NP
- CPV in decay: $|A_f| \neq |\bar{A}_f|$
- CPV in mixing: $|q/p| \neq |p/q|$
- CPV in interference through $\phi = \text{arg} \left( \frac{q \bar{A}_f}{p A_f} \right)$
- No strong evidence for CPV in charm$^1$.

$^1$ Averages of b-hadron, c-hadron, and tau-lepton properties as of summer 2014, Y. Amhis et al., arXiv:1412.7515
Impact parameter (IP) \( \sim 0 \)

Impact parameter large

IP and related quantities allow to distinguish between prompt and secondary decays.
CHARM MIXING AND INDIRECT CPV SEARCHES
MIXING IN $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Different superposition of amplitudes at each point in phase-space
- Strong phase $\delta_D$ varies continuously across phase-space
- Multiple interfering amplitudes enhance sensitivity to mixing

arXiv: 1510.01664
MIXING IN \( D^0 \rightarrow K_S^0 \pi^+ \pi^- \)

- Dalitz plane divided in 16 bins with constant strong phase difference \( \Delta \delta_D \)
  \( \rightarrow \) model-independent approach

- Time-dependent decay rate from CLEO
  \[ P_{D^0} = e^{-\Gamma t} \left( T_i - \Gamma t \sqrt{T_i T_{-i}} \{ y c_i + x s_i \} \right) \]

Parameters of interest

CLEO 
PRD 82 (2010) 112006
**MIXING IN** \( D^0 \rightarrow K_S^0 \pi^+ \pi^- \)

- Measurement of mixing parameters x and y on 1 fb\(^{-1}\) in 2011
- \( D^0 \rightarrow K_S^0 \pi^+ \pi^- \) originate from prompt \( D^{*+} \rightarrow D^0 \pi_S^+ \)
- Separate \( D^0 \) signal and combinatorial background by fit to \( D^0 \) mass \( m_D \)
- Yield: 178k, purity 97.4%

**arXiv: 1510.01664**
MIXING IN $D^0 \rightarrow K^0_S \pi^+ \pi^-$

- Separate prompt from secondary $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays
- Two-dimensional fits it to $D^0$ decay time and $\ln \chi^2_{IP}$ to samples in each Dalitz bin to extract mixing parameters
MIXING IN $D^0 \rightarrow K^0_S \pi^+ \pi^-$

- Dominant sources of systematic uncertainties from resolution, efficiency variation over phase-space, uncertainty on $T_i$, ...

- First model-independent measurement of $x$ and $y$ in the decay $D^0 \rightarrow K^0_S \pi^+ \pi^-$
  - $x = (+0.86 \pm 0.53 \pm 0.17) \times 10^{-2}$
  - $y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}$

Contours hold 68% CL

Courtesy M Gersabeck

arXiv: 1510.01664
DIRECT CPV SEARCHES
\[ A_{CP} \ln D^0 \rightarrow K_S^0 K_S^0 \]

- Measurement of CP asymmetry $A_{CP}$ on 3fb$^{-1}$ dataset recorded in 2011 and 2012

- $D^0$ flavour determined by charge of $\pi_s^+$ from $D^{*+} \rightarrow D^0 \pi_s^+$ decay produced directly in pp collisions (prompt)

- Raw time-integrated CP asymmetry
  \[ A_{\text{raw}} \approx A_{CP} + A_D + A_D(\pi_s^+) + A_P(D^*) \]
  depends on detection and production asymmetries
  \[ O(1\%) \]
  \[ = 0 \]
  \[ O(1\%) \]
  → can be determined from control channels
$A_{CP} \ln D^0 \rightarrow K^0_SK^0_S$

$D^0 \rightarrow K^0_SK^0_S$ categories:
LL, LLtrig with a dedicated software trigger, DD and LD

The LHCb detector at the LHC, The LHCb collaboration, J. Instrum. 3 S08005 (2008)
$A_{CP} \ln D^0 \rightarrow K^0_S K^0_S$

$A_{CP} \equiv \frac{N^+ - N^-}{N^+ + N^-}$

- Fit to $\Delta m \equiv m(D^*) - m(D^0)$ for each decay category and split by $D^{*+}$ and $D^{*-}$ to extract $N^+$ and $N^-$

- Dominant systematic uncertainty from production and detection asymmetries
\[ A_{CP} \mid \mathbf{D}^0 \rightarrow K_S^0 K_S^0 \]

- Time-integrated CP asymmetry \( A_{CP} \) for \( D^0 \rightarrow K_S^0 K_S^0 \) decays

\[ A_{CP} = -0.029 \pm 0.052 \pm 0.022 \]

- Previous CLEO measurement \( A_{CP} \) in \( D^0 \rightarrow K_S^0 K_S^0 \)

\[ A_{CP} = (23 \pm 19)\% \]

- Run 2 sensitivity will greatly improve due to dedicated trigger lines

**Best measurement of \( A_{CP} \) in \( D^0 \rightarrow K_S^0 K_S^0 \)**
$\Delta A_{CP}$

THE SAGA CONTINUES
Thou shall not cite unofficial results!
THE $\Delta A_{CP}$ SAGA

$A_{\text{raw}}(f) \approx A_{CP}(f) + A_D(f) + A_D(\pi_s^+ / \mu \text{tag}) + A_P(D^* / B)$

- Cancel detection and production asymmetries using final states with similar kinematics

- Difference in time-integrated $CP$ asymmetries

$$\Delta A_{CP} \equiv A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+)$$

$$\approx A_{\text{raw}}(K^- K^+) - A_{\text{raw}}(\pi^- \pi^+)$$
THE $\Delta A_{CP}$ SAGA

- The $\Delta A_{CP}$ saga:
  - Prompt $\Delta A_{CP}$ on $0.6 \text{ fb}^{-1}$:  
    $\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$
    → theorists: clear sign of NP!
  - Semileptonic $\Delta A_{CP}$ on $3 \text{ fb}^{-1}$:  
    $\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$
    → no CPV in charm
  - Prompt $\Delta A_{CP}$ on $1 \text{ fb}^{-1}$:  
    $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$

https://indico.cern.ch/event/253826/session/10/contribution/113
\[ \Delta A_{CP} \]

- Prompt \( \Delta A_{CP} \) updated to full 3fb\(^{-1} \) dataset

- \( K^- K^+ \) and \( \pi^- \pi^+ \) samples reweighted to have same kinematics

- Time-integrated raw CP asymmetries from binned \( \chi^2 \) fit to \( \delta m \) of weighted events

\[
\mathcal{A}_{\text{raw}}(f) \equiv \frac{N^+(f) - N^-(f)}{N^+(f) + N^-(f)}
\]
Dominant systematic uncertainties from fiducial cut on $\pi^+_S$, $\delta m$ fit model, and treatment of multiple candidates

Unofficial result

$\Delta A_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$

Most precise measurement of direct CPV in charm decays
CONCLUSION

\[ \Delta A_{CP} \approx \left( 1 + \frac{\langle t \rangle}{\tau} y_{CP} \right) \Delta a_{CP}^{\text{dir}} + \frac{\langle t \rangle}{\tau} a_{CP}^{\text{ind}} \]

\[ A_{\Gamma} \approx -a_{CP}^{\text{ind}} - y_{CP} a_{CP}^{\text{dir}} \]
CONCLUSION

- Measurements of mixing and CP violation in charm still being published from Run 1 data

- Presented today:
  - first model-independent measurement of $x$ and $y$ with $D^0 \to K^0_S \pi^+ \pi^-$ decays
  - single best measurement of $A_{CP}$ in $D^0 \to K^-_S K^0_S$ decays
  - update of prompt $\Delta A_{CP}$ will be published soon

- No evidence for CPV in charm yet. Let’s see what Run 2 brings ...
OUTLOOK

- $\Delta A_{CP}$ uncertainty (stat. + syst.) at 50fb$^{-1}$: $10^{-4}$

- Mixing and indirect CPV sensitivities of current WA and LHCb:

| Run | $x$ [$10^{-3}$] | $y$ [$10^{-3}$] | $|q/p|$ [$10^{-3}$] | $\phi$ [mrad] |
|-----|----------------|----------------|-----------------|--------------|
| 1   | 1.22           | 0.53           | 59              | 89           |
| 2   | 0.92           | 0.37           | 44              | 70           |
| 3   | 0.42           | 0.15           | 20              | 33           |
| 4   | 0.25           | 0.09           | 12              | 20           |

Courtesy M Gersabeck
Mixing and indirect CP violation

\[ D^0 \rightarrow K_S^0 \pi^+ \pi^- \quad D \rightarrow K 3\pi \]

WS \[ D \rightarrow K \pi \] (SL – tagged)

Time-integrated CP asymmetries

\[ D \rightarrow 4\pi \quad D_{(s)} \rightarrow \eta^{(')} h \]

\[ D^+ \rightarrow hh\pi^+ \quad L_c^+ \rightarrow phh \]

Updates

\[ A_{\Gamma} \quad y_{CP} \]

Triple product asymmetries

\[ D^0 \rightarrow K^- K^+ \pi^- \pi^+ \]
THEORY PREDICTIONS

- Cancellation via GIM mechanism and CKM suppression → mixing in charm suppressed

- Early SM calculations: indirect CPV, $A_T \leq 10^{-5}$, $x \sim \mathcal{O}(10^{-3})$
  direct CPV $\leq 10^{-3}$ - $10^{-2}$

- New physics calculations: indirect CPV $\sim \mathcal{O}(10^{-3})$,
  $x \sim \mathcal{O}(10^{-2})$

- Less stringent limit on indirect CPV due to phase of leading HQE contributions

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2 JHEP 03(2010)009
MIXING IN $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Amplitudes $\mathcal{A}_{D^0}(m_+^2, m_-^2)$ and $\mathcal{A}_{\bar{D}^0}(m_+^2, m_-^2)$ for $D^0$ and $\bar{D}^0$

- Fraction of $D^0$ events in bin $i$

$$T_i \equiv \int_i |\mathcal{A}_{D^0}(m_+^2, m_-^2)|^2 dm_+^2 dm_-^2$$

- Interference terms between $D^0$ and $\bar{D}^0$ amplitudes

$$c_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}_{D^0}^*(m_+^2, m_-^2)||\mathcal{A}_{\bar{D}^0}(m_+^2, m_-^2)| \cos(\Delta \delta_D) dm_+^2 dm_-^2$$

$$s_i \equiv \frac{1}{\sqrt{T_i T_{-i}}} \int_i |\mathcal{A}_{D^0}^*(m_+^2, m_-^2)||\mathcal{A}_{\bar{D}^0}(m_+^2, m_-^2)| \sin(\Delta \delta_D) dm_+^2 dm_-^2$$
MIXING IN $D^0 \rightarrow K_S^0 \pi^+ \pi^-$

- Two-dimensional fit to $D^0$ decay time & $\ln \chi^2_{IP}$ to separate prompt from secondary
- Fit $D^{*+}$ and $D^{*-}$ samples separately in each Dalitz bin → in total 32 two-dimensional fits to $m_D$ and $\Delta m \equiv m_{D^*} - m_D$
MIXING IN $D^0 \rightarrow K^0_S\pi^+\pi^-$

Table 1: Systematic uncertainties on $x$ and $y$. The statistical uncertainties, which include the uncertainties associated with the CLEO parameters ($c_i, s_i$), are shown for comparison.

<table>
<thead>
<tr>
<th>Source</th>
<th>$x \times 10^{-2}$</th>
<th>$y \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit bias</td>
<td>0.021</td>
<td>0.020</td>
</tr>
<tr>
<td>Decay time resolution</td>
<td>0.065</td>
<td>0.039</td>
</tr>
<tr>
<td>Turning point (TP) resolution</td>
<td>0.020</td>
<td>0.022</td>
</tr>
<tr>
<td>Invariant mass resolution</td>
<td>0.073</td>
<td>0.028</td>
</tr>
<tr>
<td>Prompt/secondary TP distributions</td>
<td>0.051</td>
<td>0.023</td>
</tr>
<tr>
<td>Efficiency over phase space</td>
<td>0.057</td>
<td>0.071</td>
</tr>
<tr>
<td>Tracking efficiency parameterisation</td>
<td>0.015</td>
<td>0.025</td>
</tr>
<tr>
<td>Kinematic boundary</td>
<td>0.012</td>
<td>0.006</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>0.061</td>
<td>0.052</td>
</tr>
<tr>
<td>Treatment of secondary $D$ decays</td>
<td>0.046</td>
<td>0.025</td>
</tr>
<tr>
<td>Uncertainty from $T_i$</td>
<td>0.079</td>
<td>0.056</td>
</tr>
<tr>
<td>Uncertainties from $(m_D, \Delta m)$ fits</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>Uncertainties from lifetime fit</td>
<td>0.020</td>
<td>0.043</td>
</tr>
<tr>
<td>$D^0$ background</td>
<td>0.001</td>
<td>0.006</td>
</tr>
<tr>
<td>Variation of signal components across the phase space</td>
<td>0.013</td>
<td>0.017</td>
</tr>
<tr>
<td>Total systematic uncertainty</td>
<td>0.171</td>
<td>0.134</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>0.527</td>
<td>0.463</td>
</tr>
</tbody>
</table>

Conclusions

The charm mixing parameters $x$ and $y$ have been measured using a novel method that does not require the use of an amplitude model but instead uses external measurements of the strong phase made at an $e^+e^-$ collider running at the $(3770)$ resonance [13]. A sample of $pp$ collision data recorded by the LHCb experiment was used, corresponding to an integrated luminosity of $1.0 \ fb^{-1}$ at a centre-of-mass energy of $7 \ TeV$. Neglecting $CP$ violation, the measured values are $x = (0.37 \pm 0.15) \times 10^{-2}$ and $y = (0.66 \pm 0.23) \times 10^{-2}$. The first uncertainties are combinations of the LHCb statistical uncertainties and those due to the CLEO measurements of the ($c_i, s_i$) parameters, whose exact is too small to determine precisely from the fit but is estimated to be in the range $(0.05–0.15) \times 10^{-2}$. The second uncertainties are systematic. The correlation coefficient between $x$ and $y$ for the first uncertainty is $0.37$, and the systematic uncertainties are considered uncorrelated. The analysis prefers a positive value of $x$. The measured values are fully consistent with the current HFAG world averages $x = (0.37 \pm 0.16) \times 10^{-2}$ and $y = (0.66 \pm 0.07 \pm 0.10) \times 10^{-2}$. The total systematic uncertainty is $0.171 \times 10^{-2}$.
\[ A_\Gamma = \frac{\hat{\Gamma}_{D^0} - \hat{\Gamma}_{\bar{D}^0}}{\hat{\Gamma}_{D^0} + \hat{\Gamma}_{\bar{D}^0}} \approx \left( \frac{A_d + A_m}{2} \right) y \cos \varphi - x \sin \varphi \]

- Asymmetry of the inverse effective lifetimes of \( D^0 \) and \( \bar{D}^0 \) decays to CP-even final states, e.g. \( \pi^+ \pi^- \) or \( K^+ K^- \)

- Effective lifetimes are lifetimes measured using a single-exponential model

- SM: CP-violating phase \( \phi \) independent of final state
  \[ \rightarrow \] Expect same results for \( A_\Gamma \) measured with kaons and pions
SEMILEPTONIC $A_{\Gamma}$

- Measurement of $A_{\Gamma}(K^+ K^-)$ and $A_{\Gamma}(\pi^+ \pi^-)$ on combined 2011 & 2012 dataset corresponding to 3 fb$^{-1}$

- $D^0$ flavour determined by $\mu^-$ charge from semileptonic B decay $B^- (\overline{B}^0) \rightarrow D^0 \mu^- \bar{\nu}_\mu X$

- $D^0 \rightarrow K^+ K^-:$
  Yield $\sim2.3$M signal candidates

- $D^0 \rightarrow \pi^+ \pi^-:$
  Yield $\sim0.8$M signal candidates
SEMILEPTONIC $A_{\Gamma}$

$$A_{CP}^{\text{raw}}(t) \approx A_d - A_{\Gamma} \frac{t}{\tau}$$

- Raw CP asymmetry determined from mass fits in 50 bins of decay time
- Simultaneous fits to $D^0$ and $\bar{D}^0$ samples
- $A_{\Gamma}$ determined from $\chi^2$ fit to time-dependent $A_{CP}^{\text{raw}}(t)$
• Dominant systematic uncertainty from combination of random muon with $D^0$
  • mistag probability
  • uncertainty of mistag asymmetry

• Results
  • $A_\Gamma(K^+K^-) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$
  • $A_\Gamma(\pi^+\pi^-) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$
Assuming universal indirect CPV:

\[ \text{LHCb: } A_\Gamma = (-0.056 \pm 0.044)\% \text{, WA: } A_\Gamma = (-0.058 \pm 0.040)\% \]
Invariant mass distributions

LHCb

$M(K^-K^+)$ [MeV/c$^2$]

$M(\pi^-\pi^+)$ [MeV/c$^2$]

Data

Total fit

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

Comb. bkg.

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

Comb. bkg.

K$\pi$ bkg.
SEMILEPTONIC $A_\Gamma$

$A_\Gamma$ results split by magnet polarity and year

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Implications Workshop 2015
SEMILEPTONIC \( A_r \)

- Control channel \( D^0 \rightarrow K^- \pi^+ \) used to study mistag
- CF decay
  - direct CPV negligible
  - indirect CPV suppressed
- Half of available sample analysed \( \sim 11.3 \text{M} \) signal candidates

![Invariant mass distribution](image_url)

In JHEP 04 (2015) 043
SEMILEPTONIC $A_{\Gamma}$

Left: Fit to $A_{CP}^{raw}(t)$ on control channel $D^0 \rightarrow K^- \pi^+$

Right: $A_{\Gamma}$ results split by magnet polarity and year

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Table 1: Contributions to the systematic uncertainty of $A_{\Gamma}(K^- K^+)$ and $A_{\Gamma}(\pi^- \pi^+)$. The constant and multiplicative scale uncertainties are given separately.

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$D^0 \rightarrow K^- K^+$</th>
<th></th>
<th>$D^0 \rightarrow \pi^- \pi^+$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mistag probability</td>
<td>0.006%</td>
<td>0.05</td>
<td>0.008%</td>
<td>0.05</td>
</tr>
<tr>
<td>Mistag asymmetry</td>
<td>0.016%</td>
<td></td>
<td>0.016%</td>
<td></td>
</tr>
<tr>
<td>Time-dependent efficiency</td>
<td>0.010%</td>
<td></td>
<td>0.010%</td>
<td></td>
</tr>
<tr>
<td>Detection and production asymmetries</td>
<td>0.010%</td>
<td></td>
<td>0.010%</td>
<td></td>
</tr>
<tr>
<td>$D^0$ mass fit model</td>
<td>0.011%</td>
<td></td>
<td>0.007%</td>
<td></td>
</tr>
<tr>
<td>$D^0$ decay-time resolution</td>
<td></td>
<td>0.09</td>
<td></td>
<td>0.07</td>
</tr>
<tr>
<td>$B^0-\bar{B}^0$ mixing</td>
<td>0.007%</td>
<td></td>
<td>0.007%</td>
<td></td>
</tr>
<tr>
<td>Quadratic sum</td>
<td>0.026%</td>
<td>0.10</td>
<td>0.025%</td>
<td>0.09</td>
</tr>
</tbody>
</table>
$A_{CP} \ln D^0 \rightarrow K_S^0 K_S^0$

Figure 1. Distribution of $\Delta m$ for the control channel $D^0 \rightarrow K^- \pi^+$ in (left) linear and in (right) log-arithmic scale. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, and the dash-dotted (red) line represents the signal contribution.

Figure 2. Distributions of $\Delta m$ split into (left) $D^{\ast \ast}$+, (right) $D^{\ast \ast}$− and (top) LL, (bottom) LLtrig, including the fit function. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, and the dash-dotted (red) line represents the signal contribution.
$$A_{CP} \mid \mathcal{N} \quad D^0 \rightarrow K^0_S K^0_S$$

Figure 3. Distributions of $\Delta m$ split into (left) $D^{*+}$, (right) $D^{*-}$ and (top) LD, (bottom) DD, including the fit function. The solid (black) line corresponds to the total fit, the dashed (blue) line corresponds to the background, while the dash-dotted (red) line represents the signal contribution.

The systematic effects that arise due to the slow pion charge asymmetry in the detector and a possible charge asymmetry of $D^{*-}$ production in pp collisions in the LHCb acceptance are determined using the control channel. However, the control channel contains charged kaons which introduce an additional detection asymmetry, as the interaction cross-sections of $K^+$ and $K^-$ with the detector material are different. In ref. [26], the charged kaon detection asymmetry has been measured to be in the range 0.008 to 0.012. Assuming the pion detection asymmetry to be negligible, and including possible trigger effects, a correction of $-0.010 \pm 0.005$ is applied to the observed asymmetry in the control channel, resulting in a corrected value of $-0.009 \pm 0.005$. The absolute value of this number and its uncertainty are added in quadrature and assigned as a conservative estimate of the systematic uncertainty due to production and detection asymmetries.
\[ \Delta A_{CP} \approx \left( 1 + \frac{\langle t \rangle}{T} y_{CP} \right) \Delta a_{CP}^{\text{dir}} + \frac{\Delta \langle t \rangle}{T} a_{CP}^{\text{indr}} \]

- Kinematic reweighting in \( p, p_T \) (adaptive binning) and \( \varphi \) (uniform binning) of \( D^* \) with

\[ f_i(p, p_T, \varphi) = \frac{N_i^{\pi\pi}(p, p_T, \varphi)}{N_i^{KK}(p, p_T, \varphi)} \frac{N_{\text{tot}}^{KK}}{N_{\text{tot}}^{\pi\pi}} \]

after background subtraction
Figure 2: Distributions of the mass difference $\Delta m$ with the results of the fits superimposed for final state candidates for (left) TOS and (right) TIS events and (top) 2012 magnet up and (bottom) 2012 magnet down data sample. The dashed grey line represents the background.

Systematic uncertainties:
Systematic shifts in the observed $A_{CP}$ asymmetries can arise from imperfect modelling of the signal and background distributions, biases due to the presence of multiple candidates in the event, peaking backgrounds in the $\Delta m$ distribution and non-cancellation of production and detection asymmetries. Systematic shift can also be observed if the edge regions with very high raw asymmetries are not well excluded. The presence of secondary charm decays in the sample can also cause a systematic shift of the result due to the different production asymmetries of prompt and secondary charm. The contributions to the systematic uncertainties in $A_{CP}$ are described below.

A systematic uncertainty related to the $m$ shape modelling is estimated by performing...
$\Delta A_{CP}$

Figure 1: Distributions of the mass difference $m$ with the results of the fits superimposed for $K^+K^-$ final state candidates for (left) TOS and (right) TIS events and (top) 2012 magnet up and (bottom) 2012 magnet down data sample. The dashed grey line represents the background.

Kinematical weights are applied on all $K^+K^-$ final state candidates in order to equalise their kinematical distributions with those of the $\pi^+\pi^-$ final state candidates. The reweighting procedure is performed on the $D^*$ meson, but the reweighted kinematical distributions of the $\pi^+$s are in excellent agreement reflecting the correlation with the $D^*$ meson kinematics.

4.2 Measurement of the $CP$ asymmetries

For each of the 8 subsamples separated in year, magnet polarity and hardware trigger category, $A_{CP}$ is calculated following Eq. (16). The individual results, together with the weighted average per year, are summarised in Tab. 4. The 2012 results were obtained after a linear analysis, the 2011 results were unblinded in 2012 but the data were re-analysed with a new version of the reconstruction software. The measurements in the various data subsamples are in good agreement for both years.

The various sources of systematic uncertainties are discussed in the next section.
$\Delta A_{CP}$

No CPV: $\Delta \chi^2 = 2.27$ corresponds to CL of 0.322