Results presented today

- Search for Direct $CP$ in $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ and $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$

Other selected results:

- $\Delta A_{CP}(KK - \pi\pi)$ from tagged $D^*$ and semi-leptonic $B$ decays
- Direct $CP$ Search in $D^+ \rightarrow \phi \pi^+$ and $D_s^+ \rightarrow K_s^0 \pi^+$
- $D^0 - \bar{D}^0$ mixing from $D^0 \rightarrow K^- \pi^+$ and $D^0 \rightarrow K^+ \pi^-$

All reported results are from data collected in 2011, integrated luminosity of 1.0 fb$^{-1}$, $\sqrt{s} = 7$ TeV
Both mixing and CP violation are well established in $B$ and $K$ sectors
Charm is the only up-type system where these effects can occur
Mixing in $D^0\bar{D}^0$ verified - but until 2013 no single $5\sigma$ observation

**Charm Mixing and CP**

- mass eigenstates:
  \[|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle\]
  \[|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle\]
  \[m = \frac{m_1 + m_2}{2}\]
  \[\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}\]
- oscillation parameters
  \[x = \frac{\Delta m}{\Gamma}\]
  \[y = \frac{\Delta \Gamma}{2\Gamma}\]
- predicted to be small from the SM
  $x, y$ at most $10^{-2}$
- CP arising through mixing if
  \[|q/p| \neq 1 \text{ or } \phi = \arg(q/p) \neq 0\]
  expected to be $O(10^{-4})$ from the SM

**Direct CP in Charm**

- direct CP can appear in singly
  Cabibbo Suppressed (SCS) decays
  interference between tree and penguin diagrams
- SM predictions up to a few $O(10^{-3})$
- Usually measuring time-integrated asymmetry:
  \[A(f) = \frac{\Gamma(D\to f) - \Gamma(\bar{D}\to \bar{f})}{\Gamma(D\to f) + \Gamma(\bar{D}\to \bar{f})}\]
- promising:
  \[\star\] asymmetries in 2-body SCS decays
  \[\star\] asymmetries across the phase space in multi-body decays
LHCb & Charm

- LHCb designed as a forward spectrometer for the study of $B$ hadron decays
- excellent vertexing, time resolution, tracking, momentum resolution and particle ID
- very good conditions for charm physics too!

A dedicate charm trigger:

- charm produced both promptly or from $B$ decays ($B \sim 50\%$)
- charm cross section $\sim 20 \times$ larger than $b$ cross section @ 7 TeV:
  \[ \sigma(c\bar{c}) = 1419 \pm 133 \mu b \quad \text{Nucl. Phys B 871(2013), 1} \]
  \[ \sigma(b\bar{b}) = 75.3 \pm 14.1 \mu b \quad \text{Phys. Lett. B 694 (2010), 209} \]

- huge charm samples!

<table>
<thead>
<tr>
<th>LHC rate - 15 MHz</th>
<th>$c\bar{c}$ fraction - 10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hardware $E_T$ trigger - 1 MHz</td>
<td>$c\bar{c}$ fraction - 50%</td>
</tr>
<tr>
<td>High $p_T$, IP track - 80 kHz</td>
<td>efficiency ~ 50%</td>
</tr>
<tr>
<td>Exclusive $D\to hh/3h/4h$ - 2 kHz</td>
<td>efficiency ~ 50-90%</td>
</tr>
</tbody>
</table>

up to 2kHz for charm
Search for $\mathcal{C}/\mathcal{P}$ in $D^0 \rightarrow 4\phi$

- $D^0 \rightarrow K^-K^+\pi^-\pi^+$ and $D^0 \rightarrow \pi^-\pi^+\pi^+\pi^-$ are SCS decays

interference between tree and penguin amplitudes can provide mechanism for $\mathcal{C}/\mathcal{P}$ in the SM

⇒ new physics can enhance penguin contributions potentially increasing $\mathcal{C}/\mathcal{P}$ effects

- rich resonance substructure
  $D^0 \rightarrow KK\pi\pi$: $\phi^0$, $K_1(1270)^\pm K^\mp$, $K^*(1410)^\pm K^\mp$, ...
  $D^0 \rightarrow \pi\pi\pi\pi$: $\rho\rho$, $a_1(1260)^\pm\pi^-$, ...

- 4-body decay dynamics described by 5 invariants (5D phase space)
  choose 2-body and 3-body squared-mass combinations
  ex.: $(\pi^-\pi^+\pi^+\pi^-) = (1\ 2\ 3\ 4) \Rightarrow s(1, 2), s(2, 3), s(3, 4), s(1, 2, 3), s(2, 3, 4)$

- flavor of $D$ is tagged through decay chain $D^{*+} \rightarrow D^0\pi^+$
Search for $CP$ in $D^0 \to 4h$

- Selection of candidates includes criteria on: $D^0$ transverse momentum ($p_T$), daughters momentum ($p$) and $p_T$, particle identification, among others
- two-dimensional fit performed to $m(D)$ and $\Delta m \equiv m(D^*) - m(D)$
- sPlot statistical tool: assign an s-weight based on the probability of being signal

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

5.7 $\times$ 10^4 signal events

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

3.3 $\times$ 10^5 signal events

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

2.9 $\times$ 10^6 signal events
Analysis Strategy

- The 5D phase space is divided in bins with same occupancy (adaptive binning).
- for each bin $i$, $D^0$ and $\bar{D}^0$ bin occupancies are compared through

$$S_{CP}^i = \frac{N_i(D^0) - \alpha N_i(\bar{D}^0)}{\sqrt{\alpha \left(\sigma_i^2(D^0) + \sigma_i^2(\bar{D}^0)\right)}}, \quad \alpha = \frac{\sum_i N_i(D^0)}{\sum_i N_i(\bar{D}^0)}$$

- $N_i$ is the sum of signal s-weights in bin $i$, $\sigma_i$ is the sum of s-weights squared.
- absence of any asymmetry: $S_{CP}$ is Gaussian distributed (mean 0, width 1).
- $\chi^2 = \sum_i (S_{CP}^i)^2$; ndf = $N_{bins} - 1 \Rightarrow$ obtain p-value for the hypothesis of no $CP$.

An example: Pseudo experiments for $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$

- tests with samples with comparable size to data.
- left plot: without $CP$.
- right plot: $10^\circ$ phase difference between $D^0 \rightarrow a_1^+(1260)\pi^-$ and $\bar{D}^0 \rightarrow a_1^-(1260)\pi^+$. 
Search for $CP$ in $D^0 \rightarrow 4\ell$

Before looking specifically at the signal modes, a number of cross-checks are made:

- study left/right asymmetries in the detector
- effects of magnet polarity
- asymmetries in the background
- particle/anti-particle asymmetries through $D^0 \rightarrow K\pi\pi\pi$ channel

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

- It is Cabibbo favored, no $CP$ expected
- Asymmetry: $A_{\text{raw}}^i = \frac{N_i(D^0) - \alpha N_i(\bar{D}^0)}{N_i(D^0) + \alpha N_i(\bar{D}^0)}$
- Results:

<table>
<thead>
<tr>
<th>bins</th>
<th>$\chi^2$/ndf</th>
<th>p-value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>16.5/15</td>
<td>34.8</td>
</tr>
<tr>
<td>128</td>
<td>113.4/127</td>
<td>80.0</td>
</tr>
<tr>
<td>1024</td>
<td>1057.5/1023</td>
<td>22.1</td>
</tr>
</tbody>
</table>

(preliminary)

- data also divided for: magnet polarity, run period
- no evidence for local asymmetries
Search for $CP$ in $D^0 \rightarrow 4h$

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

- study based on $3.3 \times 10^5$ s-weighted signal events
- p-values are consistent with hypothesis of no CP violation

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<thead>
<tr>
<th>bins</th>
<th>$\chi^2$/ndf</th>
<th>p-value(%)</th>
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</thead>
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<tr>
<td>64</td>
<td>68.8/63</td>
<td>28.8</td>
</tr>
<tr>
<td>128</td>
<td>130.0/127</td>
<td>41.0</td>
</tr>
<tr>
<td>256</td>
<td>247.7/255</td>
<td>61.7</td>
</tr>
</tbody>
</table>

(preliminary)
Search for $CP$ in $D^0 \to 4h$

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

- study based on $5.7 \times 10^4$ s-weighted signal events
- p-values are consistent with hypothesis of no CP violation

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<tr>
<td>16</td>
<td>22.7/15</td>
<td>9.1</td>
</tr>
<tr>
<td>32</td>
<td>42.0/31</td>
<td>9.1</td>
</tr>
<tr>
<td>64</td>
<td>75.7/63</td>
<td>13.1</td>
</tr>
</tbody>
</table>

(preliminary)

No evidence for CP Violation in both $D^0 \to K^- K^+ \pi^- \pi^+$ and $D^0 \to \pi^- \pi^+ \pi^+ \pi^-$ channels
$\Delta A_{CP}$ from $D^0 \rightarrow K^- K^+ \& \pi^- \pi^+$

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

- $\Delta A_{CP} = a_{CP}^{dir}(K^- K^+) - a_{CP}^{dir}(\pi^- \pi^+) + \frac{\Delta(t)}{\tau} a_{CP}^{ind}$
- Production and detection asymmetries are cancelled:
  $$\Delta A_{CP} \approx A_{raw}(K^- K^+) - A_{raw}(\pi^- \pi^+)$$
  $$A_{raw}(f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)}$$

Two independent analyses:

**LHCb-CONF-2013-003**

**prompt:** $D^{*+} \rightarrow D^0 \pi_s^+$

- $\pi_s$ tags the flavor of $D^0$

**secondary:** $B \rightarrow D^0 \mu X$

- $\mu$ tags the flavor of $D^0$
$\Delta A_{CP}$ from $D^0 \rightarrow K^- K^+ / \pi^- \pi^+$

**Fit results:**

**Prompt:** (preliminary)

$\Delta A_{CP} = (-0.34 \pm 0.15_{\text{stat}} \pm 0.10_{\text{sys}})\%$

**Secondary:**

$\Delta A_{CP} = (+0.49 \pm 0.30_{\text{stat}} \pm 0.14_{\text{sys}})\%$

**LHCb average:**

$\Delta a^\text{dir}_{CP} = (-0.15 \pm 0.16)\%$

**Previous measurements:**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\Delta A_{CP}$ (%)</th>
<th>ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$-0.82 \pm 0.21 \pm 0.11$</td>
<td>PRL108.111602</td>
</tr>
<tr>
<td>CDF</td>
<td>$-0.62 \pm 0.21 \pm 0.10$</td>
<td>PRL109.111801</td>
</tr>
<tr>
<td>Belle</td>
<td>$-0.87 \pm 0.41 \pm 0.06$</td>
<td>arXiv:1212.1975</td>
</tr>
<tr>
<td>BaBar</td>
<td>$+0.24 \pm 0.62 \pm 0.26$</td>
<td>PRL 100 (2008) 061803</td>
</tr>
</tbody>
</table>

**HFAG average:**

$\Delta a^\text{dir}_{CP} = (-0.329 \pm 0.121)\%$
Search for $CP$ in $D^+ \to \phi \pi^+$, $D_s^+ \to K^0_S \pi^+$

$$A_{CP}(D^+ \to \phi \pi^+) = A_{raw}(D^+ \to \phi \pi^+) - A_{raw}(D^+ \to K^0_S \pi^+) + A_{CP}(K^0 - \bar{K}^0)$$

$$A_{CP}(D_s^+ \to K^0_S \pi^+) = A_{raw}(D_s^+ \to K^0_S \pi^+) - A_{raw}(D_s^+ \to \phi \pi^+) + A_{CP}(K^0 - \bar{K}^0)$$

Improve sensitivity in $\phi$ region:

$$A_{CP|S} = \frac{1}{2} [(A_{raw}^A + A_{raw}^C) - (A_{raw}^B A_{raw}^D)]$$

$$A_{CP}(D_s^+ \to K^0_S \pi^+) = (-0.61 \pm 0.83_{stat} \pm 0.13_{sys})\%$$

$$A_{CP}(D^+ \to \phi \pi^+) = (-0.04 \pm 0.14_{stat} \pm 0.13_{sys})\%$$

$$A_{CP|S} = (-0.18 \pm 0.17_{stat} \pm 0.18_{sys})\%$$
$D^0\bar{D}^0$ Mixing from WS/RS $D^0 \rightarrow K^\mp\pi^\pm$

- $D^0$ flavour at production tagged through $D^*^+ \rightarrow D^0\pi^+$ chain
- $8.2 \times 10^6$ RS and $3.6 \times 10^4$ WS decays

Time-dependent ratio of WS and RS rates:

$$R(t) = \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_D + \sqrt{R_D}y' \left( \frac{t}{\tau} \right) + \frac{x'^2 + y'^2}{4} \left( \frac{t}{\tau} \right)^2$$

where $x' = x \cos \delta + y \sin \delta$ and $y' = y \cos \delta - x \sin \delta$

- $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$
- $y' = (7.2 \pm 2.4) \times 10^{-3}$
- $R_D = (3.52 \pm 0.15) \times 10^{-3}$

**no mixing** excluded at $9.1\sigma$
No evidence for local CP asymmetries in SCS 4-body decays

p-values for no CPV hypothesis: 9.1% for $D^0 \rightarrow K^- K^+ \pi^+ \pi^-$
41% for $D^0 \rightarrow \pi^- \pi^+ \pi^+ \pi^-$

but sensitivity still at the level of a few %

LHCb does not confirm previous reported evidence for CP

$\Delta A_{CP} = (-0.34 \pm 0.15_{stat} \pm 0.10_{sys})\%$ [pion tagged]
$\Delta A_{CP} = (+0.49 \pm 0.30_{stat} \pm 0.14_{sys})\%$ [muon tagged]

CP constrained to a few $\mathcal{O}(10^{-3})$ also for $D^+ \rightarrow \phi \pi^+, D_s^+ \rightarrow K_S^0 \pi^+$

Charm mixing firmly stablished: small $x$ and $y$ as expected from the SM

$x' = (-0.9 \pm 1.3) \times 10^{-4}; \quad y' = (7.2 \pm 2.4) \times 10^{-3}$

no mixing hypothesis excluded at 9.1$\sigma$

2 fb$^{-1}$ from 2012 8TeV pp collisions yet to be fully analyzed

still many LHCb results on charm physics to appear soon!
Time-dependent $CP$ asymmetry for $D^0$ decays to a $CP$ eigenstate $f$:

$$A_{CP}(f; t) \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} \approx a^\text{dir}_{CP}(f) + \frac{t}{\tau} a^\text{ind}_{CP},$$

$$a^\text{dir}_{CP}(f) \Rightarrow |\langle f | \mathcal{H}_{\Delta F=1} | D^0 > | \neq |\langle f | \mathcal{H}_{\Delta F=1} | \bar{D}^0 > |;$$

$$a^\text{ind}_{CP} \Rightarrow CPV \text{ in mixing and/or interference between mixing and decay: universal, to a good approximation. Depends on the experimental decay-time acceptance.}$$

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

$$= a^\text{dir}_{CP}(K^- K^+) - a^\text{dir}_{CP}(\pi^- \pi^+) + \frac{\Delta \langle t \rangle}{\tau} a^\text{ind}_{CP}$$

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<thead>
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<th>Experiment</th>
<th>$\Delta A_{CP}(%)$</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>-0.82±0.21 ± 0.11</td>
<td>PRL 108 (2012) 111602</td>
</tr>
<tr>
<td>CDF</td>
<td>-0.62±0.21 ± 0.10</td>
<td>PRL 109 (2012) 111801</td>
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<td>BaBar</td>
<td>+0.24±0.62 ± 0.26</td>
<td>PRL 100 (2008) 061803</td>
</tr>
</tbody>
</table>

Agreement with no CP violation $\Rightarrow CL = 2.0 \times 10^{-5}$
Analysis strategy: the sign of the soft $\pi^+$ from $D^{*+} \rightarrow D^0 \pi_s^+$ tags the $D^0$ flavor.

$$A_{\text{raw}}(f) = \frac{N(D^{*+} \rightarrow D^0 \pi_s^+) - N(D^{*-} \rightarrow \bar{D}^0 \pi_s^-)}{N(D^{*+} \rightarrow D^0 \pi_s^+) + N(D^{*-} \rightarrow \bar{D}^0 \pi_s^-)}.$$ 

- To first order, $A_{\text{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+})$.
- $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$, and $A_D(\pi_s^+)$, $A_P(D^{*+})$ independent of $f$:

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

Signal yields from 2011 data:

- 2.2 million $D^0 \rightarrow K^-K^+$;
- 0.7 million $D^0 \rightarrow \pi^-\pi^+$.

$$\Delta\langle t\rangle/\tau = (11.19 \pm 0.13 \pm 0.17)\%$$

LHCb-CONF-2013-003
- Fiducial requirements to exclude kinematic regions with large $\pi^+_s$ detection asymmetry.

- IP requirement reduces contamination from $D^0$ originated from $b$-hadron decays.

- Weighting procedure to adjust kinematic distributions of the $K^-K^+$ and $\pi^-\pi^+$ final states.

- Data divided into several disjoint samples (magnet polarity and hardware trigger).

- Signal yields extracted from a fit to $\delta m \equiv m(h^+ h^- \pi^+) - m(h^+ h^-) - m(\pi^+)$. 

- Constrain the $D^{*+}$ vertex to coincide with the PV substantially improves $\delta m$ resolution.
$D^*$ momentum before weighting.

$D^*$ momentum after weighting.

Systematic uncertainties

<table>
<thead>
<tr>
<th>source</th>
<th>Uncertainty(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial cut</td>
<td>0.02</td>
</tr>
<tr>
<td>Peaking Background</td>
<td>0.04</td>
</tr>
<tr>
<td>Fit model</td>
<td>0.03</td>
</tr>
<tr>
<td>Multiple candidates</td>
<td>0.01</td>
</tr>
<tr>
<td>Weighting</td>
<td>0.01</td>
</tr>
<tr>
<td>Soft pion IP$^2$</td>
<td>0.08</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.10</strong></td>
</tr>
</tbody>
</table>

$\Delta A_{CP} = (-0.34 \pm 0.15\text{(stat)} \pm 0.10\text{(syst)})\%$

LHCb-CONF-2013-003
Updated LHCb result from 1.0 fb$^{-1}$:

$$\Delta A_{CP} = (-0.34 \pm 0.15 \text{(stat)} \pm 0.10 \text{(syst)})\%$$

Differences from previous result:

1) New reconstruction changed the selected signal events (600 fb$^{-1}$):
   a) 15% of signal events no longer selected;
   b) 17% ($K^-K^+$) and 34% ($\pi^-\pi^+$) new events selected:

   $$\Delta A_{CP} : (-0.82 \pm 0.21)\% \rightarrow (-0.55 \pm 0.21)\%.$$

2) Including new data (+ 400 fb$^{-1}$): $\Delta A_{CP} = (-0.55 \pm 0.21) \rightarrow (-0.45 \pm 0.16)\%$.

3) Constraining the soft pion and the $D^0$ to originate from a primary vertex:

   $$\Delta A_{CP} : (-0.45 \pm 0.16)\% \rightarrow (-0.34 \pm 0.15)\%.$$

2012 data set (2 fb$^{-1}$) currently being analysed.
$D^0$ flavor is tagged by the muon sign in $B \to D^0 \mu^- \chi$. Statistically independent from the prompt $D^*$ sample.

Lower rate partially compensated by a higher trigger efficiency. Different trigger composition and systematics involved.

$$A_{\text{raw}} = \frac{\Gamma(D^0 \to f)\varepsilon(\mu^-)\mathcal{P}(D^0) - \Gamma(\bar{D}^0 \to f)\varepsilon(\mu^+)\mathcal{P}(\bar{D}^0)}{\Gamma(D^0 \to f)\varepsilon(\mu^-)\mathcal{P}(D^0) + \Gamma(\bar{D}^0 \to f)\varepsilon(\mu^+)\mathcal{P}(\bar{D}^0)} \approx A_{CP}^f + A_D^\mu + A_P^B$$

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

$$\frac{\Delta \langle t \rangle}{\tau} = 0.018 \pm 0.007$$

$$\Delta A_{CP} \simeq \Delta a_{CP}^{\text{dir}}$$
Raw asymmetries determined from a simultaneous fit of four data subsets.

$5.6 \times 10^5 \ D^0 \rightarrow K^- K^+$

$2.2 \times 10^5 \ D^0 \rightarrow \pi^- \pi^+$

Differences in the kinematics of the two final states are accounted by a weighting procedure.

Wrong flavor tag dilutes the observed asymmetry:

$$A_{\text{raw}} \approx (1 - 2\omega)(A^f_{\text{CP}} + A^\mu_D + A^B_P) - \Delta\omega,$$

$$\omega = (\omega^+ + \omega^-)/2 = (0.982 \pm 0.012)\%,$$

$$\Delta\omega = \omega^+ - \omega^- = (0.006 \pm 0.021)\%.$$
Extras

$D^0$ $p_T$ before weighting

$D^0$ $p_T$ after weighting

Muon $\eta$ before weighting

Muon $\eta$ after weighting

arXiv:1303.2614
Carla Göbel (PUC-Rio)  Charm Mixing and $\mathcal{Q}/\mathcal{P}$ at LHCb  25 / 15

2011 data set
(1.0 fb$^{-1}$ @ 7 TeV)

Hardware trigger (L0) decision based on $K_S^0$ and $\phi$ daughter tracks

All tracks must have been detected in the vertex finder (VELO).

Signal yields measured in 12 bins of $p_T$ and $\eta$ for each charge and magnet polarity.

$1.6 \times 10^6 \quad D^+ \rightarrow \phi \pi^+$

$3.0 \times 10^6 \quad D_s^+ \rightarrow \phi \pi^+$

$1.1 \times 10^6 \quad D^+ \rightarrow K_S^0 \pi^+$,

$2.5 \times 10^4 \quad D_s^+ \rightarrow K_S^0 \pi^+$
### Systematic uncertainties

| Source                                | $A_{CP}(D^+)$ [%] | $A_{CP}(D_s^+)$ [%] | $A_{CP}|S$ [%] |
|---------------------------------------|-------------------|---------------------|----------------|
| Triggers                              | 0.114             | 0.114               | n/a            |
| $D_s^+$ control sample size           | n/a               | n/a                 | 0.169          |
| Kaon asymmetry                        | 0.031             | 0.002               | 0.009          |
| Binning                               | 0.035             | 0.035               | n/a            |
| Resolution                            | 0.007             | 0.006               | 0.056          |
| Fitting                               | 0.033             | 0.033               | n/a            |
| Kaon CP violation                     | 0.028             | 0.028               | n/a            |
| Fiducial effects                      | 0.022             | 0.022               | n/a            |
| Backgrounds                           | 0.008             | n/a                 | 0.007          |
| $D$ from $B$                          | 0.003             | 0.015               | 0.003          |
| Regeneration                          | 0.010             | 0.010               | n/a            |
| **Total**                             | **0.133**         | **0.130**           | **0.178**      |

$$A_{CP}(D^+ \rightarrow \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%,$$

$$A_{CP}|S(D^+ \rightarrow \phi\pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%,$$

$$A_{CP}(D_s^+ \rightarrow K_s^0\pi^+) = (+0.61 \pm 0.83 \pm 0.13)\%.$$

No evidence for CPV.
2011 data – 1.0 fb⁻¹ at 7 TeV

Charge of soft pion $\pi_s^+$ tags the flavor of the $D^0$.

Background of WS data dominated by real $D^0$ associated to a random $\pi$.

Contamination from $B \rightarrow D^0 X$ reduced by IP requirements on $D^0$ and $\pi_s^+$.

$D^{*+} \rightarrow D^0(K^-\pi^+)\pi_s^+$
8.4 x $10^6$ decays

$D^{*+} \rightarrow D^0(K^+\pi^-)\pi_s^+$
3.6 x $10^4$ decays

$D^0$ and $\pi_s^+$ required to form a vertex constrained to PV.

PRL 110 (2013) 101802
2011 data – 1.0 fb^{-1} at 7 TeV

Charge of soft pion $\pi_s^+$ tags the flavor of the $D^0$.

Background of WS data dominated by real $D^0$ associated to a random $\pi$.

Contamination from $B \rightarrow D^0 X$ reduced by IP requirements on $D^0$ and $\pi_s^+$.

$D^{*+} \rightarrow D^0 (K^- \pi^+) \pi_s^+ \quad 8.4 \times 10^6$ decays

$D^{*+} \rightarrow D^0 (K^+ \pi^-) \pi_s^+ \quad 3.6 \times 10^4$ decays

$D^0$ and $\pi_s^+$ required to form a vertex constrained to PV.

PRL 110 (2013) 101802
Data divided into 13 $D^0$ decay time bins with similar number of candidates.

RS and WS yields determined in each decay time bin using fits to $M(D^0\pi^+_s)$.

Most systematics affecting the determination of yields as a function of decay time cancel in the ratio between WS and RS.

Doubly misidentified RS events correspond to (0.4±0.2)% of WS signal.

Residual (2.7±0.2)% contamination from secondary $D^0$ survives the IP cut.
\[ \langle x \rangle = (0.49^{+0.17}_{-0.18})\% \]
\[ \langle y \rangle = (0.66 \pm 0.09)\% \]

\[ \langle x \rangle = (0.49^{+0.17}_{-0.18})\% \]
\[ \langle y \rangle = (0.74 \pm 0.09)\% \]

http://www.slac.stanford.edu/xorg/hfag/charm

Latest results on "WS" $D^0 \rightarrow K\pi$ decay.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>$R_D$ ($10^{-3}$)</th>
<th>$y'$ ($10^{-3}$)</th>
<th>$x'^2$ ($10^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHCb</td>
<td>$3.52 \pm 0.15$</td>
<td>$7.2 \pm 2.4$</td>
<td>$-0.09 \pm 0.13$</td>
</tr>
<tr>
<td>Belle</td>
<td>$3.64 \pm 0.17$</td>
<td>$0.6^{+4.0}_{-3.9}$</td>
<td>$0.18^{+0.21}_{-0.23}$</td>
</tr>
<tr>
<td>BaBar</td>
<td>$3.03 \pm 0.19$</td>
<td>$9.7 \pm 5.4$</td>
<td>$-0.22 \pm 0.37$</td>
</tr>
<tr>
<td>CDF</td>
<td>$3.51 \pm 0.35$</td>
<td>$4.3 \pm 4.3$</td>
<td>$0.08 \pm 0.18$</td>
</tr>
</tbody>
</table>
http://www.slac.stanford.edu/xorg/hfag/charm

\[ \langle \chi_{CP} \rangle = (0.866 \pm 0.155)\% \]

\[ \langle A_\Gamma \rangle = (-0.022 \pm 0.161)\% \]
Time evolution of neutral $D$ mesons:

$$i \frac{d}{dt} \left( \frac{D_0^0}{D^0} \right) = \begin{pmatrix} M_{11} - \frac{i}{2} \Gamma_{11} & M_{12} - \frac{i}{2} \Gamma_{12} \\ M^{*}_{12} - \frac{i}{2} \Gamma^{*}_{12} & M_{22} - \frac{i}{2} \Gamma_{22} \end{pmatrix} \left( \begin{array}{c} D_0^0 \\ D^0 \end{array} \right),$$

CPT invariance:

$M_{11} = M_{22}, \Gamma_{11} = \Gamma_{22}.$

Mass eigenstates:

$$|D_1\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left( p|D^0\rangle + q|\bar{D}^0\rangle \right), \quad |D_2\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}} \left( p|D^0\rangle - q|\bar{D}^0\rangle \right),$$

Parameters governing mixing:

$$x = \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma},$$

$$y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta \Gamma}{2\Gamma},$$

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

Parameters governing CPV:

$$\lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} = -\eta_{CP} \left| \frac{q}{p} \right| \left| \frac{\bar{A}_f}{A_f} \right| e^{i\phi},$$

$$A_f \equiv \langle f|\mathcal{H}|D^0\rangle, \quad \bar{A}_f \equiv \langle f|\mathcal{H}|\bar{D}^0\rangle,$$

$$\frac{q}{p} = \sqrt{\frac{M^{*}_{12} - \frac{i}{2} \Gamma^{*}_{12}}{M_{12} - \frac{i}{2} \Gamma_{12}}},$$
In the SM $D^0 - \bar{D}^0$ oscillations are slow and have two mechanisms,

Short distance box amplitudes:

- GIM+CKM suppression, negligible contribution from $b$ ($|V_{ub}V_{cd}| \sim \mathcal{O}(\lambda^5)$);
- contribute only to $\Delta m$;
- Where NP could manifest.

long distance amplitudes:

- dominant mechanism, but not calculable from first principles;
- contribute to both $\Delta m$ and $\Delta \Gamma$;
- hardly sensitive to NP.

SM predictions (still rather uncertain): $x, y \sim \mathcal{O}(10^{-2} - 10^{-3})$.

$D^0 - \bar{D}^0$ oscillations driven by the first two generations:

negligible CPV in mixing.