Charm mixing and $CP$ violation at LHCb

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On behalf of the LHCb collaboration

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Mixing and CP violation

Flavor eigenstates

\[ |D^0\rangle, |\bar{D}^0\rangle \]

- Well defined flavor

Hamiltonian eigenstates

\[ |D_1\rangle, |D_2\rangle \]

- Well defined \( m \) and \( \Gamma \)
- Define the mixing parameters

\[
x = \frac{m_1 - m_2}{\Gamma}; \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}; \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}
\]

Mixing determines the states’ time evolution

\[
|D_{1,2}\rangle = p |D^0\rangle \pm q |\bar{D}^0\rangle
\]

CPV in the decay

- Different decay amplitudes for \( D^0 \) and \( \bar{D}^0 \) decays.

CPV in the mixing

- Hamiltonian eigenstates \( \neq \) CP eigenstates.
  - Different mixing rates \( D^0 \to \bar{D}^0 \) and \( \bar{D}^0 \to D^0 \).

CPV in the interference

- Hamiltonian eigenstates \( \neq \) CP eigenstates
  - Phase effect
Standard model predictions

- Short distance contributions
  - Mixing box diagrams
  - SM predicts small mixing effects
  - $b$ quarks are CKM suppressed, $s$ and $d$ quarks are GIM suppressed
  - They mainly contribute to the $\times$ mixing parameter

- Long distance contributions
  - Hadronic intermediate states
  - Expected to be dominant, but still small
  - Hard to estimate, since they are not perturbative
  - Predictions give $\times$ and $y$ in the range $[10^{-3}, 10^{-2}]$, and $|\times| < |y|$

- CPV is predicted to be $O(10^{-5} - 10^{-2})$
Charm mixing
Mixing in $D \to K^-\pi^+$

- Based on the time-evolving ratio of wrong-sign ($D^0 \to K^+\pi^-$) to right-sign ($D^0 \to K^-\pi^+$) decay rates.

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

$$\frac{A(D^0 \to K^+\pi^-)}{A(\bar{D}^0 \to K^+\pi^-)} = -\sqrt{R_D} e^{-i\delta}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

- Use flavor-conserving strong decay $D^{*\pm} \to \bar{D}^0 \pi^\pm$, where the charge of the soft pion tags the flavor of the $\bar{D}^0$ meson.
Mixing in $D \rightarrow K^-\pi^+$

- 3 fb$^{-1}$ of integrated luminosity (1 fb$^{-1}$ @ 7 TeV, 2 fb$^{-1}$ @ 8 TeV).
- 13 bins in $t$. Yields evaluated from a fit to $m_D$.
- Minimization of $\chi^2$.

$$\chi'^2 = (5.5 \pm 4.9) \cdot 10^{-5}$$

$$y' = (4.8 \pm 1.0) \cdot 10^{-3}$$

$$R_D = (3.568 \pm 0.066) \cdot 10^{-3}$$

**CP-violating parameters**

$$A_D = (-0.7 \pm 1.9) \cdot 10^{-2}$$

$$|q/p| \in (0.75, 1.24) @ 68.3\% CL.$$
Searches for localised $CP$ asymmetries
Binned approach

- Model-independent searches for CPV in distribution across phase space.
- Evaluate local population significance difference in $k$ bins

$$S_{\text{CP}}^k = \frac{N_k - \alpha \bar{N}_k}{\sqrt{\alpha (\sigma_k^2 + \bar{\sigma}_k^2)}} \quad \alpha = \frac{N}{\bar{N}}$$

- If CP is conserved, the observed $\chi^2_{\text{obs}} = \sum_k S_{\text{CP}}^k$ should have a $\chi^2$ distribution with $N_{\text{bins}} - 1$ degrees of freedom.
Search for \textit{CPV} in $D \to h^- h^+ \pi^- \pi^+$

- Binned approach.
- 1 fb$^{-1}$ of integrated luminosity @ 7 TeV.
- $D \to K^- \pi^+ \pi^- \pi^+$ control channel.
- Yields obtained from a fit to $(m_D, \Delta m)$ in 128 bins for $h = \pi$ and 32 bins for $h = K$.
- Sensitive to phase differences of 10° and magnitude differences of 10% in $D^0 \to a^+_1(1260)\pi^-$ (for $h = \pi$) and in $D^0 \to \phi \rho^0$ (for $h = K$).
  - Estimated from toy simulation using CLEO and a FOCUS amplitude models.
Search for $CPV$ in $D^+ \rightarrow \pi^- \pi^+ \pi^+$

- Binned approach crosschecked with an unbinned approach.
- 1 fb$^{-1}$ of integrated luminosity @ 7 TeV.
- $D_s \rightarrow \pi^- \pi^+ \pi^+$ control channel.
- Yields obtained from a fit to $(m_D, \Delta m)$.
- Sensitive to phase differences of $2^\circ$ and magnitude differences of 2 % in $\rho^0\pi^+$, $\sigma(500)\pi^+$ and $f_2(1270)\pi^+$.
  - Estimated from toy simulation using E791 amplitude model.
Searches for global $CP$ asymmetries
Measurement of $A_{\Gamma}$ in $D \to h^- h^+$

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

$A_{\Gamma} \equiv \frac{\bar{\tau} - \tau}{\bar{\tau} + \tau} \approx \eta_{CP} \left( \frac{A_d + A_m}{2} y \cos \phi - x \sin \phi \right)$

$A_d \equiv \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$ \hspace{1cm} $A_m \equiv \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$

- Contributions from direct CPV on $A_{\Gamma}$ measured to be small wrt $A_{\Gamma}$ precision so far.
  - This makes $A_{\Gamma}$ a measurement of indirect CP violation.
  - Important to quantify the contribution of indirect CPV to $\Delta A_{CP}$.

- 1 $fb^{-1}$ of integrated luminosity @ 7 TeV.

- Measurement in CP-even states $K^- K^+$ and $\pi^- \pi^+$.
Measurement of $A_\Gamma$ in $D \rightarrow h^- h^+$

- Two-stage fit.
  - Fit to $(m_D, \Delta m)$ to extract signal and background yields.
  - Fit to $(t, \ln \chi^2_{IP})$ to extract average lifetime $\tau$.

\[
A_\Gamma(K^- K^+) = (-0.35 \pm 0.62_{\text{stat}} \pm 0.12_{\text{syst}}) \cdot 10^{-3}
\]
\[
A_\Gamma(\pi^- \pi^+) = (+0.33 \pm 1.06_{\text{stat}} \pm 0.14_{\text{syst}}) \cdot 10^{-3}
\]
Measurement of $\Delta A_{\text{CP}}$ in $D \to h^- h^+$

- 3 fb$^{-1}$ of integrated luminosity (1 fb$^{-1}$ @ 7 TeV, 2 fb$^{-1}$ @ 8 TeV).
- Tag the $D$ flavor using the $\mu$ charge in $\bar{B} \to D^0 \mu^- \bar{\nu}_\mu X$.

$$A_{\text{raw}} \equiv \frac{N(D \to f) - N(\bar{D} \to f)}{N(D \to f) + N(\bar{D} \to f)} = A_{\text{CP}} + A_d(\mu^-) + A_p(\bar{B})$$

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

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

$$A_{\text{CP}} \approx a_{\text{CP}}^{\text{dir}} - A_F \frac{\langle t \rangle}{\tau}$$

- $\langle t \rangle / \tau$ is very similar for $K^- K^+$ and $\pi^- \pi^+$.
- $\Delta A_{\text{CP}} \approx \Delta a_{\text{CP}}^{\text{dir}}$, i.e. $\Delta A_{\text{CP}}$ contains mainly direct $CPV$ contribution.
Measurement of $\Delta A_{\text{CP}}$ in $D \rightarrow h^- h^+$

$\Delta A_{\text{CP}} = (+0.14 \pm 0.16_{\text{stat}} \pm 0.08_{\text{syst}}) \cdot 10^{-2}$

$A_{\text{CP}}(K^- K^+) = (-0.06 \pm 0.15_{\text{stat}} \pm 0.10_{\text{syst}}) \cdot 10^{-2}$

$A_{\text{CP}}(\pi^- \pi^+) = (-0.20 \pm 0.19_{\text{stat}} \pm 0.10_{\text{syst}}) \cdot 10^{-2}$

• $A_{\text{CP}}(h^- h^+)$ are the most precise measurements from a single experiment to date.
Measurement of $A_{CP}$ in $D^{\pm} \rightarrow K_s K^{\pm}$ and $D_s^{\pm} \rightarrow K_s \pi^{\pm}$

PRELIMINARY

\[ A_{CP} \equiv \frac{\Gamma(D^{+(s)} \rightarrow K_s h^+) - \Gamma(D^{-+(s)} \rightarrow K_s h^-)}{\Gamma(D^{+(s)} \rightarrow K_s h^+) + \Gamma(D^{-+(s)} \rightarrow K_s h^-)} \]

\[ A_{raw} = \frac{N^+ - N^-}{N^+ + N^-} \approx A_{CP} + A_p(D_{(s)}^{\pm}) + A_d^{h^\pm} + A_{K^0/\bar{K}^0} \]

\[ A_{DD}^{CP} = \left[ A_{raw} \left( D_s^+ \rightarrow K_s \pi^{\pm} \right) - A_{raw} \left( D_s^+ \rightarrow K_s K^{\pm} \right) \right] - \left[ A_{raw} \left( D^+ \rightarrow K_s \pi^{\pm} \right) - A_{raw} \left( D^+ \rightarrow K_s K^{\pm} \right) \right] - 2A_{K^0} \]

\[ \approx A_{CP} \left( D^+ \rightarrow K_s K^{\pm} \right) + A_{CP} \left( D_s^+ \rightarrow K_s \pi^{\pm} \right) \]

Determined using $D_s^{\pm} \rightarrow \phi \pi^{\pm}$ as control channel.
Measurement of $A_{CP}$ in $D^\pm \to K_s K^\pm$ and $D_s^\pm \to K_s \pi^\pm$

PRELIMINARY

- 3 fb$^{-1}$ of integrated luminosity (1 fb$^{-1}$ @ 7 TeV, 2 fb$^{-1}$ @ 8 TeV).

\[ A_{CP}(D^+ \to K_s K^\pm) = (+0.03 \pm 0.17_{\text{stat}} \pm 0.14_{\text{syst}}) \cdot 10^{-2} \]

\[ A_{CP}(D_s^+ \to K_s \pi^\pm) = (+0.38 \pm 0.46_{\text{stat}} \pm 0.17_{\text{syst}}) \cdot 10^{-2} \]

\[ A_{DD}^{CP} = (+0.41 \pm 0.49_{\text{stat}} \pm 0.26_{\text{syst}}) \cdot 10^{-2} \]
Conclusions
Conclusions

- LHCb has done the most significant charm mixing measurement so far.
- $CPV$ in charm not yet observed with LHCb’s current $3 \text{ fb}^{-1}$.
  - Some analysis results still to be completed.
- Sensitivity to charm $CPV$ in LHCb will become very exciting as more data are available.
Backup slides
Unbinned approach

- Test whether $D^+$ and $D^-$ samples share the same parent pdf by checking nearest neighbor events in a combined $D^+/D^-$ sample.

$$T = \frac{1}{n_k(N_+ + N_-)} \sum_{e} \sum_{k=1}^{n_k} I(e, k),$$

with

$$I(e, k) = \begin{cases} 
1 & \text{if } e\text{'s } k\text{th nearest neighbor event has same charge} \\
0 & \text{otherwise}
\end{cases}$$

- If $CP$ is conserved, $\mu_T$ approaches $1/2$ for large $N$. 
Search for $CPV$ in $D^+ \rightarrow \pi^- \pi^+ \pi^+$

- Unbinned approach in regions of phase space
  - 7 divisions separating highly resonant and highly non-resonant regions.
  - 3 divisions separating more complicated structure.
- $p$-value for $CP$ conserving hypothesis: 44%.
- Both binned and unbinned approaches are consistent with the $CP$ conserving hypothesis.

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