Mixing using multi-body decays at LHCb

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Outline

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- The LHCb detector
- Model-independent mixing measurement in $D^0 \rightarrow K^0_S \pi^+ \pi^-$
- Mixing measurement in $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$
- 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 $\Delta \Gamma \equiv \Gamma_2 - \Gamma_1 \neq 0$

- $|D_{1,2}\rangle$ expressed as linear combination of flavour eigenstates $|D^0\rangle$ and $|\overline{D}^0\rangle$

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

with $p, q \in \mathbb{C}$ satisfying $|p|^2 + |q|^2 = 1$

- Mixing parameters $x \equiv \Delta m/\Gamma$ and $y \equiv \Delta \Gamma/(2\Gamma)$

$$P(D^0 \rightarrow \overline{D}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left\{ - \cos(x \Gamma t) + \cosh(y \Gamma t) \right\}$$
The LHCb detector

Cherenkov detectors

Forward spectrometer with acceptance $2 < \eta < 5$
MODEL-INDEPENDENT MIXING MEASUREMENT IN $D^0 \rightarrow K^0_S \pi^+ \pi^-$ DECAYS
Method

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay amplitudes carry
  - strong phase → invariant under CP transformation
  - weak phase → change sign under CP transformation

- Strong phase difference $\Delta \delta_D$ measurable
- Sensitivity to mixing is large in regions of phase-space where interference between $D^0$ and $\overline{D}^0$ amplitudes is large
- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ allows to disentangle $\Delta \delta_D$ and $x$ & $y$
Method

- Dalitz plane divided in 16 bins with constant $\Delta \delta_D$
- Bins symmetric around $m^2(\pi^+\pi^-)$ axis
- Binned measurements provided by CLEO for various amplitude models
  - Here: equal $\Delta \delta_D$ Babar 2008
- Method not sensitive to model-dependent systematics
Method

- Phase-space dependent amplitudes for
  - $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays: $A$
  - $\bar{D}^0 \rightarrow K_S^0 \pi^- \pi^+$ decays: $B$

- Fraction of $D^0$ events in bin $i$ → $T_i = \int_i |A|^2 dm_+^2 dm_-^2$

- Interference terms between amplitudes $A$ and $B$

$$c_i \equiv \frac{1}{\sqrt{T_i T_i}} \int_i |A^*||B| \cos(\Delta \delta_D) dm_+^2 dm_-^2$$

$$s_i \equiv \frac{1}{\sqrt{T_i T_i}} \int_i |A^*||B| \sin(\Delta \delta_D) dm_+^2 dm_-^2$$

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Method

- Time-dependent decay rates expressed as

\[
\mathcal{P}(D^0) \approx e^{\Gamma t} \left( T_{-i} - \Gamma t \sqrt{T_i T_{-i}} \{ yc_i + xs_i \} \right) \\
\mathcal{P}(\overline{D}^0) \approx e^{\Gamma t} \left( T_{-i} - \Gamma t \sqrt{T_i T_{-i}} \{ yc_i - xs_i \} \right)
\]

assuming CP symmetry

- \( T_i, c_i \) and \( s_i \) provided by CLEO

→ allows model-independent measurement of mixing parameters \( x \) and \( y \)
Analysis

- Model-independent measurement of $\times$ and $y$ using $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays on 2011 dataset of 1/fb at 7TeV
- $D^0$ originate from decay of $D^{*+} \rightarrow D^0 \pi^+_S$ directly produced in pp collision (prompt)
- Difference in $\chi^2$ between PV reconstructed with and without $D^0$ to discriminate prompt against secondary decays ($\ln \chi^2_{\text{IP}}$)
Analysis

Extended ML fit to $m_D$
(signal and combinatorial background)

ML fit to $(t_D, \ln \chi^2_{IP})$
(background shapes from sidebands)

Extended ML fits to $(m_D, \delta m)$
(per bin for $D^{*+}$ and $D^{*-}$ separately)

Simultaneous ML fits to $(t_D, \ln \chi^2_{IP})$
(background shapes from sidebands)

$n(sig)$ and $n(comb)$

Shape of $\ln \chi^2_{IP}$ for prompt and secondary

$n(sig)$ and $n(bkg)$ per bin

$x, y$
Results

- First model-independent measurement of $x$ and $y$ using $D^0 \rightarrow K^0_S \pi^+ \pi^-$ decays on 1/ fb dataset
  - $x = (-0.86 \pm 0.53 \pm 0.17) \times 10^{-2}$
  - $y = (+0.03 \pm 0.46 \pm 0.13) \times 10^{-2}$

- Systematics from $T_i$ values, resolution effects, background, ...

- Current world averages\(^1\)
  - $x = (+0.37 \pm 0.16) \times 10^{-2}$
  - $y = (+0.66^{+0.07}_{-0.10}) \times 10^{-2}$

\(^1\) arXiv:1412.7515 and online update at http://www.slac.stanford.edu/xorg/hfag
MIXING MEASUREMENT IN \( D^0 \rightarrow K^+ \pi^- \pi^+ \pi^- \) DECAYS
Method

- Measurement of time-dependent ratio of wrong-sign $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ to right-sign $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decays

$$R(t) \approx (r_D^{K3\pi})^2 - r_D^{K3\pi} R_D^{K3\pi} \cdot y'_K \frac{t}{\tau} + \frac{x^2 + y^2}{4} \left( \frac{t}{\tau} \right)^2$$

assuming CP symmetry

- Allows measurements of
  - phase-space averaged ratio of DCS to CF amplitudes $r_D^{K3\pi}$
  - coherence factor $R_D^{K3\pi}$
  - mixing parameter $y'_K = y \cos(\Delta \delta_D^{K3\pi}) - x \sin(\Delta \delta_D^{K3\pi})$

$r_D^{K3\pi}, R_D^{K3\pi}$ and $\Delta \delta_D^{K3\pi}$ needed for $\gamma$ measurement
Analysis

- Measurement of $R_D^{K3\pi} \cdot y'_{K3\pi}$ and $r_D^{K3\pi}$ using $D^0 \rightarrow K3\pi$ decays on Run 1 dataset of 3/fb at 7 and 8TeV
- $D^0$ originate from prompt $D^{*+} \rightarrow D^0\pi^+_s$ decays

Yields
- Right-sign (RS): 11.4M
- Wrong-sign (WS): 43k
Analysis

- Extract ratio of WS to RS yields by fitting $\delta m$ in ten different bins of decay time simultaneously for WS/RS and $D^0/\bar{D}$.

- Ratio in each bin calculated as

$$\sqrt{(N_{WS}D^0 \cdot N_{WS}\bar{D}^0)/(N_{RS}D^0 \cdot N_{RS}\bar{D}^0)}$$

→ effects of $D^*$ production asymmetries or $\pi_s$ detection efficiency largely cancel

- Systematics (amongst others) from
  - misidentification of kaon and pion
  - $D^0 \rightarrow K^+\pi^-K_S^0$, $K_S^0 \rightarrow \pi^+\pi^-$ and secondary decays
  - fake tracks reconstructed as $\pi_s$
Results

- **Unconstrained fit**
  
  \[ r_D^{K3\pi} = (5.67 \pm 0.12) \times 10^{-2} \]
  
  \[ R_D^{K3\pi} \cdot y'_K3\pi = (0.3 \pm 1.8) \times 10^{-3} \]
  
  \[ \frac{x^2 + y^2}{4} = (4.8 \pm 1.8) \times 10^{-5} \]

- **Mixing-constrained\(^1\) fit**
  
  \[ r_D^{K3\pi} = (5.50 \pm 0.07) \times 10^{-2} \]
  
  \[ R_D^{K3\pi} \cdot y'_K3\pi = (-3.0 \pm 0.7) \times 10^{-3} \]

\(^1\) x and y constrained to WA from arXiv:1412.7515 and online update at [http://www.slac.stanford.edu/xorg/hfag](http://www.slac.stanford.edu/xorg/hfag)

No-mixing hypothesis excluded at 8.2\(\sigma\)
Results

- Mixing-constrained fit allows determination of lines of solutions in \((R_{D}^{K3\pi}, \Delta\delta_{D}^{K3\pi})\) plane

![Diagram showing the lines of solutions in the \((R_{D}^{K3\pi}, \Delta\delta_{D}^{K3\pi})\) plane, with contours for 68.3%, 95.4%, and 99.7% CL.]
Comparison with result from CLEO-c

\[ \Delta \chi^2 = 1 \]
\[ \Delta \chi^2 = 4 \]
\[ \Delta \chi^2 = 9 \]
Conclusion

- First model-independent measurement of mixing parameters in $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decays as proof of principle

- Sensitivity will improve significantly with full Run 1 (and Run 2) data due to dedicated trigger lines
Conclusion

- Mixing observed in $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ with significance of $8.2\sigma$
- $D^0 \rightarrow K^+\pi^-\pi^+\pi^-$ analysis provides input for $\gamma$ measurement
- Stay tuned for Run II!