Charm mixing & CP violation

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Moriond QCD and High Energy Interactions
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Mixing

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle$$

Mass eigenstates  Flavour eigenstates

Width difference  →  Lifetime difference

$$\Delta \Gamma \equiv \Gamma_2 - \Gamma_1$$  \quad  $$y \equiv \Delta \Gamma/(2\Gamma)$$

Mass difference  →  Oscillation

$$P(M^0 \rightarrow \bar{M}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} (\cosh(y\Gamma t) - \cos(x\Gamma t))$$

$$\Delta m \equiv m_2 - m_1$$  \quad  $$x \equiv \Delta m/\Gamma$$

Charm mixing:  Need ~1000 lifetimes to see a full oscillation!
Old habits die hard...

• The chains of habit are too light to be felt until they are too heavy to be broken. – W. Buffet

• The charm quarks are too light to be felt by $\Lambda_{QCD}$ and they are too heavy to be perturbed chirally.

• But are they?

  ➔ HQE might still work
e.g. Lenz, Rauh, Phys.Rev. D88 (2013) 034004

  ➔ Lattice QCD may one day be able to provide input on hadronic matrix elements of open charm decays.
e.g. Carrasco et al., PoS LATTICE2012 (2012) 105
Mixing &
Indirect CP violation
Measuring mixing

\[ P(M^0 \rightarrow \bar{M}^0, t) = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left( \cosh(y \Gamma t) - \cos(x \Gamma t) \right) \]

\[ \approx \frac{1}{2}(x^2 + y^2)(\Gamma t)^2 - \frac{1}{24}(x^4 - y^4)(\Gamma t)^4 \]

current world averages → 3×10^{-5} \hspace{2cm} -7×10^{-11}

need \( t > 200\tau \) for a 10% contribution of this term
Mixing discovery

- First single-experiment measurement >5σ significance
- Rotation of mixing parameters by strong phase difference
Mixing

- First single-experiment measurement $>5\sigma$ significance
- Rotation of mixing parameters by strong phase difference

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

$R(t) \equiv \frac{N_{WS}(t)}{N_{RS}(t)} \approx R_d + \sqrt{F} \left( t, x'^2 + y'^2, t \right)$

CDF, PRL 111 (2013) 231802

Belle, PRL 112 (2014) 111801

PRL 110 (2013) 101802
Mixing and CP violation

- Update with 3 fb$^{-1}$
- Split by flavour to search for CP violation
  \[ x'^{\pm} = |q/p|^{\pm 1} (x' \cos \Phi \pm y' \sin \Phi) \]
  \[ y'^{\pm} = |q/p|^{\pm 1} (y' \cos \Phi \mp x' \sin \Phi) \]
- No indication for indirect or direct CP violation
Indirect CP violation

• Measure asymmetries of effective lifetimes of decays to CP eigenstates:
  \[ A_\Gamma \approx A_M y \cos \phi + x \sin \phi \equiv -a_{\text{CP}}\text{ind} \]
  (Neglecting \(A_d y \cos \phi\))

• Measures ability of both mass eigenstates to decay to CP eigenstate

• Measurements use \(D^0 \to K^-K^+\) and \(D^0 \to \pi^-\pi^+\) decays (1 fb\(^{-1}\))

  \[ A_\Gamma(KK) = (-0.35\pm0.62\pm0.12)\times10^{-3} \]
  \[ A_\Gamma(\pi\pi) = (0.33\pm1.06\pm0.14)\times10^{-3} \]
Direct CP violation
D^+ \rightarrow 3\pi

- Model-independent searches for CP violation
  - Over 3M D^+ & D^- decays in 1 fb^{-1}
  - Search for asymmetry significances in bins of phase space
  - Search for local asymmetries through un-binned comparison with nearest neighbours
Binned method

$$S_{CP}^i = \frac{N^i(D^+) - \alpha N^i(D^-)}{\sqrt{N^i(D^+) + \alpha^2 N^i(D^-)}}$$

$$\alpha = \frac{N_{tot}(D^+)}{N_{tot}(D^-)}$$

$$\chi^2 = \sum (S_{CP}^i)^2$$

removes sensitivity to global asymmetries

p-values for no-CPV hypothesis

> 50% for different binnings
\[ D^0 \rightarrow 4h \]

- 4-body phase space has 5 dimensions!
  - Bin in 5D hypercubes
- Analyse 1 fb\(^{-1}\) of \( D^0 \rightarrow 4\pi/\Lambda K\Lambda K \) decays
  - Use search for asymmetry significances in 128/32 bins of 5D phase space
  - \( p \)-values for no CPV hypothesis are 9.1% for \( \Lambda K\Lambda K \pi\pi \) and 41% for \( 4\pi \)

Simulation of \( D^0 \rightarrow \Lambda K\Lambda K \pi\pi \) courtesy of D. Saunders

PLB 726 (2013) 623
The $\Delta A_{CP}$ saga*

- Measure time-integrated CP asymmetries in $D \rightarrow hh$ decays

$$A_{CP}(f) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow \bar{f})}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow \bar{f})}$$

- Decays to CP eigenstates: $f = K^+K^-, \pi^+\pi^+$

- $A_{CP}$ is a sum of direct and indirect CP violation, leading to

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi) \approx \Delta a_{CP}^{\text{dir}} (1 + y_{CP} \langle t \rangle /\tau) + a_{CP}^{\text{ind}} \Delta \langle t \rangle /\tau$$

- Need to measure asymmetries and time distributions


- More news to be expected soon!

*after A. Lenz, arXiv:1311.6447
Interplay
Theory

- $\delta_{K\pi\pi\pi\pi\pi}$
- $\delta_{K\pi\pi}$
- $\delta_{K\pi\pi\pi0}$
- $R_D$
- $x$
- $y$
- $|q/p|$
- $\phi$
- $A_K$
- $A_{\pi\pi}$
- $\Delta A_{CP}$

Experiment

- $K\pi\pi\pi\pi\pi$
- $K\pi\pi$
- $K\pi\pi\pi^0$
- $K_{l3}\nu$
- $K_{l3}h$
- $\chi$
- $\gamma$
- $\gamma_{CP}$
- $A_R$
- $K_{S,h}\phi$

CHARM 2013

Before

After

$Arg(q/p)$ [deg.

$Arg(q/p)$ [deg.]

Before and After:

- Charmed Baryon Mixings
- Theory and Experiment
- CP violation
- Direct and Indirect

HFAG-Charm
April 2013
CHARM 2013

HFAG-charm

CHARM 2013

no CPV
Conclusions

• Charm physics has received precision input from hadron colliders

• Large advances in searches for CP violation
  ➡ Reached sub-$10^{-3}$ precision
  ➡ Also large numbers of charm baryons available

• Need combination of measurements to
  ➡ Extract mixing and indirect CPV parameters
  ➡ Identify source of possible direct CPV

• Experimental upgrade programmes, particularly LHCb upgrade, vital for charm physics
Backup
Observables

Construct observable without external input:

\[ A_{CP}^{RAW}(KK)^* = A_{CP}(KK) + A_D(\pi_s) + A_P(D^*) \]

\[ A_{CP}^{RAW}(\pi\pi)^* = A_{CP}(\pi\pi) + A_D(\pi_s) - A_P(D^*) \]

2 observables  2 CP asymmetries  1 detection asymmetry  1 production asymmetry

Expect indirect CP violation to cancel in difference as caused by common mixing process
Direct CP violation expected to differ for different final states
Expect non-zero result in presence of direct CP violation
Complementary New Physics search to \( A_\Gamma \) measurement
An idea

\[ A_{CP}^{RAW}(KK)^* = A_{CP}(KK) + A_D(\pi_s) + A_P(D^*) \]

measure \xleftarrow{\text{want}}

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

\[ A_D(K^-\pi^+) \]

\[ D^+ \rightarrow K^-\pi^+\pi^+ \]

\[ A_P(D^+), A_D(\pi^+) \]

\[ D^+ \rightarrow K_S\pi^+ \]

\[ A_{CP/1}(K_S) \]

assume no CPV in Cabibbo-favoured final states