$D^0$ Mixing and CP Violation at the BABAR Experiment

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Outline

1. Introduction to Mixing and CP Violation in the Charm Sector
2. Peculiarity of $D$ Mixing & New Physics (NP)
3. Analysis on $D$ Mixing at the $BABAR$ experiment
   - $D^0 \rightarrow K^+\pi^-$ (Wrong Sign)
   - $D^0 \rightarrow K^+K^-, K^-\pi^+$ (lifetime ratio)
4. New analysis in $BABAR$: $D^0 \rightarrow K^0_S h^+h^-, h = K, \pi$
   - peculiarity of the method
   - status and expectations
5. Conclusions
Part I

Mixing in the Charm Sector
\(D^0\) and \(\bar{D}^0\) are created as \textit{flavour eigenstate} by the strong interaction, they mix via the weak interaction. Their evolution is obtained by solving:

\[
i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left( M - \frac{i}{2} \Gamma \right) \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}
\]

diagonalized by the \textit{mass eigenstates}:

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

where

\[
\frac{q}{p} = \sqrt{\frac{M_{12}^* - i \Gamma_{12}^*/2}{M_{12} - i \Gamma_{12}/2}} \quad \text{and} \quad |q^2| + |p^2| = 1 \quad \text{(assuming CPT invariance)}
\]

\textbf{Mixing Parameters:}

\[
x_D = \frac{m_1 - m_2}{\Gamma} \quad y_D = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \quad \lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f} = |\lambda_f| e^{i(\delta_f + \phi)}
\]

\textbf{CP Violation (CPV) can occur in 3 ways:}

- in decay: \(|A_f| \neq |\bar{A}_f|\) \quad (\(|A_f| = \langle D^0 \mid \mathcal{H} \mid f \rangle\), \(|\bar{A}_f| = \langle \bar{D}^0 \mid \mathcal{H} \mid \bar{f} \rangle\))
- in mixing: \(|q/p| \neq 1\)
- in the \textit{interference} between decay and mixing: \(\arg(\lambda_f) \neq 0\)
Peculiarity of $D$ Mixing & NP

1 Important measurement for the **Standard Model**:
   - complete the picture of neutral meson mixing in the SM;
   - virtual down type quarks involved in mixing loop (only in $D$ system).

2 **Standard Model predictions**:
   - important uncertainties on SM prediction due to long distance diagrams

3 Important contribution in the search for **New Physics**:
   - $D$ exhibits the smallest mixing and CPV $\Rightarrow$ NP detection is facilitated
   - $|x_D| >> |y_D|$ or CP violation would be a sign of NP;
   - NP models must account for this measure $\Rightarrow$ important constraints on NP models;
Part II

$D^0$ Mixing at the BABAR Experiment
\[ D^0 \rightarrow K^+\pi^- \]

wrong sign decay time distribution

discriminate DCS and MIX-CF by the time dependance of the WS decay of a meson which was a \( D^0 \) at \( t = 0 \):

\[
T_{WS}(t) \propto e^{-\Gamma t} (R_D + \sqrt{R_D}y'\Gamma t + \frac{x'^2 + y'^2}{2}(\Gamma t)^2)
\]

(in the limit of CP conservation and \( |x_D|, |y_D| \ll 1 \))

where:

\[
R_D = \frac{\text{DCS decay rate}}{\text{CF decay rate}}
\]

\[
x' = x_D \cos \delta_{K\pi} + y_D \sin \delta_{K\pi}
\]

\[
y' = -x_D \sin \delta_{K\pi} + y_D \cos \delta_{K\pi}
\]

\[
\delta_{K\pi} = \text{strong phase} \text{ between the DCS and the CF decay}
\]

(Not measurable at B-Factories)

Evidence for \( D^0 \) mixing (3.9\( \sigma \)) & No evidence for CPV

\[
R_D = (0.303 \pm 0.016 \pm 0.01)\%
\]

\[
x'^2 = (-0.022 \pm 0.03 \pm 0.021)\%
\]

\[
y' = (0.97 \pm 0.44 \pm 0.31)\%
\]

\( N_{\text{sig}} = 4k \)

\( L_{\text{int}} = 384 \text{ fb}^{-1} \)
For $D^0 \rightarrow K^+ K^-, K^- \pi^+$, a lifetime difference measurement, one manifestation of $D$ mixing is differing $D^0$ decay time distributions for decays to different CP eigenstates:

$$y_{CP} = \frac{\langle \tau_{K\pi} \rangle}{\langle \tau_{KK} \rangle} - 1$$

(in the limit of $|x_D|, |y_D| << 1$ and no CPV in mixing and interference)

$\langle \tau_{K\pi} \rangle$ is the $D^0$ mean lifetime of decays to a state of indefinite CP

$\langle \tau_{KK} \rangle$ is the $D^0$ mean lifetime of decays to a CP-even final state

Untagged sample:

- $N_{K\pi} = 2.7M$
- $N_{KK} = 264k$
- $L_{int} = 384 \text{ fb}^{-1}$

Evidence for $D^0$ mixing (3.3σ):

$$y_{CP} = (1.12 \pm 0.26 \pm 0.22)\%$$

Combining the tagged $y_{CP}$ and the untagged $y_{CP}$:

Evidence for $D^0$ mixing (4.1σ):

$$y_{CP} = (1.16 \pm 0.22 \pm 0.18)\%$$

Ref: PRD 78, 011105 (2008)
The Dalitz Plot (DP): $(m^2_{K^0_S\pi^-}, m^2_{K^0_S\pi^+})$

- many resonances contribute and interfere: 
  \[ A_f(m_-, m_+) = \sum_r a_r e^{i\phi_r} A_r(m^2_-, m^2_+) + a_{NR} r^{i\phi_{NR}}; \]

- a Dalitz model is assumed and all the amplitudes and phases are extracted in the fit;

- in the limit of no direct CP violation we can write the PDF as a function of only one amplitude, let’s say $A_f$, and extract all the parameters from data ⇒ NO strong phase rotation of the mixing parameters!!

\[ \Gamma(D^0 \to f, t) \propto |A_f|^2 e^{-\Gamma t} \left[ \frac{1+|\lambda_f|^2}{2} \cosh(y_D \Gamma t) + \frac{1-|\lambda_f|^2}{2} \cos(x_D \Gamma t) - Re\lambda_f \sinh(y_D \Gamma t) - Im\lambda_f \sin(x_D \Gamma t) \right] \]

\[ \lambda_f = \frac{q \hat{A}_f}{p \bar{A}_f} \]

- the sensitivity to mixing is amplified by the fact that $\lambda_f$ varies on the DP: $\lambda_f = \lambda_f(m_-, m_+) \Rightarrow$ there can be big interferences and relative phases.
ongoing analysis

\[ L_{\text{int}} = 468 \text{ fb}^{-1} \]

\[ D^0 \rightarrow K^0_S h^+ h^-, \ h = K, \pi \]

The Method

- The decay chain is fully reconstructed:
  \[ D^{*+} \rightarrow D^0 \pi^+_s \text{ (or c.c.), } D^0 \ (\overline{D^0}) \rightarrow K^0_S h^+ h^-, \ K^0_S \rightarrow \pi^+ \pi^- \]
  - \( D \) flavour is tagged by the charge of the (slow) pion emitted by the \( D^* \);
  - a beam spot constraint to the \( D^* \) decay reconstruction is applied.

- Selection of the events
  - \( e^+ e^- \rightarrow c \bar{c} \) events have high \( D^0 \) momentum in the CM frame \( \Rightarrow \) momentum cut to reject \( D^0 \) from \( B\bar{B} \) events (\( p_{D^0}^* > 2.5 \text{ GeV}/c \));
  - quality cuts in order to have well measured tracks and a well measured \( D^0 \) lifetime (e.g. \( p_t(\text{tracks}) > 100 \text{ MeV}/c, \sigma_t < 1\text{ps} \))
  - dedicated cuts on \( K^0_S \) flight length and collinearity angle in order to remove bkg events with the same final state as signal (\( D^0 \rightarrow KK\pi\pi \) or \( D^0 \rightarrow 4\pi \)).

- Discrimination between signal and background events
  - use the distribution of the variables \( m_{D^0} \) and \( \Delta m \) in order to discriminate signal events from bkg categories events:
    \[ \Delta m = m_{D^*} - m_{D^0}, \ m_{D^0} = \text{the reconstructed mass of the } D^0; \]
  - very good resolution on \( \Delta m \) due to the small Q-value of the \( D^* \) reaction.
bkg categories:
Cat2 = true $D^0$ & misrec $\pi_s$
Cat3 = misrec $D^0$ & true $\pi_s$
Cat4 = misrec $D^0$ & misrec $\pi_s$

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

Fit to MonteCarlo events

- proper time fit to full MC: $\tau = (412.4 \pm 0.8)$ ps compatible with the generated lifetime
- we found no bias on lifetime fitting a full MC sample implemented with mixing

the purity of the selection is greater than 98%
$D^0 \rightarrow K_s^0 h^+ h^-, \; h = K, \pi$

Status and Expectations

blind fit and evaluation of systematics is done:

- statistical errors:
  $\sigma_{x}^{\text{stat}} = 0.23\%, \; \sigma_{y}^{\text{stat}} = 0.20\%$

- most important sources of systematic error:

<table>
<thead>
<tr>
<th>source</th>
<th>$\sigma_{x}^{\text{syst}} / \sigma_{x}^{\text{stat}}$</th>
<th>$\sigma_{y}^{\text{syst}} / \sigma_{y}^{\text{stat}}$</th>
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<tbody>
<tr>
<td>Dalitz Model</td>
<td>49%</td>
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<tr>
<td>Fit Bias</td>
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<td>Final Fit Cuts</td>
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<tr>
<td>Mistag</td>
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<td>16%</td>
</tr>
<tr>
<td>Efficiency Map</td>
<td>16%</td>
<td>9%</td>
</tr>
</tbody>
</table>

N.B.: the central point is moved by an unknown quantity

world single measurement best sensitivity on $x_D$ and $y_D$ expected
Part III

Conclusions
Conclusions

- Measuring $x_D$ and $y_D$ is important for SM Physics and for New Physics models which must be able to account for the result of this measure;
- $BABAR$ had evidence of mixing in $D \to K^+\pi^-$ wrong sign decay time analysis and $D \to KK, K\pi$ lifetime difference analysis but no evidence for CP violation;
- The Time Dependent Analysis on the Dalitz Plot $D^0 \to K_S^0 h^+ h^-$ ($h = K, \pi$) allows a direct measurement of the mixing parameters; this analysis is actually ongoing in $BABAR$. 