D⁰ Mixing at the B-Factories

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Topics

✓ Introduction
✓ $D^0$ mixing formalism
✓ BABAR results
  • $D^0 \rightarrow K\pi$ mixing analysis
✓ Belle results
  • Lifetime difference analysis
  • $D^0 \rightarrow K_s\pi\pi$ analysis
✓ Summary
Introduction

- Neutral meson mixing has been already observed in the K (1956), B_d (1987) and B_s (2006) systems

- Why is D^0 mixing interesting?
  - It completes the picture of quark mixing already observed in other systems
  - Provides new information about processes with down-type quarks in the mixing loop diagram
  - It is an important step towards the observation of CP violation in the Charm sector
  - New physics may be present depending on the measured values of the mixing parameters
**D⁰ Mixing Formalism**

Neutral $D$ mesons are produced as *flavor eigenstates* $D^0$ and $\overline{D^0}$ and decay via:

$$i \frac{\partial}{\partial t} \left( \frac{D^0(t)}{\overline{D^0}(t)} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{D^0(t)}{\overline{D^0}(t)} \right)$$

as *mass eigenstates* $D_1, D_2$

$$|D_1\rangle = p|D^0\rangle + q|\overline{D^0}\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D^0}\rangle$$

where $|q|^2 + |p|^2 = 1$ and

$$\left( \frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}}$$

$D_1, D_2$ have masses $M_1, M_2$ and widths $\Gamma_1, \Gamma_2$

Mixing occurs when there is a *non-zero* mass difference

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta \Gamma = \Gamma_1 - \Gamma_2$$

For convenience define quantities $x$ and $y$

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2\Gamma}$$

where

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$
D^0 Mixing Processes

• Short-distance contributions from mixing box diagrams in the Standard Model are expected to be small:
  - b quark is CKM-suppressed
    • |V_{ub}V^{*}_{cb}|^2
  - s and d quarks are GIM suppressed
    • (m_s^2-m_d^2)/m_W
  - mainly contributes to the mass diff.
    • x \approx \mathcal{O}(10^{-5})

• Long-distance contributions dominate
  - non-perturbative effects (hard to calculate)
  - expect to be \mathcal{O}(10^{-2}) or less in the SM
  - mainly affect the lifetime diff. y (but also x)
    • x, y \approx \sin^2 \theta_C x [SU(3) breaking]^2
New Physics $D^0$ Mixing Predictions

- Possible enhancements to mixing due to new particles and interactions in new physics models.
- Most new physics predictions for $x$:
  - Extended Higgs, tree-level FCNC
  - Fourth generation down-type quarks
  - Supersymmetry: gluinos, squarks
  - Lepto-quarks

- Large possible SM contributions to mixing require observation of either a CP-violating signal or $|x| >> |y|$ to establish presence of NP.
- A recent survey (arXiv:0705.365v1) summarizes models and constraints:

<table>
<thead>
<tr>
<th>Fourth generation</th>
<th>Vector leptoquarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = -1/3$ singlet quark</td>
<td>Flavor-conserving Two-Higgs</td>
</tr>
<tr>
<td>$Q = +2/3$ singlet quark</td>
<td>Flavor-changing neutral Higgs</td>
</tr>
<tr>
<td>Little Higgs</td>
<td>Scalar leptoquarks</td>
</tr>
<tr>
<td>Generic $Z'$</td>
<td>MSSM</td>
</tr>
<tr>
<td>Left-right symmetric</td>
<td>Supersymmetric alignment</td>
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</tbody>
</table>
BABAR $D^0 \rightarrow K\pi$ mixing analysis

We select a clean sample of $D^0$ and $\bar{D}^0$ by tagging the flavor at production time using the decays of $D^{*\pm} \rightarrow \pi^{\pm} D^0$

- We select events around the expected $\Delta m = m(D^0_{\text{rec.}}) - m(D^0_{\text{rec.}})$
- The charge of the slow pion determines the flavor of the $D^0$

We identify the $D^0$ flavor at decay time using the charge of the Kaon

$D^0 \rightarrow K^- \pi^+$ right-sign (RS)

$D^0 \rightarrow K^+ \pi^-$ wrong-sign (WS)

Vertices fit with beamspot constraint determines $m_{K\pi}$, $\Delta m$, proper-time $t$ and error $\delta_t$

Typical $D^0$ flight length $d \sim 240 \ \mu m$

Average resolution $\sigma_d \sim 95 \ \mu m$
**Time evolution of $D^0 \rightarrow K\pi$ decays**

Mixing occurs when a meson produced as a $D^0$ decays as a $\bar{D}^0$ or vice versa.

Right sign decays (RS):
- Cabibbo-favored (CF) $D^0 \rightarrow K^-\pi^+$ → no mixing

Wrong sign decays (WS):
- Doubly Cabibbo-suppressed (DCS)
  - Rate ($R_D$): $\tan^4 \theta_C \approx 0.3\%$
- Mixing followed by CF decay
  - Rate ($R_M$): $10^{-4}$ or less

Need to discriminate between DCS and Mixing decays by their proper time evolution (assuming CP-conservation and $|x|\ll 1$, $|y|\ll 1$):

$$\frac{d\Gamma}{dt} \left[|D^0(t)\rangle \rightarrow f\right] \propto e^{-\Gamma t} \left( R_D + \sqrt{R_D} y' \Gamma t + \frac{x'^2 + y'^2}{4} (\Gamma t)^2 \right)$$

$x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}$, $y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}$

$\delta_{K\pi}$: strong phase difference between CF and DCS decay amplitudes
RS and WS $m_{K\pi}, \Delta m$ Distributions

All fits are over the full range shown in the plots
1.81 GeV/c² < $m_{K\pi}$ < 1.92 GeV/c² and 0.14 GeV/c² < $\Delta m$ < 0.16 GeV/c²

Define a signal region
1.843 GeV/c² < $m_{K\pi}$ < 1.883 GeV/c² and 0.1445 GeV/c² < $\Delta m$ < 0.1465 GeV/c²
Mixing WS decay time fit

The difference between the no-mixing fit and the fit with mixing is shown in the residuals plot.

The points represent the data minus the no-mixing fit (effectively the dashed line ---).

The solid curve represents the mixing fit minus the no-mixing fit.

The fit is significantly improved by allowing for mixing.

WS mixing fit projection in the signal region

\[ 1.843 \text{ GeV}/c^2 < m < 1.883 \text{ GeV}/c^2 \]
\[ 0.1445 \text{ GeV}/c^2 < \Delta m < 0.1465 \text{ GeV}/c^2 \]
Mixing fit likelihood contours

Contours in $y', x'^2$ computed from $-2\Delta \ln L$
- Best-fit point is in the non-physical region $x'^2 < 0$
- $1\sigma$ contour extends into physical region
- Correlation: $-0.95$

Contours include systematic errors

The no-mixing point is at the $3.9\sigma$ contour

Fits show no evidence for CP violation

Best fit: $x'^2 \geq 0$
Best fit, $x'^2 \geq 0$
No mixing: (0,0)

$-2\Delta \ln L = 0.7$
$-2\Delta \ln L = 23.9$

$1 - \text{CL} = 3.17 \times 10^{-1} (1\sigma)$
$4.55 \times 10^{-2} (2\sigma)$
$2.70 \times 10^{-3} (3\sigma)$
$6.33 \times 10^{-5} (4\sigma)$
$5.73 \times 10^{-7} (5\sigma)$

$R_D: (3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
$x'^2: (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
$y': (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$
BABAR vs. BELLE $D^0 \rightarrow K\pi$ result

Results consistent within $2\sigma$

PRL 96, 151801
$400 \text{ fb}^{-1}$

PRL 98, 211802 (2007)
$384 \text{ fb}^{-1}$

no-mixing excluded at $2\sigma$

BELLE $2\sigma$ statistical

BABAR $1\sigma$

BABAR $2\sigma$

BABAR $3\sigma$
Average $K\pi$ Mixing Results

Heavy flavor averaging group (HFAG) provides “official” averages

Combine BaBar and Belle likelihoods in 3 dimensions $(R_D, x'^2, y')$

July 2007 Averages:

$R_D = (3.30^{+0.14}_{-0.12}) \times 10^{-3}$

$x'^2 = (-0.01 \pm 0.20) \times 10^{-3}$

$y' = (5.5^{+2.8}_{-3.7}) \times 10^{-3}$

No mixing excluded $> 4\sigma$
Look for a lifetime difference $y_{CP}$ between $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$ (CP-even) and the $D^0 \rightarrow K^-\pi^+$ (CP-mixed)

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1$$

If CP is conserved, then $y_{CP} = y$

CP violation would give a lifetime difference in $D^0$ and $\bar{D}^0$ decays to $K^+K^-$, $\pi^+\pi^-$ final states,

Measure e.g. :

$$\Lambda_{\Gamma} = \frac{\tau(\bar{D}^0 \rightarrow K^-K^+)}{\tau(\bar{D}^0 \rightarrow K^-K^+)} - \frac{\tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^+K^-)}$$
Measure lifetime difference of CP eigenstates

\[ y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1 \]

From the combined fit to KK and \( \pi\pi \):

Evidence for \( D^0 - \bar{D}^0 \) mixing (regardless of possible CPV)

\[ y_{CP} = (1.31\pm0.32\pm0.25) \% \]

> 3\( \sigma \) above zero

\[ A_{\Gamma} = (0.01\pm0.30\pm0.15) \% \]

no evidence for CP violation

BELLE \( K^+K^-, \pi^+\pi^- \) lifetime ratio

PRL 98,211803 (2007)
BELLE $D^0 \rightarrow K_s \pi \pi$ Analysis

Time-dependent, Dalitz-plot analysis using $D^{*+} \rightarrow D^0 \pi^+$,
$D^0 \rightarrow K_s \pi \pi + \text{c.c.}$ decays

Self-conjugate mode
Initially-produced $D^0$ decay amplitude is given by

$$M(m_-^2, m_+^2, t) = A(m_-^2, m_+^2) \frac{e_1(t) + e_2(t)}{2} + \frac{q}{p} \overline{A}(m_+^2, m_-^2) \frac{e_1(t) - e_2(t)}{2}$$

where $A$ and $\overline{A}$ are amplitudes for decay to $D^0$ or $D^0$ as functions of phase-space variables, and

$$m_{\pm} = \begin{cases} m(K_s, \pi^\pm) & D^{*+} \rightarrow D^0 \pi^+ \\ m(K_s, \pi^\mp) & D^{*-} \rightarrow \overline{D}^0 \pi^- \end{cases} \quad e_{1,2}(t) = \exp(-i(m_{1,2} - i\Gamma_{1,2}/2)t)$$

Measures $x$ and $y$ directly
All phases are measured in the Dalitz plot analysis
BELLE $D^0 \rightarrow K_s \pi \pi$ Analysis

- Dalitz fit model
  - 18 BW resonances + a non-resonant contribution:

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^{*}(892)^-$</td>
<td>1.629 ± 0.005</td>
<td>134.3 ± 0.3</td>
<td>0.6277</td>
</tr>
<tr>
<td>$K_S^0(1430)^-$</td>
<td>2.12 ± 0.02</td>
<td>−0.9 ± 0.5</td>
<td>0.0724</td>
</tr>
<tr>
<td>$K^0(1430)^-$</td>
<td>0.87 ± 0.01</td>
<td>−47.3 ± 0.7</td>
<td>0.0133</td>
</tr>
<tr>
<td>$K^{*}(1410)^-$</td>
<td>0.55 ± 0.02</td>
<td>111 ± 2</td>
<td>0.0048</td>
</tr>
<tr>
<td>$K^{*}(1680)^-$</td>
<td>0.60 ± 0.05</td>
<td>147 ± 5</td>
<td>0.0002</td>
</tr>
<tr>
<td>$K^{*}(892)^+$</td>
<td>0.152 ± 0.003</td>
<td>−37.5 ± 1.1</td>
<td>0.0054</td>
</tr>
<tr>
<td>$K_S^0(1430)^+$</td>
<td>0.541 ± 0.013</td>
<td>91.8 ± 1.5</td>
<td>0.0047</td>
</tr>
<tr>
<td>$K^0(1430)^+$</td>
<td>0.276 ± 0.010</td>
<td>−106 ± 3</td>
<td>0.0013</td>
</tr>
<tr>
<td>$K^{*}(1410)^+$</td>
<td>0.333 ± 0.016</td>
<td>−102 ± 2</td>
<td>0.0013</td>
</tr>
<tr>
<td>$K^{*}(1680)^+$</td>
<td>0.73 ± 0.10</td>
<td>103 ± 6</td>
<td>0.0004</td>
</tr>
<tr>
<td>$\rho(770)$</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td>0.2111</td>
</tr>
<tr>
<td>$\omega(780)$</td>
<td>0.038 ± 0.0006</td>
<td>115.1 ± 0.9</td>
<td>0.0063</td>
</tr>
<tr>
<td>$f_0(980)$</td>
<td>0.380 ± 0.002</td>
<td>−147.1 ± 0.9</td>
<td>0.0452</td>
</tr>
<tr>
<td>$f_0^+(1370)$</td>
<td>1.46 ± 0.04</td>
<td>98.6 ± 1.4</td>
<td>0.0162</td>
</tr>
<tr>
<td>$f_2(1270)$</td>
<td>1.43 ± 0.02</td>
<td>−13.6 ± 1.1</td>
<td>0.0180</td>
</tr>
<tr>
<td>$\rho(1450)$</td>
<td>0.72 ± 0.02</td>
<td>40.9 ± 1.9</td>
<td>0.0024</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>1.387 ± 0.018</td>
<td>−147 ± 1</td>
<td>0.0014</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>0.257 ± 0.009</td>
<td>−157 ± 3</td>
<td>0.0088</td>
</tr>
<tr>
<td>NR</td>
<td>2.36 ± 0.05</td>
<td>155 ± 2</td>
<td>0.0615</td>
</tr>
</tbody>
</table>
Bellele \( D^0 \rightarrow K_s \pi \pi \) Results

Proper-time fit results
\[
x = (0.80 \pm 0.29 \pm 0.17)\% \quad (2.4\sigma)
\]
\[
y = (0.33 \pm 0.24 \pm 0.15)\%
\]

No-mixing excluded at 2.2\( \sigma \)

Largest systematics:
- \( x \): from Dalitz fit model
- \( y \): from event selection

arXiv:0704.1000 540 fb\(^{-1}\)
Average $D^0$ Mixing Results

Heavy flavor averaging group (HFAG)

Combine all available measurements (likelihoods) in 3 dimensions $(x, y, \delta)$

July 2007 Averages:

$\delta = 0.33 \pm 0.26 - 0.29$

$x = (0.87 \pm 0.30 - 0.34 ) \times 10^{-2}$

$y = (0.66 \pm 0.21 - 0.20 ) \times 10^{-2}$

No mixing excluded $> 5\sigma$
Summary

• BABAR: Evidence for $D^0$ mixing at $3.9\sigma$ ($K\pi$ analysis)

• BELLE: Evidence for $D^0$ mixing at $3.2\sigma$ (Lifetime ratio)

• The combined BABAR plus Belle result is inconsistent with the null mixing hypothesis at the $4\sigma$ level and show no evidence for CP violation.

• HFAG combined average in 3 dimensions ($x$, $y$, $\delta$) excludes the no mixing hypothesis at $5\sigma$ level

• Oscillations in the theory of SM long-distance contributions to $D^0$ mixing have been observed.

• More precise measurements of D-meson mixing and CP violation parameters as well as better calculations are needed in order to find hints of New Physics effects.

• New results from BABAR (Lifetime ratio, Dalitz) and Belle analyses are underway.
Backup Slides
Fit Procedure

Unbinned maximum likelihood fit in several steps
(high demand on computing resources, 1+ million events)

**Fit to m(Kπ) and Δm distribution:**
- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

**Fit RS decay time distribution:**
- Determines D⁰ lifetime and resolution function
- Include event-by-event decay time error δt in resolution
- Use m(Kπ) and Δm to separate signal/bkgd (fixed shapes)

**Fit WS decay time distribution:**
- Use D⁰ lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)
Wrong-sign $m_{K\pi}, \Delta m$ fit

The $m_{K\pi}, \Delta m$ fit determines the WS b.r. $R_{WS} = N_{WS}/N_{RS}$

$BABAR$ (384 fb$^{-1}$): $R_{WS} = (0.353 \pm 0.008 \pm 0.004)\%$ (PRL 98, 211802 (2007))

$BELLE$ (400 fb$^{-1}$): $R_{WS} = (0.377 \pm 0.008 \pm 0.005)\%$ (PRL 96, 151801 (2006))
No-mixing WS decay time fit

The parameters fitted are
WS category yields
WS combinatoric shape parameter

As can be seen in the residual plot, there are large residuals.
Residuals = data - fit

WS no-mixing fit projection in signal region
1.843 GeV/c^2 < m < 1.883 GeV/c^2
0.1445 GeV/c^2 < Δm < 0.1465 GeV/c^2
$R_{WS}$ vs. decay-time slices

If mixing is present, it should be evident in a $R_{WS}$ rate that increases with decay-time.

Perform the $R_{WS}$ fit in five time bins with similar RS statistics.

Cross-over occurs at $t \approx 0.5$ psec

Similar to residuals plot.

Dashed line: standard $R_{WS}$ fit ($\chi^2=24$).
Solid, red line: independent $R_{WS}$ fits to each time bin ($\chi^2 = 1.5$).
List of systematics, validations

Systematics: variations in
  Functional forms of PDFs
  Fit parameters
  Event selection
Computed using full difference
with original value
Results are expressed in units of
the statistical error

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>$R_D$</th>
<th>$y'$</th>
<th>$\chi'^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDF:</td>
<td>0.59σ</td>
<td>0.45σ</td>
<td>0.40σ</td>
</tr>
<tr>
<td>Selection criteria:</td>
<td>0.24σ</td>
<td>0.55σ</td>
<td>0.57σ</td>
</tr>
<tr>
<td>Quadrature total:</td>
<td>0.63σ</td>
<td>0.71σ</td>
<td>0.70σ</td>
</tr>
</tbody>
</table>

Validations and cross-checks
  Alternate fit ($R_{WS}$ in time bins)
  Fit RS data for mixing
    $\chi'^2 = (-0.01\pm0.01) \times 10^{-3}$
    $y' = (0.26\pm0.24) \times 10^{-3}$
  Fit generic MC for mixing
    $\chi'^2 = (-0.02\pm0.18) \times 10^{-3}$
    $y' = (2.2\pm3.0) \times 10^{-3}$
  Fit toy MCs generated with various values of mixing
    Reproduces generated values
  Validation of proper frequentist coverage in contour construction
    Uses 100,000 MC toy simulations
PEP-II a Charm Factory: We use \( 384 \text{ fb}^{-1} e^+e^- \rightarrow c,\bar{c} \)
\[
\sigma(b\bar{b}) = 1.1 \text{ nb} \\
\sigma(c\bar{c}) = 1.3 \text{ nb}
\]
\[\rightarrow 500 \times 10^6 \text{ cc}^{-} \text{ events}\]
Average $K\pi$ Mixing Results

Heavy flavor averaging group (HFAG) provides “official” averages

Combine BaBar and Belle likelihoods in 3 dimensions ($R_D, x'^2, y'$)

May 2007 Averages:

- $R_D$: $(3.30^{+0.14}_{-0.12}) \times 10^{-3}$
- $x'^2$: $(-0.01\pm0.20) \times 10^{-3}$
- $y'$: $(5.5^{+2.8}_{-3.7}) \times 10^{-3}$

No mixing excluded $> 4\sigma$
Average $y_{cp}$

- E791 1999: $0.732 \pm 2.890 \pm 1.030 \%$
- FOCUS 2000
- CLEO 2002
- BaBar 2003: $3.420 \pm 1.390 \pm 0.740 \%$
- Belle 2007
- Belle 2002
- Belle 2007
- World average: $1.122 \pm 0.321 \%$

Average $A_\Gamma$

- HFAG-charm FPCP 2007
- E791 1999: $-0.800 \pm 0.600 \pm 0.200 \%$
- FOCUS 2000
- CLEO 2002
- BaBar 2003: $0.010 \pm 0.300 \pm 0.150 \%$
- Belle 2007
- Belle 2002
- Belle 2007
- World average: $-0.168 \pm 0.296 \%$

World average $y_{cp}$: $1.122 \pm 0.321 \%$

World average $A_\Gamma$: $-0.168 \pm 0.296 \%$
Average $y$

- All $y_{CP}$
- All $K_S\pi^+\pi^-$
- CLEOc 2006 double-tag
- World average

\begin{align*}
\text{World average} & : \quad 0.655 \pm 0.211 \%
\end{align*}

Average $x$

- CLEO 2005/2007
- Belle 2007
- HFAG-charm Moriond 2007
- HFAG-charm FPCP 2007

\begin{align*}
\text{CLEO 2005/2007} & : \quad 1.122 \pm 0.321 \%
\text{Belle 2007} & : \quad -5.800 \pm 6.600 \%
\text{World average} & : \quad 0.811 \pm 0.334 \%
\text{HFAG-charm Moriond 2007} & : \quad 0.800 \pm 0.290 \pm 0.170 \%
\text{HFAG-charm FPCP 2007} & : \quad 1.900 \pm 3.300 \pm 0.566 \%
\end{align*}