D⁰-D⁰ Mixing
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APS 2007

Outline

- Charm Meson Mixing
- Review of Recent Mixing Analysis
  - Mixing in Semileptonic Decays by Belle and BaBar
  - Quantum Correlation Analysis in CLEO-c
  - Mixing with t-dependent Dalitz Plot by Belle Using $D^0 \rightarrow K_s \pi^- \pi^+$
  - Evidence for Mixing from BaBar Using $D^0 \rightarrow K\pi^+$
  - Evidence for Mixing from Belle Using $D^0 \rightarrow KK, \pi\pi, \text{and } K\pi$
- Summary
Brief History

- Neutral Charm meson is one of the four neutral mesons that can mix with its anti-particle
  - $K^0$, $B^0$ and $B_s^0$ are the other three
- $K^0$ mixing first observed in 1958
- $B^0$ mixing first observed by ARGUS experiment in 1987
- $B_s^0$ mixing rate first measured by CDF and D0 in 2006
Neutral Charm meson is one of the four neutral mesons that can mix with its anti-particle
- $K^0$, $B^0$ and $B_s^0$ are the other three
- $K^0$ mixing first observed in 1958
- $B^0$ mixing first observed by ARGUS experiment in 1987
- $B_s^0$ mixing rate first measured by CDF and D0 in 2006
- $D^0$ mixing was not observed until a few weeks ago
Neutral mesons $D^0$ and $D^0$ are flavor eigenstates produced via strong interactions.

Due to weak force, evolve into a mixture of $D^0$ and $D^0$.

- Time evolution described by the weak Hamiltonian

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - i \frac{\Gamma}{2} \end{pmatrix}_{\text{weak}} \times \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

- Mass eigenstates: $|D_{1,2}(t)\rangle = p|D^0(t)\rangle \pm q|\bar{D}^0(t)\rangle$

- Mixing is parameterized by $x$ and $y$
  - $m_{1,2}$ and $\Gamma_{1,2}$ are $D_{1,2}$ mass and lifetimes

- Express time evolution of $D^0$ as:

$$|D^0(t)\rangle = e^{-(im+\frac{\Gamma}{2})t} \begin{pmatrix} D^0 \rangle \cosh [(y+ix)\Gamma t] + \frac{q}{p} |\bar{D}^0\rangle \sinh [(y+ix)\Gamma t] \end{pmatrix}$$

$$m_{12} = m_1 - m_2$$
$$\Gamma_{12} = \Gamma_1 - \Gamma_2$$
$$m = \frac{m_1 + m_2}{2}$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$x = \frac{m_1 - m_2}{\Gamma}$

$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$
Mixing Process

- Box diagram Standard Model charm mixing rate naively expected to be very low (mainly contribute to $x$)
  - Cabibbo-Kobayashi-Maskawa and Glashow-Iliopoulus-Maiani suppressed

\[
\begin{align*}
\text{Mass difference} & \quad x \approx O(10^{-6}) - O(10^{-5}) \\
\text{Lifetime difference} & \quad x \leq O(10^{-2}) \quad R_M = \frac{x^2 + y^2}{2} \leq O(10^{-4}) \\
\text{Long distance effects dominate} \quad (\text{mainly contribute to } y)
\end{align*}
\]

$D^0 \rightarrow u \quad d, s, b \quad u$

$\bar{D}^0 \rightarrow \bar{u} \quad d, s, b \quad \bar{c}$

SM Mixing: a long-range contribution

New Physics Contribution to Charm Mixing

Possible enhancements to mixing due to new physics
Contributions from new physics enhance $x$

Indication of NP would be observation of CP-violation or $\Delta(\text{mass}) \gg \Delta(\text{lifetime})$

Mass difference


- FCNC
- Supersymmetry
- Fourth quark generation

Paper reference

2006 upper limit
Already constraining New Physics models

Mass difference

hep-ph/0311371 (A. Petrov)
## $D^0$-$D^0$ Mixing Parameters

Mixing parameters and the quantities measured in the experiments (analyses which are most relevant to this talk):

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Decay Modes</th>
<th>Time dependence</th>
<th>parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong-Sign (WS) semileptonic decays</td>
<td>$D^0 \rightarrow K \nu$, etc.</td>
<td>Time integrated</td>
<td>$R_M = \frac{x^2 + y^2}{2} = \frac{N_{WS}}{N_{RS}}$</td>
</tr>
<tr>
<td>WS hadronic decays</td>
<td>$D^0 \rightarrow K \pi$, etc.</td>
<td>Decay time analysis</td>
<td>$x^2$, $y'$ and $r$ (Doubly Cabibbo Suppressed (DCS) Rate)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$x' = x \cos(\delta) + y \sin(\delta)$</td>
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<td></td>
<td></td>
<td></td>
<td>$y' = y \cos(\delta) - x \sin(\delta)$</td>
</tr>
<tr>
<td>CP eigenstate lifetime differences</td>
<td>$D^0 \rightarrow KK, (\pi\pi)$, etc.</td>
<td>Decay time analysis</td>
<td>$y_{CP} = \frac{\Gamma(CP+) - \Gamma(CP-)}{\Gamma(CP+) + \Gamma(CP-)}$</td>
</tr>
<tr>
<td>Time dependent Dalitz plot analysis</td>
<td>$D^0 \rightarrow K_s \pi\pi$, etc.</td>
<td>Decay time analysis</td>
<td>If no CPV: $y_{CP} = y$</td>
</tr>
<tr>
<td>Quantum Correlations</td>
<td>$e^+e^- \rightarrow \psi(3770) \rightarrow DD$</td>
<td>Time integrated</td>
<td>$x$, $y$, $\delta$, $r$</td>
</tr>
<tr>
<td></td>
<td>- flavored ($K\pi^*$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- CP+ eigenstates ($K\kappa^+$)</td>
<td></td>
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<tr>
<td></td>
<td>- CP- eigenstates ($K_s\pi^0$)</td>
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</tr>
<tr>
<td></td>
<td>- semileptonic (Xev)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Several common event selection in B-Factories

- Flavor-tag using the charge $\pi_s$
- Proper lifetime measurement
- $CM \; P^*(D^0) > 2.5 \; GeV/c$
- Common background categories
  - Correct $D^0$, wrong $\pi_s$
  - Misreconstructed $D^0$
    - Partially reconstructed or double misid $D^0$
  - Combinatorial
  - Each tend to have distinct ($M(K\pi)$, $\Delta M$) distributions

- General Parameters of interest to measure mixing parameters
  - $D^0$ mass = $m(D^0_{\text{candidate}})$
  - $\Delta m = m(D^{*\text{candidate}}) - m(D^0_{\text{candidate}})$
  - $D^0$ proper decay time $t$
Mixing with Semileptonic Modes
From Belle and BaBar

Belle: PRD (RC) 72, 071101 (2005)
BaBar: Moriond 2007

Previous analysis:
E.M. Aitala et al. (E791), PRL 77, 2384 (1996)
C. Cawlfield et al. (CLEO II), PRD 71, 077101 (2005)
B. Aubert et al. (BABAR), PRD 70, 091102 (2004)
D^0 \rightarrow K\bar{\nu} Results from Belle

- No DCS decays in semi-leptonic modes
- Simpler time dependence

$$\Gamma_{WS}(t) \approx \exp\left(-\frac{t}{\tau_{D^0}}\right) \left(\frac{t}{\tau_{D^0}}\right)^2 \left(\frac{x^2 + y^2}{4}\right)$$

- In the limit of no CP violation measure time integrated mixing rate

$$R_M = \frac{x^2 + y^2}{2} = \frac{x'^2 + y'^2}{2}$$

- Observable: $\Delta M = M(\pi\text{Kev}) - M(K\nu)$
- Fit of WS is performed in bins of lifetimes to increase sensitivity

$R_M < 1.2 \times 10^{-3} \text{ @95\% CL}$

PRD (RC) 72, 071101 (2005)
D⁰ \rightarrow \text{Kev Results from BaBar}

- Observable: $\Delta M = M(\pi\text{K}e) - M(\text{Ke})$, 344 fb⁻¹
- Double tag
  - $D^{*+} \rightarrow D^{0} \pi_{s}^{+}$ in semileptonic
  - Five fully reconstructed hadronic tagging modes
- Unbinned maximum likelihood fit to RS $\Delta M$
- Predict 2.85 background events, observe 3 (dark gray)

\[-1.3 \times 10^{-3} < R_{M} < 1.2 \times 10^{-3} @ 90\% \ C.\ L.\]
$D^0 D^0$ Quantum Correlations: Measuring $x$, $y$, $r$ (DCS rate) and $\delta$ Simultaneously at CLEO-c

Quantum-coherent $D^0D^0$ at CLEO-c

Quantum-coherent $D^0D^0$ state provides time-integrated sensitivity for simultaneously measuring $x$, $y$, $r$, and $\delta$.

Four types of final states considered:
- flavored ($K^+\pi^+$)
- CP+ eigenstates
- CP- eigenstates
- semileptonic ($Xe\nu$)

Reconstruct one (ST) or both (DT) $D$ mesons

Event yields can be expressed as a function of:
- $D^0D^0$ pairs produced
- Branching fractions
- Mixing parameters $y$ and $R_M = (x^2 + y^2)/2$
- DCS rate $r$ and the strong phase $-\delta$

Fit to the yields to extract these parameters

$e^+e^- \rightarrow \psi(3770) \rightarrow \gamma^* \rightarrow D^0 \bar{D}^0$  $C = -1$
Preliminary Fit Results and Future Work at CLEO-c

- Fit inputs: 6 ST, 14 hadronic DT, 10 semileptonic DT, efficiencies, crossfeeds, background branching fractions and efficiencies

  - Preliminary fitted results when $r^2$ constrained (281 pb$^{-1}$ dataset)
    - $\cos \delta = 1.08 \pm 0.66 \pm ?$
    - $y = -0.057 \pm 0.066 \pm ?$
  - Final results on 281 pb$^{-1}$ dataset awaiting collaboration approval
    - Includes systematic errors and new modes $K_s \eta$, $K_s \omega$, and $K_L \pi^0$
    - First measurement of $\delta$
    - Expect $\sigma(y) \sim 0.015$ and $\sigma(\cos \delta_{K\pi}) \sim 0.3$
    - Project 750 pb$^{-1}$ by 2008
    - Expect $\sigma(y) \sim 0.01$ and $\sigma(\cos \delta_{K\pi}) \sim 0.1-0.2$

$\chi^2 = 17.0$ for 19 d.o.f. (C.L. = 59%).

Uncertainties are statistical only

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{b^{0}b^{0}}$</td>
<td>$(1.09 \pm 0.04 \pm ?) \times 10^6$</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$-0.057 \pm 0.066 \pm ?$</td>
</tr>
<tr>
<td>$r^2$</td>
<td>$-0.028 \pm 0.069 \pm ?$</td>
</tr>
<tr>
<td>$r(2\cos \delta_{K\pi})$</td>
<td>$0.130 \pm 0.082 \pm ?$</td>
</tr>
<tr>
<td>$R_M$</td>
<td>$(1.74 \pm 1.47 \pm ?) \times 10^{-3}$</td>
</tr>
</tbody>
</table>

Q.C. technique very promising for future high-statistics experiments (BES III, “Super Flavor Factory”)
Time-dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s \pi^- \pi^+$ at Belle


Previous analysis:
D. M. Asner et al. (CLEO), PRD 72, 012001 (2005)
H. Muramatsu et al. (CLEO), PRL 89, 251802 (2002)
Time-dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s \pi^- \pi^+$

- Decay matrix element to a final state $|f\rangle$

\[
\mathcal{M}(m_-^2, m_+^2, t) = \langle f | D^0(t) \rangle = \frac{1}{2} \mathcal{A}(m_-^2, m_+^2) \left[ e^{-\lambda_1 t} + e^{-\lambda_2 t} \right] + \frac{1}{2} \frac{p}{q} \mathcal{A}(m_+^2, m_-^2) \left[ e^{-\lambda_1 t} - e^{-\lambda_2 t} \right]
\]

- Where: $\lambda_{1,2} = i(m_{1,2} - \frac{i}{2} \Gamma_{1,2})$ (function of $x$ and $y$)

Using the notation:

$\mathcal{M}(m_{K_s^-}^2, m_{K_s^+}^2, t) \equiv \mathcal{M}(m_-^2, m_+^2, t)$

Analogous for $\overline{\mathcal{M}}$ and $\overline{D^0(t)}$

\[
m_{\pm} = \begin{cases} m(K_s, \pi^\pm) & D^{*+} \rightarrow D^0 \pi^+ \\ m(K_s, \pi^+) & D^{*-} \rightarrow \overline{D^0} \pi^- \end{cases}
\]

- In the limit of CP conservation:

$\left( \frac{p}{q} = 1, \mathcal{A} = \overline{\mathcal{A}} \right) \Rightarrow \mathcal{M} = \overline{\mathcal{M}}$

- Measurement directly sensitive to $x$ and $y$
Mass plots and Dalitz Fit for $D^0 \rightarrow K_s \pi^- \pi^+$

- Dalitz model: 13 (BW) resonances, non-resonant, bkg.
- For scalar $\pi\pi$, K-matrix formalism also used
- Results with refined model consistent with Belle $\phi_3/\gamma$ meas.

Belle preliminary, 540 fb$^{-1}$
~700 Million Charm Pairs

$M = M(K\pi)$

$Q = M(K_s\pi^- \pi^-) - M(K_s\pi^- \pi^-) - M(\pi_{slow})$

- $534 \times 10^3$ signal events
- purity 95%

PRD73, 112009 (2006)
Results of Time-dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s \pi^\mp \pi^+$ at Belle


Results:

\[ x = 0.80 \pm 0.29 \pm 0.17 \% \]
\[ y = 0.33 \pm 0.24 \pm 0.15 \% \]
\[ \tau = 409.9 \pm 0.9 \text{ fs} \]

Most sensitive measurement of $x$;
(2.4 $\sigma$ 1-d significance)

Cleo, PRD72, 012001 (2005)

\[ x = 1.8 \pm 3.4 \pm 0.6\% \]
\[ y = -1.4 \pm 2.5 \pm 0.9 \% \]

95% C.L. contour;

(0,0) point has $-2\Delta \log(L)=7.3$
C.L. 2.6% (1.9 $\sigma$)
Evidence For Mixing Using $D^0 \rightarrow K^-\pi^+$ at BaBar

hep-ex/0703020
Submitted To PRL

Previous analysis:
R. Godang et al. (CLEO), PRL 84, 5038 (2000)
J.M. Link et al. (FOCUS), PRL 86, 2955 (2001)
B. Aubert et al. (BABAR), PRL 91, 171801 (2003)
J.M. Link et al. (FOCUS), PLB 618, 23 (2005)
J. Li et al. (Belle), PRL 94, 071801 (2005)
L.M. Zhang et al. (Belle), PRL 96, 151801 (2006)
Time-dependent Mixing Analysis
Using $D^0 \rightarrow K\pi$ at BaBar

Hadronic wrong-sign (WS) decay

Separate DCS decays from the mixed decays using their different time evolution

There is also interference effect

Time evolution, assuming $|x| \ll 1$ and $|y| \ll 1$

$$\Gamma_{WS}(t) = e^{-\Gamma t} \left( R_D + y' \sqrt{R_D} (\Gamma t) + \left( \frac{x'^2 + y'^2}{4} \right)(\Gamma t)^2 \right)$$

$x' = x \cos(\delta) + y \sin(\delta)$  \(\delta\) is the phase difference between DCS and CF decays

$y' = y \cos(\delta) - x \sin(\delta)$

Mixing

note: $x'^2 + y'^2 = x^2 + y^2$
RS and WS Data Sets After Event Selection

- Fit $M$, $\Delta M$ and lifetime using unbinned maximum likelihood method
RS Decay Time Fit

- $D^0$ lifetime and resolution function fitted in the RS sample

$\tau = (410.3 \pm 0.6 \text{ (stat)}) \text{ fs}$

- Consistent with PDG
  - $410.1 \pm 1.5 \text{ fs}$

plot selection:
- $1.843 < m < 1.883 \text{ GeV}/c^2$
- $0.1445 < \Delta m < 0.1465 \text{ GeV}/c^2$
WS Fit With no Mixing

- Fit results assuming no mixing
- Poor residuals in the signal region
  - $\chi^2$/bin = 49.7/28

WS decay time, signal region:

- $1.843 < m < 1.883$ GeV/c$^2$
- $0.1445 < \Delta m < 0.1465$ GeV/c$^2$
WS Fit with Mixing

Fit results allowing mixing:
- $R_D = (3.03\pm0.16\pm0.10) \times 10^{-3}$
- $x'{}^2 = (-0.22\pm0.30\pm0.21) \times 10^{-3}$
- $y' = (9.7\pm4.4\pm3.1) \times 10^{-3}$
  - $x'{}^2$ and $y'$ correlation = -0.94
- Mixing fit describes data better
  - $\chi^2$/bin = 31/28

What is the significance of the signal?

plot signal region:
1.843 < $m$ < 1.883 GeV/$c^2$
0.1445 < $\Delta m$ < 0.1465 GeV/$c^2$
Signal Significance for $K\pi$ Mixing Results at BaBar

- $y', x'^2$ contours computed by change in log likelihood
  - Best-fit point in non-physical region $x'^2 < 0$, but 1-sigma contour extends into physical region
- Contours include systematic errors
- Accounting for systematic errors, the no-mixing point is at 3.9-sigma contour
- $\rightarrow$ clear evidence for $D^0\bar{D}^0$ mixing

No evidence for CP violation found

$R_D$: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

$x'^2$: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

$y'$: $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

hep-ex/0703020
Submitted To PRL
Validation: Alternative Fit Strategy

- Fit $\Delta M$ and $M(K\pi)$ in bins of lifetime
  - If no mixing the ratio of WS to RS signal should be constant
  - No assumptions made in resolution model and the time evolution of background
  - Each time bin is fit independently

Consistent with prediction based on resolution model and mixing parameters from full likelihood fit

$\chi^2 = 1.5$

Inconsistent with no-mixing hypothesis

$\chi^2 = 24$
Evidence For Mixing From Belle Using CP modes $K\bar{K}$ and $\pi\pi$ and flavor mode $K\pi$

hep-ex/0703036v1
Submitted to PRL

Previous analysis:
E791, PRL 83, 32 (1999)
FOCUS, PLB 485, 62 (2000)
CLEO, PRD 65, 092001 (2002)
Belle, PRL 88, 162001 (2002)
BABAR, PRL 91, 121801 (2003)
Belle, Lepton Photon 2004
Mixing with CP Lifetimes at Belle

- Mixing alters the decay time distribution of $D^0 D^0$ decaying into CP states.
- The CP lifetime difference can be expressed as:
  \[ y_{CP} = \frac{\tau^0}{\langle \tau \rangle} - 1 \quad \text{where} \quad \langle \tau \rangle = \frac{(\tau^+ + \tau^-)}{2} \]
- $\tau^0$ is $K\pi$ lifetime
- $\tau^+ (\tau^-)$ is lifetime for CP+ final states of $D^0 (D^0)$
  - KK and $\pi\pi$
- Mixing (and CPV) studied with $K^-\pi^+$, $K^+K^-$ and $\pi^-\pi^+$ at Belle:
  \[ y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = y \frac{\Delta \Gamma}{2 \Gamma} \]
  \[ CPV : A_{\Gamma} = \frac{\Gamma(D^0 \rightarrow K^-K^+)}{\Gamma(D^0 \rightarrow K^-K^+)} \frac{\Gamma(D^0 \rightarrow K^-K^+)}{\Gamma(D^0 \rightarrow K^-K^+)} + \Gamma(\bar{D}^0 \rightarrow K^-K^+) \]
  \[ \text{Same for } \pi\pi \]
Decay Time Fit

- Simultaneous binned likelihood fit to KK/Kπ/ππ final states
  - Parameters to vary include $\tau_{D_0}$, $\gamma_{CP}$, some of the resolution func. parameters and the normalizations

Quality of fit: $\chi^2=1.084$ (289)

<table>
<thead>
<tr>
<th>channel</th>
<th>$K\bar{K}$</th>
<th>$K\pi$</th>
<th>$\pi\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal purity</td>
<td>110K</td>
<td>1.2M</td>
<td>50K</td>
</tr>
<tr>
<td>purity</td>
<td>98%</td>
<td>99%</td>
<td>92%</td>
</tr>
</tbody>
</table>
Mixing Results with $K^-\pi^+$, $K^+K^-$ and $\pi^-\pi^+$ at Belle

Results

<table>
<thead>
<tr>
<th>$KK$</th>
<th>$y_{CP}$ (%)</th>
<th>$A_\Gamma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi\pi$</td>
<td>$1.25\pm0.39\pm0.28$</td>
<td>$0.15\pm0.34\pm0.16$</td>
</tr>
<tr>
<td>$KK + \pi\pi$</td>
<td>$1.44\pm0.57\pm0.42$</td>
<td>$-0.28\pm0.52\pm0.30$</td>
</tr>
</tbody>
</table>

$y_{CP} = 1.31 \pm 0.32 \pm 0.25 \%$

3.2 $\sigma$ (stat.+syst.)
4.1 $\sigma$ (stat.)

Clear evidence for $D^0$-$\bar{D}^0$ mixing

To measure CPV, fit for $\tau_D$ of $D0$ and $D\bar{0}$ separately:

$A_\Gamma = 0.01 \pm 0.30 \pm 0.15 \%$

Consistent with no CPV

Submitted to PRL

Amir Rahimi

hep-ex/0703036

Submitted to PRL
Summary I: $R_M$ and $Y_{cp}$

- Statistical and systematic errors assumed uncorrelated
- Symmetrized statistical, systematic errors
- Stat. errors for two Belle analysis have correlation=0.0165
- All systematic errors assumed uncorrelated

Many Thanks to Heavy Flavor Averaging Group (HFAG) 2007
Summary II

- **Mixing contours from 2006 PDG**
  - $K\pi$ decay the dominant mode in the search for mixing
  - CP lifetimes sensitive to measuring $\gamma$
  - Semileptonic sensitive to $R_M = (x^2 + y^2)/2$

**Figure: PDG 2006**

- 95% CL allowed
- CPV allowed
- $\gamma_{CP} = (0.90 \pm 0.42)\%$
- $\delta_{K\pi} = 0^\circ$ assumed
- $\delta_{K\pi} = 0^\circ$: measured by CLEO
Assuming CP conservation BaBar has found evidence for mixing at $3.9\sigma$ CL using $D^0 \rightarrow K\pi$ decay mode (384 fb$^{-1}$)

$\gamma_{cp}$ by Belle also evidence for mixing at $3.2\sigma$ CL (540 fb$^{-1}$)

**Mixing is observed**

Most sensitive measurement of $x$ by Belle ($D^0 \rightarrow K_s\pi\pi$)

A precision measurement of $\cos\delta$ needed to express mixing in $x$ and $y$

- CLEO-c quantum correlation
- BaBar and Belle B-factories
  - Are also charm factories

Searches for CP violation

- Improved techniques
- More data
Recent Theoretical Work

- D-Dbar Mixing And New Physics: General Considerations and Constraints on the MSSN (M. Ciuchini et al)
  - hep-ph/0703204v1
- Lessons from BaBar and Belle measurements of D0-D0bar mixing parameters, (Y. Nir)
  - hep-ph/0703235v1
- Littlest Higgs Model with T-Parity Confronting the New Data on D0-D0bar Mixing, (M. Blanke et al)
  - hep-ph/0703254v1
- Basics of D0-D0bar Mixing, (P. Ball)
  - hep-ph/0703245v1
Extra Slides
Comparison of Results
Fully consistent with previous BaBar analysis

Previous BaBar $K\pi$ Analysis

PRL 91,171801

384 fb$^{-1}$

57 fb$^{-1}$

Best fit

$1\sigma$

$2\sigma$

$3\sigma$

$4\sigma$

$5\sigma$

$\chi^2 / 10^3$ vs. $y' / 10^3$

CPV allowed

CP conserved
Kπ Analysis from Belle

Last year Belle published analysis of Kp decays:

PRL 96,151801

400 fb⁻¹

no-mixing excluded at 2σ
Last year Belle published analysis of $K\pi$ decays:

- No-mixing excluded at 2$\sigma$
- Results consistent within 2$\sigma$:

PRL 96,151801

400 fb$^{-1}$
Belle Results from Moriond

Belle presented two new mixing results at Moriond EW:

Dalitz analysis of $D^0 \rightarrow K_s \pi \pi$

- 540 fb$^{-1}$
- no-mixing excluded at 2.4$\sigma$

\[ x = 0.80 \pm 0.29 \pm 0.17 \% \]

\[ y = 0.33 \pm 0.24 \pm 0.15 \% \]
Belle Results from Moriond

Belle presented two new mixing results yesterday at Moriond EW:

Dalitz analysis of $D^0 \to K_s \pi \pi$

- No-mixing excluded at 2.4σ

$x = 0.80 \pm 0.29 \pm 0.17 \%$

$y = 0.33 \pm 0.24 \pm 0.15 \%$

Compare assuming $\delta = 0$:

$x' = x$, $y' = y$

Best fit

Within 1σ

540 fb$^{-1}$

384 fb$^{-1}$
Belle Results from Moriond

Lifetime ratio in $D^0 \rightarrow KK/\pi\pi$ to $K\pi$

$K^+K^-/\pi^+\pi^-$ are CP-even eigenstates
If no CP violation, directly measures lifetime of mass eigenstate

$y_{CP} = 1.31 \pm 0.32 \pm 0.25 \%$

$> 3\sigma$ above zero (4.1\sigma stat. only)

Also evidence of $D^0$ mixing!
Belle Results from Moriond

Lifetime ratio in $D^0 \rightarrow KK/\pi\pi$ to $K\pi$

Compare assuming $\delta=0$:

$y_{CP} = 1.31 \pm 0.32 \pm 0.25 \%$

$> 3\sigma$ above zero (4.1\sigma stat. only)

Also evidence of $D^0$ mixing!
### Single-tag and Double-tag rates

- Hadronic rates (flavored and CP eigenstates) depend on mixing/DCSD.
- Semileptonic modes ($r = \delta = 0$) resolve mixing and DCSD.
- Also measure BF's simultaneously.

### Rate enhancement factors, to leading order in $x$, $y$ and $r^2$:

<table>
<thead>
<tr>
<th></th>
<th>$f$</th>
<th>$l^+$</th>
<th>CP+</th>
<th>CP−</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>${R_m/r^2}$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$f$</td>
<td>$1+r^2(2-(2\cos\delta)^2)$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$l^−$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CP+</td>
<td>$1+r(2\cos\delta)$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CP−</td>
<td>$1-r(2\cos\delta)$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$x$</td>
<td>$1+ry(2\cos\delta)$</td>
<td>1</td>
<td>1−$y$</td>
<td>1+$y$</td>
</tr>
</tbody>
</table>

---

**Data clearly favors QC interpretation showing constructive and destructive interference and no effect as predicted.**

![Graph showing data ratios](image)

**CLEO-c**

Amir Rahimi  
APS2007
Several Other Validation Studies

- **Fit to MC with no mixing**
  - No signal found
  - \( \rightarrow \) Fit not biased

- **Fit to MC with mixing**
  - Fit reproduces the signal
  - \( \rightarrow \) Fit not biased

- **Fit RS data for mixing**
  - No signal found
  - \( \rightarrow \) \( D^0 \) decay time distribution is described properly

- **Tested the coverage of \(-2\Delta \text{Log} \mathcal{L}\)**
  - Generated \( >10000 \) toys without mixing to test coverage
  - Toys expected consistent with number observed
  - \( \rightarrow \Delta \text{LL} \) is \( \chi^2 \) distributed for 2-DOF
  - \( \rightarrow -2\Delta \text{ln} \mathcal{L} \) gives correct frequentist coverage
Validation: Coverage of $-2\Delta \log L$

- Generated >10000 toys without mixing to test coverage
  - $-2\Delta \ln L$ gives correct frequentist coverage

$\chi^2$ for 2 DOF

-2$\Delta L = 23.9$ observed in data
CPV Allowed Contours

- Fit $D^0$ and $\bar{D}^0$ separately:
  
  $x'^+ : (-0.24\pm0.43\pm0.30) \times 10^{-3}$
  
  $y'^+ : (9.8\pm6.4\pm4.5) \times 10^{-3}$
  
  $x'^- : (-0.20\pm0.41\pm0.29) \times 10^{-3}$
  
  $y'^- : (9.6\pm6.1\pm4.3) \times 10^{-3}$

\[ A_D = (-2.1 \pm 5.2 \pm 1.5)\% \]

A significant difference in (+), (-) fits would suggest CP violation

$\rightarrow$ No evidence for CP violation found
Decay Time Fit

- Lifetime distribution

\[ \frac{dN}{dt} = \frac{N_{\text{sig}}}{\tau} \int e^{-t'/\tau} R(t - t') dt' + B(t). \]

Resolution function:

- from normalized distribution of event proper time uncertainty \( \sigma_t \)
- ideally, each \( \sigma_i \) represents Gaussian p.d.f.
- distribution of pulls? p.d.f. = sum of 3 Gaussians for each \( \sigma_i \)

\[ R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t; \sigma_{ik}, t_0), \quad \sigma_{ik} = s_k \sigma_{k}^{\text{pull}} \sigma_i \]

- \( R(t) \) studied in details with \( D^0 \) ? \( K^-\pi^+ \) and dedicated MC samples, including slight changes in running conditions (two SVD detectors, small misalignments)