$D^0 - \bar{D}^0$ Mixing and $T$-Odd Asymmetry Search at BaBar

ICHEP 2010

Paris, FR

M. Bellis
for the BaBar collaboration

Department of Physics
Stanford University

July 23rd, 2010
Outline

1. Overview
2. Measurements
   - Mixing parameters ($x$ and $y$)
     - PRELIMINARY...but just accepted to PRL!
     - arXiv:1004.5053
   - Mixing parameter ($y_{CP}$)
     - PhysRevD.80.071103
   - Search for $T$-odd correlations ($CP$-violation)
     - PhysRevD.81.111103
3. Summary
Overview

Mixing
- $K^0 - K^0, B^0 - \bar{B}^0$
- $D^0 - \bar{D}^0$
  - BaBar, 2007 *PhysRevLett.98.211802*
  - Belle, 2007 *PhysRevLett.98.211803, PhysRevLett.99.131803*
  - CDF, 2007 *PhysRevLett.100.121802*
- Sensitive to *New Physics*

**Figure:** Examples of diagrams that contribute to mixing in the Standard Model.
<table>
<thead>
<tr>
<th>Flavour eigenstates</th>
<th>Mass eigenstates</th>
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<tr>
<td>$</td>
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$D^0 - \bar{D}^0$ MIXING

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$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$

$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$

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

$p = q = \frac{1}{\sqrt{2}}$ if there is no $CP-$violation
\( D^0 - \bar{D}^0 \) MIXING

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|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \\
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\]

\[|p|^2 + |q|^2 = 1 \quad p = q = \frac{1}{\sqrt{2}} \text{ if there is no CP-violation}\]

Define some useful quantities:

\[
M = \frac{M_1 + M_2}{2} \\
x = \frac{M_1 - M_2}{\Gamma} \\
\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \\
y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\]
### Flavour eigenstates | Mass eigenstates
--- | ---
$|D^0(c\bar{u})\rangle$ | $|D_1(M_1, \Gamma_1)\rangle$
$|\bar{D}^0(\bar{c}u)\rangle$ | $|D_2(M_2, \Gamma_2)\rangle$

\[
|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle \\
|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle
\]

\[|p|^2 + |q|^2 = 1 \quad p = q = \frac{1}{\sqrt{2}}\text{ if there is no } CP-\text{violation}\]

Define some useful quantities:

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x = \frac{M_1 - M_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\]

In the Standard Model:

- Mixing parameters $\sim 10^{-2}$
- $CP-$violation $< 10^{-3}$
First evidence for $D^0 - \bar{D}^0$ mixing

- First observation of $D^0 - \bar{D}^0$ mixing at $3.9\sigma$ (BaBar, 2007).
  
  10.1103/PhysRevLett.98.211802

- Confirmed by Belle and CDF.
  
  PhysRevLett.98.211803, PhysRevLett.99.131803, PhysRevLett.100.121802
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- “Right” sign (RS) $D^0 \rightarrow K^-\pi^+$ (Cabibbo favoured)
- “Wrong” sign (WS) $D^0 \rightarrow K^+\pi^-$ (Doubly Cabibbo suppressed (DCS))

- Tag charm meson flavor at $t = 0$ with $D^{*+} \rightarrow D^0\pi^+$ ($m_{D^{*+}} - m_{D^0} \approx 145\text{MeV}$)
  - Characteristic “slow” pion ($\pi_s$)
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\[ e^- \quad \text{---} \quad \text{---} \quad e^+ \]
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---

Diagram:

```
\[ \text{e}^- \rightarrow \text{D}^{*+} \rightarrow \text{D}^0 \rightarrow \text{e}^+ \]
```
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- Tag flavor at $t = 0$ with $D^{*+} \rightarrow D^0 \pi^+$ ($m_{D^{*+}} - m_{D^0} \approx 145$MeV)
  - Characteristic “slow” pion ($\pi_s$)

- Use WS events

$$
\begin{align*}
D^0 & \rightarrow K^+ \pi^- \\
D^0 & \rightarrow \bar{D}^0 \rightarrow K^+ \pi^-
\end{align*}
$$

- Strong phase difference ($D^0$ or $\bar{D}^0$) in final state hadronization ($\delta_f$) is significant for non-$CP$-conjugate decay modes.

$$
\begin{align*}
x' &= x \cos \delta_{K\pi} + y \sin \delta_{K\pi} \\
y' &= -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}
\end{align*}
$$

$$
|A_\bar{f}(t)|^2 = e^{-\Gamma t}. 
$$

<table>
<thead>
<tr>
<th>Direct(DCS)</th>
<th>Mixing</th>
<th>Interference</th>
</tr>
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<tbody>
<tr>
<td>$</td>
<td>A_\bar{f}</td>
<td>^2$</td>
</tr>
</tbody>
</table>
Determination of $x$ and $y$

- Measure $x$ and $y$ directly in self-conjugate final states.
- Analysis insensitive to strong phase, $\delta_f$.
  - $D \rightarrow K_S^0\pi^+\pi^-$
  - $D \rightarrow K_S^0K^+K^-$
  - 609M $c\bar{c}$ pairs. (468.5 fb$^{-1}$)
Determination of $x$ and $y$

- Measure $x$ and $y$ directly in self-conjugate final states.
- Analysis insensitive to strong phase, $\delta_f$.
  - $D \rightarrow K_S^0 \pi^+ \pi^-$
  - $D \rightarrow K_S^0 K^+ K^-$
  - 609M $c\bar{c}$ pairs. (468.5 fb$^{-1}$)

- Perform time-dependent Dalitz plot analysis
  $$s_+ = m^2(K_S^0 h^+)$$
  $$s_- = m^2(K_S^0 h^-)$$
- If there is no $CP$-violation then
  $$A(s_+, s_-) = \bar{A}(s_-, s_+)$$
- $x$ and $y$ are common across both decay modes.
- Exploit time-dependence of mixing to observe changes in population of Dalitz plot.
Determination of $x$ and $y$

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$
- 540,800±800 events (98.5% pure)
- Use "slow" pion to tag flavour. $D^{*+} \rightarrow D^0 \pi^+$
  $\Delta m = m_{D^{*+}} - m_{D^0}$

**PRELIMINARY**

```
<table>
<thead>
<tr>
<th>$m_{D^0}$ (GeV/c²)</th>
<th>Events / 0.8 MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.84</td>
<td>$10^4$</td>
</tr>
<tr>
<td>1.86</td>
<td>$10^3$</td>
</tr>
<tr>
<td>1.88</td>
<td>$10^4$</td>
</tr>
<tr>
<td>1.9</td>
<td>$10^3$</td>
</tr>
</tbody>
</table>
```

```
<table>
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<tr>
<th>$\Delta m$ (GeV/c²)</th>
<th>Events / 0.8 MeV/c²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.144</td>
<td>$10^4$</td>
</tr>
<tr>
<td>0.146</td>
<td>$10^3$</td>
</tr>
<tr>
<td>0.148</td>
<td>$10^4$</td>
</tr>
</tbody>
</table>
```

```
<table>
<thead>
<tr>
<th>$t$ (ps)</th>
<th>Events / 0.08 ps</th>
</tr>
</thead>
<tbody>
<tr>
<td>-2</td>
<td>$10^3$</td>
</tr>
<tr>
<td>0</td>
<td>$10^4$</td>
</tr>
<tr>
<td>2</td>
<td>$10^5$</td>
</tr>
<tr>
<td>4</td>
<td>$10^6$</td>
</tr>
</tbody>
</table>
```
Determination of $x$ and $y$

- $D^0 \rightarrow K_S^0 K^+ K^-$
- 79,900±300 events (99.2% pure)
- Use “slow” pion to tag flavour. $D^{*+} \rightarrow D^0 \pi^+$
  $\Delta m = m_{D^{*+}} - m_{D^0}$

PRELIMINARY

![Graph](image1)

PRELIMINARY

![Graph](image2)

PRELIMINARY

![Graph](image3)
Determination of $x$ and $y$

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

Time integrated Dalitz plot.

Average lifetime as function of position in Dalitz plot.

Monte Carlo $x = y = 1\%$
Determination of $x$ and $y$

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

Time integrated Dalitz plot.

Average lifetime as function of position in Dalitz plot.

Monte Carlo

$x = y = 1\%$
Determination of $x$ and $y$

- PRELIMINARY...but just accepted to PRL!
- $x = [1.6 \pm 2.3\,\text{(stat.)} \pm 1.2\,\text{(sys.)} \pm 0.8\,\text{(model)}] \times 10^{-3}$
- $y = [5.7 \pm 2.0\,\text{(stat.)} \pm 1.3\,\text{(sys.)} \pm 0.7\,\text{(model)}] \times 10^{-3}$
- Most precise single measurement of $x$.
- Assumes no $CP$-violation.

Figure 82: Contours for the combined $K^0\pi^+\pi^-$ + $K^0\bar{K}^+K^-$ fit results on data including the systematic errors due to the experimental analysis method and to the Dalitz model assumption. The marker at (0,0) represents the no mixing point, while the other ones represent the fit results.
LIFETIME RATIO

- Measure $y_{CP}$
  - 500M $c\bar{c}$ pairs. (384 fb$^{-1}$)
- Lifetime ratio using $D^0 \rightarrow K^+ K^-, K^- \pi^+$
- Untagged (recoil charm meson is *not* reconstructed).
  - Results are later combined with a previous tagged analysis: recoil charm meson is reconstructed.
- Assume no $CP$-violation.
Lifetime ratio

- **Measure** $y_{CP}$
  - 500M $c\bar{c}$ pairs. (384 fb$^{-1}$)
- **Lifetime ratio using** $D^0 \rightarrow K^+K^-, K^-\pi^+$
- **Untagged** (recoil charm meson is not reconstructed).
  - Results are later combined with a previous tagged analysis: recoil charm meson is reconstructed.
- **Assume no $CP$-violation.**

\[
\begin{align*}
D_1 \quad &\text{is} \quad CP - \text{even} \\
D_2 \quad &\text{is} \quad CP - \text{odd} \\
y_{CP} \quad &\approx \quad y \\
\Gamma \quad &\approx \quad \frac{\Gamma_1 + \Gamma_2}{2} \\
y_{CP} \quad &\approx \quad \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\end{align*}
\]
Lifetime ratio

- Measure $y_{CP}$
- BaBar (2009) \((\text{PhysRevD.80.071103})\)
  - 500M $c\bar{c}$ pairs. \((384 \text{ fb}^{-1})\)
- Lifetime ratio using $D^0 \to K^+ K^-, K^- \pi^+$
- Untagged (recoil charm meson is \textit{not} reconstructed).
  - Results are later combined with a previous tagged analysis: recoil charm meson is reconstructed.
- Assume no $CP$-violation.

\[
\begin{align*}
D_1 & \quad \text{is} \quad CP - \text{even} \\
D_2 & \quad \text{is} \quad CP - \text{odd} \\
y_{CP} & \approx y \\
\Gamma & = \frac{\Gamma_1 + \Gamma_2}{2} \\
y_{CP} & = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\end{align*}
\]

\[
y_{CP} = \frac{\langle \tau(\text{Mixed } CP \text{ final state}) \rangle}{\langle \tau(CP \text{ even final state}) \rangle} - 1
\]

\[
= \frac{\langle \tau(D^0 \to K^- \pi^+) \rangle}{\langle \tau(D^0 \to K^+ K^-) \rangle} - 1
\]
$D^0 \rightarrow K^- \pi^+$
- 2.7M signal yield
- 94.2% purity
**Lifetime ratio**

- \( D^0 \rightarrow K^- \pi^+ \)
  - 2.7M signal yield
  - 94.2% purity

- \( D^0 \rightarrow K^+ K^- \)
  - 0.26M signal yield
  - 80.9% purity

---

![Graph showing m_{K\bar{K}} (GeV/c^2) vs. Events/0.5 MeV/c^2 with lower and upper sidebands highlighted.](image-url)
\[ \tau_{K\pi} = 410.39 \pm 0.38 \text{(stat.)} \text{ps} \]
\[ \tau_{KK} = 405.85 \pm 1.00 \text{(stat.)} \text{ps} \]

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

\[ D^0 \rightarrow K^+K^- \]
Lifetime ratio

- $\tau_{K\pi} = 410.39 \pm 0.38 \text{(stat.)} \text{ps}$
- $\tau_{KK} = 405.85 \pm 1.00 \text{(stat.)} \text{ps}$
- $y_{CP} = [1.12 \pm 0.26 \text{(stat.)} \pm 0.22 \text{(syst.)}] \%$
- No-mixing excluded at $3.3\sigma$. 

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

$D^0 \rightarrow K^+K^-$
**Lifetime ratio**

- $\tau_{K\pi} = 410.39 \pm 0.38\text{(stat.)}\text{ps}$
- $\tau_{KK} = 405.85 \pm 1.00\text{(stat.)}\text{ps}$
- $y_{CP} = [1.12 \pm 0.26\text{(stat.)} \pm 0.22\text{(syst.)}]\%$
- No-mixing excluded at $3.3\sigma$.
- Combining with previous tagged analysis
  - PhysRevD.78.011105
  - $y_{CP} = [1.16 \pm 0.22\text{(stat.)} \pm 0.18\text{(syst.)}]\%$
  - No-mixing excluded at $4.1\sigma$. 

---

**Graphs**

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

---

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HFAG (World Averages) $y_{CP}$

**HFAG-charm EPS 2009**

- **E791 1999**: $0.732 \pm 2.890 \pm 1.030 \%$
- **FOCUS 2000**: $3.420 \pm 1.390 \pm 0.740 \%$
- **CLEO 2002**: $-1.200 \pm 2.500 \pm 1.400 \%$
- **Belle 2002**: $-0.500 \pm 1.000 \pm 0.800 \%$
- **Belle 2007**: $1.310 \pm 0.320 \pm 0.250 \%$
- **Belle 2009**: $0.110 \pm 0.610 \pm 0.520 \%$
- **BaBar 2009**: $1.160 \pm 0.220 \pm 0.180 \%$
- **World average**: $1.107 \pm 0.217 \%$

M. Bellis July 2010
No mixing is excluded at the $10\sigma$ level.
No mixing is excluded at the $10\sigma$ level.
Observed CP-violation insufficient to explain matter/anti-matter asymmetry 
(when combined with Standard Model baryon number violating processes)

Searches in other modes could reveal new physics.
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(when combined with Standard Model baryon number violating processes)

Searches in other modes could reveal new physics.


Assume CPT invariance and look for T-violation.

Form T-odd correlation and difference of asymmetries.
Observed \( CP \)-violation insufficient to explain matter/anti-matter asymmetry
\((\text{when combined with Standard Model baryon number violating processes})\)
Searches in other modes could reveal \textbf{new physics}.
Assume \( CPT \) invariance and look for \( T \)-violation.
Form \( T \)-odd correlation and difference of asymmetries.
\begin{itemize}
  \item 611M \( c\bar{c} \) pairs. (470 \( fb^{-1} \))
  \item \( D^0 \rightarrow K^+K^-\pi^+\pi^- \)
\end{itemize}
Observed CP-violation insufficient to explain matter/anti-matter asymmetry (when combined with Standard Model baryon number violating processes)

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BaBar (2010) *PhysRevD.81.111103*

- 611M c\bar{c} pairs. (470 fb$^{-1}$)
- $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$

\[ C_T \equiv \langle p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-}) \rangle \]
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- \(D^0 \rightarrow K^+K^−\pi^+\pi^−\)

\[
C_T \equiv \langle p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-}) \rangle
\]

\[
A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \quad \tilde{A}_T = \frac{\Gamma(-\tilde{C}_T > 0) - \Gamma(-\tilde{C}_T < 0)}{\Gamma(-\tilde{C}_T > 0) + \Gamma(-\tilde{C}_T < 0)}
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\[ C_T \equiv \langle p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-}) \rangle \]

\[ A_T = \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)} \quad \bar{A}_T = \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)} \]

\[ A_T = \frac{1}{2}(A_T - \bar{A}_T) \]
Use “slow” pion to tag flavour.
Count the yields

<table>
<thead>
<tr>
<th>Condition</th>
<th>Yield (±Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0, C_T &gt; 0$</td>
<td>10974 ± 117</td>
</tr>
<tr>
<td>$D^0, C_T &lt; 0$</td>
<td>12587 ± 125</td>
</tr>
<tr>
<td>$\bar{D}^0, \bar{C}_T &gt; 0$</td>
<td>10749 ± 116</td>
</tr>
<tr>
<td>$\bar{D}^0, \bar{C}_T &lt; 0$</td>
<td>12380 ± 124</td>
</tr>
</tbody>
</table>

Consistent with no CP-violation.
Count the yields

<table>
<thead>
<tr>
<th>Raw event yields from fit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0, C_T &gt; 0$</td>
<td>$10974 \pm 117$</td>
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<tr>
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</tbody>
</table>

$A_T = [-68.5 \pm 7.3 \text{(stat.)} \pm 5.8 \text{(sys.)}] \times 10^{-3}$

$\bar{A}_T = [-70.5 \pm 7.3 \text{(stat.)} \pm 3.9 \text{(sys.)}] \times 10^{-3}$

$A_T = [1.0 \pm 5.1 \text{(stat.)} \pm 4.4 \text{(sys.)}] \times 10^{-3}$

Consistent with no CP-violation.
Summary

- BaBar is very active and producing great physics results!
- Much analysis in the *charm* sector.

\[ x = [1.6 \pm 2.3^{(\text{stat})} \pm 1.2^{(\text{sys})} \pm 0.8^{(\text{model})}] \times 10^{-3} \]

\[ y = [5.7 \pm 2.0^{(\text{stat})} \pm 1.3^{(\text{sys})} \pm 0.7^{(\text{model})}] \times 10^{-3} \]

\[ y_{CP} = [1.16 \pm 0.22^{(\text{stat})} \pm 0.18^{(\text{syst})}] \% \]

Combination of tagged and un-tagged analysis excluded no-mixing at 4.3 \( \sigma \).

PhysRevD.80.071103

Search for \( CP \)-violation using \( T \)-odd correlations.

No significant \( CP \)-violation observed.

PhysRevD.81.111103

Thanks for your time!

M. Bellis July 2010
BaBar is very active and producing great physics results!

Much analysis in the *charm* sector.

Measurement of $x$ and $y$ in Dalitz plot analysis.

- $x = [1.6 \pm 2.3({\text{stat.}}) \pm 1.2({\text{sys.}}) \pm 0.8({\text{model}})] \times 10^{-3}$
- $y = [5.7 \pm 2.0({\text{stat.}}) \pm 1.3({\text{sys.}}) \pm 0.7({\text{model}})] \times 10^{-3}$

arXiv:1004.5053
BaBar is very active and producing great physics results!

Much analysis in the *charm* sector.

Measurement of $x$ and $y$ in Dalitz plot analysis.

- $x = [1.6 \pm 2.3{\text{(stat.)}} \pm 1.2{\text{(sys.)}} \pm 0.8{\text{(model)}}] \times 10^{-3}$
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- arXiv:1004.5053

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**Thanks for your time!**
The B-factories

- BaBar (SLAC)

Significant backgrounds under the resonance ($c\bar{c}$, $\tau^+\tau^-$,...)

Wealth of rich physics under the resonance.

High luminosity

On the order of 1.5 billion $B\bar{B}$ pairs in the world's dataset!

M. Bellis July 2010
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**$\Upsilon(nS)$ resonances**

- $\Gamma = 54$ KeV
- $\Gamma = 32$ KeV, $\sigma_{\text{vis}} \approx 7$ nb
- $\Gamma = 20$ KeV, $\sigma_{\text{vis}} \approx 4$ nb
- $\Gamma = 20$ MeV

High luminosity
On the order of 1.5 billion $B\bar{B}$ pairs in the world's dataset!

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The B-factories
- BaBar (SLAC)
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- High luminosity
- On the order of 1.5 billion \( B\bar{B} \) pairs in the world’s dataset!
BaBar

- 600 million $c\bar{c}$ pairs.
### $D^0 - \bar{D}^0$ Mixing

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<thead>
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\[ D^0 \rightarrow \bar{D}^0 \text{ MIXING} \]

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\begin{align*}
|D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle \\
|D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle
\end{align*}
\]

\[ |p|^2 + |q|^2 = 1 \quad p = q = \frac{1}{\sqrt{2}} \text{ if there is no } CP - \text{ violation} \]
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$$i \frac{\partial}{\partial t} \begin{pmatrix} |D^0\rangle \\ |\bar{D}^0\rangle \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} |D^0\rangle \\ |\bar{D}^0\rangle \end{pmatrix}$$
### Flavour eigenstates vs. Mass eigenstates

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

Define some useful quantities:

\[
M = \frac{M_1 + M_2}{2} \quad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \\
x = \frac{M_1 - M_2}{\Gamma} \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}
\]

Where do we go to measure this?
What is mixing

\[ |D_1(t)\rangle = |D_1\rangle e^{-i(\Gamma_1/2 + i \Gamma_1) t} \]

\[ |D_2(t)\rangle = |D_2\rangle e^{-i(\Gamma_2/2 + i \Gamma_2) t} \]

\[ x = \frac{m_1 - m_2}{\Gamma} \]

\[ y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \]

\[ \left| \begin{array}{c} p \\ q \end{array} \right| \]

\[ \psi_M = \text{Arg} \left\{ \frac{p}{q} \right\} \]
Determination of \( x \) and \( y \)

- Measure \( x \) and \( y \) directly in self-conjugate final states.
  - \( D \rightarrow K^0_S\pi^+\pi^- \)
  - \( D \rightarrow K^0_SK^+K^- \)

- Time-dependent Dalitz analysis

\[
\begin{align*}
  s_+ &= m^2(K^0_Sh^+) \\
  s_- &= m^2(K^0_Sh^-)
\end{align*}
\]

- Decay amplitude

\[
\mathcal{A}(s_+, s_-)
\]

- If \( CPV = 0 \),

\[
\mathcal{A}(s_+, s_-) = \overline{\mathcal{A}}(s_-, s_+)
\]

\[
g_\pm = \frac{1}{2} \left[ e^{i(m_1 - i\Gamma_1/2)t} \pm e^{i(m_2 - i\Gamma_2/2)t} \right]
\]

Process is function of \((s_-, s_+)\) and proportional to \( \cosh(y\Gamma t), \sinh(y\Gamma t), \cos(x\Gamma t), \sin(x\Gamma t) \), and modulated by \( e^{-\Gamma t} \).

\( x \) and \( y \) are common across both topologies. Time dependance can be written as

\[
\mathcal{M}(s_+, s_-, t) = \mathcal{A}(s_+, s_-)g_+(t) + \frac{q}{p}\mathcal{A}(s_-, s_+)g_-(t)
\]

\[
M(s_+, s_-, t) = \frac{q}{p}\overline{\mathcal{A}}(s_+, s_-)g_+(t) + \overline{\mathcal{A}}(s_-, s_+)g_-(t)
\]
First evidence for $D^0 - \bar{D}^0$ mixing

- $x'^2 = [-0.22 \pm 0.30 \text{(stat.)} \pm 0.21 \text{(sys.)}]$
- $y' = [9.7 \pm 4.4 \text{(stat.)} \pm 3.1 \text{(sys.)}]$
- No-mixing excluded at 3.9$\sigma$. 

![Graphical representation of $D^0 - \bar{D}^0$ mixing data and analysis results.](image-url)
$D^0$ mixing in $K^0_S h^+ h^-$ ($h = K, \pi$)

No strong phase: $\delta_{K\pi\pi} = 0$

- CP-eigenstates in the final state.
- This ties the phase of the $D^0$ and $\bar{D}^0$ decay amplitudes together. (ref Brian’s ICHEP 2008)
- Assume CPV=0
- Can pull out $x$ and $y$.

Time dependent.

$D^{*+} \rightarrow \pi^+ D^0$

- “slow” $\pi$ ($\pi_s$) tags flavour.
- $\pi_s$ and $D^0$ decay products are tracked back to a common origin for timing information.
  - $K^0_S \pi^+ \pi^-$: $\sigma_t = 0.2$ ps
  - $K^0_S K^+ K^-$: $\sigma_t = 0.3$ ps
**Determination of $x$ and $y$**

- Measure $x$ and $y$ directly in self-conjugate final states.
  - $D \rightarrow K_S^0 \pi^+ \pi^-$
  - $D \rightarrow K_S^0 K^+ K^-$

- Time-dependent Dalitz analysis

\[
\begin{align*}
  s_+ &= m^2(K_S^0 h^+) & \text{If } CPV = 0, \quad A(s_+, s_-) = \bar{A}(s_-, s_+), \\
  s_- &= m^2(K_S^0 h^-)
\end{align*}
\]

- Time dependence

\[
\begin{align*}
  g_\pm &= \frac{1}{2} \left[ e^{i(m_1 - i\Gamma_1/2)t} \pm e^{i(m_2 - i\Gamma_2/2)t} \right] \\
  \mathcal{M}(s_+, s_-, t) &= A(s_+, s_-)g_+(t) + \frac{q}{p} A(s_-, s_+)g_-(t) \\
  \overline{\mathcal{M}}(s_+, s_-, t) &= \frac{q}{p} \bar{A}(s_+, s_-)g_+(t) + \bar{A}(s_-, s_+)g_-(t)
\end{align*}
\]

$x$ and $y$ are common across both topologies.
Determination of $x$ and $y$

Time integrated Dalitz plots

$$D^0 \rightarrow K^0_S \pi^+ \pi^-$$

$$D^0 \rightarrow K^0_S K^+ K^-$$
**Determination of $x$ and $y$**

- Measure $x$ and $y$ directly in self-conjugate final states.
  - $D \rightarrow K_S^0 \pi^+ \pi^-$
  - $D \rightarrow K_S^0 K^+ K^-$
- 600M $c\bar{c}$ pairs. (468.5 fb$^{-1}$)
  - arXiv:1004.5053

- Time-dependent Dalitz plot analysis
  
  $s_+ = m^2(K_S^0 h^+)$
  
  $s_- = m^2(K_S^0 h^-)$

- If $CPV = 0$, $A(s_+, s_-) = \bar{A}(s_-, s_+)$

- Time dependence

- $x$ and $y$ are common across both topologies.

---

![Graph showing $m^2(K_S^0 \pi^-)$ vs. $m^2(K_S^0 \pi^+)$ with different time intervals highlighted.](image)
- $D^0$ and $D^{*+}$ identification.
- ALSO INCLUDE PURITIES AND PERCENT OF BACKGROUND STUFF
HFAG (World averages) $x$ and $y$

**HFAG-charm FPCP 2010**

**World average**

- $x$:
  - $0.419 \pm 0.211\%$
  - CLEO 2005/2007: $1.900 \pm 3.300 \pm 0.566\%$
  - BaBar 2010: $0.160 \pm 0.230 \pm 0.144\%$
  - Belle 2007: $0.800 \pm 0.290 \pm 0.170\%$
  - CLEO 2005/2007: $1.900 \pm 3.300 \pm 0.566\%$

- $y$:
  - $0.456 \pm 0.186\%$
  - CLEO 2005/2007: $-1.400 \pm 2.400 \pm 0.894\%$
  - BaBar 2010: $0.570 \pm 0.200 \pm 0.148\%$
  - Belle 2007: $0.330 \pm 0.240 \pm 0.150\%$

M. Bellis July 2010

ICHEP 2010