$D^0 - \bar{D}^0$ Mixing/CP Violation at CDF

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5th International Workshop on the CKM Unitarity Triangle
Rome, September 9-13, 2008
Introduction

$D^0$ mixing: expected small in the SM $\Rightarrow$ very interesting
- $D^0$ is the only up type meson which shows mixing
- Discrepancies with SM $\Rightarrow$ New Physics

Short range processes $\Rightarrow$ small amplitude
($m_b$ small, CKM suppression)

Long range processes $\Rightarrow$ larger amplitude
(model dependent)
Important CDF features

- Central Drift chamber in B field
  - $\sigma(p_T)/p_T^2 \sim 0.1\% \text{GeV/c}^{-1}$
    (excellent tracking/mass res)
  - $dE/dx$ measurement

- Silicon Vertex detector
  - I.P. resolution 35 um @2 GeV/c

- Hadronic B/D triggers
  3D tracks in the COT, $p_T > 2 \text{ GeV/c}$
  2D tracks in COT+SVX, $p_T > 2 \text{ GeV/c}$
  Offline quality I.P. measurement
Measurement Technique

- Measure $R(t) =$ Wrong Sign/Right Sign in $D^0 \rightarrow K^-\pi^+$ decay

- WS also due to $D^0 \rightarrow \overline{D}^0 \rightarrow K^+\pi^-$ ($D^0$ mixing + CF decay)

- If no CP violation and small mixing ($x, y << 1$):

  $$ R(t/\tau) = R_D + \sqrt{R_D} \, y' x(t/\tau) + \frac{1}{4} x(x'^2 + y'^2) x(t/\tau)^2 $$

CDF-II: PRD-RC 74,031109 (2006) (time ind. meas.)
Measurement Technique

1) Measure proper decay time
2) Identify charm @production
3) Identify charm @decay

\[ D^* \to D^0 \pi_s \]
\[ D^0 \to K^- \pi^+ \]

\( \pi_s \) tags charm @production

Lxy measures decay time

\( K\pi \) final state tags charm @decay
Data Sample

$\int L \approx 1.5 \text{ fb}^{-1}$ CDF data (Feb 2002 - Jan 2007)

Hadronic Trigger requires
- 2 Tracks from a displaced vertex ($d > 100$ um)
  (good acceptance for $> 0.5 - 10$ $D^0$ lifetimes)

Offline reconstruction requires
- 2 Trigger tracks form $D^0 \rightarrow K\pi$
- Add soft track to form $D^{*+} \rightarrow \pi_s^+ D^0$

\[ \begin{align*}
D^0 & \quad \pi^+ \\
D^{*} & \quad \pi^+ \\
D^0 & \quad K^- \\
\text{d}>100 \text{ um} & \\
\end{align*} \]
Extract RS & WS signals

WS signal blinded during cut optimization
- scaled RS signal acts as substitute ($WS = 0.004 \times RS$)

Same selection for RS and WS (same kinematics)

Events have decay times from 0.75–10 $D^0$ lifetimes
- Trigger acceptance is low for shorter decay times
- Few events at long decay time (exponential decay)

CDF Run II (1.5/fb)

3.3x10^6 RS $D^0$ (time integrated)
Analysis Overview

What we need to measure

\[ R(t/\tau) = R_D + \sqrt{R_D} y'x(t/\tau) + 1/4(x'^2+y'^2)x(t/\tau)^2 \]

<table>
<thead>
<tr>
<th>20 decay time bins</th>
<th>Fit ( R(t) ) to determine mixing parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Divide events into RS and WS</td>
<td>Ratio ( R ) for each time bin</td>
</tr>
<tr>
<td>Two ( d_0(D^0) ) bins: ( \leq 60 \mu m, &gt;60 \mu m )</td>
<td>Prompt or from B-decay (wrong decay time)</td>
</tr>
<tr>
<td>60 bins ( \Delta m ) (( D^* - D^0 - \pi ))</td>
<td>( D^* ) or not ( D^* )</td>
</tr>
<tr>
<td>( K\pi ) mass distribution</td>
<td>( D^0 ) or not ( D^0 )</td>
</tr>
</tbody>
</table>
**m(Kπ) spectrum**

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<th>Fit R(t) to determine mixing parameters</th>
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<tr>
<td>Divide events into RS and WS</td>
<td>Ratio R for each time bin</td>
</tr>
<tr>
<td>Two d₀ bins: ≤ 60 µm, &gt;60 µm</td>
<td>Prompt or from B-decay</td>
</tr>
<tr>
<td>60 bins Δm ((D^* - D^0 - π))</td>
<td>(D^<em>) or not (D^</em>)</td>
</tr>
<tr>
<td>(Kπ) mass distribution</td>
<td>(D^0) or not (D^0)</td>
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</tbody>
</table>

Fit for \(D^0\) yields
- Single signal shape used for all fits
- Parameters for background independent for all fits
- Typical \(\chi^2/\text{dof}\) for these fits = 1.0

![Graph showing m(Kπ) spectrum distribution](image.png)

- 0.35 fb\(^{-1}\)  
- WS \(D^0\) signal
- \(D^0\) or not \(D^0\)
- Prompt or from B-decay
- Δm \((D^* - D^0 - π)\)

Fake WS \(D^0\) signal  
Comb. bck
Mis-id \(D^0\)
20 decay time bins

Divide events into RS and WS

Two $d_0$ bins:
- $\leq 60 \mu m$
- $>60 \mu m$

60 bins $\Delta m$
($D^* - D^0 - \pi$)

$K\pi$ mass distribution

Fit $R(t)$ to determine mixing parameters

Ratio $R$ for each time bin

Prompt or from B-decay

$D^*$ or not $D^*$

$D^0$ or not $D^0$

Fit for $D^*$ yield
- Same signal shape for all fits
- Background shape is time independent
- Independent parameters for signal and background amplitudes
**B-Decay Background**

D* produced from B-decays has the wrong proper decay time
- decay length is measured from the primary vertex

Extrapolate the D⁰ towards the primary vertex
- D* produced at a secondary vertex has a larger \(d_0(D^0)\) value
Prompt $D^*$: narrow $d_0$ distribution (time independent)

$D^*$ from $B$: wide $d_0$ distribution (width increases with decay time)

Fit distribution using RS signal (RS width same as WS)

Get fraction of distribution with $d_0 < 60 \, \mu m$ and $d_0 > 60 \, \mu m$

Calculate number of prompt $D^*$ in each time bin
**Best Fit Parameters**

- $R_D = (3.04 \pm 0.55) \times 10^{-3}$
- $y' = (8.54 \pm 7.55) \times 10^{-3}$
- $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$
- $\chi^2 = 19.2$ for 17 dof

**No mixing fit**

- $R_D = (4.15 \pm 0.10) \times 10^{-3}$
- $x'^2 = y' = 0$
- $\chi^2 = 36.8$ for 19 dof

**Note**: Parameters heavily correlated
Uncertainties

Quoted uncertainties are statistical + systematic

Most parameters for the background shapes and amplitudes are determined by the fits of the data, associated syst. uncertainties already included in the uncertainty on the RS and WS signal yields.

We added additional systematic effects that were not part of the fit procedure (bck. shape in the $\Delta m$ distribution)

Detector geometric acceptance, trigger efficiency, particle id, time resolution have negligible effect on the WS/RS ratio (compared to current uncertainties)
Probability Contours

Bayesian probability intervals equivalent to 1-4σ

Solid point = best fit

Open diamond = highest prob.

Phys. allowed point (x'^2>0)

Cross = no-mixing (y'=x'^2=0)

No-mixing excluded at 3.8 Gaussian standard deviations level
CDF results in context

<table>
<thead>
<tr>
<th>Source</th>
<th>Data</th>
<th>$N_{WS}$</th>
<th>$x'^2 \times 10^{-3}$</th>
<th>$y' \times 10^{-3}$</th>
<th>Signif</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>400 fb$^{-1}$</td>
<td>4024</td>
<td>0.18±0.23</td>
<td>0.6±4.0</td>
<td>2.0</td>
</tr>
<tr>
<td>BaBar</td>
<td>384 fb$^{-1}$</td>
<td>4030</td>
<td>0.22±0.37</td>
<td>9.7±5.4</td>
<td>3.9</td>
</tr>
<tr>
<td>CDF</td>
<td>1.5 fb$^{-1}$</td>
<td>12700</td>
<td>-0.12±0.35</td>
<td>8.5±7.6</td>
<td>3.8</td>
</tr>
</tbody>
</table>

CDF has already ~2x data for analysis, will be ~4x in 2009
Meas. improves with $1/\sqrt{N}$
Prospects for CP violation

\[ A_{CP}(D^0 -> KK) = (2.0 \pm 1.2 \pm 0.6) \times 10^{-2} \]
\[ A_{CP}(D^0 -> \pi\pi) = (1.0 \pm 1.3 \pm 0.6) \times 10^{-2} \]

Expect 40 data by 2009
\[ \pm 0.2 \times 10^{-2} \text{ stat. error} \]

(PRL 94, 122001, 2005)

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>N(KK)</th>
<th>(A_{CP} \times 10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>540 fb-1</td>
<td>120 K</td>
<td>-0.43(\pm 0.30 \pm 0.11)</td>
</tr>
<tr>
<td>BaBar</td>
<td>386 fb-1</td>
<td>130 K</td>
<td>0.00(\pm 0.34 \pm 0.13)</td>
</tr>
</tbody>
</table>
CDF confirmed the evidence for charm mixing seen by BaBar with time dep. $D^0 \rightarrow K^+\pi^-, K^-\pi^+$ analysis
- No-mixing excluded @3.8$\sigma$, PRL 100, 121802 (2008)

CDF future prospects
- Improve the existing analysis (>2x data already available)
- Perform also lifetime/CP analysis in $D^0 \rightarrow KK/\pi\pi$
  (we expect a very precise CP measurement)