D-mixing at CDF

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On behalf of the CDF collaboration

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   - Charm Mixing in $D^0 \to K^+ \pi^-$
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   - CP Violation

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Neutral Flavored Mesons Mixing

- Neutral mesons can oscillate between matter and anti-matter: mass eigenstates are different from flavor eigenstates

$$i \frac{d}{dt} \left( |D^0\rangle \right) = \left[ \left( \begin{array}{cc} M_{11} & M_{12} \\ M^*_{12} & M_{22} \end{array} \right) - \frac{i}{2} \left( \begin{array}{cc} \Gamma_{11} & \Gamma_{12} \\ \Gamma^*_{12} & \Gamma_{22} \end{array} \right) \right] \left( |D^0\rangle \right)$$

$$|D_{L,H}\rangle = p |D^0\rangle \pm q |\overline{D}^0\rangle \quad \text{where} \quad \frac{q}{p} = \sqrt{\frac{M^*_{12} - \frac{i}{2} \Gamma^*_{12}}{M_{12} - \frac{i}{2} \Gamma_{12}}}$$

- Mixing usually described by two parameters

$$x = \frac{\Delta M}{\Gamma} = \frac{M_H - M_L}{(\Gamma_H + \Gamma_L)/2}, \quad y = \frac{\Delta \Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)}$$

- Charm mixing is much slower than kaon or beauty mixing

$$x, y \lesssim \mathcal{O}(10^{-3})$$

- Signals for New Physics would be $|x| \gg |y|$ or evidence for CP violation
Charm Mixing in $D^0 \rightarrow K^+\pi^-$

- Tag $D^0$ flavor at production time by $D^{*+} \rightarrow D^0\pi^+_s$ decay
- Measure time-dependence of Wrong-Sign $D^{*+} \rightarrow [K^+\pi^-]\pi^+_s$ to Right-Sign $D^{*+} \rightarrow [K^-\pi^+]\pi^+_s$ decay rates ratio

For WS two processes interfere:
- Mixing then Cabibbo-Favoured decay
- Doubly-Cabibbo-Suppressed decay

\[
R(t) = R_D + \sqrt{R_D} \ y' \ (\Gamma_D t) + \frac{x'^2 + y'^2}{4} \ (\Gamma_D t)^2
\]

\[
\frac{A_f(DCS)}{A_f(CF)} = \sqrt{R_D} \ e^{-i\delta_{K\pi}}
\]

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

\[
y' = y \cos \delta_{K\pi} - x \sin \delta_{K\pi}
\]
Important CDFII features

- Central drift chamber in magnetic field
  - $\sigma(p_t)/p_t^2 \sim 0.15\% \ (\text{GeV/c})^{-1}$ (excellent tracking/mass resolution)
  - dE/dx measurement

- Silicon Vertex detector
  - I.P. resolution $\sim 35 \, \mu\text{m}$, $p_t > 2 \, \text{GeV/c}$

- Hadronic trigger
  - Two tracks in COT+SVX, $p_t > 2 \, \text{GeV/c}$
Data Sample

Data collected from Feb 2002 to Jan 2007: $\int L \, dt \sim 1.5/\text{fb}$ @ $\sqrt{s} = 1.96$ TeV

Decay reconstruction:

- Two opposite charge tracks from a displaced vertex (hadronic trigger) form $D^0 \rightarrow K \pi$ candidate
  - $|d_0(K, \pi)| > 100 \, \mu\text{m}$
  - $L_{xy} > 200 \, \mu\text{m}$
  - (good acceptance for proper decay time $\gtrsim 0.5 \, D^0$ lifetimes)

- Add a “soft” track to form $D^* \rightarrow D^0 \pi_s$ candidate

$D^0$ life times

$\pi_s$ transverse to beam plane

$L_{xy}$ measures proper decay time

Beam spot

Primary interaction vertex
\(D^0\) candidate considered with both \(K^-\pi^+\) and \(\pi^-K^+\) particle assignments

- Mis-assigned mass distribution has width \(10 \times\) the correct assignment width (\(\sim 8 \text{ MeV}/c^2\))
Extract RS and WS Signals

- $D^0$ candidate considered with both $K^-\pi^+$ and $\pi^-K^+$ particle assignments
  - Mis-assigned mass distribution has width $10\times$ the correct assignment width ($\sim 8\text{ MeV}/c^2$)

- For RS exclude candidates with WS mass $|m_{K\pi} - m_{D^0}| < 20\text{ MeV}/c^2$ and vice versa
  - Keeps 78% of signal, 3.6% mis-assigned
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- Compare two-track PID probability (from measured dE/dx) for $K^-\pi^+$ and $\pi^-K^+$ assignments, use higher value

- Mass and PID cuts greatly clean up the mis-assigned background

![Graphs showing before and after selection for RS and WS m_{K\pi}](image-url)
When events are divided into RS and WS perform a series of binned fits to look for mixing:

- Signal yields from a set of fits is used in the next round of fits
- Deal with particular backgrounds one at a time
- Backgrounds from early fit stages are not present in later fits
Analysis Strategy

**Clean RS signal:**
- RS signal PDFs obtained from fits of the RS data
- WS signal events have the same distributions as RS except for decay time (same kinematics)
- Use data as much as possible, MC only for guidance

**fit** $R(t)$ **to determine mixing parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ratio $R$ for each decay time bin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proper decay time</td>
<td></td>
</tr>
<tr>
<td>$D^*$ impact parameter</td>
<td>prompt or from $B$-decay</td>
</tr>
<tr>
<td>$\Delta m$</td>
<td>$D^<em>$ or not $D^</em>$</td>
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<td>$m_{K\pi}$</td>
<td>$D^0$ or not $D^0$</td>
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**3.04 \cdot 10^6** RS events (time integrated)

![Histogram of $m_{K\pi}$](chart.png)
Analysis Strategy: step 1

- Single signal shape used for all fits
- Parameters for background independent for all fits
- Typical $\chi^2$/ndf $\approx 1$

Fit $R(t)$ to determine mixing parameters

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Events / 2 MeV/c^2

$D^0$ signal

Combinatorial bkg

Mis-identified $D^0$
Analysis Strategy: step 2

fit $R(t)$ to determine mixing parameters

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Fit for $D^*$ yield:
- Same signal shape for all fits
- Background shape constant in time
- Time-independent parameters for signal and background yields

WS $D^*$ signal
12700 events (time integrated)

$D^0$ + random $\pi_s$
Analysis Strategy: step 3

Fit $R(t)$ to determine mixing parameters

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Fit for prompt $D^*$:

- $D^*$ from $B$ decays will have wrong decay time
- $D^*$ from $B$ decays have a broader impact parameter ($d_0$) distribution than promptly produced $D^*$
Analysis Strategy: step 4

Fit $R(t)$ to determine mixing parameters

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$$R(t) = R_D + \sqrt{R_D} \ y' \ (\Gamma_D t) + \frac{x'^2 + y'^2}{4} \ (\Gamma_D t)^2$$

Quoted uncertainties are statistical + systematic

<table>
<thead>
<tr>
<th>Best fit (red curve)</th>
<th>$\chi^2/ndf$</th>
<th>$R_D \ (10^{-3})$</th>
<th>$y' \ (10^{-3})$</th>
<th>$x'^2 \ (10^{-3})$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>19.2/17</td>
<td>3.04 ± 0.55</td>
<td>8.54 ± 7.55</td>
<td>−0.12 ± 0.35</td>
</tr>
<tr>
<td>No mixing fit (blue line)</td>
<td>36.8/19</td>
<td>4.15 ± 0.10</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Results on Mixing Hypothesis

No-mixing excluded at 3.8 Gaussian standard deviations level

- Probability intervals for the mixing parameters equivalent to 1-4 $\sigma$
- $+$ = no mixing point $(x'^2, y' = 0)$
- $\bullet$ = best fit point
- $\Diamond$ = highest probability physically allowed point $(x'^2 > 0)$

<table>
<thead>
<tr>
<th>data</th>
<th>$N_{WS}$</th>
<th>$x'^2(10^{-3})$</th>
<th>$y'(10^{-3})$</th>
<th>signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>400/fb</td>
<td>4024</td>
<td>$0.18^{+0.21}_{-0.23}$</td>
<td>$0.6^{+4.0}_{-3.9}$</td>
</tr>
<tr>
<td>BaBar</td>
<td>384/fb</td>
<td>4030</td>
<td>$-0.22 \pm 0.37$</td>
<td>$9.7 \pm 5.4$</td>
</tr>
<tr>
<td>CDF</td>
<td>1.5/fb</td>
<td>12700</td>
<td>$-0.12 \pm 0.35$</td>
<td>$8.5 \pm 7.6$</td>
</tr>
<tr>
<td><em>Phys. Rev. Lett.</em> <strong>100</strong> (2008) 121802</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CDF has world’s largest charm sample:

\[ D^{*+} \rightarrow D^0 \pi^+ + \text{C.C.} \]

\[ \pi^+ \pi^- \approx 170 \cdot 10^3 \text{ events} \]

\[ K^\mp \pi^\pm \approx 4 \cdot 10^6 \text{ events} \]

\[ K^+ K^- \approx 360 \cdot 10^3 \text{ events} \]

Physics backgrounds:

**Partially reconstructed** \[ D^0/\pm \rightarrow 3\text{Bodies} \]
Prospects: Charm Mixing

- Improve the existing analysis
  - more data
  - more sophisticated techniques
  - allowing for CPV
- Perform also lifetime analysis in $D^0 \rightarrow h^+ h^- (h = K \text{ or } \pi)$

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

<table>
<thead>
<tr>
<th></th>
<th>data</th>
<th>$y_{CP}$ (%)</th>
<th>signif.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belle</strong></td>
<td>540/fb</td>
<td>$1.31 \pm 0.32 \text{ (stat.)} \pm 0.25 \text{ (syst.)}$</td>
<td>3.2 $\sigma$</td>
</tr>
<tr>
<td><strong>BaBar</strong></td>
<td>384/fb</td>
<td>$1.03 \pm 0.33 \text{ (stat.)} \pm 0.19 \text{ (syst.)}$</td>
<td>3.0 $\sigma$</td>
</tr>
</tbody>
</table>

Preliminary study on 2.9/fb to estimate statistical resolution
Estimated statistical uncertainty on $D^0 \to \pi^+\pi^-$ CP asymmetry based on counting:

$$A_{CP}(h^+h^-) = \frac{N(D^0 \to h^+h^-) - N(D^0 \to h^-h^+)}{N(D^0 \to h^+h^-) + N(D^0 \to h^-h^+)}$$

<table>
<thead>
<tr>
<th>data</th>
<th>$A_{CP}(\pi^+\pi^-)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Our estimate</td>
<td>2.9/fb</td>
</tr>
<tr>
<td>CDF</td>
<td>0.123/fb</td>
</tr>
<tr>
<td>BaBar</td>
<td>386/fb</td>
</tr>
<tr>
<td>Belle</td>
<td>540/fb</td>
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similar estimate for $D^0 \to K^+K^-$
Conclusions

- CDF has the world's largest charm sample: rich program that includes access to CPV asymmetries, branching fractions, mixing, mixing-induced CPV

- In 2007 CDF confirmed the *BaBar* evidence for charm mixing with time dependent $D^0 \rightarrow K^+\pi^-$ analysis: no mixing excluded @ 3.8 $\sigma$

- Now a lot of promising work in progress: e.g. expected statistical resolutions on CPV asymmetries in Cabibbo-suppressed $D^0$ decays $2 \times$ better than B-Factories
Backup Slides
Charm Mixing Predictions

Standard Model


Box diagram SM charm mixing rate naively expected to be very low:

\[ x, y \lesssim \mathcal{O}(10^{-5}) \]

\[ D^0 \xrightarrow{W^+} W^- \xrightarrow{D^0} \]

- \( b \) loop CKM suppressed \( \rightarrow \) \( |V_{ub} V_{cb}^*|^2 \ll 1 \)
- \( s, d \) loops GIM suppressed \( \rightarrow \) \( \frac{(m_s^2 - m_d^2)}{m_W^2} \)

Enhanced rate SM calculations generally due to long-distance contributions:

\[ x, y \lesssim \mathcal{O}(10^{-3}) \]

Generally: calculations are difficult and uncertainties are quite large

New Physics

[arXiv:0705.3650]

Possible enhancements to mixing due to new particles and interactions in new physics models

Most new physics predictions for \( x \):

- Fourth generation down-type quarks
- Extended Higgs, tree-level FCNC
- Supersymmetry: gluinos, squarks

Signals for NP would be \( |x| \gg |y| \) or evidence for CPV
CDF:
- Binned fits
- 12700 WS $D^*$ produced at primary vertex
- $D^0$ decay times from 0.75 to 10 lifetimes
- Only no CPV fit ($D^{*+}$ and $D^{*-}$ combined)

BaBar and Belle:
- Unbinned maximum likelihood fit
- 4000 WS but better signal/background
- $D^0$ decay times from 0 to $\sim 4$ lifetimes
- Additional fit allowing for CPV ($D^{*+}$ and $D^{*-}$ separated)
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 (bkg shape in the $\Delta m$ distribution)
- Detector geometric acceptance, trigger efficiency, PID, time resolution have negligible effect on the WS/RS ratio (compared to current uncertainties)