OBSERVATION OF $D^0$ MIXING AT CDF

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Neutral mesons can oscillate between matter and anti–matter

- Mass eigenstates ≠ flavor eigenstates

\[ D^0 = \frac{\langle D_1 + D_2 \rangle}{\sqrt{2}} \quad \bar{D}^0 = \frac{\langle D_1 - D_2 \rangle}{\sqrt{2}} \]

- Time evolution

\[ D_{1,2}(t) = D_{1,2}(0) e^{-t(\Gamma_{1,2} + iM_{1,2})} \]

- Mixing well established in $K^0$ (1962), $B^0$ (1987), and $B_s^0$ (CDF 2006) decays
  - Evidence for $D^0$ from Belle (2006), Babar and CDF(2007)
  - Observation by LHCb (2012)
Mixing Characteristics

- Two sources
  - Long-range intermediate states
    - Dominant
    - Large theoretical uncertainties
  - Short-range box diagram
    - Suppressed
      - No GIM suppression from heavy top quark
    - Possible enhancement by New Physics
- Charm mixing slow
  - $x, y \ll 1$
Mixing Signature

- Compare rate of wrong-sign $D^0 \rightarrow K^+ \pi^-$ decays to right-sign $D^0 \rightarrow K\pi^+$ decays
  - Tag flavor at production with $D^{*+} \rightarrow D^0 \pi^+$ decays
  - Wrong sign events can come from mixing or doubly Cabibbo-suppressed (DCS) decays
    - DCS decays are time independent

- Time evolution

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

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

$\delta_{K\pi}$: strong phase difference between CF and DCS amplitudes
Data Sample

- Full CDF II data set
  - 9.6 pb\(^{-1}\) p\(\bar{p}\) at \(\sqrt{s}=1960\) GeV
- Heavy flavor hadronic decay trigger
  - Two opposite-charge tracks with \(p_T>2\) GeV/c, \(d_0>100\mu m\)

1.4T Solenoid

COT Drift Chamber
- \(\delta p_T/p_T^2 \approx 0.07\%\)
- PID from dE/dx with ~1.5\(\sigma\) K–\(\pi\) separation at \(p_T=2\) GeV

SVX Vertex Detector
- \(\delta d_0 \approx 25\mu m\)
- Beam spot rms 25\(\mu m\)

7/18/2013

Charm Meson Mixing at CDF
Reconstruct events with both RS and WS hypotheses.

Large background to WS decays from incorrect charge assignment in RS decays.
Reduce misassignment background

- Remove WS candidates consistent with RS hypothesis and vice versa
  - Removes 96% of background
  - 78% efficient for signal

CDF Run II preliminary, L=9.6 fb⁻¹

Wrong-sign Kπ mass [GeV/c²]

RS after WS cut

Charm Meson Mixing at CDF

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D* Reconstruction

- Standard method
  - Fit $\Delta m = m(K\pi\pi_{\text{tag}}) - m(K\pi) - m_{\pi}$
- Must account for $D^0$ and $D^*$ backgrounds
  - Cutting on $D^0$ peak would include fake $D$ mesons in $D^*$ fit
  - In 10 bins of $D^0$ decay time, for RS and WS candidates, find the $D^0$ yield in 60 bins of $\Delta m$
    - Fit the resulting $\Delta m$ distribution to get the $D^*$ yields
Wrong-Sign Ratio

- From $D^*$ yields, get measured ratio in each time bin

\[
R_i = \frac{N_i(D^{*+} \to [K^{+}\pi^-]\pi^+) + N_i(D^{-} \to [K^{-}\pi^+]\pi^-)}{N_i(D^{*+} \to [K^{-}\pi^+]\pi^+) + N_i(D^{-} \to [K^{+}\pi^-]\pi^-)}
\]
Must account for $B$ decay component
- $D^0$ will have larger apparent lifetime
- Mixing sample is required to be consistent with prompt production, but some $B$ contamination remains

\[
R_m(t) = \frac{N^{WS}(t) + N^{WS}_B(t)}{N^{RS}(t) + N^{RS}_B(t)}
\]
Use impact parameter of reconstructed $D^0$ mesons

Prompt production $D^0$ from PV

Secondary production $D^0$ from $B$ decay
B Fraction

- Measured in RS data
- Fit to 4th order polynomial

CDF Run II preliminary, L=9.6 fb^{-1}

Data: RS D^0 \rightarrow K\pi
χ² fit vs. decay time

- Correct for B component using MC for D decay time distribution as a function of apparent decay time

\[ \chi^2 = \sum_{i=1}^{20} \left[ \frac{r_i - R_m(t_i)}{\sigma_i} \right]^2 + C_{f_B}(p) + C_{R_B}(h) \]

- 20 measured WS/RS points \( r_i \) with error \( \sigma_i \)
- Gaussian constraint on \( f_B \) parameters (p)
- Gaussian constraint on MC decay time distributions of \( D^* \) from B

\[ R_m(t) = \frac{N^{WS}(t) + N^{WS}_B(t)}{N^{RS}(t) + N^{RS}_B(t)} = R(t) \left[ 1 + f^{RS}_B(t) \left( \frac{R_B(t)}{R(t)} - 1 \right) \right] \]

\[ f^{RS}_B(t) = \frac{N^{RS}_B(t)}{N^{RS}(t) + N^{RS}_B(t)} \]

Fraction of RS \( D^* \) from B decays

\[ R_B(t) = \frac{N^{WS}_B(t)}{N^{RS}_B(t)} \]

WS/RS ratio of non-prompt \( D^0 \)
Calculated by weighting \( R(t) \) with the decay-time distribution of secondary \( D^0 \) from MC
Mixing Fit Results

<table>
<thead>
<tr>
<th>Fit type</th>
<th>$\chi^2$/ndf</th>
<th>Parameter</th>
<th>Fitted values $\times 10^{-3}$</th>
<th>Correlation coefficient $R_D$</th>
<th>$y'$</th>
<th>$x'^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixing</td>
<td>16.91/17</td>
<td>$R_D$</td>
<td>$3.51 \pm 0.35$</td>
<td>1</td>
<td>-0.967</td>
<td>0.900</td>
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<tr>
<td></td>
<td></td>
<td>$y'$</td>
<td>$4.3 \pm 4.3$</td>
<td></td>
<td>1</td>
<td>-0.975</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$x'^2$</td>
<td>$0.08 \pm 0.18$</td>
<td></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>No-mixing</td>
<td>58.75/19</td>
<td>$R_B$</td>
<td>$4.30 \pm 0.06$</td>
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<td></td>
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</tr>
</tbody>
</table>
Significance

- Bayesian probability contour
  - No mixing hypothesis excluded at 6.1\(\sigma\)
- Frequentist method using toy-MC in samples without
  - \(\Delta \chi^2\) difference exceeds observed in 6 of \(10^{10}\) trials
  - No-mixing case excluded at 6.1\(\sigma\)
CDF confirms observation of $D^0$ mixing at $6.1\sigma$
- Parameters similar to other experiments
- Nature is giving up her charms, but without indication of new physics