Mixing in the D-System at BaBar

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For the BaBar collaboration
HF9, Pasadena, Sept. 12 2001

$D^0$ CP-eigenstates in absence of CP-violation:

CP-even $D_1$ with $m_1, \Gamma_1$  
CP-odd $D_2$ with $m_2, \Gamma_2$

Mixing parameters: Expected to be small in Standard Model

$y = \frac{(\Gamma_1 - \Gamma_2)}{(\Gamma_1 + \Gamma_2)} = \frac{\Delta \Gamma}{2 \Gamma}$ 
$x = \frac{(m_1 - m_2)}{\Gamma} = \frac{\Delta m}{\Gamma}$

- Search for a lifetime difference in $D^0 \to K^- \pi^+, K^-K^+$ ($y$)
- Time evolution of the $D^0 \to K^+ \pi^-$ (wrong-sign) decay ($x^2, y$)
- Measurement of the wrong-sign decay rate
Method of measurements

$D^0$ candidates reconstructed through decay $D^{*+} \to D^0 \pi^+$

Slow pion, $\pi_s$

Global vertex fit in 3 dim to all tracks in candidate decay chain to take correlations properly into account

Main constraints:
- Beamspot and $D^*$ vertex have to coincide
- $D^0$ momentum vector points back to $D^*$ decay point

$D^0 \to K^- K^+$: CP even
$D^0 \to K^- \pi^+$: equal mix of CP-even, CP-odd

$$y = \frac{\tau_{D^0} (K^- \pi^+)}{\tau_{D^0} (K^- K^+)} - 1$$

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2001 data set and event selection

Data set: 12.4 fb$^{-1}$ of Run2 BaBar data, taken in 2001 on and off $\Upsilon$(4S) reconstructed with most advanced internal alignment of the Si-vertex tracker (SVT)

Beamspot: 1 $\sigma$ envelop in plane transverse to beam:
6 $\mu$m vertically ($y\parallel p$), 120 $\mu$m horizontally ($x\parallel p$)

Selection of events:
- $D^*$ momentum $p^* > 2.6$ GeV (continuum $c\overline{c}$bar)
- Track quality and vertex probability cuts
- $\delta m$ window $\pm 3 \sigma$ (value depends on whether or not $\pi_s$ track has drift chamber hits)
- Particle ID requirement for kaon $D^0$ daughter candidates

After all cuts:
- $D^0 \rightarrow K^- \pi^+$ candidates ~45 k with purity in MC 98%
- $D^0 \rightarrow K^- K^+$ candidates ~4 k with purity in MC 95%

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Importance of particle ID

$p > 0.6 \text{ GeV}$
mainly DIRC

$p < 0.6 \text{ GeV}$
mainly $dE/dx$
from SVT
and drift chamber

Kaon PID required for both kaon candidates

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D⁰ signals after event selection

δm: mass difference between D* and D⁰

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Elements of fit to the $D^0$ decay time distribution
Signal probability

Log Scale!

Per-evt probability to be signal evt from reco’d mass of $D^0$ candidate
Assume linear distribution for background, double Gaussian for signal

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Elements of fit to the $D^0$ decay time distribution
Lifetime fit function

Signal:

\[ \tau_D \]

Decay function

\[ f_0 + \]

Resolution function

\[ f_0 + \]

Bckgrd:

\[ f_0 + \]

\[ f_0 + \]

\[ f_0 + \]

Typical value $\sigma(\text{decay time}) \sim 180 \text{ fs}; \quad \tau_D \text{ was blinded throughout analysis}$

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Overlay data - Fit result

Unbinned maximum likelihood fit

Points:
Data with stat. error
White: Sig + Bckgrd
Grey: Bckgrd only

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Systematic checks for $y$

Many sys. errors of lifetimes cancel in ratio

$$y = \frac{\tau_{D0} (K^- \pi^+)}{\tau_{D0} (K^- K^+)} - 1$$

A: Event selection and background $\pm 1.7\%$
B: Reconstruction and vertexing $\pm 0.4\%$
C: Alignment $\pm 0.3\%$

TOTAL: $\pm 1.7\%$

A: Vary event sel. cuts within their uncertainties and re-measure $y$
- $\chi^2$ criterion to differentiate between purely statistical and systematic fluctuation
- Checks vary size of background contribution and composition of background events
- Biggest contributors are varying $\delta m$ window and varying kaon-PID criterion

B: Use alternative reconstruction methods
- Biggest contributors are using an alternative vertexing method and changing the $p(\pi_s)$ resolution so that MC matches data

C: Si-vertex tracker (SVT) internal alignment
- Biggest contributors are shifting yLP position and yLP correction from e+e- $\rightarrow \gamma\gamma \rightarrow 4\pi$
Result for $y$ (preliminary)

$$y = (-1.0 \pm 2.2 \pm 1.7)\ \%$$

\begin{itemize}
\item stat.
\item sys.
\end{itemize}

$y$ and the two lifetimes were kept blind throughout analysis

Lifetime of $D^0 \rightarrow K^-\pi^+$:

- used as cross check, provided criterion whether or not to unblind $y$
- $\tau_{D(K\pi)} = (412 \pm 2)$ fs
- sys. error of order 6 fs, dominated by SVT alignment
- correction of $(+5 \pm 5)$ fs, applied to fit result, derived from $e^+e^- \rightarrow \gamma\gamma \rightarrow 4\pi$ events
Near-term prospects for measurement of $\gamma$

Add CP-even $D^0 \rightarrow \pi^+\pi^-$ channel: $\sim 1.2 \text{ k events in } 12.4 \text{ fb}^{-1}$ of 2001 data reduces stat. error in $\gamma$ to $\sim 1.9\%$

Add 23 fb$^{-1}$ of 2000 data reprocessed with most advanced SVT alignment reduces stat. error in $\gamma$ to $\sim 1.1\%$

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Time evolution of $D^0 \rightarrow K^+\pi^-$ (wrong sign decay)

\[ \Gamma(t) \propto \exp(-t) \left[ R + \sqrt{R} y' t + \frac{1}{4} \left( x'^2 + y'^2 \right) t^2 \right] \]

DCSD: interference
mixing

$x' = x \cos \delta + y \sin \delta$

$y' = y \cos \delta - x \sin \delta$; $\delta$: strong phase

Wrong sign (WS) decay:
$\pi_s$ and kaon have same charge

Simultaneous fit to decay time distr. in WS and RS decays:
- Resolution and background description from RS events
- Decay function
  - for WS: 3 components above
  - for RS: only pure exponential

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Statistical uncertainty in \((x'^2, y')\) plane for 23 fb\(^{-1}\) (2000 data)

- Strong correlation \(x'^2, y'\)
- Important to fit with unphysical \((x'^2<0)\) region
- Study of systematic effects: SVT internal alignment in 2000 data dominating
- Extraction of central values soon with more data

Data analysis (vertex reconstr., evt. sel., etc.) similar to analysis for \(y\) measurement
D⁰→K⁺π⁻ (wrong sign) decay rate (preliminary)

R_{WS} = \frac{\text{number wrong sign decays}}{\text{number right sign decays}}

= (0.38 ± 0.04 \text{ (stat.)} ± 0.02 \text{ (sys.)})\%

Extracted from fit to D⁰ decay time distribution (n_{WS} \sim 0.2 \text{ k})
Summary and outlook

- Result from 12.4 fb⁻¹ of 2001 BaBar data:
  \[ y = (-1.0 \pm 2.2 \text{ (stat.)} \pm 1.7 \text{ (sys.)}) \% \] preliminary

- Prospect of cutting statistical error by half in the near future

- Extraction of mixing parameters \( x^2, y \) from combined 2000+2001 BaBar data sample of 35 fb⁻¹ possible soon

- Already with 23 fb⁻¹ of 2000 BaBar data alone achieved most precise existing measurement of wrong-sign decay rate:
  \[ R_{WS} = (0.38 \pm 0.04 \text{ (stat.)} \pm 0.02 \text{ (sys.)}) \% \] preliminary
4-prong events originating from interaction point (IP):
\[ e^+e^- \rightarrow \gamma\gamma \rightarrow 4\pi \]
- Vtx of oppositely charged track pairs in 4-prong sample (2-prong vtx)
- Compare average apparent y(2-prong vtx) with y_{IP}
- Residual SVT misalignment would cause displacement

\[ \sigma(y_{IP}) = \pm 5 \mu m \]
\[ \sigma(x_{IP}) = \pm 120 \mu m \]

\[ 4\text{-prong event} \]

**Observed displacement:**
For track pairs with $\sum p$ pointing in vertical direction -2.7 $\mu m$
(stat. error negligible, sys. error $\pm 2.7 \mu m$)

**Effect in MC:**
$\tau_d$ lowered systematically by $5 \pm 5$ fs
Proton production caused by inelastic scattering of stray beam particles in beam pipe (BP) wall
Production vertices of p tracks in transverse plane
protonography of BP

Comparison of fit to protonography with known dimensions of BP
uncertainty in radial scale
3/1000 ± 1/1000
Pull of reconstructed $D^0$ decay time
nicely centered around zero
In data rms width $\sim 1.2$
Likelihood curves for fit to $D^0$ decay time distribution

$\ BABAR$

Preliminary

12.4 fb$^{-1}$

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

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

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# Systematic errors

<table>
<thead>
<tr>
<th>Type</th>
<th>Variation</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kaon ID</td>
<td>Loose – Tight</td>
<td>0.001</td>
</tr>
<tr>
<td>Pion ID</td>
<td>Loose – Tight</td>
<td>0.010</td>
</tr>
<tr>
<td>Kaon $p_t$ cutoff</td>
<td>0.1 – 0.5 GeV/c</td>
<td>0.009</td>
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<tr>
<td>$\cos(\theta^*)$</td>
<td>0.65 – 1.0</td>
<td>0.006</td>
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<tr>
<td>$D^0$ mass window</td>
<td>±40 – ±80 MeV/c$^2$</td>
<td>0.010</td>
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<tr>
<td>$\Delta m$ window</td>
<td>15 – 28 MeV/c$^2$</td>
<td>0.004</td>
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<tr>
<td>SVT track quality</td>
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<td>0.011</td>
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<td>Background shape</td>
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<tr>
<td>Background fractions</td>
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<td>0.005</td>
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<tr>
<td>$D^+ \rho^*$ cutoff</td>
<td>2.4–2.8 GeV/c</td>
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<tr>
<td>Prob($\chi^2$) vertex fit</td>
<td>0.002 – 0.05</td>
<td>0.001</td>
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<tr>
<td>Other</td>
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<tr>
<td>Sum in quadrature</td>
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<td>0.022</td>
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<tr>
<td>Statistical error</td>
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<td>0.044</td>
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</table>

Wrong sign decay rate $R_{WS}$
BABAR

PEP-II Delivered 45.2/fb
BABAR Recorded 42.8/fb
BABAR off-peak 4.05/fb