Search for D–mixing at BaBar

Determination of the wrong sign decay rate $D^0 \to K^+ \pi^-$ and the sensitivity to $D^0 - \bar{D}^0$ mixing.

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For the BaBar collaboration
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$D^0$ two–body decays

- What can we learn from these decays?
  - $D^0$ lifetime from Cabibbo favoured $D^0 \to K^- \pi^+$.  
  - $y = \Delta \Gamma / 2 \Gamma$ from lifetime difference in $D^0 \to K^- \pi^+$ and $D^0 \to K^+ K^- / \pi^+ \pi^-$.  
  - CP violation from $\Gamma(D^0 \to K^+ K^-) / \Gamma(D^0 \to K^+ K^-)$.  
  - The mixing parameters $x = \Delta m / \Gamma$ and $y$ from time evolution of the decays $D^0 \to K^+ \pi^- / D^0 \to D^0 \to K^+ \pi^-$.  
- Mixing expected to be small in Standard Model.
The raw data after all selections

\[ D^0 \text{ candidate mass} \]

\[ \Delta m = m_{D^*} - m_{D^0} \]

Rate \( \sim 1/9 \)

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

Rate \( \sim 1/300 \)

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

\[ D^0 \rightarrow \overline{D}^0 \rightarrow K^+ \pi^- \]

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D–mixing

- A discovery would be a sign of new physics.

- Time evolution of $D^0 \rightarrow K^+ \pi^-$ decays reveals mixing:

$$\Gamma(t) \approx \exp\left(-\frac{t}{\tau_{D^0}}\right) \left[ R + \sqrt{R} y' \frac{t}{\tau_{D^0}} + \frac{x'^2 + y'^2}{4} \frac{t^2}{\tau_{D^0}^2} \right]$$

- Pure exponential from doubly Cabibbo suppressed decays.

- Interference term depends on strong phase difference $\delta$:
  
  $$x' = x \cos \delta + y \sin \delta, \quad y' = y \cos \delta - x \sin \delta$$

- Pure mixing term:

$$\frac{R_{\text{mix}}}{2} = \frac{x'^2 + y'^2}{4} = \frac{x^2 + y^2}{4}$$

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Outline of method

- The decay chain $D^{* \pm} \rightarrow D^0 \pi^\pm$, $D^0 \rightarrow K^\pm \pi^\mp$ is reconstructed.
  - Sign of the slow pion tags production flavour of the $D^0$.
  - Opposite charge of $K$ and $\pi_s$ identifies Cabibbo favoured (right sign) decays.
  - Identical charge identifies doubly Cabibbo suppressed or mixing (wrong sign) decays.
- $D^0$ lifetime is determined from the difference between the $D^{*+}$ and $D^0$ vertex.
Event selection

- Data set is $23.2 \text{ fb}^{-1}$ of data collected during 1999 and 2000.
- Momentum of $D^{*+}$ in $Y(4S)$ rest frame above 2.6 GeV/c to select events from the $c\bar{c}$ continuum.
- Particle identification on both $D^0$ daughters.
- Good tracks and good vertex fit required.
- At least 6 hits on all tracks in Silicon Tracker (SVT).
- $2\phi$ and $2z$ hits in first 3 layers of SVT.
- Helicity cut on $\cos \theta_{KD^0}^*.$
- Pion $p_T>0.5$ GeV/c for $D^0$ daughter.
- Multiple overlapping candidates are rejected.
Vertexing method

- Common fit made to $D^0$, $D^{*+}$ and beam spot.
- Small beam spot size greatly improves $\Delta m$ resolution.
  \[(\sigma_x, \sigma_y, \sigma_z) \approx (5.6 \, \mu m, 120 \, \mu m, 7.9 \, mm)\]
- $D^{*+}$ production point given as intersection of $D^0$ momentum vector with beam spot.
- Correlations taken into account by simultaneous fit.
Background sources

- Background for $D^{*+}$ candidates are:
  - True $D^0$ with a fake slow $\pi^+_s$.
  - Combinatorial background.
  - Partially reconstructed $D^0$ with correct $\pi^+_s$.
  - Correctly reconstructed $D^0$ where $K$ and $\pi$ hypothesis are swapped.

- Different backgrounds have different lifetime evolution.
  - Need to be measured individually to avoid bias of fit.
**Δm background shape**

- Background shape under Δm signal peak hard to fit.
  - Create $D^{*+}$ by mixing $D^0$ candidates with $\pi^+_s$ from other events.
  - Data used in fit but method validated on Monte Carlo.

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![Graphs](image-url)
**D^0 with K and π hypothesis swapped**

- Dangerous background as it fakes wrong sign signal.
  - Peaks in $\Delta m$ but is flat in $m_{K\pi}$.
  - Particle ID very powerful to suppress this background.

- Shape distorting cuts on *flipped* mass hypothesis not required.

- Makes up 3% of wrong sign signal in region of $m_{D^0} \pm 2 \sigma_{D^0}$.

![MC study of swapped Kσ shape](image)

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The fit method

- An unbinned likelihood fit is used to fit at the same time:
  - Right sign signal $D^0 \rightarrow K^-\pi^+$ decays (Cabibbo favoured).
  - Wrong sign signal $D^0 \rightarrow K^+\pi^-$ decays (mixing and DCSD).
  - Background in both samples.

- For each decay the parameters used in the fit are:
  - The reconstructed $D^0$ mass, $m_{K\pi}$.
  - The $D^{*+}/D^0$ mass difference, $\Delta m$.
  - The proper time $t$ and the estimated error $\delta t$. 
The fit result in $m_{K\pi}$ and $\Delta m$

Preliminary results

- **Signal**
- **Incomplete $D^0$**
- **True $D^0$ fake $\pi_s$**
- **Combinatorial**
- **Swapped K/π**

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The Wrong Sign decay rate

- $R_{WS}$ is defined as:
  $$R_{WS} \equiv \frac{\text{number wrong sign decays}}{\text{number right sign decays}}$$

- Preliminary result extracted from fit:
  $$R_{WS} = (0.38 \pm 0.04 \pm 0.02 \text{ (sys)})\%$$
  $$n_{RS} = 54120 \text{ events}$$
  $$n_{WS} = 207 \text{ events}$$

### Systematic errors

<table>
<thead>
<tr>
<th>Type</th>
<th>Variation</th>
<th>Error (%)</th>
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</thead>
<tbody>
<tr>
<td>Kaon ID</td>
<td>Loose – Tight</td>
<td>0.001</td>
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<tr>
<td>Pion ID</td>
<td>Loose – Tight</td>
<td>0.010</td>
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<tr>
<td>Kaon $p_t$ cutoff</td>
<td>0.1 – 0.5 GeV/c</td>
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<tr>
<td>$\cos(\theta^*)$</td>
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<td>$D^0$ mass window</td>
<td>±40 – ±80 MeV/c$^2$</td>
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<tr>
<td>$\Delta m$ window</td>
<td>15 – 28 MeV/c$^2$</td>
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<td>SVT track quality</td>
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<td>Background shape</td>
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<td>Background fractions</td>
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<td>$D^* \ p^*$ cutoff</td>
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<td>$\text{Prob}(\chi^2)$ vertex fit</td>
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<td>Other</td>
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<tr>
<td>Sum in quadrature</td>
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</tr>
<tr>
<td>Statistical error</td>
<td></td>
<td>0.044</td>
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</table>
Comparisons to other results

\[
\begin{array}{c}
\text{BaBar (prelim)} \\
\text{Belle (prelim)} \\
\text{FOCUS} \\
\text{E791} \\
\text{CLEO} \\
\text{ALEPH}
\end{array}
\]
Time evolution

- Signal part of wrong sign fit has the free parameters $\tau_{D^0}$, $x'^2$ and $y'$.

$$\Gamma(t) = \exp\left(-\frac{t}{\tau_{D^0}}\right) \left[ R + \sqrt{R} y' \frac{t}{\tau_{D^0}} + \frac{x'^2 + y'^2}{4} \frac{t^2}{\tau_{D^0}^2} \right] \oplus \mathcal{R}(\sigma_t)$$

- The resolution model $\mathcal{R}(\sigma_t)$ has:
  - 2 Gaussian terms scaled with event–by–event errors.
  - $\sigma_t \approx 0.4 \tau_{D^0}$
  - 1 fixed width Gaussian for outliers.

- $D^0$ lifetime effectively controlled by right sign sample.
Monte Carlo study of mixing

- Toy Monte Carlo study of 10000 fits to 100 wrong sign decays with mixing.
- Strong correlation between $x'^2$ and $y'$.
- Important to fit with unphysical region $x'^2 < 0$. 

\[(x'^2, y') = (0.001, 0.03)\]
\[(x'^2, y') = (0, 0)\]
Error on mixing

- Numbers correspond to a sample of 23 fb\(^{-1}\).
- Statistical uncertainty in full \((x'^2, y')\) plane illustrated.
- Systematics evaluated in the \((x'^2, y')\) plane to take into account high correlations.
Systematics on mixing

- Dominant systematics are cut on momentum of $D^{*+}$ and alignment.
- To interpret as result in the physical region $x'^2 > 0$ complicated.
- Extraction of central value waits for ongoing reprocessing of the data.
Summary

- We have large and very clean samples of:
  
  \[(54120 \text{ events})\] \(D^0 \rightarrow K^- \pi^+\)
  
  \(D^0 \rightarrow K^+ K^-\)
  
  \[(207 \text{ events})\] \(D^0 \rightarrow K^+ \pi^- / D^0 \rightarrow \bar{D}^0 \rightarrow K^+ \pi^-\)

- A preliminary precision result for the wrong sign decay rate:
  
  \(R_{WS} = (0.38 \pm 0.04 \text{ (stat)} \pm 0.02 \text{ (sys)})\%\)

- The reach for D–mixing with BaBar is great.
D–mixing

- Time evolution for mixing at a level close to the expected sensitivity.