Recent $\textit{Babar}$ results on mixing in the charm sector

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on behalf of the $\textit{Babar}$ Collaboration

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Mixing in the charm sector

We present the first measurement of mixing parameters in the singly Cabibbo-suppressed channel $D^0 \rightarrow \pi^+ \pi^0 \pi^0$ (no CPV), PRD 93, 112014 (2016)

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$$

$$x = \frac{m_1 - m_2}{\Gamma_D}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

Mixing and CPV parameters for charm are small in the SM

$$x, y \sim \lambda_C^2 \times SU(3) \text{ breaking} \sim O(10^{-3})$$

We present the first measurement of mixing parameters in the singly Cabibbo-suppressed channel $D^0 \rightarrow \pi^+ \pi^- \pi^0$ (no CPV), PRD 93, 112014 (2016)

$$|\mathcal{M}(D^0)|^2 \propto \frac{1}{2} e^{-\Gamma_D t} \left\{ |A_f|^2 [\cosh (y \Gamma_D t) + \cos (x \Gamma_D t)] + \left| \frac{q}{p} \bar{A}_f \right|^2 [\cosh (y \Gamma_D t) - \cos (x \Gamma_D t)] \right\}$$

$$- 2 \left[ \text{Re} \left( \frac{q}{p} A_f^* \bar{A}_f \right) \sinh (y \Gamma_D t) - \text{Im} \left( \frac{q}{p} A_f^* \bar{A}_f \right) \sin (x \Gamma_D t) \right]$$
The $\textit{BABAR}$ experiment

The $\textit{BABAR}$ detector was located at the interaction point of PEP II at SLAC Asymmetric $e^+e^-$ collider, mostly at $\sqrt{s} \sim 10.58$ GeV

\[ \int L \, dt \sim 514 \text{ fb}^{-1} \] close to the $\Upsilon(4S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ peaks, $670 \times 10^6 \, c\bar{c}$ pairs
Event selection

- Reconstructed $D^{*+} \to \pi_S^+ D^0$ to select flavor ($\pi_S^+ = \text{soft pion}$)
- Vetoes on $D^0 \to K^- \pi^+, D^0 \to K^- \pi^+ \pi^0$, $D^0 \to K_S \pi^+ \pi^0, D^0 \to K_S \pi^0$
- $E_{\text{lab}}(\pi^0) > 350$ MeV
- $p_{\text{cm}}(D^0) > 2.8$ GeV to remove $B \to D$ events
- $-2 < t(D^0) < 3$ ps, $\sigma_t < 0.8$ ps
- $P(\chi^2) > 0.1\%$ for the $D^*$ candidates
- $|m(D^0) - m_{\text{PDG}}| < 15$ MeV, $|\Delta m - \Delta m_{\text{PDG}}| < 600$ keV

138k events, 91% purity
Time-Integrated Dalitz plot/1

An unbinned maximum-likelihood fit is performed to extract the parameters using GooFit


• **Signal:** Dalitz Plot (DP) distribution given by isobar model (coherent sum of Breit-Wigners); decay time distribution given by an exponential convolved with resolution (3 gaussians $\propto \sigma_t$). $\sigma_t$ modeled separately in 6 regions of the Dalitz plot.

![Events and Pulls](image-url)
Time-Integrated Dalitz plot/2

- **Wrong $\pi^+_s$ bkg:** ($< 1\%$) same DP and decay time distributions as the signal, $\sim 50\%$ gives right flavor assignment (lucky pion)
- **Broken charm bkg:** misreconstructed $D^0$ (but peaks in $\Delta m$). DP distribution from MC, decay time distributions given by two exponentials convolved with gaussians.
- **Combinatorial bkg:** DP distribution from sidebands, decay time distributions given by two exponentials convolved with gaussians. $\sigma_t$ modeled separately in 6 regions of decay time.

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Time-Integrated Dalitz plot/3

\[ A(s_+, s_-) = \sum_i c_i \frac{T(s)}{M_r - s - i M_r \Gamma(s)} F(s) \]

\( T \) is a tensor structure depending on spin

\[ \Gamma(s) = \Gamma \left( \frac{q(s)}{q(M_r)} \right)^{2l+1} \left( \frac{M_r}{\sqrt{s}} \right) F^2 \]

\( F \) is the Blatt-Weisskopf barrier factor

\[ F_0 = 1, F_1 = \sqrt{\frac{1+R^2q^2(M_r)}{1+R^2q^2(s)}}, F_2 = \ldots \]

To estimate systematics:

- We vary the radii \( R \) from 1.5 to 5 GeV\(^{-1}\)
- We remove a resonance from the fit, and if \( \Delta \chi^2 < 100 \), we estimate the variation in \( x, y \)
- We also allow the mass and width of \( f_0(500) \) to float

Masses and widths fixed to the PDG value

<table>
<thead>
<tr>
<th>State</th>
<th>( J^{PC} )</th>
<th>Resonance parameters</th>
<th>Fit to data results</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho (770)^+ )</td>
<td>1--</td>
<td>775.8 150.3</td>
<td>1 0 66.4±0.5</td>
</tr>
<tr>
<td>( \rho (770)^0 )</td>
<td>1--</td>
<td>775.8 150.3</td>
<td>0.55±0.01 16.1±0.4 23.9±0.3</td>
</tr>
<tr>
<td>( \rho (770)^- )</td>
<td>1--</td>
<td>775.8 150.3</td>
<td>0.73±0.01 −1.6±0.5 35.6±0.4</td>
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<tr>
<td>( \rho (1450)^+ )</td>
<td>1--</td>
<td>1465 400</td>
<td>0.55±0.07 −7.7±0.2 1.1±0.3</td>
</tr>
<tr>
<td>( \rho (1450)^0 )</td>
<td>1--</td>
<td>1465 400</td>
<td>0.19±0.07 −70.4±15.9 0.1±0.1</td>
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<tr>
<td>( \rho (1450)^- )</td>
<td>1--</td>
<td>1465 400</td>
<td>0.53±0.06 8.2±6.7 1.0±0.2</td>
</tr>
<tr>
<td>( \rho (1700)^+ )</td>
<td>1--</td>
<td>1720 250</td>
<td>0.91±0.15 −23.3±10.3 1.5±0.5</td>
</tr>
<tr>
<td>( \rho (1700)^0 )</td>
<td>1--</td>
<td>1720 250</td>
<td>0.60±0.13 −56.3±16.0 0.7±0.3</td>
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<tr>
<td>( \rho (1700)^- )</td>
<td>1--</td>
<td>1720 250</td>
<td>0.98±0.17 78.9±8.5 1.7±0.6</td>
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<tr>
<td>( f_0(980) )</td>
<td>0++</td>
<td>980 44</td>
<td>0.06±0.01 −58.8±2.9 0.3±0.1</td>
</tr>
<tr>
<td>( f_0(1370) )</td>
<td>0++</td>
<td>1434 173</td>
<td>0.20±0.03 −19.6±9.5 0.3±0.1</td>
</tr>
<tr>
<td>( f_0(1500) )</td>
<td>0++</td>
<td>1507 109</td>
<td>0.18±0.02 7.4±7.4 0.3±0.1</td>
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<tr>
<td>( f_0(1710) )</td>
<td>0++</td>
<td>1714 140</td>
<td>0.40±0.08 42.9±8.8 0.3±0.1</td>
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<tr>
<td>( f_2(1270) )</td>
<td>2++</td>
<td>1275.4 185.1</td>
<td>0.25±0.01 8.8±2.6 0.9±0.1</td>
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<tr>
<td>( f_0(500) )</td>
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<td>500 400</td>
<td>0.26±0.01 −4.1±3.7 0.9±0.1</td>
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<tr>
<td>( NR )</td>
<td></td>
<td></td>
<td>0.43±0.07 −22.1±11.7 0.4±0.1</td>
</tr>
</tbody>
</table>
Time-Dependent fit results

Large pull values near low and high values of $m^2$ in all projections, similar effect in MC

Likely due to migration from the edge, due to misreconstruction + constrained fit

\[ \tau_D = (410.2 \pm 3.8) \text{ fs} \]
\[ x_{\text{raw}} = (2.08 \pm 1.17)\% \]
\[ y_{\text{raw}} = (0.14 \pm 0.89)\% \]

To estimate any possible bias, the same fit is performed to MC samples with given $x = \pm 1\%$, $y = \pm 1\%$

The mean bias is

\[ \Delta x = 0.58\% \]
\[ \Delta y = -0.05\% \]
Systematic uncertainties

Dominant sources of systematics are:

- **Amplitude-model variations**, estimated removing the least relevant resonances
- **Combinatorial DP distribution**, when the MC is used instead of data
- **Different decay time windows**, and number of $\sigma_t$ ranges
- **Fit bias correction**, taken as half of the bias measured from MC
- **Effect of SVT misalignment**, estimated creating MC signal samples with deliberately-wrong alignment files

<table>
<thead>
<tr>
<th>Source</th>
<th>$x$ [%]</th>
<th>$y$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Lucky” false slow pion fraction</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Time resolution dependence on reconstructed $D^0$ mass</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Amplitude-model variations</strong></td>
<td><strong>0.31</strong></td>
<td><strong>0.12</strong></td>
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<tr>
<td>Resonance radius</td>
<td>0.02</td>
<td>0.10</td>
</tr>
<tr>
<td>DP efficiency parametrization</td>
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<td>DP normalization granularity</td>
<td>0.03</td>
<td>0.04</td>
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<tr>
<td><strong>Background DP distribution</strong></td>
<td><strong>0.21</strong></td>
<td><strong>0.11</strong></td>
</tr>
<tr>
<td>Decay time window</td>
<td>0.18</td>
<td>0.19</td>
</tr>
<tr>
<td>$\sigma_t$ cutoff</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td><strong>Number of $\sigma_t$ ranges</strong></td>
<td><strong>0.11</strong></td>
<td><strong>0.26</strong></td>
</tr>
<tr>
<td>$\sigma_t$ parametrization</td>
<td>0.05</td>
<td>0.03</td>
</tr>
<tr>
<td>Background-model MC time distribution parameters</td>
<td>0.06</td>
<td>0.11</td>
</tr>
<tr>
<td><strong>Fit bias correction</strong></td>
<td><strong>0.29</strong></td>
<td><strong>0.02</strong></td>
</tr>
<tr>
<td>SVT misalignment</td>
<td>0.20</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.56</strong></td>
<td><strong>0.46</strong></td>
</tr>
</tbody>
</table>
We present the first measurement of charm mixing in the singly Cabibbo-suppressed $D^0 \rightarrow \pi^+\pi^-\pi^0$ channel

PRD 93, 112014 (2016)

$$x = (1.5 \pm 1.2 \pm 0.6)\%$$
$$y = (0.2 \pm 0.9 \pm 0.5)\%$$

to compare with the HFAG average (from $D^0 \rightarrow K_S^0\pi^+\pi^-$ and indirectly from other channels):

$$x = (0.49^{+0.14}_{-0.15})\%$$
$$y = (0.61 \pm 0.08)\%$$
BACKUP
Definition of mixing and CPV parameters

\[ R_M = \frac{1}{2}(x^2 + y^2) \]

\[ \begin{align*}
2 \gamma_{CP} &= (|q/p| + |p/q|)y \cos \phi - (|q/p| - |p/q|)x \sin \phi \\
2 A_T &= (|q/p| - |p/q|)y \cos \phi - (|q/p| + |p/q|)x \sin \phi
\end{align*} \]

\[ \begin{align*}
x_{K^0\pi\pi} &= x \\
y_{K^0\pi\pi} &= y \\
|q/p|_{K^0\pi\pi} &= |q/p| \\
\text{Arg}(q/p)_{K^0\pi\pi} &= \phi
\end{align*} \]

\[ \begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K^+\pi^-\pi^0} = \begin{pmatrix} \cos \delta_{K\pi\pi} & \sin \delta_{K\pi\pi} \\ -\sin \delta_{K\pi\pi} & \cos \delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \]

\[ \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \]

\[ A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2} \]

\[ x'^\pm = \left( 1 \pm A_M \right)^{1/4} \left( x' \cos \phi \pm y' \sin \phi \right) \]

\[ y'^\pm = \left( 1 \pm A_M \right)^{1/4} \left( y' \cos \phi \mp x' \sin \phi \right) \]

If no CPV is allowed,
\[ y_{CP} = y, \phi = A_* = 0, |q/p| = 1 \]
Measurements of $x$ and $y$

The combination $R_M = \frac{1}{2} (x^2 + y^2)$ can be measured in semileptonic decays

- BaBar, PRD 76, 14018
- Belle, PRD77, 112003

If no CPV is allowed, $y$ can be measured in $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-, K^+ K^- K_S^0$ decays

- BaBar, PRD 87, 120004
- Belle, arXiv:1212.3478
- LHCb, JHEP 1204, 129

$x$ and $y$ can be independently measured:

- In coherent production, $\psi(3770) \rightarrow D^0 \bar{D}^0$, CLEO-c, PRD 86, 112001
- In self-conjugate final states, $D^0 \rightarrow K_S^0 \pi^+ \pi^-$, Belle, PRD 89, 91103; BaBar, PRL 105, 81803

The Cabibbo-favored mode has more statistics and give much more precise measurements wrt the singly-Cabibbo suppressed $D^0 \rightarrow \pi^+ \pi^- \pi^0$

Nevertheless, the latter can get larger contributions from New Physics, and deserve an independent measurement