Particle-Antiparticle Oscillation and CP Violation in the Neutral Charm Meson System

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University of Cincinnati

Particle-antiparticle oscillation (also called mixing) and CP violation (CPV) are sensitive to Beyond the Standard Model (BSM) amplitudes as well as Standard Model amplitudes. Studies of mixing and CPV in the neutral $K$, $B(s)$, and $D$ meson systems probe mass scales much higher than the Higgs mass and complement direct searches for BSM physics at the LHC. This talk will provide a general introduction to the phenomenology of particle-antiparticle mixing and CPV, followed by discussions of specific measurements. The primary focus will be the study of $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$ oscillations using $\sim 2.3 \times 10^5$ “wrong-sign” (WS) $K\pi$ decays and approximately 230 times more “right sign” (RS) decays. The differences of the $D^0$ and $\bar{D}^0$ WS/RS ratios as functions of decay time are sensitive to both direct indirect CPV. I will discuss the results themselves and bounds on CP violation when they are combined with other measurements.
"It is generally accepted that the microscopic laws of physics are invariant to the operation of charge conjugation (CC); we shall take the rigorous validity of this postulate for granted."

At that time, the discovery that weak interactions violate CC symmetry almost maximally was two years in the future. Nonetheless, the essential insights from their seminal paper hold true:

- neutral kaons are produced in strong interactions in two “opposite” flavors, as particle and antiparticle;
- the eigenstates of the strong interaction in which flavor is produced and the eigenstates of the weak interaction by which neutral kaons decay differ;
- the weak eigenstates are (approximately) equal admixtures of flavor eigenstates;
- the lifetimes of the weak neutral eigenstates could differ substantially, and that the “mass difference is surely tiny.”
Mixing Phenomenology

Neutral $D$ mesons are produced as flavor eigenstates $D^0$ and $\bar{D}^0$ and decay via

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right)$$

as mass, lifetime eigenstates $D_1$, $D_2$

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

where $|q|^2 + |p|^2 = 1$ and

$$\left( \frac{q}{p} \right)^2 = \frac{M_{12}^* - \frac{i}{2} \Gamma_{12}^*}{M_{12} - \frac{i}{2} \Gamma_{12}}$$

$D_1$, $D_2$ have masses $M_1$, $M_2$ and widths $\Gamma_1$, $\Gamma_2$

Mixing occurs when there is a non-zero mass

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta \Gamma = \Gamma_1 - \Gamma_2$$

For convenience define, $x$ and $y$

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta \Gamma}{2 \Gamma}$$

where

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

and define the mixing rate

$$R_M = \frac{x^2 + y^2}{2} (< 5 \times 10^{-4})$$
Weak Charged Current Interactions

As a first approximation, the weak charged current interaction couples fermions of the same generation. The Standard Model explains couplings between quark generations in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matrix.
Weak Phases in the Standard Model

The Cabibbo-Kobayashi-Maskawa (CKM) matrix transforms flavor eigenstates to weak eigenstates at the quark level:

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} =
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix}
\begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

The CKM matrix should be unitary:

\[
\begin{pmatrix}
  V_{ud}^* & V_{cd}^* & V_{td}^* \\
  V_{us}^* & V_{cs}^* & V_{ts}^* \\
  V_{ub}^* & V_{cb}^* & V_{tb}^*
\end{pmatrix}
\begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} =
\begin{pmatrix}
  1 & 0 & 0 \\
  0 & 1 & 0 \\
  0 & 0 & 1
\end{pmatrix}
\]

e.g., \[ V_{ub}V_{ud}^* + V_{cb}V_{cd}^* + V_{tb}V_{td}^* = 0 \]

In the Wolfenstein parameterization:

\[
V_W = \begin{pmatrix}
  1 - \frac{1}{2} \lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\
  -\lambda & 1 - \frac{1}{2} \lambda^2 - iA^2\lambda^4\eta & A\lambda^2 \\
  A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} \approx \begin{pmatrix}
  \cos \theta_C & \sin \theta_C & 0 \\
  -\sin \theta_C & \cos \theta_C & 0 \\
  0 & 0 & 1
\end{pmatrix}
\]
Charm Meson Mixing

Why is observing charm mixing interesting?

It completes the picture of quark mixing already seen in the $K$, $B_d$, and $B_s$ systems.

$K$ — PR 103, 1901 (1956); PR 103, 1904 (1956).


$B_s$ — PRL 97, 021802 (2006); PRL 97, 242003 (2006).

In the Standard Model, it relates to processes with down-type quarks in the mixing loop diagram.

Mixing, itself, could indicate new physics.

It is a significant step toward observation of CP violation in the charm sector, a clear indication of new physics.
Box diagram SM charm mixing rate naively expected to be very low ($R_M \sim 10^{-10}$) (Datta & Kumbhakar)

Z.Phys. C27, 515 (1985)

CKM suppression $\rightarrow |V_{ub}V_{cb}^*|^2$

GIM suppression $\rightarrow (m_s^2 - m_d^2)/m_W^2$

Di-penguin mixing, $R_M \sim 10^{-10}$


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

first discussion, L. Wolfenstein

**Standard Model Mixing Predictions**

(mostly 20\textsuperscript{th} century)

<table>
<thead>
<tr>
<th>Box diagram SM charm mixing rate naively expected to be very low ($R_M \sim 10^{-10}$) (Datta &amp; Kumbhakar)</th>
</tr>
</thead>
<tbody>
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<td>Z.Phys. C27, 515 (1985)</td>
</tr>
<tr>
<td>CKM suppression $\rightarrow</td>
</tr>
<tr>
<td>GIM suppression $\rightarrow (m^2_s - m^2_d)/m_W^2$</td>
</tr>
<tr>
<td>Di-penguin mixing, $R_M \sim 10^{-10}$</td>
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</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Partial History of Long-Distance Calculations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early SM calculations indicated long distance contributions produce $x \ll 10^{-2}$:</td>
</tr>
<tr>
<td>$- x \sim 10^{-3}$ (dispersive sector)</td>
</tr>
<tr>
<td>$\quad$ - PRD 33, 179 (1986)</td>
</tr>
<tr>
<td>$- x \sim 10^{-5}$ (HQET)</td>
</tr>
<tr>
<td>More recent SM predictions can accommodate $x, y \sim 1%$ [of opposite sign] (Falk et al.)</td>
</tr>
<tr>
<td>$- x, y \approx \sin^2 \theta_C x$ [SU(3) breaking]$^2$</td>
</tr>
<tr>
<td>$\quad$ - Phys.Rev. D 65, 054034 (2002)</td>
</tr>
</tbody>
</table>

first discussion, L. Wolfenstein

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

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

Large possible SM contributions to mixing require observation of either a CP-violating signal or $|x| >> |y|$ to establish presence of NP

A relatively recent survey ([Phys. Rev. D76, 095009 (2007), et al. & Petrov]) summarizes models and constraints:

<table>
<thead>
<tr>
<th>Fourth generation</th>
<th>Vector leptoquarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q = -1/3$ singlet quark</td>
<td>Flavor-conserving Two-Higgs</td>
</tr>
<tr>
<td>$Q = +2/3$ singlet quark</td>
<td>Flavor-changing neutral Higgs</td>
</tr>
<tr>
<td>Little Higgs</td>
<td>Scalar leptoquarks</td>
</tr>
<tr>
<td>Generic $Z'$</td>
<td>MSSM</td>
</tr>
<tr>
<td>Left-right symmetric</td>
<td>Supersymmetric alignment</td>
</tr>
</tbody>
</table>

and more
Time-Evolution of $D^0 \rightarrow K\pi$ Decays

DCS and mixing amplitudes interfere to give a “quadratic” WS decay rate ($x, y << 1$):

$$\Gamma_{WS}(t) e^{-t/\tau} \propto R_D + \sqrt{R_D} y' \left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right) \left(\frac{t}{\tau}\right)^2$$

where $x' = x \cos \delta + y \sin \delta$ and $y' = y \cos \delta - x \sin \delta$ and $\delta$ is the phase difference between DCS and CF decays.
$D^0 \rightarrow K\pi$ Reconstruction

$D^*\pm \rightarrow \pi^\pm D^0$, $D^0 \rightarrow K^\mp\pi^\pm$

Slow pion charge tags neutral
D production flavor

384 fb$^{-1}$ $e^+e^- \rightarrow c\bar{c}$

The BaBar Detector

1.5 T solenoid
(superconducting)

Cherenkov
Detector
144 quartz bars
11,000 PMTs

e$^-$ (9 GeV)

Calorimeter
6500 CsI(Tl) crystals

e$^+$ (3.1 GeV)

Silicon Vertex
Tracker
5 double-sided
layers

Drift Chamber
40 layers

Instrumented Flux Return
18–19 layers

Typical $D^0$ flight length $d \sim 240 \mu m$
Average resolution $\sigma_d \sim 95 \mu m$

Beam spot:
$\sigma_x \approx 100 \mu m$
$\sigma_y \approx 7 \mu m$
Full Fit Procedure

Unbinned maximum likelihood fit in several steps
(fitting 1+ million events takes a long time)

Fit to $m(K\pi)$ and $\Delta m$ distribution:
- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

Fit RS decay time distribution:
- Determines $D^0$ lifetime and resolution function
- Include event-by-event decay time error $\delta t$ in resolution
- Use $m(K\pi)$ and $\Delta m$ to separate signal/bkgd (fixed shapes)

Fit WS decay time distribution:
- Use $D^0$ lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)
Simplified Fit Strategy & Validation

Fit $m(K\pi)$ and $\Delta m$ in bins of time:

- If no mixing, ratio of WS to RS signal should be constant
- No assumptions made on time evolution of background
- Each time bin is fit independently

Time bins:
- $-2 < t < 0$ psec
- $0 < t < 0.2$ psec
- $0.2 < t < 0.4$ psec
- $0.4 < t < 0.75$ psec
- $0.75 < t < 2.5$ psec
Rate of WS events clearly increases with time:

\[
\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2
\]

(stat. only)
Rate of WS events clearly increases with time:

\[
\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2
\]

Inconsistent with no-mixing hypothesis: \(\chi^2=24\)
Simplified Fit Strategy & Validation

Rate of WS events clearly increases with time:

$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D} y' \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2$$

Consistent with prediction from full likelihood fit: \( \chi^2 = 1.5 \)

Inconsistent with no-mixing hypothesis: \( \chi^2 = 24 \)
Signal Significance

Significance calculated from change in log likelihood:

![Graph showing signal significance with contours and labels for 1σ, 2σ, 3σ, 4σ, and 5σ regions, with a best fit point and a no mixing point labeled.(stat. only)]
Signal Significance

Significance calculated from change in log likelihood:

\[ \frac{1}{2} \ln L = 23.9 \]

Corresponds to 4.5\( \sigma \) (with 2 parameters)
Signal Significance

Best fit is in unphysical region ($x'^2<0$)

No mixing

Corresponds to 4.5σ (with 2 parameters)

Physical solution ($y'=6.4\times10^{-3}$)

1σ

2σ

3σ

4σ

5σ

(stat. only)
Signal Significance with Systematics

Including systematics ($\sim 0.7 \times \text{stat}$) decreases signal significance

Best fit

No mixing

Fit is inconsistent with no-mixing at $3.9\sigma$

[ PRL. 98, 211802 (2007) ]
1.5 fb$^{-1}$ $K\pi$ Mixing Results from CDF
[arXiv:0712.1567 (fall 2007) & PRL 100, 121802 (2008)]

Best fit for mixing parameters
(uncertainties are combined stat. and systematic)

- Fit $\chi^2 = 19.2$ for 17 dof
- 3.8 $\sigma$ from Null Hypothesis

$R_D: (3.04 \pm 0.55) \times 10^{-3}$
$x'^2: (-0.12 \pm 0.35) \times 10^{-3}$
$y': (8.5 \pm 7.6) \times 10^{-3}$
First Evidence for $\Delta \Gamma \neq 0$ in $D^0 \rightarrow h^+ h^-$

$$|D_1\rangle = p|D^0\rangle + q|D^0\rangle,$$
$$|D_2\rangle = p|D^0\rangle - q|D^0\rangle,$$
$$|p|^2 + |q|^2 = 1$$

$$r_m \equiv \left| \frac{q}{p} \right| \quad \text{and} \quad \varphi_f \equiv \arg \left( \frac{qA_f}{pA_f} \right) ,$$

- $r_m \neq 1 \Rightarrow CP$ violation in mixing.
- non-zero $\varphi_f \Rightarrow CP$ violation in the interference of mixing and decay amplitudes.

To a good approximation, $D^0$ and $\bar{D}^0$ mesons decay into specific $CP$ eigenstates (even for $K^- K^+$ and $\pi^- \pi^+$) with effective lifetimes

$$\tau_{hh}^+ = \tau_{K\pi} \left[ 1 + r_m (y \cos \varphi_f - x \sin \varphi_f) \right]^{-1},$$
$$\tau_{hh}^- = \tau_{K\pi} \left[ 1 + r_m^{-1} (y \cos \varphi_f + x \sin \varphi_f) \right]^{-1} .$$

These effective lifetimes can be combined into

$$y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1 , \quad \rightarrow y \quad \text{for} \quad r_m = 1, \varphi_f = 0$$

$$\Delta Y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau , \quad A_\tau = \frac{\tau_{hh}^+ - \tau_{hh}^-}{\tau_{hh}^+ + \tau_{hh}^-} .$$

FIG. 2. Results of the simultaneous fit to decay-time distributions of (a) $D^0 \rightarrow K^+ K^-$, (b) $D^0 \rightarrow K^- \pi^+$, and (c) $D^0 \rightarrow \pi^+ \pi^-$ decays. The cross-hatched area represents background contributions, the shape of which was fitted using $M$ sideband events. (d) Ratio of decay-time distributions between $D^0 \rightarrow K^+ K^-$, $\pi^+ \pi^-$ and $D^0 \rightarrow K^- \pi^+$ decays. The solid line is a fit to the data points.
First Evidence for $\Delta \Gamma \neq 0$ in $D^0 \rightarrow h^+h^-$

\[
|D_1\rangle = p|D_0^0\rangle + q|D_0^0\rangle, \\
|D_2\rangle = p|D_0^0\rangle - q|D_0^0\rangle, \\
|p|^2 + |q|^2 = 1
\]

\[
r_m \equiv \left| \frac{q}{p} \right| \quad \text{and} \quad \varphi_f \equiv \arg \left( \frac{q A_f}{p A_f} \right)
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\]

These effective lifetimes can be combined into

\[
y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1, \quad \rightarrow y \text{ for } r_m = 1, \varphi_f = 0 \\
\Delta Y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau, \quad A_\tau = \frac{(\tau_{hh}^+ - \tau_{hh}^-)}{(\tau_{hh}^- + \tau_{hh}^+)}
\]

$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$

540 fb$^{-1}$
Adding Babar’s $D^0 \to h^+h^-$ Results

Babar’s results from 384 fb$^{-1}$

<table>
<thead>
<tr>
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<th>$y_{CP}$ [%]</th>
<th>$\Delta Y$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^-$</td>
<td>1.60 ± 0.46 ± 0.17</td>
<td>−0.40 ± 0.44 ± 0.12</td>
</tr>
<tr>
<td>$\pi^+\pi^-$</td>
<td>0.46 ± 0.65 ± 0.25</td>
<td>0.05 ± 0.64 ± 0.32</td>
</tr>
</tbody>
</table>

Combining KK and $\pi\pi$ results gives

$y_{CP} = (1.24 ± 0.39 ± 0.13)$%

CP violation consistent with zero.

my private fall 2007 $y_{CP}$ average

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>BaBar</td>
<td>Tagged (384 fb$^{-1}$)</td>
<td>(1.24 ± 0.39 ±0.13)%</td>
</tr>
<tr>
<td>BaBar</td>
<td>Untagged (91 fb$^{-1}$)</td>
<td>(0.2 ± 0.4 ± 0.5)%</td>
</tr>
<tr>
<td>BaBar</td>
<td>Combined</td>
<td>(0.94 ± 0.35)%</td>
</tr>
<tr>
<td>Belle</td>
<td>Tagged</td>
<td>(1.31 ± 0.32 ± 0.25)%</td>
</tr>
<tr>
<td>BaBar + Belle</td>
<td>Combined</td>
<td>(1.10 ± 0.27)%</td>
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</tbody>
</table>
Mixing in $D^0 \rightarrow K_S \pi^+ \pi^-$

The decay amplitude at time $t$ of an initially produced $|D^0\rangle$ or $|\bar{D}^0\rangle$ can be expressed as

$$M(m_-^2, m_+^2, t) = A(m_-^2, m_+^2) e_1(t) + e_2(t)$$
$$+ \frac{q}{p} A(m_-^2, m_+^2) e_1(t) - e_2(t),$$

$$\overline{M}(m_-^2, m_+^2) = \overline{A}(m_-^2, m_+^2) e_1(t) + e_2(t)$$
$$+ \frac{q}{p} \overline{A}(m_-^2, m_+^2) e_1(t) - e_2(t).$$

The time dependence is contained in the terms

$$e_{1,2}(t) = \exp[-i(m_{1,2} - i \Gamma_{1,2}/2)t].$$

Upon squaring $M$ and $\overline{M}$, one obtains decay rates containing terms $\exp(-\Gamma t) \cos(x \Gamma t)$, $\exp(-\Gamma t) \sin(x \Gamma t)$, and $\exp[-(1 \pm y) \Gamma t]$.

Each amplitude is a function of $m_+^2$ and $m_-^2$, expressed as a sum of quasi-two-body amplitudes (subscript $r$) and a constant non-resonant term (subscript NR):

$$A(m_-^2, m_+^2) = \sum_r a_r e^{i \phi_r} A_r(m_-^2, m_+^2) + a_{NR} e^{i \phi_{NR}}$$
$$\overline{A}(m_-^2, m_+^2) = \sum_r a_r e^{i \phi_r} A_r(m_+^2, m_-^2) + a_{NR} e^{i \phi_{NR}}$$

The $A_r$ are products of Blatt-Weisskopf form factors and relativistic Breit-Wigner functions.
Mixing in $D^0 \rightarrow K_S\pi^+\pi^-$

$\chi : (0.80 \pm 0.35 \pm 0.15)\%$

$\gamma : (0.33 \pm 0.24 \pm 0.14)\%$

(assuming no CP violation)
**Time-Dependence in $D^0 \rightarrow K_S \pi^+ \pi^-$**

These plots illustrate the average decay time as a function of position in the Dalitz plot for $(x,y) = (0.8\%, 0.3\%)$. The sizes of the boxes reflect the number of entries, and the colors reflect the average decay time.
Mixing Well Established by Summer 2008

CPV-allowed plot, no mixing \((x, y) = (0, 0)\) point: \(\Delta \chi^2 = 102.6\), 
\(CL = 5.3 \times 10^{-23}\), no mixing excluded at 9.8\(\sigma\)

No CPV \(|q/p|, \varphi = (1,0)\) point: \(\Delta \chi^2 = 1.33\), \(CL = 0.486\), consistent with CP conservation
\textbf{SU}(3) Breaking and $D^0$-$\bar{D}^0$ mixing}


\[ y = \frac{1}{2\Gamma} \sum_n \rho_n \left[ \langle D^0 | \mathcal{H}_w | n \rangle \langle n | \mathcal{H}_w | \bar{D}^0 \rangle + \langle \bar{D}^0 | \mathcal{H}_w | n \rangle \langle n | \mathcal{H}_w | D^0 \rangle \right] \]

\[ y = \sum_n \eta_{\text{CKM}}(n) \eta_{\text{CP}}(n) \cos \delta_n \sqrt{\mathcal{B}(D^0 \to n) \mathcal{B}(\bar{D}^0 \to n)} \]

- $\delta_n$ is the strong phase difference between the $D^0 \to n$ and $\bar{D}^0 \to n$ amplitudes
- $\eta_{\text{CKM}} = (-1)^{n_s}$, where $n_s$ is the number of $s$ and $\bar{s}$ quarks in the final state.

- $CP | f \rangle = \eta_{\text{CP}} | f \rangle$, well-defined as $| f \rangle$, $| \bar{f} \rangle$ in the same $SU(3)$ multiplet

\[ y = \sum_a y_a, \quad y_a = \eta_{\text{CP}}(a) \sum_{n \in a} \eta_{\text{CKM}}(n) \cos \delta_n \sqrt{\mathcal{B}(D^0 \to n) \mathcal{B}(\bar{D}^0 \to n)} \]

\[ y_{\pi K} = \mathcal{B}(D^0 \to \pi^+ \pi^-) + \mathcal{B}(D^0 \to K^+ K^-) \]
\[ - 2 \cos \delta_{K\pi} \sqrt{\mathcal{B}(D^0 \to K^- \pi^+) \mathcal{B}(D^0 \to K^+ \pi^-)} \]

\[ y_{\pi K} \approx (5.76 - 5.29 \cos \delta_{K\pi}) \times 10^{-3} \]
SU(3) Breaking and $D^0$-$\bar{D}^0$ mixing


<table>
<thead>
<tr>
<th>Final state representation</th>
<th>$y_{F,R}/s_1^2$</th>
<th>$y_{F,R}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PP$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.0038</td>
<td>-0.018</td>
</tr>
<tr>
<td>27</td>
<td>-0.00071</td>
<td>-0.0034</td>
</tr>
<tr>
<td>$PV$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$8_S$</td>
<td>0.031</td>
<td>0.15</td>
</tr>
<tr>
<td>$8_A$</td>
<td>0.032</td>
<td>0.15</td>
</tr>
<tr>
<td>10</td>
<td>0.020</td>
<td>0.10</td>
</tr>
<tr>
<td>10</td>
<td>0.016</td>
<td>0.08</td>
</tr>
<tr>
<td>27</td>
<td>0.040</td>
<td>0.19</td>
</tr>
<tr>
<td>$(VV)_s$-wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.081</td>
<td>-0.39</td>
</tr>
<tr>
<td>27</td>
<td>-0.061</td>
<td>-0.30</td>
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<tr>
<td>$(VV)_p$-wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.10</td>
<td>-0.48</td>
</tr>
<tr>
<td>27</td>
<td>-0.14</td>
<td>-0.70</td>
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<tr>
<td>$(VV)_d$-wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.51</td>
<td>2.5</td>
</tr>
<tr>
<td>27</td>
<td>0.57</td>
<td>2.8</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Final state representation</th>
<th>$y_{F,R}/s_1^2$</th>
<th>$y_{F,R}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(3P)_s$-wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.48</td>
<td>-2.3</td>
</tr>
<tr>
<td>27</td>
<td>-0.11</td>
<td>-0.54</td>
</tr>
<tr>
<td>$(3P)_p$-wave</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-1.13</td>
<td>-5.5</td>
</tr>
<tr>
<td>27</td>
<td>-0.07</td>
<td>-0.36</td>
</tr>
<tr>
<td>$(3P)$form-factor</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-0.44</td>
<td>-2.1</td>
</tr>
<tr>
<td>27</td>
<td>-0.13</td>
<td>-0.64</td>
</tr>
<tr>
<td>$4P$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>3.3</td>
<td>16</td>
</tr>
<tr>
<td>27</td>
<td>2.2</td>
<td>9.2</td>
</tr>
<tr>
<td>27$'$</td>
<td>1.9</td>
<td>11</td>
</tr>
</tbody>
</table>

Values of $y_{F,R}$ for two-body final states. This represents the value which $y$ would take if elements of $F_R$ were the only channel open for $D^0$ decay.

"On the basis of this analysis, in particular as applied to the $4P$ final state, we would conclude that $y$ on the order of a percent would be completely natural. Anything an order of magnitude smaller would require significant cancellations which do not appear naturally in this framework. Cancellations would be expected only if they were enforced by the OPE, that is, if the charm quark were heavy enough that the "inclusive" approach were applicable. The hypothesis underlying the present analysis is that this is not the case."
Fast Forward to Charm at LHCb
Fast Forward to Charm at LHCB
The LHCb Detector

Hardware trigger system for hadrons: based on large $E_t$ depositions in the hadron Cal.

Tracking system:
$\Delta p/p = 0.4\text{-}0.6\% @ 5\text{-}100 \text{ GeV/c}$, corresponding to $\sim 8 \text{ MeV/c}^2$ mass resolution for $D \rightarrow K\pi$

Requiring $|M(K\pi) - M(D^0)| < 24 \text{ MeV/c}^2$

RICH detectors:
Good $K/\pi$ separation for $p < 100 \text{ GeV/c}$ with mis-ID rate at a few percent

Silicon Vertex Locator:
20 $\mu$m impact parameter (IP) resolution, corresponding to $\sim 0.1\tau$ decay-time resolution for $D \rightarrow K\pi$
$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb

Example fits with part of full data. In total $\sim 54 \text{ M }$ RS candidates and $\sim 0.23 \text{ M }$ WS candidates are collected.
$D^0 \rightarrow K\pi$ Mixing and CPV Measurements at LHCb

\[ R^\pm(t) \equiv \frac{WS(t)}{RS(t)} = R_D^\pm + \sqrt{R_D^\pm} y'^\pm \left( \frac{t}{\bar{\tau}} \right) + \left( \frac{x'^\pm + y'^\pm}{4} \right) \left( \frac{t}{\bar{\tau}} \right)^2 \]

- Measure the WS/RS ratio in each of 13 decay time bins, separately for $D^0$ and $\bar{D}^0$.
- Fit the WS/RS ratio as a function of decay time under three hypotheses:
  - No CPV
  - No direct CPV ($R_D^+ = R_D^-$)
  - Full CPV allowed
- Account for feed-through from secondary charm production.
- Account for relative reco efficiency $\varepsilon_R = \varepsilon(K^-\pi^+)/\varepsilon(K^+\pi^-)$
$D^0 \to K\pi$ Mixing and CPV Measurements at LHCb

$$R^\pm(t) \equiv \frac{WS(t)}{RS(t)} = R_D^\pm + \sqrt{R_D^\pm y^\pm} \left( \frac{t}{\tau} \right) + \left( \frac{x'^2 + y'^2}{4} \right) \left( \frac{t}{\tau} \right)^2$$

- Measure the WS/RS ratio in each of 13 decay time bins, separately for $D^0$ and $\bar{D^0}$.
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- Account for feed-through from secondary charm production.
- Account for relative reco efficiency $\varepsilon_R = \varepsilon(K^-\pi^+)/\varepsilon(K^+\pi^-)$

\[ \Delta \sim 0.1 \]
\[ \Delta \sim 2.0 \]
**D^0 → Kπ Mixing and CPV Results**

**LHCb preliminary**

<table>
<thead>
<tr>
<th>Direct and indirect CP violation</th>
<th>Uncertainties are statistical and systematic combined</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>R_D</strong></td>
<td>3.568 ± 0.066</td>
</tr>
<tr>
<td><strong>A_D</strong></td>
<td>-0.7 ± 1.9</td>
</tr>
<tr>
<td><strong>y^+</strong></td>
<td>5.1 ± 1.4</td>
</tr>
<tr>
<td><strong>x^{2+}</strong></td>
<td>4.9 ± 7.0</td>
</tr>
<tr>
<td><strong>y^-</strong></td>
<td>4.5 ± 1.4</td>
</tr>
<tr>
<td><strong>x^{2-}</strong></td>
<td>6.0 ± 6.8</td>
</tr>
<tr>
<td><em><em>χ^2</em>/ndf</em>*</td>
<td>85.87/98</td>
</tr>
</tbody>
</table>

**Results are consistent with CP conservation**
Formalism for $D^0 \to K\pi$ Mixing and CPV

Using standard notation, and in the limit $x, y \ll 1$, the rates for $\bar{D}^0$ and $D^0$ decay to the wrong-sign (WS) $K\pi$ final states are

$$\left| \langle f|H|\bar{D}^0(t)\rangle \right|^2 \approx \frac{e^{-\Gamma t}}{2} |A_f|^2 \left\{ R_D + \left| \frac{p}{q} \right| \sqrt{R_D} [y \cos(\delta + \varphi) - x \sin(\delta + \varphi)](\Gamma t) + \left| \frac{p}{q} \right| \frac{x^2 + y^2}{4} (\Gamma t)^2 \right\}$$

and

$$\left| \langle f|H|D^0(t)\rangle \right|^2 \approx \frac{e^{-\Gamma t}}{2} |A_f|^2 \left\{ \bar{R}_D + \left| \frac{q}{p} \right| \sqrt{\bar{R}_D} [y \cos(\delta - \varphi) - x \sin(\delta - \varphi)](\Gamma t) + \left| \frac{q}{p} \right| \frac{x^2 + y^2}{4} (\Gamma t)^2 \right\}.$$

In the Standard Model and in most New Physics scenarios, the CF and DCS $K\pi$ amplitudes are CP symmetric. In the limit that all direct CPV is negligible, to a very good degree of precision

$$\tan \varphi = \left( 1 - \left| \frac{q}{p} \right| \right) \frac{x}{y} \quad \text{analogous to Wolfenstein's superweak relationship}$$
**D^0 \rightarrow K\pi Mixing and CPV Results**

### Graphs

- **Left Graph:**
  - LHCb
  - BaBar
  - Belle
  - CDF
  - Standard deviation contours

- **Right Graph:**
  - 1σ and 2σ contours
  - LHCb 2013 wrong sign DCPV
  - WA: w/ CDF WS, w/o HLCb A, w/o LHCb WS
  - WA: w/ CDF WS, w/o LHCb A, w/ LHCb WS

### Parameters

- **BaBar:**
  - PRL 98, 211802 (2007)

- **Belle:**
  - PRL 96, 151801 (2006)

- **CDF:**
  - Public Note 109990 (2013)

- **LHCb:**
  - PRL 111, 251801 (2013)

### Results

- **|q/p|**
  - 100.9 ± 1.6%
  - 99.3 ± 1.3%
  - 100.4 ± 6.5%

- **φ**
  - -0.5 ± 0.8°
  - +0.4 ± 0.7°
  - -1.6 ± 2.5°

### Notes

- No other CPV
- Use prior CPV measurements

### References

- HFAG 4/2013
- Superweak constraint (Rolf Andreassen, Adam Davis, MDS)
New $A_{\Gamma}$ Measurement from LHCb

$$A_{\Gamma} \equiv \frac{(\tau_{hh}^+ - \tau_{hh}^-)}{(\tau_{hh}^+ - \tau_{hh}^-)} = (|q/p| - |p/q|) y \cos \phi - (|q/p| + |p/q|) x \sin \phi$$

- Measurement of the lifetime for each final state and each $D^0$ flavour

$A_{\Gamma}(KK) = (-0.35 \pm 0.62_{\text{stat}}) \times 10^{-3}$

$A_{\Gamma}(\pi \pi) = (0.33 \pm 1.06_{\text{stat}}) \times 10^{-3}$
New HFAG Average for $A_\Gamma$

$$A_\Gamma \equiv \frac{(\tau_{hh}^+ - \tau_{hh}^-)}{(\tau_{hh}^+ - \tau_{hh}^-)} = (\frac{|q/p| - |p/q|}{y \cos \phi} - (\frac{|q/p| + |p/q|}{x \sin \phi})$$

- Belle 2012: $(-0.030 \pm 0.200 \pm 0.080)\%$
- BaBar 2012: $(0.088 \pm 0.255 \pm 0.058)\%$
- LHCb 2013 KK: $(-0.035 \pm 0.062 \pm 0.012)\%$
- LHCb 2013 $\pi\pi$: $(0.033 \pm 0.106 \pm 0.014)\%$
- Sept. 2013 World Average: $(-0.014 \pm 0.052)\%$
- April 2013 ave was $(-0.022 \pm 0.161)\%$
April → September, 2013

\[
\tan \varphi = \left(1 - \frac{q}{p}\right) \frac{x}{y} \Rightarrow \begin{cases}
|q/p| & \varphi \\
|q/p| & \varphi \\
(100.9 \pm 1.6)\% & (-0.5 \pm 0.8)^\circ \\
(99.3 \pm 1.3)\% & (+0.4 \pm 0.7)^\circ \\
(100.4 \pm 6.5)\% & (-1.6 \pm 2.5)^\circ \\
\end{cases}
\]

no other CPV
params used
use prior CPV
measurements
HFAG 4/2013
Study of $D^0-\bar{D}^0$ Mixing


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(2) Carleton University, Ottawa, Ontario, Canada K1S 5B6
(3) Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil
(4) University of Colorado, Boulder, Colorado 80309
(5) Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(6) National Research Council, Ottawa, Ontario, Canada K1A 0R6
(7) Universidade de São Paulo, São Paulo, Brazil
(8) University of Toronto, Toronto, Ontario, Canada M5S 1A7
(Received 18 December 1987)

We present a study of $D^0$ mixing using events of the type $D^{*+}\to \pi^+D^0$, with $D^0\to K^+\pi^-$ and $D^0\to K^+\pi^-\pi^+\pi^-$. The decay time is used to separate mixing from doubly Cabibbo-suppressed decays. We observe no evidence for mixing in either mode. Combining the results from the two decay modes, we find $r_M=0.0005\pm0.0020$ or $r_M<0.0037$ at the 90% confidence level, where $r_M$ is the ratio of wrong-sign decays from mixing to right-sign decays. We also present limits on doubly Cabibbo-suppressed decays and consider the effect of possible interference.
Search for $D^0$-$\bar{D}^0$ mixing and doubly-Cabibbo-suppressed decays of the $D^0$ in hadronic final states


(Fermilab E791 Collaboration)

(Received 29 August 1996; revised manuscript received 27 August 1997; published 8 December 1997)

We present results of a search for $D^0$-$\bar{D}^0$ mixing and doubly-Cabibbo-suppressed decays of the $D^0$ in Fermilab experiment E791, a fixed-target charm hadroproduction experiment. We look for evidence of mixing in the decay chain $D^* \rightarrow \pi D \rightarrow \pi (K \pi$ or $K \pi \pi \pi)$. If the charge of the pion from the $D^*$ decay is the same as the charge of the kaon from the $D$ decay (a “wrong-sign” event), mixing may have occurred. Mixing can be distinguished from other sources of wrong-sign events (such as doubly-Cabibbo-suppressed decays) by analyzing the distribution of decay times. We see no evidence of mixing. Allowing for $CP$ violation in the interference between DCS and mixing amplitudes our fitted ratio for mixed to unmixed decay rates is $r_{mix} = (0.39^{+0.36}_{-0.32} \pm 0.16)\%$. This corresponds to a 90% C.L. upper limit of $r_{mix} < 0.85\%$. The sensitivity of this result is comparable to that of previous measurements, but the assumptions made in fitting the data are notably more general. We present results from many fits to our data under various assumptions. If we assume $r_{mix} = 0$, we find a two-sigma wrong-sign enhancement in the $K\pi$ mode which we ascribe to doubly Cabibbo-suppressed decays. The ratios of doubly Cabibbo-suppressed decays to Cabibbo-favored decays are $r_{dcs}(K\pi) = (0.68^{+0.34}_{-0.33} \pm 0.07)\%$ and $r_{dcs}(K\pi\pi\pi) = (0.25^{+0.36}_{-0.34} \pm 0.03)\%$. [S0556-2821(98)01103-5]
Charm Mixing: Thoughts and Projections

- **D⁰ - D̄° mixing** is firmly established
  - level is consistent with Standard Model or New Physics amplitudes, or both.

- **CPV in mixing** is being probed at the n% level
  - Observation at this level would indicate New Physics.

- Data already on tape will help us probe CPV in mixing with somewhat greater precision (D⁰ → K⁰Sπ⁻π⁺ from Belle and LHCb, in particular).

- Forthcoming experiments (LHCb, Belle-II) will enable measurements of CPV in mixing at the 0.n% level.

- **Relax superweak constraint:**
  - use \( \tan(\phi_{\lambda_f} + \phi_{12,f}^\Gamma) = -A_M x/y \); \( \lambda_f \equiv \frac{q}{p} \frac{\bar{A}_f}{A_f} \)
Summary and Conclusions

- Flavor physics provides complementary sensitivity to Beyond the Standard Model physics with respect to the general purpose LHC detectors ATLAS and CMS.

- Our $D^0 \rightarrow K\pi$ mixing measurement constrains CPV in mixing $(|q/p|)$ to $\pm (10\% - 1\%)$ depending on what assumptions are made with respect to direct CPV in CF and DCS amplitudes.

- More results from the $3 \text{ fb}^{-1}$ Run 1 (2011/2012) data set are on the way. We expect to record $\sim 3$ times as many B's and $> 5$ times as many D's in the LHC's Run 2.

- The upgrade should provide another order of magnitude increase in statistics.