Oscillazioni del mesone $D^0$

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Outline

• Neutral mesons flavor oscillation
• Charm meson mixing
• Evidence from B-factories
  – $D^0 \rightarrow K^-\pi^+$
  – $D^0 \rightarrow K^- l^+ \nu_l$, $D^0 \rightarrow K_s \pi^+\pi^-$, $D^0 \rightarrow K^+K^-/\pi^+\pi^-$
• Outlook
Neutral Mesons systems

- Two-level system \((M^0, \bar{M}^0)\)
  - Weak interactions remove degeneracy, make them unstable

Time evolution by Schrödinger eq.:
\[
\frac{i}{\partial t} \left( \begin{array}{c} M^0(t) \\ \bar{M}^0(t) \end{array} \right) = \left( \begin{array}{cc} M & \frac{i}{2} \Gamma \\ -\frac{i}{2} \Gamma & \bar{M} \end{array} \right) \left( \begin{array}{c} M^0(t) \\ \bar{M}^0(t) \end{array} \right)
\]

2x2 hermitian matrices

Mass eigenstates:
\[
|M_{1,2}\rangle = p|M^0\rangle \pm q|\bar{M}^0\rangle
\]

Propagate with separate mass \(m_{1,2}\) and width \(\Gamma_{1,2}\):
\[
|M_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t} |M_{1,2}(t = 0)\rangle
\]
Neutral mesons oscillations

Time evolution for meson of **known flavor at** $t=0$

\[
x = \frac{m_2 - m_1}{\Gamma}, \quad \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}
\]

\[
y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}
\]

\[
|M^0(t)\rangle = e^{-\tilde{\gamma}t/2} \left( \cosh(\Delta\gamma t/2)|M^0\rangle - \frac{q}{p} \sinh(\Delta\gamma t/2)|\bar{M}^0\rangle \right)
\]

Where

\[
\Delta\gamma = (y + ix)\Gamma \quad \tilde{\gamma} = (\Gamma_1 + \Gamma_2)/2 - i(m_1 + m_2)
\]

$M^0$ “oscillates” into $\bar{M}^0$!

(\textit{also dubbed “mixing”})

An opposite flavor component appears after a while!
Some visual examples

Probability to find a $M^0(\bar{M}^0)$ after a given time

Lifetime units
How to generate this??

Mixing through box diagram:

No tree level Flavor Changing Neutral Currents (FCNC) in SM

Glashow, Iliopoulos and Maiani (1970):
FCNC calculated from single quark loop still too large

Introduce additional loop with new $c$ quark

GIM predicted charm quark 4 years before observation

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Can you see New Physics?

$B^0$ mixing was argued by UA1 and directly observed by ARGUS in 1987.

Large mixing frequency implied $t$ quark was heavy ($m_t > 50$ GeV/c$^2$)

And the top was discovered 8 years after!
Even more ambitious today!

$B_{d,s}$ (K) mixing on the punch line for virtual effects from NP

Not only $x$ and $y$ but also **phases** in the mixing  **CP violation**

\[
C_{B_q} e^{2i\phi_{B_q}} = \frac{\langle B_q^0 | H_{eff}^{full} | B_q^0 \rangle}{\langle B_q^0 | H_{eff}^{SM} | B_q^0 \rangle}, \quad (q = d, s)
\]

\[
C_{\epsilon_K} = \frac{\Im \langle K^0 | H_{eff}^{full} | K^0 \rangle}{\Im \langle K^0 | H_{eff}^{SM} | K^0 \rangle}
\]

**M. Bona et al. (UTfit Collaboration)**

The missing tile

$K^0$ mixing

$x = 0.474$
$y = 0.997$

$D^0$ mixing

$B^0$ mixing

$x = 0.776$
$|y| < 0.1$

$B_{s^0}$ mixing

$x = 24.8$
$y = 0.12$
Charm Meson Mixing
**Short** and **Long** distance

- Prediction $x$ and $y$

$$
\left( M - \frac{i}{2} \Gamma \right)_{ij} = \frac{\langle D_i | H_{\text{eff}} | D_j \rangle}{2m_D} = m_D^{(0)} \delta_{ij} \quad \Downarrow \quad x \quad \text{VIRTUAL states}
$$

$$
+ \frac{\langle D_i | H_w | D_j \rangle}{2m_D} + \frac{1}{2m_D} \sum_n \frac{\langle D_i | H_w | n \rangle \langle n | H_w | D_j \rangle}{m_D^{(0)} - E_n + i\epsilon}.
$$

$$
\gamma_{ij} = \frac{1}{2m_D} \sum_n \langle D_i | H_w | n \rangle \langle n | H_w | D_j \rangle \delta(E_n - m_D) \quad \Uparrow \quad \text{Sum of intermediate REAL states}
$$

Makes it difficult to predict SM expectation
SM prediction for charm mixing

SM charm mixing box has down-type quarks in loop

\[
\begin{array}{c}
\bar{c} \rightarrow W \rightarrow \bar{d}, s, b \\
\end{array}
\]

Box diagram contribution

Effective GIM suppression:

\[
x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2}
\]

bottom quark ruled out by \( V_{CKM} \)

\[ x \sim 10^{-5} \quad \text{Tiny!} \]

Naively

\[
x, \ y \sim \sin \theta_c^2 \times \left[ \text{SU}(3) \text{ breaking} \right].
\]

Always hard to evaluate SU(3) breaking !!!

(HQET, propagation of common hadronic states, …)

SU(3) breaking effect more important for \( y \)

\[
x \lesssim 10^{-3}, \quad y \lesssim 10^{-2}.
\]


New Physics in Charm?

**D^0-\bar{D}^0 Mixing Predictions**

- △: Standard-model predictions for x
- □: Standard-model predictions for y
- ●: New-physics predictions for x

Hard to see a clear cut

*Pushing the limit down excludes models*

Try to separate x and y!
Experimental Searches
Charm physics with B-factory

BaBar is a B-factory: $e^+ e^- \rightarrow \Upsilon(4S) \rightarrow b \bar{b}$
$\sigma_{\text{eff}}(b \bar{b}) = 1.1 \text{ nb}$, but
$\sigma(c \bar{c}) = 1.3 \text{ nb}$

Millions of reconstructed charm hadrons

*BaBar is also a charm factory*

- Run1-5, more than 500M $c \bar{c}$ events
The technique

- Produce clean sample of $D^0$ and $\bar{D}^0$
- Identify flavor ($D^0$ or $\bar{D}^0$?) at decay time
- Measure rate of mixed decays as function of time

![Graph showing intensity vs. time normalized by $\tau$. The graph includes two curves, one for unmixed decays $D^0 \rightarrow D^0$ and $D^0 \rightarrow \bar{D}^0$, and one for mixed decays $D^0 \rightarrow \bar{D}^0$ and $\bar{D}^0 \rightarrow D^0$. The ratio $x = \frac{\Delta m}{\Gamma} = 0.01$. The mixed decays constitute 0.005% of the total.](image-url)
Flavor tagging

Use $D^0$ from $D^{*+} \rightarrow D^0 \pi^+$ decays:

$D^{*+} \left\{ \begin{array}{c}
\frac{c}{d} \\
\frac{u}{d}
\end{array} \right\} D^0$  

Flavor at production
Charge of pion "tags" initial flavor as $D^0$ or $\bar{D}^0$

$\bar{D}^0 \rightarrow K^+ \pi^-$

Flavor at decay

- Same flavour: Wrong-Sign (WS) mixing may have occured
- Opposite flavour: Right-Sign (RS) unmixed events

Charge of $K$ identifies decay flavor

$\bar{A}_f \equiv \langle f | H | D^0 \rangle$

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Double-Cabibbo Suppressed Decays

Hadronic decays do not uniquely identify decay flavor. Get unmixed wrong-sign decays from DCS decays.

**DCS decay:**

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

Relative rate \( \sim 0.3\% \)

\[ A_f \equiv \langle f \mid H \mid D^0 \rangle \]

**Mixed decay:**

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

Relative rate: 0.005\% (for \( x=0.01 \))
Time evolution

Discriminate DCS and mixing by their different time evolution

Also have interference effect:

$WS$ (relative to $RS$) time-dep. rate (small $x$ and small $y$ limit)

$$r(t) = \overline{r}(t) = e^{-t} \left( R_D \left( D^0 \right) + \sqrt{R_D} y' t + \frac{1}{2} R_M t^2 \right)$$

$$\frac{A_f}{A_f} = -\sqrt{R_D} e^{-i\delta}$$

$\delta$ is the (relative) strong phase

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

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

\[ Q = m(D^{*+}) - m(D^0) - m(\pi^+) \approx 6 \text{ MeV/}c^2 \]

Excellent background suppression

\(D^0\) selection:
- Identified \(K\) and \(\pi\)
- \(p^*(D^0) > 2.5 \text{ GeV/c}\)
- \(1.81 < m(K\pi) < 1.92 \text{ GeV/c}^2\)

Slow \(\pi\) selection:
- \(p^*(\pi_s) < 0.45 \text{ GeV/c}\)
- \(p_{\text{lab}}(\pi_s) > 0.1 \text{ GeV/c}\)
- \(0.14 < \Delta m < 0.16 \text{ GeV/c}^2\)

\[ \Delta m = m(K\pi\pi_s) - m(K\pi) \]
RS and WS data set

1,229,000 RS events

64,000 WS events

RS data sample

WS data sample

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

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Decay time analysis

- $D^0$ and $\pi_s$ constrained to luminous region
- Fit probability $> 0.1$
- Reconstructed decay time, $t$: $-2 < t < 4$ ps
- Estimated decay time error, $\delta t < 0.5$ ps

Resolution function from RS sample

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Random $\pi_S$:  
- Correct $D^0$, wrong $\pi_S$  
- Peaks in $m(K\pi)$, not $\Delta m$

Misreconstructed $D^0$:  
- Partially reco. $D^0$,  
  $D^0\rightarrow K^-\mu^+\nu$  
- Double misid $D^0\rightarrow K^-\pi^+$  
  (WS events only)  
- Peaks in $\Delta m$, not $m(K\pi)$

Combinatorially:  
- Random tracks

*Discrimination power from* $m(K\pi)$ and $\Delta m$
Signal extraction

384 fb$^{-1}$

RS signal: $1,141,500 \pm 1200$ combinations

WS signal: $4,030 \pm 90$ combinations
RS decay time analysis

$D^0$ lifetime and time resolution function from RS sample

$\tau = (410.3\pm0.6{\text{(stat.)}})\text{ fs}$

Consistent with PDG $(410.1\pm1.5\text{ fs})$

Systematics dominated by resolution function
WS decay time with mixing

384 fb⁻¹

Fit results allowing mixing:
\[ R_p: (3.03\pm0.16\pm0.10) \times 10^{-3} \]
\[ x'^2: (-0.22\pm0.30\pm0.21) \times 10^{-3} \]
\[ y': (9.7\pm4.4\pm3.1) \times 10^{-3} \]
\[ x'^2, y' \text{ correlation: } -0.94 \]

\[ \chi^2/bin = 31/28 \]

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Evidence for $D^0$ mixing!

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

Best fit

$-2 \Delta \ln L = 23.9$
Corresponds to 4.5$\sigma$
(with 2 parameters)

No mixing

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

$2 \Delta \ln L = 0.7$

Including systematics decreases signal significance 3.9 $\sigma$
Validation: $m(K\pi)$ and $\Delta m$ fit in t bins

- No assumptions made on time-evolution of background
- Each time bin is fit independently

Relative rate of WS events clearly increases with time
Validation: fit RS for mixing

Fit RS data with PDF allowing mixing

\[ x': (-0.01 \pm 0.01) \times 10^{-3} \]
\[ y': (0.26 \pm 0.24) \times 10^{-3} \]
\[ -2 \Delta \ln \mathcal{L} = 1.4 \quad (w.r.t. \text{ no mixing}) \]

\( D^0 \) decay time distribution is described properly.
Systematics uncertainty

Two types of systematic uncertainties considered:

**Fit model variations:**
- Change signal and background models used in fit, to test assumptions made

**Selection criteria:**
- Mainly decay time (error) ranges used in fit

<table>
<thead>
<tr>
<th>Systematic:</th>
<th>( R_D )</th>
<th>( \chi^2 )</th>
<th>( y' )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fit Model</td>
<td>0.59( \sigma )</td>
<td>0.40( \sigma )</td>
<td>0.45( \sigma )</td>
</tr>
<tr>
<td>Selection Criteria</td>
<td>0.24( \sigma )</td>
<td>0.57( \sigma )</td>
<td>0.55( \sigma )</td>
</tr>
<tr>
<td>Total</td>
<td>0.63( \sigma )</td>
<td>0.70( \sigma )</td>
<td>0.71( \sigma )</td>
</tr>
</tbody>
</table>

Fraction of statistical uncertainty

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Systematics on Decay time

Decay time resolution function in data has non-zero mean

**Core Gaussian shifted** \(3.6 \pm 0.6\text{fs}\)

Effect is not seen in MC
- probably due to misalignment

For systematics set mean to 0:

Variation: \(y' = 0.3\sigma\)

No reason why resolution should be different for RS and WS decays
Allowing for CP violation

Results of fitting $D^0$ and $\bar{D}^0$ separately:

$x^{'+2}$: $(-0.24\pm0.43\pm0.30)\times10^{-3}$
$y^{'+}$: $(9.8\pm6.4\pm4.5)\times10^{-3}$

$x^{-2}$: $(-0.20\pm0.41\pm0.29)\times10^{-3}$
$y^{-}$: $(9.6\pm6.1\pm4.3)\times10^{-3}$

$A_D=(-2.1\pm5.2\pm1.5)\%$  CP asymmetry in DCSD !

No evidence for CP violation found

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$K\pi$ analysis from Belle

Results consistent within $2\sigma$:
More evidence...!
Belle evidence on $y_{CP}$

“Apparent” lifetime difference between $D^0 \rightarrow K^-\pi^+$ and $K^+K^-$, $\pi^+\pi^-$

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$

$$y_{CP} = y \cos 2\phi_D - A_m x \sin 2\phi_D$$

$$A_m = 1 - |q/p|$$

$$A_\Gamma = A_m y \cos 2\phi_D - x \sin 2\phi_D$$

$$\phi_D = \text{mixing phase}$$

Stable $\tau_{K\pi}$ over different run periods

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Results on $y_{CP}$

Belle hep-ex/0703036

540 fb$^{-1}$

$y_{CP} = (1.31 \pm 0.32 \text{(stat.)} \pm 0.25 \text{(syst.)})\%$

- $>3\sigma$ effect
  (4.1 stat only)

$A_{\Gamma} = (0.01 \pm 0.30 \text{(stat.)} \pm 0.15 \text{(syst.)})\%$

No evidence of CP violation
Separating x and y

- $K\pi$ only cannot separate x and y

Need info on **strong phases**
  - Multibody decays: Dalitz models

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

DCS decays proceed primarily through $K^{*-}\pi^-$ while CF through $K^-\rho^+$
$D^0 \rightarrow K^+\pi^0, K^-\pi^+\pi^0$

Select special region of Dalitz plot

$$\frac{dN}{dt} \propto [\tilde{R}_D + \alpha \gamma' \sqrt{\tilde{R}_D} (\Gamma t) + \frac{\tilde{x}r^2 + \tilde{y}r^2}{4} (\Gamma t)^2]e^{-\Gamma t} , \quad 0 \leq \alpha \leq 1$$

Mixing rate

$$R_M = \frac{\frac{\tilde{x}r^2 + \tilde{y}r^2}{2}}{2} = \frac{x^2 + y^2}{2}$$

Effective phase

Results

- Assuming CP conservation
- Upper limits (95% C.L.)

$$K\pi\pi^0 \quad R_M < 0.054\%$$
$$K3\pi \quad R_M < 0.048\%$$

Combined result

$$R_M < 0.42 \times 10^{-3} \quad @ \ 95\% \ C.L.$$

(BaBar, 230 fb⁻¹)
Both flavor \((K^*\pi^+/K^{*+}\pi^-)\) final states in the same Dalitz plot! CP-eigenstate \((\rho K_S)\) and flavor states \((K^*\pi^+)\) in the same Dalitz plot!
\[ D^0 \rightarrow K_S \pi^+ \pi^- \] Dalitz model

Belle, 540 \( fb^{-1} \)

Very pure sample (95%)

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Amplitude</th>
<th>Phase (deg)</th>
<th>Fit fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>( K^*(892)^- )</td>
<td>1.629 ± 0.005</td>
<td>134.3 ± 0.3</td>
<td>0.6227</td>
</tr>
<tr>
<td>( K_0(1430)^- )</td>
<td>2.12 ± 0.02</td>
<td>-0.9 ± 0.5</td>
<td>0.0724</td>
</tr>
<tr>
<td>( K_0(1430)^+ )</td>
<td>0.87 ± 0.01</td>
<td>-47.3 ± 0.7</td>
<td>0.0133</td>
</tr>
<tr>
<td>( K^*(1410)^- )</td>
<td>0.65 ± 0.02</td>
<td>111 ± 2</td>
<td>0.0048</td>
</tr>
<tr>
<td>( K^*(1680)^- )</td>
<td>0.60 ± 0.05</td>
<td>147 ± 5</td>
<td>0.0002</td>
</tr>
<tr>
<td>( K^*(892)^+ )</td>
<td>0.152 ± 0.003</td>
<td>-37.5 ± 1.1</td>
<td>0.0054</td>
</tr>
<tr>
<td>( K_0(1430)^+ )</td>
<td>0.541 ± 0.013</td>
<td>91.8 ± 1.5</td>
<td>0.0047</td>
</tr>
<tr>
<td>( K_0(1430)^+ )</td>
<td>0.276 ± 0.010</td>
<td>-106 ± 3</td>
<td>0.0013</td>
</tr>
<tr>
<td>( K^*(1410)^+ )</td>
<td>0.333 ± 0.016</td>
<td>-102 ± 2</td>
<td>0.0013</td>
</tr>
<tr>
<td>( K^*(1680)^+ )</td>
<td>0.73 ± 0.10</td>
<td>103 ± 6</td>
<td>0.0004</td>
</tr>
<tr>
<td>( \rho(770) )</td>
<td>1 (fixed)</td>
<td>0 (fixed)</td>
<td>0.2111</td>
</tr>
<tr>
<td>( \omega(782) )</td>
<td>0.0380 ± 0.0006</td>
<td>115.1 ± 0.9</td>
<td>0.0003</td>
</tr>
<tr>
<td>( f_0(980) )</td>
<td>0.380 ± 0.002</td>
<td>-147.1 ± 0.9</td>
<td>0.0452</td>
</tr>
<tr>
<td>( f_0(1370) )</td>
<td>1.46 ± 0.04</td>
<td>98.6 ± 1.4</td>
<td>0.0162</td>
</tr>
<tr>
<td>( f_2(1270) )</td>
<td>1.43 ± 0.02</td>
<td>-13.6 ± 1.1</td>
<td>0.0180</td>
</tr>
<tr>
<td>( \rho(1450) )</td>
<td>0.72 ± 0.02</td>
<td>40.9 ± 1.9</td>
<td>0.0024</td>
</tr>
<tr>
<td>( \sigma_1 )</td>
<td>1.387 ± 0.018</td>
<td>-147 ± 1</td>
<td>0.0914</td>
</tr>
<tr>
<td>( \sigma_2 )</td>
<td>0.267 ± 0.009</td>
<td>-157 ± 3</td>
<td>0.0088</td>
</tr>
<tr>
<td>NR</td>
<td>2.36 ± 0.05</td>
<td>155 ± 2</td>
<td>0.0615</td>
</tr>
</tbody>
</table>

- Dalitz model: 13 different (BW) resonances and a non-resonant contribution
- Results with this refined model consistent with the analysis performed for the Belle \( \phi_3 \) measurement, PRD73, 112009 (2006)
- To test the scalar \( \pi \pi \) contributions, K-matrix formalism is also used
Sensitivity regions

\[ |M|^2 \approx |A(m_-^2, m_+^2)|^2 \left\{ 1 + [\text{Im}(\chi) x - \text{Re}(\chi) y] t + |\chi|^2 \left( \frac{x^2 + y^2}{4} \right) t^2 \right\} e^{-\Gamma t} \]

⇒ much of sensitivity comes from the \( K^*(890)^+ \) region and interference region between \( \rho(770) \) and \( \omega \).
Belle $D^0 \rightarrow K_S \pi^+ \pi^-$ results

Time fit (in projection):

$x = (0.80 \pm 0.29)\%$

$y = (0.33 \pm 0.24)\%$

$t_D = (409.9 \pm 0.9) \text{ fs}$

consistent with PDG

(in fact better precision)

Largest systematic errors:

<table>
<thead>
<tr>
<th></th>
<th>$\Delta x \times 10^{-2}$</th>
<th>$\Delta y \times 10^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p(D^*)$ cut</td>
<td>$+0.076$</td>
<td>$-0.078$</td>
</tr>
<tr>
<td>t dependence of Dalitz background</td>
<td>$-0.056$</td>
<td>$-0.057$</td>
</tr>
<tr>
<td>background timing parameters</td>
<td>$\pm 0.037$</td>
<td>$\pm 0.063$</td>
</tr>
<tr>
<td>decay model (form factors, variation of fixed masses &amp; widths, K-matrix, no non-resonant comp., others)</td>
<td>$+0.13$</td>
<td>$-0.051$</td>
</tr>
<tr>
<td></td>
<td>$-0.11$</td>
<td>$-0.066$</td>
</tr>
<tr>
<td>TOTAL</td>
<td>$(+0.17, -0.15)$</td>
<td>$(+0.10, -0.15)$</td>
</tr>
</tbody>
</table>

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Allowing for CP violation

\[ x = (0.80 \pm 0.29 \pm 0.17)\% \]
\[ y = (0.33 \pm 0.24 \pm 0.15)\% \]

\[ -2\Delta \ln L = 7.33 \Rightarrow \text{CL= only 2.6\%} \]

**Allow for CPV:**

\[ e_{(1,2)} = e^{-i(m_{(1,2)} - i\Gamma_{(1,2)}/2)t} \]

\[ \mathcal{M}(m_-, m_+, t) = \mathcal{A}(m_-, m_+) \frac{e_1(t) + e_2(t)}{2} + \left( \frac{q}{p} \right) \overline{\mathcal{A}}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2} \]

\[ \overline{\mathcal{M}}(m_-, m_+, t) = \mathcal{A}(m_-, m_+) \frac{e_1(t) + e_2(t)}{2} + \left( \frac{p}{q} \right) \overline{\mathcal{A}}(m_-, m_+) \frac{e_1(t) - e_2(t)}{2} \]

**CPV result:**

\[ x = (0.81 \pm 0.30 \pm 0.17)\% \]
\[ y = (0.37 \pm 0.25 \pm 0.15)\% \]

\[ lq/pl = 0.86^{+0.30}_{-0.29} \]
\[ \arg(q/p) = -14^{+16}_{-18} \]

\[ lq/pl = 0.95^{+0.22}_{-0.20} \]
\[ \arg(q/p) = -2^{+10}_{-11} \]
D-mixing with Semileptonic decay

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

No DCS sl. ! \[ A_f = \bar{A}_{\bar{f}} = 0 \]

\[ r(t) = \frac{e^{-t}}{4} \left( x^2 + y^2 \right) t^2 \left| \frac{q}{p} \right|^2 \]

Double tag

\[ D^{*+} \rightarrow D^0 \pi^+ , \text{ semil. and hadronic (fully rec.)} \]

Several hadronic tagging modes

\[ \Delta M \text{ RS events} \]

\[ \Delta M \text{ WS events} \]

\[ -1.3 \times 10^{-3} < R_M < 1.2 \times 10^{-3} \text{ @ 90\% C.L.} \]

BaBar, 344 fb\(^{-1}\)
Summary and Outlook
Summary

**BaBar studied** $D^0 \rightarrow K\pi$ decay
- Evidence for mixing (3.9σ)
- No sign of CP violation
- Consistent with other measurements and SM

**New results from Belle**
- Evidence for mixing (3.2σ)
- Measures $x$ and $y$ directly
- No sign of CP violation

$x = 0.80 \pm 0.29 \pm 0.17 \% \ (2.4\sigma)$

$y_{CP}(WA) = 1.12 \pm 0.32 \%$

» BaBar updating multibody decays analysis, $y_{CP}$ measurements
» BaBar $K_S\pi\pi$ on-going
Interpreting the results

$D^0$ and $\bar{D}^0$ weak phase $2\phi_D$ of the mixing amplitude

\[
y'_{\pm} = (1 \pm A_m)(y' \cos 2\phi_D \mp x' \sin 2\phi_D),
\]
\[
x'^2_{\pm} = (1 \pm 2A_m)(x' \cos 2\phi_D \pm y' \sin 2\phi_D)^2,
\]
\[
y_{CP} = y \cos 2\phi_D - A_m x \sin 2\phi_D,
\]
\[
A_{\Gamma} = A_m y \cos 2\phi_D - x \sin 2\phi_D,
\]

\[
A_m = 1 - \frac{|q/p|}{1}
\]

\[
x = (0.87^{+0.30}_{-0.34})\%
\]
(2.6σ above zero)

\[
y = (0.66 \pm 0.21)\%
\]
(3.2σ above zero)

\[
\delta = (19^{+15}_{-17})^\circ
\]
(consistent w/zero)
Measuring $\delta$

To beat down the model systematics measure phases directly

- Correlated D production - $DD \rightarrow f_1 f_2$

$$\left|\psi(3770)\right\rangle \rightarrow \left|DD\right\rangle_L = \frac{1}{\sqrt{2}} \left[ D^0(k_1)\overline{D}^0(k_2) + (-1)^L D(k_2)\overline{D}^0(k_1) \right]$$

- For $L=1$ DCS contribution to $f_1=f_2=K\cdot\pi^+$ cancels

- Of course no DCS semileptonic amplitude

$$R_M \approx \frac{(K^-\pi^+)^2}{(K^-\pi^+)(K^+\pi^-)} \quad R_M = \frac{(K^-\ell^+\nu)^2}{(K^-\ell^+\nu)(K^+\ell^-\bar{\nu})}$$

- $0.75 \text{ fb}^{-1} \sim 1.6K K\cdot\pi^+, \sim 6.5K K\cdot\ell^+\nu$ double tags

$$\Rightarrow \sqrt{2R_M} < 4\% @ 95\% C.L.$$  

- Note CF vs CF indistinguishable from DCS vs DCS
  - Amplitudes interfere
  - correction factor  
    $$\left( 1 + 2\sqrt{R_D} \cos\delta + R_D \right) \sim 1 + 0.12 + 0.0036$$

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Double tag at $\psi(3770)$ [CLEO-c]

- Reconstruct Double Tags: CP vs K\pi
- Asymmetry in CP$^+$ vs CP$^-$ related to $\cos\delta$

\[
A \equiv \frac{B(D_{CP^+} \to K^-\pi^+) - B(D_{CP^-} \to K^-\pi^+)}{B(D_{CP^+} \to K^-\pi^+) + B(D_{CP^-} \to K^-\pi^+)}
\]

- $R_D$ is ratio of DCS to Cabibbo favored rates

\[
\cos\delta = \frac{A}{2\sqrt{R_D}}
\]

- Input $R_D = (3.60\pm0.08)\%$ from PDG2006+CDF $\sim\pm2\%$

- Updated results with 281 pb$^{-1}$ at Winter Conferences
  - Expect $\sigma(y)\sim\pm1.5\%$ and $\sigma(\cos\delta_{K\pi})\sim\pm0.3$
  - Including systematic uncertainties
- Full CLEO-c dataset $\sim750$ pb$^{-1}$
  - Expect $\sigma(y)\sim\pm1.0\%$ and $\sigma(\cos\delta_{K\pi})\sim\pm0.1-0.2$
And CP violation?

In the standard model, $\phi \sim 2 A^2 \lambda^4 \eta \lesssim 10^{-3}$

In general NP weakly constrained if SM not known

Nevertheless SUSY coupling can be constrained

hints on squark and gluino masses!

Neutral meson mixing always a window into unknown (virtual) states!

Ciuchini et al.
hep-ph/0703294
Back up slides
Performing extensive checks of mixing signal:
- Could something fake signal?
- Is significance estimated correctly?
- Are mixing parameters unbiased?

No signal found in MC:
- $x'': (-0.02\pm0.18) \times 10^{-3}$
- $y': (-2.2\pm3.0) \times 10^{-3}$

In MC with signal, fit reproduces signal
- No intrinsic bias

Fit to MC with no mixing

Gianluca Cavoto
Coverage test

Significance of signal is calculated as change in log likelihood with respect to no-mixing hypothesis

Generated >10000 toys without mixing to test $-2\Delta \ln \mathcal{L}$ gives correct frequentist coverage

$-2\Delta \ln \mathcal{L} = 23.9$

#toys to the right of line
#toys expected

observed in data