Review of Charm Sector Mixing & CP Violation

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Beauty 2006, Oxford, UK
Brief History (I)

• Discovery of Charm at SPEAR in 1976
• Immediately several theoretical papers on mixing & CP violation in Charm sector
  - $K^0$ sector: Observed mixing ('56) & CPV ('64)
  - $B^0$ sector: Observed mixing ('87) & CPV ('99)
• Experimental searches for mixing & CPV in charm sector began immediately
  - 2 pubs in '77 from SPEAR
• Searches on going at BABAR, Belle, CLEO-c
Brief History (II)

- Many techniques used - not a complete of results
  - “Indirect”: search for like sign muons
    - 1981 (CERN) $\mu^+N \rightarrow \mu^+(\mu^+\mu^+) <20\% @ 90\%$ C.L.
    - 1982 (FNAL-E595) $\pi^-Fe \rightarrow X(\mu^+\mu^+) <4.4\% @ 90\%$ C.L.
    - 1985 (CERN -NA-004) $\mu^+N \rightarrow \mu^+(\nu^-\mu^-) <1.2\% @ 90\%$ C.L.
    - 1985 (CERN-WA-001-2) $\nu N \rightarrow \mu^+\mu^+ (5.1\pm2.3)%;(3.2\pm1.2)\%$
  - “Direct”: reconstruct $D^0$. Tag production & decay flavor
    - Early measurements used $D^{*+} \rightarrow D^{0}\pi^+, D^0 \rightarrow K+\pi^-$
      - 1977 (SPEAR) $e^+e^- (6.8 \text{ GeV}), D^0 \rightarrow K+\pi^- < 16\% @ 90\%$ C.L.
      - 1980 (E87) $\langle E_\gamma \rangle = 50 \text{ GeV} < 11\% @ 90\%$ C.L.
      - 1983 (ACCMOR) $\langle E_\gamma \rangle \sim 120-200 \text{ GeV} < 7\% @ 90\%$ C.L
      - 1987 (ARGUS) $e^+e^- \sim 10.6 \text{ GeV} < 1.4\%@90\%$ C.L.
      - 1991 (CLEO I.5) $e^+e^- \sim 10.6 \text{ GeV} < 1.1\% @90\%$ C.L.
      - 1997 (E791) $\pi^- \text{ beam} \sim 500 \text{ GeV} (0.21\pm0.09)\%$
“Modern Era” - Constraints on charm mixing approach

Standard Model expectation for doubly-Cabibbo suppressed (DCS) decay

- CLEO II.V (2000) Observed $D^0 \rightarrow K^+\pi^-$
- $R_D = \left(3.32^{+0.63}_{-0.65} \pm 0.40\right)\%$
- DCS is distinguished from mixing using decay time
- Need to resolve charm decay times
- Combined B-factory precision now about 10x better
- Search for mixing intimating tied to DCS processes

PDG06 averages charm mixing results from

- E791, FOCUS, CLEO, BABAR, Belle
  - More recent updates from BABAR, Belle, CLEO-c
- CPV averages also include some old E687 & new CDF results

Mixing & CPV not yet observed in Charm Sector

- Still window to search for New Physics!
Charm Mixing Primer

- Flavor eigenstate $\neq$ mass eigenstate
- Expected to be small in Standard Model
  - GIM suppression
  - CKM suppression
- Sensitive to new physics
- Mixing amplitudes $\sim 0$ in the SU(3) limit
- “Interesting” experimental sensitivity to charm mixing amplitudes starts at $\sim 10^{-3}$
  - Experiments will achieve this soon (Belle, BESIII)
CPV in Brief

Baryon # of the universe ⇒ new physics in CPV dynamics

Three types of CP violation

1) CPV in mixing
2) CPV in direct decay
3) CPV in interference between 1) and 2)

Standard Model

• Highly diluted weak phase in 1xCabibbo suppressed decay
  \[ V_{cs} = 1 + \ldots + i \lambda^4 \]
• No weak phases in Cabibbo favored or 2xCabibbo suppressed decay - except \[ D^+ \rightarrow K_{S,L} \pi^\pm \]
• CP asymmetry is linear in new physics amplitude
• Final state interactions are large
• CP eigenstate BR are large
• D mixing is slow

Require two coherent weak amplitudes to observe CPV
Direct CPV

- CF & DCS decay: Direct CPV requires New Physics
  - Exception: interference between CF & DCS amplitudes to $D^\pm \rightarrow K_{S,L}^{\pm} \pi^\mp$
  - SM contribution due to $K^0$ mixing is $A_S = [+]_S - [-]_S \sim -3.3 \times 10^{-3}; A_S = -A_L$
  - New Physics could be ~%

- SCS decay
  - Expect $O(\lambda^4) \sim 10^{-3}$ from CKM matrix
  - New Physics could be ~%

- Only type of CPV possible for charge mesons

- Requires two amplitudes with different strong & weak phases
  - In SM different weak phases often from tree & penguin processes

Experimentally:
- Measure asymmetry in time integrated partial widths
- Measure final state distributions on Dalitz plots, T-odd correlation
# Direct CPV Results

<table>
<thead>
<tr>
<th>$A_{CP}$ mode</th>
<th>E791(%)</th>
<th>FOCUS(%)</th>
<th>CLEO(%)</th>
<th>BABAR(%)</th>
<th>Belle(%)</th>
<th>CDF(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \to K^+\pi^-$</td>
<td>$18 \pm 14 \pm 4$</td>
<td>$2^{+19}_{-20}$</td>
<td>$9.5 \pm 10.3$</td>
<td>$2.3 \pm 4.7$</td>
<td>$-0.6 \pm 5.3$</td>
<td></td>
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<tr>
<td>$D^0 \to K^+\pi^-\pi^0$</td>
<td></td>
<td>$9^{+25}_{-22}$</td>
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<tr>
<td>$D^0 \to K^-K^+$</td>
<td>$-1.0 \pm 4.9 \pm 1.2$</td>
<td>$-0.1 \pm 2.2 \pm 1.5$</td>
<td>$0.0 \pm 2.2 \pm 0.8$</td>
<td>$0.2 \pm 0.7$</td>
<td>$1.0 \pm 1.3 \pm 0.6$</td>
<td>$2.0 \pm 1.2 \pm 0.6$</td>
</tr>
<tr>
<td>$D^0 \to \pi^-\pi^+$</td>
<td>$-4.9 \pm 7.8 \pm 3.0$</td>
<td>$4.8 \pm 3.9 \pm 2.5$</td>
<td>$1.9 \pm 3.2 \pm 0.8$</td>
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<tr>
<td>$D^0 \to \pi^0\pi^0$</td>
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<td></td>
<td>$0.1 \pm 4.8$</td>
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<tr>
<td>$D^0 \to K_S^0 K_S^0$</td>
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<td></td>
<td>$-23 \pm 19$</td>
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<tr>
<td>$D^0 \to K_S^0\pi^+\pi^-$</td>
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<td>$0.1 \pm 1.3$</td>
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<tr>
<td>$D^0 \to K_S^0\phi$</td>
<td></td>
<td></td>
<td>$-0.9 \pm 2.1^{+1.6}_{-5.7}$</td>
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<tr>
<td>$D^+ \to K_S^0\pi^+$</td>
<td>$-1.6 \pm 1.5 \pm 0.9$</td>
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<tr>
<td>$D^+ \to K_S^0 K^+$</td>
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<tr>
<td>$D^0 \to K^+\pi^-\pi^0$</td>
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<td>$6.9 \pm 6.0 \pm 1.8$</td>
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<tr>
<td>$D^+ \to K^-K^+\pi^+$</td>
<td>$-1.4 \pm 2.9$</td>
<td>$0.6 \pm 1.1 \pm 0.5$</td>
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<td>$1.4 \pm 1.0 \pm 0.8$</td>
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<tr>
<td>$D^+ \to \phi\pi^+$</td>
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<td></td>
<td></td>
<td>$-2.8 \pm 3.6$</td>
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<tr>
<td>$D^+ \to K^* K^+$</td>
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<td></td>
<td></td>
<td>$-1.0 \pm 5.0$</td>
<td></td>
<td>$0.9 \pm 1.7 \pm 0.7$</td>
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<tr>
<td>$D^+ \to \pi^-\pi^+\pi^+$</td>
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<td>$-1.7 \pm 4.2$</td>
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<tr>
<td>$D^0 \to \pi^+\pi^-\pi^0$</td>
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<td></td>
<td>$-1^{+9}_{-7} \pm 5$</td>
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<tr>
<td>$D^0 \to K^+\pi^-\pi^+\pi^-$</td>
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<td></td>
<td>$-1.8 \pm 4.4$</td>
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<tr>
<td>$D^0 \to K^+ K^-\pi^+\pi^-$</td>
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<tr>
<td>$D^+ \to K_S^0 K^+\pi^+$</td>
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<td></td>
<td></td>
<td>$-8.2 \pm 5.6 \pm 4.7$</td>
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<tr>
<td>$D^+ \to K_S^0 K^+\pi^+\pi^-$</td>
<td></td>
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<td></td>
<td></td>
<td>$-4.2 \pm 6.4 \pm 2.2$</td>
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</tbody>
</table>

| $A_T$ mode |        |        |        |        |        |        |
| $D^0 \to K^+ K^-\pi^+$ |  |  |  |  |  |  |
| $D^+ \to K_S^0 K^+\pi^+\pi^-$ |  |  |  | $1.0 \pm 5.7 \pm 3.7$ |  |  |
| $D^+ \to K_S^0 K^+\pi^+\pi^-$ |  |  |  | $2.3 \pm 6.2 \pm 2.2$ |  |  |
**Do–D̅o Mixing Formalism**

- Double Cabibbo suppressed
- GIM mechanism cancellation
- Long Distance Contributions

Flavor eigenstates are not mass eigenstates

\[ |D_1\rangle = p |D^0\rangle + q |\overline{D}^0\rangle \]

\[ |D_2\rangle = p |D^0\rangle - q |\overline{D}^0\rangle \]

\[ |D^0\rangle = \frac{1}{2p} (|D_1\rangle + |D_2\rangle) \]

\[ |\overline{D}^0\rangle = \frac{1}{2q} (|D_1\rangle - |D_2\rangle) \]

\[ |D_1(t)\rangle = |D_1\rangle \exp \left[ -\left( \frac{\Gamma_1}{2} + i m_1 \right) t \right] \]

\[ |D_2(t)\rangle = |D_2\rangle \exp \left[ -\left( \frac{\Gamma_2}{2} + i m_2 \right) t \right] \]

\[ |D^0(t)\rangle = \exp \left[ -\left( \frac{\Gamma}{2} + i m \right) t \right] \left\{ \cosh \left( \frac{\Delta \gamma}{4} + i \frac{\Delta m}{2} \right) |D^0\rangle + \frac{q}{p} \sinh \left( \frac{\Delta \gamma}{4} + i \frac{\Delta m}{2} \right) |\overline{D}^0\rangle \right\} \]

\[ |\overline{D}^0(t)\rangle = \exp \left[ -\left( \frac{\Gamma}{2} + i m \right) t \right] \left\{ \frac{p}{q} \sinh \left( \frac{\Delta \gamma}{4} + i \frac{\Delta m}{2} \right) |D^0\rangle + \cosh \left( \frac{\Delta \gamma}{4} + i \frac{\Delta m}{2} \right) |\overline{D}^0\rangle \right\} \]

\[ m = \frac{1}{2} (m_1 + m_2) \]

\[ \Gamma = \frac{1}{2} (\Gamma_1 + \Gamma_2) \]

\[ \Delta m = m_2 - m_1 \]

\[ \Delta \gamma \equiv \Gamma_2 - \Gamma_1 \]
Since $\Delta m \tau << 1$ & $\Delta \gamma \tau << 1$, expand $\sin$, $\cos$, $\sinh$ & $\cosh$.
Expectations for $D^0$-$\bar{D}^0$ Mixing

- Presence of d-type quarks in the loop makes the SM expectations for $D^0$-$\bar{D}^0$ mixing small compared with systems involving u-type quarks in the box diagram because these loops include 1 dominant super-heavy quark (t): $K^0$ (50%), $B^0$ (20%) & $B_s$ (50%)
- In SM $x \leq y$: Short distance $10^{-6}$ - $10^{-3}$
  Long distance $10^{-3}$ - $10^{-2}$
- New physics (NP) in loops implies $x = \Delta m/\Gamma >> y = \Delta \Gamma/2\Gamma$; but long range effects complicate predictions.
- Large CPV in mixing indicates NP

From H. Nelson, hep-ex/9908021
updated by A.A. Petrov hep-ph/0311371
See also Golowich,Petrov PLB 625 (2005) 53
Recall parameter definitions

- **Mixing parameters:** \( x = \frac{\Delta M}{\Gamma}, \ y = \frac{\Delta \Gamma}{2 \Gamma} \)
- **Mixing Rate:** \( R_M = \frac{(x^2 + y^2)}{2} \)
- **\( D^0/\bar{D}^0 \)** relative strong phase \( \delta \)
- **Effective parameters** \( y' = y \cos \delta - x \sin \delta; \ x' = y \sin \delta + x \cos \delta \)

**Several Experimental probes**

- **Semileptonic Decay:** Sensitive to \( R_M \), No DCS process
  - Search for \( \Gamma(D^0 \rightarrow K^*(n)l^-\nu) \)  (E791, CLEO, BABAR, Belle)
- **\( D^0(t) \rightarrow CP \)** Eigenstate: Sensitive to \( y \)  (E791, CLEO, FOCUS, BABAR, Belle)
- **Wrong-sign \( D^0(t) \rightarrow K^+\pi^- \)**: Sensitive to \( x'^2, y' \)  (CLEO, FOCUS, BABAR, Belle)
- **Wrong-sign multibody \( D^0(t) \rightarrow K^+\pi^-\pi^0, K^+3\pi \)** (CLEO, BABAR, Belle)
- **Dalitz plot \( D^0 (t)\rightarrow K_s^0\pi^+\pi^- \)**: Sensitive to \( x, y \)  (CLEO, Belle*)
- **Quantum Correlations:** \( e^+e^- \rightarrow D^0\bar{D}^0(n)\gamma(m)\pi^0 \)** (CLEO-c)
  - Primarily sensitive to \( y, \cos \delta \)
Some Analysis Details

- All analyses (except CLEO-c) share many common features
- Initial flavor of $D^0(t)$ determined by $D^{*\pm} \rightarrow D^0\pi^\pm$
  - $Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi} \sim 6$ MeV (near threshold)
  - $\sigma_Q < 200$ keV @ CLEO II.V (suppresses background)
- Common backgrounds
  - Random $\pi$ combining with Cabibbo favored (CF) $D^0 \rightarrow K^{+}\pi^{-}$
  - Multibody $D^0$ decay with $D^{*\pm} \rightarrow D^0\pi^\pm$
  - Random $K\pi\pi$ combinatorial background
- Signal & bkgd yield taken from $m_{K\pi}$ vs $Q$
- Signal shape/resolution functions taken from CF modes
- $x$ & $y$ obtained from (unbinned) ML fit to $\Delta t = (l/p)(m/c)$
  - $(l/p)$ at $e^+e^-$ calculated in $y$ projection due to beam profile
- $p(D^*)$ cut to suppress D's from B decay
- Mixing constraints obtained with & without CPV

Reconstruction of $t$

$$t = \frac{M}{p_y} \frac{y_v - y_b}{c\tau_{D^0}}$$

$\sigma_t \approx 1/2$

$D^{*+} \rightarrow \pi^{+}_s D^0$

$e^+e^-$ beam annihilations

CESR Plane (x) - 700 $\mu$m

vertical (y) 20 $\mu$m
Wrong-sign $D^0(t) \rightarrow K(\ast) + l^- \nu$ Decays

- E.M. Aitala et al. (E791), PRL 77, 2384 (1996): 2504 RS events
- C. Cawlfield et al. (CLEO II), PRD 71, 077101 (2005): (9 1/fb) 638 RS events
- B. Aubert et al. (BABAR), PRD 70, 091102 (2004): (87 1/fb) 49620 RS events
- U. Bitenc et al. (Belle), PRD 72, 071101 (2005): (253 1/fb) 229452 RS events

- Tag production flavor with $D^{\ast+} \rightarrow D^0 \pi^+$ (pion charge)
- Tag decay flavor with $K(\ast)^+ l^- \nu$ (kaon charge)
- Mixing signal is $\pi^+ l^-$ or $\pi^- l^+$ (wrong-sign)
- Normalize to $\pi^\pm l^\pm$ (right-sign)

Belle measures

$$R_M = \frac{(x^2+y^2)/2}{\#WS/\#RS}$$

in six bins of decay time

$$R_M = (0.20 \pm 0.47 \pm 0.14) \times 10^{-3}$$

$< 0.10\% @ 90\% C.L.$

$x,y < 4.5\% @ 90\% C.L.$

$$\Delta M = m_{K\pi
u} - m_{Ke\nu}$$
Wrong-sign $D^0(t) \to K^+\pi^-$ Decays - I

- R. Godang et al. (CLEO), PRL 84, 5038 (2000): (9.1 fb) 45 WS events
- J.M. Link et al. (FOCUS), PRL 86, 2955 (2001):
- PLB 618, 23 (2005)
- B. Aubert et al. (BABAR), PRL 91, 171801 (2003) (57.1 fb) 430 WS events
- J. Li et al. (Belle), PRL 94, 071801 (2005) (90 fb) 845 WS events
- L.M. Zhang et al. (Belle), PRL 96, 151801 (2006) (400 fb) 4024 WS events

Analysis Detail:
• $P(D^*) > 2.7$ GeV/c to reject $D$'s from $B$
• $m_{K\pi}-Q$ fit to determine WS yield $N_{WS}$
• $\Delta t$ fit to determine $R_D$, $x^2$, $y'$:
  • Recall 'strong phase ambiguity'
  $$\lambda \equiv \frac{q}{p} \overline{A_f} = \left| \frac{q}{p} \sqrt{R_D e^{i(\phi + \delta)}} \right| \overline{\lambda} \equiv \frac{p}{q} \overline{A_f} = \left| \frac{p}{q} \sqrt{R_D e^{i(-\phi + \delta)}} \right|$$
  • And mixing equations become
    - $R_{WS} = R_D + y'\sqrt{R_D} + R_M$
    - $y' = y\cos\delta - x\sin\delta$, $x = y\sin\delta + x\cos\delta$
    - $R_M = (x^2 + y^2)/2 = (x'^2 + y'^2)/2$
• WS resolution fn fixed to RS resolution
• $\Delta t$ bkgd shapes from $m-Q$ sideband
Wrong-sign $D^0(t) \rightarrow K^+\pi^-$ Decays - II

Determine $R_D, x, y$ Separately for $D^*+$ & $D^*-\ tags$

Fit Result (x10^{-3})

<table>
<thead>
<tr>
<th>Fit Case</th>
<th>Parameter</th>
<th>Fit Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>No CPV</td>
<td>$x'^2$</td>
<td>$0.18^{+0.21}_{-0.23} &lt; 0.72 \ @ 95%\ C.L.$</td>
</tr>
<tr>
<td>No CPV</td>
<td>$y'$</td>
<td>$0.6^{+4.0}_{-3.9} -9.9&lt;y'&lt;6.8 \ @ 95%\ C.L.$</td>
</tr>
<tr>
<td>No CPV</td>
<td>$R_D$</td>
<td>$3.65 \pm 0.17$</td>
</tr>
<tr>
<td>CPV</td>
<td>$A_D$</td>
<td>$23 \pm 47$ $-76&lt;A_D&lt;107$</td>
</tr>
<tr>
<td>CPV</td>
<td>$A_M$</td>
<td>$670 \pm 1200$ $-995&lt;A_M&lt;1000$</td>
</tr>
<tr>
<td>No mixing/No CPV</td>
<td>$R_D$</td>
<td>$3.77 \pm 0.08 \pm 0.05$</td>
</tr>
</tbody>
</table>
Wrong Sign Multibody Decay - I

- E.M. Aitala et al. (E791), PRD 57, 13 (1998)
- G. Brandenburg et al. (CLEO), PRL 87, 071802 (2001) (9 1/fb)
- S. Dytman et al. (CLEO), PRD 64, 111101 (2001) (9 1/fb)
- X.C. Tian et al. (Belle), PRL 95, 231801 (2005): (281 1/fb)
- B. Aubert et al. (BABAR), to PRL, hep-ex/0608006: (230 1/fb)
- B. Aubert et al. (BABAR), hep-ex/0607090: (230 1/fb)

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

- 7 WS K+3π
- 38 WS K+π-π^0
- 54 WS K+3π
- 1978 WS K+π-π^0
- 1721 WS K+3π
- 1560 WS K+π-π^0
- 2002 WS K+3π

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

background subtracted & efficiency corrected
Wrong Sign Multibody Decay - II

- Cut on Dalitz plot to remove DCS K*’s
- Reduces sensitivity to mixing but avoids complication of a time-dependent fit of the Dalitz plot
- Now similar to semileptonic mixing search but no $\nu$
  - better mass & decay resolution (no $\nu$)
  - Lower backgrounds (no $\nu$)
  - $R_M < 0.054\%$ @ 95% C.L. (230 1/fb) compare with best (Belle) semileptonic results $< 0.10\%$ @90% C.L. (281 1/fb)
$D^0(\tau) \rightarrow K^+3\pi$

- Decay time resolution better than $K\pi\pi^0$
- Background is lower
- No cut on phase space
  - $R_M < 0.048\% @ 95\%$ C.L.
- Combine with $K\pi\pi^0$
  - $R_M < 0.042 @ 95\%$ C.L.
- Note no mixing NOT inside 95\% C.L.
  - $K\pi\pi^0$ consistent with no mixing @ 4.5\%
  - $K3\pi$ consistent with no mixing @ 4.3\%
  - $K\pi\pi^0+K3\pi$ consistent with no mixing@ 2.1\%
- CPV results
  - $K\pi\pi^0$: $\left| \frac{p}{q} \right| = 2.2^{+1.9}_{-1.1} \pm 0.1$
  - $K3\pi$: $\left| \frac{p}{q} \right| = 1.1^{+4.0}_{-0.6} \pm 0.1
Dalitz plot analysis of $D^0(t) \rightarrow K_S \pi^+ \pi^-$

- D. M. Asner et al. (CLEO), PRD 72, 012001 (2005): (9 1/fb) 5299 events
- H. Muramatsu et al. (CLEO), PRL 89, 251802 (2002)

• Full time-dependent fit to Dalitz plot

$$\langle K_S^0 \pi^+ \pi^- | H | D^0(t) \rangle = \frac{1}{2p} \left( \langle K_S^0 \pi^+ \pi^- | H | D_1(t) \rangle + \langle K_S^0 \pi^+ \pi^- | H | D_2(t) \rangle \right)$$

$$\equiv A_1 e^{-(\Gamma_1/2 + im_1)t} + A_2 e^{-(\Gamma_2/2 + im_2)t}$$

$$R(D^0(t) \rightarrow K_S^0 \pi^+ \pi^-) = |A_1|^2 e^{-\Gamma(1+y)t} + |A_2|^2 e^{-\Gamma(1-y)t} + 2 \left[ \text{Re}(A_1 A_2^*) \cos(xt) - \text{Im}(A_1 A_2^*) \sin(xt) \right]$$

$$A_n \propto \sum_j a_j e^{i\delta_j} A^j$$

Note: Depends linearly on $y$ and $x$  
$\Rightarrow$ First sensitivity to the sign of $x$
Dalitz plot analysis of $D^0(t)\rightarrow K_S\pi^+\pi^-$

- Full time-dependent fit to Dalitz plot

Analysis Technique
- Select $K_S\pi^+\pi^-$ final state consistent with $M(D^0)$
- Require $D^{*\pm}\rightarrow D^0\pi^\pm$ to determine production flavor
- Do unbinned ML fit to $D_t$ and Dalitz plot variable $m^2(K_S\pi^+), m^2(K_S\pi^-)$
- 11 intermediate states:
  - $K^*(892)^{\pm}, K_0(1430)^{\mp}, K_2(1430)^{\pm}, K^*(1680)^{\mp}$
  - $K_{S\rho}, K_{S\omega}$
  - $K_{Sf_0}(980), K_{Sf_0}(1370), K_{Sf_2}(1270)$
  - $K^*(892)^{\pm}$
  - Non-resonant
- Also CPV search at amplitude level
  - D. Asner et al. (CLEO) PRD 70, 091101 (2004)
  - CPV limits (95% C.L.) range from $3.5\times10^{-4}$ to $28.4\times10^{-4}$
**CP eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>untagged events</th>
<th>tagged events</th>
<th>$\langle \sigma_t \rangle$</th>
</tr>
</thead>
<tbody>
<tr>
<td>E791, PRL 83, 32 (1999)</td>
<td>3200</td>
<td>16532</td>
<td>&lt;40 fs</td>
</tr>
<tr>
<td>CLEO, PRD 65, 092001 (2002)</td>
<td>18306</td>
<td>215 fs</td>
<td></td>
</tr>
<tr>
<td>Belle, PRL 88, 162001 (2002)</td>
<td>145826</td>
<td>38933</td>
<td>160 fs</td>
</tr>
<tr>
<td>BABAR, PRL 91, 121801 (2003)</td>
<td></td>
<td>36480</td>
<td>180 fs</td>
</tr>
<tr>
<td>Belle, Lepton Photon 2004</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**BABAR**

$$y = \left(0.8 \pm 0.4^{+0.5}_{-0.4}\right)\%$$

$$\Delta Y = (-0.8 \pm 0.6 \pm 0.2)\%$$

**PDG06**

$$y = (0.7 \pm 0.5)\%$$

$$\Delta Y = (-0.5 \pm 0.5)\%$$

---

**Yields**

- Reconstructed Mass
- Decay Time
**CLEO-c & D Tagging**

**e^+e^- → ψ(3770) → DD**

Pure DD final state, no additional particles (E_D = E_{beam}). Low particle multiplicity ~ 5-6 charged particles/event. Good coverage to reconstruct ν in semileptonic decays. Pure J^{PC} = 1^- initial state - flavor tags (K^-π^+), CP tags (K^-K^+, K_Sπ^0), Semileptonic (Xeν).

**Targeted Analyses - Double Tags**
- **Mixing (x^2+y^2):** DD → (K^-π^+)^2, (K^-π^+)^2
- **cosδ:** Double Tag Events: K^-π^+ vs CP±
- **Charm Mixing (y):** FlavorTag vs CP±
- **DCS:** Wrong sign decay K^-π^+ vs K^-l^+ν

**Comprehensive Analysis - ST & DT**
Combined analysis to extract mixing parameters, DCS, strong phase & charm hadronic branching fractions.

**Mixing Analyses**

Charm Mixing, DCS, & cosδ impact naïve interpretation of branching fractions.

Introduction: Quantum Correlations

\[ e^+ e^- \rightarrow \gamma^* \rightarrow D^0 \bar{D}^0 \]

- The Quantum Correlation Analysis (TQCA)
- Due to quantum correlation between \( D^0 \) and \( \bar{D}^0 \), not all final states allowed.
- Two paths to \( K^- \pi^+ \) vs \( K^+ \pi^- \) interfere and thus the rate is sensitive to DCS & strong phase
- Time integrated rate depends on both \( \cos \delta_{D \rightarrow K\pi} \) and mixing parameter \( y = \Delta \Gamma / 2 \Gamma \)
- \( K^- \pi^+ \) vs \( K^- \pi^+ \) forbidden without D mixing
Introduction: Quantum Correlations

\[ e^+e^- \rightarrow \gamma^* \rightarrow D^0\overline{D^0} \]

\[ C = -1 \]

- \( K^-\pi^+ \) vs semileptonic measures isolated decay rate and tags flavor of decaying D
- Different sensitivity to mixing vs DCSD
- D decays to CP eigenstates also interfere and opposite semileptonics to get isolated rate, flavor tags for yet another dependence on \( y \) and strong phase
- CP eigenstate vs CP eigenstate shows maximal correlation
## Single Tag & Double Tag Rates

<table>
<thead>
<tr>
<th></th>
<th>$f$</th>
<th>$l^+$</th>
<th>$CP^+$</th>
<th>$CP^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f$</td>
<td>$R_M/r^2$</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$\bar{f}$</td>
<td>$1+r^2(2-(2\cos\delta)^2)$</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$l^-$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$CP^+$</td>
<td>$1+r(2\cos\delta)$</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>$CP^-$</td>
<td>$1-r(2\cos\delta)$</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$X$</td>
<td>$1+ry(2\cos\delta)$</td>
<td>1</td>
<td>1-y</td>
<td>1+y</td>
</tr>
</tbody>
</table>

And measure branching fractions simultaneously.
Data clearly favors QC interpretation showing constructive and destructive interference and no effect as predicted.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>CLEO-c TQCA</th>
<th>PDG or CLEO-c</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma$</td>
<td>$-0.057 \pm 0.066 \pm ?$</td>
<td>$0.008 \pm 0.005$</td>
</tr>
<tr>
<td>$r^2$</td>
<td>$-0.028 \pm 0.069 \pm ?$</td>
<td>$(3.74 \pm 0.18) \times 10^{-3}$</td>
</tr>
<tr>
<td>$r (2 \cos \delta_{D \to K\pi})$</td>
<td>$0.130 \pm 0.082 \pm ?$</td>
<td></td>
</tr>
<tr>
<td>$R_M$</td>
<td>$(1.74 \pm 1.47 \pm ?) \times 10^{-3}$</td>
<td>$&lt; \sim 1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$B(D \to K\pi)$</td>
<td>$(3.80 \pm 0.029 \pm ?)%$</td>
<td>$(3.91 \pm 0.12)%$</td>
</tr>
<tr>
<td>$B(D \to KK)$</td>
<td>$(0.357 \pm 0.029 \pm ?)%$</td>
<td>$(0.389 \pm 0.012)%$</td>
</tr>
<tr>
<td>$B(D \to \pi\pi)$</td>
<td>$(0.125 \pm 0.011 \pm ?)%$</td>
<td>$(0.138 \pm 0.005)%$</td>
</tr>
<tr>
<td>$B(D \to K_s\pi^0\pi^0)$</td>
<td>$(0.932 \pm 0.087 \pm ?)%$</td>
<td>$(0.89 \pm 0.41)%$</td>
</tr>
<tr>
<td>$B(D \to K_s\pi^0)$</td>
<td>$(1.27 \pm 0.09 \pm ?)%$</td>
<td>$(1.55 \pm 0.12)%$</td>
</tr>
<tr>
<td>$B(D^0 \to X_{e\nu})$</td>
<td>$(6.21 \pm 0.42 \pm ?)%$</td>
<td>$(6.46 \pm 0.21)%$</td>
</tr>
</tbody>
</table>

Fitted $r^2$ unphysical. If constrained to WA, $\cos \delta = 1.08 \pm 0.66 \pm ?$. 

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TQCA @ CLEO-c Summary

- With correlated $D^0D^0$ system, probe mixing & DCSD in time-integrated yields with double tag technique similar to hadronic BF analysis.
- Simultaneously fit for:
  - Hadronic/semileptonic/CP eigenstate branching fractions
  - Mixing parameters ($x$ & $y$) and DCSD parameters ($r$ & $\delta$).
- Ultimate sensitivity with projected CLEO-c data set
  - $y \pm 0.012$, $x^2 \pm 0.0006$, $\cos\delta_{D\rightarrow K\pi} \pm 0.13$, $R_M < \text{few } 10^{-4}$
  - $x(\sin\delta_{D\rightarrow K\pi}) \pm 0.024$ - Needs $C=+1$ initial state from DD$\gamma$ & DD$\gamma\pi^0$ from 4170 MeV
- TQCA currently limited by # of CP tags - working to add more
  - Add $D^0 \rightarrow K^0_S\omega$, $K^0_S\eta$, $K^0_S\eta'$, $K^0_S\phi$
  - Add $D^0 \rightarrow K^0_S\pi^+\pi^-$ with Dalitz plot fits
  - Add $D^0 \rightarrow K^0_L\pi^0$, etc..
- Other potential additions include
  - WS $e^{-}$ vs $K^{-}\pi^{+}$
  - Add 4170 data (320 1/pb in hand)

For winter conferences will update 281 1/pb to include $D^0 \rightarrow K^0_S\omega$, $K^0_S\eta$ (70% more CP- tags) and $D^0 \rightarrow K^0_L\pi^0$ vs. $\{K\pi, K^0_S\pi^0, K^0_S\eta, K^0_S\omega\}$.
Expect $\sigma(y)-0.02$ and $\sigma(\cos\delta)-0.3$

- Preliminary determination of $y$ and first measurement of $\delta(K\pi)$.
  - $C=+1$ fraction $< 0.06\pm 0.05\pm$ on $\psi(3770)$
- Systematic uncertainties being studied (<statistical error)
Summary of Mixing Results

Full time-dependent Dalitz plot of $D^0 \rightarrow K_{S\pi\pi}$ from Belle (in progress) & BaBar would be a nice addition. Expect twice the sensitivity per Luminosity as BELLE ($K\pi\pi$) or BaBar ($K\pi\pi^0+K3\pi$).

Need precision $\cos \delta$ measurement (CLEO-c)
So that all limits can be expressed in $x$ vs $y$
Conclusions

• No mixing or CPV in observed charm sector
• Experiments approaching interesting sensitivity, $10^{-3}$ for both mixing & CPV searches
• 20 $1/fb$ at 3770 MeV at BESIII will have sensitivity to SM SCS CPV
• CPV in CF, DCS is zero in SM - window for NP
• CPV in mixing is small in SM - window for NP
• 20 $1/fb$ at BES III & 2 $1/ab$ at B-factories will attain $10^{-3}$ sensitivity to $x,y$
• Reach of LHC-b is understudy - see talk by Raluca Muresan
• Best bet to observe D mixing is at a Super B factory
Final Comment

• Several times I have been asked what I make of the mixing “signals” at Belle & Babar

• My answer is “there has been a 2σ mixing signal for a decade!”

- E791 (1997) $R_M = (0.21\pm0.09\pm0.02)\%$ $D^0 \rightarrow K\pi,K3\pi$
- CLEO (2000) $y' = (-2.5\pm1.5\pm0.3)\%$ $D^0 \rightarrow K\pi$
- FOCUS (2002) $y = (3.4\pm1.4\pm0.7)\%$ $D^0 \rightarrow KK$
- BELLE (2006) $x'^2 = y' = 0 @ 3.1% \text{ C.L.}$ $D^0 \rightarrow K\pi$
- BABAR (2006) $R_M = 0 @ 4.5\%, 4.3\% \text{ C.L.}$ $D^0 \rightarrow K\pi\pi^0,K3\pi$