Charm mixing in the Standard Model and Beyond

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Introduction: identifying New Physics

The LHC ring is 27km in circumference

How can SLAC and other older machines help with New Physics searches?
Charm transitions serve as excellent probes of New Physics

1. Processes forbidden in the Standard Model to all orders
   Examples:
   \[ D^0 \rightarrow p^+ \pi^- \nu \]

2. Processes forbidden in the Standard Model at tree level
   Examples:
   \[ D^0 - \bar{D}^0 \text{ mixing, } D \rightarrow X\gamma, D \rightarrow X\nu\bar{\nu} \]

3. Processes allowed in the Standard Model
   Examples: relations, valid in the SM, but not necessarily in general
   \[ \text{CKM triangle relations} \]
Introduction: mixing

\[ \Delta Q=2: \] only at one loop in the Standard Model: possible new physics particles in the loop

\[ \Delta Q=2 \] interaction couples dynamics of \( D^0 \) and \( \overline{D}^0 \)

\[ |D(t)\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t) |D^0\rangle + b(t) |\overline{D}^0\rangle \]

- Time-dependence: coupled Schrödinger equations

\[ i \frac{\partial}{\partial t} |D(t)\rangle = \left( M - \frac{i}{2} \Gamma \right) |D(t)\rangle = \begin{bmatrix} A \\ q^2 \end{bmatrix} \begin{bmatrix} p \\ A \end{bmatrix} |D(t)\rangle \]

- Diagonalize: mass eigenstates \( \neq \) flavor eigenstates

\[ |D_{1,2}\rangle = p |D^0\rangle \pm q |\overline{D}^0\rangle \]

Mass and lifetime differences of mass eigenstates:

\[ x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma} \]
**Introduction: mixing**

\[ \Delta Q = 2: \text{ only at one loop in the Standard Model:} \]

\[ \text{possible new physics particles in the loop} \]

\[ \Delta Q = 2 \text{ interaction couples dynamics of } D^0 \text{ and } \overline{D}^0 \]

\[ |D(t)\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t) |D^0\rangle + b(t) |\overline{D}^0\rangle \]

\[ \text{Time-dependence: coupled Schrödinger equations} \]

\[ i \frac{\partial}{\partial t} |D(t)\rangle = \left( M - i \frac{\Gamma}{2} \right) |D(t)\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix} |D(t)\rangle \]

\[ \text{Diagonalize: mass eigenstates} \neq \text{flavor eigenstates} \]

\[ \text{No CPV:} \quad |D_{1,2}\rangle \Rightarrow |D_{CP \pm}\rangle = \frac{1}{\sqrt{2}} \left[ |D^0\rangle \pm |\overline{D}^0\rangle \right] \]

**Mass and lifetime differences of mass eigenstates:**

\[ x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2 \Gamma} \]
### Introduction: why do we care?

#### $D^0 - D^0$ mixing

- Intermediate down-type quarks
- SM: b-quark contribution is negligible due to $V_{cd}V_{ub}^*$
  - \( \text{rate} \propto f(m_s) - f(m_d) \) (zero in the SU(3) limit)


2nd order effect!!!

1. Sensitive to long distance QCD
2. Small in the SM: New Physics! (must know SM x and y)

#### $B^0 - B^0$ mixing

- Intermediate up-type quarks
- SM: t-quark contribution is dominant
  - \( \text{rate} \propto m_t^2 \) (expected to be large)

1. Computable in QCD (*)
2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators
How would new physics affect mixing?

- Look again at time development:

\[ i \frac{\partial}{\partial t} |D(t)\rangle = \left( M - \frac{i}{2} \Gamma \right) |D(t)\rangle = \begin{bmatrix} A \\ p^2 \\ q^2 \end{bmatrix} |D(t)\rangle \]

- Expand \( D^0 - D^0 \) mass matrix:

\[
M - \frac{i}{2} \Gamma \right)_{ij} = m_D^{(0)} \delta_{ij} + \frac{1}{2m_D} \langle D_i^0 | H_w^{\Delta C=2} | D_j^0 \rangle + \frac{1}{2m_D} \sum_I \frac{\langle D_i^0 | H_w^{\Delta C=1} | I \rangle \langle I | H_w^{\Delta C=1} | D_j^0 \rangle}{m_D^2 - m_I^2 + i\varepsilon}
\]

Local operator, affects \( x \), possible \( \Delta C=2 \) new physics

Real intermediate states, affect both \( x \) and \( y \) ⇒ SM, \( \Delta C=1 \) NP!

1. \( x >> y \) : signal for New Physics?

\( x \approx y \) : Standard Model?

2. CP violation in mixing/decay

new CP-violating phase \( \phi \)
**Experimental constraints on mixing**

Idea: look for a wrong-sign final state

1. **Time-dependent or time-integrated semileptonic analysis**

   \[ \text{rate} \propto x^2 + y^2 \]

   Quadratic in x,y: not so sensitive

2. **Time-dependent \( D^0(t) \rightarrow K^+ K^- \) analysis (lifetime difference)**

   \[ y_{CP} = \frac{\tau(D \rightarrow \pi^+ K^-)}{\tau(D \rightarrow K^+ K^-)} - 1 = y \cos \phi - x \sin \phi \frac{1 - R_m}{2} \]

3. **Time-dependent \( D^0(t) \rightarrow K^+ \pi^- \) analysis**

   \[
   \Gamma[D^0(t) \rightarrow K^+ \pi^-] = e^{-\Gamma t} |A_{K^+ \pi^-}|^2 \left[ R + \sqrt{R R_m} (y' \cos \phi - x' \sin \phi) \Gamma t + \frac{R^2_m}{4} (y^2 + x^2)(\Gamma t)^2 \right]
   \]

   \[
   R^2_m = \left( \frac{q}{p} \right)^2, \quad x' = x \cos \delta + y \sin \delta, \quad y' = y \cos \delta - x \sin \delta
   \]
Recent results from BaBar

- Time-dependent $D \rightarrow K\pi$ analysis
  \[ \Gamma_{ws}(t) = e^{-\Gamma t} \left( R_D + y'\sqrt{R_D} \Gamma t + \left( \frac{x^2 + y'^2}{4} \right)(\Gamma t)^2 \right) \]
- No evidence for CP-violation
- Accounting for systematic errors, the no-mixing point is at 3.9-sigma contour

Evidence for $D\bar{D}$ mixing!

\[ R_b: (3.03 \pm 0.16 \pm 0.10) \times 10^{-3} \]
\[ x^2: (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3} \]
\[ y': (9.7 \pm 4.4 \pm 3.1) \times 10^{-3} \]
Recent results from Belle

- Time-dependent $D \to KK/\pi\pi$ analysis

$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\Delta \Gamma}{2 \Gamma}$$

$$CPV : A_\Gamma = \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\bar{D}^0 \to K^-K^+)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\bar{D}^0 \to K^-K^+)}$$

- Belle data

<table>
<thead>
<tr>
<th></th>
<th>$y_{CP}$ (%)</th>
<th>$A_\Gamma$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$KK$</td>
<td>1.25±0.39±0.28</td>
<td>0.15±0.34±0.16</td>
</tr>
<tr>
<td>$\pi\pi$</td>
<td>1.44±0.57±0.42</td>
<td>-0.28±0.52±0.30</td>
</tr>
<tr>
<td>$KK + \pi\pi$</td>
<td>1.31±0.32±0.25</td>
<td>0.01±0.30±0.15</td>
</tr>
</tbody>
</table>

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

- No evidence for $CP$-violation

**Evidence for $D\bar{D}$ mixing!**
Recent results: summary

• BaBar and Belle results

\[ y_D' = (0.97 \pm 0.44 \pm 0.31) \cdot 10^{-2} \quad \text{(BaBar)}, \]
\[ y_D^{(CP)} = (1.31 \pm 0.32 \pm 0.25) \cdot 10^{-2} \quad \text{(Belle)}. \]

Similar results from CDF

• Belle Dalitz plot result \((D^0 \rightarrow K_S \pi^+ \pi^-)\)

\[ x_D = (0.80 \pm 0.29 \pm 0.17) \cdot 10^{-2}, \]
\[ y_D = (0.33 \pm 0.24 \pm 0.15) \cdot 10^{-2}. \]

• Preliminary HFAG numbers

\[ x_D = 8.5^{+3.2}_{-3.1} \cdot 10^{-3}, \]
\[ y_D = 7.1^{+2.0}_{-2.1} \cdot 10^{-3} \quad \text{(cos} \delta_{K\pi} = 1.09 \pm 0.66) \]
Mixing: theoretical estimates

Updated predictions
A.A.P. hep-ph/0311371

New Physics mixing predictions

Standard Model mixing predictions

- Theoretical predictions are all over the board... so:
- Can $x, y \sim 1\%$ be a SM signal?
- What is the relationship between $x$ and $y$ ($x \sim y, x > y, x < y$?) in the Standard Model?

- $x$ from new physics
- $y$ from Standard Model
- $\Delta$ from Standard Model

(papers from SPIRES)
Theoretical estimates I

A. Short distance gives a tiny contribution

\[ z = \frac{m_s^2}{m_c^2} \]

... as can be seen from a "straightforward computation"...

\[ y_{LO}^{(z^3)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3 \pi \Gamma_D} \xi_3^3 z^3 \left( C_2^2 - 2 C_1 C_2 - 3 C_1^2 \right) \left[ B_D - \frac{5}{2} B_D^{(S)} \right] \propto m_s^6 \Lambda^{-6} \]

\[ x_{LO}^{(z^2)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3 \pi^2 \Gamma_D} \xi_2^2 z^2 \left[ C_2^2 B_D - \frac{5}{4} (C_2^2 - 2 C_1 C_2 - 3 C_1^2) B_D^{(S)} \right] \propto m_s^4 \Lambda^{-4} \]

with \( \langle D^0 \left| \bar{u} \Gamma_\mu c \bar{u} \Gamma_\mu c \right| D^0 \rangle = \frac{1 + N_c}{N_c} \frac{4 F_D^2 m_D^2}{2 m_D} B_D, \text{ etc.} \)

Notice, however, that at NLO in QCD \( (x_{NLO}, y_{NLO}) \gg (x_{LO}, y_{LO}) \):

\[ y_{NLO}^{(2)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3 \pi \Gamma_D} \xi_2^2 \frac{\alpha_s}{4\pi} \frac{z^2}{2} \left( B_D - \frac{77}{6} - \frac{8\pi^2}{9} \right) C_2^2 + 14 C_1 C_2 + 8 C_1^2 \]
\[ \quad - \frac{5}{2} B_D^{(S)} \left( \frac{8\pi^2}{9} - \frac{25}{3} \right) C_2^2 + 20 C_1 C_2 + 32 C_1^2 \]

Example of NLO contribution

Similar for \( x \) (trust me) E. Golowich and A.A.P. Phys. Lett. B625 (2005) 53
Theoretical estimates I

A. Short distance + “subleading corrections” (in \{m_s, 1/m_c\} expansion):

\begin{align*}
y_{sd}^{(6)} &\propto \frac{(m_s^2 - m_d^2)^2}{m_c^2} \frac{m_s^2 + m_d^2}{m_c^2} \mu_{had}^{-2} \propto m_s^6 \Lambda^{-6} \\
x_{sd}^{(6)} &\propto \frac{(m_s^2 - m_d^2)^2}{m_c^2} \mu_{had}^{-2} \propto m_s^4 \Lambda^{-4}
\end{align*}

...subleading effects?

\begin{align*}
y_{sd}^{(9)} &\propto m_s^3 \Lambda^{-3} \\
x_{sd}^{(9)} &\propto m_s^3 \Lambda^{-3}
\end{align*}

\begin{align*}
y_{sd}^{(12)} &\propto \beta_0 \alpha_s^2(\mu)m_s^2 \Lambda^{-2} \\
x_{sd}^{(12)} &\propto \alpha_s(\mu)m_s^2 \Lambda^{-2}
\end{align*}

Leading contribution!!!

4 unknown matrix elements

15 unknown matrix elements

Twenty-something unknown matrix elements

Guestimate: \ x \sim y \sim 10^{-3} \ ?
Resume: model-independent computation with model-dependent result
Theoretical estimates II

B. Long distance physics dominates the dynamics...

\[ y = \frac{1}{2\Gamma} \sum \rho_n \left[ \langle D^0 \mid H_{w}^{A_{C}=1} \mid n \rangle \langle n \mid H_{w}^{A_{C}=1} \mid \overline{D}^0 \rangle + \langle \overline{D}^0 \mid H_{w}^{A_{C}=1} \mid n \rangle \langle n \mid H_{w}^{A_{C}=1} \mid D^0 \rangle \right] \]

... with \( n \) being all states to which \( D^0 \) and \( \overline{D}^0 \) can decay. Consider \( \pi\pi, \pi K, K K \) intermediate states as an example...

\[ y_2 = Br \left( D^0 \rightarrow K^+ K^- \right) + Br \left( D^0 \rightarrow \pi^+ \pi^- \right) \]

\[ -2 \cos \delta \sqrt{Br \left( D^0 \rightarrow K^+ \pi^- \right) Br \left( D^0 \rightarrow \pi^+ K^- \right)} \]

Cancellation expected!

If every \( Br \) is known up to \( O(1\%) \) the result is expected to be \( O(1\%) \)!

The result here is a series of large numbers with alternating signs, \( SU(3) \) forces 0

\[ x = ? \text{ Extremely hard…} \]

Need to “repackage” the analysis: look at the complete multiplet contribution

\[ m_c \text{ is NOT large} !!! \]
SU(3) and phase space

• “Repackage” the analysis: look at the complete multiplet contribution

\[ y = \sum_{F_R} y_{F,R} \text{Br} \left( D^0 \rightarrow F_R \right) \sim \sum_{F_R} y_{F,R} \frac{1}{\Gamma} \sum_{n \in F_R} \Gamma \left( D^0 \rightarrow n \right) \]

- y for each SU(3) multiplet
- Each is \( \theta \) in SU(3)

• Does it help? If only phase space is taken into account: no (mild) model dependence

\[ y_{F,R} = \frac{\sum_{n \in F_R} \langle \bar{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \langle D^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle} \]

if CP is conserved

\[ = \frac{\sum_{n \in F_R} \langle \bar{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \Gamma \left( D^0 \rightarrow n \right)} \]

Can consistently compute
Example: PP intermediate states

- $n=PP$ transforms as $(8 \times 8)_s = 27 + 8 + 1$, take 8 as an example:

Numerator:

\[
A_{N,8} = |A_o|^2 S_1^2 \left[ + \frac{1}{2} \Phi (\eta, \eta) + \frac{1}{2} \Phi (\pi^0, \pi^0) + \frac{1}{3} \Phi (\eta, \pi^0) + \Phi (\pi^+, \pi^-) - \Phi (\bar{K}^0, \pi^0) + \Phi (K^+, K^-) - \frac{1}{6} \Phi (\eta, K^0) - \frac{1}{6} \Phi (\eta, \bar{K}^0) - \Phi (K^+, \pi^-) - \Phi (K^-, \pi^+) \right]
\]

Denominator:

\[
A_{D,8} = |A_o|^2 \left[ + \frac{1}{6} \Phi (\eta, K^0) + \Phi (K^+, \pi^-) + \frac{1}{2} \Phi (K^0, \pi^0) + O (S_1^2) \right]
\]

- This gives a calculable effect!

\[
y_{2,8} = \frac{A_{N,8}}{A_{D,8}} = -0.038 S_1^2 = -1.8 \times 10^{-4}
\]

1. Repeat for other states
2. Multiply by $Br_{F_i}$ to get $y$
Results

- Product is naturally $O(1\%)$
- No (symmetry-enforced) cancellations
- Disp relation: compute $x, y \sim 1\%$ is expected in the Standard Model

<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>8</td>
<td>-0.0038</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>-0.00071</td>
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<tr>
<td>$PV$</td>
<td>8</td>
<td>0.031</td>
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<tr>
<td></td>
<td>27</td>
<td>0.032</td>
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<tr>
<td></td>
<td>10</td>
<td>0.020</td>
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<tr>
<td></td>
<td>27</td>
<td>0.016</td>
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<td>$(VV)_s$-wave</td>
<td>8</td>
<td>-0.081</td>
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<tr>
<td></td>
<td>27</td>
<td>-0.061</td>
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<tr>
<td>$(VV)_p$-wave</td>
<td>8</td>
<td>-0.10</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>-0.14</td>
</tr>
<tr>
<td>$(VV)_d$-wave</td>
<td>8</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>27</td>
<td>0.57</td>
</tr>
<tr>
<td>$(3P)_{s}$-wave</td>
<td>8, 27</td>
<td>-0.48, -0.39</td>
</tr>
<tr>
<td>$(3P)_{p}$-wave</td>
<td>8, 27</td>
<td>-1.13, -0.07</td>
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<tr>
<td>$(3P)_{f}$orm-factor</td>
<td>8, 27</td>
<td>-0.44, -0.13</td>
</tr>
<tr>
<td>$4P$</td>
<td>8</td>
<td>3.3</td>
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<tr>
<td></td>
<td>27</td>
<td>2.2</td>
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</table>

<table>
<thead>
<tr>
<th>Final state</th>
<th>fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$PP$</td>
<td>5%</td>
</tr>
<tr>
<td>$PV$</td>
<td>10%</td>
</tr>
<tr>
<td>$(VV)_s$-wave</td>
<td>5%</td>
</tr>
<tr>
<td>$(VV)_d$-wave</td>
<td>5%</td>
</tr>
<tr>
<td>$3P$</td>
<td>5%</td>
</tr>
<tr>
<td>$4P$</td>
<td>10%</td>
</tr>
</tbody>
</table>

Resume: a contribution to $x$ and $y$ of the order of 1% is natural in the SM

What about New Physics?
New Physics in $x$ and $y$

- Local $\Delta C=2$ piece of the mass matrix affects $x$:

\[
\left(M - \frac{i}{2} \Gamma\right)_{ij} = m_D^{(0)} \delta_{ij} + \frac{1}{2m_D} \left\langle D_i^0 \left| H^{\Delta C=2}_w \right| D_j^0 \right\rangle + \frac{1}{2m_D} \sum_i \left\langle D_i^0 \left| H^{\Delta C=1}_w \right| I \right\rangle \left\langle I \left| H^{\Delta C=1}_w \right| D_j^0 \right\rangle \delta_{ij} \n\]

- Double insertion of $\Delta C=1$ affects $x$ and $y$:

Amplitude $A_n = \left\langle D^0 \left| (H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}) \right| n \right\rangle \equiv A_n^{SM} + A_n^{NP}$

Suppose $\left| A_n^{NP} \right| / \left| A_n^{SM} \right| \sim O(\text{exp. uncertainty}) \leq 10\%$

Example:

\[
y = \frac{1}{2\Gamma} \sum_n \rho_n \left( \overline{A}_n^{SM} + \overline{A}_n^{NP} \right) \left( A_n^{SM} + A_n^{NP} \right) \approx \frac{1}{2\Gamma} \sum_n \rho_n \overline{A}_n^{SM} A_n^{SM} + \frac{1}{2\Gamma} \sum_n \rho_n \left( \overline{A}_n^{SM} A_n^{NP} + \overline{A}_n^{NP} A_n^{SM} \right)
\]

Zero in the SU(3) limit

Can be significant!!!

Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002
2nd order effect!!!
Global Analysis of New Physics: $\Delta C=1$

- Let's write the most general $\Delta C=1$ Hamiltonian

$$\mathcal{H}^{\Delta C=1}_{NP} = \sum_{q, q'} D_{qq'} [ \bar{c}_1(\mu) Q_1 + \bar{c}_2(\mu) Q_2 ],$$

$$Q_1 = \bar{u}_i \bar{\Gamma}_1 q_j \bar{\Gamma}_2 c_i, \quad Q_2 = \bar{u}_i \bar{\Gamma}_1 q_j \bar{\Gamma}_2 c_j,$$

Only light on-shell (propagating) quarks affect $\Delta \Gamma$:

$$y = - \frac{4\sqrt{2} G_F}{M_D \Gamma_D} \sum_{q, q'} V_{cq'}^* V_{uq} D_{qq'} (K_1 \delta_{i k} \delta_{j \ell} + K_2 \delta_{i \ell} \delta_{j k})$$

$$\times \sum_{\alpha=1}^5 I_{\alpha}(x, x') \langle \bar{D}^0 | O_{ijk}^\ell | D^0 \rangle,$$

with $K_1 = [C_1 \bar{C}_1 N_c + (C_1 \bar{C}_2 + \bar{C}_1 C_2)], \quad K_2 = C_2 \bar{C}_2$ and

This is the master formula for NP contribution to lifetime differences in heavy mesons

$$O_{i j k}^\ell = \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma_\gamma \Gamma_\mu c_i$$

$$O_{i j k}^\ell = \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma_\gamma \Gamma_\mu c_i$$

$$O_{i j k}^\ell = \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma_\gamma \Gamma_\mu c_i$$

$$O_{i j k}^\ell = \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma_\gamma \Gamma_\mu c_i$$

$$O_{i j k}^\ell = \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma_\gamma \Gamma_\mu c_i,$$
Global Analysis of New Physics: $\Delta C=1$

- Some examples of New Physics contributions

<table>
<thead>
<tr>
<th>Model</th>
<th>$y_D$</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPV-SUSY</td>
<td>$6 \times 10^{-6}$</td>
<td>Squark Exch.</td>
</tr>
<tr>
<td></td>
<td>$-4 \times 10^{-2}$</td>
<td>Slepton Exch.</td>
</tr>
<tr>
<td>Left-right</td>
<td>$-5 \times 10^{-6}$</td>
<td>‘Manifest’.</td>
</tr>
<tr>
<td></td>
<td>$-8.8 \times 10^{-5}$</td>
<td>‘Nonmanifest’.</td>
</tr>
<tr>
<td>Multi-Higgs</td>
<td>$2 \times 10^{-10}$</td>
<td>Charged Higgs</td>
</tr>
<tr>
<td>Extra Quarks</td>
<td>$10^{-8}$</td>
<td>Not Little Higgs</td>
</tr>
</tbody>
</table>

For considered models, the results are smaller than observed mixing rates

E. Golowich, S. Pakvasa, A.A.P.

A.A.P. and G. Yeghiyan
Multitude of various models of New Physics can affect $x$

- $\Delta C = 2$
- $\mu \geq 1 \text{ TeV}$
- $\mu \leq 1 \text{ TeV}$
- $\mu \sim 1 \text{ GeV}$
Global Analysis of New Physics: $\Delta C=2$

- Multitude of various models of New Physics can affect $x$

$\mu \geq 1\text{TeV}$
$\mu \leq 1\text{TeV}$
$\mu \sim 1\text{GeV}$

E. Golowich, J. Hewett, S. Pakvasa and A.A.P.

"Four amigos"
Global Analysis of New Physics: $\Delta C=2$

Let’s write the most general $\Delta C=2$ Hamiltonian

$$\langle f|\mathcal{H}_{NP}|i\rangle = G \sum_{i=1} C_i(\mu) \langle f|Q_i|i\rangle(\mu)$$

... with the following set of 8 independent operators...

$$Q_1 = (\bar{u}_L \gamma_\mu c_L)(\bar{u}_L \gamma^\mu c_L), \quad Q_5 = (\bar{u}_R \sigma_{\mu\nu} c_L)(\bar{u}_R \sigma^{\mu\nu} c_L),$$

$$Q_2 = (\bar{u}_L \gamma_\mu c_L)(\bar{u}_R \gamma^\mu c_R), \quad Q_6 = (\bar{u}_R \gamma_\mu c_R)(\bar{u}_R \gamma^\mu c_R),$$

$$Q_3 = (\bar{u}_L c_R)(\bar{u}_R c_L), \quad Q_7 = (\bar{u}_L c_R)(\bar{u}_L c_R),$$

$$Q_4 = (\bar{u}_R c_L)(\bar{u}_R c_L), \quad Q_8 = (\bar{u}_L \sigma_{\mu\nu} c_R)(\bar{u}_L \sigma^{\mu\nu} c_R).$$

RG-running relate $C_i(\mu)$ at NP scale to the scale of $\mu \sim 1$ GeV, where ME are computed (on the lattice)

$$\frac{d}{d \log \mu} \tilde{C}(\mu) = \tilde{\gamma}^T(\mu)\tilde{C}(\mu)$$

Each model of New Physics provides unique matching condition for $C_i(\Lambda_{NP})$
Resume: New Physics contributions do not suffer from QCD uncertainties as much as SM contributions since they are short-distance dominated.
New Physics in x: lots of extras

- Extra gauge bosons
  Left-right models, horizontal symmetries, etc.
- Extra scalars
  Two-Higgs doublet models, leptoquarks, Higgsless, etc.
- Extra fermions
  4th generation, vector-like quarks, little Higgs, etc.
- Extra dimensions
  Universal extra dimensions, split fermions, warped ED, etc.
- Extra symmetries
  SUSY: MSSM, alignment models, split SUSY, etc.

Total: 21 models considered
Consider an example: FCNC $Z^0$-boson appears in models with extra vector-like quarks little Higgs models

1. Integrate out $Z$: for $\mu < M_Z$ get

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_w M_Z^2} (\lambda_{uc})^2 \bar{u}_L \gamma^\mu c_L \bar{u}_L \gamma^\mu c_L$$

2. Perform RG running to $\mu < m_c$ (in general: operator mixing)

$$\mathcal{H}_{2/3} = \frac{g^2}{8 \cos^2 \theta_w M_Z^2} (\lambda_{uc})^2 r_1(m_c, M_Z) Q_1$$

3. Compute relevant matrix elements and $x_D$

$$x_D^{(2/3)} = \frac{2 G_F f_D^2 M_D}{3 \sqrt{2} \Gamma_D} B_D (\lambda_{uc})^2 r_1(m_c, M_Z)$$
New Physics in $x$: extra fermions

- **Fourth generation**

$$x_{D}^{(4th)} = \frac{G_{F}^{2}M_{W}^{2}}{6\pi^{2}T_{D}}f_{D}^{2}M_{D}B_{D}\lambda_{V}^{2}S(x_{W}, x_{W})r_{1}(m_{c}, M_{W})$$

- **Vector-like quarks (Q=+2/3)**

$$x_{D}^{(-1/3)} \approx \frac{G_{F}^{2}}{6\pi^{2}T_{D}}f_{D}^{2}B_{D}r_{1}(m_{c}, M_{W})M_{D}M_{W}^{2}(V_{eS}V_{\mu S})^{2}f(x_{S})$$

- **Vector-like quarks (Q=-1/3)**

$$x_{D}^{(2/3)} = \frac{2G_{F}}{3\sqrt{2}T_{D}}(\lambda_{uc})^{2}r_{1}(m_{c}, M_{Z})f_{D}^{2}M_{D}B_{1}$$

$$\lambda_{uc} \equiv -(V_{ud}^{*}V_{cd} + V_{us}^{*}V_{cs} + V_{ub}^{*}V_{cb})$$
New Physics in x: extra vector bosons

- **Generic Z’ models**

\[
x_{D}^{(Z')} = \frac{f_{D}^{2}B_{D}M_{D}}{2\Gamma_{D}M_{Z'}^{2}} \left[ \frac{2}{3} \left( C_{1}(m_{e}) + C_{6}(m_{e}) \right) + C_{2}(m_{e}) \left( -\frac{1}{2} + \frac{\eta}{3} \right) + C_{3}(m_{e}) \left( \frac{1}{12} - \frac{\eta}{2} \right) \right]
\]

- **Family symmetry**

\[
x_{D}^{(FS)} = \frac{2}{3\Gamma_{D}} r_{1}(m_{e}, M) \left( \frac{f_{1}^{2}}{m_{LQ}^{2}} - \frac{f_{2}^{2}}{m_{LQ}^{2}} \right) f_{D}^{2}M_{D}B_{D}
\]

- **Vector leptoquarks**

\[
x_{D}^{(VLQ)} = -\frac{1}{8\pi^{2}m_{LQ}^{2}\Gamma_{D}M_{D}} \left[ (\lambda_{L}(Q_{1}) + \lambda_{R}(Q_{6})) + \frac{10}{9} \frac{m_{e}^{2}}{m_{LQ}^{2}} (\lambda_{L}(Q_{7}) + \lambda_{R}(Q_{4})) \right]
\]

\[= -\frac{f_{D}^{2}M_{D}B_{D}}{12\pi^{2}m_{LQ}^{2}\Gamma_{D}} (\lambda_{L} + \lambda_{R}) \left( 1 + \frac{5\eta}{3} \frac{m_{e}^{2}}{m_{LQ}^{2}} \right),
\]
New Physics in $x$: extra scalars

- 2-Higgs doublet model

\[
x_D^{(2HDM)} = \frac{G_F^2 M_W^2}{6\pi^2 \Gamma_D} f_D^2 M_D B_D r_1(m_c, M_{H^\pm}) \times \sum_{i,j} \lambda_i \lambda_j \left[ \tan^4 \beta A_{HH}(x_i, x_j, x_H) + \tan^2 \beta A_{WH}(x_i, x_j, x_H) \right]
\]

- Flavor-changing neutral Higgs

\[
x_D^{(H)} = \frac{5 f_D^2 M_D B_D}{24 \Gamma_D M_H^2} \left[ \frac{1 - 6\eta}{5} C_3(m_c) + \eta (C_4(m_c) + C_7(m_c)) - \frac{12\eta}{5} (C_5(m_c) + C_8(m_c)) \right]
\]

- Higgsless models

\[
x_D^{(H)} = \frac{f_D^2 M_D B_D}{\Gamma_D} (c_L s_L e_L^2)^2 \frac{g^2}{M^2} \left[ \frac{2}{3} (C_1(m_c) + C_6(m_c)) + C_2(m_c) \left( -\frac{1}{2} + \frac{\eta}{3} \right) \right. \\
\left. + \frac{1}{12} C_3(m_c) \left( 1 - 6\eta \right) \right].
\]
New Physics in x: extra dimensions

- Split fermion models

\[ \omega^{(\text{split})} = \frac{2}{9 \Gamma_D g_s^2 R_c R_s^2 a^2 \Delta y} r_1(m_c, M) |V_{L11}^u V_{L12}^{u*}|^2 f_D^2 M_D B_1 \]

- Warped geometries

\[ \omega^{(\text{RS})} = \frac{g_s^2 f_D^2 B_D M_D}{3 M_T^2 \Gamma_D} \left( \frac{2}{3} \left[ C_1(m_c) + C_6(m_c) \right] - \frac{1}{6} C_2(m_c) - \frac{5}{12} C_3(m_c) \right) \]

+ others...
# Summary: New Physics

- Considered 21 well-established models
- Only 4 models yielded no useful constraints
- Consult paper for explicit constraints

<table>
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<th>Model</th>
<th>Approximate Constraint</th>
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<td>(</td>
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<tr>
<td>(Q = -1/3) Single Quark (Fig. 4)</td>
<td>(a_{1} \cdot m_{S} &lt; 0.27 \text{ (GeV)})</td>
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<tr>
<td>(Q = +2/3) Single Quark (Fig. 6)</td>
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<tr>
<td>Little Higgs</td>
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<td>Generic Z' (Fig. 7)</td>
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<td>Left-Right Symmetric (Fig. 9)</td>
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<td>Scalar Lepotquark Bosons</td>
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<td>Higgsless (Fig. 17)</td>
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<td>Universal Extra Dimensions</td>
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<td>Split Fermion (Fig. 19)</td>
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<td>Warped Geometries (Fig. 21)</td>
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<td>Minimal Supersymmetric Standard (Fig. 23)</td>
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<td>Supersymmetric Alignment</td>
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<td>Supersymmetry with RPV (Fig. 27)</td>
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<tr>
<td>Split Supersymmetry</td>
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<tr>
<td>(M_{Z'}/C &gt; 2.2 \cdot 10^{5} \text{ TeV})</td>
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<tr>
<td>(m_{1}/f &gt; 1.2 \cdot 10^{5} \text{ TeV (with } m_{1}/m_{2} = 0.5)</td>
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<tr>
<td>No constraint</td>
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<tr>
<td>(M_{R} &gt; 1.2 \text{ TeV (} m_{R} = 0.5 \text{ TeV)})</td>
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<tr>
<td>((\Delta m/m_{\tau})/M_{R} &gt; 0.4 \text{ TeV}^{-1})</td>
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<tr>
<td>(M_{Z'}/C &gt; 5.5 (m_{R}/0.1) \text{ TeV})</td>
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<tr>
<td>No constraint</td>
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<tr>
<td>(M_{H}/m_{H} &gt; 0.6 \text{ TeV})</td>
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<tr>
<td>No constraint</td>
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<tr>
<td>(M_{H}/</td>
<td>\Delta m</td>
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<tr>
<td>See entry for RPV SUSY</td>
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<tr>
<td>(M &gt; 100 \text{ TeV})</td>
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<tr>
<td>No constraint</td>
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<tr>
<td>(M/</td>
<td>\Delta m</td>
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<tr>
<td>(M_{1} &gt; 3.5 \text{ TeV})</td>
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<td>(</td>
<td>\delta_{12}^{[\ell R \ell L]}</td>
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<td>(</td>
<td>\delta_{2}^{[\ell L \ell R]}</td>
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<td>(\tilde{m} &gt; 2 \text{ TeV})</td>
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<tr>
<td>(\lambda_{12}^{[\ell R \ell L]}/m_{H} &lt; 1.8 \cdot 10^{-3}/100 \text{ GeV})</td>
<td></td>
</tr>
<tr>
<td>No constraint</td>
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</table>
Conclusions

- **Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC**
  - a combination of bottom/charm sector studies
  - don't forget measurements unique to tau-charm factories
- **Charm provides great opportunities for New Physics studies**
  - unique access to up-type quark sector
  - large available statistics
  - mixing: $x, y = 0$ in the SU(3) limit (as $V_{cb}^* V_{ub}$ is very small)
  - mixing is a second order effect in SU(3) breaking
  - it is conceivable that $y \sim x \sim 1\%$ in the Standard Model
  - large contributions from New Physics are possible
  - out of 21 models studied, 17 yielded competitive constraints
  - additional input to LHC inverse problem
- **Observation of CP-violation in the current round of experiments provide “smoking gun” signals for New Physics**
Additional slides
Questions:

1. Can any model-independent statements be made for $x$ or $y$?

What is the order of SU(3) breaking?
   i.e. if $x, y \propto m_s^n$ what is $n$?

2. Can one claim that $y \sim 1\%$ is natural?
Theoretical expectations

At which order in $\text{SU}(3)_F$ breaking does the effect occur? Group theory?

\[
\langle D^0 | H_w \ H_w | \bar{D}^0 \rangle \Rightarrow \langle 0 | D \ H_w \ H_w \ D | 0 \rangle
\]

is a singlet with $D \rightarrow D_i$ that belongs to $3$ of $\text{SU}(3)_F$ (one light quark)

The $\Delta C=1$ part of $H_W$ is \((q_i c_i q_j q_k)\), i.e. \(3 \times \bar{3} \times \bar{3} = 15 + 6 + \bar{3} + \bar{3} \Rightarrow H_{ij}^{kk}\)

\[
O_{15} = (\bar{s}d)(\bar{u}d) + (\bar{u}c)(\bar{s}d) + s_1(\bar{d}c)(\bar{u}d) + s_1(\bar{u}c)(\bar{d}d) - s_1(\bar{s}c)(\bar{u}s) - s_1(\bar{u}c)(\bar{s}s) - s_1^2(\bar{d}c)(\bar{u}s) - s_1^2(\bar{u}c)(\bar{d}s)
\]

\[
O_6 = (\bar{s}d)(\bar{u}d) - (\bar{u}c)(\bar{s}d) + s_1(\bar{d}c)(\bar{u}d) - s_1(\bar{u}c)(\bar{d}d) - s_1(\bar{s}c)(\bar{u}s) + s_1(\bar{u}c)(\bar{s}s) - s_1^2(\bar{d}c)(\bar{u}s) + s_1^2(\bar{u}c)(\bar{d}s)
\]

Introduce $\text{SU}(3)$ breaking via the quark mass operator $M_{ij} = \text{diag} \ (m_u, m_d, m_s)$

All nonzero matrix elements built of $D_i, H_{ij}^k, M_{ij}^i$ must be $\text{SU}(3)$ singlets
Theoretical expectations

\[ \langle D^0 | H_w H_w | D^0 \rangle \Rightarrow \langle 0 | D H_w H_w D | 0 \rangle \]

\[ DD \Rightarrow D_6 \]

\[ H_w H_w \Rightarrow O_{60} + O_{42} + O_{15}. \]

1. No 6 in the decomposition of \( H_w H_w \) \( \Rightarrow \) no SU(3) singlet can be formed

\[ \Rightarrow \text{D mixing is prohibited by SU(3) symmetry} \]

2. Consider a single insertion of \( M^i_j \Rightarrow D_6 M \) transforms as \( 6 \times 8 = 24 + 15 + 6 + 3 \Rightarrow \)

\[ \text{still no SU(3) singlet can be formed} \]

\[ \Rightarrow \text{NO D mixing at first order in SU(3) breaking} \]

3. Consider double insertion of \( M \Rightarrow DMM : 6 \times (8 \times 8)_S = (60 + 42) + 24 + 15 + 15 + 6 + (24 + 15 + 6 + 3) + 6 \)

\[ \Rightarrow \text{D mixing occurs only at the second order in SU(3) breaking} \]

A.F., Y.G., Z.L., and A.A.P.

Phys.Rev. D65, 054034, 2002
Quantum coherence: supporting measurements

Time-dependent $D^0(t) \rightarrow K^+\pi^-$ analysis

$$
\Gamma[D^0(t) \rightarrow K^+\pi^-] = e^{-\Gamma t} \left| A_{K^+\pi^-} \right|^2 \left[ R + \sqrt{R} R_m \left( y'\cos\phi - x'\sin\phi \right) \Gamma t + \frac{R_m^2}{4} \left( y'^2 + x'^2 \right) (\Gamma t)^2 \right]
$$

where $R = \left| \frac{A_{K^+\pi^-}}{A_{K^+\pi^-}} \right|^2$ and $x' = x \cos \delta + y \sin \delta$ $y' = y \cos \delta - x \sin \delta$

Strong phase $\delta$ is zero in the SU(3) limit and strongly model-dependent

A. Falk, Y. Nir and A.A.P., JHEP 12 (1999) 019

Strong phase can be measured at CLEO-c!

$$\sqrt{2} A(D_{CP\pm} \rightarrow K^-\pi^+) = A(D^0 \rightarrow K^-\pi^+) \pm A(D^0 \rightarrow K^-\pi^+) $$

$$
\cos \delta = \frac{Br(D_{CP+} \rightarrow K^-\pi^+) - Br(D_{CP-} \rightarrow K^-\pi^+)}{2\sqrt{R} Br(D^0 \rightarrow K^-\pi^+)}
$$

With 3 fb$^{-1}$ of data $\cos \delta$ can be determined to $|\Delta \cos \delta| < 0.05$!
Theoretical expectations

• If SU(3) breaking enters perturbatively, it is a second order effect…

\[ A_i = A_{SU(3)} + \delta_i \]

• Known counter-example:

1. Very narrow light quark resonance with \( m_R \sim m_D \)

\[ x, y \sim \frac{g_{DR}^2}{m_D^2 - m_R^2} \sim \frac{g_{DR}^2}{m_D^2 - m_0^2 - 2m_0\delta_R} \]

Most probably don’t exists…

see E. Golowich and A.A.P.

• What happens if part of the multiplet is kinematically forbidden?

Example: both \( D^0 \rightarrow 4\pi \) and \( D^0 \rightarrow 4K \) are from the same multiplet, but the latter is kinematically forbidden

see A.F., Y.G., Z.L., and A.A.P.
Phys.Rev. D65, 054034, 2002
CP violation: new experimental possibilities 1

1. Time dependent $D^0(t) \rightarrow K^+K^-$ (lifetime difference analysis):
   separate datasets for $D^0$ and $D^0$

$$A_{CP}(f) = \frac{\Gamma'(D^0 \rightarrow K^+K^-) - \Gamma'(\overline{D^0} \rightarrow K^+K^-)}{\Gamma'(D^0 \rightarrow K^+K^-) + \Gamma'(\overline{D^0} \rightarrow K^+K^-)} = \frac{A_m}{2} y \cos \phi - x \sin \phi$$

This analysis requires

1. time-dependent studies
2. initial flavor tagging ("the D* trick")

Cuts statistics/sensitivity
How would CP violation manifest itself in charm?

- Possible sources of NP in CP violation in charm transitions:
  - CPV in decay amplitudes (“direct” CPV)
    \[ A(D \rightarrow f) \neq A(\bar{D} \rightarrow \bar{f}) \]
  - CPV in \( D^0 - \bar{D}^0 \) mixing matrix
    \[ R_m^2 = \left| \frac{p}{q} \right|^2 = \frac{2M_{12} - i\Gamma_{12}}{2M_{12}^* - i\Gamma_{12}^*} \neq 1 \]
  - CPV in the interference of decays with and without mixing
    \[ \lambda_f = \frac{q}{p} \frac{A_f}{\bar{A}_f} = R_m e^{i(\phi + \delta)} \left| \frac{A_f}{\bar{A}_f} \right| \]

With b-quark contribution neglected:
- only 2 generations contribute
  \( \Rightarrow \) real 2x2 Cabibbo matrix

At this point CP-violating signal is a “smoking gun” signature of New Physics
A bit more about CP violation in charm
1. Standard analysis: rate asymmetries

\[ A_{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = 1 - \frac{|\overline{A_{f}}/A_f|^2}{1 + |\overline{A_{f}}/A_f|^2} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>E791, %</th>
<th>FOCUS, %</th>
<th>CLEO, %</th>
</tr>
</thead>
<tbody>
<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>
</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>
</tr>
<tr>
<td>( D^0 \to K_S \pi^0 )</td>
<td></td>
<td>0.1 \pm 1.3</td>
<td></td>
</tr>
<tr>
<td>( D^0 \to \pi^0 \pi^+K^- )</td>
<td></td>
<td></td>
<td>-3.1 \pm 8.6</td>
</tr>
</tbody>
</table>

… which is of the first order in CPV parameters, but requires tagging

2. Recall that CP of the states in \( D^0 \bar{D}^0 \to (F_1)(F_2) \) are anti-correlated at \( \psi(3770) \):

- a simple signal of CP violation: \( \psi(3770) \to D^0 \bar{D}^0 \to (CP\pm)(CP\pm) \)

\[ \Gamma_{F_1F_2} = \frac{\Gamma_{F_1} \Gamma_{F_2}}{2R_m^2} \left[ \left(2 + x^2 + y^2\right)\lambda_{F_1} - \lambda_{F_2} \right]^2 + \left(2 + x^2 + y^2\right)\left[1 - \lambda_{F_1} \lambda_{F_2}\right]^2 \]

\[ \lambda_f = \frac{q_{A_f}}{p_{A_f}} \]

… which is of the second order in CPV parameters, i.e. tiny
CP violation: new experimental possibilities

Look for CPV signals that are

1. first order in CPV
2. do not require flavor tagging

Consider the final states that can be reached by both \( \overline{D}^0 \) and \( D^0 \), but are not CP eigenstates (\( \pi\rho, KK^*, K\pi, K\rho, ... \))

\[
A^{U}_{CP}(f,t) = \frac{\sum_f - \sum_{\overline{f}}}{\sum_f + \sum_{\overline{f}}}
\]

where

\[
\sum_f = \Gamma(D^0 \rightarrow f)[t] + \Gamma(\overline{D}^0 \rightarrow f)[t]
\]

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030
CP violation: untagged asymmetries

Expect time-dependent asymmetry...

\[ A_{CP}^U (f,t) = \frac{1}{D(t)} e^{-\Gamma t} \left[ A + B (\Gamma t) + C (\Gamma t)^2 \right] \]

... and time-integrated asymmetry

\[ A_{CP}^U (f,t) = \frac{1}{D} [A + B + 2C] \]

... whose coefficients are computed to be

\[
A = |A_f|^2 \left[ \left( 1 - |\overline{A_f}|^2 / |A_f|^2 \right) + R \left( 1 - |\overline{A_f}|^2 / |A_f|^2 \right) \right],
\]

\[
B = -2y\sqrt{R} \left[ \sin \phi \sin \delta \left( |\overline{A_f}|^2 + |A_f|^2 \right) - \cos \phi \cos \delta \left( |\overline{A_f}|^2 - |A_f|^2 \right) \right],
\]

\[
C = \frac{x^2}{2} A.
\]

This is true for any final state \( f \).
CP violation: untagged asymmetries ($K^+\pi^-$)

For a particular final state $K\pi$, the time-integrated asymmetry is simple

$$A_{CP}^U(K^+\pi^-) = -y \sin \delta \sin \phi \sqrt{R}$$

This asymmetry is
1. non-zero due to large SU(3) breaking
2. contains no model-dependent hadronic parameters ($R$ and $\delta$ are experimental observables)
3. could be as large as 0.04% for NP

Note: larger by $O(100)$ for SCS decays ($\pi\rho$, ...) where $R \sim 1$

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030
What if time-dependent studies are not possible I?

**τ-charm factory (BES/CLEO-c)**

Time-integrated $D^0 \rightarrow K^+\pi^−$ analysis: DCSD contribution cancels out for double-tagged $D^0D^0 \rightarrow (K^-\pi^+)(K^-\pi^+)$ decays!

\[
D \rightarrow f_1 f_2
\]

\[
D \rightarrow f_3 f_4
\]

\[
\begin{align*}
|D^0\bar{D}^0\rangle_{L=1} & = \frac{1}{\sqrt{2}} \left[ |D^0(k_1)\bar{D}^0(k_2)\rangle - |D^0(k_2)\bar{D}^0(k_1)\rangle \right] \\
A(D^0\bar{D}^0 \rightarrow (K^-\pi^+)^2) & = \frac{1}{\sqrt{2}} \langle (K^-\pi^+)(K^-\pi^+) | H_{\text{eff}} | D^0\bar{D}^0 \rangle - \frac{1}{\sqrt{2}} \langle (K^-\pi^+)(K^-\pi^+) | H_{\text{eff}} | D^0\bar{D}^0 \rangle \\
R\left(\frac{(K^-\pi^+)(K^-\pi^+)}{(K^-\pi^+)(K^+\pi^-)}\right) & = \frac{x^2 + y^2}{2} \left| \frac{p}{q} \right|^2 = r_D^2 \left| \frac{p}{q} \right|^2
\end{align*}
\]

Quadratic in x,y: not so sensitive

\[
\text{wanted: linear in x or y}
\]

H. Yamamoto; I. Bigi, A. Sanda

Alexey A Petrov  (WSU)

FNAL seminar, November 15 2007
What if time-dependent studies are not possible II?

- If CP violation is neglected: mass eigenstates = CP eigenstates
- CP eigenstates do NOT evolve with time, so can be used for “tagging”

\[ D_{CP}^{(+)} \rightarrow f_1 f_2 \]

\[ \left| D^0 \bar{D}^0 \right|_l = \frac{1}{\sqrt{2}} \left[ \left| D^0(k_1) \bar{D}^0(k_2) \right| + (-1)^L \left| D^0(k_2) \bar{D}^0(k_1) \right| \right] \]

- \( \tau \)-charm factories have good CP-tagging capabilities
  - CP anti-correlated \( \psi(3770) \): \( CP(\text{tag}) (-1)^L = [CP(K_S) CP(\pi^0)] (-1) = +1 \)
  - CP correlated \( \psi(4140) \)

Can still measure \( y \):

\[ B^I_\pm = \frac{\Gamma(D_{CP\pm} \rightarrow Xl\nu)}{\Gamma_{tot}} \]

\[ y \cos \phi = \frac{1}{4} \left( \frac{B^I_+ - B^-_+}{B^I_- - B^I_+} \right) \]