$D^0$ – $\bar{D}^0$ mixing and CPV at BES-III

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(for BES-III collaboration)
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Outline

• A brief review
• Mixing and strong phase at BES-III
• Sensitivity to CPV at BES-III
• CPV in angular correlation
• Rare and forbidden charm decays
• Summary
Neutral D mixing --general definitions

\( D^0 \) and \( \bar{D}^0 \) can transform into each other under weak interaction

\[
\begin{align*}
D^0 & \rightarrow \mathcal{C} \quad \mathcal{U} \quad \bar{D}^0 \\
\mathcal{U} & \rightarrow \bar{C} \quad \mathcal{U} \quad \bar{D}^0
\end{align*}
\]

The weak eigenstates are

\[
\begin{align*}
|D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle \\
|D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle
\end{align*}
\]

With eigenvalues

\[
\begin{align*}
x &= \frac{\Delta m}{\Gamma}, \quad y &= \frac{\Delta \Gamma}{2\Gamma} \\
m &= \frac{m_1 + m_2}{2}, \quad \Delta m = m_2 - m_1 \\
\mu_1 &= m_1 - \frac{i}{2} \Gamma_1 \\
\mu_2 &= m_2 - \frac{i}{2} \Gamma_2
\end{align*}
\]

Weak interaction, long-distance strong interaction make an observable mixing rate. While new physics favor \( x \gg y \).
D mixing at B factories

- Two ways to reach same final state:
  - interference

- Distinguish doubly Cabibbo-suppressed (DCS) from mixing using proper time evolution
  - DCS: exponential proper time distribution
  - Mixed decays only occur after some time

- Time evolution: \( |x| \ll 1, |y| \ll 1 \), \( CP \)-conserving

\[
T_{WS}(t) = e^{-\Gamma t} \left( \frac{R_D}{\sqrt{R_D y'}} + \Gamma t + \frac{x'^2 + y'^2}{4(\Gamma t)^2} \right)
\]

- strong phase:

\[
x' = x \cos \delta_{K\pi} + y \sin \delta_{K\pi}, \quad y' = -x \sin \delta_{K\pi} + y \cos \delta_{K\pi}
\]

\( \delta_{K\pi} \) is the strong phase between DCS and CF amplitudes
Combined results from HFAG

Semileptonic and hadronic D decays

\[ R_M = \frac{x^2 + y^2}{2} = \frac{x'^2 + y'^2}{2} \]

\[ R_M = (2.1 \pm 1.1) \times 10^{-4} \]

Averaged WS K\pi mixing results (time-dependent):

\[ x' = (-0.1 \pm 2.0) \times 10^{-4} \]

\[ y' = (0.55^{+0.28}_{-0.37})\% \]

\[ R_D = (0.330^{+0.014}_{-0.012})\% \]

Averaged mixing results (time-dependent):

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

\[ y = (0.66 \pm 0.21)\% \]

This average include preliminary CLEO-c measurement of \( \cos \delta_{K\pi} = 1.09 \pm 0.66 \)

\[ -2\Delta \log(L) = 37 \text{ at (0,0) corresponds to } 5.7\sigma \]

\[ y_{CP} = (1.12 \pm 0.32)\% \ (3.9 \sigma) \]
The detector is hermetic for neutral and charged particle with excellent resolution, PID, and large coverage.
DD Pairs from different experiments

128 M are expected at BES-III with 4 years’ luminosity@ψ(3770). 5 M are expected at CLEO-c until 2008@ψ(3770).
Quantum Correlation

At BES-III:

\[ |D^0\bar{D}^0\rangle^C = \frac{1}{\sqrt{2}} [|D^0\rangle|\bar{D}^0\rangle - |\bar{D}^0\rangle|D^0\rangle] \]

the interference comes for free:

\[ M^2_i = \left| \langle i | D^0 \rangle \langle j | \bar{D}^0 \rangle - \langle j | D^0 \rangle \langle i | \bar{D}^0 \rangle \right|^2 \]

\[
\begin{array}{|c|c|c|}
\hline
(C=-1) & e^+e^- \rightarrow \psi(3770) \rightarrow & D & \bar{D} \\
\hline
Forbidden if no mixing & K^-\pi^+ & K^-\pi^+ \\
\hline
Forbidden if no mixing & K^-\pi^+ & K^-\pi^+ \\
\hline
Forbidden by CP conservation & CP^+ & CP^+ \\
\hline
Forbidden by CP Conservation & CP^- & CP^- \\
\hline
Interference of CF with DCS & K^-\pi^+ & CP_{\pm} \\
\hline
\end{array}
\]

The mixing rate \( R_M \) can be measured at the first order

Strong phase \( \delta_{K\pi} \) is from CP tagged \( D \rightarrow K\pi \)

CP violation is measured in a production rate.
Mixing rate $R_M$ from

Sensitivity in 20 fb$^{-1}$ data at BES-III:

$\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow (K^-\pi^+)(K^-\pi^+)$

**Background estimate:**

| $(K^+K^-) vs. (K^+)K^-$ | 1078 | 0  |
| $(\pi^+\pi^-) vs. (\pi^+\pi^-)$ | 136  | 0  |
| $(K^+\pi^-) vs. (K^+)K^-$ | 21057 | 0  |
| $(K^+\pi^-) vs. (\pi^+\pi^-)$ | 7470 | 0  |
| $(K^+K^-) vs. (\pi^+\pi^-)$ | 765  | 0  |
| $(K^+\pi^-) vs. K^-\pi^+$ | 150000 | 2  |

2 events in the signal region due to mis-ID. (the mis-ID rate for $\pi$ as a Kaon is 1%).

$RM < 1.5 \times 10^{-4}$
Challenge to PID in mixing rate measurements

TABLE III. The expected mixing signal for $N_{\text{sig}} = N(K^+\pi^-)(K^-\pi^+)$, background $N_{\text{bkg}}$, and the Poisson probability $P(n)$ in 10 fb$^{-1}$ and 20 fb$^{-1}$ at BES-III at $\psi(3770)$ peak, respectively. Here, we take the mixing rate $R_M = 1.18 \times 10^{-4}$.

<table>
<thead>
<tr>
<th>$10$ fb$^{-1}$ ($\psi(3770)$)</th>
<th>20 fb$^{-1}$ ($\psi(3770)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$36 \times 10^6 D^0 \bar{D}^0$</td>
<td>$72 \times 10^6 D^0 \bar{D}^0$</td>
</tr>
<tr>
<td>$N_{\text{sig}}$</td>
<td>1.5</td>
</tr>
<tr>
<td>$N_{\text{bkg}}$</td>
<td>0.3</td>
</tr>
<tr>
<td>$P(n = 0)$</td>
<td>15.7%</td>
</tr>
<tr>
<td>$P(n = 1)$</td>
<td>29.1%</td>
</tr>
<tr>
<td>$P(n = 2)$</td>
<td>26.9%</td>
</tr>
<tr>
<td>$P(n = 3)$</td>
<td>16.6%</td>
</tr>
<tr>
<td>$P(n = 4)$</td>
<td>7.7%</td>
</tr>
<tr>
<td>$P(n = 5)$</td>
<td>2.8%</td>
</tr>
<tr>
<td>$P(n = 6)$</td>
<td>0.9%</td>
</tr>
<tr>
<td>$P(n = 7)$</td>
<td>0.2%</td>
</tr>
<tr>
<td>$P(n = 8)$</td>
<td>0.1%</td>
</tr>
<tr>
<td>$P(n = 9)$</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

$R_M < 1.5 \times 10^{-4}$ @ 95% C.L. with 20 fb$^{-1}$ data at BES-III.
Mixing rate from semileptonic mode

20 fb$^{-1}$ data at BES-III: $e^+e^- \rightarrow \gamma^* \rightarrow D\bar{D} \rightarrow (K^-l^+\nu)(K^-l^+\nu)$

Dilepton with right sign

Dilepton with the same sign is the signal for “mixing” in SM.

The background is high and the sensitivity is about $1 \times 10^{-3}$, which is “second order effect”.

Of course, since the time-evolution is not measured, observation of this reaction would indicate the violation of the selection rule relating the change in charm to the change in leptonic charge: it is true in SM, but new physics may make it without need of mixing.

I.I.Bigi SLAC report-33, 1989 page 169
Sensitivity to $y$ and $y_{CP}$ at BES-III

The $y$ can be probed at the first order sensitivity:

✓ Reconstruct $K+K$- ($CP^+$) decay $\rightarrow$ other side must be $D_1$ ($CP^-$)

✓ Inclusive $K+K$- rate probes $y$:

$$n_{KK} = 2B_{KK} \Gamma_1 = 2B_{KK} (1 - \eta y) \Gamma$$

where $\eta = \pm 1$ for $CP = \pm$

$$1 - y = \frac{n_{KK}}{2N_{DD} B_{KK}}$$

✓ $y_{CP}$ in semileptonic tag + CP tags:

$$y_{CP} = \frac{\Gamma(CP^+) - \Gamma(CP^-)}{\Gamma(CP^+) + \Gamma(CP^-)}$$

$$= y \cos \phi + x \cdot \Delta \sin \phi$$

No CPV in mixing

$y_{CP} \approx y \cos \phi$

PRD 75, 094019 (2007)
Cheng, He, Li and Wang

With 20 fb$^{-1}$ data at BES-III, and the CP tag rate is 1.1%, thus the sensitivity to $y_{CP}$ is 0.003, which could be 4.3 $\sigma$ if the world average hold up.

$$\Delta(y) = \frac{\pm 26}{\sqrt{N(D^0D^0)}} = \pm 0.003.$$
The first order sensitivity to strong phase

\[ A \equiv \frac{\Gamma_{K\pi,f_+} - \Gamma_{K\pi,f_-}}{\Gamma_{K\pi,f_+} + \Gamma_{K\pi,f_-}} = 2\sqrt{R_D}\cos\delta. \]

\[ \Delta(\cos\delta) \approx \frac{1}{2\sqrt{R_D}\sqrt{N_{K^+\pi^-}}}. \]

At BES-III, 20 fb-1 data, the sensitivity:
\[ \delta(\cos\delta) = 0.04 \]

CLEO PRELIMINARY is hold on:
\[ \cos\delta = 1.03 \pm 0.19 \text{ (stat)} \pm 0.08 \text{ (syst)} \]

BESIII will pin down [ -25° – 25°]

The model independent strong phase determination is useful for $\gamma/\phi_3$
See A. Poluektov’s talk.

11-26-2007    Hai-Bo Li (IHEP)
Estimation of TQCA scaled from CLEO-c

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
<th>CLEO-c (3x10^6 D^0 D^0 b)</th>
<th>BESIII (20 fb^-1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C=-1</td>
<td>C=+1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=-1</td>
<td>C=-1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C=+1</td>
<td>C=+1</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>0</td>
<td>±0.01</td>
<td>±0.007</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.003</td>
<td>±0.002</td>
</tr>
<tr>
<td>$x^2$</td>
<td>0</td>
<td>±0.0006</td>
<td>±0.0003</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.00013</td>
<td>±0.0001</td>
</tr>
<tr>
<td>$\cos \delta_{K\pi}$</td>
<td>1</td>
<td>±0.15</td>
<td>±0.13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>±0.035</td>
<td>±0.04</td>
</tr>
<tr>
<td>$x\sin \delta_{K\pi}$</td>
<td>0</td>
<td>—</td>
<td>±0.03</td>
</tr>
<tr>
<td></td>
<td></td>
<td>—</td>
<td>±0.003</td>
</tr>
</tbody>
</table>

From Sun’s talk from CLEO-c at Charm2007
CPV in D system at BES-III
1. \( A_D \) — CP violation in decay

\[
D^0 \to f \quad \leftrightarrow \quad \bar{D}^0 \to \bar{f}
\]

2. \( A_M \) — CP violation in mixing

\[
D^0 \to \bar{D}^0 \to f
\]

\[
\bar{D}^0 \to D^0 \to \bar{f}
\]

New physics favor: \( x >> y \)  
CP violation

3. \( \phi \) — CP violation in the interference between decays with and without mixing

\[
D^0 \begin{array}{c} \rightarrow \end{array} \bar{D}^0 \begin{array}{c} \rightarrow \end{array} f
\]

\[
D^0 \begin{array}{c} \rightarrow \end{array} \bar{D}^0 \begin{array}{c} \rightarrow \end{array} \bar{f}
\]
CP violation in D system

- CP violation in D decays is a clean way to probe new physics since the SM predicts an unobservable asymmetry: $10^{-4}$
- CPV in SCS decay is sensitive to New physics since it is the only one to probe the gluonic penguin operators in the loop.
- CPV-in-mixing is the real new physics signal.
- In SM, no direct CP asymmetry in CF and DCS charm decay modes. Sensitive to new physics.
- 1% level CPV likely indicates new physics!

CPV in D decays is the next big thing in charm physics, but one has to think about the systematic effect, which should be controlled under $10^{-3}$ level. It is really a challenge to experiments.
CP violation at BES-III

• Quantum correlation
  – $\psi(3770) \to D(CP^+)D(CP^+), D(CP^-)D(CP^-)$

• CP asymmetry in $D^+$ and $D_s$ decays

• CP asymmetry in $D^0$ decays
  – Have to pay price for tag
  – Flavor tag with semileptonic mode at $\psi(3770)$
  – Flavor tag with $D^+ \to K^-\pi^+\pi^+$ modes above $DD^*$ threshold (4.03GeV / 4.17 GeV)

\[
e^+e^- \to D^+\bar{D}^{*-} \to D^+(\bar{D}^0\pi^-_{soft})
\]
### Expected event numbers of the double tag modes in 20 fb$^{-1}$ $\Psi(3770)$ data

<table>
<thead>
<tr>
<th>Mode</th>
<th>Exp. number (if totally CPV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^- , \bar{\psi} , K^+K^-$ (signal)</td>
<td>1078</td>
</tr>
<tr>
<td>$K^+K^- , \bar{\psi} , \pi^+\pi^-$ (signal)</td>
<td>765</td>
</tr>
<tr>
<td>$\pi^+\pi^- , \bar{\psi} , \pi^+\pi^-$ (signal)</td>
<td>136</td>
</tr>
<tr>
<td>$K^+K^- , \bar{\psi} , K^-\pi^+$ (background)</td>
<td>21056</td>
</tr>
<tr>
<td>$\pi^+\pi^- , \bar{\psi} , K^-\pi^+$ (background)</td>
<td>7470</td>
</tr>
<tr>
<td>$K^-\pi^+ , \bar{\psi} , K^+\pi^-$ (background)</td>
<td>102847</td>
</tr>
</tbody>
</table>

### Efficiencies of signal channels

- $K^+K^- \, \bar{\psi} \, K^+K^-$: $\varepsilon = 43.8\%$
- $K^+K^- \, \bar{\psi} \, \pi^+\pi^-$: $\varepsilon = 47.2\%$
- $\pi^+\pi^- \, \bar{\psi} \, \pi^+\pi^-$: $\varepsilon = 53.3\%$

### Main background

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\varepsilon$ (%)</th>
<th>Tot CPV</th>
<th>$K^+K^- , \bar{\psi} , K^-\pi^+$</th>
<th>$\pi^+\pi^- , \bar{\psi} , K^-\pi^+$</th>
<th>$K^-\pi^+ , \bar{\psi} , K^+\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^+K^- , \bar{\psi} , \pi^+\pi^-$</td>
<td>43.8</td>
<td>440</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\pi^+\pi^- , \bar{\psi} , K^-\pi^+$</td>
<td>47.2</td>
<td>340</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$K^-\pi^+ , \bar{\psi} , K^+\pi^-$</td>
<td>53.3</td>
<td>66</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The sensitivity is about: $A_{CP} \sim 5 \times 10^{-3}$ @ 90% C.L.
CPV in angular analyses
a proposal
Poor data for $D \rightarrow V_1 V_2$ in PDG

**D⁰ decay**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0 \rho^0$</td>
<td>$(1.50 \pm 0.33)$ %</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^0$ transverse</td>
<td>$(1.6 \pm 0.5)$ %</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^0$ S-wave</td>
<td>$(2.9 \pm 0.6)$ %</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^0$ S-wave long.</td>
<td>$&lt; 3 \times 10^{-3}$ CL=90%</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^0$ P-wave</td>
<td>$&lt; 3 \times 10^{-3}$ CL=90%</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^0$ D-wave</td>
<td>$(2.0 \pm 0.6)$ %</td>
</tr>
<tr>
<td>$K^*(892)^- \rho^+$</td>
<td>$(6.4 \pm 2.5)$ %</td>
</tr>
<tr>
<td>$K^*(892)^- \rho^+$ longitudinal</td>
<td>$(3.1 \pm 1.2)$ %</td>
</tr>
<tr>
<td>$K^*(892)^- \rho^+$ transverse</td>
<td>$(3.4 \pm 2.0)$ %</td>
</tr>
<tr>
<td>$K^*(892)^- \rho^+$ P-wave</td>
<td>$&lt; 1.5$ % CL=90%</td>
</tr>
</tbody>
</table>

**D⁺ decay**

<table>
<thead>
<tr>
<th>Decay Mode</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$K^*(892)^0 \rho^+$ total</td>
<td>[ss] $(1.8 \pm 1.4)$ %</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^+$ S-wave</td>
<td>[ss] $(1.4 \pm 1.5)$ %</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^+$ P-wave</td>
<td>$&lt; 1 \times 10^{-3}$ CL=90%</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^+$ D-wave</td>
<td>$(8 \pm 7) \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^*(892)^0 \rho^+$ D-wave longitudinal</td>
<td>$&lt; 7 \times 10^{-3}$ CL=90%</td>
</tr>
<tr>
<td>$K^<em>(892)^0 + \overline{K}^</em>(892)^0$</td>
<td>$(2.6 \pm 1.1)$ %</td>
</tr>
</tbody>
</table>

Large branching ratios!

Missing modes

ρρ

ρω

ωω
Angular measurement in $D \rightarrow V_1 V_2$

- Basic quantum mechanics

\[ H_1 = \cos(\theta_1); \quad H_2 = \cos(\theta_2) \]

Longitudinal

Transverse

- 10 parameters for $D^0$ and $\bar{D}^0$:

\[
|A_{\text{total}}|: \quad n_{\text{sig}} \quad \text{and} \quad A_{CP}
\]

\[
|A_0|: \quad f_L \quad \text{and} \quad A^{0}_{CP}
\]

\[
|A_\perp|: \quad f_\perp \quad \text{and} \quad A^{\perp}_{CP}
\]

\[
\arg(A_\parallel): \quad \phi_\parallel \quad \text{and} \quad \Delta\phi_\parallel
\]

\[
\arg(A_\perp): \quad \phi_\perp \quad \text{and} \quad \Delta\phi_\perp
\]

BaBar: $B \rightarrow \phi K^*$
A. Gritsan at ICHEP04

\[ CP\text{-even longitudinal:} \quad A_0 = -\frac{1}{\sqrt{3}} S + \sqrt{\frac{2}{3}} D \]

\[ CP\text{-even transverse:} \quad A_\parallel = \sqrt{\frac{2}{3}} S + \frac{1}{\sqrt{3}} D \]

\[ CP\text{-odd transverse:} \quad A_\perp = P \]
CP asymmetry and T odd correlation in $D \rightarrow V_1 V_2$

- CP from New Physics interference: $\Delta \delta_{\text{weak}} \neq 0$;

- Direct asymmetry $\propto \sin(\Delta \delta_{\text{weak}}) \cdot \sin(\Delta \delta_{\text{strong}})$

- Triple-product:

Asymmetry in phases (define $\Delta \phi_{\parallel} = \arg(\bar{A}_\parallel / \bar{A}_0) - \arg(A_\parallel / A_0)$...)

$\propto \sin \Delta \delta_{\text{weak}} \cos \Delta \delta_{\text{strong}}$

$\text{Im}(A_\perp A_0^*) \neq -\text{Im}(\bar{A}_\perp \bar{A}_0^*)$

$\text{Im}(A_\perp A_\parallel^*) \neq -\text{Im}(\bar{A}_\perp \bar{A}_\parallel^*)$
Maximum Likelihood Method

Estimate parameters (e.g. $N_{\text{sig}}$) with $D \rightarrow V_1 V_2$

\[
\tilde{x}_j = (m_{ES}, \Delta E, m_{V_1}, m_{V_2}, \theta_1, \theta_2, \Phi, \epsilon, Q_{\text{tag}})
\]

\[
\begin{align*}
\text{Max: } & \mathcal{L} = \exp \left( - \sum_{i,k} n_{ik} \right) \prod_{j=1}^{N} \exp \left( \ln( n_{ik} \text{PDF}(\tilde{x}_j, \tilde{\alpha})) \right) \\
\text{PDF: } & \text{PDF}_{i,k}(\tilde{x}_j) = P_{i1}(m_{ES}) \cdot P_{i2}(\Delta E) \cdot P_{i3}(\epsilon) \cdot \\
& P_{i4}(m_{V_1}) \cdot P_{i5}(m_{V_2}) \cdot P_{i,k}^{\text{hel}}(\theta_1, \theta_2, \Phi, f_L, f_\perp, \phi_\perp, \phi_\parallel)
\end{align*}
\]

\[
\begin{align*}
f_L &= \frac{|A_0|^2}{\sum |A_\lambda|^2}, & f_\perp &= \frac{|A_\perp|^2}{\sum |A_\lambda|^2}
\end{align*}
\]

Measure:

\[
\begin{align*}
\phi_\parallel &= \arg \left( \frac{A_\parallel}{A_0} \right), & \phi_\perp &= \arg \left( \frac{A_\perp}{A_0} \right).
\end{align*}
\]
Consider the Cabibbo suppressed decay

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

- Compute the angle \( \phi \) between the \( K^+ K^- \) and \( \pi^+ \pi^- \) decay planes for \( D^0 \rightarrow K^+ K^- \pi^+ \pi^- \). Then one has:

\[
\frac{d\Gamma}{d\phi}(D^0 \rightarrow K^+ K^- \pi^+ \pi^-) = \Gamma_1 \cos^2 \phi + \Gamma_2 \sin^2 \phi + \Gamma_3 \cos \phi \sin \phi
\]

\[
\frac{d\Gamma}{d\phi}(\overline{D^0} \rightarrow K^+ K^- \pi^+ \pi^-) = \overline{\Gamma}_1 \cos^2 \phi + \overline{\Gamma}_2 \sin^2 \phi + \overline{\Gamma}_3 \cos \phi \sin \phi
\]

\[ \Gamma_3 \neq \overline{\Gamma}_3 \rightarrow CP \text{ violation} \]

This is also applied to charged D 4-body decays!
Angular correlation

At BES-III:

$|D^0\bar{D}^0\rangle_{C=-1} = \frac{1}{\sqrt{2}} [ |D^0\rangle |\bar{D}^0\rangle - |\bar{D}^0\rangle |D^0\rangle ]$

the interference comes for free:

$M^2 = \langle i | D^0\rangle \langle j | \bar{D}^0\rangle - \langle j | D^0\rangle \langle i | \bar{D}^0\rangle$

$\psi(3770) \rightarrow D\bar{D} \rightarrow (V_1V_2)(\overline{V_1V_2})$

CP($V_1V_2$) = CP($\overline{V_1V_2}$) \Rightarrow CPV

Fully reconstruct both D decay to VV, if you see:

$f_L^1 \neq 0, \text{ and } f_L^2 \neq 0$


\begin{align*}
CP\text{-even longitudinal: } A_0 &= -\frac{1}{\sqrt{3}}S + \frac{\sqrt{2}}{\sqrt{3}}D \\
CP\text{-even transverse: } A_{\parallel} &= \frac{\sqrt{2}}{\sqrt{3}}S + \frac{1}{\sqrt{3}}D \\
CP\text{-odd transverse: } A_{\perp} &= P
\end{align*}

Several dilution from mis-ID.

Rich FSI and extended LH fit with multi-variables can improve the sensitivity.

Full angular analysis:
Jerome Charles
Sebastien Descotes-Genon
Hai-bo Li
Rare and forbidden Charm Decays

Charm FCNC decays heavily GIM suppressed in SM:

New Physics can contribute in loop, which is different from the cases in B and Kaon mesons.

Lepton decays: \(D^0 \rightarrow l^+ l^- \quad (l = e, \mu)\);

GIM suppressed decays: \(D^{0(\pm)} \rightarrow M^{0(\pm)} l^+ l^- \quad (M \text{ is meson allowed})\);

LFV decays: \(D^0 \rightarrow e^+ \mu^- , \quad D^{0(\pm)} \rightarrow M^{0(\pm)} e^+ \mu^- \);

LNV decays: \(D^\pm \rightarrow M^\pm l^+ l^+ \quad (l = e, \mu; \text{ the same signed-di-lepton})\);
Limits from CLEO-c

Branching-fraction UL values are all at 90% C.L.

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\epsilon$ (%)</th>
<th>$N$</th>
<th>$n$</th>
<th>$\sigma_{\text{syst}}$ (%)</th>
<th>$B$ ($10^{-6}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+e^+e^-$</td>
<td>36.41</td>
<td>1.99</td>
<td>2</td>
<td>8.7</td>
<td>&lt;7.4</td>
</tr>
<tr>
<td>$\pi^-e^+e^+$</td>
<td>43.85</td>
<td>0.48</td>
<td>0</td>
<td>7.1</td>
<td>&lt;3.6</td>
</tr>
<tr>
<td>$K^+e^+e^-$</td>
<td>26.18</td>
<td>1.47</td>
<td>0</td>
<td>10.0</td>
<td>&lt;6.2</td>
</tr>
<tr>
<td>$K^-e^+e^+$</td>
<td>35.44</td>
<td>0.50</td>
<td>0</td>
<td>7.2</td>
<td>&lt;4.5</td>
</tr>
<tr>
<td>$\pi^+\phi(e^+e^-)$</td>
<td>46.22</td>
<td>0.04</td>
<td>2</td>
<td>7.4</td>
<td>$2.7^{+3.6}_{-1.8} \pm 0.2$</td>
</tr>
</tbody>
</table>

UL = \frac{C(n; N)}{\epsilon(2\sigma_{D^+D^- L})}

N : expected backgrounds
n : observed events
C(n;N) : upper limit on signal in the presence of backgrounds

0.8×10^6 D\bar{D} pairs

Signal region: -20 < $\Delta E$ < 20 MeV; -5 < $\Delta M_{bc}$ < 5 MeV

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Rare D Decays

Although the New Physics contributions are diluted by large uncertainty of long-distance contribution, the $m(e^+e^-)$ distribution may be distinct. Burdman et. al., PRD66(2002)014009
## Rare (GIM suppressed) D Decays

![PRD66(2002)014009](image)

<table>
<thead>
<tr>
<th>Process</th>
<th>SM (×10^{-6})</th>
<th>RPV (×10^{-6})</th>
<th>Current limit (×10^{-6})</th>
<th>BESIII 10^{-8}</th>
</tr>
</thead>
<tbody>
<tr>
<td>D^+ → K^+μ^-μ^+</td>
<td>-</td>
<td>-</td>
<td>9.2 (FOCUS)</td>
<td>10.5</td>
</tr>
<tr>
<td>D^+ → π^+μ^-μ^+</td>
<td>1.9</td>
<td>15</td>
<td>8.8 (FOCUS)</td>
<td>8.7</td>
</tr>
<tr>
<td>D^+ → ρ^+μ^-μ^+</td>
<td>-</td>
<td>-</td>
<td>560 (E653)</td>
<td>24.0</td>
</tr>
<tr>
<td>D^0 → π^0μ^-μ^+</td>
<td>-</td>
<td>-</td>
<td>180 (E653)</td>
<td>12.3</td>
</tr>
<tr>
<td>D^0 → ρ^0μ^-μ^+</td>
<td>1.8</td>
<td>8.7</td>
<td>22 (E791)</td>
<td>13.7</td>
</tr>
<tr>
<td>D^0 → K^0μ^-μ^+</td>
<td>-</td>
<td>-</td>
<td>260 (E653)</td>
<td>10.6</td>
</tr>
<tr>
<td>D^+ → K^+e^-e^+</td>
<td>-</td>
<td>-</td>
<td>6.2 (CLEO-c)</td>
<td>6.7</td>
</tr>
<tr>
<td>D^+ → π^+e^-e^+</td>
<td>2.0</td>
<td>2.3</td>
<td>7.4 (CLEO-c)</td>
<td>5.6</td>
</tr>
<tr>
<td>D^+ → ρ^+e^-e^+</td>
<td>-</td>
<td>-</td>
<td>--</td>
<td>15.4</td>
</tr>
<tr>
<td>D^0 → π^0e^-e^+</td>
<td>-</td>
<td>-</td>
<td>45 (CLEO-II)</td>
<td>7.9</td>
</tr>
<tr>
<td>D^0 → ρ^0e^-e^+</td>
<td>1.8</td>
<td>5.1</td>
<td>100 (CLEO-II)</td>
<td>10.3</td>
</tr>
<tr>
<td>D^0 → K^0e^-e^+</td>
<td>-</td>
<td>-</td>
<td>110 (CLEO-II)</td>
<td>7.5</td>
</tr>
</tbody>
</table>
LFV and LNV D Decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>SM $10^{-6}$</th>
<th>RPV $10^{-6}$</th>
<th>Current limit $10^{-6}$</th>
<th>BESIII $10^{-8}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^+ \rightarrow K^- \mu^+ \mu^+$</td>
<td>0</td>
<td>--</td>
<td>13 (653)</td>
<td>10.4</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^- \mu^+ \mu^+$</td>
<td>0</td>
<td>-</td>
<td>4.8 (FOCUS)</td>
<td>8.7</td>
</tr>
<tr>
<td>$D^+ \rightarrow \rho^- \mu^+ \mu^+$</td>
<td>0</td>
<td>-</td>
<td>56 (E653)</td>
<td>19.4</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^- e^+ e^+$</td>
<td>0</td>
<td>-</td>
<td>4.5 (CLEO-c)</td>
<td>6.7</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^- e^+ e^+$</td>
<td>0</td>
<td>-</td>
<td>3.6 (CLEO-c)</td>
<td>5.6</td>
</tr>
<tr>
<td>$D^+ \rightarrow \rho^- e^+ e^+$</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>12.4</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^+ e^- \mu^+$</td>
<td>0</td>
<td>-</td>
<td>68 (E791)</td>
<td>8.3</td>
</tr>
<tr>
<td>$D^+ \rightarrow \pi^+ e^- \mu^+$</td>
<td>0</td>
<td>30</td>
<td>34 (E791)</td>
<td>5.9</td>
</tr>
<tr>
<td>$D^+ \rightarrow \rho^+ e^- \mu^+$</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>15.5</td>
</tr>
<tr>
<td>$D^0 \rightarrow \pi^0 e^- \mu^+$</td>
<td>0</td>
<td>-</td>
<td>86 (CLEO-II)</td>
<td>9.7</td>
</tr>
<tr>
<td>$D^0 \rightarrow \rho^0 e^- \mu^+$</td>
<td>0</td>
<td>14</td>
<td>49 (CLEO-II)</td>
<td>11.0</td>
</tr>
<tr>
<td>$D^0 \rightarrow \bar{K}^0 e^- \mu^+$</td>
<td>0</td>
<td>-</td>
<td>100 (CLEO-II)</td>
<td>9.6</td>
</tr>
</tbody>
</table>

PRD66(2002)014009

90%CL
D→hl⁺l⁻ Like Rare Decays

BaBar Input
ICHEP06
288 fb⁻¹ @ Y(4S)

CLEO-c
0.8 M (0.281 fb⁻¹)

\[ \frac{L_{BaBar}}{L_{CLEO-c}} = \frac{288}{0.3} = 960 \]

Background free at a tau charm factory @ 3770 peak!
## Rare Leptonic Decays

**Burdman et. al., PRD66(2002)014009**

<table>
<thead>
<tr>
<th>Decay</th>
<th>SM</th>
<th>RPV</th>
<th>Current Limit</th>
<th>CLEO-c</th>
<th>BESIII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0\rightarrow e^+e^-$</td>
<td>$10^{-23}$</td>
<td>$1.0\times10^{-10}$</td>
<td>$1.0\times10^{-6}$ (BaBar)</td>
<td>$6.9\times10^{-7}$</td>
<td>$2.4\times10^{-8}$</td>
</tr>
<tr>
<td>$D^0\rightarrow \mu^+\mu^-$</td>
<td>$10^{-13}$</td>
<td>$3.5\times10^{-6}$</td>
<td>$1.3\times10^{-6}$ (BaBar)</td>
<td>--</td>
<td>$1.7\times10^{-7}$ (dilution from $D^0\rightarrow \pi^+\pi^-$)</td>
</tr>
<tr>
<td>$D^0\rightarrow e^+\mu^-$</td>
<td>0</td>
<td>$1.0\times10^{-6}$</td>
<td>$8.1\times10^{-7}$ (BaBar)</td>
<td>-</td>
<td>$4.3\times10^{-8}$</td>
</tr>
</tbody>
</table>

The efficiency is about 70% at BES-III.
The mis-ID rate for $\pi$ misidentified as a $\mu$ is about 5% below 1.0GeV.
Sensitivity to LFV

LFV and LNV are “smoking gun”, any indication of deviation from zero will indicate new physics.
Summary

- $y_{CP}(y)$ and strong phase measured at BES-III by considering QC.
- CP violation from QC
- CP violation from angular correlation
  (QC+Partial Wave Analysis)

The 1\textsuperscript{th} order sensitivities to mixing and CPV at BES-III:
\[ \delta(y) \sim 0.003, \delta(\cos(\delta)) \sim 0.04, \text{ CPV: } 10^{-3} \]

More complicated analyses: Dalitz plot, $D \rightarrow VV$ angular correlation.
TQCA (Input from CLEO-c).
谢谢！