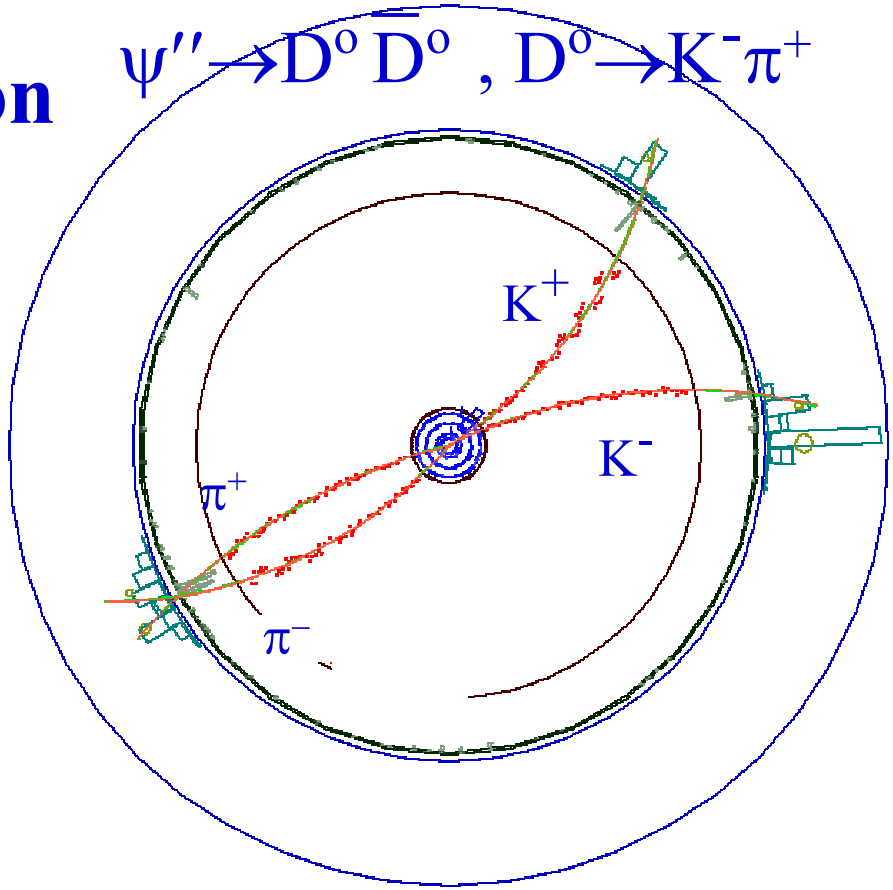
D^o–$\bar{D}^o$ Mixing, CP Violation and Rare Decays near Charm Threshold Experimental Issues:



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Overview

Results/Expectations for BABAR, BELLE, CLEO, FOCUS

- **Rare Decays, Charm Mixing, CP Violation**

Review the physics reach as outlined in the CLEO-c Yellow Book & BES-III Design Report on these topic

Usually a search for New Physics

- **What are the Standard Model expectations?**
- **What sensitivity is expected at CLEO-c/BES-III?**

Discuss more sensitive probes of New Physics than enumerated in Yellow Book

- **Charm Mixing**
- **CP Violation**

Identify studies that are better done away from threshold

Charm Production

At $\Psi(3770)$

CLEO-c

- $L = 3 \times 10^{32}\ cm^{-2}\ s^{-1}$
- Integrated Luminosity 3 fb^{-1}
- 3×10^{7} DD pairs/year (σ ~10nb)

BES-III

- $L = 10^{33}\ cm^{-2}\ s^{-1}$
- Integrated Luminosity 3-5 fb^{-1}
- 2.5×10^{7} DD pairs/year (σ~5nb)

Near $\Upsilon(4S)$

CLEO-II.V

- 6 fb-1 (on resonance) +
- 3 fb-1 (off resonance)
- 3.5×10^{7} charm hadrons produced

FOCUS

- 500,000+ reconstructed in $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^+\pi^+$ modes

BABAR+BELLE

- ~300 fb^{-1}
- ~10^{9} charm hadrons produced

Rare Charm Physics at Threshold

Rare Decays

- Search for $D \to (X)e^+e^-, (X)\mu^+\mu^-$
- Search for $D \to (X)e\mu$, Xe^+e^+, $X\mu^+\mu^+$
- Search for $D \to \rho/\omega/\phi\gamma$

D-mixing

- Correlated final states probe $R_{mix}=(x^2+y^2)/2$, $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$
- Measure relative strong phase between $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^-\pi^+$
- Exploit CP content on Dalitz plot vs flavor tag (probes $y=\Delta\Gamma/2\Gamma$)

CP Violation

- Direct CP violation – also available to B-factories
- Explicitly exploit quantum correlation
- Exploit interference on Dalitz plots (FSI in multi-body decays)

Rare Decays

Why are we interested? Small Standard Model rates

- **GIM suppression**
- **lepton family conservation**
- **lepton conservation**

Current limits (PDG2003) from few x10^{-4} to 10^{-6} most results from

- **CLEO Collaboration, Phys. Rev. Lett. 76 (3065)**
- **E791 Collaboration, Phys. Rev. Lett. 86 (3969)**

Larger data samples at B-factories and FOCUS are limited by backgrounds.

Rare Decays at Charm Threshold

Analysis procedure is straight-forward

- **Search for rare decays in tagged sample**
- **CLEO-c Yellow Book assumed**
  - **3 fb^{-1}**
  - **10 nb cross section**
  - **10% tagging efficiency**
  - **background free**

3 fb^{-1} at $\psi(3770)$ compares favorably with 400 fb^{-1} near $\Upsilon(4S)$

Most rare processes beyond CLEO-c+BES-III sensitivity.

Some radiative decays may be observable

Signatures of Charm Mixing

Charm mixing at B-factory or fixed target experiment

- **wrong-sign semileptonic decays – $\Gamma(D^0 \to K^+ l^- \nu) / \Gamma(D^0 \to K^- l^+ \nu)$**
  - **sensitive to mixing rate, R_M and CPV in mixing, A_M**
- **$D^0 \to$ CP Eigenstate decay time**
  - **sensitive to mixing amplitude $y = \Delta\Gamma/2\Gamma$**
  - **also CPV in decay, A_D, mixing, A_M and interference, ϕ**
- **wrong-sign $D^0 \to K^+\pi^-$ decay time**
  - **sensitive to x'^2, y' where $y' = y\cos\delta - x\sin\delta$, $x' = y\sin\delta + x\cos\delta$**
  - **also CPV in decay, A_D, mixing, A_M and interference, ϕ**
- **decay time dependence of interference $D^0 \to K_s \pi^+\pi^-$**
  - **sensitive to mixing amplitudes $x = \Delta m/\Gamma$, $y = \Delta\Gamma/2\Gamma$**
  - **also CPV in decay, A_D, mixing, A_M and interference, ϕ**

Charm Mixing-Current Status

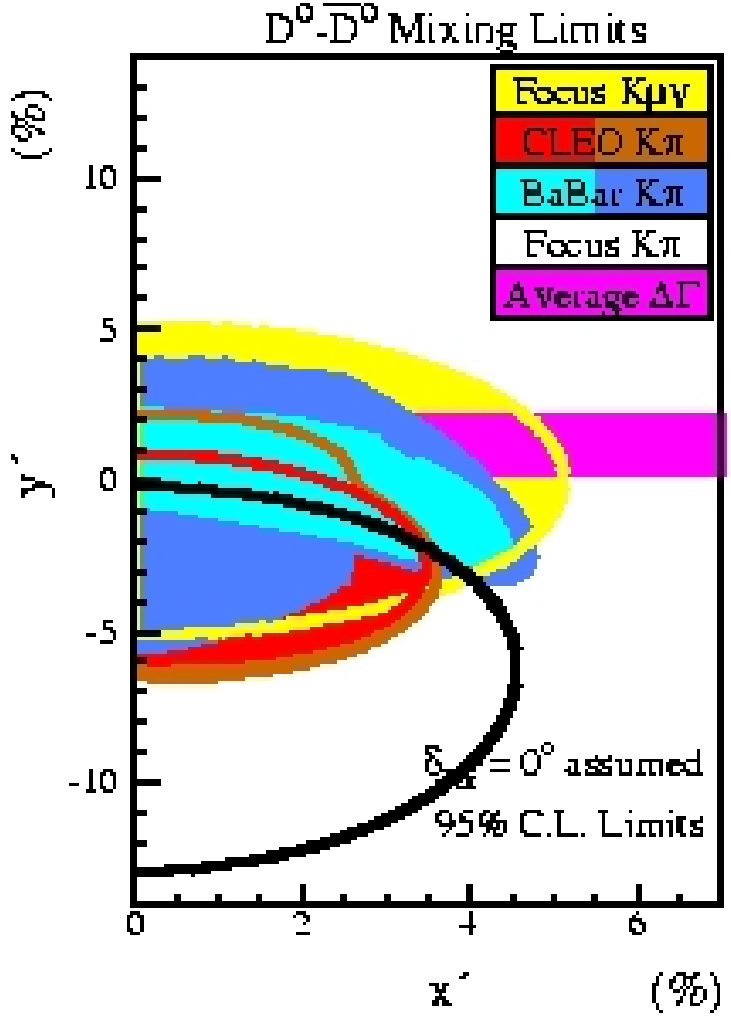
Best limits exploit finite D lifetime

- Babar result based on 57.1 fb^{-1}
- Error on x` scale as (luminosity)$^{1/4}$
- Limits are not statistics limited

Cannot resolve D lifetime near threshold

- Smaller statistical sample
- Must exploit quantum coherence
- Sensitive to $\cos\delta \sim \pm 0.05$
- $(2R_{MIX})^{1/2} < 2\%$ @ 95% C.L.
- accessing x, y possible/challenging

CLEO-c/BES-III will make important contributions



Charm Mixing at Threshold

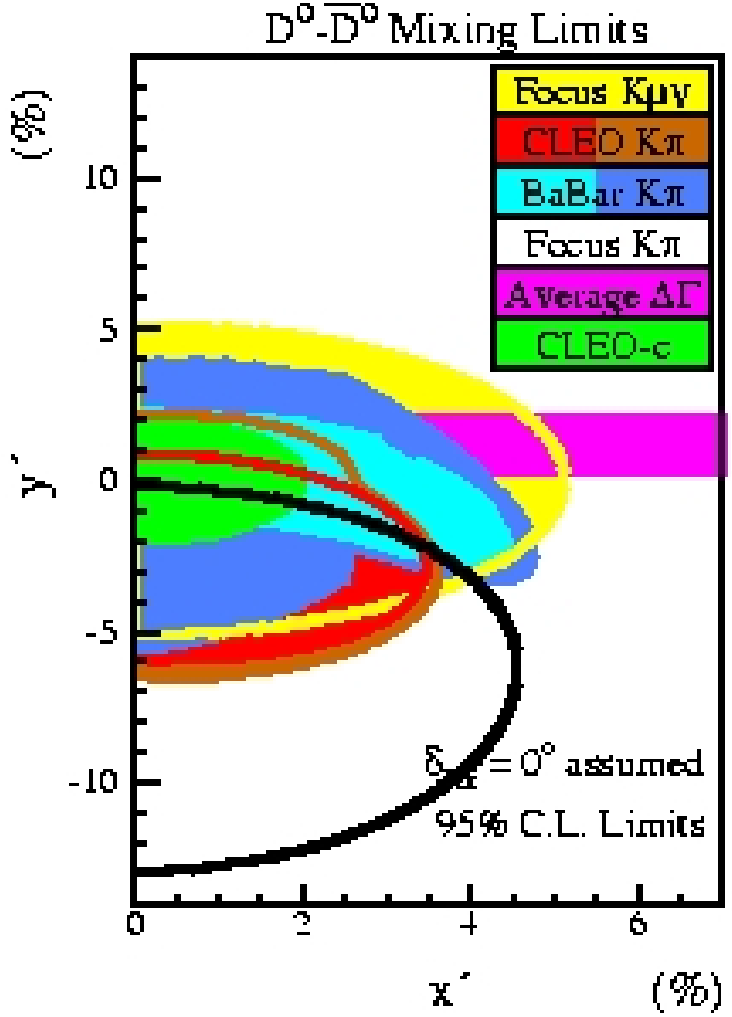
Determining strong phase δ

- Resolves phase ambiguity between y and y`
- Measure three absolute branching fractions
  - $D^0 \to K^-\pi^+$: double tag events $DD \to (K^-\pi^+)(K^+\pi^-)$
  - $D_+ \to K^-\pi^+$: $DD \to (K^-\pi^+)(CP+)$
  - $D_- \to K^-\pi^+$: $DD \to (K^-\pi^+)(CP-)$
- Neglecting CPV in Mixing

$$\cos\delta = \frac{Br(D_+ \to K^-\pi^+) - BR(D_- \to K^-\pi^+)}{2(R_{DCS})^{1/2} Br(D^0 \to K^-\pi^+)}$$

Measuring R_{mix}

- $DD \to (K^- l^+ \nu)(K^- l^+ \nu) \sim R_{mix}$
- $DD \to (K^-\pi^+)(K^-\pi^+) \sim R_{mix}$



Charm Mixing: New Idea

- **Absolute rate of flavor tags is constant in the presence of mixing via y**
- **Relative branching fractions varies with y**

$\Rightarrow$ Provides time integrated sensitivity to y

- **R =** $$\frac{\Gamma[\Psi\rightarrow(D\rightarrow CP)(D\rightarrow \text{flavor-tag})]}{\Gamma[\psi\rightarrow(D\rightarrow CP)(D\rightarrow X)\ Br(D\rightarrow \text{flavor-tag})]}$$

- **flavor tags include $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^-\pi^+$, and semileptonic decays**
  - **R ~ $(1\pm y\cos\phi)$ + for CP- and – for CP+**

Charm Mixing: New Idea Continued

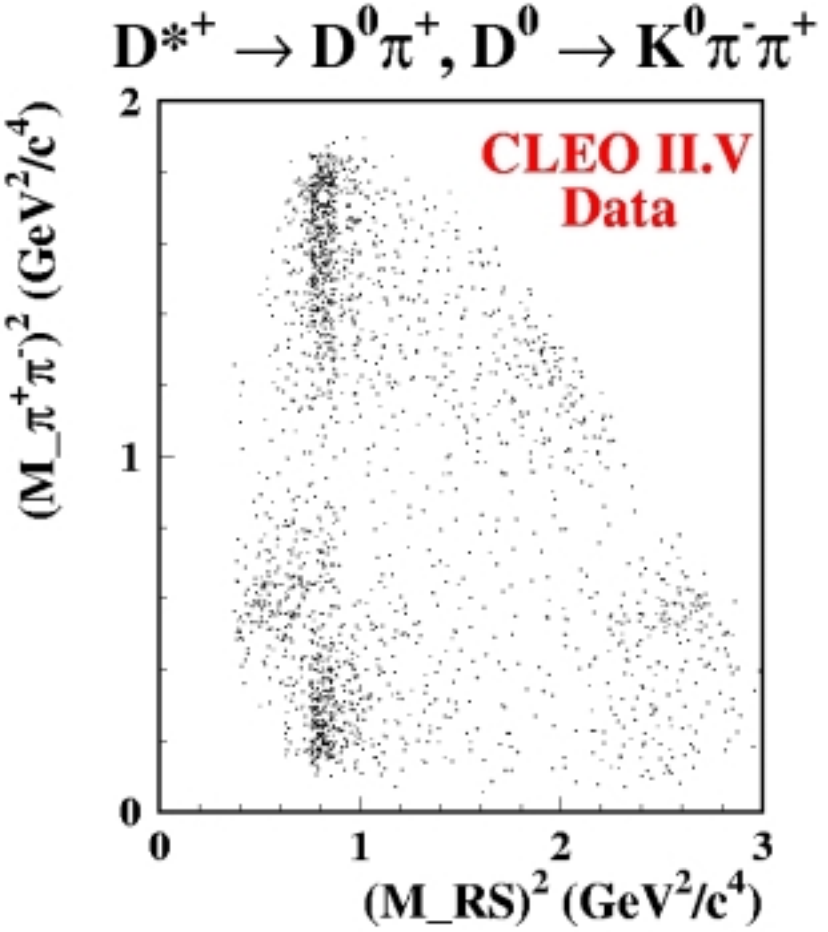
- **Consider**

DD → (flavor-tag)($K_S\pi^+\pi^-$)

- **$K_S\pi^+\pi^-$ Dalitz plot has CP+ ($K_S f^0$) and CP- ($K_S\rho$)**
- **1/3 CP- ~ (1+ ycosϕ)**
- **1/3 CP+ ~ (1 - ycosϕ)**

Expect ~100,000 event in CLEO-c + BES-III

- **y<0.6% @ 95% C.L. (stat.)**
- **PDG ±1.3% (~100 fb^{-1})**



CP Violation

Exploit Quantum Correlation

- $\Psi(3770) \rightarrow$ (CP+)(CP+) and (CP-)(CP-) forbidden
  - Maximal CPV in $\Psi(3770) \rightarrow (K^+K^-)(K^+K^-) \sim 60$ events/fb^{-1}
- E~ 4140 GeV
  - e+e- $\rightarrow \gamma DD \rightarrow \gamma$(CP+)(CP-) forbidden
  - e+e- $\rightarrow \pi^0 DD \rightarrow \pi^0$(CP+)(CP+) and π^0(CP-)(CP-) forbidden

Direct CP Violation

- $\Psi(3770) \rightarrow$ (CP±)(flavor-tag)
  - $\Psi(3770) \rightarrow (K^+K^-)$(lepton-tag) ~ 3400 events/fb^{-1}
  - $\Psi(3770) \rightarrow (K_S\pi^0)$(lepton-tag) ~ 3500 events/fb^{-1}
- Sensitive to CPV ~ 1% level

CP Violation: New Idea

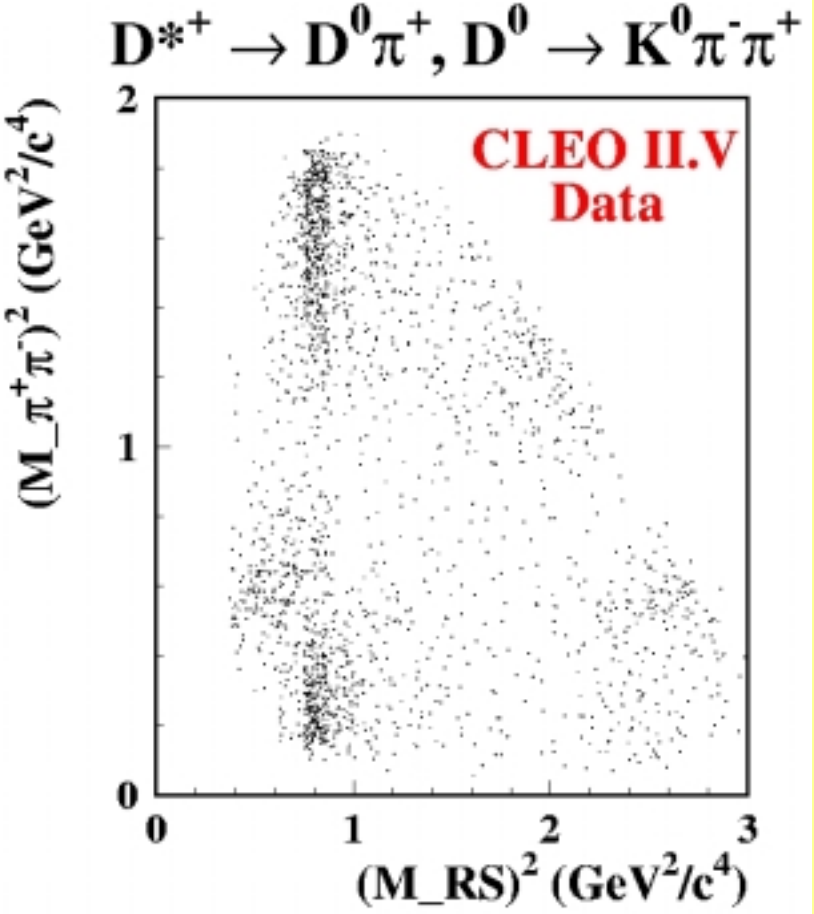
Interference between amplitudes on Dalitz plots ($D \to K_S\pi^+\pi^-$) may provide greater sensitivity to CPV ~ 10^{-4} ??

Intermediate states include
CP+: $K_S f_0(600)$, $K_S f_0(980)$, $K_S f_0(1370)$
CP- : $K_S\rho$, $K_S\omega$

Uncorrelated D's: CP conservation $\Rightarrow$ interference between CP+ & CP- amplitudes integrates to zero

Correlated D's: CP conservation $\Rightarrow$ interference between CP+ & CP- amplitudes locally zero

Dalitz plot is different for flavor tags and CP tags. In the limit of CP conservation certain intermediate states present in the flavor tag sample will be be missing in one of the CP tag samples.



H. Muramatsu *et al.* [CLEO Collaboration.], Phys. Rev. Lett. 89 251802 (2002).

Summary & Outlook

Rare Decays at $\psi(3770)$ compare favorably with $\Upsilon(4S)$

- Radiative decays may be observable
- Otherwise Standard Model predictions are many orders of magnitude beyond CLEO-c+BES-III sensitivity

D-mixing at $\psi(3770)$ compares favorably with $\Upsilon(4S)$

- Exploit CP content on Dalitz plot vs flavor tag (probes $y=\Delta\Gamma/2\Gamma$)
- Correlated final states probe $R_{mix}=(x^2+y^2)/2$, $x=\Delta m/\Gamma$, $y=\Delta\Gamma/2\Gamma$
- Measure relative strong phase between $D^0 \to K^-\pi^+$ and $\bar{D}^0 \to K^-\pi^+$
- Need to evaluate ability to distinguish x vs y at $\psi(3770)$

CP Violation: Further study is required

- Best probe of CP violation in charm is interference on Dalitz plots at both B-factories and at charm threshold
- B-factories have much larger statistics and larger backgrounds
- B-factories only have flavor tag (D^{*+}): Charm threshold also has CP tag