D^0–$\bar{D}^0$ Mixing – Theory

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Moriond EW, Mar 16 2007

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Experimental Results

Evidence for D mixing at last!

Presented at Moriond EW on Mar 13. . .

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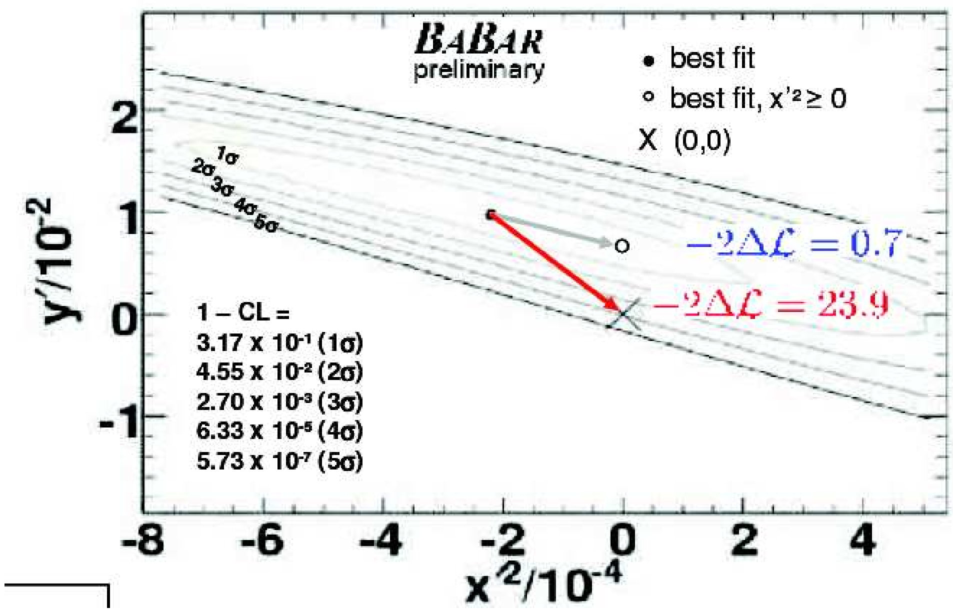

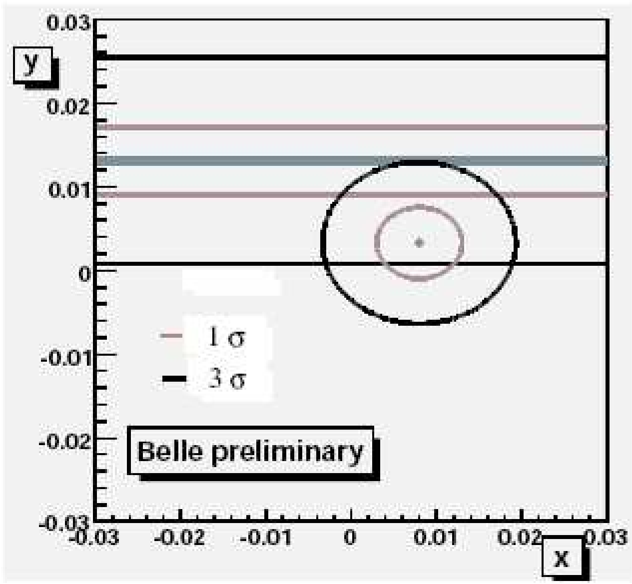

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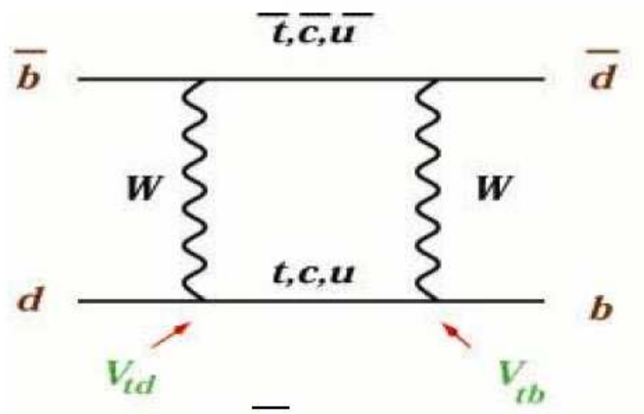
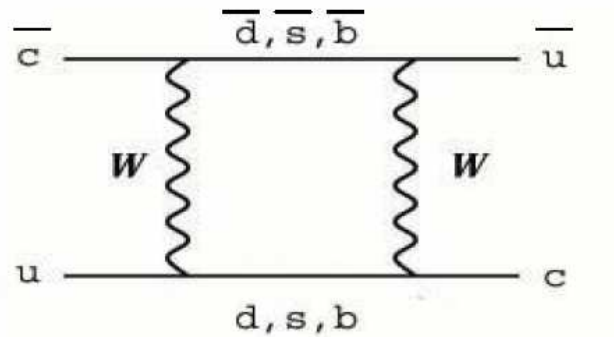
Sorry. . . What is it you are talking about?

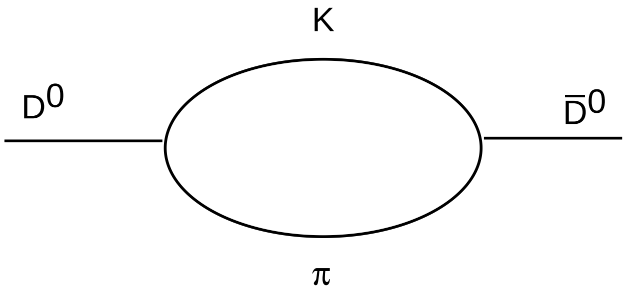
D Mixing: why do we care?



B-$\overline{B}$ mixing



D-$\overline{D}$ mixing



D mixing	B mixing
intermediate down-type quarks	intermediate up-type quarks
SM: b quark contribution is negligible due to V_{ub}	SM: t quark contribution is dominant
$\Delta M \sim$[SU(3) breaking]^2 (Falk hep-ph/0402204)	$\Delta M \propto m_t^2$ and sizeable
sensitive to long distance QCD	described by local Lagrangian

D prefers to decay rather than mix: off-shell intermediate states very relevant, outdo short-distance box diagram.

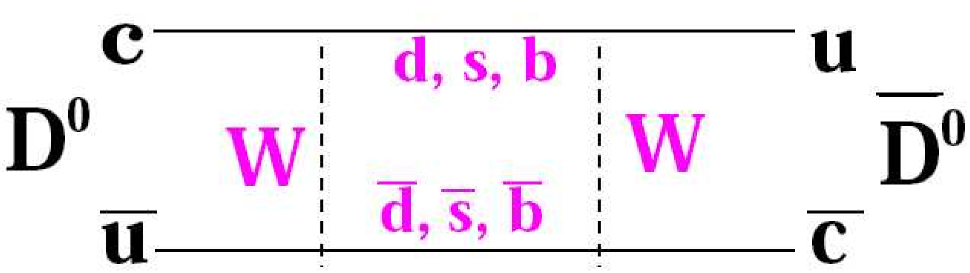
D Mixing: a story of x and y

$$\frac{\partial}{\partial t}\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix} = -i\left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix} D^0 \\ \bar{D}^0 \end{pmatrix}$$

Mass eigenstates: $|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$, $|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$, $|p|^2 + |q^2| = 1$. $|p/q| \neq 1$ sign for CP violation.

Mass and lifetime differences:

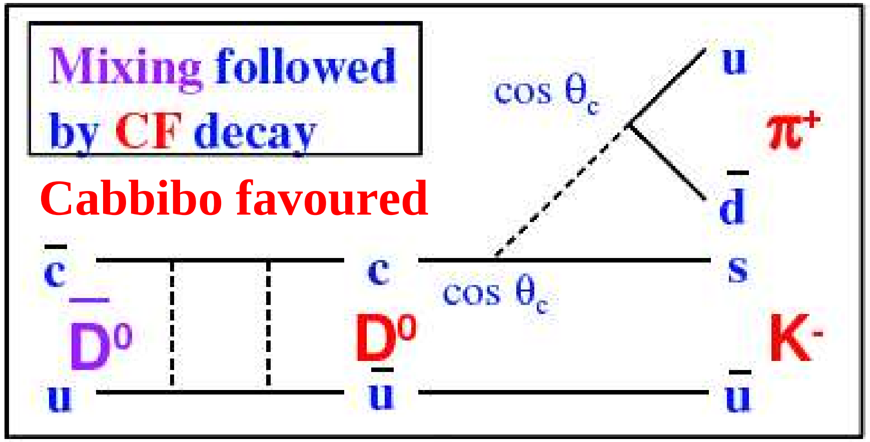
$$x \equiv \frac{\Delta M}{\Gamma} = \frac{M_2 - M_1}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_2 - \Gamma_1}{\Gamma}.$$

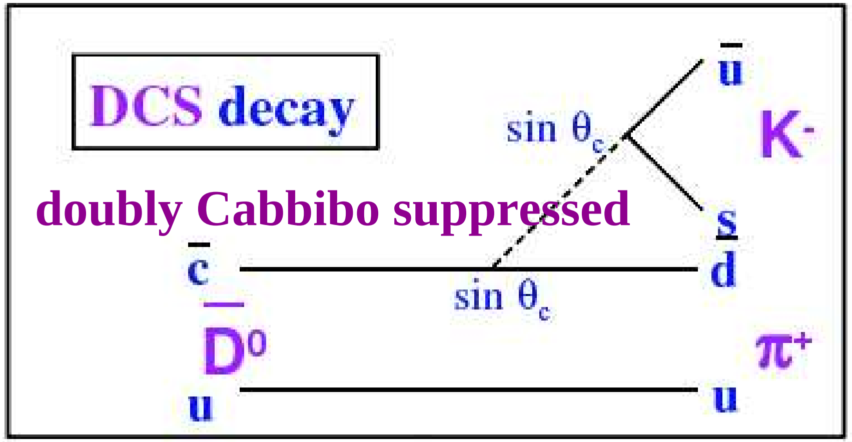


- CP violation in mixing induced by $\phi = \arg(M_{12}/\Gamma_{12})$
- $\phi \sim \lambda^4$ in SM: extremely small, excellent place for BSM to manifest itself

How BaBar and Belle measure D mixing

Time-dependent decay rates $\Gamma(D^0(t) \to K^+\pi^-)$ and $\Gamma(\bar{D}^0(t) \to K^-\pi^+)$





Neglect CP violation, expand to 2nd order in $(\Delta M, \Delta\Gamma) \ll \Gamma$:

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}\, y' \,(\Gamma t) + \frac{x'^2 + y'^2}{4}\,(\Gamma t)^2\right]$$

$R_D \sim \tan^4\theta_C \sim 0.3\%$: ratio of DCS/CF rate;
x', y': differ from x, y by strong phase δ

x', y' vs. x, y

δ : relative strong phase between DCS $A(D^0 \to K^+\pi^-)$ and CF $A(\bar{D}^0 \to K^+\pi^-)$; enters decay rate as

$$x' = x\cos\delta + y\sin\delta, \quad y' = -x\sin\delta + y\cos\delta$$

$$\Gamma(D^0(t) \to K^+\pi^-) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}\, y' \,(\Gamma t) + \frac{x'^2 + y'^2}{4}\,(\Gamma t)^2\right]$$

Extract y' and x'^2 from time-dependent rates.

δ can be (but hasn't been) measured from CP-tagged $D^0_{\rm CP} \to K^\pm\pi^\mp$ decays at Cleo-c.

Another interesting idea (M. Neubert): $\delta_{\pi K}$ could be accessible in the B^0 system from the time-dependent rates in $B^0 \to K\pi$ (measured).

Theory Predictions for x and y

Main difference to B system:

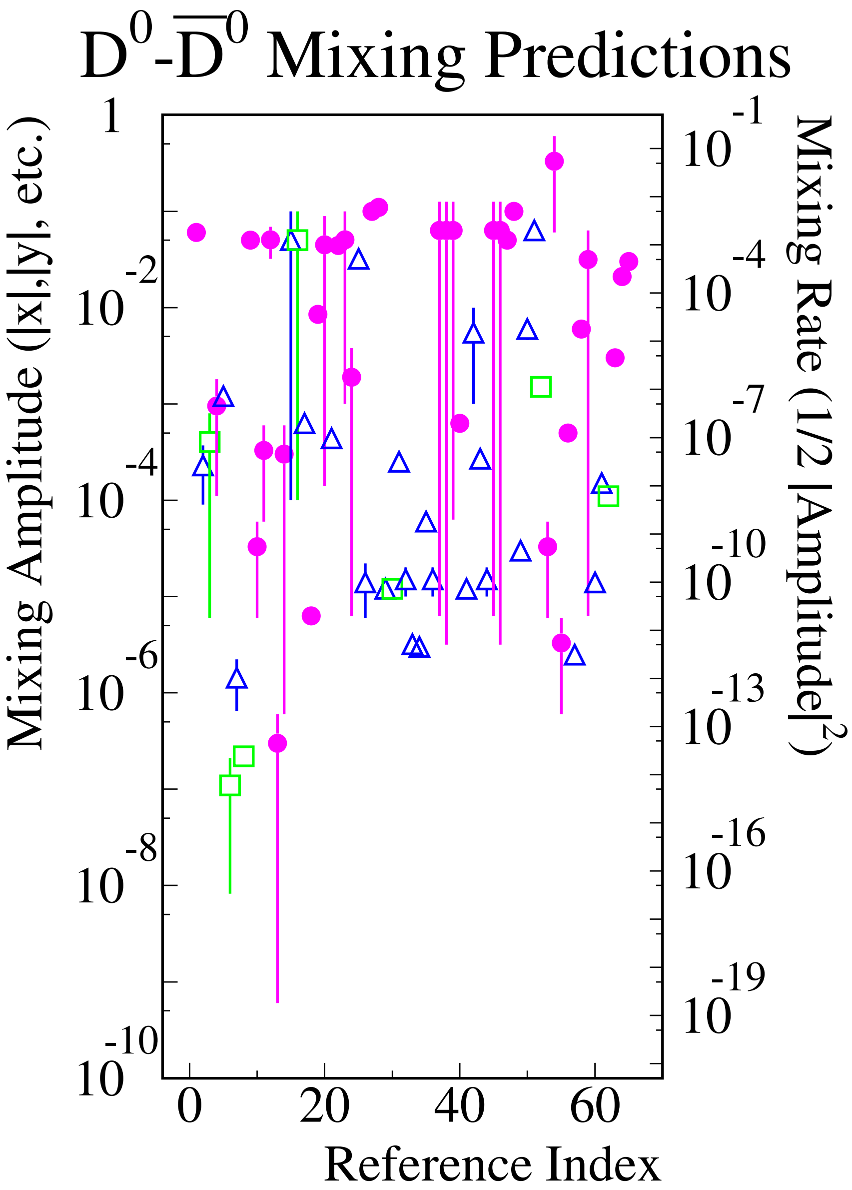
x, i.e. ΔM, dominated by light-quark loops $\Rightarrow$ long-distance (non-local) contributions

x, y given in terms of M_{12}, Γ_{12} with

$$M_{12} = \underbrace{\langle \bar{D}^0 | \mathcal{H}_{\text{eff}}^{\Delta C=2} | D^0 \rangle}_{\text{possible new physics contributions!}} + \underbrace{P \sum_n \frac{\langle \bar{D}^0 | \mathcal{H}_{\text{eff}}^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_{\text{eff}}^{\Delta C=1} | D^0 \rangle}{m_D^2 - E_n^2}}_{\text{SM dominated}}$$

$$\Gamma_{12} = \underbrace{\sum_n \rho_n^{\text{ph.sp.}} \langle \bar{D}^0 | \mathcal{H}_{\text{eff}}^{\Delta C=1} | n \rangle \langle n | \mathcal{H}_{\text{eff}}^{\Delta C=1} | D^0 \rangle}_{\text{SM dominated}}$$

Assorted Theory Predictions for x and y



H. Nelson, hep-ex/9909021

- open triangles: x in SM
- open squares: y in SM
- solid circles: x in various BSM
- y assumed to be not affected by new physics (see, however, Golowich hep-ph/0610039)

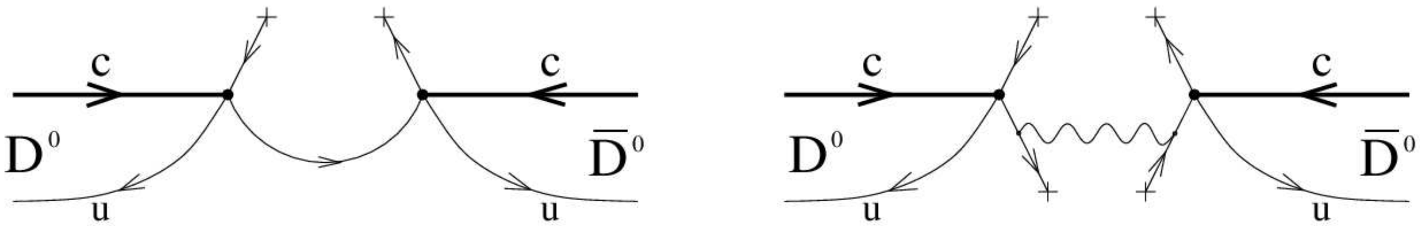
⚠ numbers slightly outdated!

Theory Calculations I: "inclusive"

- assume D is heavy enough for local operator product expansion (OPE) to hold: $m_c \gg \Lambda_{\mathrm{hadronic}}$ (Georgi 92, Ohl 93, Bigi 00)
- power-expand e.g. Γ_{12} in $\Lambda_{\mathrm{hadronic}}/m_c$:

$$\Gamma_{12} = \frac{1}{2M_D} \mathrm{Im} \langle \bar{D}^0 | i \int d^4x T\{\mathcal{H}_{\mathrm{eff}}^{\Delta C=1}(x) \mathcal{H}_{\mathrm{eff}}^{\Delta C=1}(0)\} | D^0 \rangle$$

- leading contribution from box highly GIM-suppressed, $\Delta M \sim m_s^4$, $x_{\mathrm{box}} \sim 10^{-5}$, $\Delta\Gamma \sim m_s^6$, $y_{\mathrm{box}} \sim 10^{-7}$
- suppression relieved by higher-dimensional operators, e.g.



: 6-quark operator

- final estimate: $x_{\mathrm{OPE}} \lesssim y_{\mathrm{OPE}} \lesssim 10^{-3}$: with large uncertainties from bad convergence of OPE

Theory Calculations II: “exclusive”

(Falk/Grossman/Ligeti/Petrov 02, 04)

- D mixing is 2nd order in SU(3) breaking
- assume D is light enough for sum over exclusive states to be dominated by only few terms:

$$y = \sum_n \eta_{\rm CKM}(n)\eta_{\rm CP}(n)\cos\delta_n \sqrt{\mathcal{B}(D^0 \to n)\mathcal{B}(\bar{D}^0 \to n)}$$

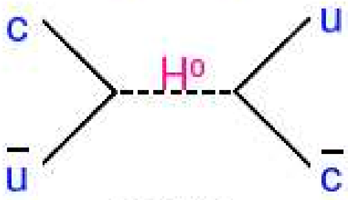
- include effects of SU(3) breaking from phase-space, but not from matrix elements and strong phases
- obtain x from y via a dispersion relation
- final estimate:

$y_{\rm excl} \sim +1\%$, $|x_{\rm excl}| \sim 10^{-3} - 10^{-2}$, $x_{\rm excl}$ and $y_{\rm excl}$ with opposite sign

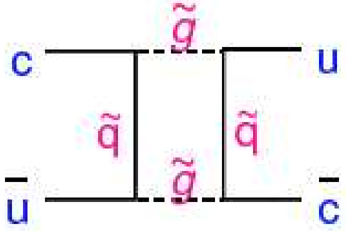
- $D \to 4P$ dominant contribution, uncertainties from measured branching fractions etc.

Possible New Physics Contributions

- Possible enhancements to mixing due to new particles and interactions in new physics models
- Most new physics predictions for ***x***
  - Extended Higgs, tree-level FCNC
  - Fourth generation down-type quarks
  - Supersymmetry: gluinos, squarks
  - Lepto-quarks



FCNC



supersymmetry

- Large possible SM contributions to mixing require observation of either a CP-violating signal or | ***x*** / >> | ***y*** | to establish presence of NP
  - Ann.Rev.Nucl.Part.Sci 53 431-499 (2003)

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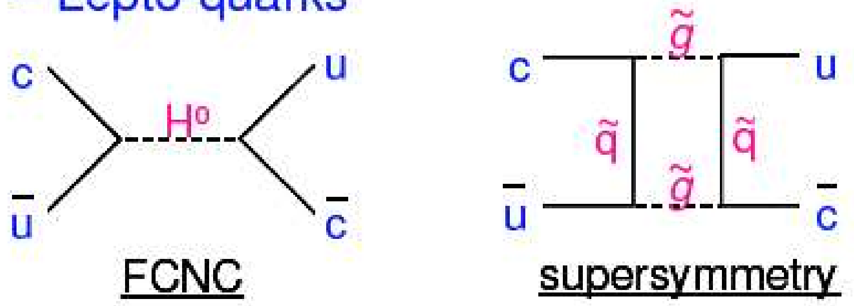

- Large possible SM contributions to mixing require observation of either a CP-violating signal or $|x| \gg |y|$ to establish presence of NP
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CP Violation

- CP violation in D mixing described by weak phase

  $\phi_D = \arg(M_{12}/\Gamma_{12})$; $\phi_D \sim \lambda^4 \sim 10^{-3}$ in SM

- time-dependent rates:

$$\frac{\Gamma(D^0 \to K^+\pi^-)}{\Gamma(\bar{D}^0 \to K^+\pi^-)} = R_D + \sqrt{R_D}\left|\frac{q}{p}\right|(y' \cos\phi_D - x' \sin\phi_D)(\Gamma t) + \left|\frac{q}{p}\right|^2 \frac{x'^2 + y'^2}{4}(\Gamma t)^2$$

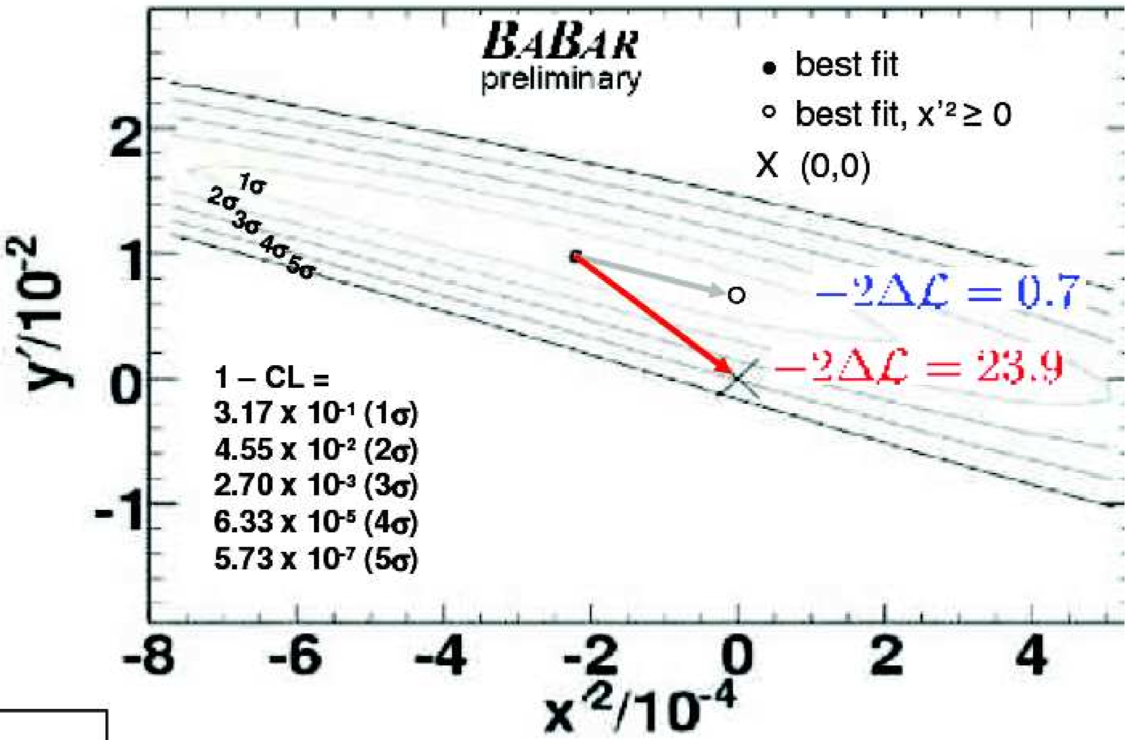
$$\frac{\Gamma(\bar{D}^0 \to K^-\pi^+)}{\Gamma(D^0 \to K^-\pi^+)} = R_D + \sqrt{R_D}\left|\frac{p}{q}\right|(y' \cos\phi_D + x' \sin\phi_D)(\Gamma t) + \left|\frac{p}{q}\right|^2 \frac{x'^2 + y'^2}{4}(\Gamma t)^2$$

- BaBar/Belle found no evidence for $|p/q| \neq 1$, but did not include mixing induced CP violation $\phi_D \neq 0$

Experimental Results – 2nd try

Mixing Contours from D^0−>pi^− K^+

- y', x'^2 contours computed by change in log likelihood
  - Best-fit point is in non-physical region $x'^2 < 0$, but 1-sigma contour extends into physical region
  - correlation: -0.94
- Contours include systematic errors



- **Accounting for systematic errors, the no-mixing point is at ~4-sigma contour**

R_D: $(3.03 \pm 0.16 \pm 0.06) \times 10^{-3}$

x'^2: $(-0.22 \pm 0.30 \pm 0.20) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 2.9) \times 10^{-3}$

Experimental Results – 2nd try

$D^0 \to K\pi$ *(Belle, 400 fb^{-1})*

Unbinned fit to time distribution

Results

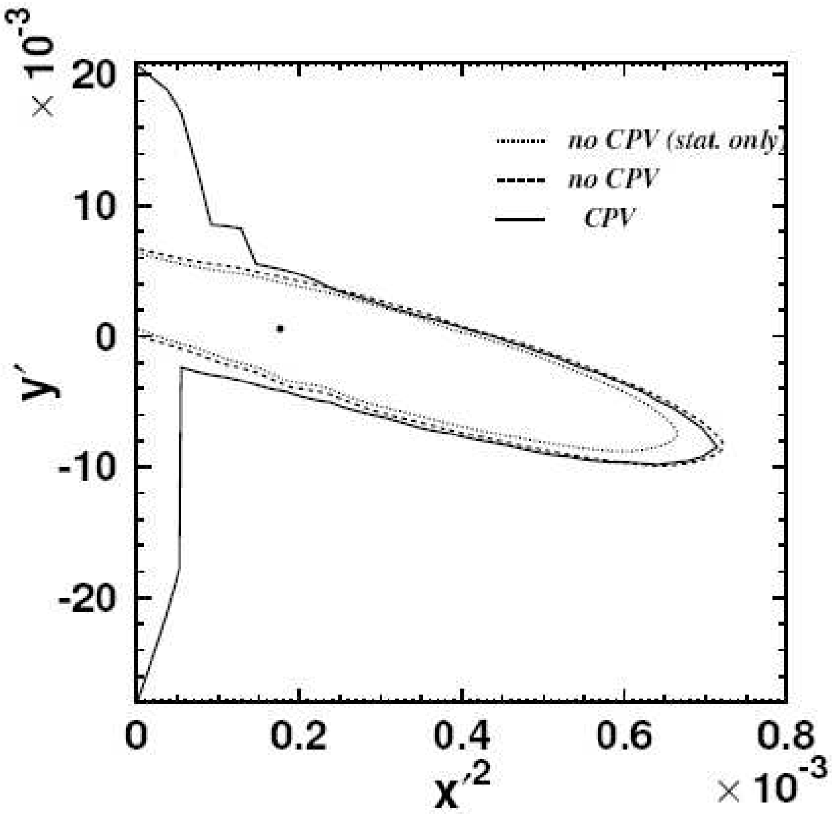
- Assuming CP conservation

$$R_D = (0.364 \pm 0.017)\%$$

$$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$$

$$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$$

- CP asymmetries consistent with 0
  $\to$ no evidence for CPV



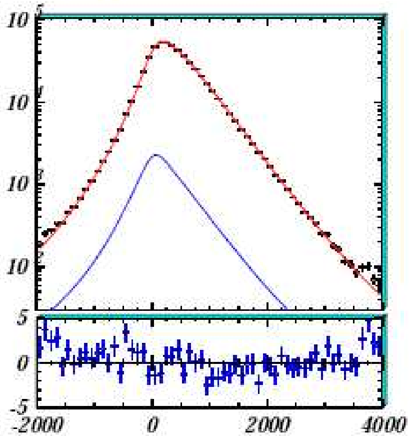
$$R_M < 0.40 \times 10^{-3} \quad @\ 95\%\ C.L.$$

R_M = (x^2+y^2)/2

Experimental Results – 2nd try

$D^0 \to K_s^0 \pi^+\pi^-$ Dalitz (Belle, 540 fb^{-1})

Time fit (in projection)



Results (preliminary)

$$x = 0.80 \pm 0.29 \pm 0.17\ \%$$

$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

$x = 1.8 \pm 3.4 \pm 0.6\%$

$y = -1.4 \pm 2.5 \pm 0.9\%$

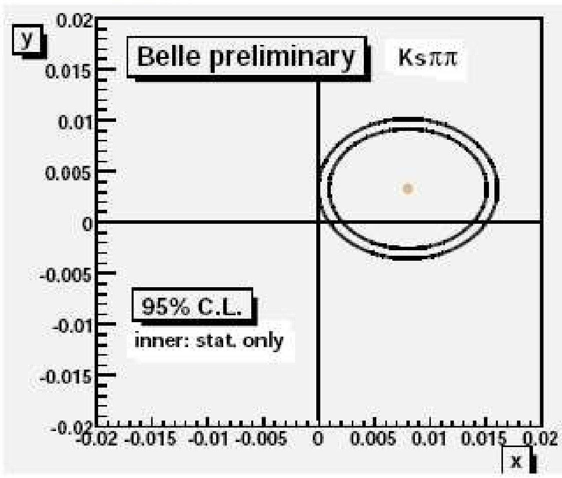
Systematics

Largest contributions ($\times 10^{-4}$)

x	y	
$^{+14.6}_{-13.6}$	$^{+7.8}_{-8.8}$	Model dependence
$^{+8.5}_{-6.8}$	$^{+6.6}_{-11.6}$	Time fit

Total ($\times 10^{-4}$)

x	y
$^{+16.9}_{-15.2}$	$^{+10.2}_{-14.6}$



Experimental Results – 2nd try

$D^0 \to K^+K^-,\ \pi^+\pi^-$ (Belle, 540 fb^{-1})

- Measurement of lifetime difference between $D^0 \to K^-\pi^+$ and $K^+K^-, \pi^+\pi^-$
  - mixing parameter: $y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$
  - in CP conservation limit: $y_{CP} = y = \Delta\Gamma/\Gamma$
- If CP not conserved, difference in lifetimes of $D^0/\bar{D}^0 \to K^+K^-, \pi^+\pi^-$
  - CP violating parameter: $A_\Gamma = \frac{\hat{\Gamma}(D^0\to KK)-\hat{\Gamma}(\bar{D}^0\to KK)}{\hat{\Gamma}(D^0\to KK)+\hat{\Gamma}(\bar{D}^0\to KK)}$

Belle preliminary (540 fb^{-1})

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

$> 3\sigma$ above zero
(4.1σ stat. only)
first evidence for $D^0 - \bar{D}^0$ mixing

$A_\Gamma = 0.01 \pm 0.30 \pm 0.15$ %

no evidence for CP violation

$$
\begin{aligned}
y_{\rm CP} &= \frac{\Gamma(\text{CP even}) - \Gamma(\text{CP odd})}{\Gamma(\text{CP even}) + \Gamma(\text{CP odd})} \\
&\approx \frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to K^-\pi^+)} - 1 \\
&= y\cos\phi - x\sin\phi(A_M + A_{\rm prod})
\end{aligned}
$$

$A_M = |q/p|^2 - 1$, $A_{\rm prod}$: production ass. of $D^0, \bar{D}^0$

Conclusions

- new at Moriond: experimental evidence for D mixing
- $\Delta\Gamma \sim y$ saturates SM predictions (BaBar/Belle) (ditto for $x'^2 + y'^2 \equiv x^2 + y^2$)
- ditto $\Delta M \sim x$ (Belle)
- interpretation in terms of large long-distance hadronic contributions
- long-distance contributions also show up in $\Delta M \sim x$ and obscure possible short-distance new-physics contributions
- tell-tale sign for NP will be CP violation (near zero in SM): no indication yet
- prospects for more accurate theory predictions not very good as D is too light to be treated as heavy and too heavy to be treated as light. . .

Backup Slides

Determination of $\delta_{K\pi}$

At Cleo-c, D and $\bar{D}$ produced in coherent state.

Use CP-specific decays of one D to "CP-tag" the other, e.g. $D \to \pi^0 K_S$ with CP=-1 implies the other state having CP=$+1$.

Neglecting CP violation in mixing (tiny in SM), one has

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

This determines $\cos\delta_{K\pi}$ as

$$1 + R_D \pm 2\sqrt{R_D}\cos\delta_{K\pi} = 2\,\frac{\mathcal{B}(D_{\mathrm{CP}=\pm} \to K^-\pi^+)}{\mathcal{B}(D^0 \to K^-\pi^+)}$$

In the SU(3) limit, $\delta_{K\pi} = 0$, but this can be badly broken.

y from SU(3)-breaking phase-space effects

(Falk/Grossman/Ligeti/Petrov 02)

$y = \frac{1}{\Gamma} \sum_{(F,R)} y_{F,R} \left[\sum_n \Gamma(D^0 \to n) \right]$ running over intermediate states belonging to the class F (PP,PV,VV etc.) and the SU(3) representation R. $y_{F,R}$ is given by

$$y_{F,R} = \frac{\sum_n \langle \bar{D}^0 | \mathcal{H}_{\text{eff}}^{\Delta C=1} | n \rangle \rho_n^{\text{ph.sp.}} \langle n | \mathcal{H}_{\text{eff}}^{\Delta C=1} | D^0 \rangle}{\sum_n \Gamma(D^0 \to n)}$$

In the exact SU(3) limit, all $y_{F,R} \to 0$ (as $y \to 0$). In the real world, SU(3) is broken by different values of the matrix elements and phase-space effects. The biggest such effect occurs if the sum cannot be completed because some members of R are too heavy for the D to decay into. While the estimated values for PP etc., when all PP decays are physical, are $y_{F,R} \sim 10^{-3}$, for F=4P the cancellation is incomplete ($D \not\to 4K$) and $y_{F,R} \sim 10^{-2}$ can be reached, although with large uncertainties.