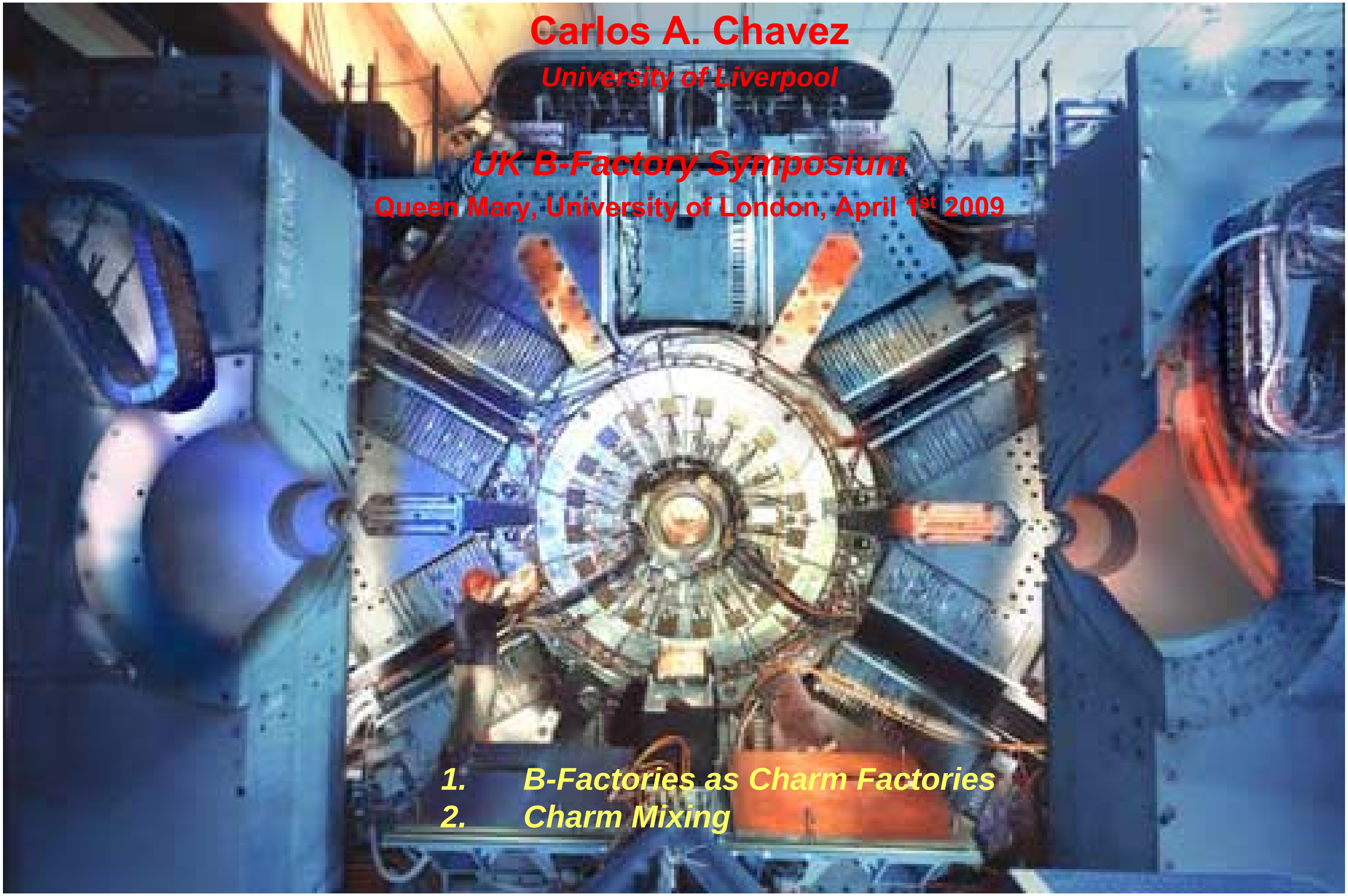
Charm Mixing at BABAR



Carlos A. Chavez

University of Liverpool

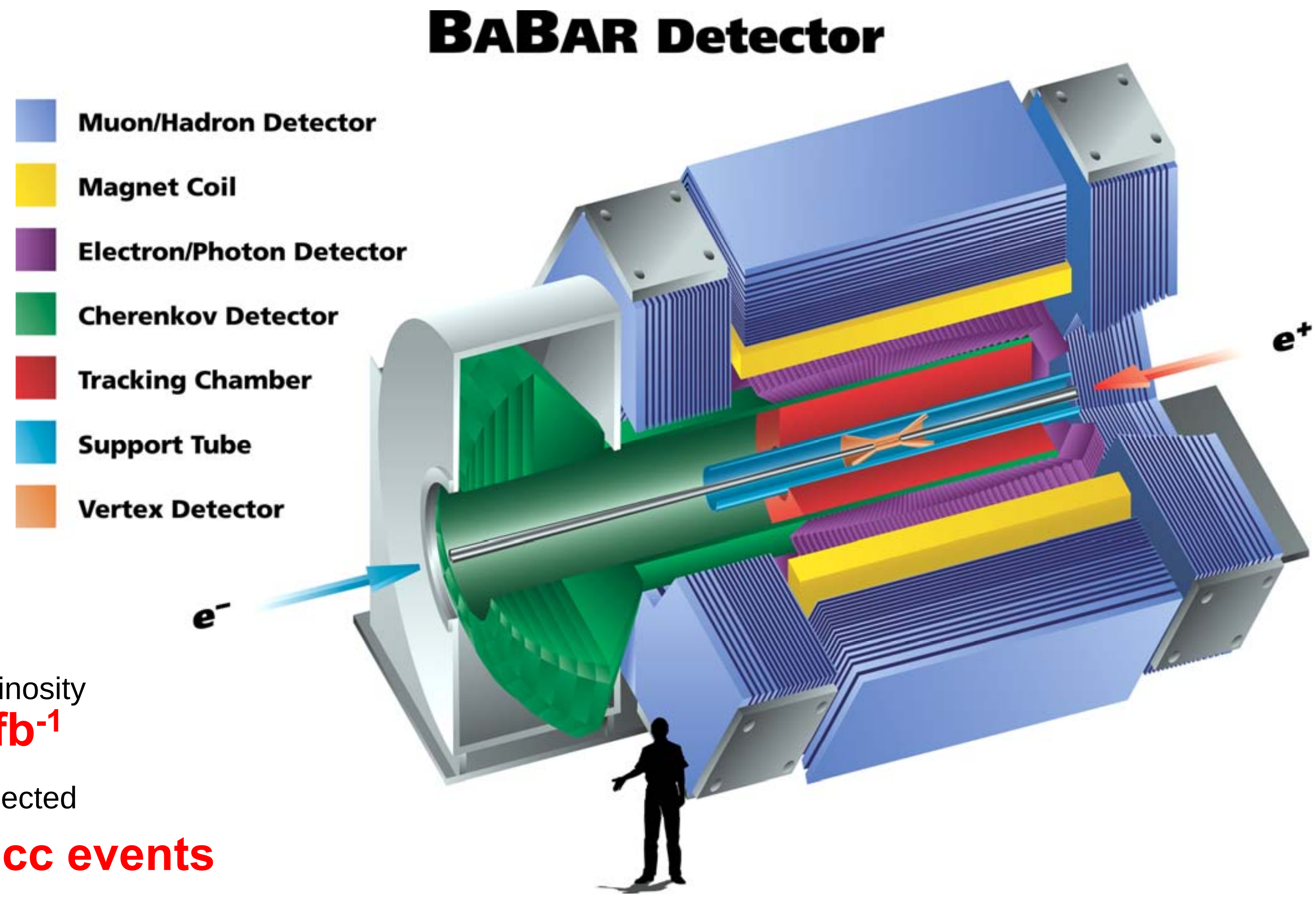
UK B-Factory Symposium

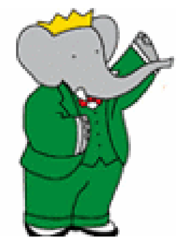
Queen Mary, University of London, April 1st 2009

1. *B-Factories as Charm Factories*
2. *Charm Mixing*

B-Factories as Charm Factories

Production Cross section	Charm σ_{cc} ~ 1.30 nb





Rec. Luminosity
~530 fb^{-1}

Data collected
630M cc events

Charm Mixing Results

BABAR D^0 Mixing Measurements

- $D^0 \to K^+\pi^-$ (WS)
- $D^0 \to K^+K^-, \pi^+\pi^-$ vs $K^-\pi^+$ (Lifetime ratio)
- $D^0 \to K_s\pi^+\pi^-$ (TD Dalitz)

Mixing in D^0 mesons

- Neutral meson mixing has been already observed in the K (1956), B_d (1987) and B_s (2006) systems

- Why is D^0 mixing interesting ?
  - It completes the picture of quark mixing already observed in other systems
  - Provides new information about processes with down-type quarks in the mixing loop diagram
  - It is an important step towards the observation of CP violation in the Charm sector
  - New physics may be present depending on the measured values of the mixing parameters

D^0 Mixing Formalism

Neutral D mesons are produced as *flavor eigenstates* D^0 and $\overline{D}^0$ and decay via :

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

as *mass eigenstates* D_1, D_2

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

where $|q|^2 + |p|^2 = 1$ and

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

D_1, D_2 have masses M_1, M_2 and widths Γ_1, Γ_2

Mixing occurs when there is a *non-zero* mass difference

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

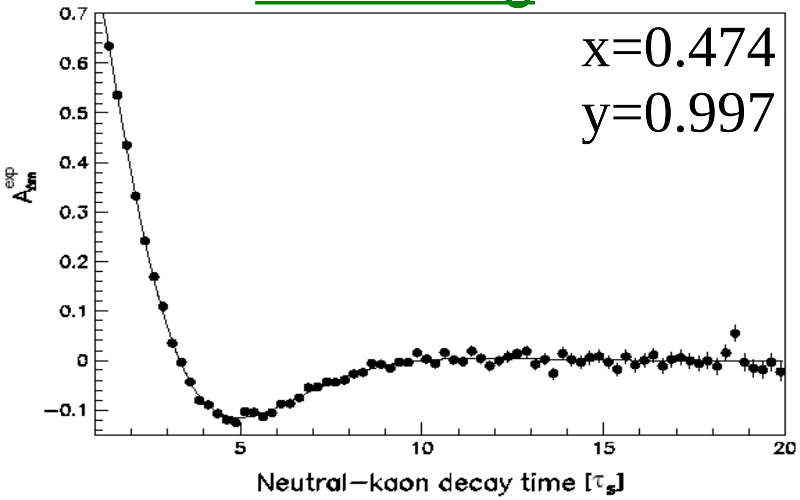
For convenience define quantities $\boldsymbol{x}$ and $\boldsymbol{y}$

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

where $$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Status of Mixing in 2006

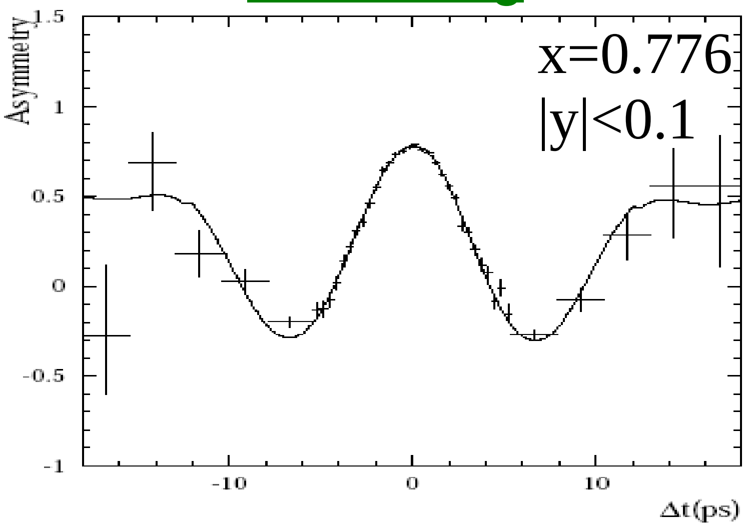
K^0 mixing



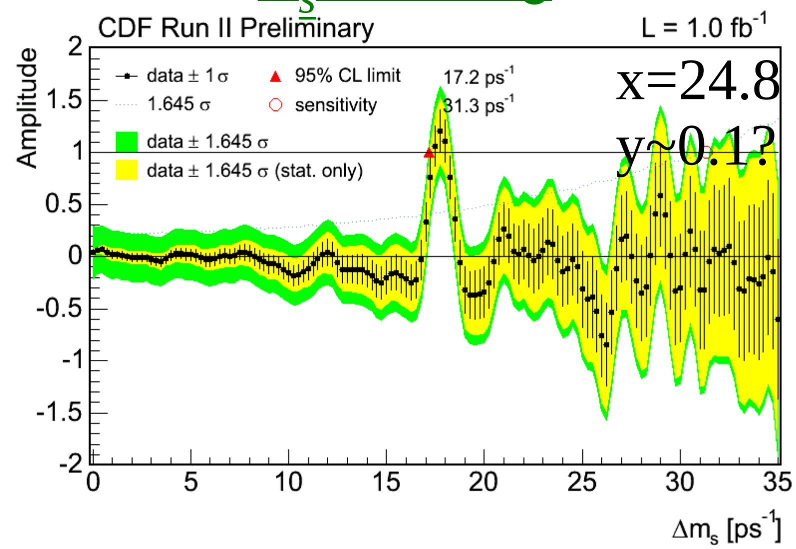
D^0 mixing

?

B^0 mixing



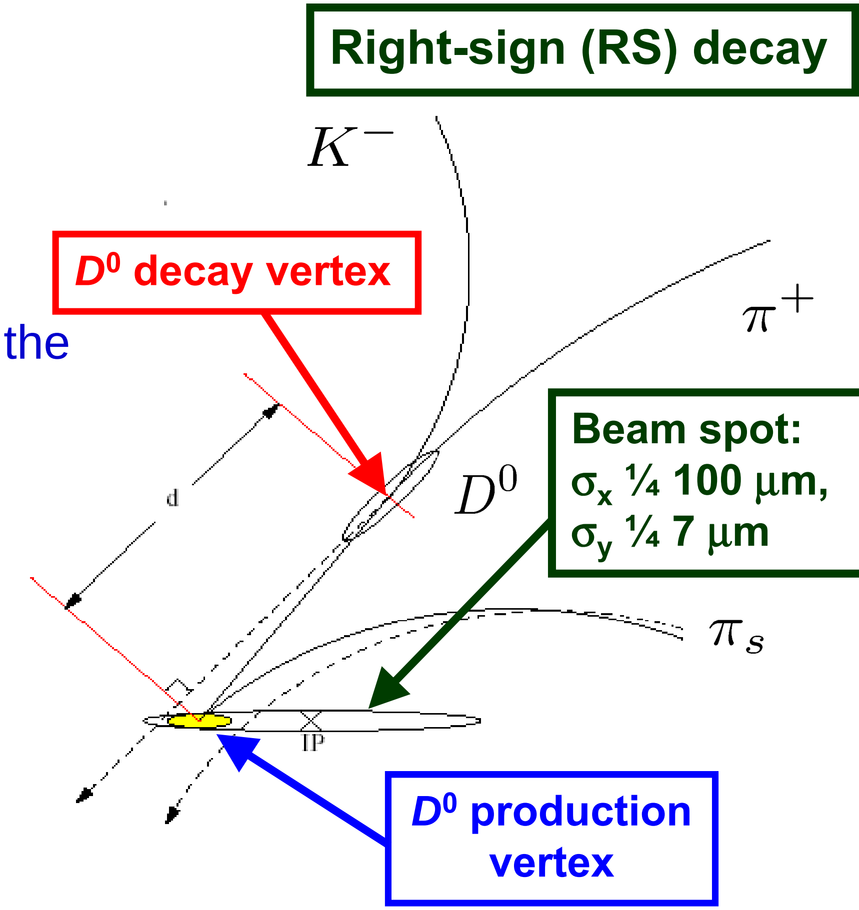
B_s^0 mixing



Generic Mixing Analysis

Select a clean sample of D^0 and $\overline{D}^0$ by tagging the *flavor at production time* using the decays of $D^{*\pm} \to \pi_s^{\pm} D^0$

- We select events around the expected
$$\Delta m = m(D^{*+}_{\text{rec.}}) - m(D^0_{\text{rec.}})$$
- The charge of the slow pion determines the flavor of the D^0



Identify the D^0 *flavor at decay time* using the charge of the Kaon

$D^0 \to K^- \pi^+$ right-sign (RS)

$D^0 \to K^+ \pi^-$ wrong-sign (WS)

Vertices fit with beamspot constraint determines **$m_{K\pi}$, Δm, proper-time t** and **error δ_t**

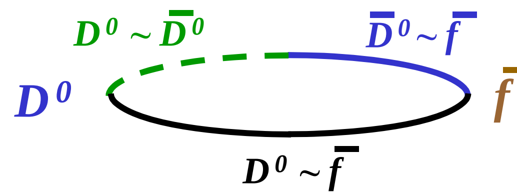
Typical D^0 flight length $d \sim 240\ \mu\text{m}$
Average resolution $\sigma_d \sim 95\ \mu\text{m}$

Mixing in "Wrong Sign" Decays ($D^0 \to K^+\pi^-$)

Two types of WS Decays:

– Doubly Cabibbo-supressed (DCS)

– Mixing followed by Cabibbo-Favored (CF) decay



Two ways to reach same final state ⇒ interference!

Discriminate between DCS and Mixing decays by their proper time evolution

(assuming *CP*-conservation and |x|«1, |y|«1) :

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(R_\mathrm{D} + \sqrt{R_\mathrm{D}}y'\;\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

DCS decay **Interference between DCS and mixing** **Mixing**

$\delta_{K\pi}$ strong phase difference between CF and DCS decay amplitudes

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

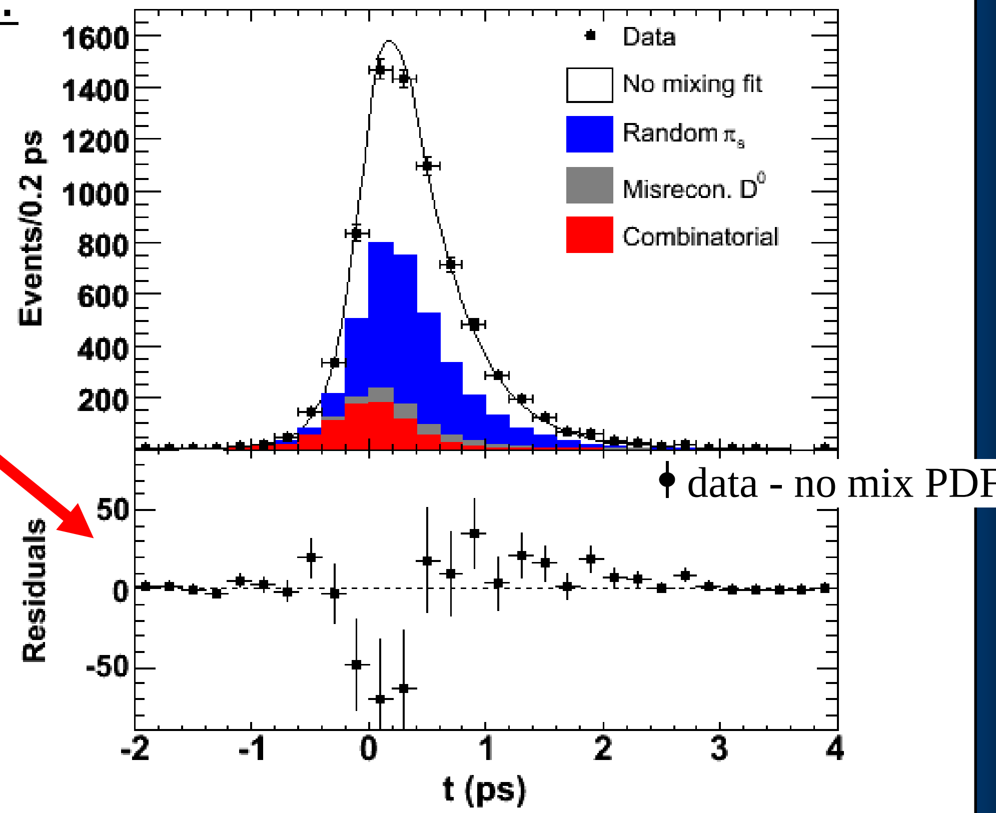
WS Fit with no Mixing

Fit results assuming no mixing:

R_D: $(3.53 \pm 0.08 \pm 0.04) \times 10^{-3}$

However, residuals in signal region are not good

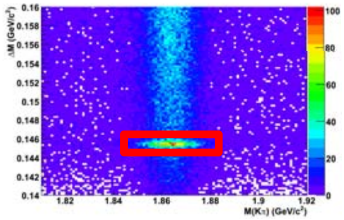
WS decay time, signal region



plot signal region:

$1.843 < m < 1.883$ GeV/c^2

$0.1445 < \Delta m < 0.1465$ GeV/c^2



WS Fit with Mixing

<u>Fit results allowing mixing:</u>

R_D: $(3.03\pm0.16\pm0.10)\times10^{-3}$

x'^2: $(-0.22\pm0.30\pm0.21)\times10^{-3}$

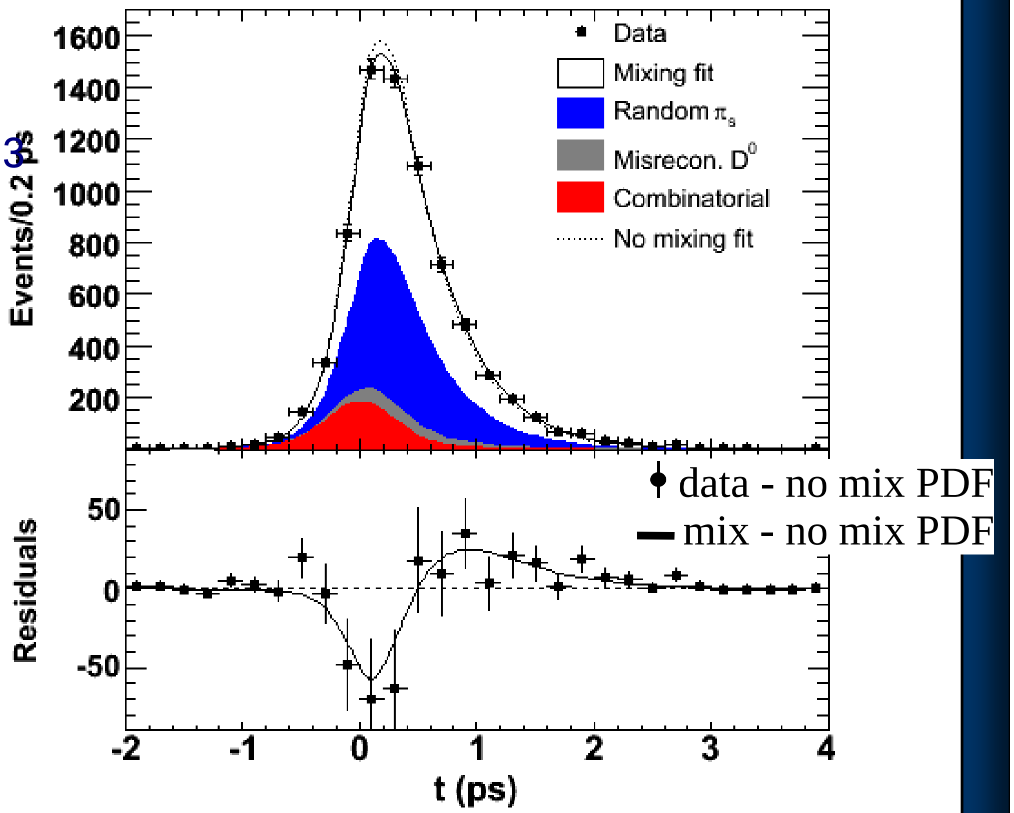
y': $(9.7\pm4.4\pm3.1)\times10^{-3}$

x'^2, y' correlation: -0.94

Fit with gives better description of data →

How significant?

WS decay time, signal region



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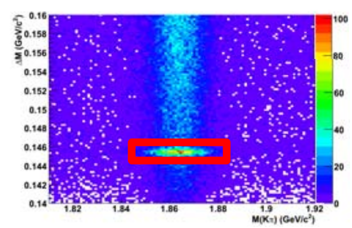
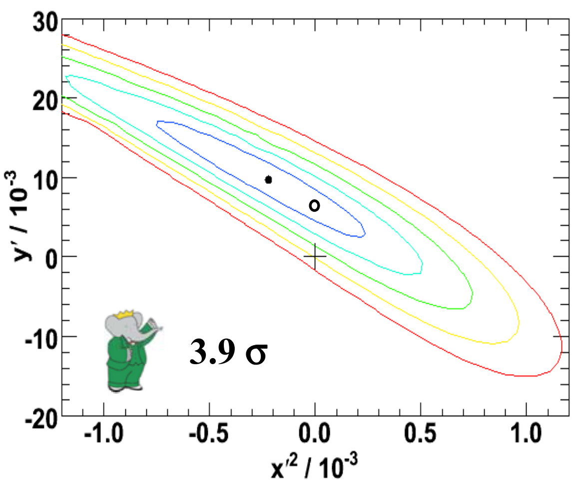


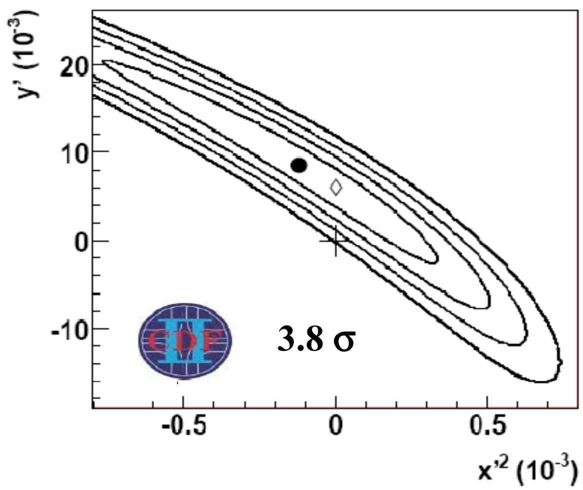
Observations of Mixing in $D^0 \to K^+\pi^-$

Evidence for mixing from *BaBar* (3.9σ) and confirmation by *CDF* (3.8σ)

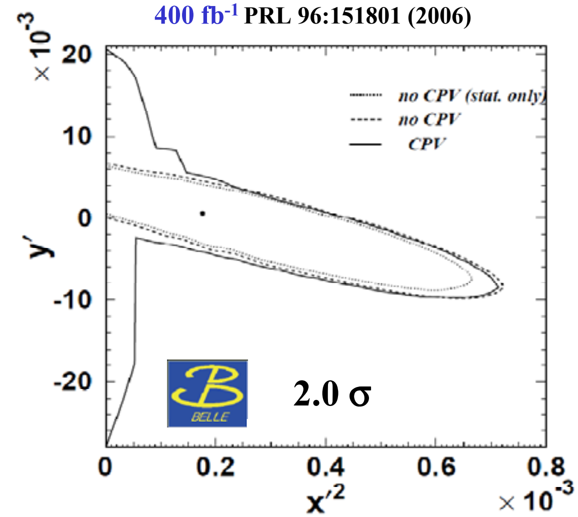
384 fb^{-1} PRL 98,211802 (2007)



1.5 fb^{-1} PRL 100,121802 (2008)



400 fb^{-1} PRL 96:151801 (2006)



Experiment	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$	Mixing Signif.
CDF	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	3.8
BABAR	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle	3.64 ± 0.17	$0.6 + 4.0 - 3.9$	$0.18 + 0.21 - 0.23$	2.0

CLEOc has measured $\delta_{K\pi}$, used to translate x'~x and y'~y, Phys. Rev. D 78, 012001 (2008)

Lifetime Ratio Analysis

- In the absence of *CPV*, D_1 is *CP*-even and D_2 is *CP*-odd
  - Measurement of lifetimes τ for D^0 decays to *CP*-even and *CP*-odd final states lead to a measurement for y_{cp}

$$y_{CP} \equiv \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1, \quad h = K \text{ or } \pi$$

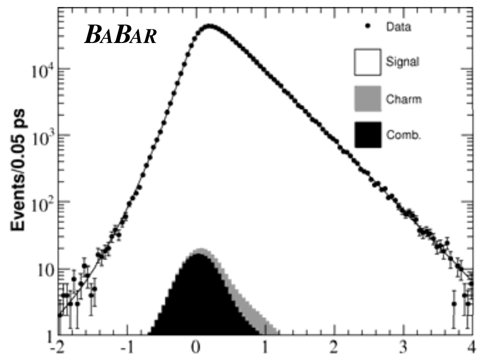
- Allowing for *CPV*, measure the D^0 and D^0 asymmetry

$$\Delta Y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} \frac{\tau_{hh}^{+} - \tau_{hh}^{-}}{\tau_{hh}^{+} + \tau_{hh}^{-}} = -(1 + y_{cp}) A_{\Gamma}$$

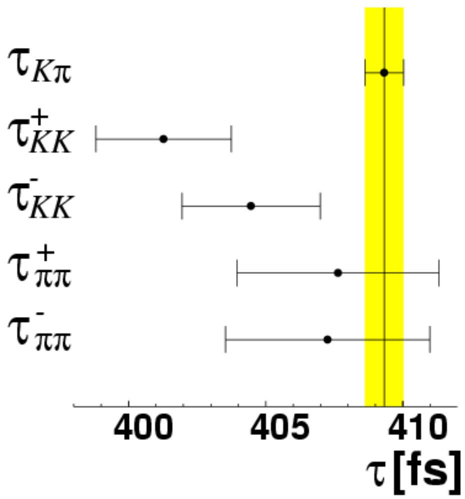
- Tagged events (from D^{*+}! $D^0\pi^+$, decays)
- Most of systematic error cancels in the lifetime ratio.
- Bkg related systematics don't.
- Require:p*>2.5GeV/c, σ_t<0.37ps
- Purity of selection 98%, 98%, 92% for KK, Kπ, $\pi\pi$, respec.

Lifetime Ratio Measurements

$D^0 \to K^-\pi^+ + \text{c.c.}$

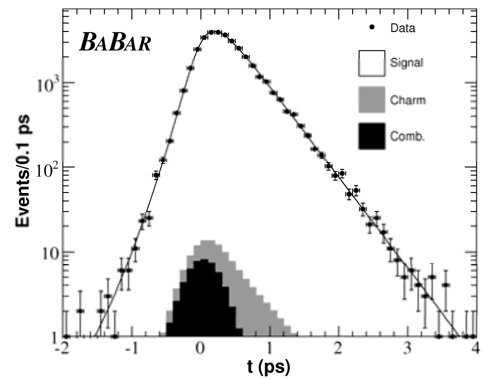


τ=409.3±0.7 fs



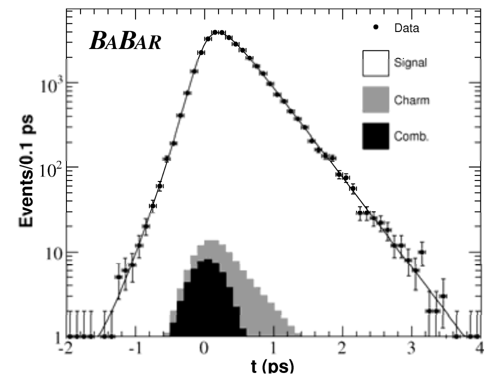
***Kπ* and *KK* lifetimes differ**

$D^0 \to K^+K^-$



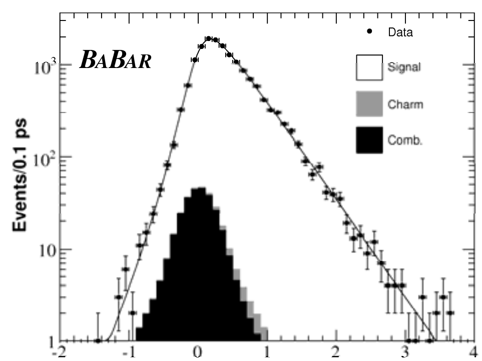
τ=401.3±2.5 fs

$\overline{D}^0 \to K^+K^-$



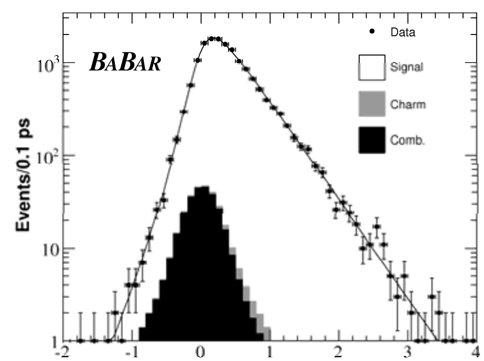
τ=404.5±2.5 fs

$D^0 \to \pi^+\pi^-$



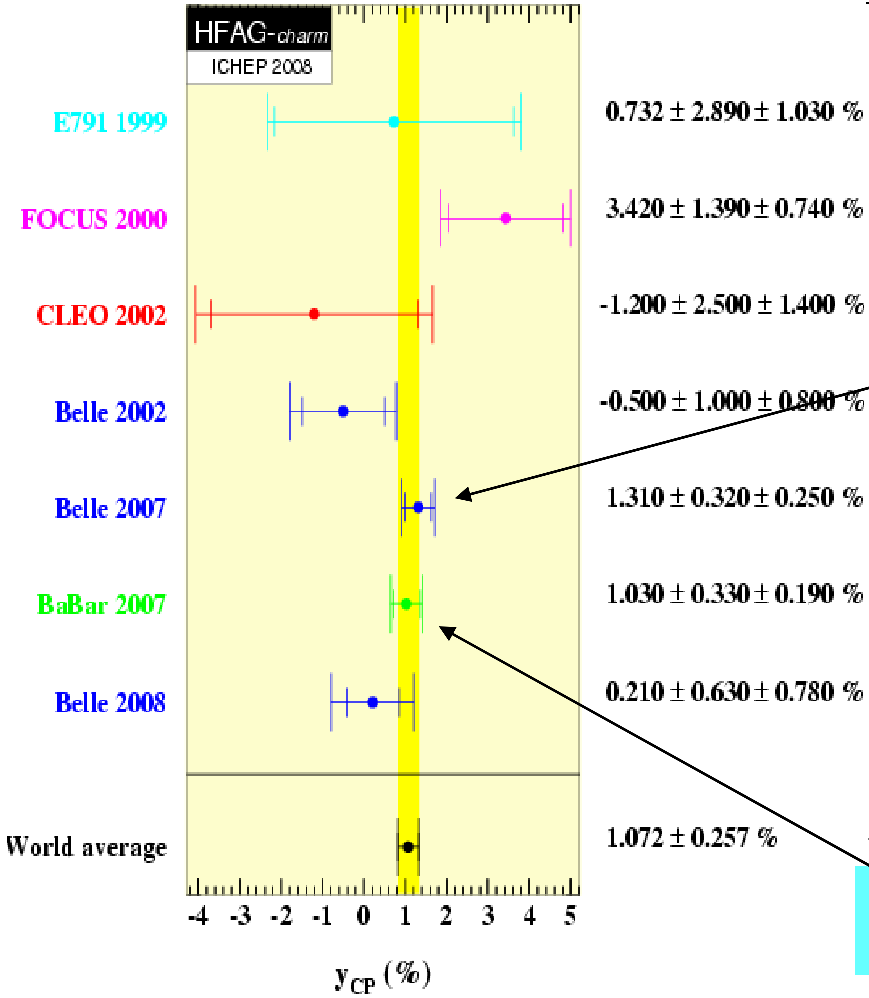
τ=407.6±3.7 fs

$\overline{D}^0 \to \pi^+\pi^-$



τ=407.3±3.8 fs

Lifetime Difference Results



Mode	y_{CP} (%)	A_τ (%)
K^+K^-	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^+\pi^-$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

3.2 σ evidence - no *CPV*

PRL 98 211803 (2007) 540 fb^{-1}

Mode	y_{CP} (%)	$\Delta Y = (1 - y_{CP}) A_\tau$ (%)
K^+K^-	$1.60 \pm 0.46 \pm 0.17$	$-0.40 \pm 0.44 \pm 0.12$
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$
Combined	$1.24 \pm 0.39 \pm 0.13$	$-0.26 \pm 0.36 \pm 0.08$

3.0 σ evidence - no *CPV*

PRD 78 011105(R) (2008) 384 fb^{-1}

Combining 384 /fb tagged and 91 /fb untagged (*BaBar*):
y_{CP} = (1.03 ± 0.33(stat.) ± 0.19(syst.))%

HFAG World Average:
y_{CP} = (1.072 ± 0.257)%
arXiv 0808:1297 (2008)

Mixing in *WS* $D^0 \rightarrow K^+\pi^-\pi^0$ Decays

- Analysis formally similar to the wrong sign $D^0 \rightarrow K^+\pi^-$ analysis but now mixing depends on position in Dalitz plot.

$$\frac{dN_{\bar f}(s_{12}, s_{13}, t)}{ds_{12}ds_{13}dt} = e^{-\Gamma t}\{|A_{\bar f}|^2 + |A_{\bar f}||\bar A_{\bar f}|\left[y\cos\delta_{\bar f} - x\sin\delta_{\bar f}\right](\Gamma t) + \frac{x^2+y^2}{4}|\bar A_{\bar f}|^2(\Gamma t)^2\} \quad (1)$$

DCS → $|A_{\bar f}|^2$; Interference → $|A_{\bar f}||\bar A_{\bar f}|[y\cos\delta_{\bar f} - x\sin\delta_{\bar f}](\Gamma t)$; Mixing → $\frac{x^2+y^2}{4}|\bar A_{\bar f}|^2(\Gamma t)^2$

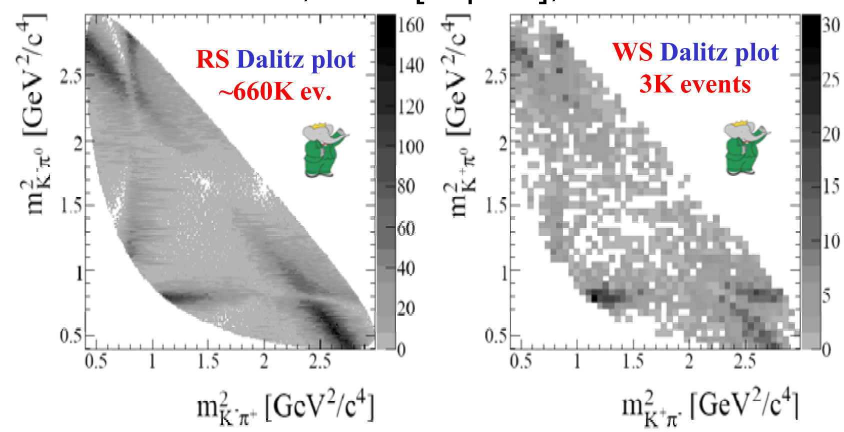
$$\bar A_{\bar f} = \bar A_{\bar f}(s_{12}, s_{13}) = \langle K^+\pi^-\pi^0|H|\bar D^0\rangle$$
$$A_{\bar f} = A_{\bar f}(s_{12}, s_{13}) = \langle K^+\pi^-\pi^0|H|D^0\rangle$$
$$s_{12} = m_{K^+\pi^-}$$
$$s_{13} = m_{K^+\pi^0}$$

- The measured mixing parameters are:

$$x'_{K\pi\pi} = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$
$$y'_{K\pi\pi} = y\cos\delta_{K\pi\pi^0} - y\sin\delta_{K\pi\pi^0}$$

where $\delta_{K\pi\pi^0}$= phase difference between DCS $D^0 \rightarrow \rho K^+$ and CF $\bar D^0 \rightarrow \rho K^+$ reference amplitudes (and cannot be determined in this analysis)

384 fb-1 : arXiv:0807, 4544 [hep-ex], submitted to PRL



Results : No evidence of CPV

$$x'_{K\pi\pi^0} = \left[\ 2.61^{+0.57}_{-0.68}(stat.) \pm 0.39(syst.)\right]\%$$
$$y'_{K\pi\pi^0} = \left[-0.06^{+0.55}_{-0.64}(stat.) \pm 0.34(syst.)\right]\%$$

- Main systematics:
  - Dalitz plot model
  - Event selection criteria
  - Signal and background yields

signal box:
0.1449<Δm<0.1459 GeV/c^2
1.8495<$m_{K\pi\pi}$*<1.8795* GeV/c^2

RS signal purity: 99%
WS signal purity: 50%

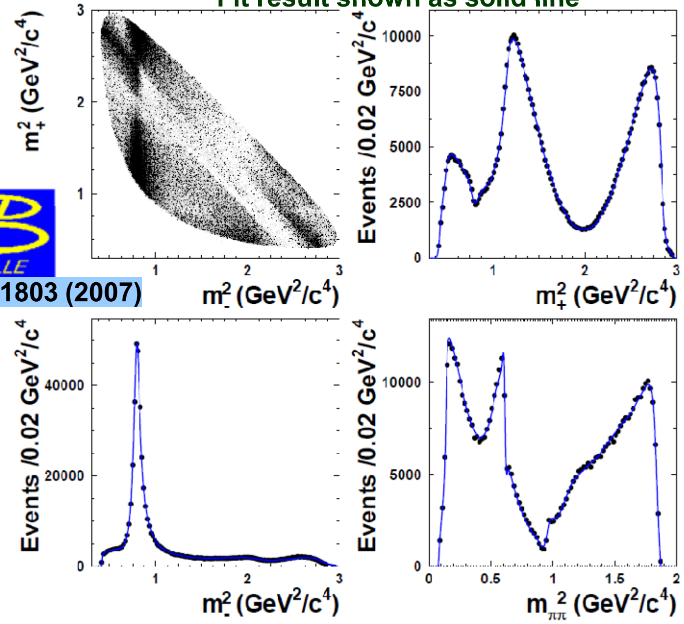
Mixing in $D^0 \to K_s\pi\pi$ Decays

Dalitz plot distribution and projections.
Fit result shown as solid line

Time-dependent, Dalitz-plot mixing analysis

- Uses D^{*+}! $D^0\pi^+$, $D^0 \to K_s\pi\pi$ + c.c. decays
- Observe time dependence of D^0 decays
  - complexity due to Dalitz plot structure
- Analysis assumes *CP* conservation

PRL 99, 131803 (2007)



D^0 decay amplitude is given by

$$M(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2)\frac{e_1(t)+e_2(t)}{2} + \frac{q}{p}\overline{\mathcal{A}}(m_+^2, m_-^2)\frac{e_1(t)-e_2(t)}{2}$$

where $\mathcal{A}$ and $\overline{\mathcal{A}}$ are amplitudes for decay to D^0 or $\overline{D}^0$ as functions of phase-space variables, and

$$m_\pm = \begin{cases} m(K_s, \pi^\pm) & D^{*+} \to D^0\pi^+ \\ m(K_s, \pi^\mp) & D^{*-} \to \overline{D}^0\pi^- \end{cases} \qquad e_{1,2}(t) = \exp\left(-i(m_{1,2} - i\Gamma_{1,2}/2)t\right)$$

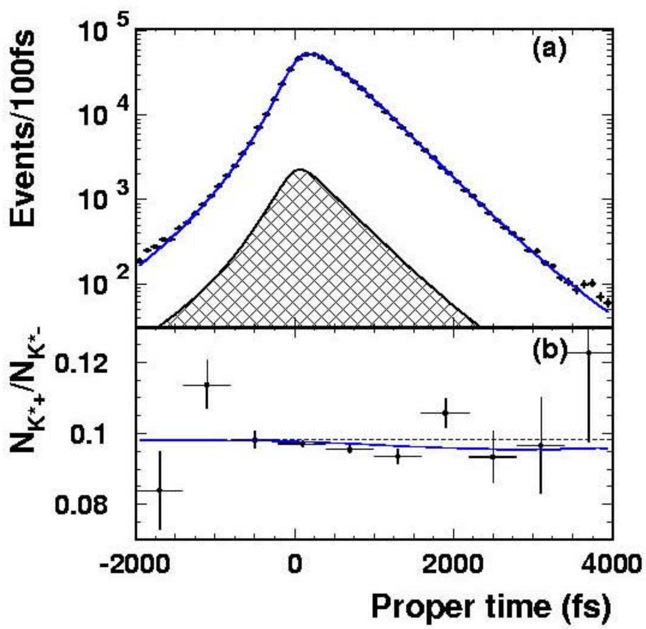
Measures *x* and *y* : no strong phase, *sensitive to x directly*

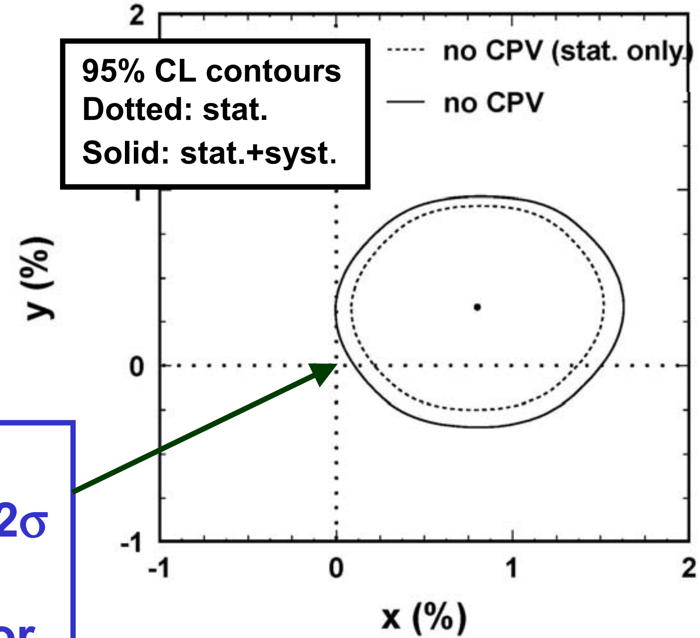
$D^0 \to K_s \pi\pi$ Results

PRL 99, 131803 (2007)
Lumi=540 fb^{-1}

Proper-time fit results

$$x_{K_s\pi\pi} = [0.80 \pm 0.29(stat.) \pm 0.17(syst.)]\%$$
$$y_{K_s\pi\pi} = [0.33 \pm 0.24(stat.) \pm 0.12(syst.)]\%$$





No-mixing excluded at 2.2σ

No evidence for CP violation

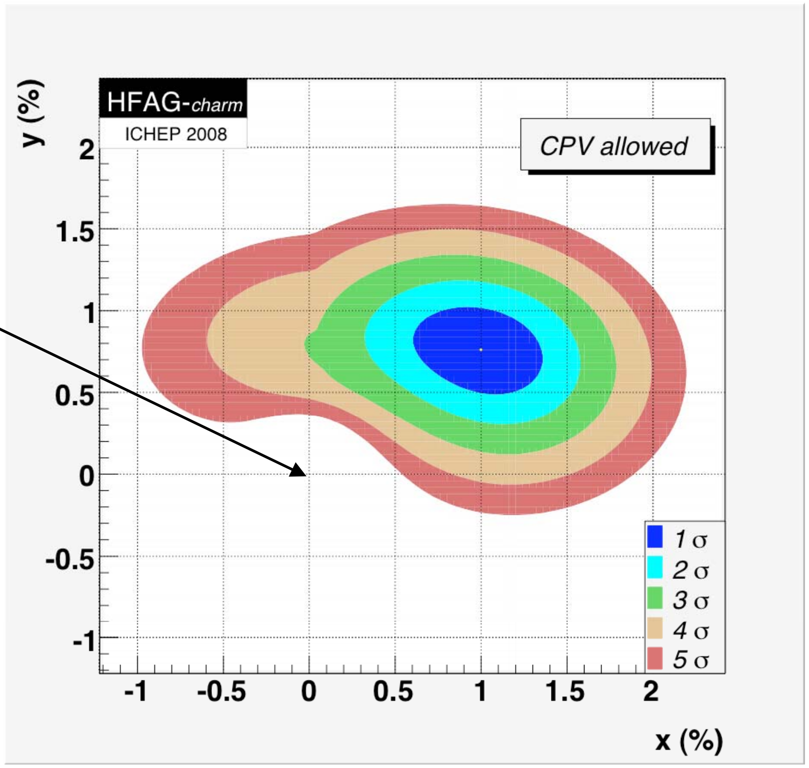
Largest systematics:
- In *x*: from Dalitz fit model
- In *y*: from event selection

(a) Decay-time distribution for total Dalitz-plot region.
(b) Ratio of decay-time distributions for $K^*(892)^+$ and $K^*(892)^-$ regions.

Collective Evidence for D^0 Mixing

*BABAR: PRL **98**, 211802 (2007)*	$D^0 \to K^+\pi^-$ *decay time analysis*	3.9σ
*BELLE: PRL **98**, 211803 (2007)*	$D^0 \to K^+K^-, \pi^+\pi^-$ *vs* $K^+\pi^-$ *lifetime difference analysis*	3.2σ
*BELLE: PRL **99**,131803 (2007)*	$D^0 \to K_s\pi^+\pi^-$ *time dependent amplitude analysis*	2.2σ
*CDF: PRL **100**, 121802 (2008)*	$D^0 \to K^+\pi^-$ *decay time analysis*	3.8σ
*BABAR: PRD **78**, 011105 R (2008)*	$D^0 \to K^+K^-, \pi^+\pi^-$ *vs* $K^+\pi^-$ *lifetime difference analysis*	3σ
BABAR: arXiv:0807, 4544 *(2008)*	$D^0 \to K^+\pi^-\pi^0$ *time dependent amplitude analysis*	3.1σ
	all mixing results combined by HFAG:	**$\sim 10\sigma$**

No-mixing point excluded at 9.8σ



Strong phase from CLEOc measurement
Phys Rev. D 78, 012001 (2008)

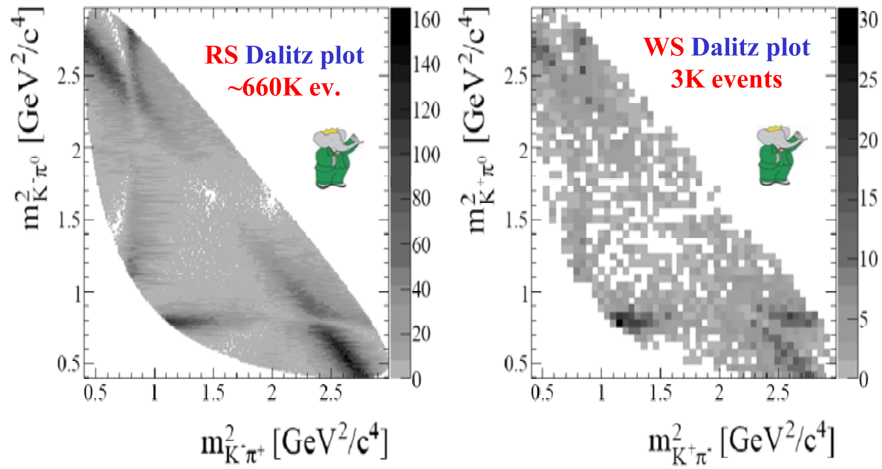
Summary

- Collective evidence for D^0 mixing is compelling when combining Belle and *BABAR* measurements
  - The no-mixing point is excluded at ~10σ, including systematic uncertainties
  - However, no single measurement exceeds 4σ
- Average values of the mixing parameters are *x~1 %, y~0.8 %*
  - compatible with the upper range of standard model predictions
- No evidence of *CP* violation in D^0 decays
- *BABAR* work ongoing:
  - Lifetime ratio analysis of $D^0 \to KK$, and $D^0 \to K\pi$ untagged samples
  - Dalitz analysis of $D^0 \to K_s\pi\pi$ decays

Backup Slides

Mixing in WS $D^0 \rightarrow K^+\pi^-\pi^0$ Decays

- Find *CF* amplitude $\overline{A}_{\bar{f}}$ from time-integrated fit to RS Dalitz plot
  - isobar model expansion
- Use this in time-dependent fit to WS plot to determine $A_{\bar{f}}$ and mixing parameters.



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- Results:

$$x'_{K\pi\pi^0} = \left[\ 2.61^{+0.57}_{-0.68}(stat.) \pm 0.39(syst.)\right]\%$$
$$y'_{K\pi\pi^0} = \left[-0.06^{+0.55}_{-0.64}(stat.) \pm 0.34(syst.)\right]\%$$

- Main systematics:
  - Dalitz plot model
  - Event selection criteria
  - Signal and background yields

- No evidence for *CPV*

Belle $D^0 \to K_s \pi\pi$ analysis

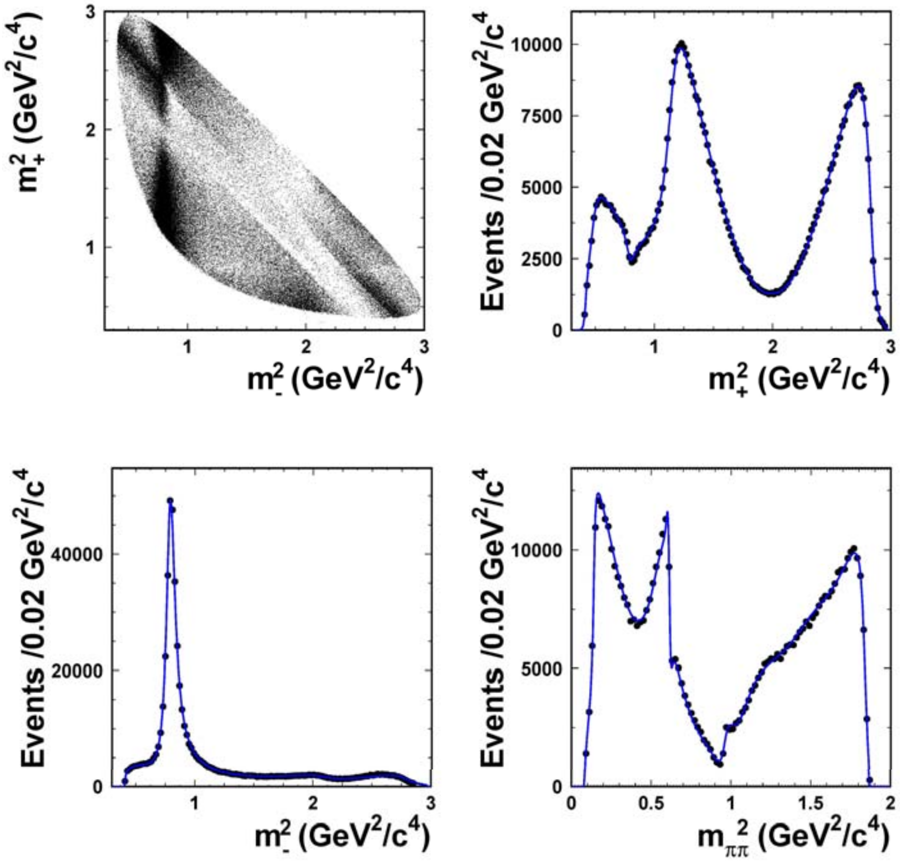
Dalitz fit model

Refinement of Belle φ_3 measurement

13 BW resonances + non-resonant contribution

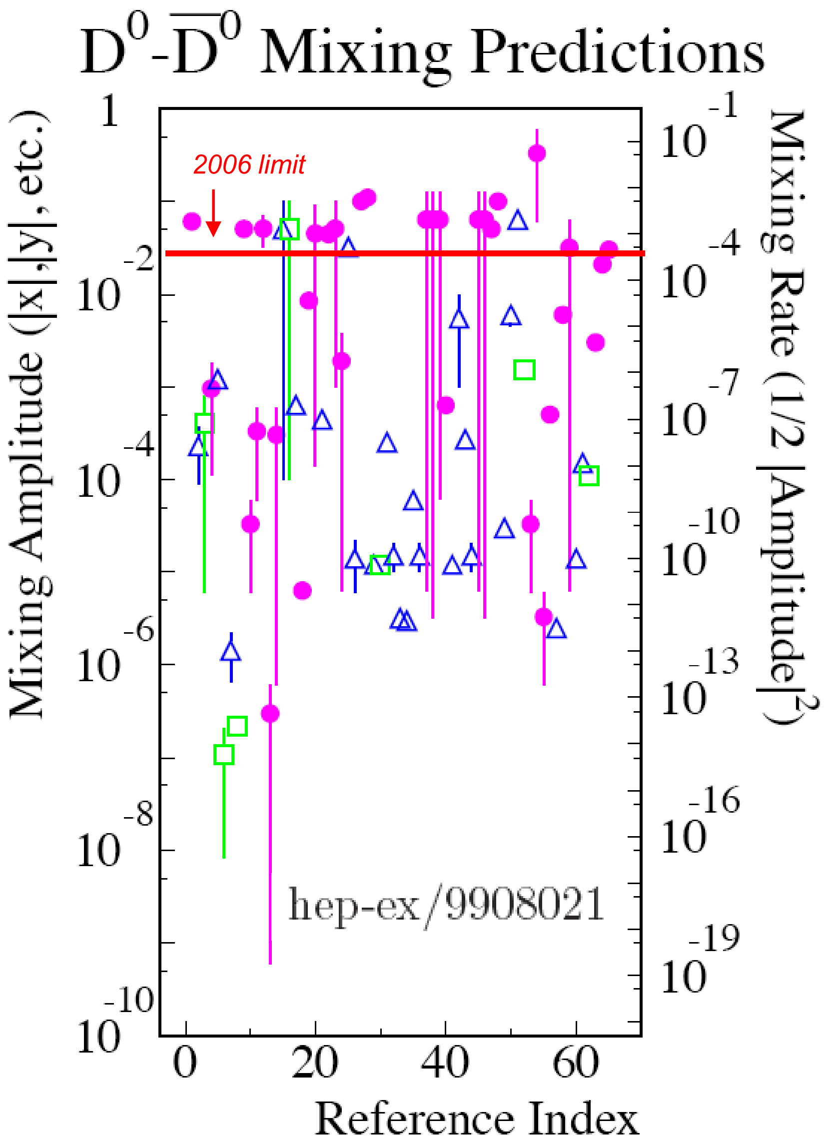
TABLE I: Fit results for Dalitz plot parameters.

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.1	0.0054
$K_0^*(1430)^+$	0.541 ± 0.013	91.8 ± 1.5	0.0047
$K_2^*(1430)^+$	0.276 ± 0.010	-106 ± 3	0.0013
$K^*(1410)^+$	0.333 ± 0.016	-102 ± 2	0.0013
$K^*(1680)^+$	0.73 ± 0.10	103 ± 6	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0006	115.1 ± 0.9	0.0063
$f_0(980)$	0.380 ± 0.002	-147.1 ± 0.9	0.0452
$f_0(1370)$	1.46 ± 0.04	98.6 ± 1.4	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.1	0.0180
$\rho(1450)$	0.72 ± 0.02	40.9 ± 1.9	0.0024
σ_1	1.387 ± 0.018	-147 ± 1	0.0914
σ_2	0.267 ± 0.009	-157 ± 3	0.0088
NR	2.36 ± 0.05	155 ± 2	0.0615



Dalitz plot distribution and projections. Fit result shown as solid line.

New Physics in Charm ?



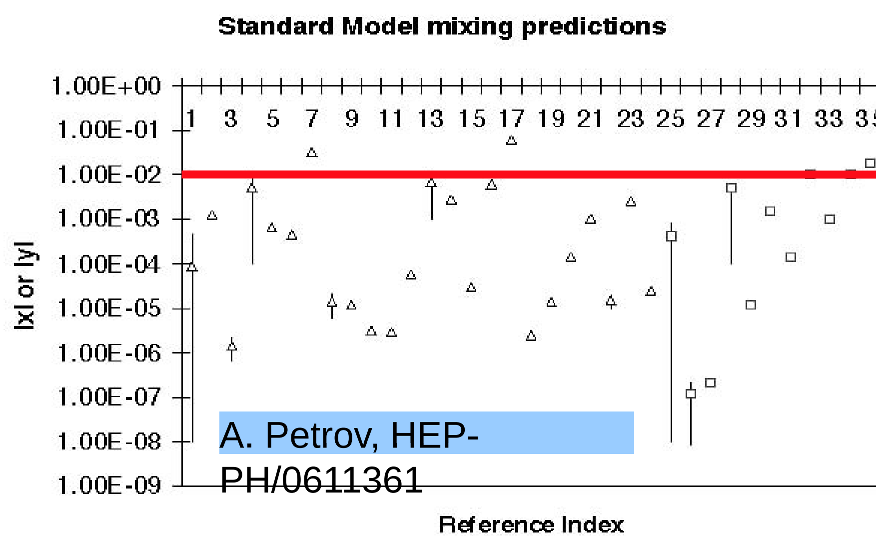
Δ: Standard model predictions for x

□: Standard model predictions for y

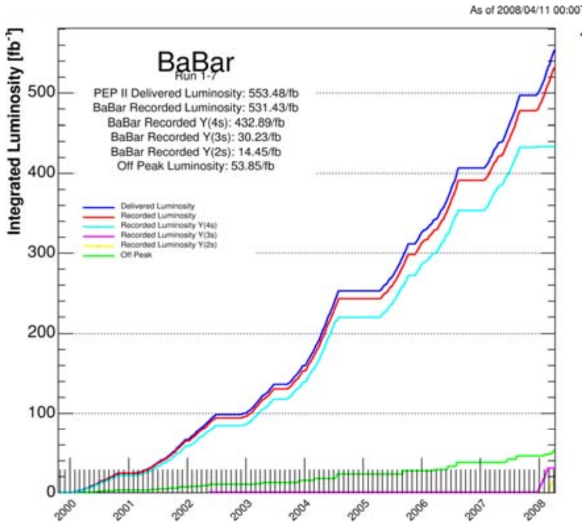
●: New physics predictions for x

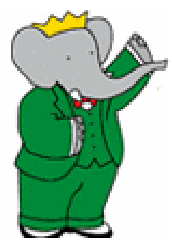
- Hard to see a clear prediction
- *Pushing the limit down excludes models*

Try to separate x and y!



Tau
$\sigma_{tt} \sim 0.92$ nb



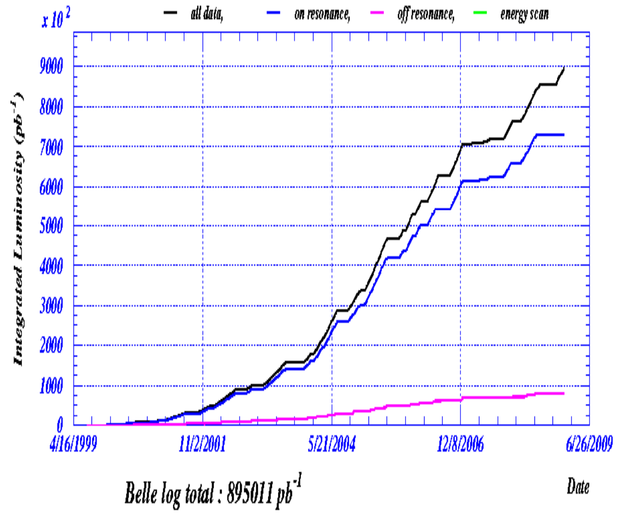


Rec. Luminosity
~530 fb^{-1}

Data collected

484M *BB* pairs,
630M cc events,
880M τ's, etc.

Charm
$\sigma_{cc} \sim 1.30$ nb



Rec. Luminosity
~710 fb^{-1}

Data collected

660M *BB* pairs,
860M cc events,
1200M τ's,
2.6M B_s , etc.