Evidence for D^0-$\overline{D}^0$ Mixing

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Topics

Neutral meson mixing and *CP* violation

Recent *BABAR* charm mixing results

$D^0 \rightarrow K\pi$ analysis

hep-ex/0703020 (submitted to PRL)

Recent BELLE charm mixing results

Lifetime difference analysis

hep-ex/0703036 (submitted to PRL)

$D^0 \rightarrow K_s\pi\pi$ analysis

arXiv:0704.1000

Summary

Charm meson mixing

Why would observation of charm mixing be interesting?

It would *complete the picture* of quark mixing already seen in the *K*, *B*, and B_s systems.

- *K* — PR 103, 1901 (1956); PR 103, 1904 (1956).
- *B* — PL B186, 247 (1987); PL B192, 245 (1987).
- B_s — PRL 97, 021802 (2006); PRL 97, 242003 (2006).

It would provide new information about processes with *down-type quarks* in the mixing loop diagram.

It would be a significant step toward observation of *CP violation* in the charm sector.

It could indicate *new physics*.

Mixing Phenomenology

Neutral *D* mesons

are produced as *flavor eigenstates* D^0 and $\bar{D}^0$

and decay via

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

as *mass, lifetime 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

$$\Delta M = M_1 - M_2$$

or lifetime difference

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

For convenience define quantities *x* and *y*

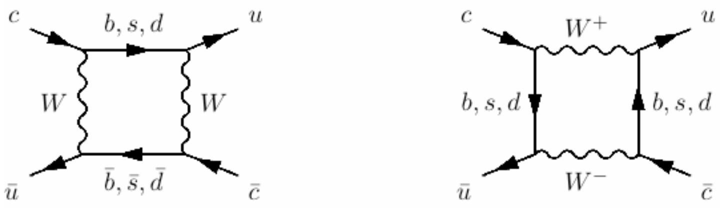
$$x = \frac{\Delta M}{\Gamma}\,, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

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

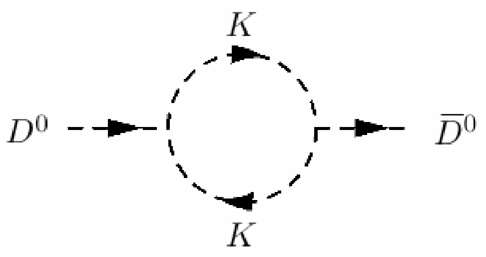
Short- and long-distance effects

- Short-distance contributions from mixing box diagrams primarily affect *x*
  - *b* quark is CKM-suppressed
  - *s* and *d* quarks are GIM suppressed
  - Expect $O(10^{-5})$ or less
- Long-distance contributions primarily affect *y*
  - Non-perturbative effects
  - Expect $O(10^{-2})$ or less
- New physics would be indicated if
  - $x \gg y$
  - *CP* violation is observed

Short-distance



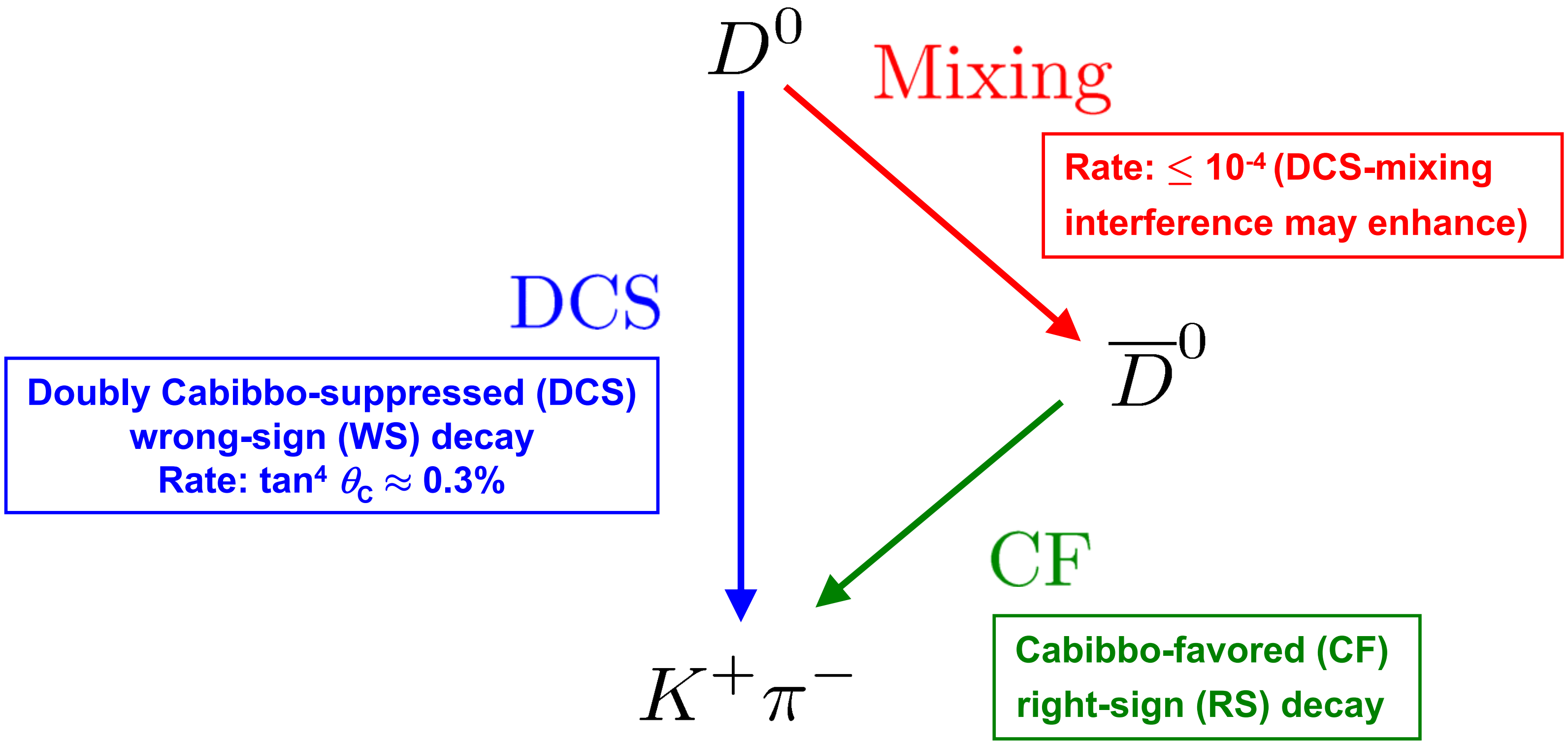
Long-distance



Patricia Ball, hep-ph/0703245, Moriond 2007:
"The central problem of all these calculations is that the D is too heavy to be treated as light and too light to be treated as heavy."

Mixing vs. suppressed decays

Study D^0-$\bar{D}^0$ mixing by tagging the D^0 flavor at production and at decay.



D^0

Mixing

Rate: $\leq 10^{-4}$ (DCS-mixing interference may enhance)

$\overline{D}^0$

DCS

Doubly Cabibbo-suppressed (DCS)
wrong-sign (WS) decay
Rate: $\tan^4 \theta_C \approx 0.3\%$

CF

$K^+\pi^-$

Cabibbo-favored (CF)
right-sign (RS) decay

Time-dependent WS decay rate

For x, $y \ll 1$

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(\underbrace{R_{\mathrm{D}}}_{\text{DCS decay}} + \underbrace{\sqrt{R_{\mathrm{D}}}y'\,\Gamma t}_{\text{Interference between DCS and mixing}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$

Allows for a strong phase difference $\delta_{K\pi}$ between CF and DCS direct decay

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

This phase may differ between decay modes.

And may vary over phase space for multi-body decays.

CP violation

***CP* violation (CPV) can be classified as occurring**

- **In direct decay:** $|\overline{A}_{\overline{f}}/A_f| \neq 1$

  where $A_f = \langle f|H_{\rm w}|D^0\rangle\,,\quad \overline{A}_{\overline{f}} = \langle \overline{f}|H_{\rm w}|\overline{D}^0\rangle$
- **In mixing:** $|q/p| \neq 1$
- **In the interference between them:** $\mathrm{Im}\left(\dfrac{q}{p}\dfrac{\overline{A}_f}{A_f}\right) \neq 0$

CPV introduces an asymmetry in the time-dependence between *D*⁰ and *D̄*⁰ decays

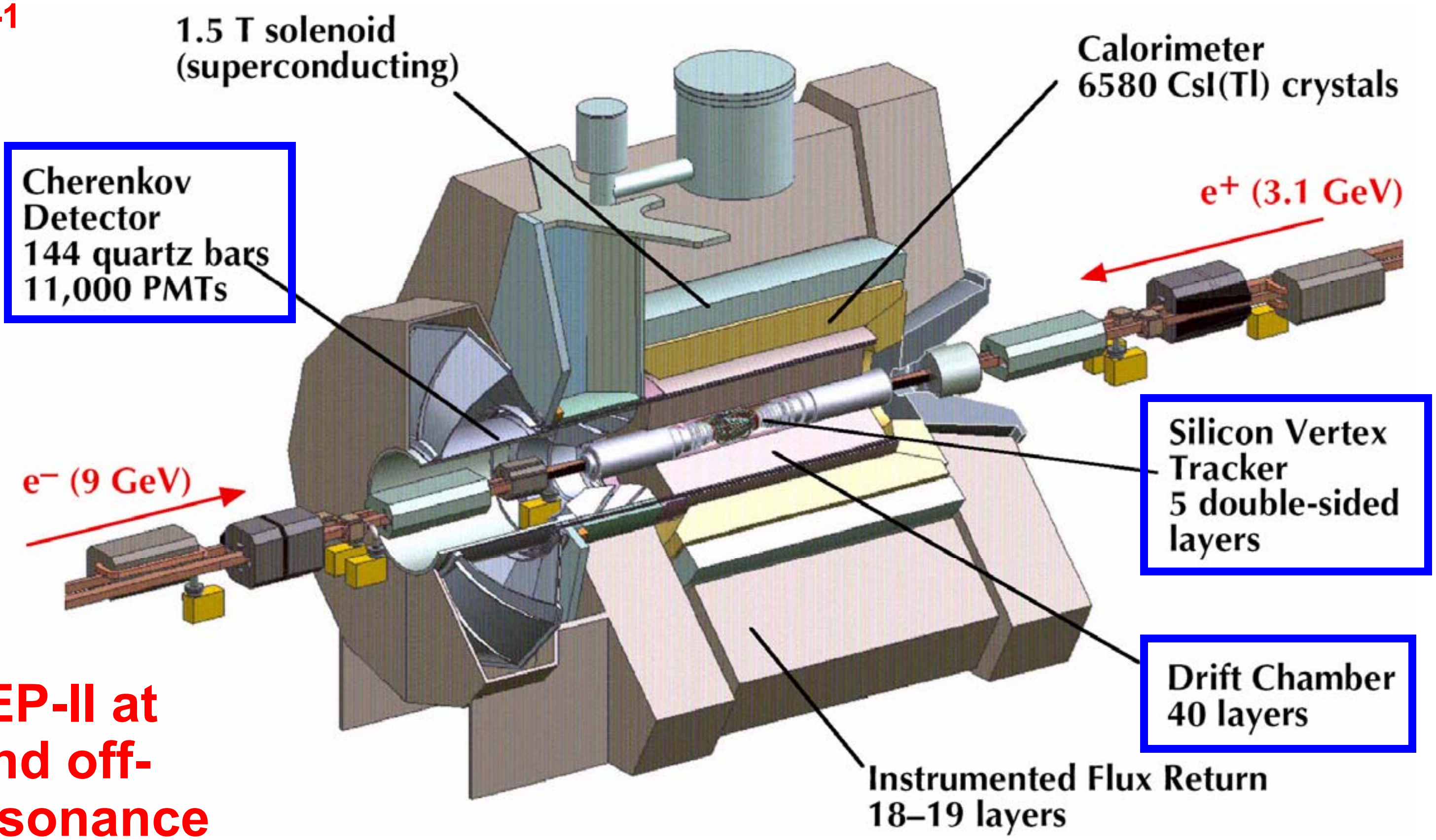
$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \quad\propto\quad e^{-\Gamma t} \times \left[R_{\rm D} + \sqrt{R_{\rm D}}\left|\frac{q}{p}\right|(y'\cos\varphi - x'\sin\varphi)\Gamma t + \left|\frac{q}{p}\right|^2 \frac{x'^2+y'^2}{4}(\Gamma t)^2\right]$$

$$\frac{d\Gamma}{dt}[|\overline{D}^0(t)\rangle \to \overline{f}] \quad\propto\quad e^{-\Gamma t} \times \left[R_{\rm D} + \sqrt{R_{\rm D}}\left|\frac{p}{q}\right|(y'\cos\varphi + x'\sin\varphi)\Gamma t + \left|\frac{p}{q}\right|^2 \frac{x'^2+y'^2}{4}(\Gamma t)^2\right]$$

where φ is the phase angle of $\lambda_f = \left(\dfrac{q}{p}\dfrac{\overline{A}_f}{A_f}\right)$**.**

BABAR detector and dataset

Dataset: 384 fb^{-1}



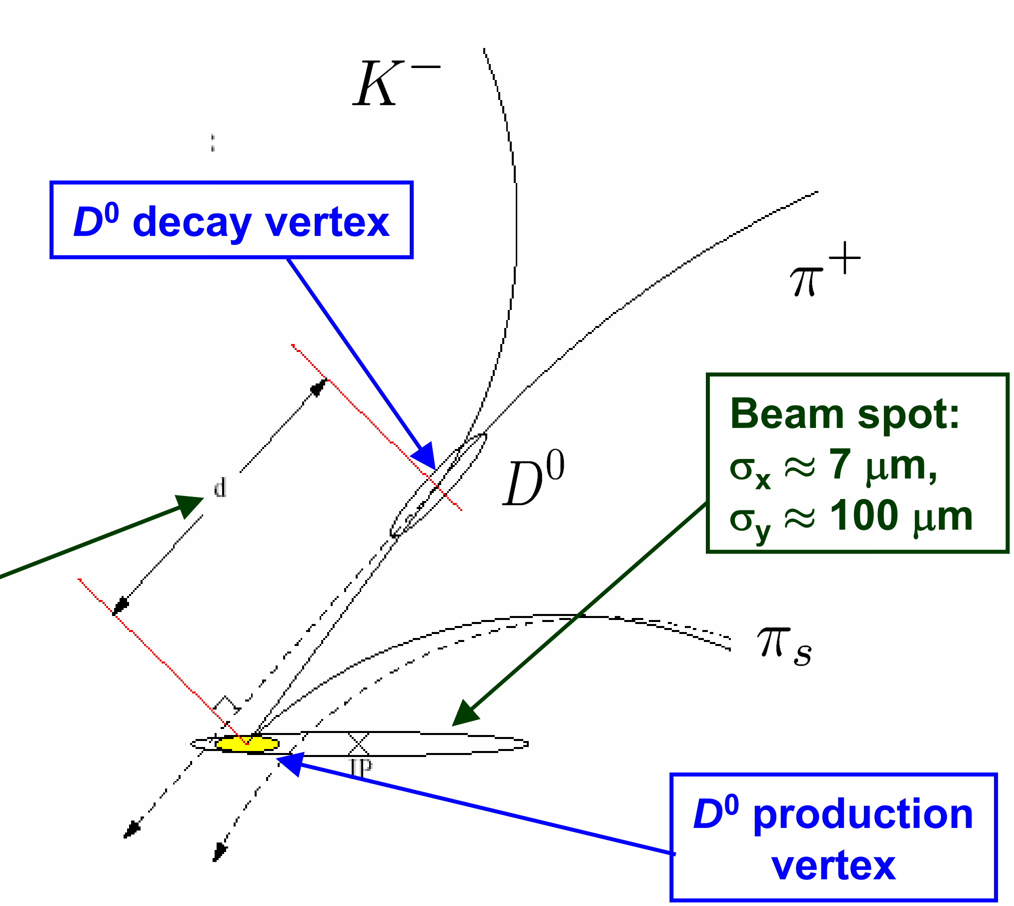
Collected at PEP-II at SLAC on- and off-the Υ(4*S*) resonance

NIM A479, 1 (2002)

$D^0 \to K\pi$ Analysis Method

$$D^{*\pm} \to \pi_s^\pm D^0,\ D^0 \to K^\mp \pi^\pm$$

- **Identify the $D^0/\bar{D}^0$ at production & decay**
  - Determines $m_{K\pi}$, Δm, proper-time t and error δ_t
  - $\Delta m = m(D^{*+}_{\text{rec.}}) - m(D^0_{\text{rec.}})$
- **Vertex fit uses beamspot constraint**
  - Improves the decay-time error
  - Improves the Δm resolution



D^0 decay vertex

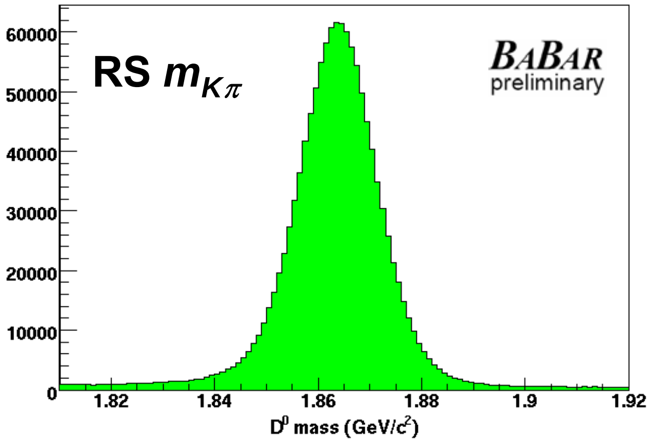
Beam spot:
$\sigma_x \approx 7$ μm,
$\sigma_y \approx 100$ μm

D^0 production vertex

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

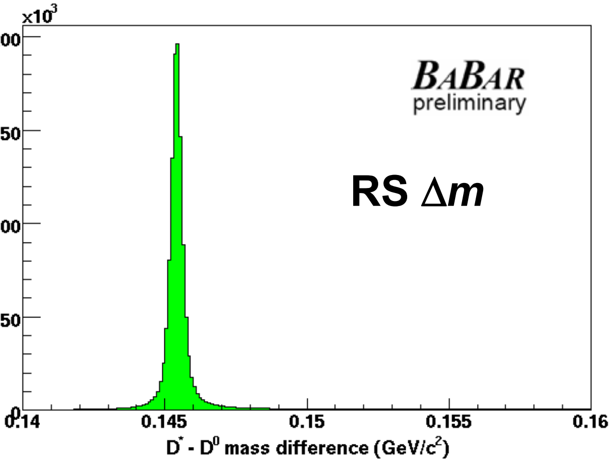
RS & WS $m_{K\pi}$, Δm projections

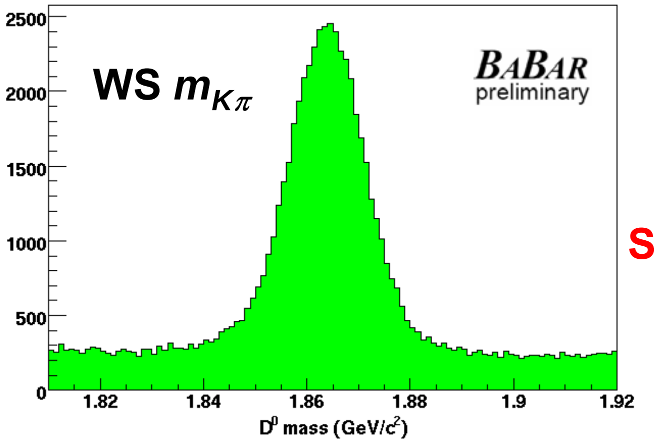
counts/1 MeV/c^2



1,229,000
RS candidates

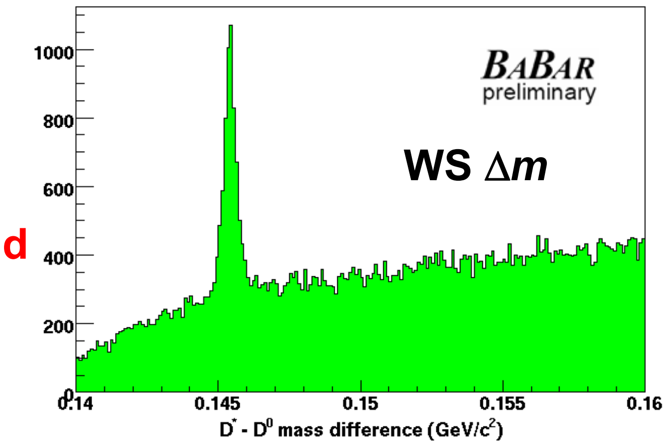
Signal:background
≈ 100:1





64,000
WS candidates

Signal:background
≈ 1:1



counts/0.1 MeV/c^2

Fitting strategy

Fitting is performed in *stages* to reduce demand on computing resources

All stages are *unbinned, extended maximum-likelihood* fits.

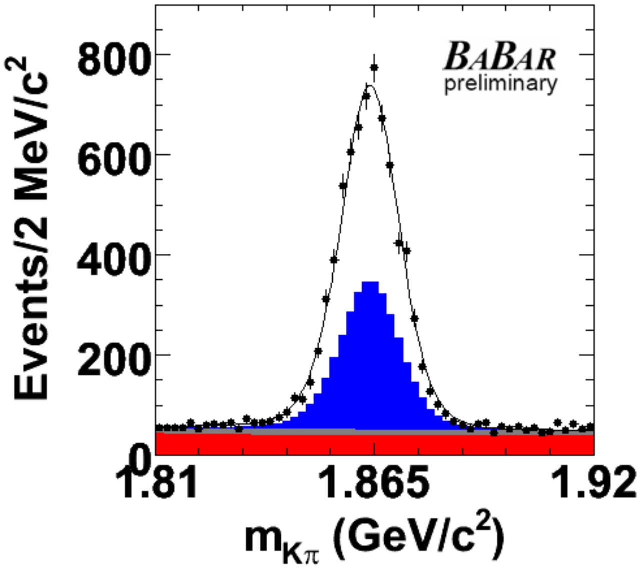
1. RS & WS $m_{K\pi}$, Δm fit.
   - Yields PDF shape parameters $m_{K\pi}$, Δm categories.
2. RS lifetime fit.
   - $m_{K\pi}$, Δm category shape parameters held constant.
   - Yields D^0 lifetime τ_D and proper-time resolution parameters.
   - Constrained by the large statistics of the RS sample.
3. WS lifetime fit.
   - Yields parameters describing the WS time dependence.

The WS fit is performed for three different assumptions:

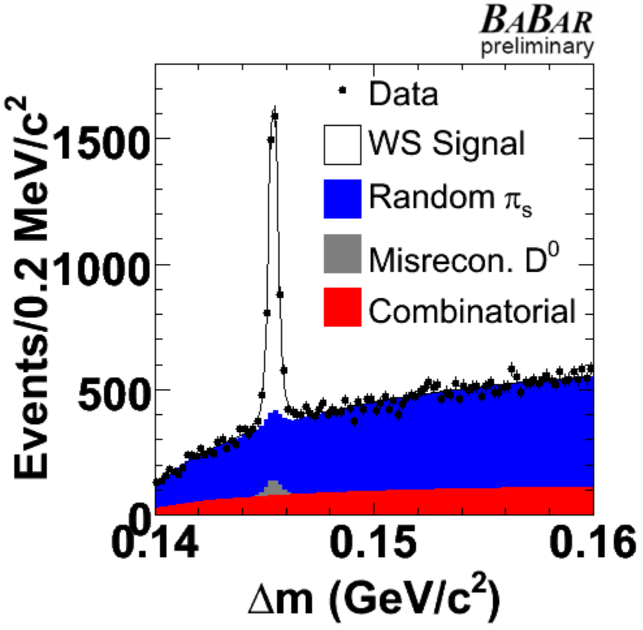
1. Mixing and *CP* violation (CPV)
2. Mixing but no CPV
3. No mixing or CPV

Wrong-sign yield

The $m_{K\pi}$, Δm fit determines the WS b.r. $R_{WS} = N_{WS}/N_{RS}$



4,030 ± 90
WS signal events



BABAR (384 fb^{-1}): R_{WS} = (0.353 ± 0.008 ± 0.004)% (hep-ex/0703020, sub. to PRL)
BELLE (400 fb^{-1}): R_{WS} = (0.377 ± 0.008 ± 0.005)% (PRL 96, 151801 (2006))

No-mixing decay time fit

Fit RS, WS proper-time for:

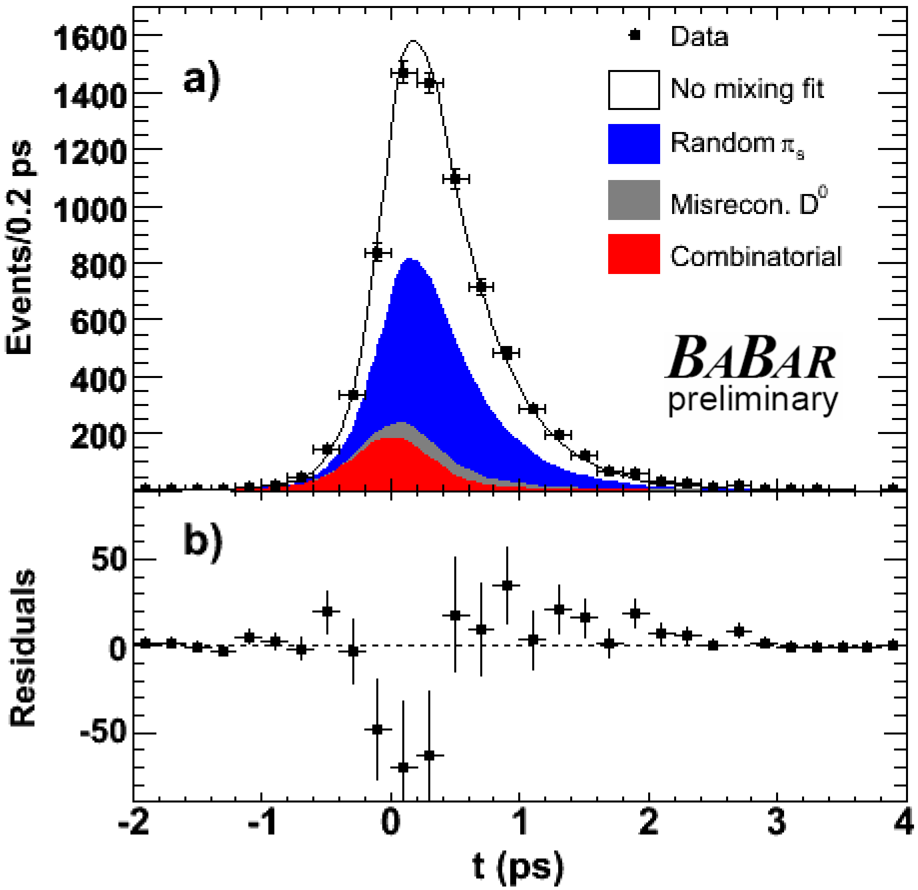
- RS & WS signal, background yields
- D^0 lifetime τ_D
- Proper-time resolution
- WS combinatoric shape parameter

Consistency check

- Fitted τ_D = (410.3 ± 0.6) fsec
  (statistical error only)
- (PDG 2006: 410.1 ± 1.5 fsec)

Residuals show difficulties with the no-mixing fit

- Residuals = data − fit



Projection of WS *no-mixing* fit in signal region
1.843 GeV/c^2 < m < 1.883 GeV/c^2
0.1445 GeV/c^2 < Δm < 0.1465 GeV/c^2

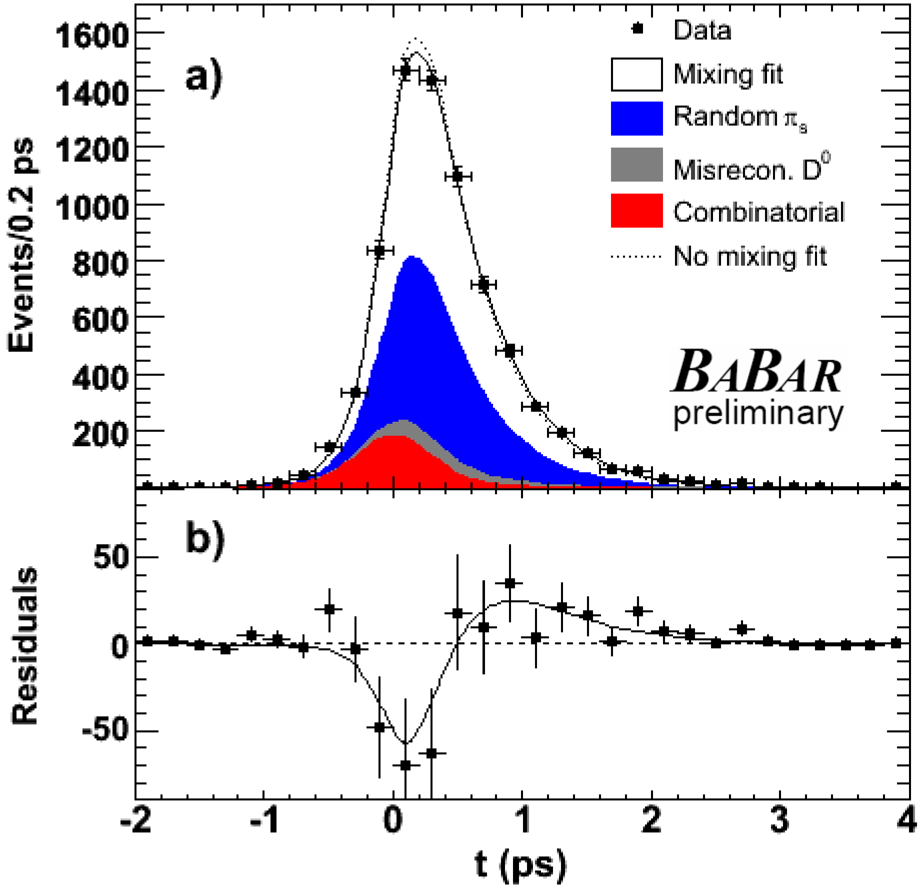
Mixing decay time fit

Fit WS proper-time for:

- Same parameters as the no-mixing case
- But now include mixing
  - The *dotted line* is the *no-mixing* fit.
  - The *solid* line is the *mixing* fit.
- The fit is significantly improved

Results:

- x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
- y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$



WS *mixing* fit projection in signal region

$1.843\ \mathrm{GeV}/c^2 < m < 1.883\ \mathrm{GeV}/c^2$

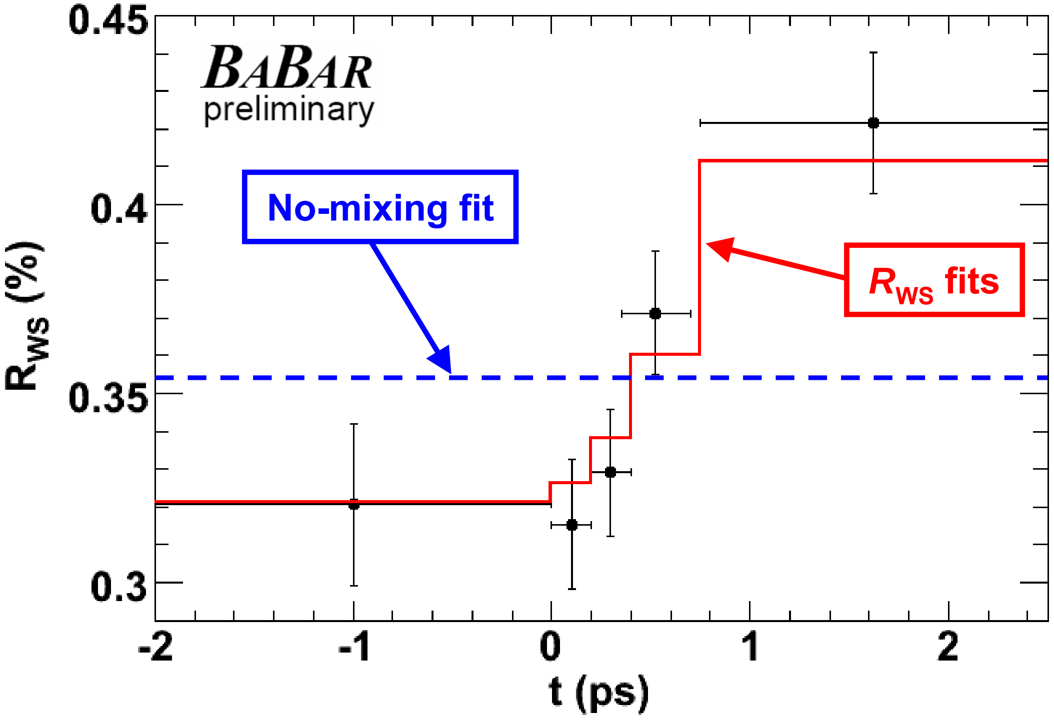
$0.1445\ \mathrm{GeV}/c^2 < \Delta m < 0.1465\ \mathrm{GeV}/c^2$

R_{WS} vs. decay-time slices

If mixing is present, it should be evident in an R_{WS} rate that *increases with decay-time.*

Perform the R_{WS} fit in *five time bins* with similar RS statistics.

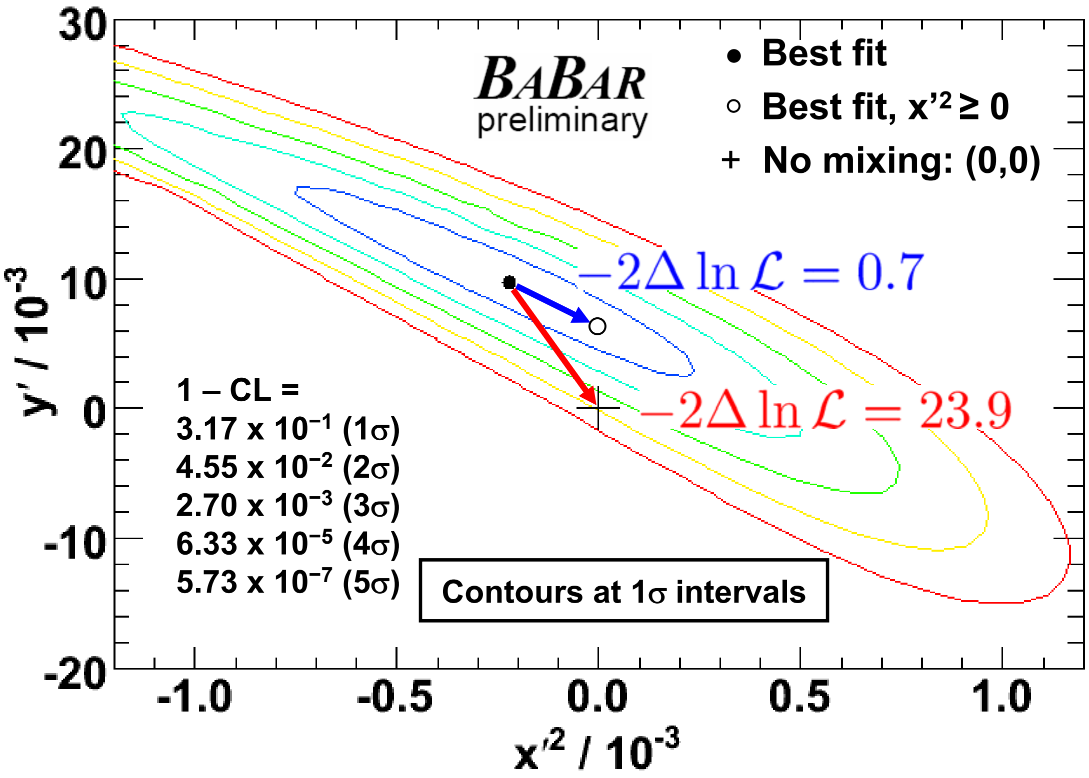
- **Cross-over occurs at $t \approx 0.5$ psec**
  - **Similar to residuals plot.**



Dashed line: standard R_{WS} fit (χ^2=24). Solid, red line: independent R_{WS} fits to each time bin (χ^2 = 1.5).

Mixing fit likelihood contours

- Contours in y', x'^2 computed from $-2\Delta \ln L$
  - Best-fit point is in the non-physical region $x'^2 < 0$
  - 1σ contour extends into physical region
  - Correlation: −0.29
- Contours include systematic errors
  - The no-mixing point is at the 3.9σ contour
- No indication of *CP* violation



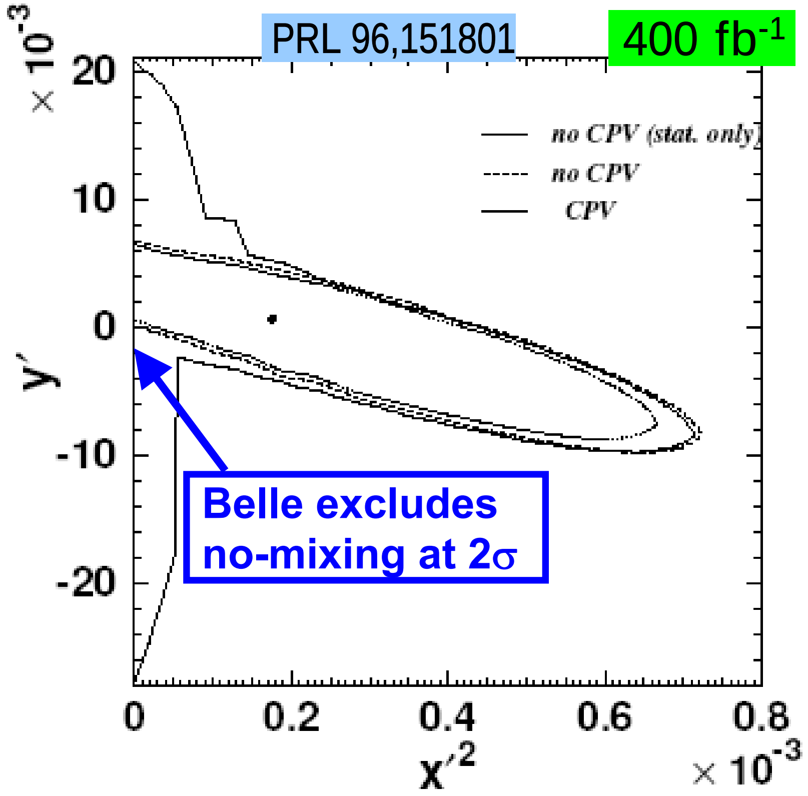
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

Comparison to BELLE *K*π result

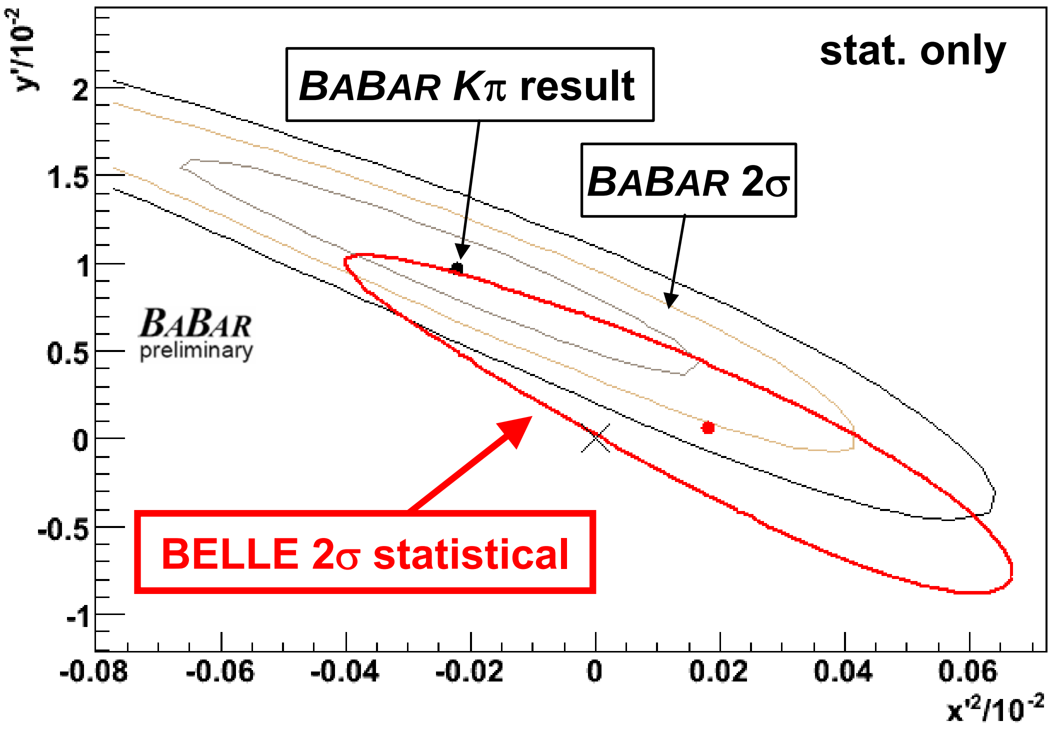
BELLE and *BABAR* are consistent within 2σ



PRL 96,151801

400 fb^{-1}

Belle excludes no-mixing at 2σ



stat. only

***BABAR* *K*π result**

***BABAR* 2σ**

BELLE 2σ statistical

Belle lifetime difference

If *CP* is conserved:

- D_1, D_2 are *CP* eigenstates
- If $\Delta\Gamma \neq 0$ there is a lifetime difference between them
- Observe any lifetime difference in
  - $D^0 \to K^+K^-$, $\pi^+\pi^-$ (*CP*-even)
  - $D^0 \to K^-\pi^+$ (*CP*-mixed, 50%)

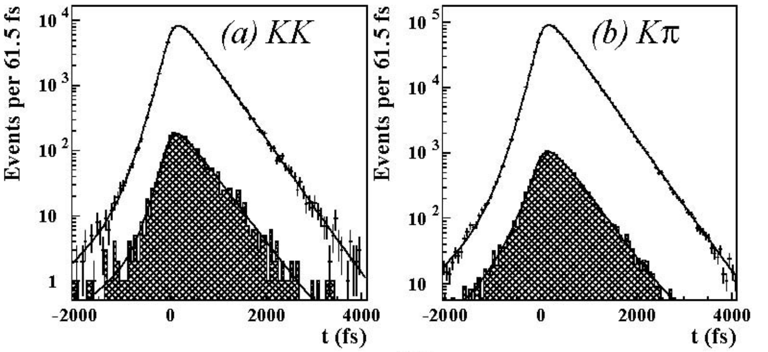
$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1$$

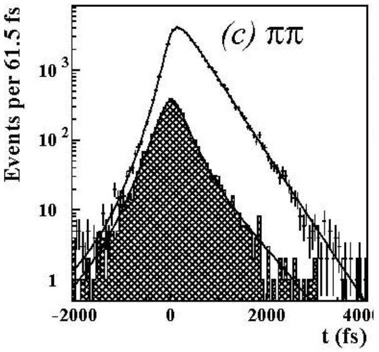
- If *CP* is conserved, $y_{CP} = y$

***CP* violation would give a lifetime difference in $D^0/\bar{D}^0 \to K^+K^-$, $\pi^+\pi^-$**

- Form the asymmetry:

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





Channel	Signal	Purity
K^+K^-	110K	98%
$\pi^+\pi^-$	50K	92%
$K\pi$	1.2M	99%

Decay-time distributions and fits.
White: signal; shaded: background.

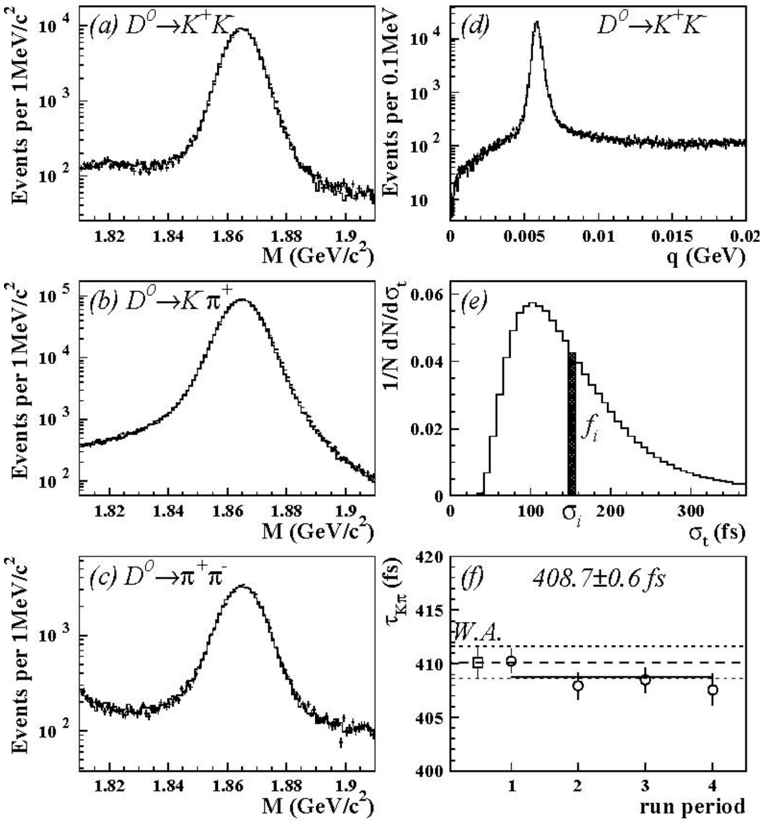
Lifetime difference reconstruction

Reconstruction

- K,π selection
- Vertex fits
- CM $p(D^{*+}) > 2.5$ GeV

Analysis:

- M,q,σ_t cuts
- Optimize on tuned MC
- Figure of merit:
  - y_{CP} statistical error
- Backgrounds estimated from sidebands



(a)–(d): Selected *M*, *q* distributions;

(e): Normalized proper-time error distribution.

(f): $D^0 \to K\pi$ lifetime for four running periods and constant fit

$$M = \text{reconstructed } D^0 \text{ mass}$$
$$q = (M_{D^*} - M - m_\pi)c^2$$

Belle K^+K^-, $\pi^+\pi^-$ lifetime ratio

Measure lifetime difference of *CP* eigenstates

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

y_{CP} = [13.1 ± 3.2 (stat.) ± 2.5 (syst.)]x10^{-3}

3.2σ significance

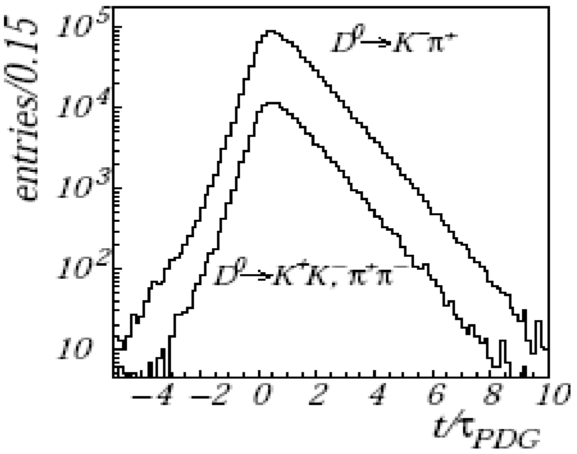
(4.1σ stat. only)

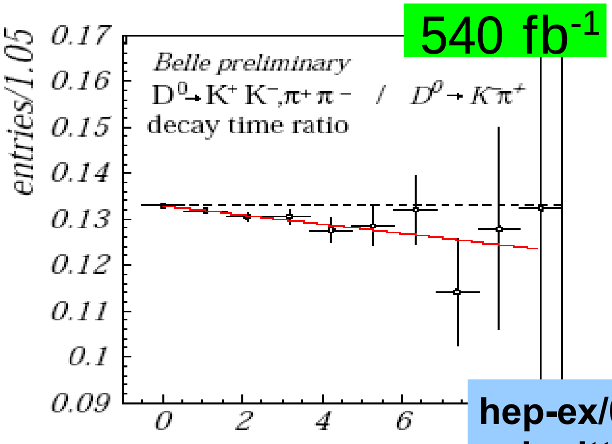
Evidence for mixing

A_Γ = [0.01 ± 0.30 (stat.) ± 0.15 (syst.)] x 10^{-3}

No evidence for *CP* violation

Decay time distributions





hep-ex/0703036 submitted to PRL

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

Time-dependent, Dalitz-plot mixing analysis

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

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 $\bar{D}^0$ as functions of phase-space variables, and

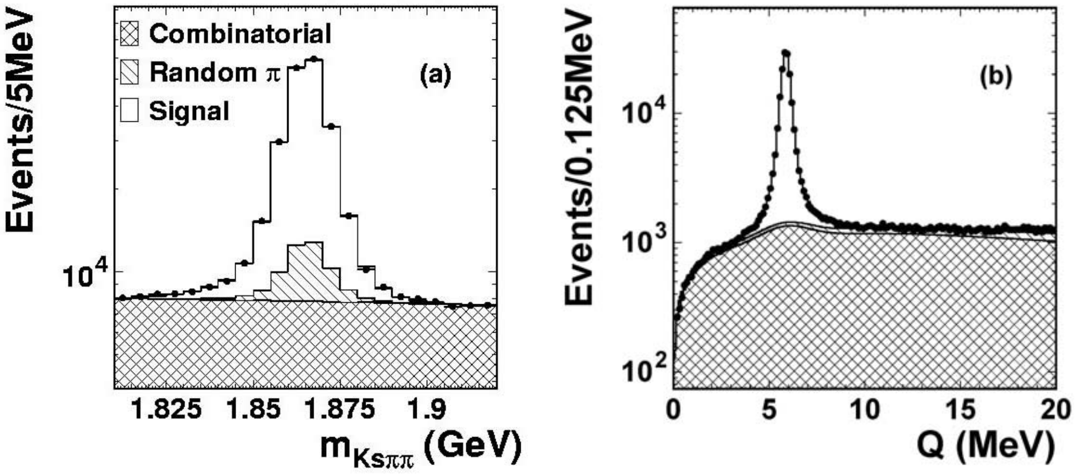
$$m_\pm = \begin{cases} m(K_s, \pi^\pm) & D^{*+} \to D^0\pi^+ \\ m(K_s, \pi^\mp) & D^{*-} \to \overline{D}^0\pi^- \end{cases} \qquad e_{1,2}(t) = \exp\left(-i(m_{1,2} - i\Gamma_{1,2}/2)t\right)$$

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

Belle $D^0 \rightarrow K_s\pi\pi$ Analysis

Uses same discriminating variables to separate signal and background components as lifetime ratio analysis

- **Perform simultaneous, unbinned likelihood fit to m_-^2 , m_+^2, and t**
- **Signal yield: 534,410 $\pm$ 830 events, 95% purity**



Fit projections

- **$m_{Ks\pi\pi}$ for selected events: $0 < Q < 20$ MeV.**
- **Q for selected events: 1.81 GeV/c^2 < $m_{Ks\pi\pi}$< 1.91 GeV/c^2**

Cross-check: fitted τ_D = 409.9$\pm$0.9 fs

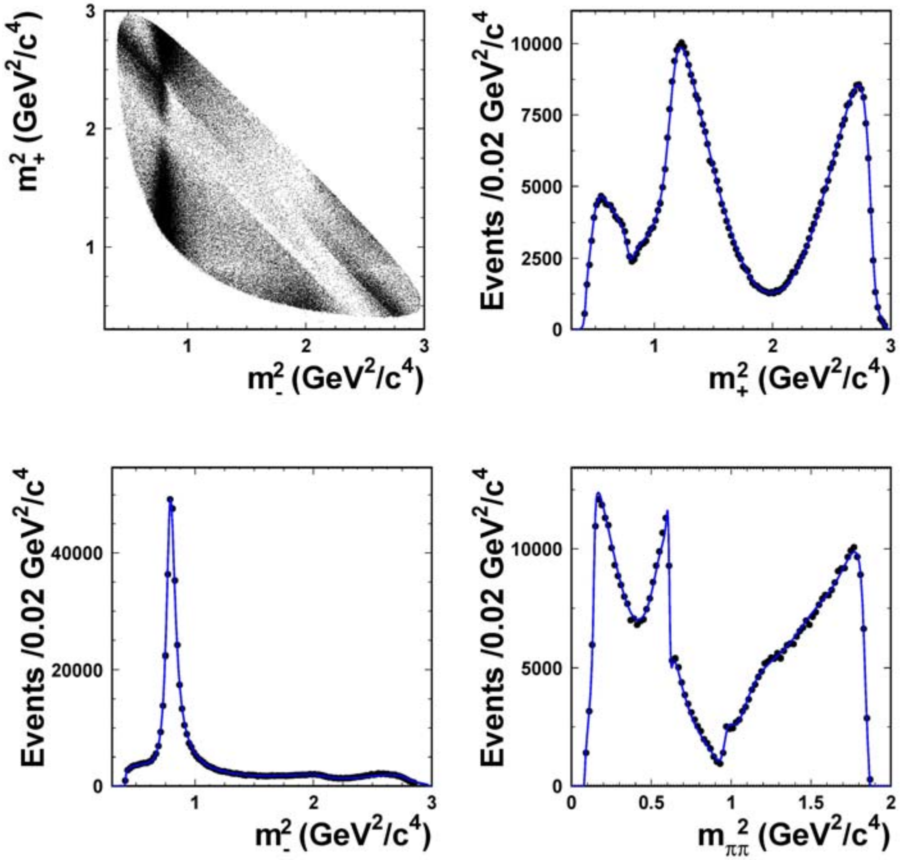
Belle $D^0 \to K_s\pi\pi$ Analysis

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



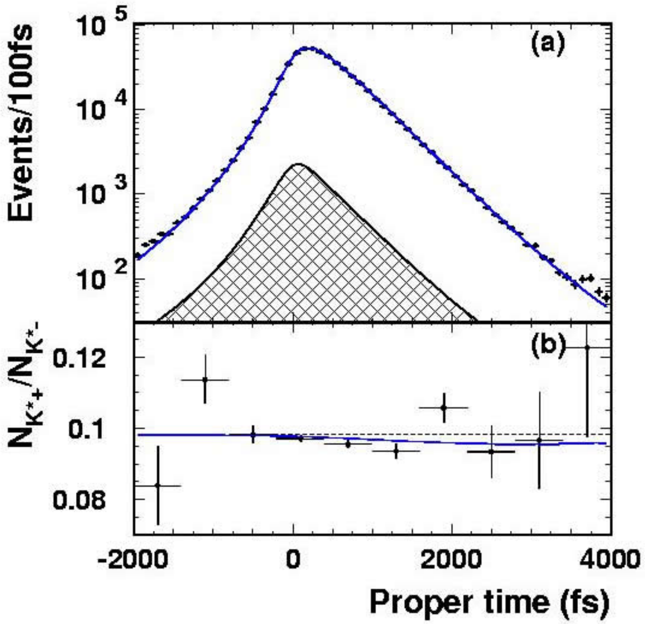
Dalitz plot distribution and projections. Fit result shown as solid line.

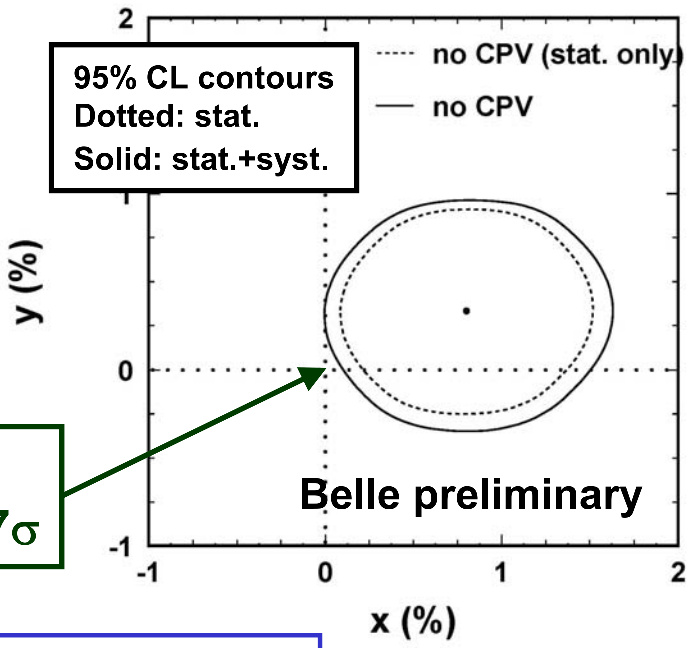
Belle $D^0 \to K_s\pi\pi$ Analysis

Proper-time fit results

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

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





95% CL contours
Dotted: stat.
Solid: stat.+syst.

No-mixing excluded at 2.7σ

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

arXiv:0704.1000

540 fb^{-1}

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

Summary

BABAR: $D^0 \rightarrow K\pi$ analysis

- $y' = [9.7 \pm 4.4\ (\text{stat.}) \pm 3.1\ (\text{syst.})] \times 10^{-3}$
- $x'^2 = [-0.22 \pm 0.30\ (\text{stat.}) \pm 0.219\ (\text{syst.})] \times 10^{-3}$
- $R_D = [0.303 \pm 0.016\ (\text{stat.}) \pm 0.010\ (\text{syst.})]\%$
- Submitted to PRL (hep-ex/0703020)
- Consistent with earlier mixing analyses
  - BABAR $K\pi$, 2003: $(-56 < y' < 39) \times 10^{-3}$, $x' < 11 \times 10^{-3}$ (95% CL)
  - Belle $K\pi$, 2006: $(-28 < y' < 21) \times 10^{-3}$, $x' < 3.6 \times 10^{-3}$ (95% CL)

BABAR: 3.9σ evidence for mixing (stat.+syst.)

Belle: lifetime difference analyses:

- Belle, 2007: $y_{CP} = (1.31 \pm 0.32 \pm 0.25) \times 10^{-2}$
- 3.2σ evidence for mixing
  - BABAR, 2003: $y_{CP} = (0.9 \pm 0.4 \pm 0.5) \times 10^{-2}$

Belle: 3.2σ evidence for mixing (stat.+syst.)

Belle: time-dependent $K_s\pi\pi$ (arXiv:0704.1000):

- $x = (0.80 \pm 0.29 \pm 0.17) \times 10^{-2}$
- $y = (0.33 \pm 0.24 \pm 0.15) \times 10^{-2}$
- 2.7σ evidence for mixing

Evidence for D^0-D^0 mixing seen by both BABAR or Belle

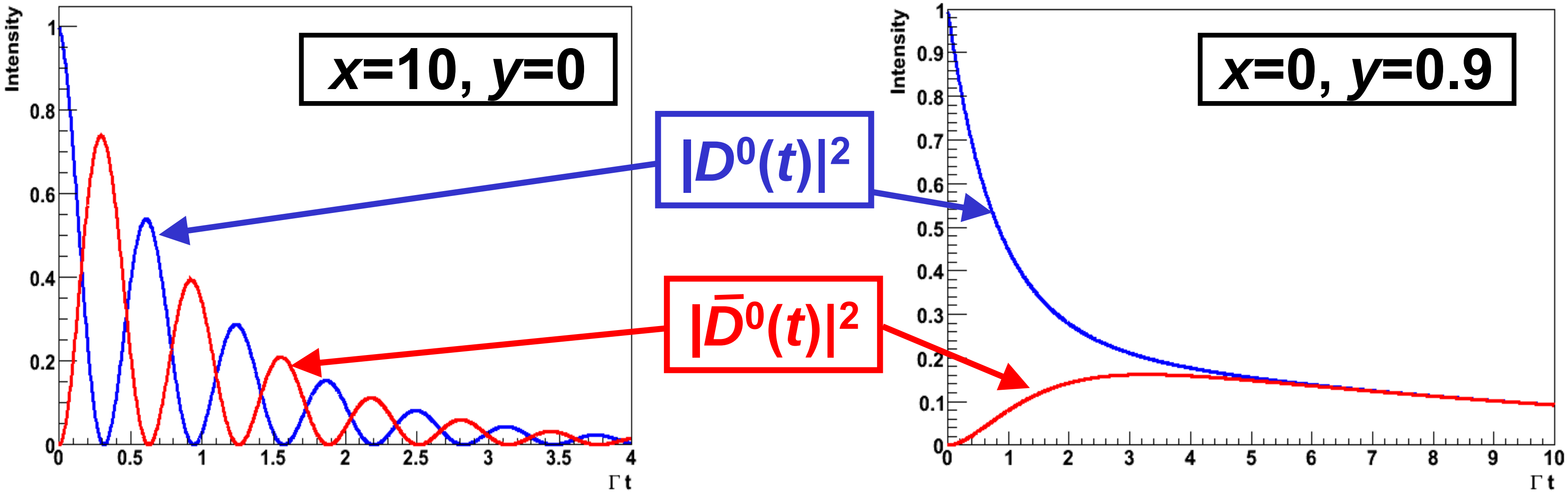
- No evidence seen for CP violation by either experiment

Backup slides

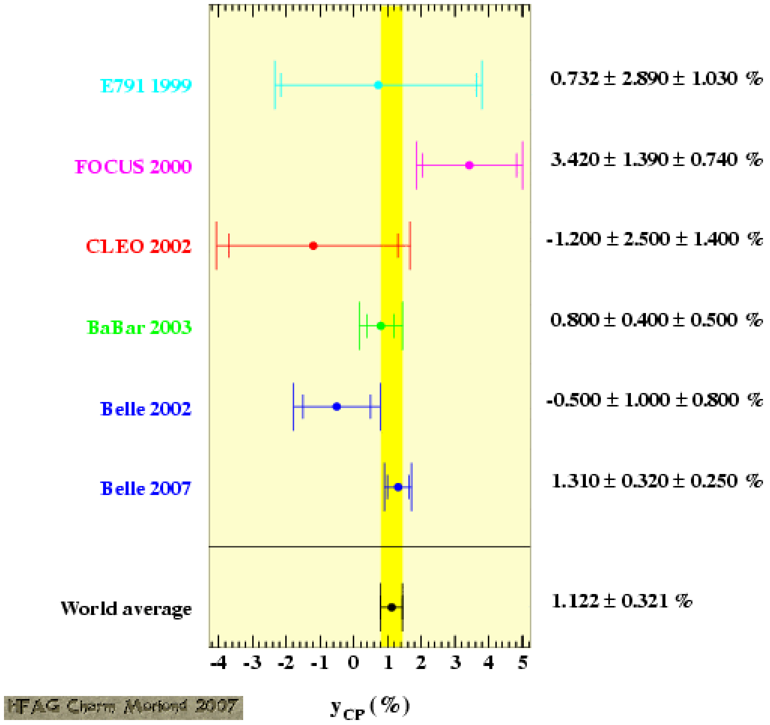
Time-dependent mixing rate

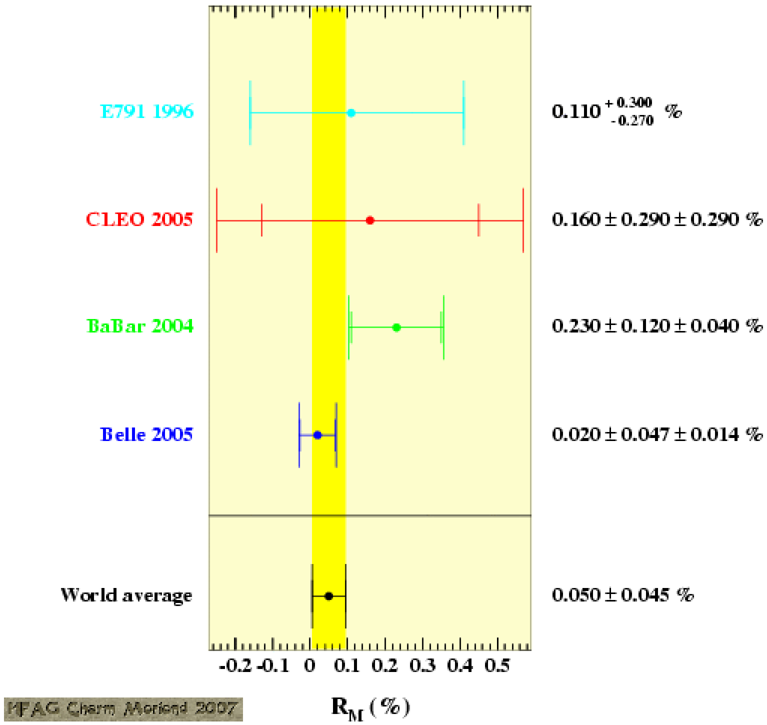
Two illustrations

- State starts as pure D^0 at $t = 0$
- Decays as D^0 or $\bar{D}^0$



▪ HFAG world averages for y_{CP} and R_{M}





$$y_{CP} = (1.12\pm3.2)\mathrm{x}10^{-2}$$

$$R_{\mathrm{M}} = (0.50\pm0.45)\mathrm{x}10^{-3}$$

Time-dependent decay rate

The time-dependent decay rate of an initially-pure D^0 or D^0 can be written

$$\begin{aligned} |D^0(t)\rangle &= g_+(t)|D^0\rangle - (q/p)g_-(t)|\overline{D}^0\rangle \\ |\overline{D}^0(t)\rangle &= g_+(t)|\overline{D}^0\rangle - (p/q)g_-(t)|D^0\rangle \end{aligned}$$

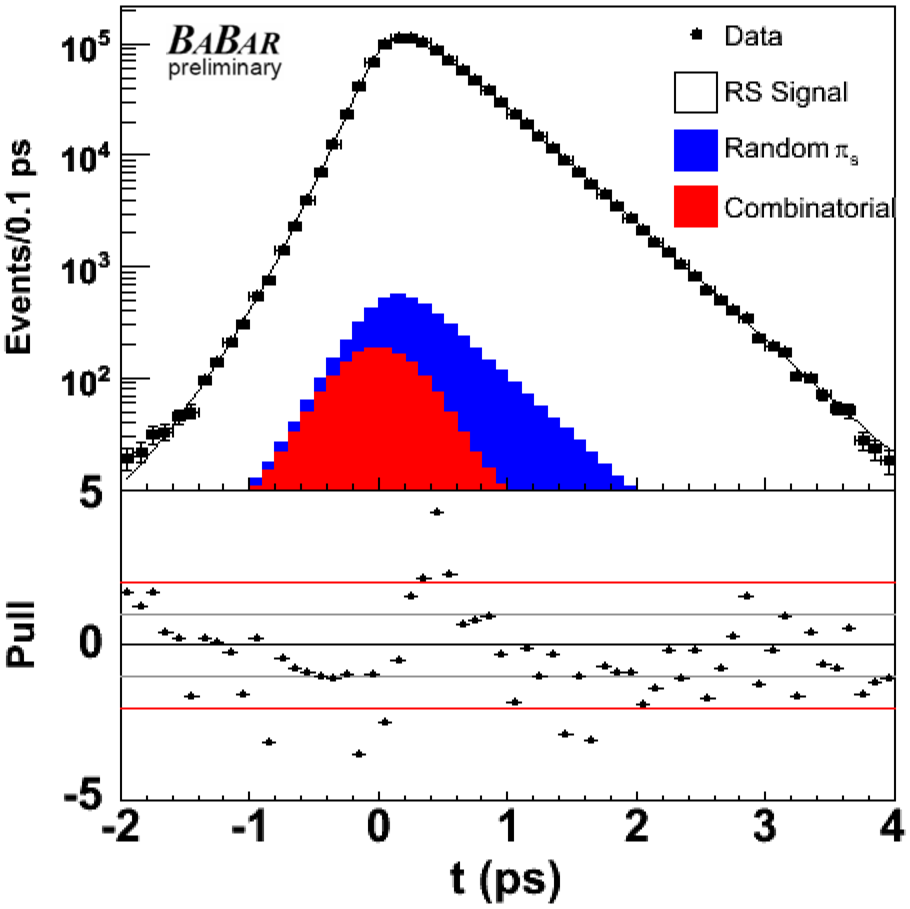
where $g_\pm(t) = \frac{1}{2}e^{-iMt-\frac{1}{2}\Gamma}\left(e^{-\frac{i}{2}\Delta Mt-\frac{1}{4}\Delta\Gamma t} \pm e^{+\frac{i}{2}\Delta Mt+\frac{1}{4}\Delta\Gamma t}\right)$

This yields the time-dependent decay rate

$$\begin{aligned} &\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t} \times \\ &\quad \left[\left(|A_f|^2 + |(q/p)\overline{A}_f|^2\right)\cosh(y\Gamma t) + \left(|A_f|^2 - |(q/p\overline{A}_f|^2\right)\cos(x\Gamma t)\right. \\ &\quad \left. + 2\mathrm{Re}((q/p)A_f^*\overline{A}_f)\sinh(y\Gamma t) - 2\mathrm{Im}((q/p)A_f^*\overline{A}_f)\sin(x\Gamma t)\right] \end{aligned}$$

Systematics: decay time resolution

- **Decay-time resolution**
  - Sum of 3 Gaussians
  - Narrowest has a non-zero mean of 3.6 fsec
  - Most likely due to alignment issues.
  - Also seen in other analyses.
- **Check by setting offset to zero and refitting for mixing parameters.**
  - x'^2 changes by -0.3σ
  - y' changes by $+0.3\sigma$



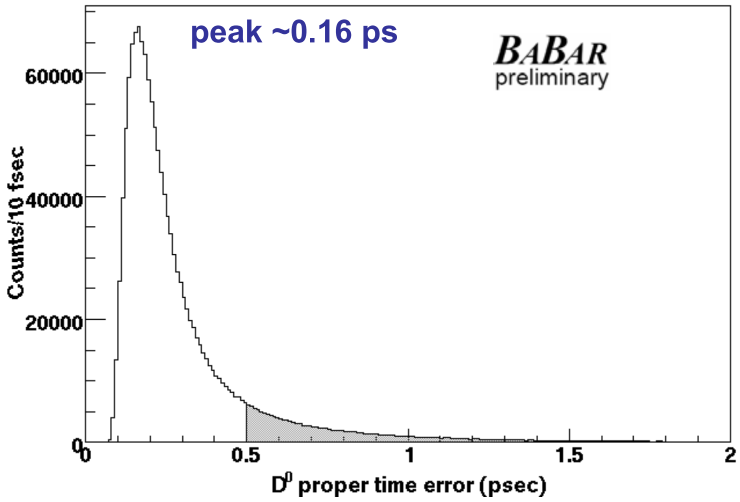
RS decay time fit with zero offset.

Event selection details

- Perform a beam-constrained fit to the full decay chain

  $$D^{*\pm} \to \pi_s^{\pm} D^0,\ D^0 \to K^{\mp}\pi^{\pm}$$

  - **Require fit probability > 0.001**
  - **$\delta t < 0.5$ ps**
  - **$-2 < t < 4$ ps**
- Select the D^0
  - **CM $p_D > 2.5$ GeV/c**
  - **K, π particle identification**
  - **$1.81 < m_{K\pi} < 1.92$ GeV/c^2**
- Select the D^{*+}
  - **CM $p_\pi < 0.45$ GeV/c**
  - **$p_\pi > 0.1$ GeV/c in lab frame**
  - **$0.14 < \Delta m < 0.16$ GeV/c^2**
- If multiple D^{*+}candidates share tracks in the event:
  - **Select candidate with greatest fit probability**
- Event selection, fitting procedures are *finalized before examining* the mixing results



Separating signal and backgrounds

- Signal and backgrounds have differing behavior in $m_{K\pi}$ and Δm.
  - We define four categories:
    - Signal, random π_s, mis-reconstructed D^0, and combinatoric.

Category	Description	Peaking Behavior
RS signal	$D^0 \to K^-\pi^+$ signal	$m_{K\pi}$ and Δm
RS random π_s	Correctly-reconstructed D^0 combined with an incorrect slow pion	$m_{K\pi}$
RS mis-recon. D^0	Mis-reconstructed D^0 from $D^0 \to Kl^+\nu$, $D^0 \to \pi l^+\nu$, $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$	Δm
RS combinatoric	Combinatoric background	non-peaking
WS signal	$D^0 \to K^+\pi^-$ signal	$m_{K\pi}$ and Δm
WS random π_s	Correctly-reconstructed D^0 combined with an incorrect slow pion	$m_{K\pi}$
WS mis-recon. D^0	Doubly mis-identified $D^0 \to K^-\pi^+$ decays and $D^0 \to \pi^+\pi^-$, $D^0 \to K^+K^-$ reflections	Δm
WS combinatoric	Combinatoric background	non-peaking

Validation: fit for mixing in RS sample

Fit the RS data using the WS mixing PDF

$x'^2 = (-0.01 \pm 0.01) \times 10^{-3}$

$y' = (0.26 \pm 0.24) \times 10^{-3}$

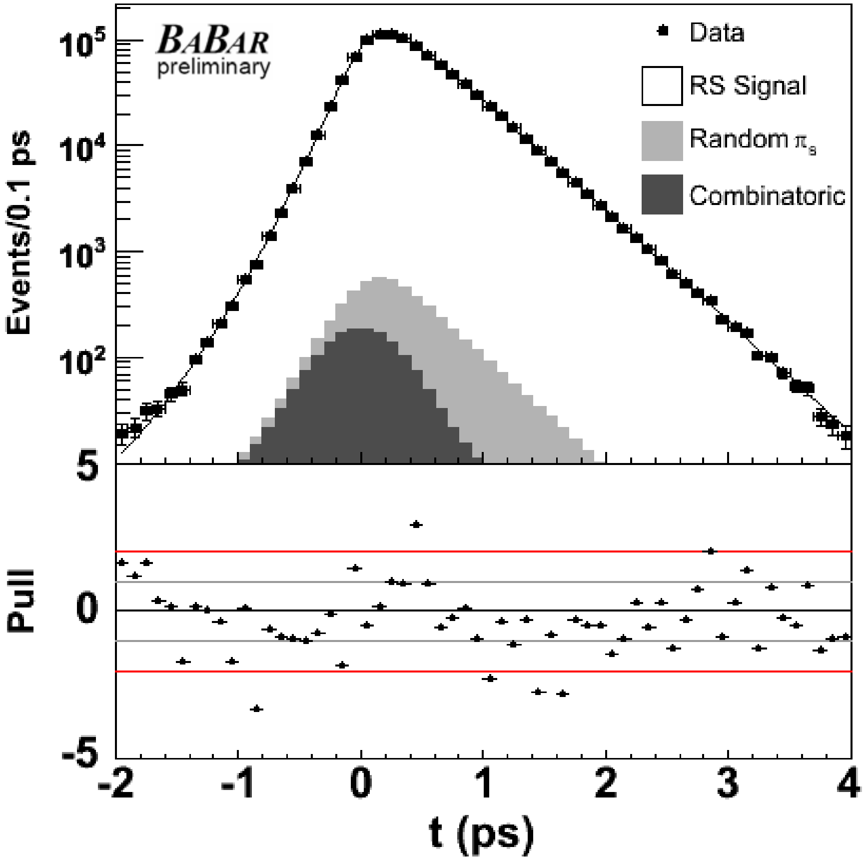
The change in $-2\Delta \ln L$ is 1.4

A very stringent test

RS sample 270× larger than WS sample

Conclusion:

D^0 decay-time distribution is properly described.

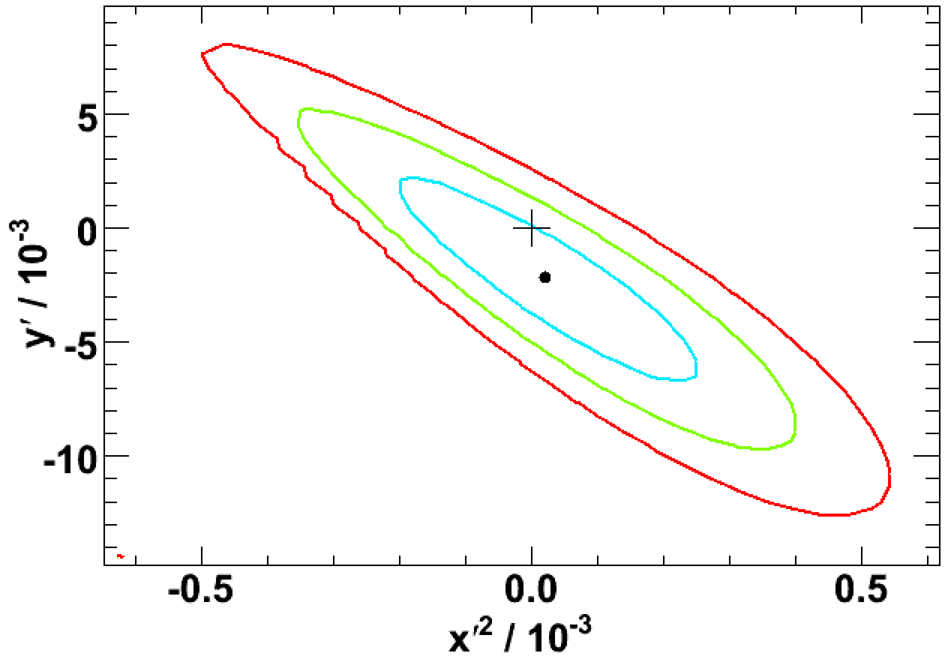


RS *mixing* fit projection in signal region
1.843 GeV/c^2<m<1.883 GeV/c^2
0.1445 GeV/c^2<Δm< 0.1465 GeV/c^2

Validation: fit for mixing in MC

Fit MC for mixing

- MC generated with no mixing
- Fit finds no mixing signal:
  - $x'^2 = (-0.02 \pm 0.18) \times 10^{-3}$
  - $y' = (2.2 \pm 3.0) \times 10^{-3}$



Result of mixing fit to MC (which has no mixing).
Contours are at 1σ, 2σ, and 3σ

Mixing and CPV fit results

Fit results for all three cases:

(1) No mixing or CPV; (2) mixing but no CPV; and (3) CPV and mixing.

R_D changes between no-mixing and mixing fits.

Fit type	Parameter	Fit Results $(/10^{-3})$
No *CP* viol. or mixing	R_D	$3.53 \pm 0.08 \pm 0.04$
No *CP* violation	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CP violation allowed	R_D	$3.03 \pm 0.16 \pm 0.10$
	A_D	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^{+}	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^{-}	$9.6 \pm 6.1 \pm 4.3$

Average $K\pi$ Mixing Results

Heavy flavor averaging group (HFAG)

http://www.slac.stanford.edu/xorg/hfag/

Combine *BABAR* and Belle likelihoods in 3 dimensions:

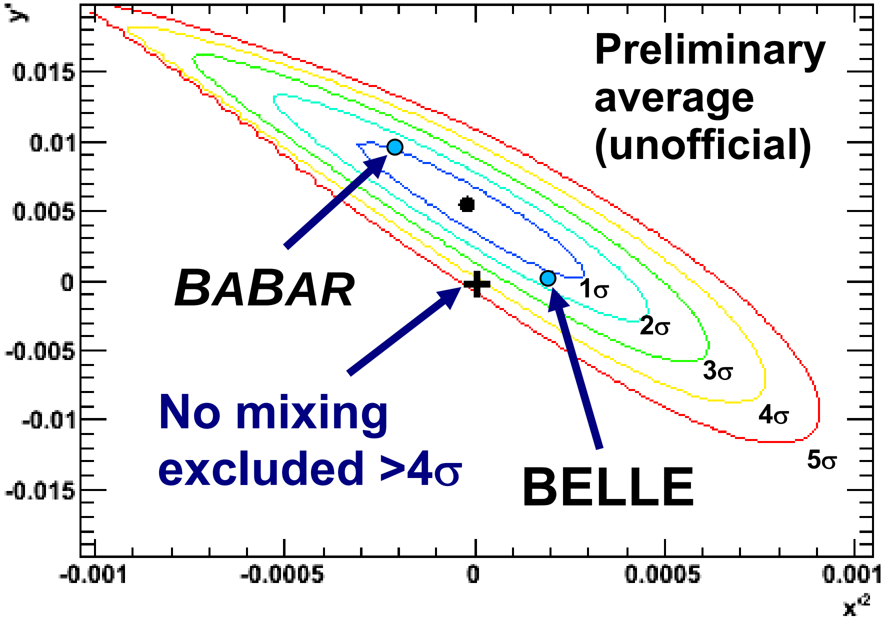
(R_D, x'^2, y')

Preliminary averages:

$R_D = (3.31 \pm 0.13) \times 10^{-3}$

$x'^2 = (-0.01 \pm 0.20) \times 10^{-3}$

$y' = (5.1 \pm 3.2) \times 10^{-3}$



Preliminary average (unofficial)

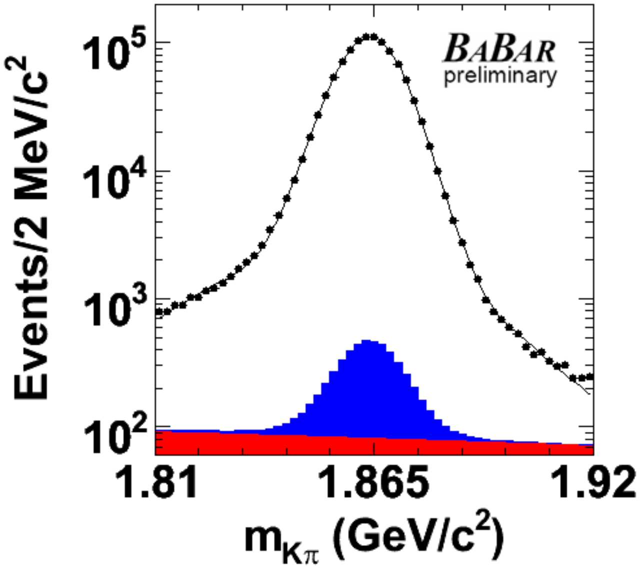
BABAR

No mixing excluded >4σ

BELLE

Right-sign $m_{K\pi}$, Δm fit

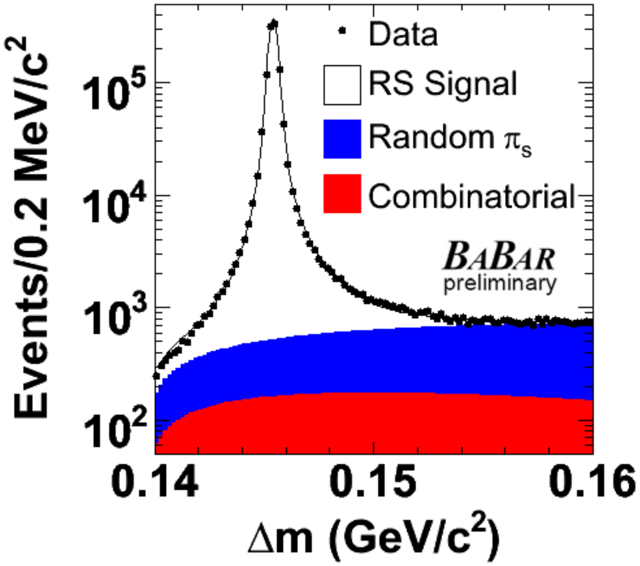
Shown are the fits to right-sign data for $m_{K\pi}$ (left) and Δm (right).



1,141,500 ± 1,200 RS signal events

The mis-reconstructed D^0 category is not included in the RS fit.

This background is too small to be reliably determined.



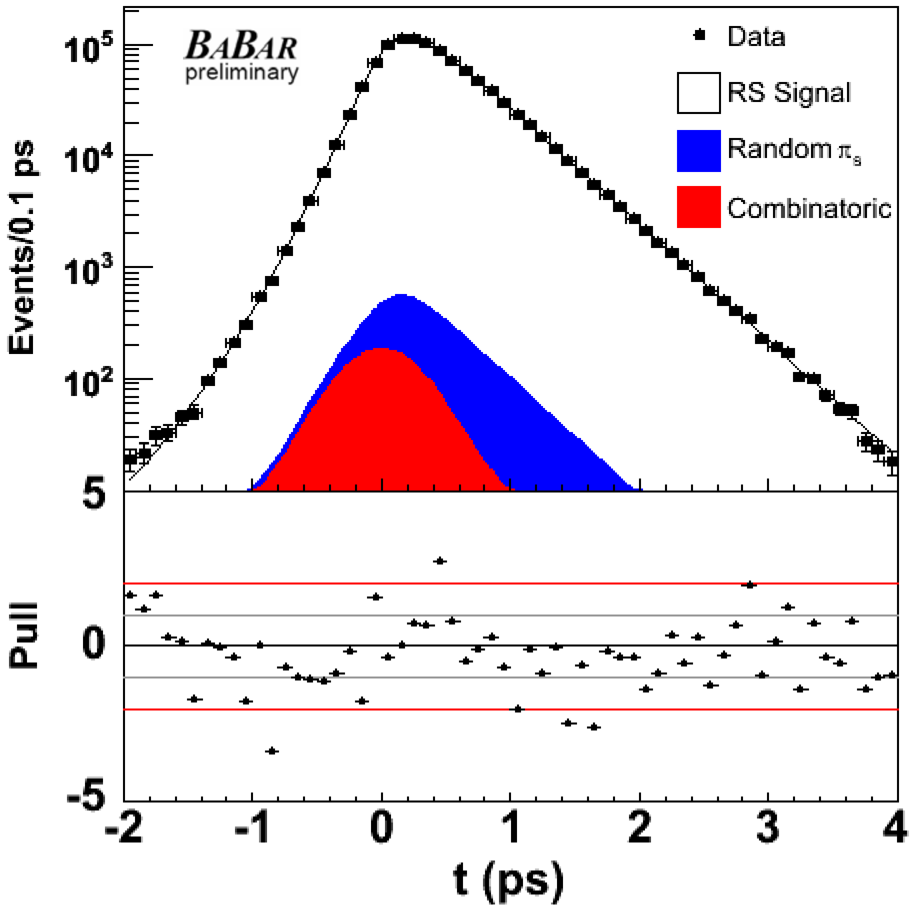
RS proper decay-time fit

The parameters fitted are

- D^0 lifetime τ_D
- Resolution parameters
  - Including a 3.6 fsec offset
- Signal, background category yields

Consistency check

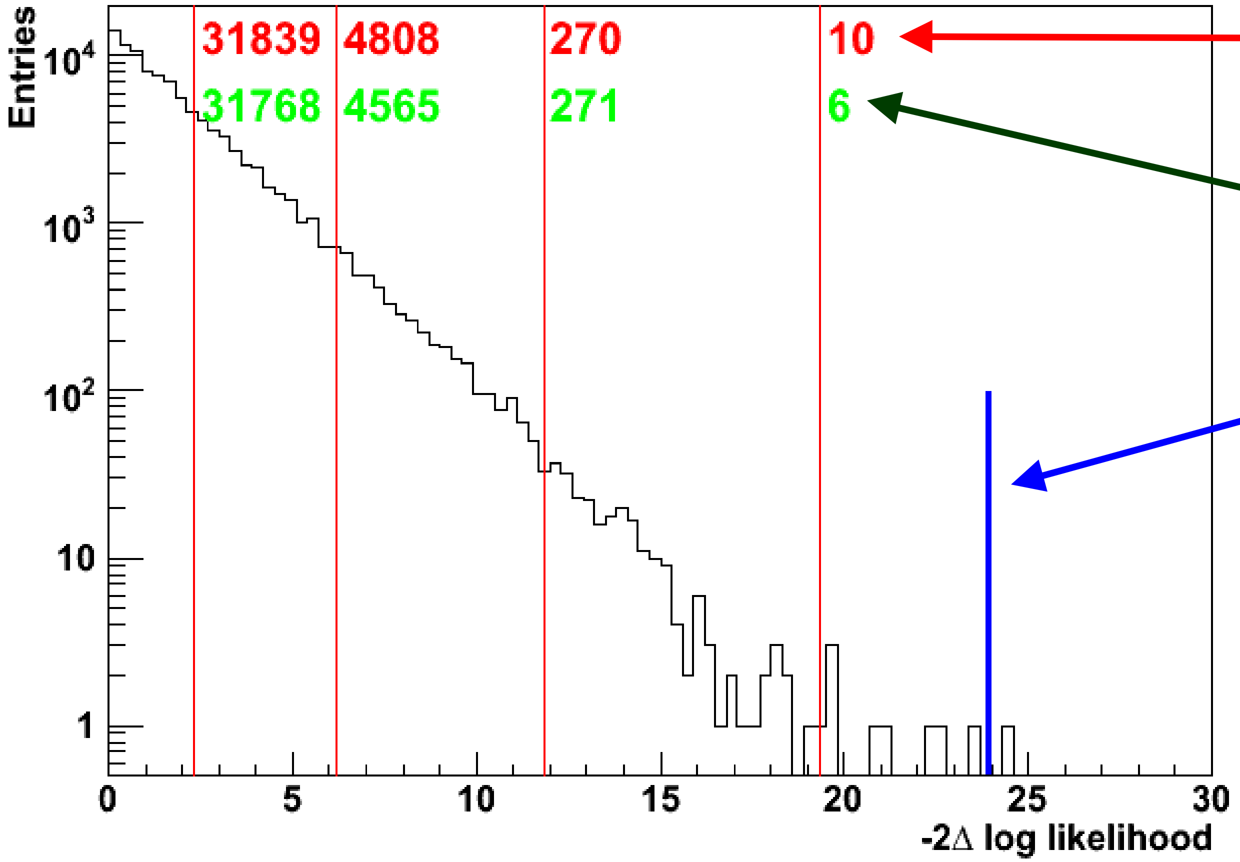
- Fitted $\tau_D = (410.3 \pm 0.6)$ fsec
  - (statistical error only)
- (PDG 2006: 410.1 ± 1.5 fsec)



RS fit projection in the signal region
$1.843\ \mathrm{GeV}/c^2 < m < 1.883\ \mathrm{GeV}/c^2$
$0.1445\ \mathrm{GeV}/c^2 < \Delta m < 0.1465\ \mathrm{GeV}/c^2$

Validation: −2Δln *L* frequentist coverage

Generated >100,000 toys without mixing to test frequentist coverage



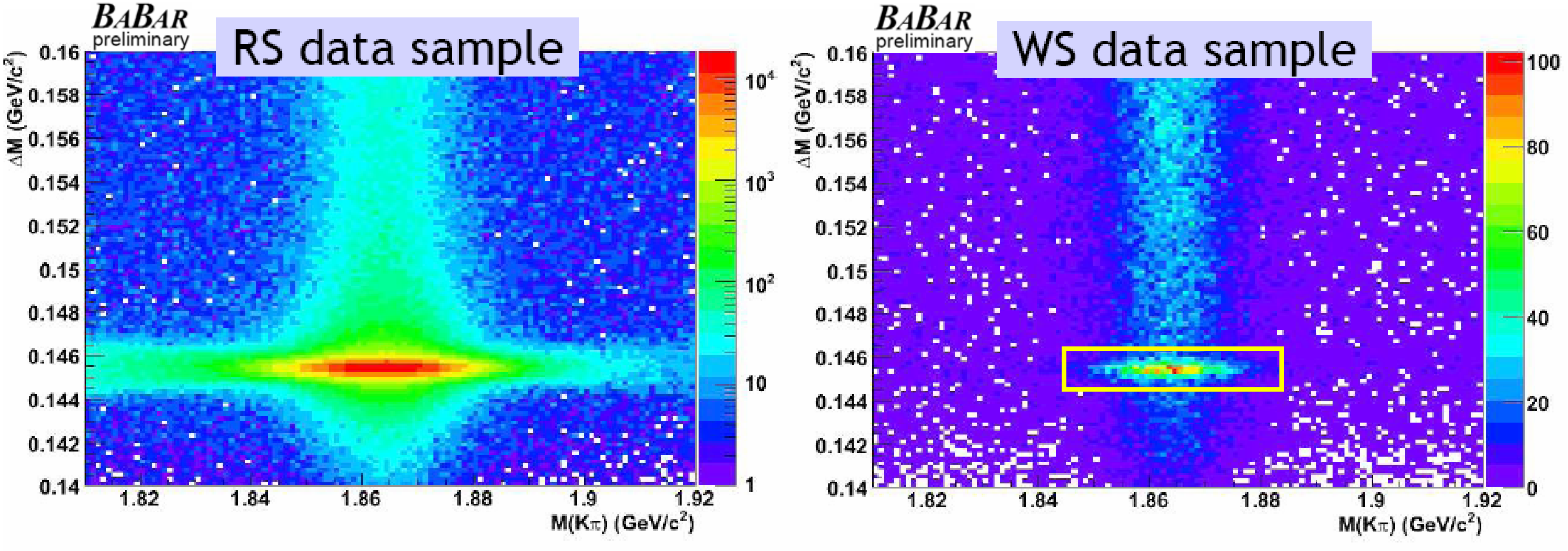
Observed N_{toys} > index line

Expected N_{toys} > index line

Location of likelihood value of fit to data

Computed assuming two degrees of freedom

RS & WS $m_{K\pi}$, Δm distributions



All fits are over the *full range* shown in the plots

1.81 GeV/c2 < $m_{K\pi}$ < 1.92 GeV/c^2 and 0.1445 GeV/c^2 < Δm < 0.1465 GeV/c^2

A *small correlation* can be seen between $m_{K\pi}$ and Δm

Define a *signal region*

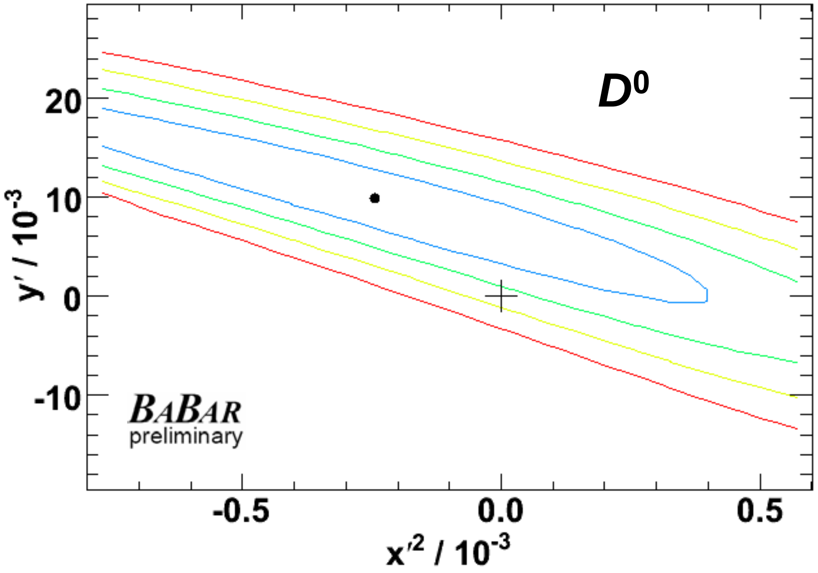
1.843 GeV/c^2 < $m_{K\pi}$ < 1.883 GeV/c^2 and 0.1445 GeV/c^2 < Δm < 0.1465 GeV/c^2

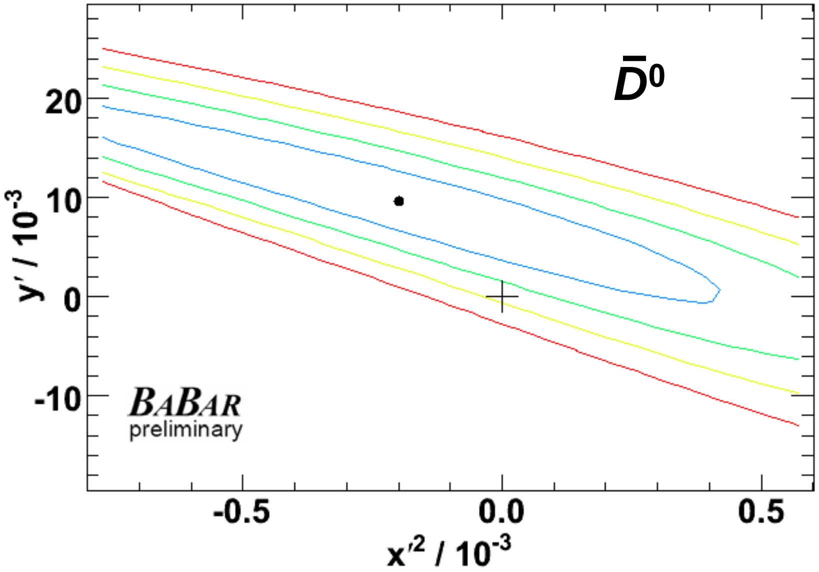
Fits allowing for *CP* violation

Fit D^0 and $\bar{D}^0$ decay-time dependence separately.

$x'^{2+} = (-0.24 \pm 0.43 \pm 0.30) \times 10^{-3}$
$y'^{+} = (9.8 \pm 6.4 \pm 4.5) \times 10^{-3}$

$x'^{2-} = (-0.20 \pm 0.41 \pm 0.29) \times 10^{-3}$
$y'^{-} = (9.6 \pm 6.1 \pm 4.3) \times 10^{-3}$





List of systematics, validations

Systematics: variations in

- Functional forms of PDFs
- Fit parameters
- Event selection

Computed using *full* difference with original value

Results are expressed in units of the statistical error

Systematic source	R_D	y'	x'^2
PDF:	0.59σ	0.45σ	0.40σ
Selection criteria:	0.24σ	0.55σ	0.57σ
Quadrature total:	0.63σ	0.71σ	0.70σ

Validations and cross-checks

- Alternate fit (R_{WS} in time bins)
- Fit RS data for mixing
  - $x'^2 = (-0.01 \pm 0.01) \mathrm{x} 10^{-3}$
  - $y' = (0.26 \pm 0.24) \mathrm{x} 10^{-3}$
- Fit generic MC for mixing
  - $x'^2 = (-0.02 \pm 0.18) \mathrm{x} 10^{-3}$
  - $y' = (2.2 \pm 3.0) \mathrm{x} 10^{-3}$
- Fit toy MCs generated with various values of mixing
  - Reproduces generated values
- Validation of proper frequentist coverage in contour construction
  - Uses 100,000 MC toy simulations