D^0 Mixing at the *B*-Factories

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SUSY 2007, Karlsruhe

BABAR

UNIVERSITY OF LIVERPOOL

Topics

- ✓ Introduction
- ✓ D^0 mixing formalism
- ✓ BABAR results
  - $D^0 \rightarrow K\pi$ mixing analysis
- ✓ Belle results
  - Lifetime difference analysis
  - $D^0 \rightarrow K_s\pi\pi$ analysis
- ✓ Summary

Introduction

- 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 x and y

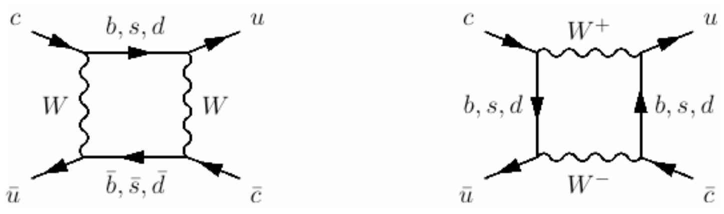
$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

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

D^0 Mixing Processes

- Short-distance contributions from mixing box diagrams in the Standard Model are expected to be small :
  - ***b*** quark is CKM-suppressed
    - $|V_{ub}V^*_{cb}|^2$
  - ***s*** and ***d*** quarks are GIM suppressed
    - $(m^2_s-m^2_d)/m^2_W$
  - mainly contributes to the mass diff.
    - $x \approx \mathcal{O}(10^{-5})$

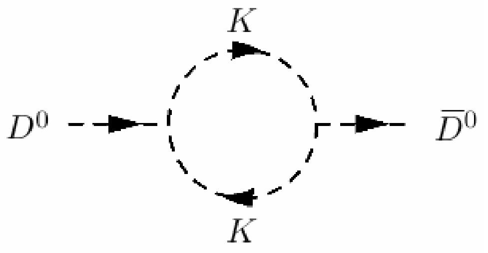
Short-distance



- Long-distance contributions dominate
  - non-perturbative effects (hard to calculate)
  - expect to be $\mathcal{O}(10^{-2})$ or less in the SM
  - mainly affect the lifetime diff. ***y*** (but also ***x***)
    - x , $y \approx \sin^2 \theta_C$ x [SU(3) breaking]^2

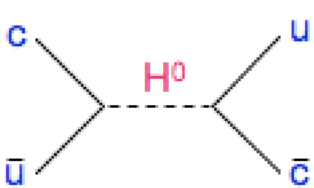
      - Phys.Rev. D **65,** 054034 (2002)
      - Phys.Rev. D **69**, 114021 (2004)

Long-distance

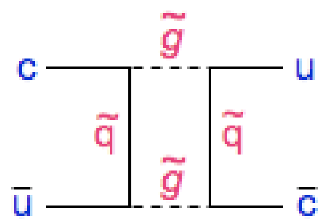


New Physics D^0 Mixing Predictions

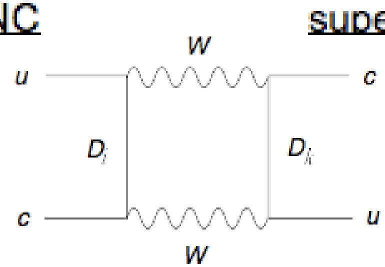
- Possible enhancements to mixing due to new particles and interactions in new physics models
- Most new physics predictions for x
  - Extended Higgs, tree-level FCNC
  - Fourth generation down-type quarks
  - Supersymmetry: gluinos, squarks
  - Lepto-quarks



FCNC



supersymmetry



Heavy weak iso-singlet quarks

- Large possible SM contributions to mixing require observation of either a CP-violating signal or $|x| \gg |y|$ to establish presence of NP
- A recent survey (arXiv:0705.365v1) summarizes models and constraints:

Fourth generation	Vector leptoquarks
Q = -1/3 singlet quark	Flavor-conserving Two-Higgs
Q = +2/3 singlet quark	Flavor-changing neutral Higgs
Little Higgs	Scalar leptoquarks
Generic Z′	MSSM
Left-right symmetric	Supersymmetric alignment

BABAR $D^0 \to K\pi$ mixing analysis

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

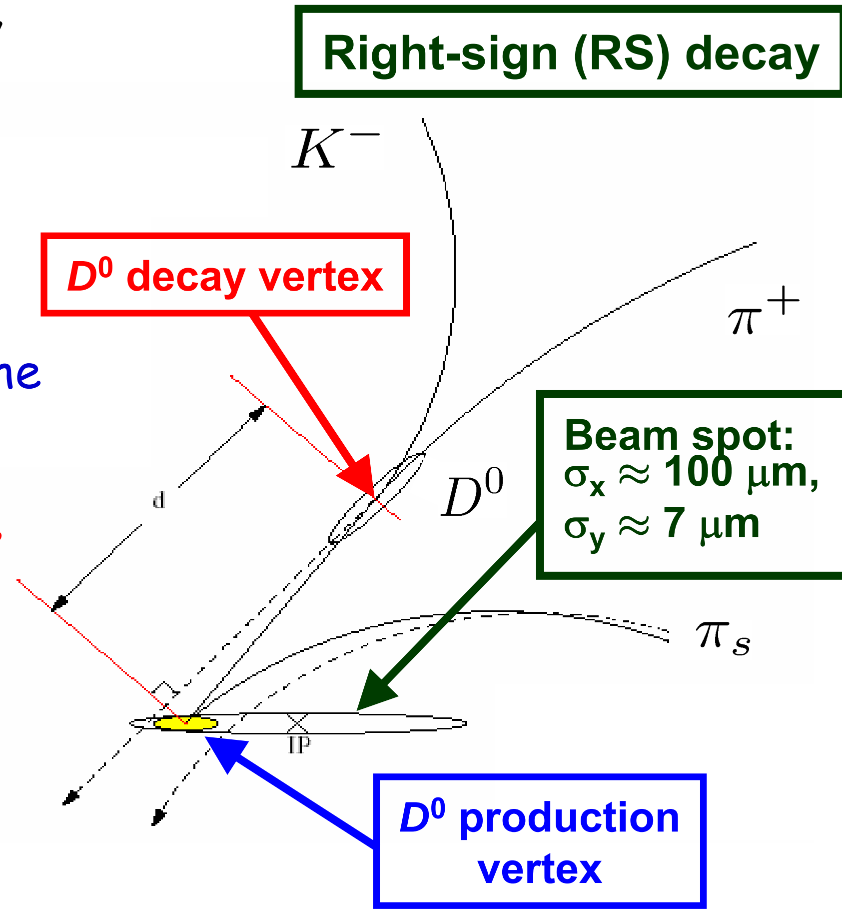
- We select events around the expected
$$\Delta m = m(D^{*+}_{\text{rec.}}) - m(D^0_{\text{rec.}})$$
- The charge of the slow pion determines the flavor of the D^0

We 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 $\mathbf{m_{K\pi}}$, $\mathbf{\Delta m}$, **proper-time *t*** and **error δ_t**



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

Time evolution of $D^0 \to K\pi$ decays

Mixing occurs when a meson produced as a D^0 decays as a $\overline{D}^0$ or vice versa

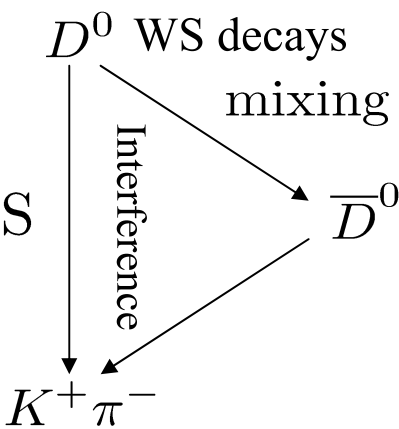
Right sign decays (RS):

- Cabibbo-favored (CF) $D^0 \to K^-\pi^+$ $\longleftrightarrow$ no mixing

Wrong sign decays (WS):

- Doubly Cabibbo-supressed (DCS) $D^0 \to K^+\pi^-$
  - Rate (R_D) : $\tan^4 \theta_C \approx 0.3\%$
- Mixing followed by CF decay $D^0 \xrightarrow[\text{mix}]{} \overline{D}^0 \to K^+\pi^-$
  - Rate (R_M): 10^{-4} or less

DCS



Need to discriminate between DCS and Mixing decays by their proper time evolution

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

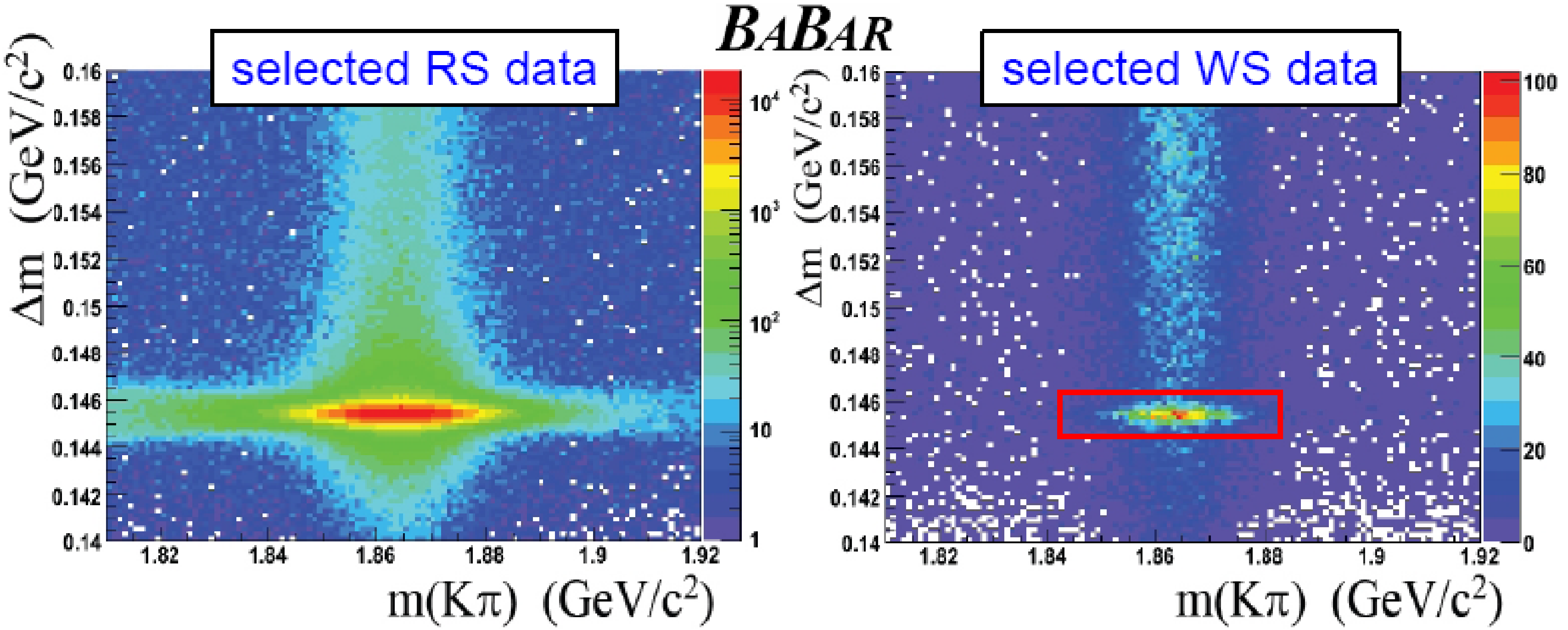
$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(R_D + \sqrt{R_D}\, y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

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

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

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

RS and 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/c² and 0.14 GeV/c² < Δm < 0.16 GeV/c²

Define a *signal region*

1.843 GeV/c² < $m_{K\pi}$ < 1.883 GeV/c² and 0.1445 GeV/c² < Δm < 0.1465 GeV/c²

Mixing WS decay time fit

The difference between the no-mixing fit and the fit with mixing is shown in the residuals plot.

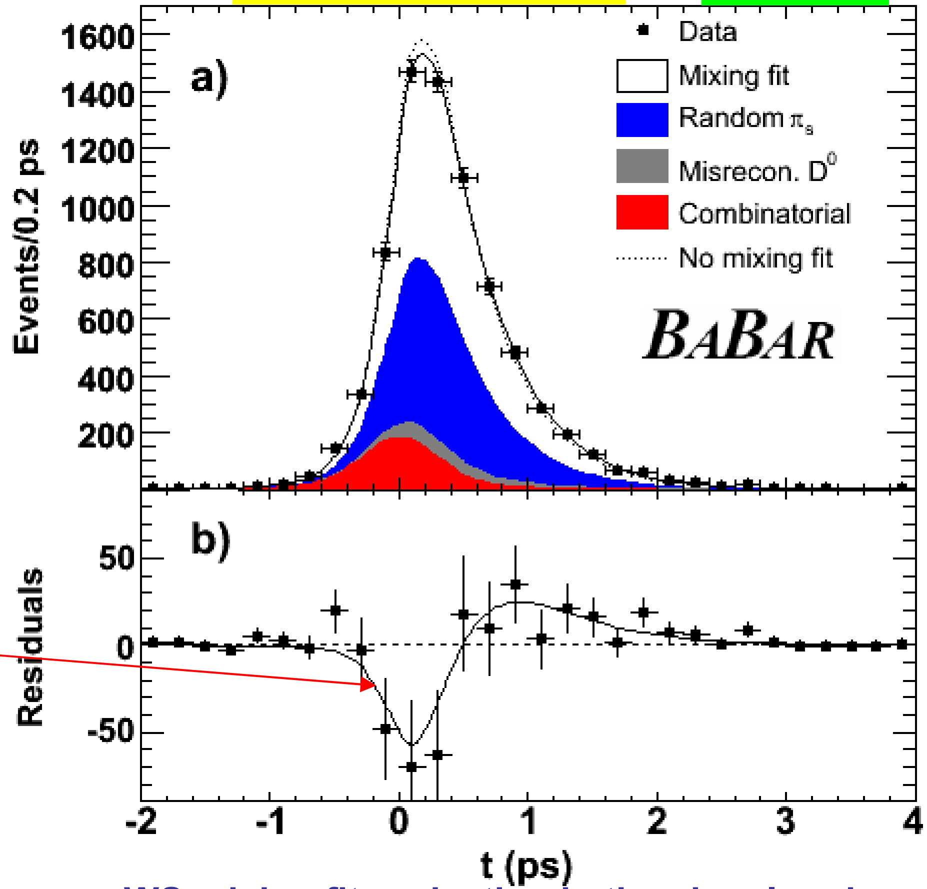
The points represent the data minus the no-mixing fit
(effectively the dashed line ---)

The solid curve represent the mixing fit minus the no-mixing fit

The fit is significantly improved by allowing for mixing.

PRL 98,211802 (2007)

384 fb^{-1}



WS mixing fit projection in the 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 fit likelihood contours

Contours in y', x'^2 computed from $-2\Delta \ln L$

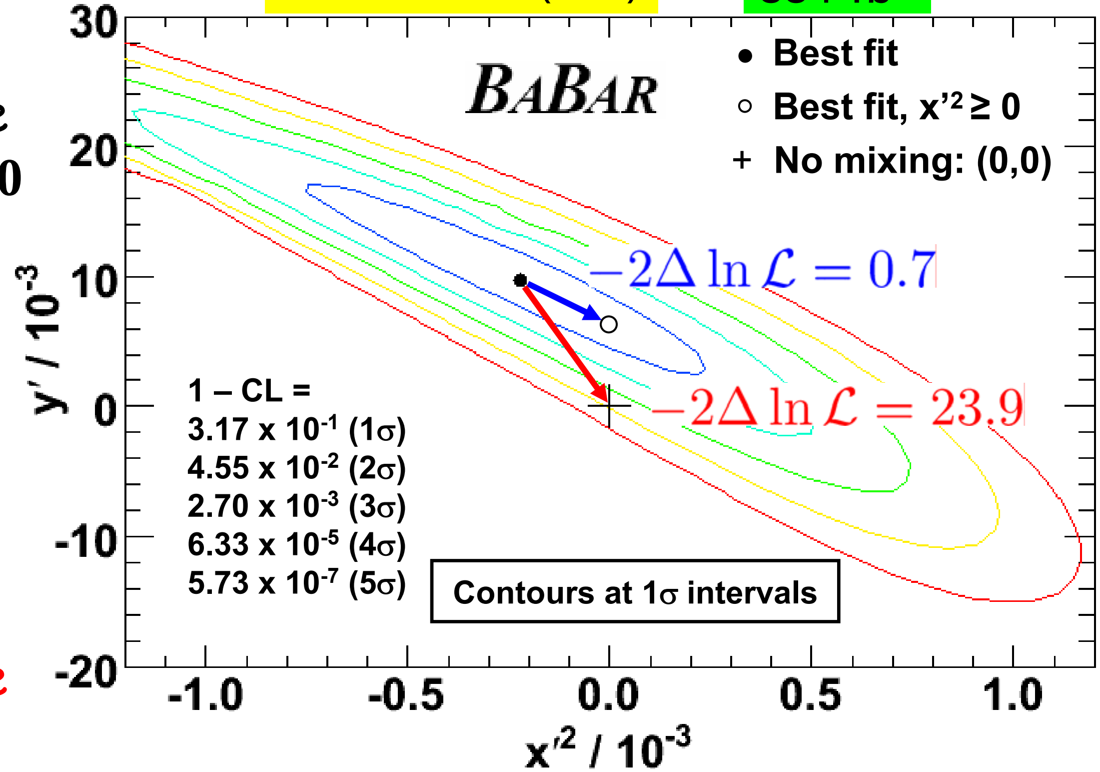
- Best-fit point is in the non-physical region $x'^2 < 0$
- 1σ contour extends into physical region
- Correlation: −0.95

Contours include systematic errors

The no-mixing point is at the 3.9σ contour

PRL 98,211802 (2007)

384 fb^{-1}



Fits show no evidence for CP violation

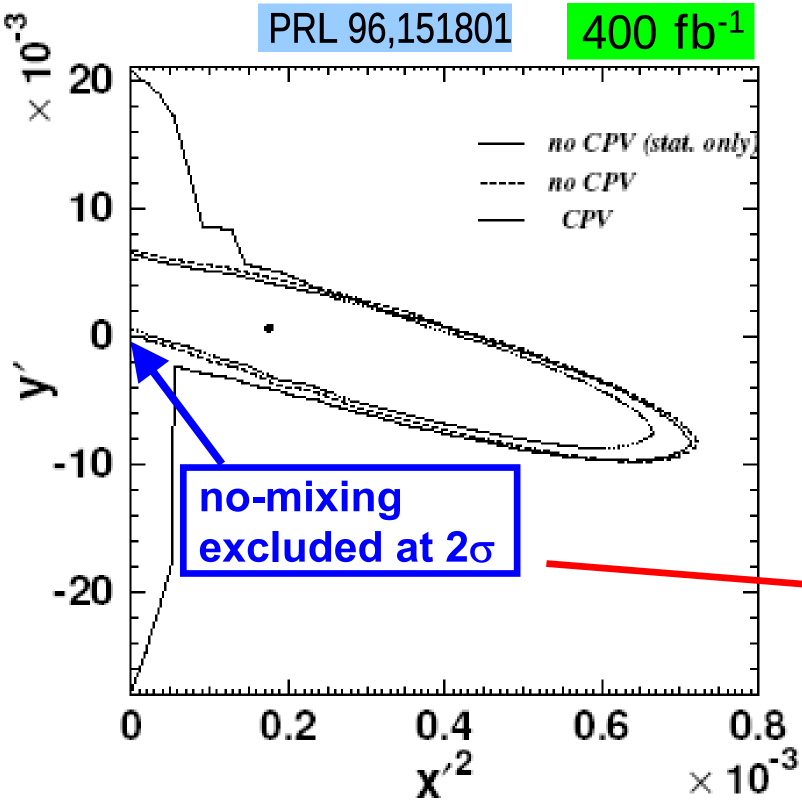
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

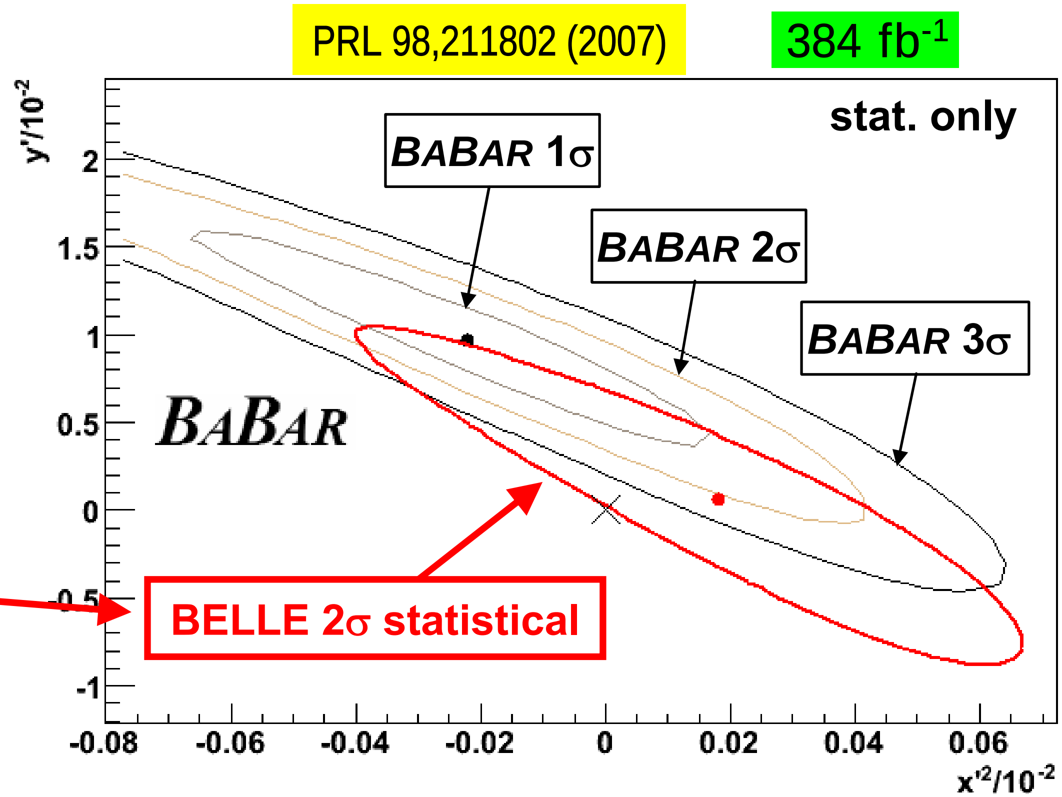
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

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

BABAR vs. BELLE $D^0 \to K\pi$ result

Results consistent within 2σ





Average Kπ Mixing Results

Heavy flavor averaging group (HFAG)
provides "official" averages

Combine BaBar and Belle likelihoods in 3 dimensions (R_D, x'^2, y')

PRL 98,211802 (2007)

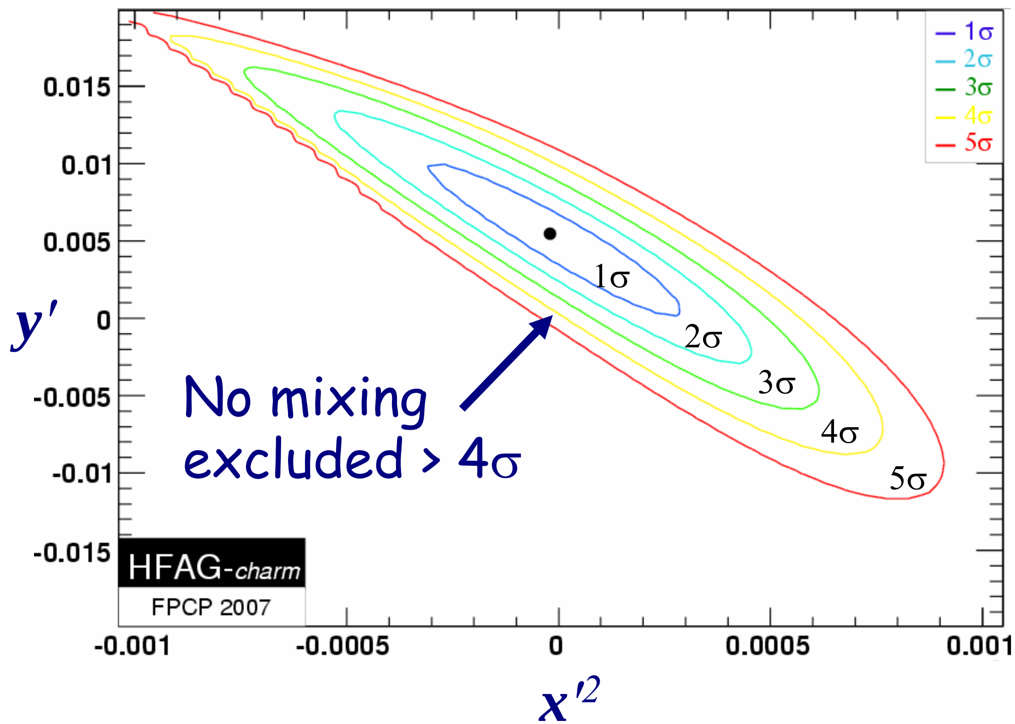
PRL 96,151801 (2006)

July 2007 Averages:

$$R_D = (3.30\,^{+0.14}_{-0.12}) \times 10^{-3}$$

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

$$y' = (5.5\,^{+2.8}_{-3.7}) \times 10^{-3}$$



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

Look for a lifetime difference y_{CP} between $D^0 \to K^+K^-, \pi^+\pi^-$ (CP-even) and the $D^0 \to K^-\pi^+$ (CP-mixed)

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

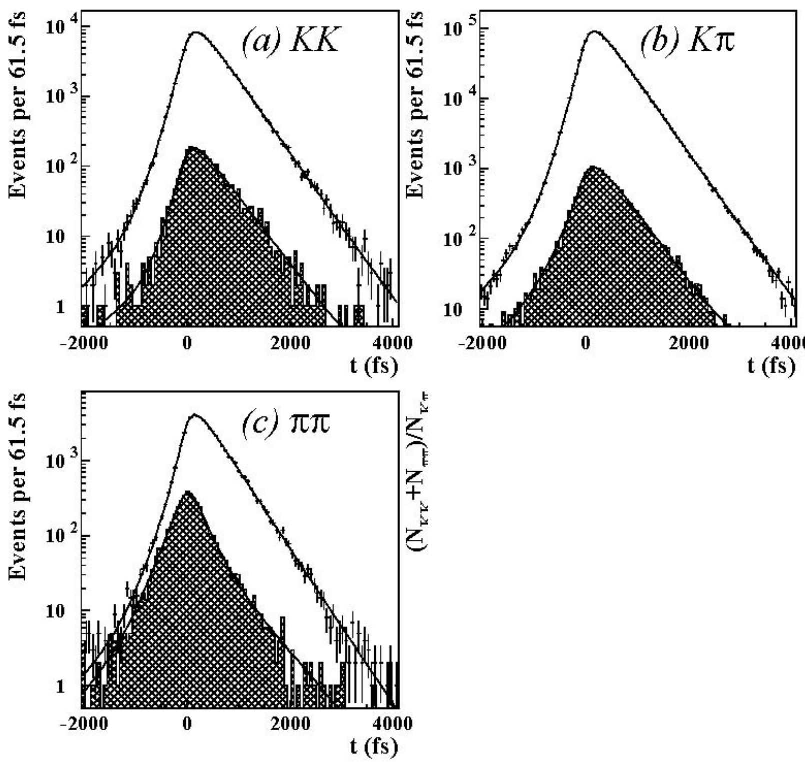
If CP is conserved, then $y_{CP} = y$

CP violation would give a lifetime difference in D^0 and $\overline{D}^0$ decays to $K^+K^-, \pi^+\pi^-$ final states,

Measure e.g. :

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

Decay time Distributions



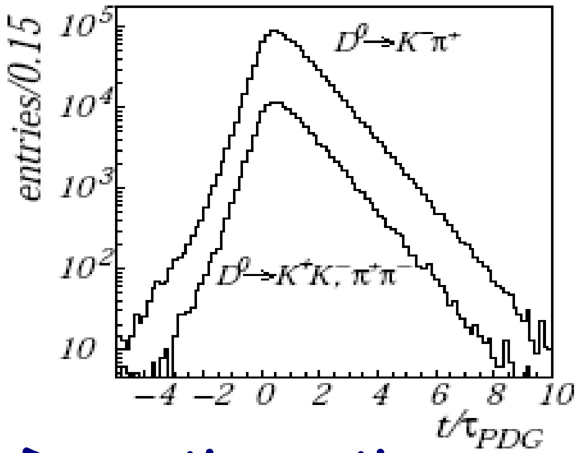
BELLE K^+K^-, $\pi^+\pi^-$ lifetime ratio

PRL 98,211803 (2007)

Measure lifetime difference of CP eigenstates

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

Decay time distributions



From the combined fit to KK and $\pi\pi$:

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

(regardless of possible CPV)

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

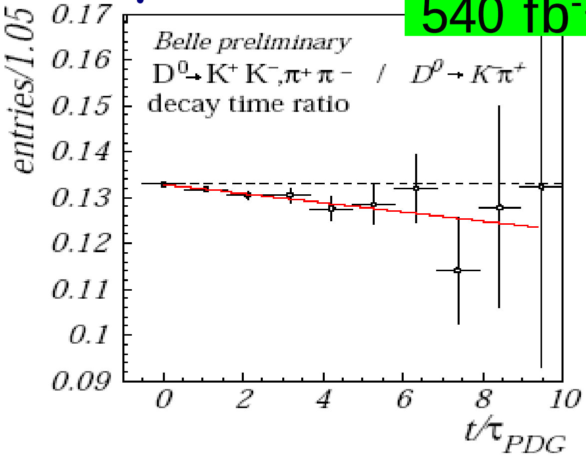
$> 3\sigma$ above zero

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

no evidence for CP violation

Decay time ratio

540 fb^{-1}



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

Time-dependent, Dalitz-plot analysis using $D^{*+} \to D^0\pi^+$, $D^0 \to K_s\pi\pi$ + c.c. decays

Self-conjugate mode

Initially-produced 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 directly

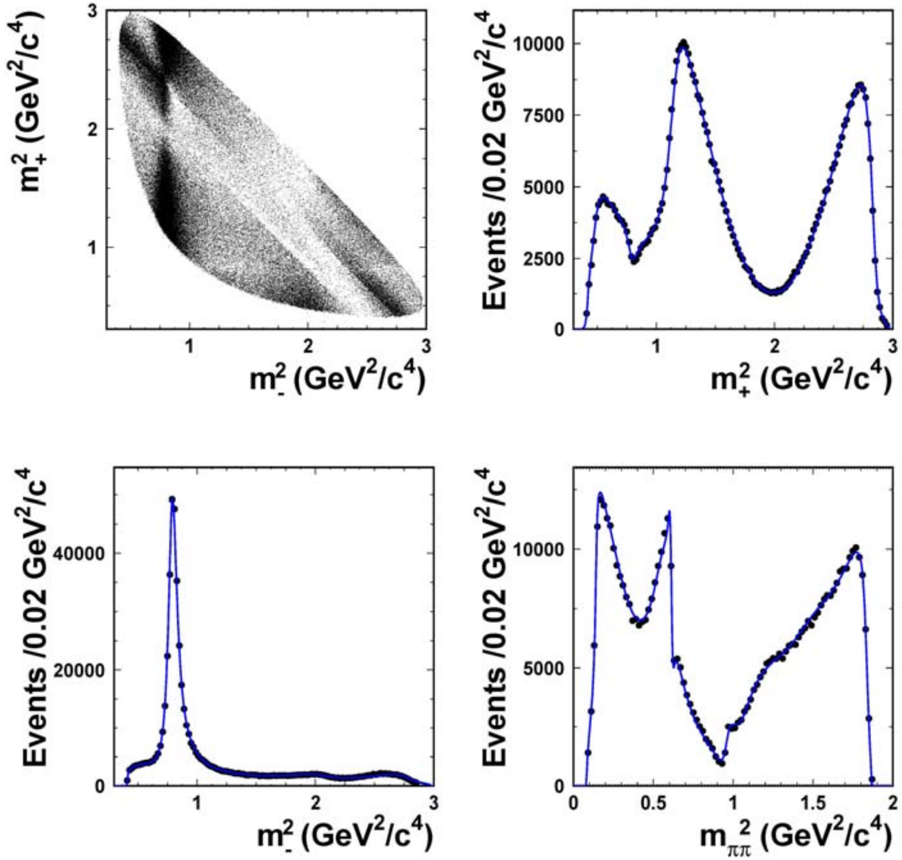
All phases are measured in the Dalitz plot analysis

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

- Dalitz fit model
  - 18 BW resonances + a 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

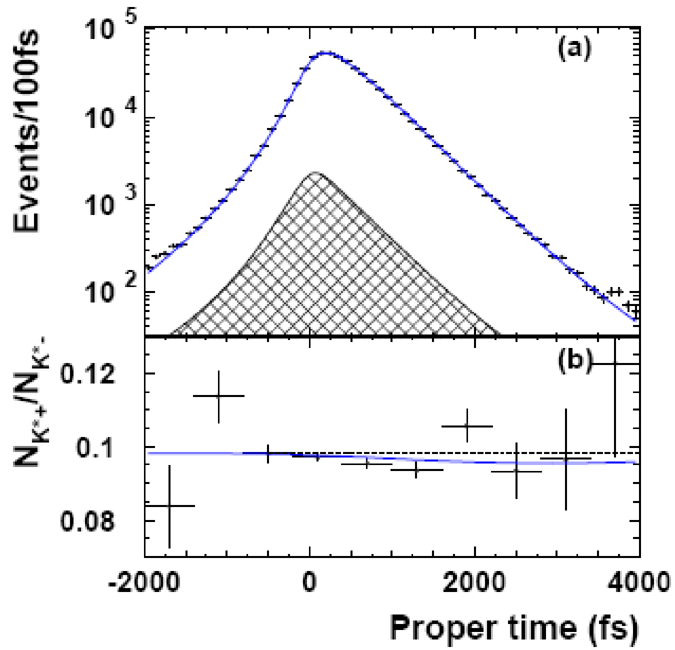


BELLE $D^0 \to K_s\pi\pi$ Results

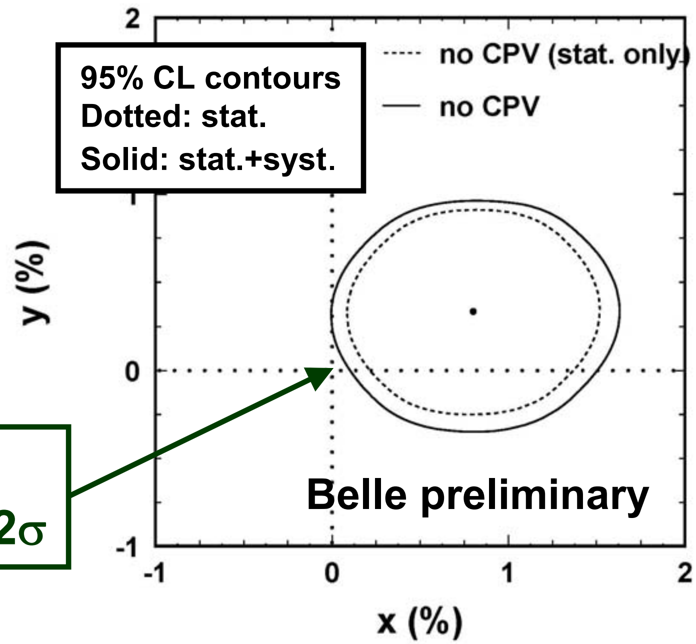
Proper-time fit results

$x = (0.80 \pm 0.29 \pm 0.17)\%$ **(2.4σ)**

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



No-mixing excluded at 2.2σ



arXiv:0704.1000

540 fb^{-1}

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

Average D^0 Mixing Results

Heavy flavor averaging group (HFAG)

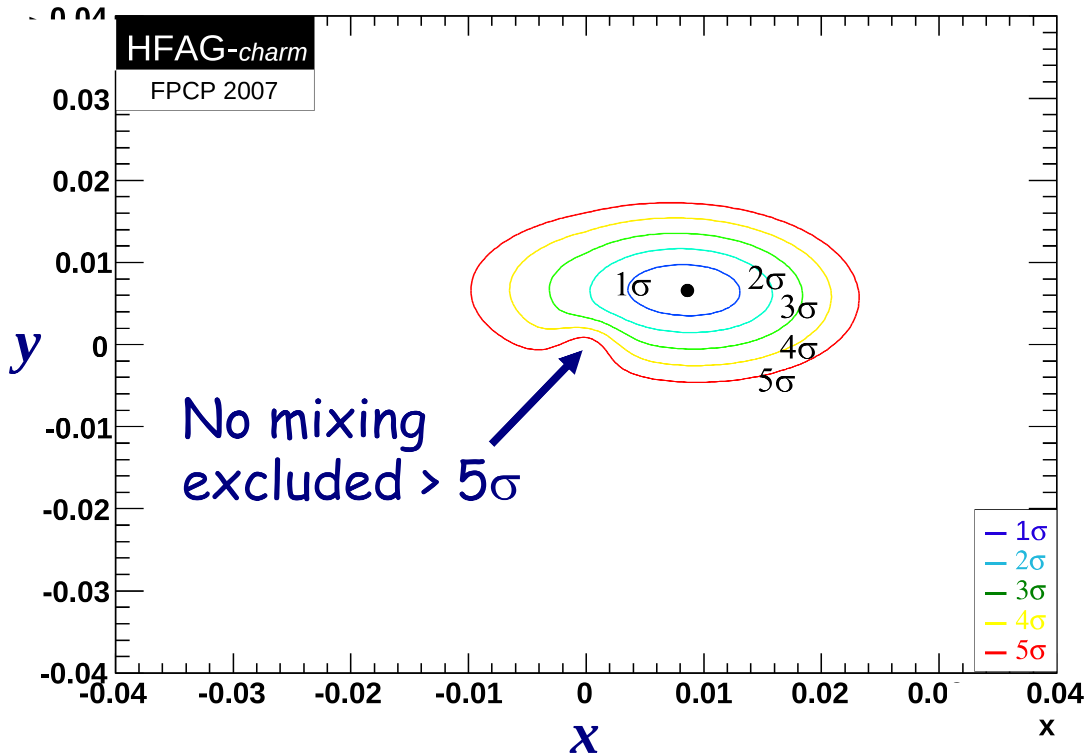
Combine all available measurements (likelihoods) in 3 dimensions (x, y, δ)

<u>July 2007 Averages:</u>

$$\delta = 0.33 \,^{+0.26}_{-0.29}$$

$$x = (0.87 \,^{+0.30}_{-0.34}) \times 10^{-2}$$

$$y = (0.66 \,^{+0.21}_{-0.20}) \times 10^{-2}$$



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Summary

- BABAR: Evidence for D^0 mixing at **3.9σ** (Kπ analysis)
- BELLE: Evidence for D^0 mixing at **3.2σ** (Lifetime ratio)
- The combined BABAR plus Belle result is inconsistent with the null mixing hypothesis at the **4σ level** and show no evidence for CP violation.
- HFAG combined average in 3 dimensions (x, y, δ) excludes the no mixing hypothesis at **5σ level**
- Oscillations in the theory of SM long-distance contributions to D^0 mixing have been observed.
- More precise measurements of D-meson mixing and CP violation parameters as well as better calculations are needed in order to find hints of New Physics effects.
- New results from BABAR (Lifetime ratio, Dalitz) and Belle analyses are underway.

Backup Slides

Fit Procedure

Unbinned maximum likelihood fit in several steps

(high demand on computing resources, 1+ million events)

Fit to m(Kπ) and Δm distribution:

- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

Fit RS decay time distribution:

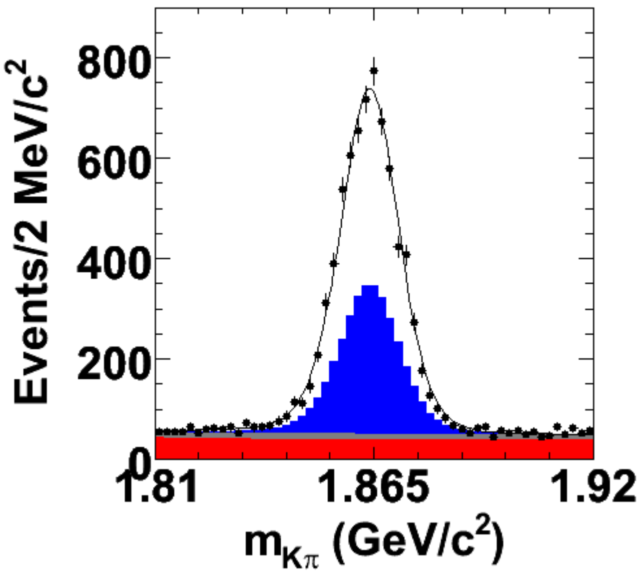
- Determines D^0 lifetime and resolution function
- Include event-by-event decay time error δt in resolution
- Use m(Kp) and Δm to separate signal/bkgd (fixed shapes)

Fit WS decay time distribution:

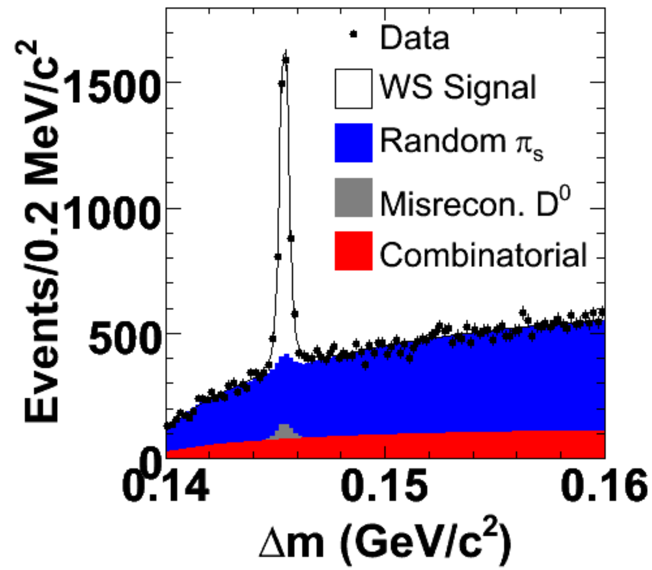
- Use D^0 lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)

Wrong-sign $m_{K\pi}$, Δm fit

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)% (PRL 98,211802 (2007))**
BELLE (400 fb^{-1}): R_{WS} = (0.377 ± 0.008 ± 0.005)% (PRL 96, 151801 (2006))

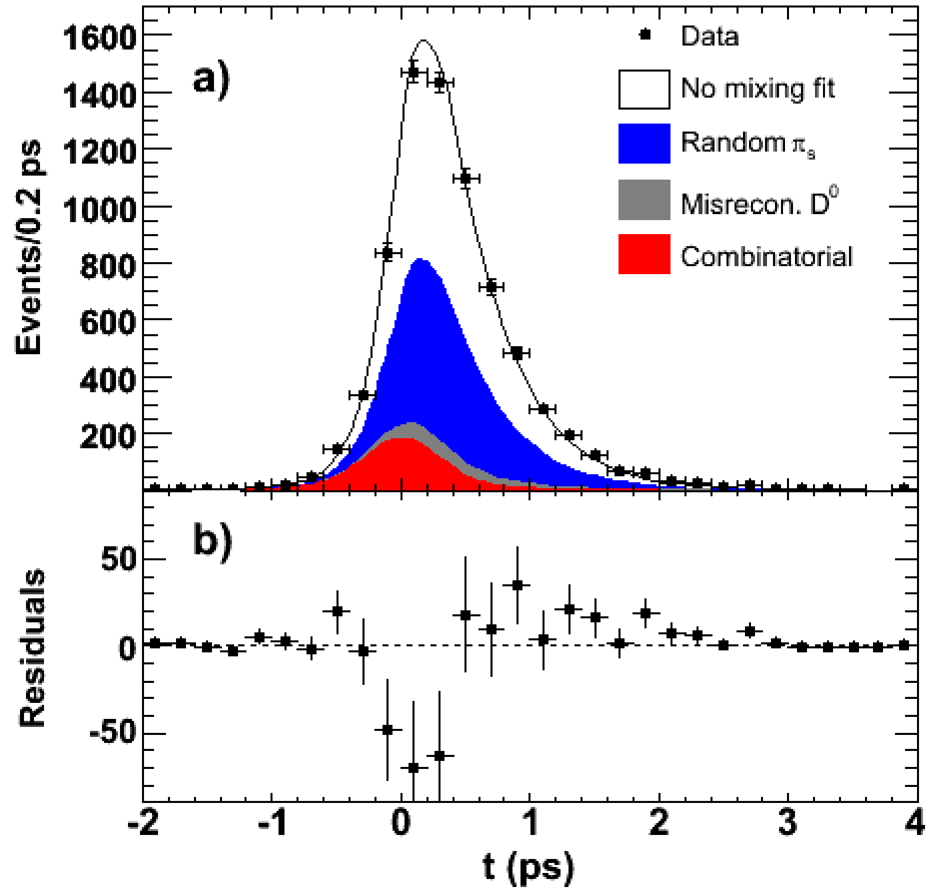
No-mixing WS decay time fit

The parameters fitted are

- WS category yields
- WS combinatoric shape parameter

As can be seen in the residual plot, there are large residuals.

Residuals = data – fit



WS *no-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

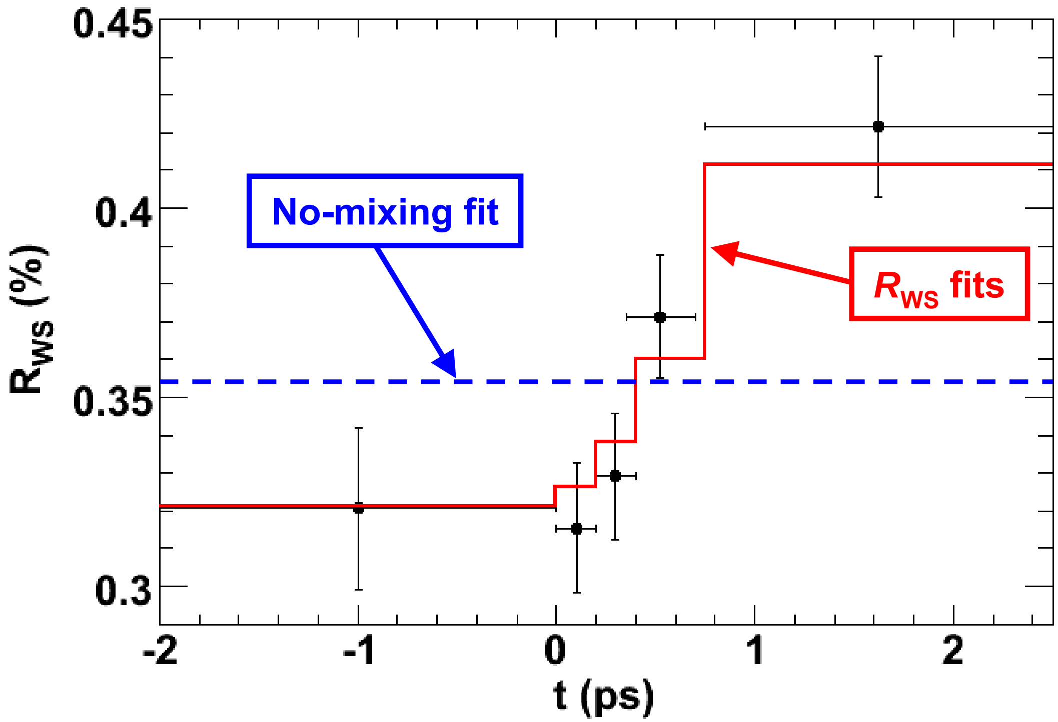
R_{WS} vs. decay-time slices

If mixing is present, it should be evident in a 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).

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
  - $x'^2 = (-0.01 \pm 0.01) \times 10^{-3}$
  - $y' = (0.26 \pm 0.24) \times 10^{-3}$
- Fit generic MC for mixing
  - $x'^2 = (-0.02 \pm 0.18) \times 10^{-3}$
  - $y' = (2.2 \pm 3.0) \times 10^{-3}$
- 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

PEP-II a Charm Factory:

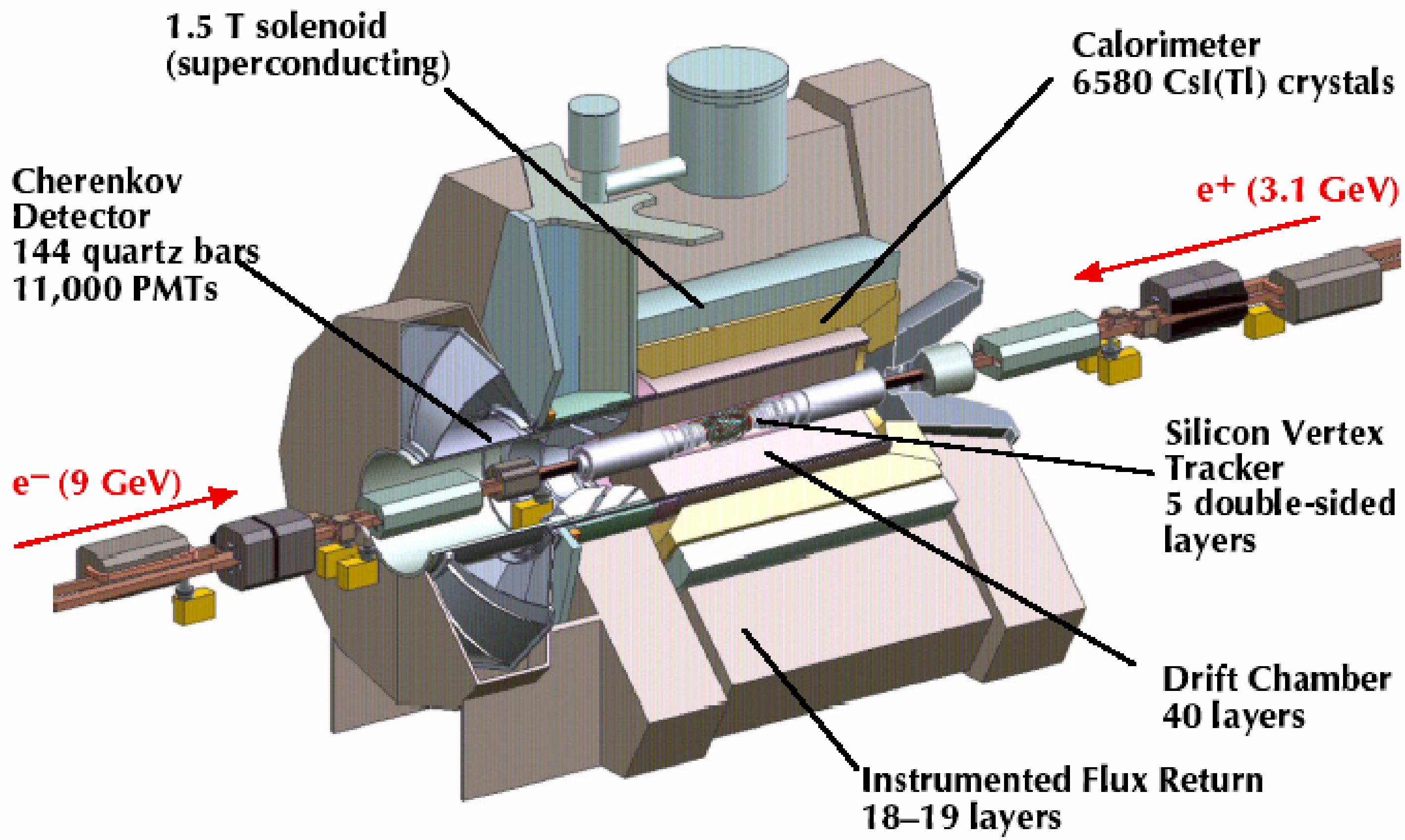
$\sigma(b\bar{b})$ = 1.1 *nb*

$\sigma(c\bar{c})$ = 1.3 *nb*

We use 384 fb^{-1} $e^+e^- \rightarrow c,\bar{c}$

→ 500 X 10^6 $c\bar{c}$ events

The BaBar Detector



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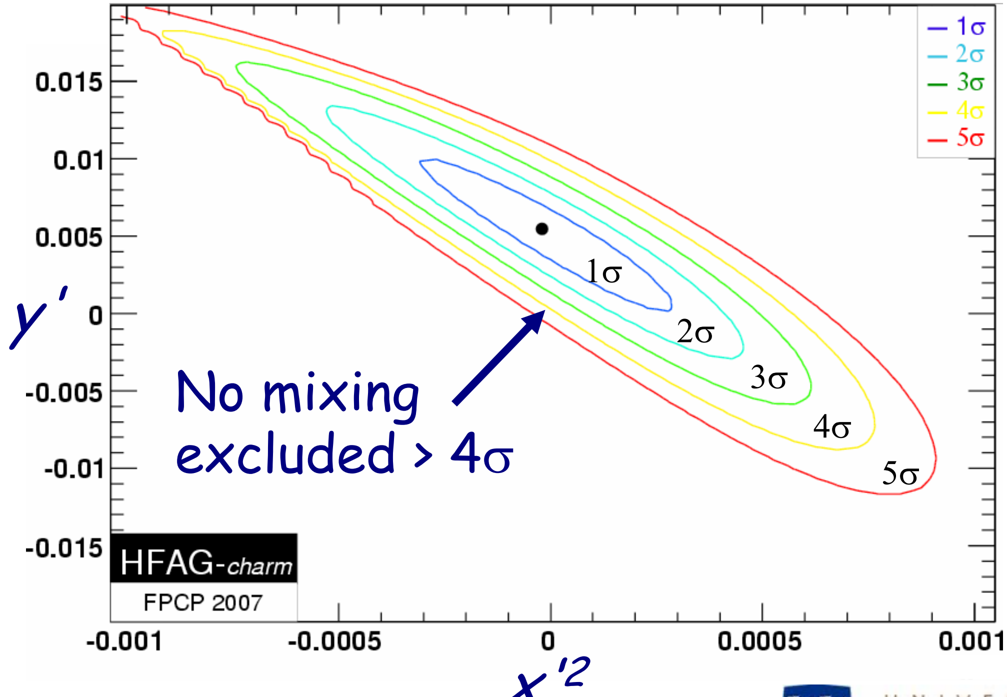
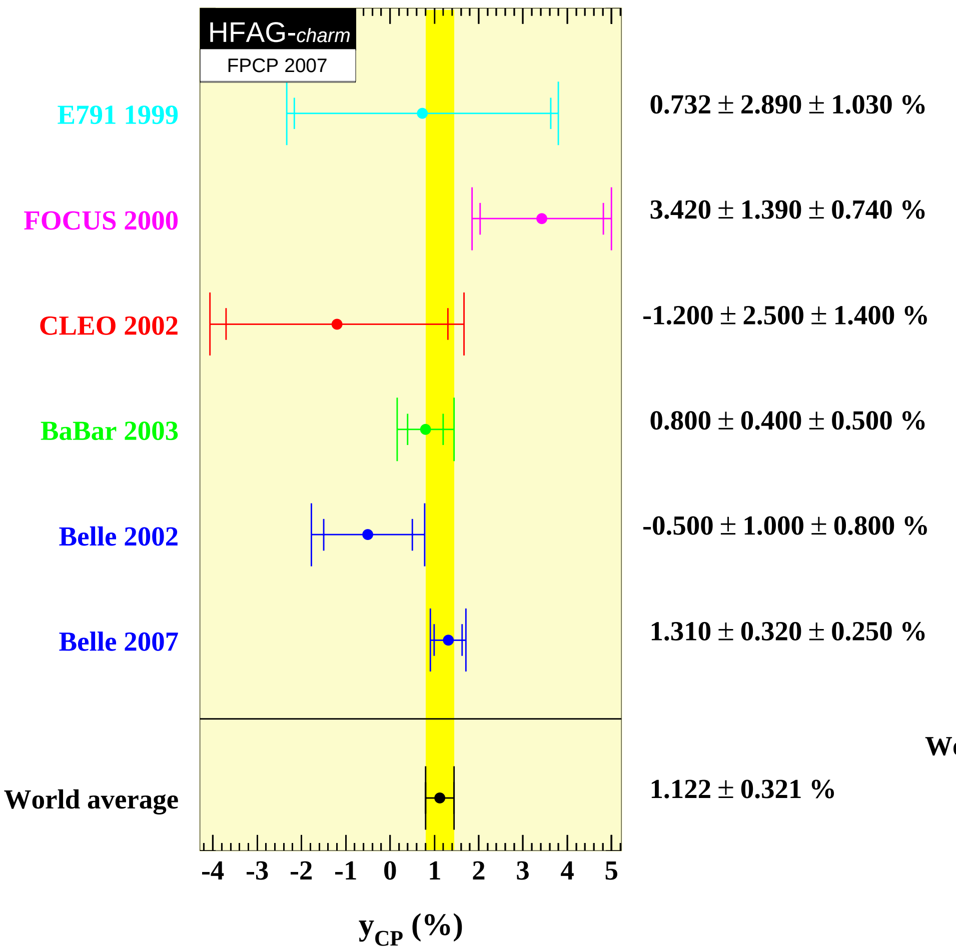
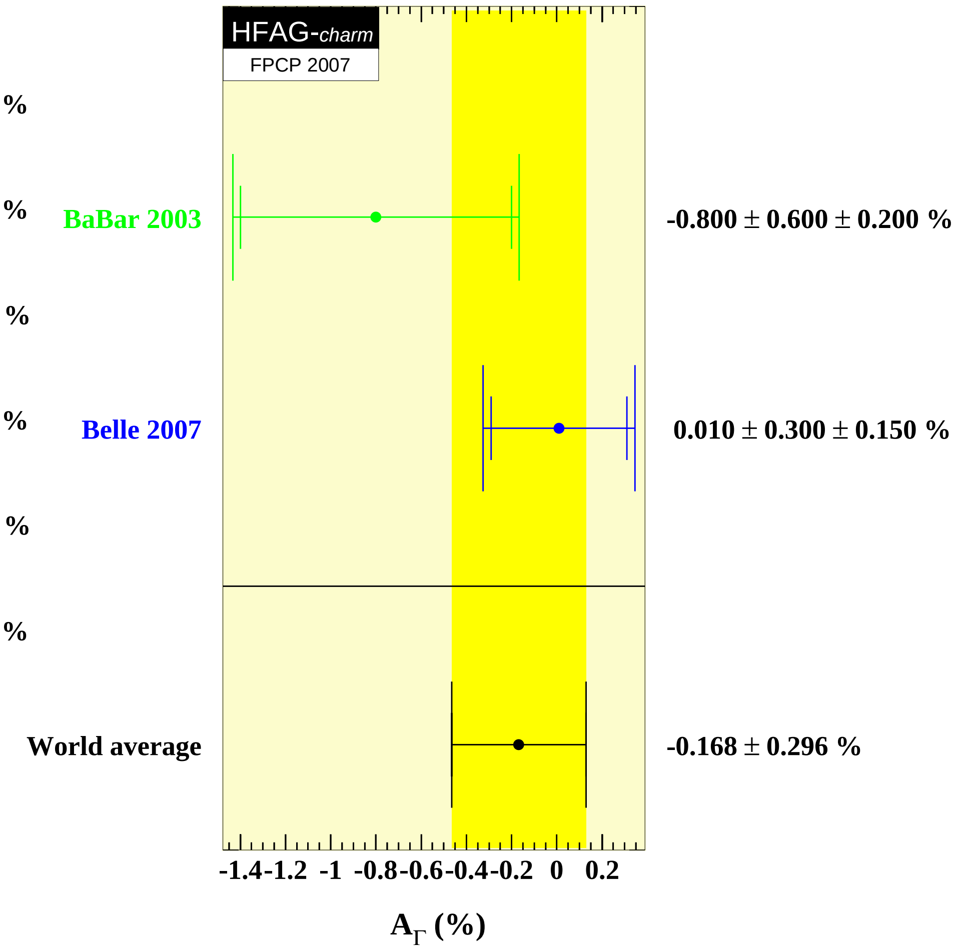
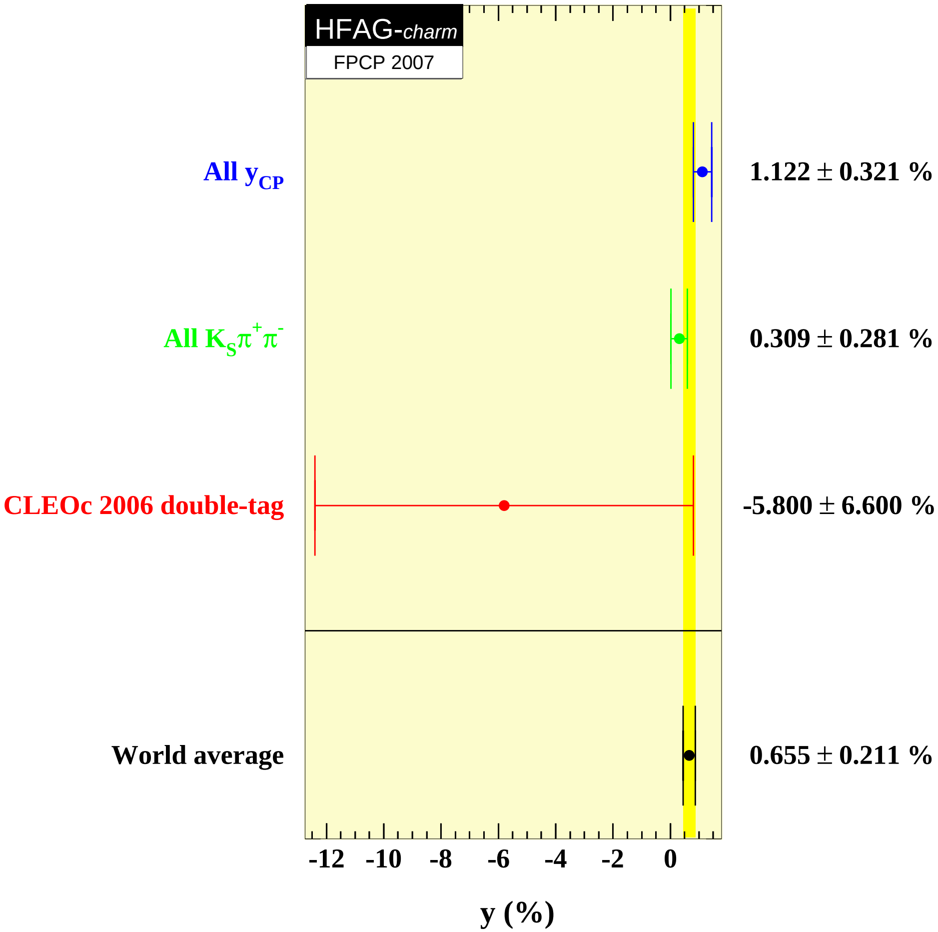


Average y_{cp} / Average A_Γ





Average *y*



Average *x*