CKM Workshop 2008 – Rome, Fri 12 Sep

D^0-$\overline{D}^0$ Mixing at the *B*-factories

Jon Coleman

SLAC

Representing the

BABAR

Collaboration

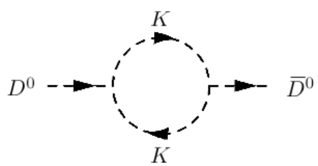
Introduction

- Mixing among the neutral meson flavor eigenstates provides important information about
  - electroweak interactions, including CP violation
  - the CKM matrix
  - mixing loop virtual constituents
- D^0 system exhibits the smallest mixing

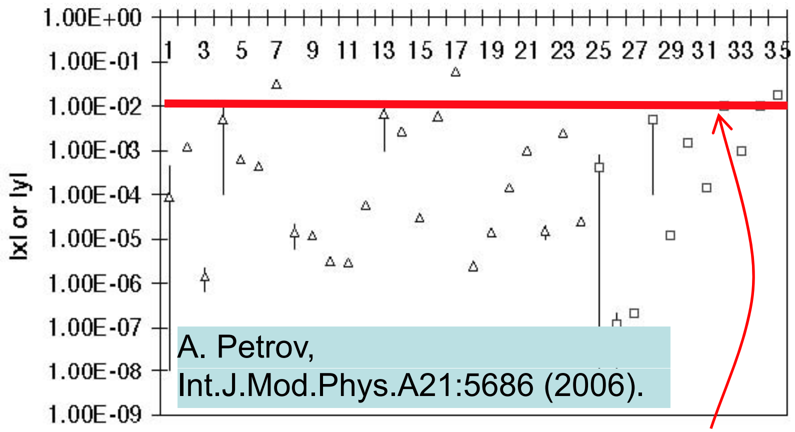
System:	x:	y:
K^0 (1956)	0.95	0.99
B_d (1987)	0.78	≈0
B_s (2006)	26	0.15
D^0 (2007)	0.0098	0.0075

- Short distance Standard Model (SM) suppression:
  - *D* mixing loop involves down-type quarks
    - b quark loop suppressed: $|V_{ub}^{*}V_{cb}| \ll 1$
    - s and d quark loops GIM suppressed
  - ⇒ mass difference amplitude O(10^{-5}) or less

- long distance mixing amplitudes



predominant but hard to quantify



Reasonable to expect $|x|\sim10^{-2}$, $|y|\sim10^{-}$

Recent Measurements

Mixing and CPV in the *D^0* system were discussed *over 30 years ago!*

- A. Pais and S.B. Treiman, Phys. Rev. D12, 2744 (1975).

BUT evidence for mixing was found only recently

* Mixing measurements
  - $D^0 \to K^+K^-, \pi^+\pi^-$
  - $D^0 \to K^+\pi^-$
  - $D^0 \to K^{(*)-}l^+\nu$
  - $D^0 \to K^+\pi^- \pi^0$
  - $D^0 \to K_s\pi^+\pi^-$
  - $D^0 \to K_sK^+K^-$
  - Quantum Corr.

Mixing Parameters

* Mixing in the neutral *D* system arises from the existence of two mass eigenstates D_1 and D_2 that are not flavour eigenstates

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

$$|D_1> \; = p|D^0> + q|\bar{D}^0> \qquad |D_1(t)> \; = |D_1> e^{-i(\Gamma_1/2 + i m_1)t}$$

$$|D_2> \; = p|D^0> - q|\bar{D}^0> \qquad |D_2(t)> \; = |D_2> e^{-i(\Gamma_2/2 + i m_2)t}$$

Eigenvalues are
$m_{1,2} + i\Gamma_{1,2}/2$

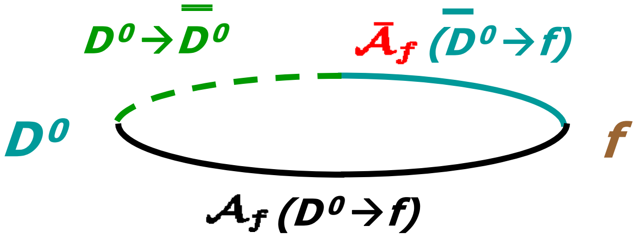
with means:
$M = (m_1 + m_2)/2$
$\Gamma = (\Gamma_1 + \Gamma_2)/2$

* It is usual to define four mixing parameters:

$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \;;\; \left|\frac{p}{q}\right| \;;\; \phi_M = \text{Arg}\left\{\frac{p}{q}\right\}$$

CPV signalled by
$p \neq q$

* *CPV* from either the mixing, or from the decay (or both) can ocur



$$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f} \propto e^{i(\delta + \phi_f)}$$

strong　　weak

Generic Mixing Analysis

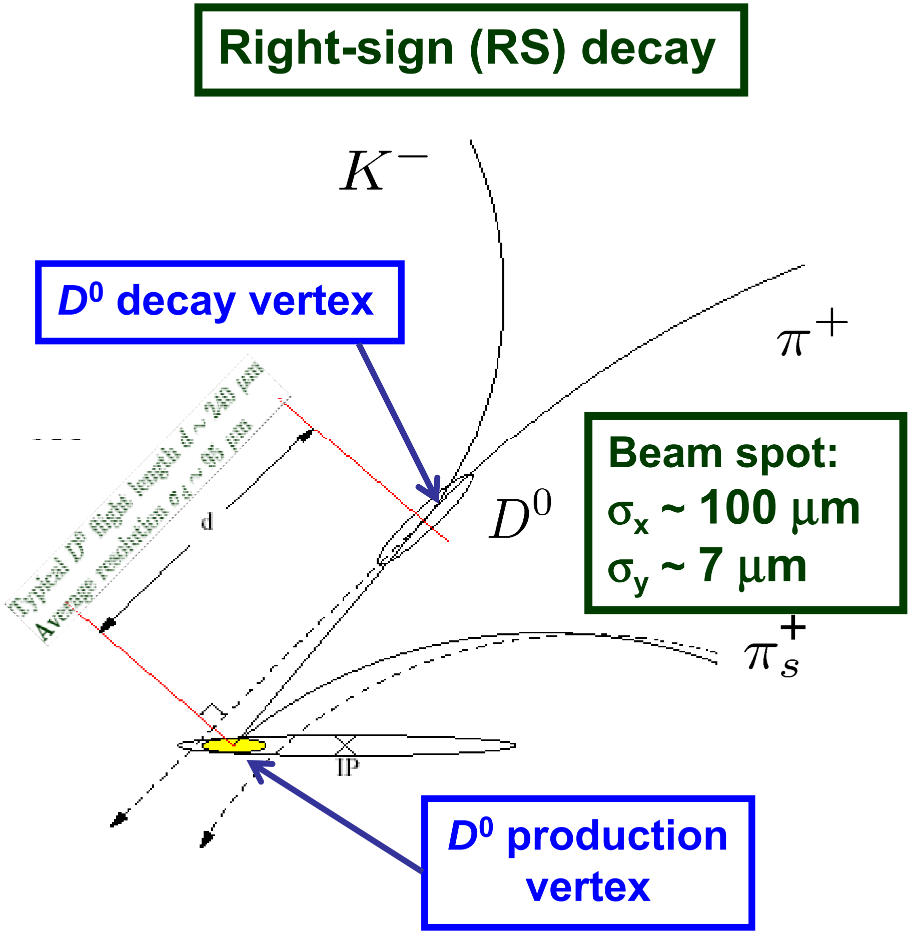
* Identify the D^0 flavor at production using the decays $D^{*\pm} \rightarrow \pi_s^{\pm} D^0$
  – select events around the expected
  $\Delta m = m(D^{*+}_{\text{rec.}}) - m(D^0_{\text{rec.}})$
  – The charge of the soft pion determines the flavor of the D^0

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

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

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

* Vertexing with beam spot constraint improves $m_{K\pi}$, Δm, flight length and hence proper decay time t, and its uncertainty σ_t



Lifetime-Difference Measurements

* 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*.

$$y_{CP} \approx y = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1$$

Mixed *CP*. Assume τ is mean of *CP*-even and *CP*-odd

K^+K^- or $\pi^+\pi^-$ *CP*-even

* Allowing for *CPV*, measure the D^0 and $\bar{D}^0$ asymmetry

$$A_\tau = \frac{\tau(\bar{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{\tau(\bar{D}^0 \to h^+h^-) + \tau(D^0 \to h^+h^-)} = \frac{1}{2} A_M y \cos\phi_M - x \sin\phi_M$$

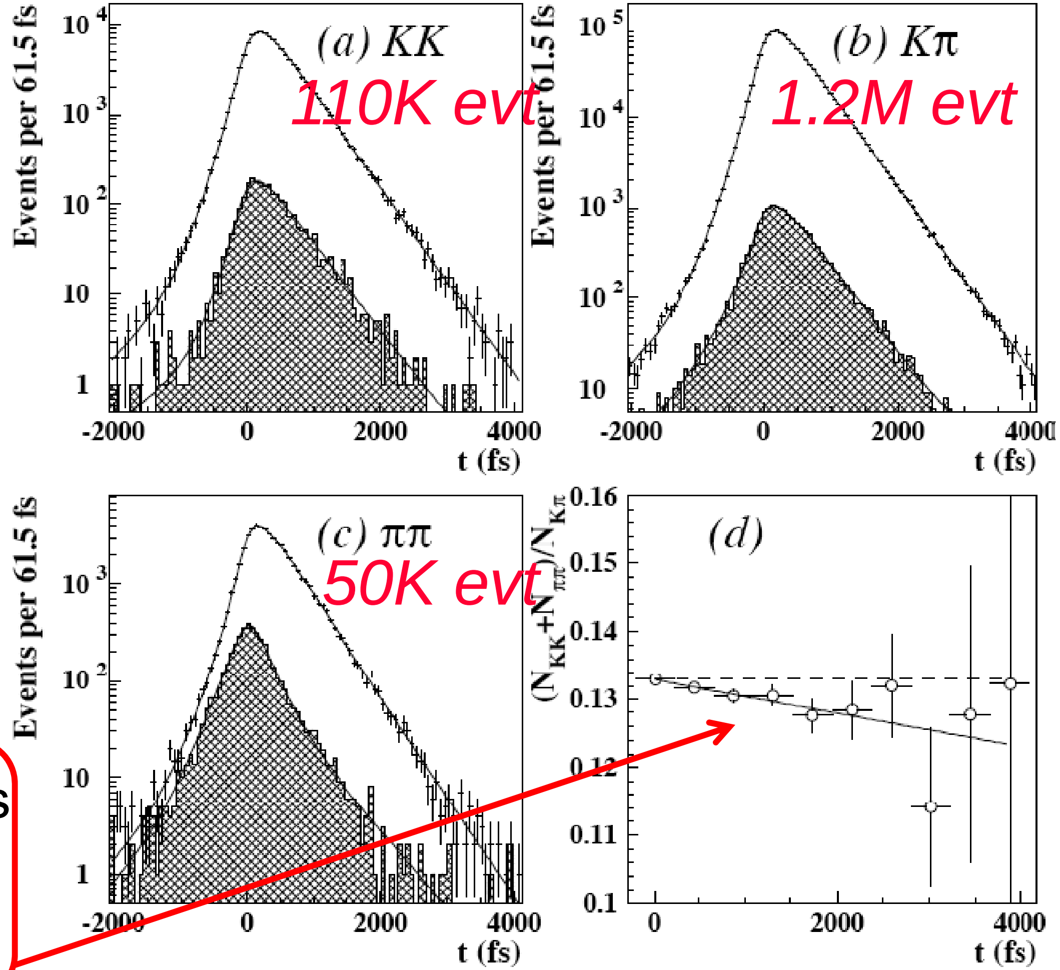
A_M: $|q/p|^2 - 1$

PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

Lifetime Ratio (y_{CP}, A_Γ): Evidence Of Mixing At 3.2σ

PRL 98, 211803 (2007)
Data: 540 fb-1

* 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, ππ, respec.

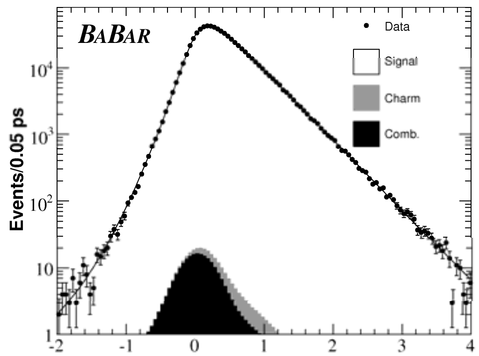


Ratio of D^0_{CP}/D^0 events varies as a function of time due to lifetime difference ($y_{CP} \neq 0$)

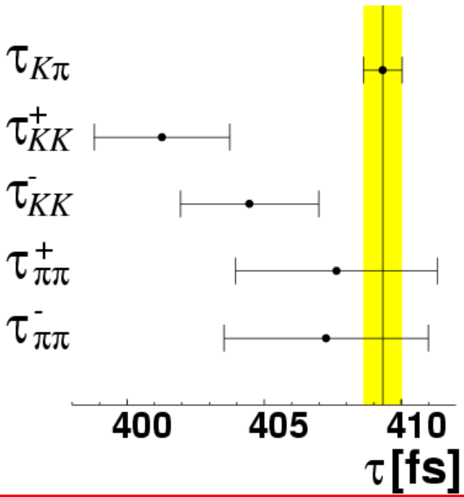
Decay time fits to determine y_{CP}, ΔY

PRD 78, 011105(R) (2008) **384 fb-1**

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

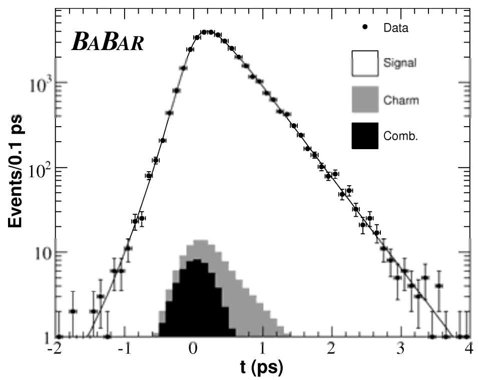


τ=409.3±0.7 fs



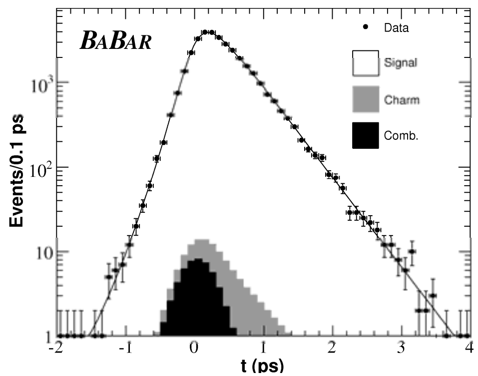
$K\pi$ and KK lifetimes differ

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



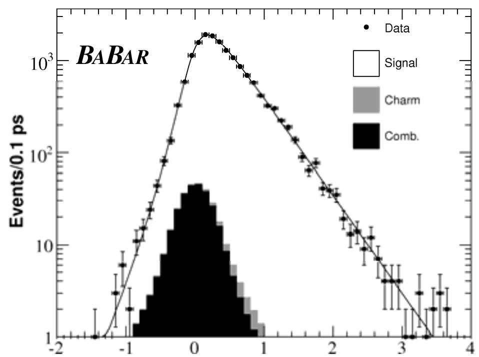
τ=401.3±2.5 fs

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



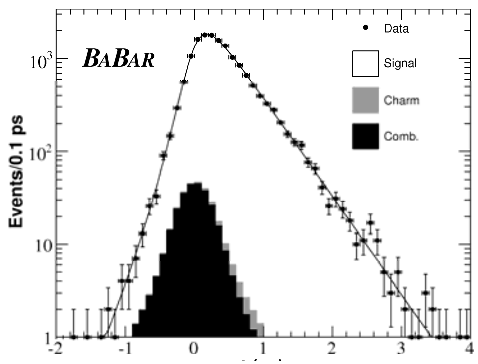
τ=404.5±2.5 fs

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



τ=407.6±3.7 fs

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

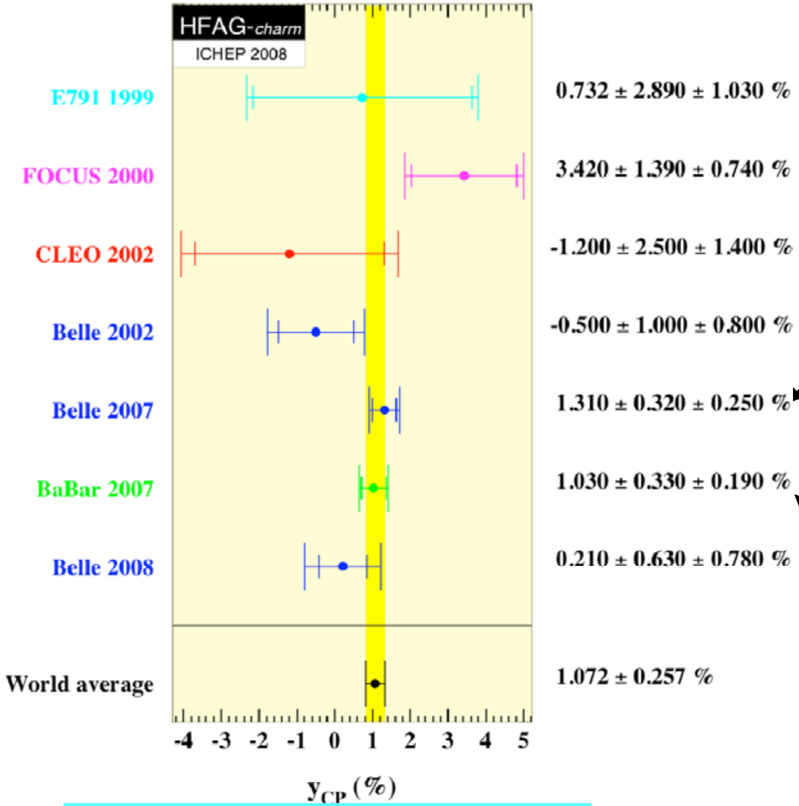


τ=407.3±3.8 fs

Lifetime-Difference Results

y_{CP} world average from HFAG

arXiv:0808.1297



$y_{CP} = (1.132 \pm 0.266)\%$

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}**

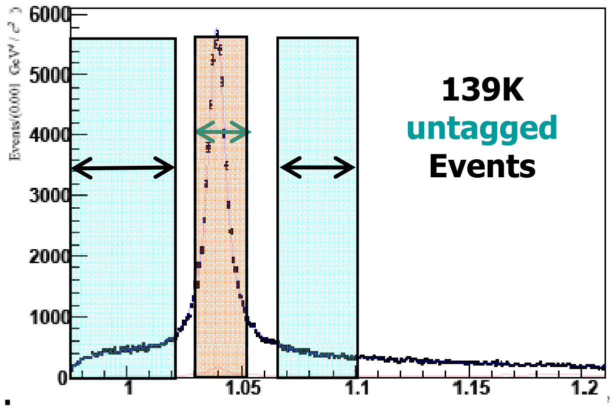
384 /fb tagged and 91 /fb untagged (*BaBar*)

Measurement of y_{CP} in $D^0 \to K_S K^+ K^-$ decays

Arxiv:0807.0148v1 (2008) 673 fb^{-1}

- In effect, this is a measurement of lifetime τ in *CP=+1* and *CP=-1* parts of the $K_s K^+ K^-$ Dalitz plot.
- Choose ϕK_s region and its sidebands

$$\frac{\tau - \tau}{\tau + \tau} = y_{CP}\frac{f - f}{1 + y_{CP}(1 - f - f)}$$



m^2_{KK} (GeV/c²)²

- Fractions *f* of *CP*-even final state in each region:

$$f = \frac{\int |A_+|^2 dm^2_{K^+K^-} dm^2_{K^+K^0_s}}{\int [|A_+|^2 + |A_-|^2]\, dm^2_{K^+K^-} dm^2_{K^+K^0_s}}$$

over appropriate $m_{K^+K^-}$ range

A_+ and A_- are *CP*-even and odd amplitudes describing Dalitz plot population.

$$y_{CP} = (0.21 \pm 0.63(\text{stat.}) \pm 0.78(\text{syst.}) \pm 0.01(\text{model}))\%$$

Belle preliminary!

Time-dependent WS decay rate

Two types of WS Decays:

- Doubly Cabibbo-supressed (DCS) $D^0 \to K^+\pi^-$
- Mixing followed by Cabibbo-Favored (CF) decay $D^0 \underset{\text{mix}}{\to} \overline{D}^0 \to K^+\pi^-$

Two ways to reach same final state ⇒ interference possible!

⇒ Use time dependence to separate DCS and mixing:

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

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

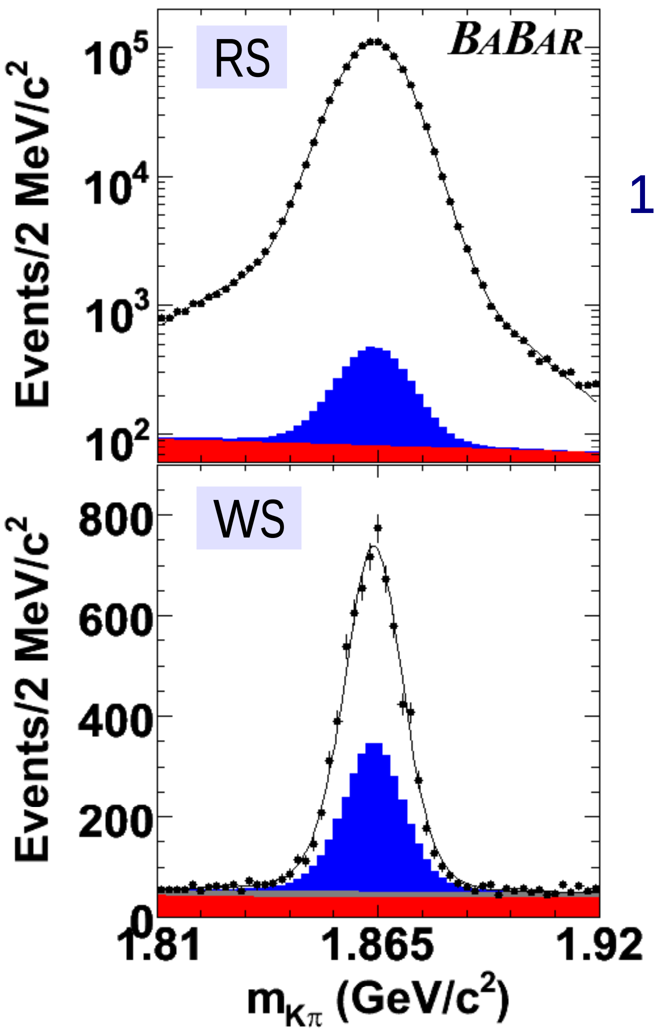
DCS decay **Interference between DCS and mixing** **Mixing**

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

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

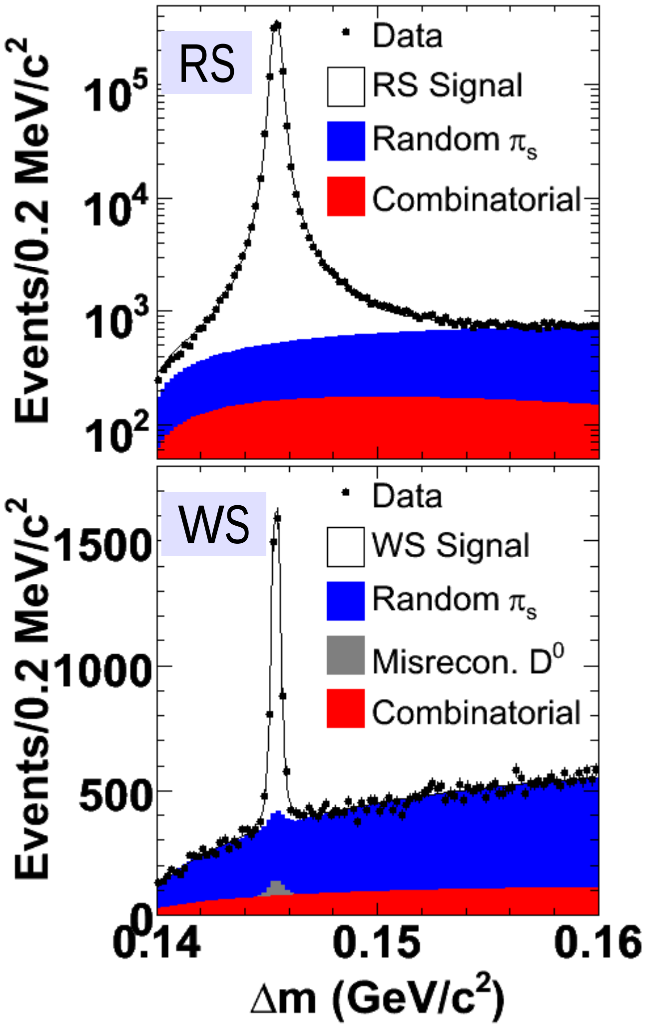
m(Kπ) & Δm Fit Results

PRL 98, 211802 (2007)



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



RS Proper Time Fit

PRL 98, 211802 (2007)

*D*⁰ lifetime and resolution function fitted in RS sample

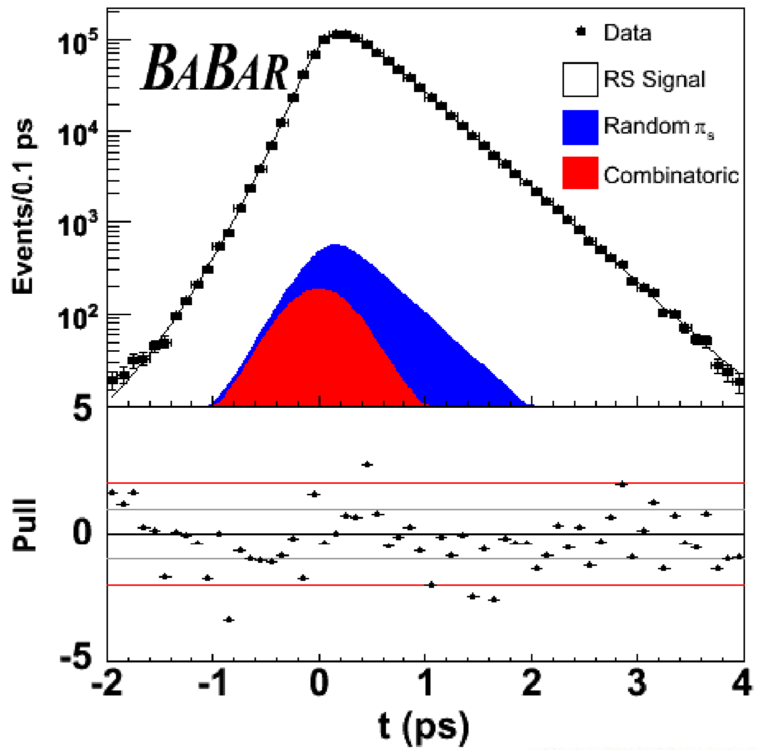
τ=410.3±0.6 (*stat*) fs

Consistent with PDG

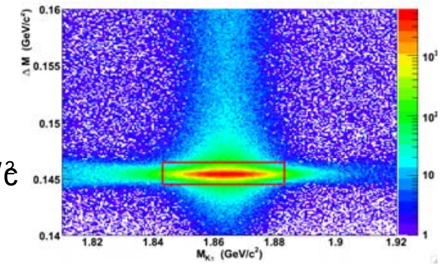
τ_{PDG}=410.1±1.5 fs

Systematics dominated by signal resolution function

RS decay time, signal region



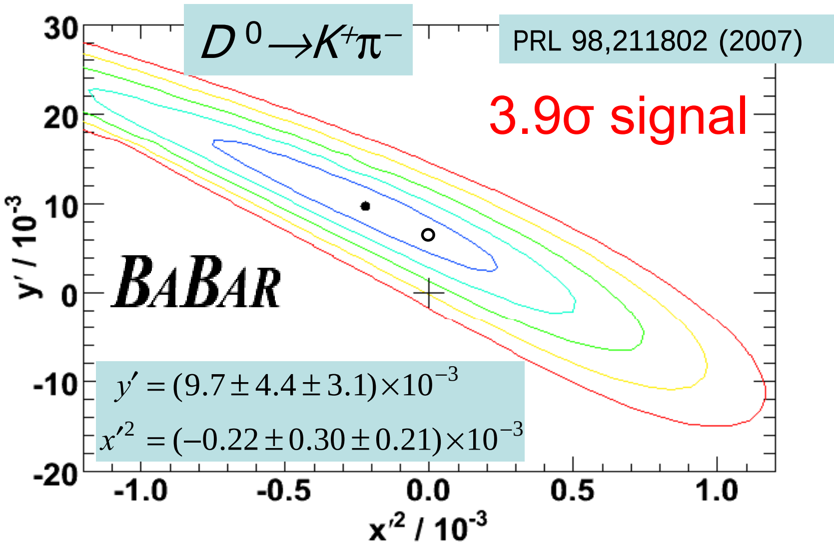
plot selection:
1.843<*m*<1.883 GeV/c^2
0.1445<Δm< 0.1465 GeV/c^2

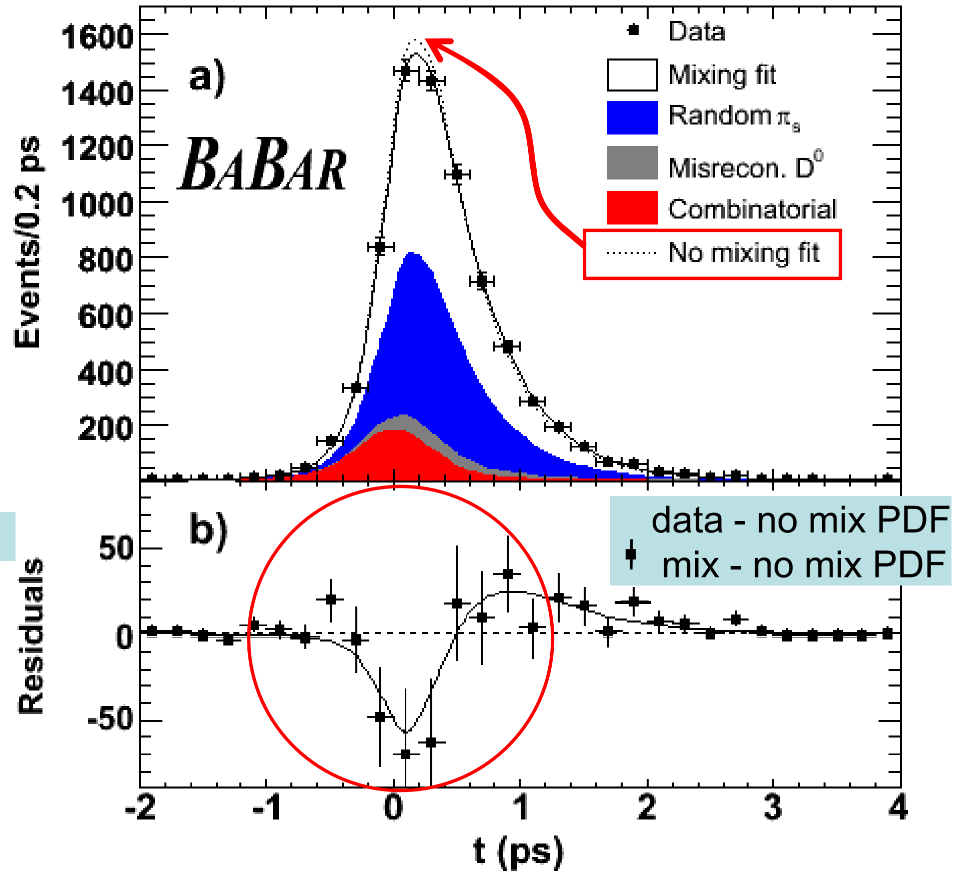


WS Decay Time Fit: Mixing Allowed

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

* The dotted line is the no-mixing expectation.
* The solid line is the mixing fit.
* The difference between no-mixing hypothesis and the fit with mixing is shown in the residuals plot.





R_D: (3.03 ± 0.16 ± 0.10) x 10^{-3}
x'^2: (-0.22 ± 0.30 ± 0.21) x 10^{-3}
y': (9.7 ± 4.4 ± 3.1) x 10^{-3}

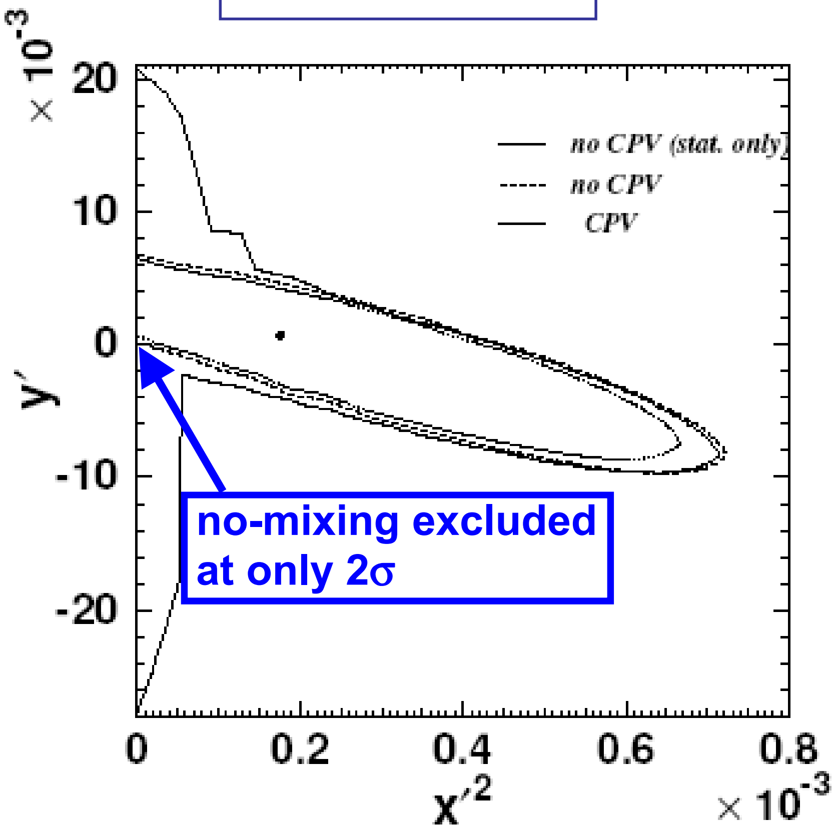
No evidence for *CPV*

$D^0 \rightarrow K\pi$ Belle Measurement

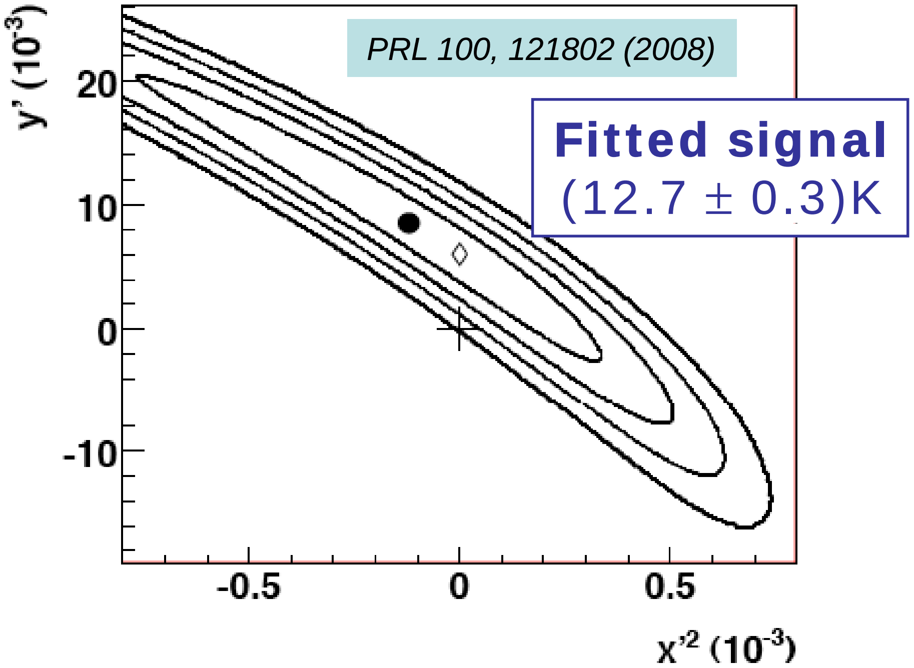
PRL 96,151801 (2006)
Data sample 400 fb^{-1}

Fit case	Parameter	Fit result $(\times 10^{-3})$	95% C.L. interval $(\times 10^{-3})$
No CPV	R_D	3.64 ± 0.17	$(3.3,\ 4.0)$
	x'^2	$0.18^{+0.21}_{-0.23}$	< 0.72
	y'	$0.6^{+4.0}_{-3.9}$	$(-9.9,\ 6.8)$
	R_M	-	$(0.63 \times 10^{-5},\ 0.40)$
CPV	A_D	23 ± 47	$(-76,\ 107)$
	A_M	670 ± 1200	$(-995,\ 1000)$
	x'^2	-	< 0.72
	y'	-	$(-28,\ 21)$
	R_M	-	< 0.40
No mixing	R_D	$3.77 \pm 0.08(\text{stat.}) \pm 0.05(\text{syst.})$	

Fitted signal
4024 ± 88



$D^0 \to K\pi$ CDF Measurement



Evidence for mixing at 3.8σ

* Different Analysis
* Different Production Environment
* Confirmation of *BaBar* mixing result
  * ***Nearly identical results!***

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

Measurement of $\delta_{K\pi}$ by CLEO-c

- **Motivation**

PRD 78, 012001 (2008)
PRL 100, 221801 (2008)

  - Need $\delta_{K\pi}$ to compare the measurements of y and y'
  - $\delta = -\delta_{K\pi}$ is defined as the phase of the $K\pi$ DCS to CF amplitude ratio $\frac{\langle K^+\pi^-|D^0\rangle}{\langle K^+\pi^-|\bar{D}^0\rangle} = re^{-i\delta}$ with $r \approx 0.06$

- **Determination of the strong phase in quantum correlated $D^0\bar{D}^0$ pairs**

$$e^+e^- \to \psi(3770) \to D^0\overline{D^0} \qquad \Rightarrow C = -1$$

  - Measure time integrated yields of correlated and uncorrelated D^0 decays
  - The ratio of correlated and uncorrelated D^0 decay rates depends on the mixing parameters and $\delta_{K\pi}$
    - $\to$ Extract x^2,y, r^2 and cos($\delta_{K\pi}$) from time integrated yields
  - External branching fraction are used and including external mixing parameter measurements improves the $\delta_{K\pi}$ extraction

Results of the $\delta_{K\pi}$ measurement

PRD 78, 012001 (2008)
PRL 100, 221801 (2008)

- Extract the strong phase $\delta_{K\pi}$ in a fit to 281pb^{-1} of CLEO-c data
  (external branching fraction measurements are used)
  $x\,sin\,(\delta_{K\pi})$ can not be determined in this fit, therefore set $x\,sin\,(\delta_{K\pi}) = 0$

$$cos\,(\delta_{K\pi}):\quad 1.03^{+0.31}_{-0.17} \pm 0.06$$

- Including in addition external measurements of mixing parameters improves the fit.
  $x\,sin\,(\delta_{K\pi})$ can now be determined

$$cos\,(\delta_{K\pi}):\qquad 1.10 \pm 0.35 \pm 0.07$$
$$x\,sin\,(\delta_{K\pi}):\qquad (4.4^{+2.7}_{-1.8} \pm 0.29)\cdot 10^{-3}$$
$$\delta_{K\pi}:\qquad (22\ ^{+11}_{-12}{}^{+\ 9}_{-11})^{\circ}$$

external input parameters

Parameter	Average
y	0.00662 ± 0.00211
x	0.00811 ± 0.00334
r^2	0.00339 ± 0.00012
y'	0.0034 ± 0.0030
x'^2	0.00006 ± 0.00018

- Established a new technique using time independent measurements of mixing parameters and the strong phase.

Time-Dependent Amplitude Analysis of $D^0 \rightarrow K^+\pi^-\pi^0$

384 fb^{-1}

arXiv:0807.4544 [hep-ex]
Submitted to PRL

* Similar to $D^0 \rightarrow K^+\pi^-$ but now $\bar f$ is an amplitude at a point in the Dalitz plot (*DP*) for the $K^+\pi^-\pi^0$ final state

* *CF* ($\bar{A}_{\bar f}$) and *DCS* ($A_{\bar f}$) amplitudes contribute to decay and describe density of points in the *DP* at time *t*:

$$\underbrace{|A_{\bar f}|^2}_{\text{DCS}} + \underbrace{|A_{\bar f}||\bar{A}_{\bar f}|\,[y''\cos\delta_f - x''\sin\delta_f]\,(\Gamma t)}_{\text{DCS-Mixing interference}} + \underbrace{\frac{x^2+y^2}{4}\,|\bar{A}_{\bar f}|^2\,(\Gamma t)^2}_{\text{Mixing}}$$

assumes $(|x|, |y| \ll 1)$

$\delta_f = \mathrm{Arg}\,\{\bar{A}_{\bar f}/A_{\bar f}\}$ Depends on DP position

* The interference term permits measurement of

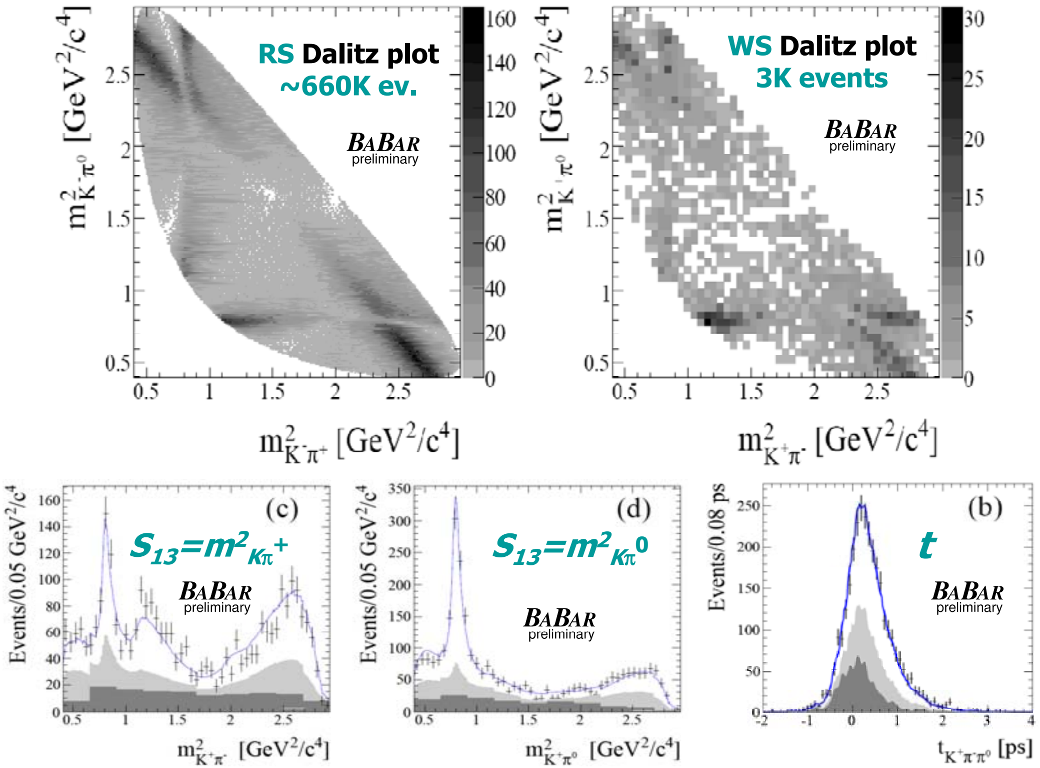
$$x'' = x\cos\delta_{K\pi\pi} + y\sin\delta_{K\pi\pi} \quad \text{and}$$
$$y'' = y\cos\delta_{K\pi\pi} - x\sin\delta_{K\pi\pi}$$

NOTE $\delta_{K\pi\pi} \neq \delta$ is also unknown

Evidence for Mixing in (*WS*) $D^0 \rightarrow K^+\pi^-\pi^0$

384 fb^{-1}

arXiv:0807.4544 [hep-ex]
Submitted to PRL



- Use D^* tagged sample
- Find *CF* amplitude $\bar{\mathcal{A}}_{\bar{f}}$ from time-integrated fit to RS Dalitz plot
  - isobar model description
- Use this in time-dependent fit to WS plot to determine $\mathcal{A}_{\bar{f}}$ and mixing parameters.

$$x'' = [\,2.61^{+0.57}_{-0.68}(\mathrm{stat.}) \pm 0.39(\mathrm{syst.})]\%$$

$$y'' = [-0.06^{+0.55}_{-0.64}(\mathrm{stat.}) \pm 0.34(\mathrm{syst.})]\%$$

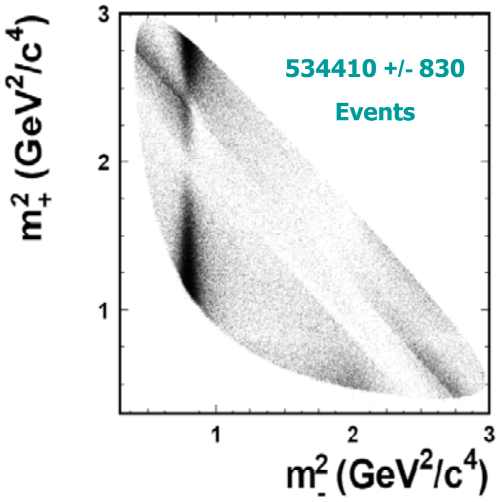
Probability for no mixing = 0.1% (3.2σ)

No evidence for *CPV*

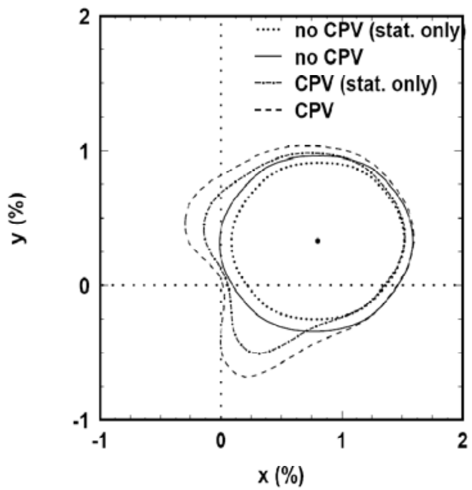
Time-Dependent Amplitude Analysis of $D^0 \to K_S\pi^+\pi^-$

PRL 98, 211803 (2007) 540 fb^{-1} PRD 72, 012001 (2005) 9 fb^{-1}

* Here, it is possible to measure *x, y,* |p/q| and arg {p/q}; the *D^0-$\bar{D}^0$* strong phase δ is fixed by presence of *CP* eigenstates in *f*
  - Strong phases of all points relative to *CP* eigenstates measured by time-dependent amplitude analysis of the *DP*.



Fit case	Parameter	Fit result	95% C.L. interval
No	$x(\%)$	$0.80 \pm 0.29 ^{+0.09}_{-0.07}{}^{+0.10}_{-0.14}$	$(0.0, 1.6)$
CPV	$y(\%)$	$0.33 \pm 0.24 ^{+0.08}_{-0.12}{}^{+0.06}_{-0.08}$	$(-0.34, 0.96)$
CPV	$x(\%)$	$0.81 \pm 0.30 ^{+0.10}_{-0.07}{}^{+0.09}_{-0.16}$	$\lvert x\rvert < 1.6$
	$y(\%)$	$0.37 \pm 0.25 ^{+0.07}_{-0.13}{}^{+0.07}_{-0.08}$	$\lvert y\rvert < 1.04$
	$\lvert q/p\rvert$	$0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$	-
	$\arg(q/p)(^\circ)$	$-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4}$	-



Mixing only at 2.4 σ level.

Hint that x > y ??

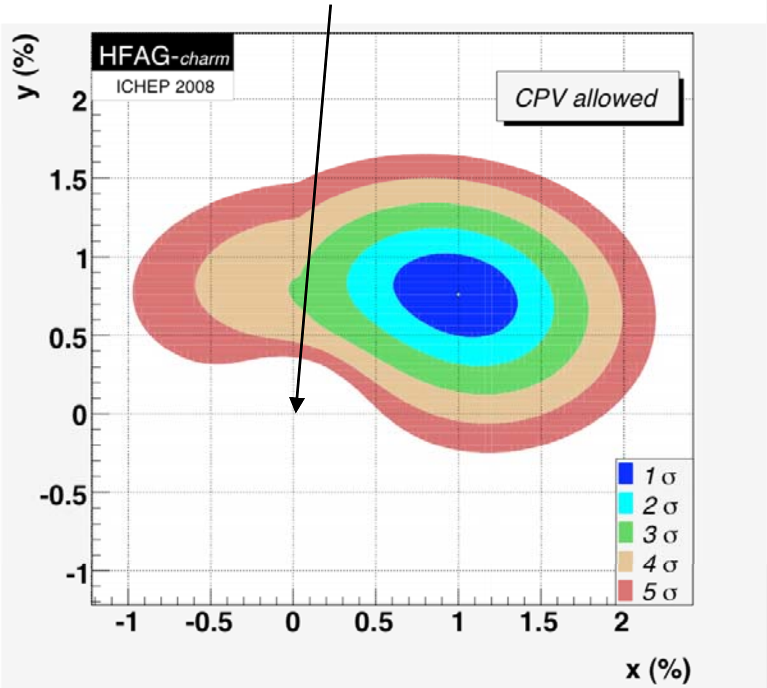
Previous result from CLEO (9 fb^{-1})

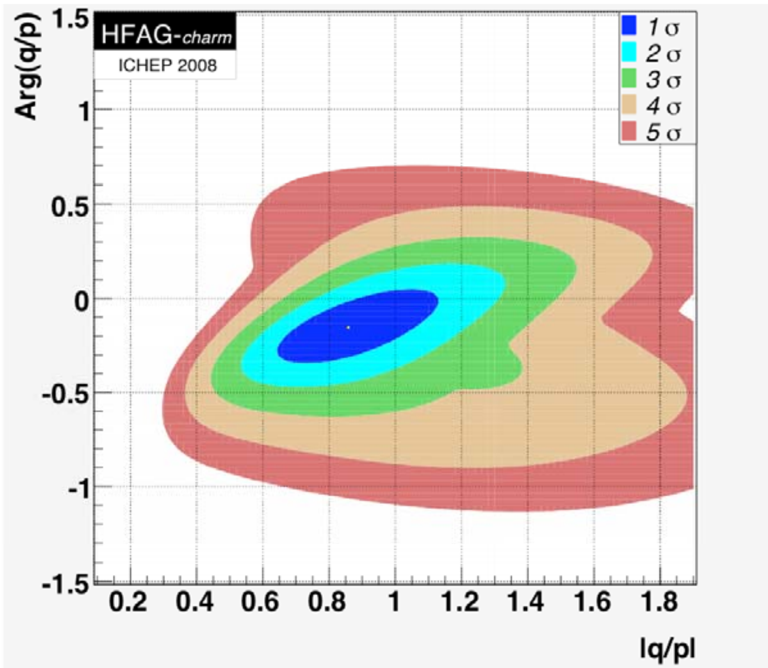
$(-4.7 < x < 8.6)\%$

$(-6.1 < y < 3.5)\%$ at 95% CL.

arXiv:0808.1297

No-mixing point excluded at 9.8σ





$x = 1.00 \pm^{0.24}_{0.25}$ % 3.4σ

$y = 0.76 \pm^{0.17}_{0.18}$ % 4.1σ

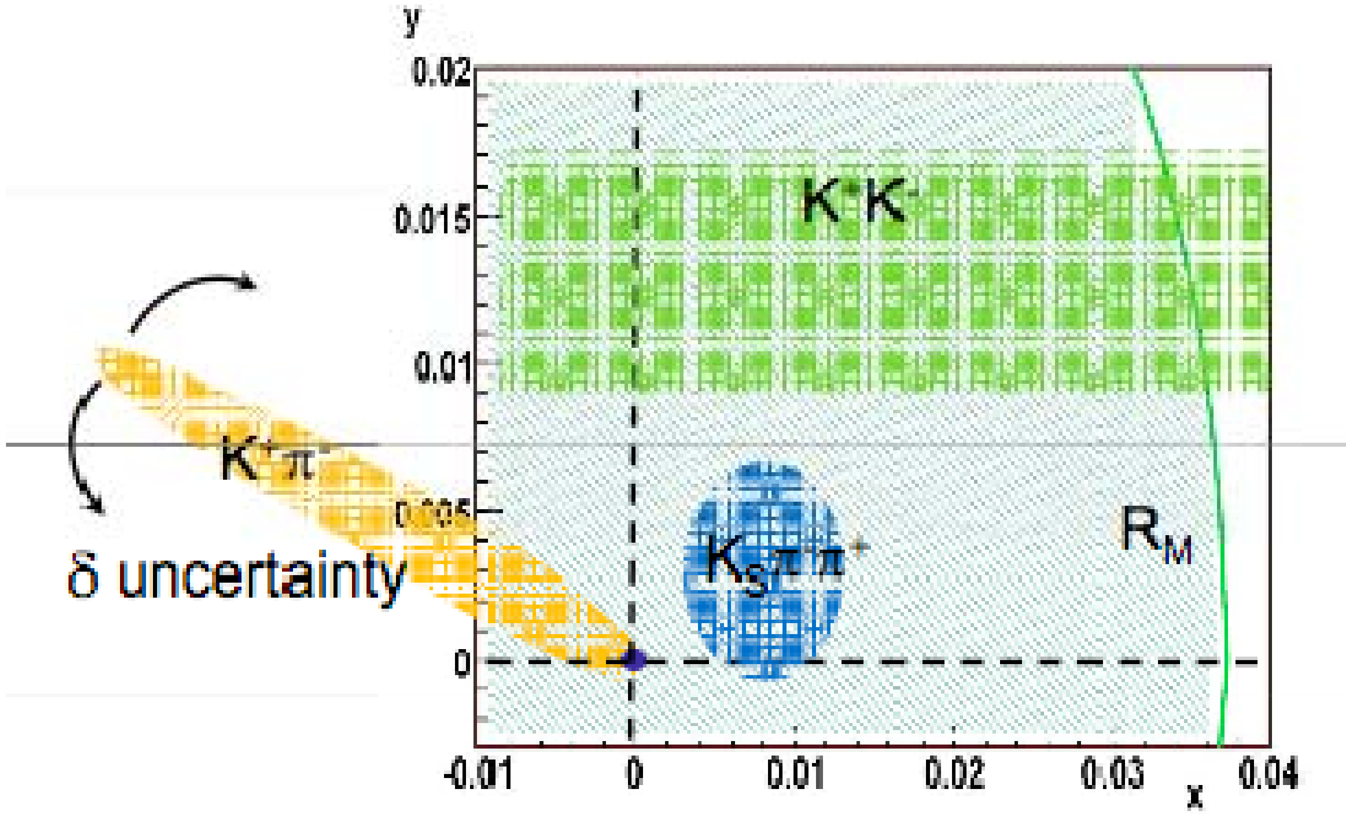
$|q/p| = 0.86 \pm^{0.17}_{0.15}$

$\mathrm{Arg}(q/p) = (8.8 \pm^{7.6}_{7.2})^{\circ}$

Summary

* After 30 years, evidence for D^0 mixing is now compelling
  – World averages of the mixing parameters exclude “No D^0 Mixing” at ~10σ
  – *But to date no single measurement exceeds 5σ.*
* Evidence of D^0 Mixing from several independent experiments
* Measured values of the mixing parameters x ≈ y ≈ 1% are compatible with Standard Model expectations
* No Evidence for CP Violation in D^0 Mixing

Extra material



D^0-$\overline{D}^0$ Mixing Interpretation: Assume NP saturates x_D

	Model	Approximate Constraint
Extra Fermions	Fourth Generation	$\|V_{ub'}V_{cb'}\| \cdot m_{b'} < 0.5$ (GeV)
	$Q = -1/3$ Singlet Quark	$s_2 \cdot m_S < 0.27$ (GeV)
	$Q = +2/3$ Singlet Quark	$\|\lambda_{uc}\| < 2.4 \cdot 10^{-4}$
	Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark Box: Parameter space can reach observed x_D
Extra Gauge Bosons	Generic Z'	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
	Family Symmetries	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
	Left-Right Symmetric	No constraint
	Alternate Left-Right Symmetric	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV) $(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
	Vector Leptoquark Bosons	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Extra Scalars	Flavor Conserving Two-Higgs-Doublet	No constraint
	Flavor Changing Neutral Higgs	$m_H/C > 2.4 \cdot 10^3$ TeV
	FC Neutral Higgs (Cheng-Sher)	$m_H/\|\Delta_{uc}\| > 600$ GeV
	Scalar Leptoquark Bosons	See entry for RPV SUSY
	Higgsless	$M > 100$ TeV
Extra Dimensions	Universal Extra Dimensions	No constraint
	Split Fermion	$M/\|\Delta y\| > (6 \cdot 10^2$ GeV$)$
	Warped Geometries	$M_1 > 3.5$ TeV
Extra Symmetry	MSSM	$\|(\delta^u_{12})_{LR,RL}\| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV $\|(\delta^u_{12})_{LL,RR}\| < .25$ for $\tilde{m} \sim 1$ TeV
	SUSY Alignment	$\tilde{m} > 2$ TeV
	Supersymmetry with RPV	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
	Split Supersymmetry	No constraint

Golowich, Hewett, Pakvasa and Petrov, PRL 98 (2007) 181801

D^0 Mixing in Semileptonic Decays

- Measurement of the WS rate of semileptonic D^0 decays

$D^0 \to K^{(*)-} l^+ \nu_l$ Right Sign (RS) decay $\pi_s^+ K^- l^+$

$D^0 \xrightarrow[\text{mixing}]{} \bar{D}^0 \to K^{(*)+} l^- \bar{\nu}_l$ Wrong Sign (WS) decay $\pi_s^+ K^+ l^-$

in final state

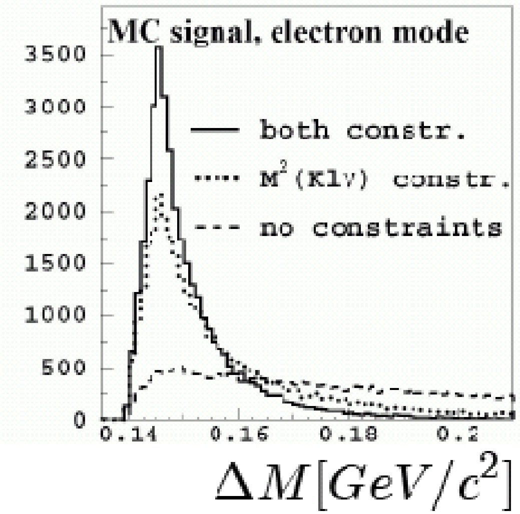
No DCS processes

- no interference
- no proper time dependent measurement needed

Detecting WS Signal $\rightarrow$ D^0 Mixing

- Mixing rate R_M is sensitive to x^2 and y^2

$$R_M = \frac{\int_0^\infty dt\, P(D^0 \to \bar{D}^0 \to X^+ l^- \nu_l)}{\int_0^\infty dt\, P(D^0 \to X^- l^+ \nu_l)} \approx \frac{x^2 + y^2}{2}$$



- Due to ν 's limited mass resolution

Use $\Delta M = M(\pi_s K l \nu) - M(K l \nu)$

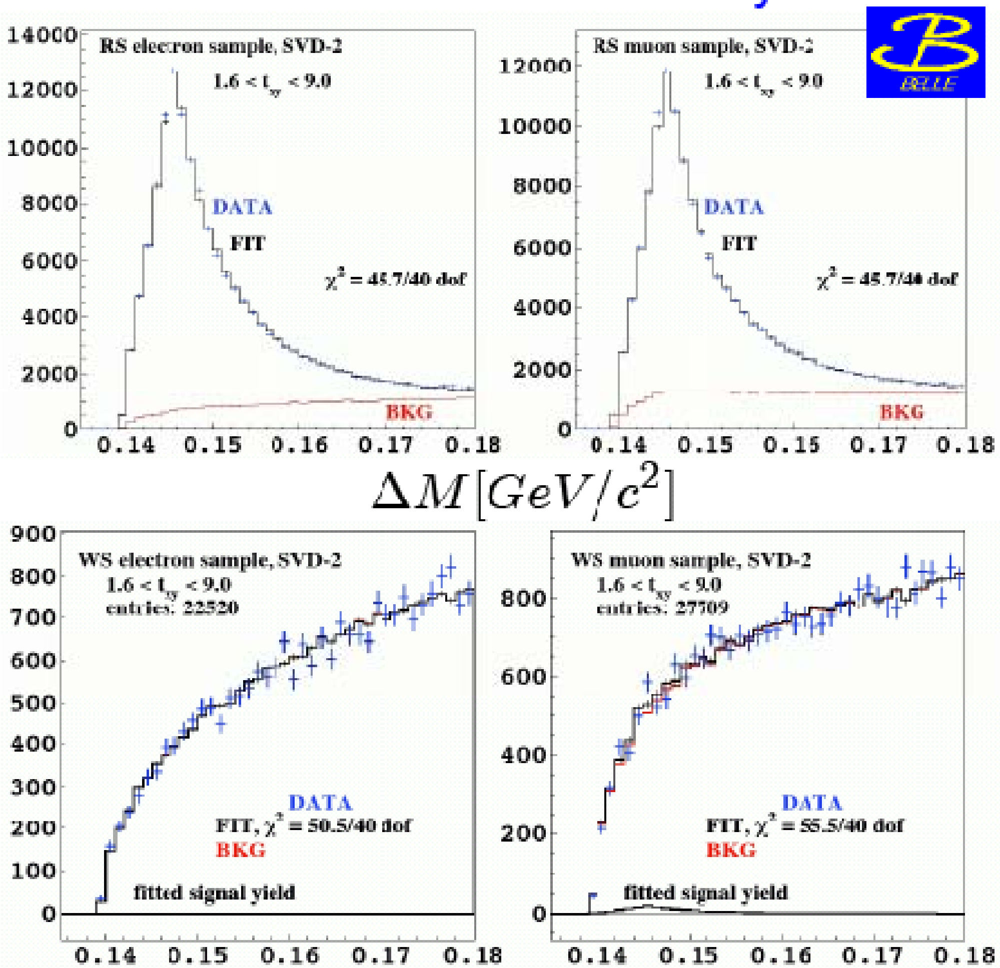
Improve ΔM resolution with kinematic constraints:

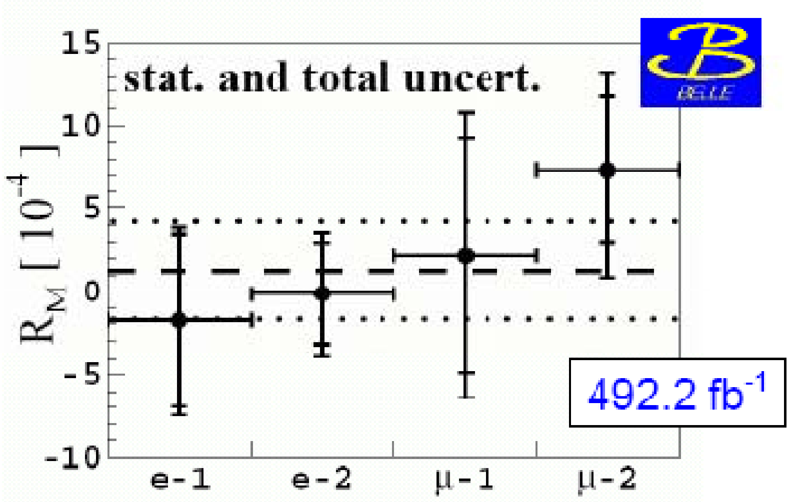
$$M^2_{Kl\nu} = m^2_{D^0}$$
$$(P^*_\nu)^2 = 0$$

Belle - D⁰ Mixing Results $D^0 \to K^{(*)} l \nu_l$

HEP-ex/0802.2952
PRD accepted

➢ ΔM for RS and WS D^0 decays





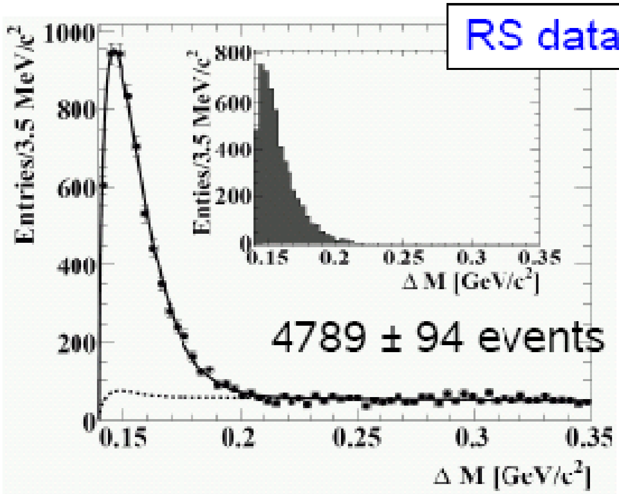
$$R_M = (1.3 \pm 2.2 \pm 2.0) \cdot 10^{-4}$$
$$R_M < 6.1 \cdot 10^{-4} \quad @\,90\,\%\ CL$$

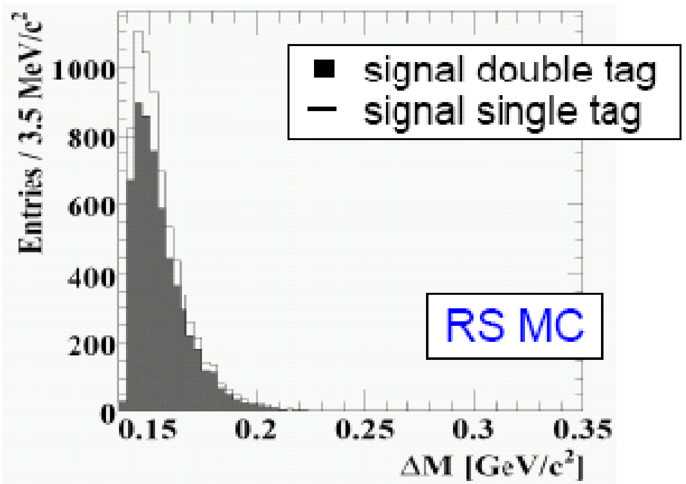
BABAR – Results for $D^0 \to K^{(*)} e \nu_e$

- ΔM for RS and WS D^0 decays

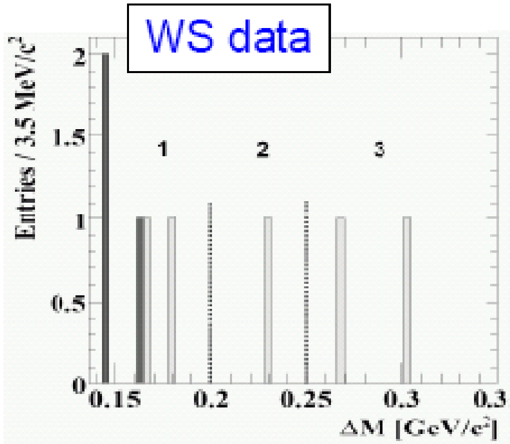
344 fb^{-1}

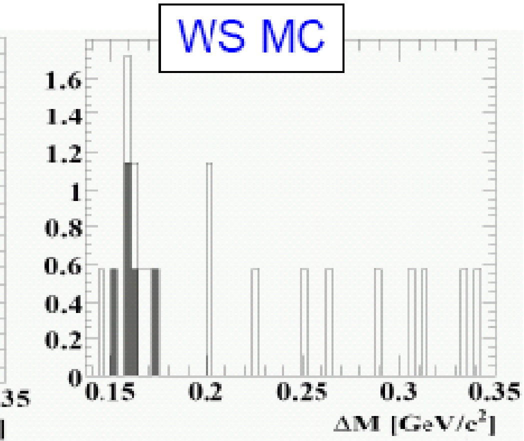
PRD 76, 014018 (2007)





Double tag of production flavor reduces WS background significantly



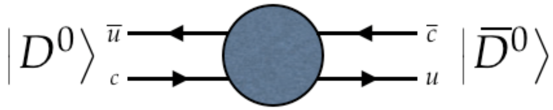


observe 3 events and expect
2.85 bckgr. events

$$R_M \in [-13, 12] \cdot 10^{-4} \quad @ 90\,\%\, CL$$

Mixing between Flavor States

- Flavor eigenstates can mix through weak interaction:



Schroedinger eqn governs time evolution

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

(off diagonal *M* and *Γ* elements determine mixing)

- Physical eigenstates D_1 and $D_2 \neq$ flavor eigenstates

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

In the limit of *CP* conservation: $D_1 = CP+$, $D_2 = CP-$

- If weak interaction *splits* the masses or widths of physical eigenstates, *flavor state mixing will occur,* as seen from the time evolution:

$$|D^0(t)\rangle = e^{-(\Gamma/2+iM)t}\left\{\cosh[(y+ix)\Gamma t/2]|D^0(0)\rangle - \left(\frac{q}{p}\right)\sinh[(y+ix)\Gamma t/2]|\overline{D}^0(0)\rangle\right\}$$
$$|\overline{D}^0(t)\rangle = e^{-(\Gamma/2+iM)t}\left\{\cosh[(y+ix)\Gamma t/2]|\overline{D}^0(0)\rangle - \left(\frac{p}{q}\right)\sinh[(y+ix)\Gamma t/2]|D^0(0)\rangle\right\}$$

⇒ *mixing parameters:*

$$x \equiv 2\frac{M_1 - M_2}{\Gamma_1 + \Gamma_2}, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

$$-\infty < x < +\infty, \quad -1 < y < 1$$

$D^0 \to K\pi$ Fit Procedure

Unbinned maximum likelihood fit performed in stages

Fit m(Kπ) and Δm distribution:

Separate signal from background in subsequent decay time fits

Fit RS decay time distribution:

Determine *D^0* lifetime and decay time resolution function *R(t)*

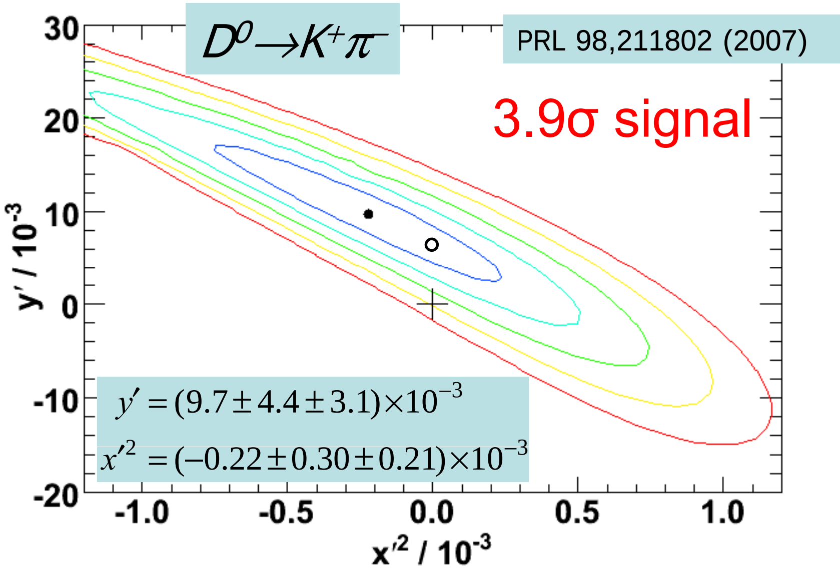
Fit WS decay time distribution:

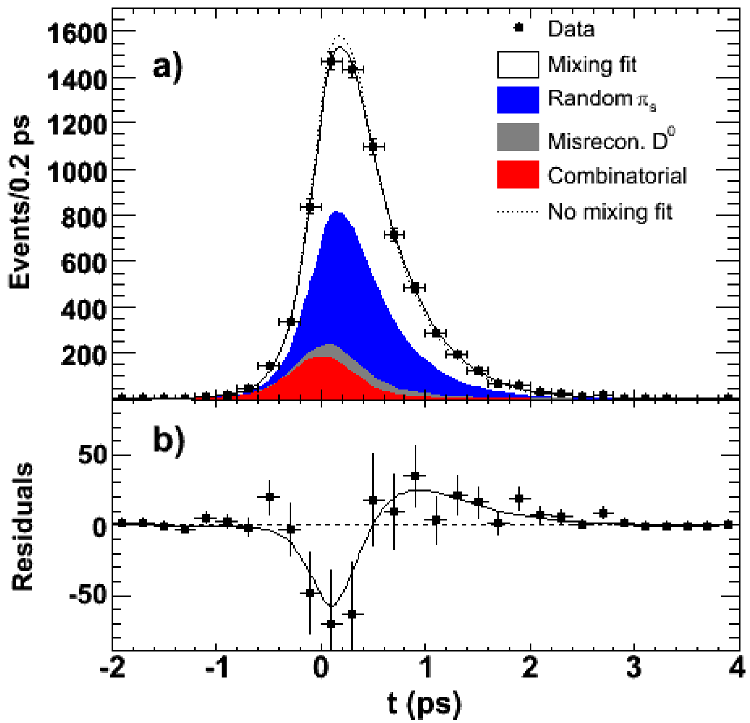
Use *D^0* lifetime and decay time resolution function from RS fit

Fit WS signal to $T_{WS} \propto e^{-\Gamma t}\left[R_\mathrm{D} + \sqrt{R_\mathrm{D}}\, y'(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right] \otimes R(t)$

- Compare fits with and without mixing to determine significance
- Fit *D^0* and *$\overline{D}^0$* samples separately to search for CP violation
- **All parameters are determined by fits to data, not from MC**

2007 $D^0 \to K^+\pi^-$ results





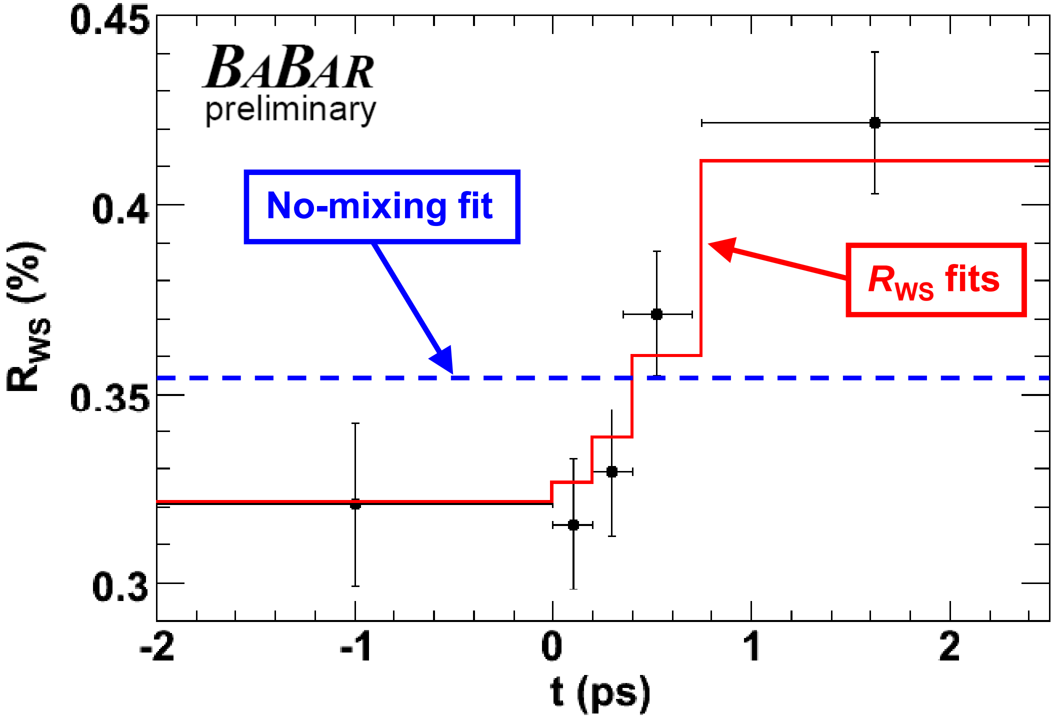
- 2007 $D^0 \to K^+\pi^-$ *decay time* analysis: *384 fb*$^{-1}$
- First evidence for mixing: 3.9σ (including systematic uncertainties)
- x'^2, y' consistent with previous BaBar result *PRL 91 171801 (2003)*
- Mainly y'
- No CP violation
- Results confirmed by CDF

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 ¼ 0.5 psec as in residuals plot.

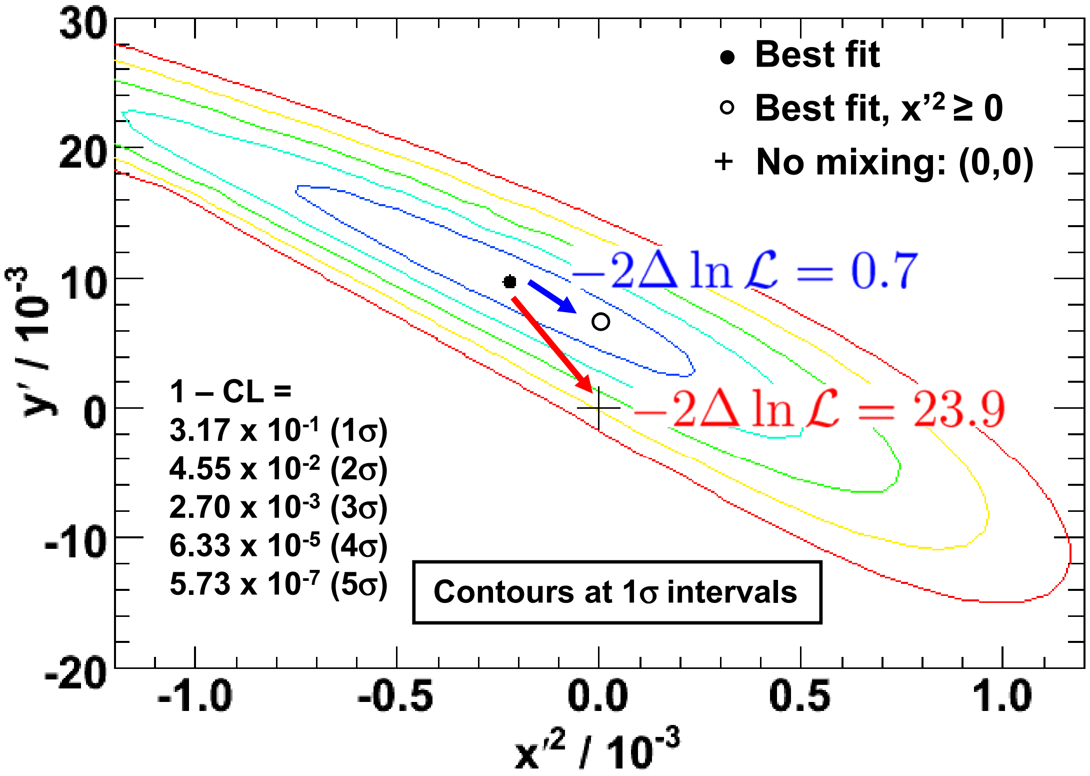


Dashed line: standard R_{WS} fit (χ^2=24).
Solid, red line: independent R_{WS} fits to each time bin (χ^2 = 1.5).

Evidence Of Mixing At 3.9σ

* Contours in y', x'^2 computed from $2\Delta(\ln L)$
* Best-fit point is in the un-physical region $x'^2 < 0$
* 1σ contour extends into physical region.
  Correlation: -0.94
* Contours incorporate systematic errors

The no-mixing point is at the 3.9σ contour



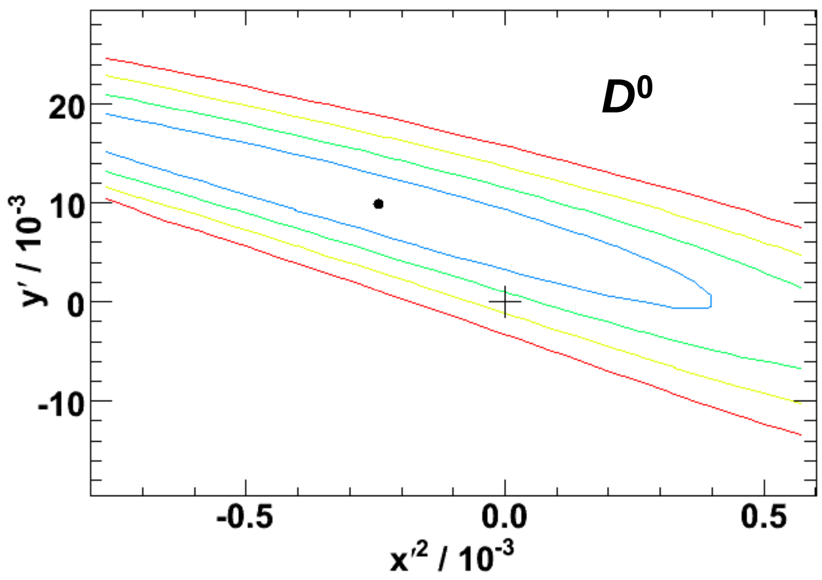
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$
x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

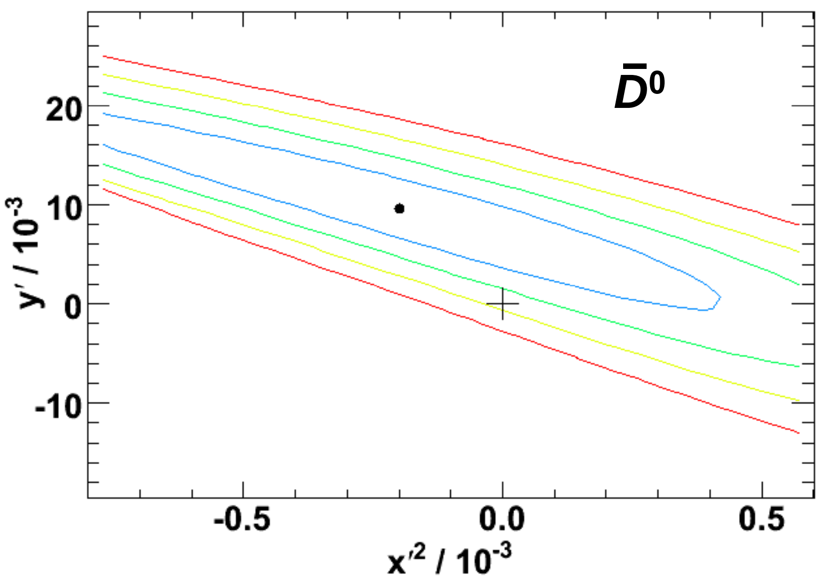
Fits Allowing For *CP* violation

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

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

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





No evidence seen for CP violation

2007 Kpi systematics, validations

Systematics: variations in

- Functional forms of PDFs
- Fit parameters
- Event selection

Computed using *full* difference w.r.t. original value

Results are expressed in units of the statistical error

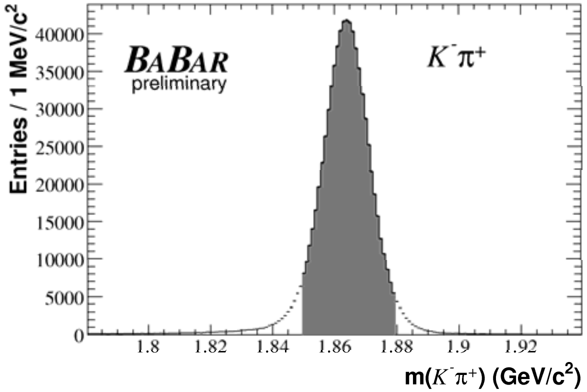
Systematic source	R_D	y'	x'^2
PDF:	0.59σ	0.45σ	0.40σ
Selection criteria:	0.24σ	0.55σ	0.57σ
Quadrature total:	0.63σ	0.71σ	0.70σ

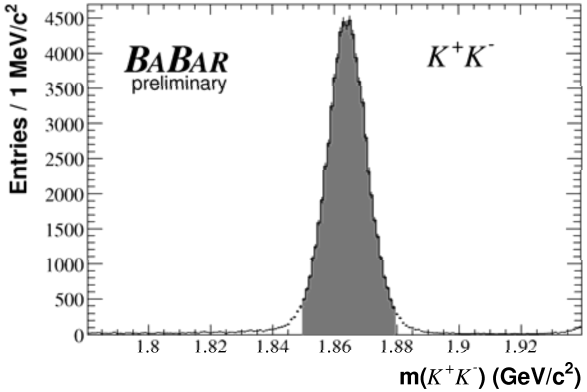
Validations and cross-checks

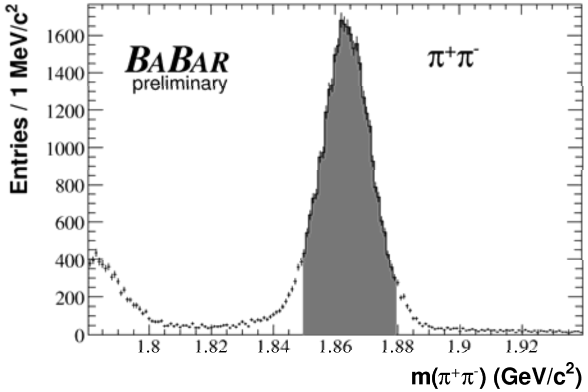
- Alternate fit (R_{WS} in time bins)
- Fit RS data for mixing
  - $x'^2 = (-0.01\pm0.01)\text{x}10^{-3}$
  - $y' = (0.26\pm0.24)\text{x}10^{-3}$
- Fit generic MC for mixing
  - $x'^2 = (-0.02\pm0.18)\text{x}10^{-3}$
  - $y' = (2.2\pm3.0)\text{x}10^{-3}$
- Fit toy MCs generated with various values of mixing
  - Reproduces generated values
- Validation of proper frequentist coverage in contour construction
  - Uses 100,000 MC toy simulations

Mass Projections

* Mass Projections ($0.1447 < \Delta m < 0.1463$ GeV/c^2):







* high signal purities ($1.8495 < m < 1.8795$ GeV/c^2)

Sample	Size	Purity (%)
$K^-\pi^+$	730,880	99.9
K^-K^+	69,696	99.6
$\pi^-\pi^+$	30,679	98.0

* minimize effect of broken charm/combinatorial backgrounds in signal box

y_{CP}, ΔY systematics

* **Systematic uncertainties (%):**

Systematic	Δy_{CP}^{KK}	$\Delta y_{CP}^{\pi\pi}$	Δy_{CP}	$\Delta(\Delta Y^{KK})$	$\Delta(\Delta Y^{\pi\pi})$	$\Delta(\Delta Y)$
Signal Model	0.130	0.059	0.085	0.072	0.265	0.062
Charm Bkgd	0.062	0.037	0.043	0.001	0.002	0.001
Combinatorial Bkgd	0.019	0.142	0.045	0.001	0.005	0.002
Selection	0.068	0.178	0.046	0.083	0.172	0.011
Detector Model	0.064	0.080	0.064	0.054	0.040	0.054
Quadrature sum	0.172	0.251	0.132	0.122	0.318	0.083

* **Variations:**

- Signal: PDF shape, polar angle dependent resolution offset, signal interval
- Charm backgrounds: yields and charm lifetime
- Combinatorial backgrounds: yields, shape and sideband region
- Selection: σ_t criterion, treatment of multiple candidates
- Detector: Alignment and energy loss

* **Tagged results limited by statistical errors (not systematics)**

Measurement of $\delta_{K\pi}$ by CLEO-c

- Rate enhancement factors

  Correlated D^0 decay rate divided by the incoherent decay rate

	$K^-\pi^+$	$l+$	$CP+$	$CP-$
$K^-\pi^+$	R_M/R_{WS}			
$K^+\pi^-$	$1+2R_{WS}-(2r\,cos(\delta_{K\pi}))^2$			
$l-$	$1-r(y\,cos(\delta_{K\pi})+x\,sin(\delta_{K\pi}))$	1		
$CP+$	$1+(2r\,cos(\delta_{K\pi})+y)$	$1+y$	0	
$CP-$	$1-(2r\,cos(\delta_{K\pi})+y)$	$1-y$	2	0
X	1	1	1	1

sensitive to δ_{Kp}

due to mixing

CP conservation

full correlation

Measurements $K_S \pi^+\pi^-$

arXiv: 0704.1000, 540 fb^{-1}

t-dependent Dalitz analysis

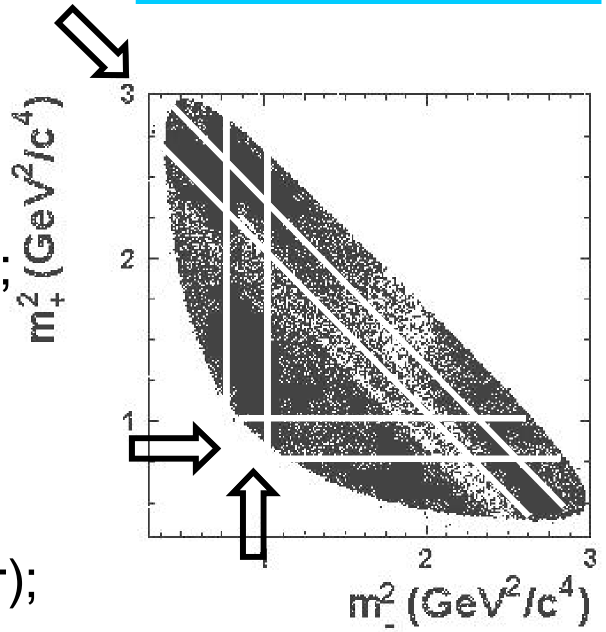
different decays identified through Dalitz analysis;

CF: $D^0 \to K^{*-}\pi^+$

DCS: $D^0 \to K^{*+}\pi^-$

CP: $D^0 \to \rho^0 K_S$

their relative phases determined (unlike $D^0 \to K^+\pi^-$);



t-dependence:

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \left\langle K_S \pi^+ \pi^- \middle| D^0(t) \right\rangle =$$

$m_\pm^2$: Dalitz variables

$$= \frac{1}{2} \mathcal{A}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] + \frac{1}{2}\frac{q}{p} \overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right]$$

< f | D^0 >   < f | $\overline{D}^0$ > $\lambda_{1,2}=f(x,y)$; n.b.: $K^+\pi^-$:x'^2, y'

analogous for $\overline{\mathcal{M}}$ = < f | $\overline{D}^0(t)$ >

sum of intermediate states

$$\mathcal{A}(m_-^2, m_+^2) = \sum a_r\, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR}\, e^{i\Phi_{NR}}$$

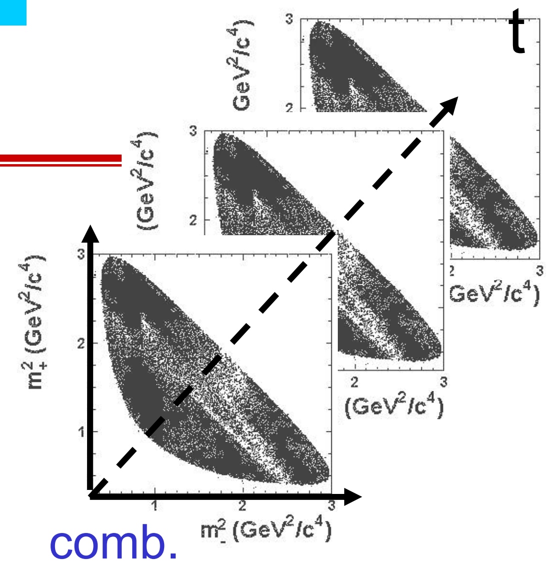
Measurements $K_S \pi^+\pi^-$

arXiv: 0704.1000, 540 fb^{-1}

Fit

no CPV: $\frac{q}{p} = 1, \mathcal{A} = \overline{\mathcal{A}} \Rightarrow \mathcal{M} = \overline{\mathcal{M}}$

fit $\mathcal{M}(m_-^2, m_+^2, t)$ to data distribution $\Rightarrow$ x, y



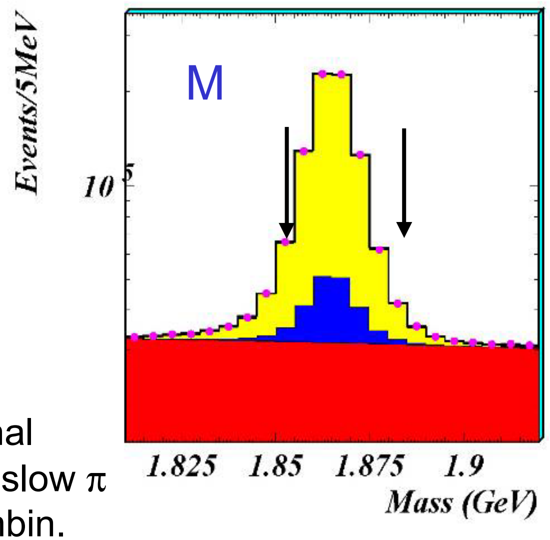
comb. bkg.

Signal

M(K_S $\pi^+\pi^-$) and

Q= M(K_S $\pi^+\pi^-\pi_s$)- M(K_S $\pi^+\pi^-$)- M(π);

3 σ signal region in M, Q

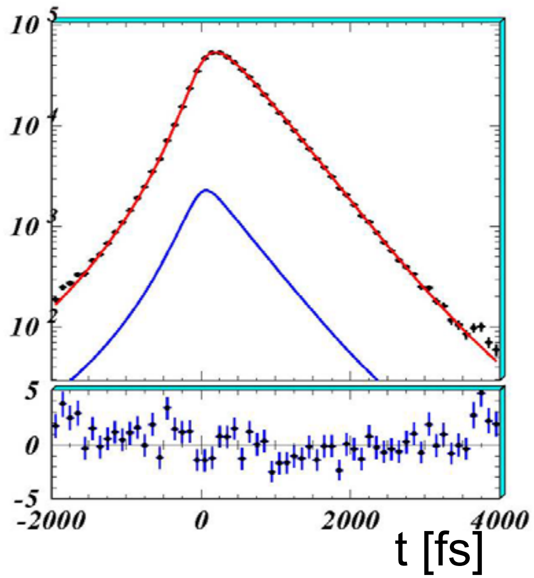


signal
rnd slow π
combin.

N_{sig}= (534.4±0.8)x10^3
Purity ≈ 95%

τ = 409.9±0.9 fs

τ_{PDG}=410.1±1.5 fs

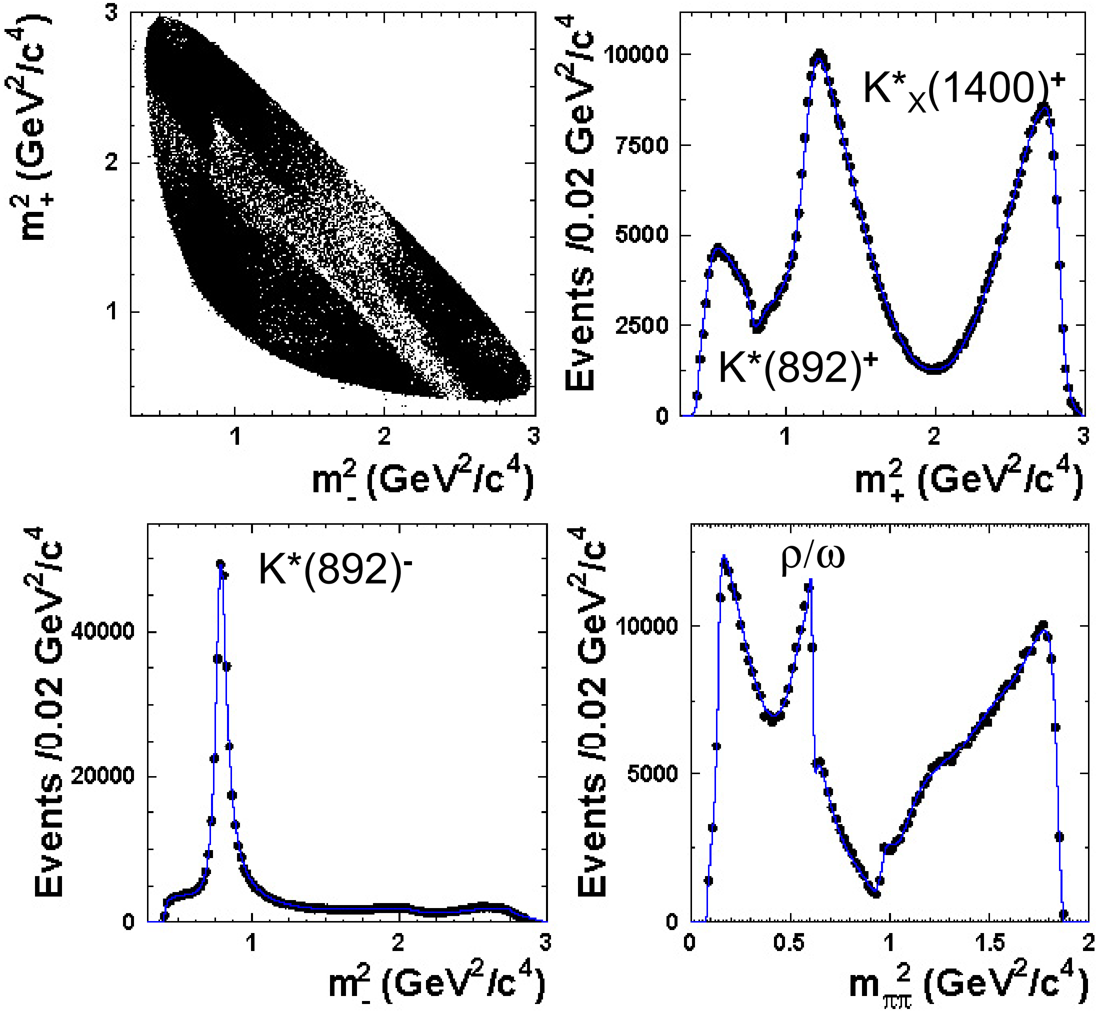


Measurements $K_S \pi^+\pi^-$

arXiv: 0704.1000, 540 fb^{-1}

Dalitz plot projection of fit

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.006	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.8	0.0724
$K_2^*(1430)^-$	0.87 ± 0.02	-47.3 ± 1.2	0.0133
$K^*(1410)^-$	0.65 ± 0.03	111 ± 4	0.0048
$K^*(1680)^-$	0.60 ± 0.25	147 ± 29	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.3	0.0054
$K_0^*(1430)^+$	0.541 ± 0.019	91.8 ± 2.1	0.0047
$K_2^*(1430)^+$	0.276 ± 0.013	-106 ± 3	0.0013
$K^*(1410)^+$	0.33 ± 0.02	-102 ± 4	0.0013
$K^*(1680)^+$	0.73 ± 0.16	103 ± 11	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0007	115.1 ± 1.1	0.0063
$f_0(980)$	0.380 ± 0.004	-147.1 ± 1.1	0.0452
$f_0(1370)$	1.46 ± 0.05	98.6 ± 1.8	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.2	0.0180
$\rho(1450)$	0.72 ± 0.04	41 ± 7	0.0024
σ_1	1.39 ± 0.02	-147 ± 1	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615



13 BW resonances, non-resonant contr.;

Results (fit fractions, phases) in agreement with (measurement of ϕ_3)

PRD73, 112009 (2006)

Test of S-wave $\pi\pi$ contr. (f_0, $\sigma_{1,2}$): K-matrix formalism

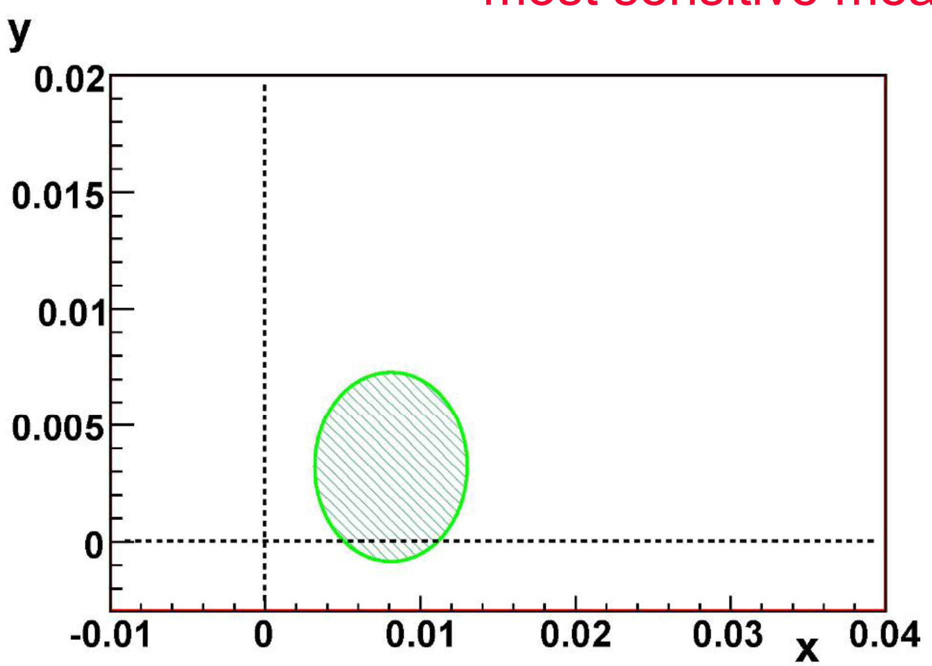
Measurements $K_S \pi^+\pi^-$

arXiv: 0704.1000, 540 fb^{-1}

Decay-time projection of fit

$$x = (0.80 \pm 0.29 \pm {}^{0.13}_{0.16})\%$$
$$y = (0.33 \pm 0.24 \pm {}^{0.10}_{0.14})\%$$

most sensitive measurement of x



Cleo, PRD72, 012001 (2005)

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

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

Towards a SuperB Factory

Table III Summary of the expected precision on charm mixing parameters. For comparison we put the reach of the B Factories at 2 ab^{-1}. The estimates for Super$B$ assume that systematic uncertainties can be kept under control.

Mode		B Factories (2 ab^{-1}	Super$B$ (75 ab^{-1}
$D^0 \to K^+K^-$	y_{CP}	2–3×10^{-3}	5×10^{-4}
$D^0 \to K^+\pi^-$	y'_D	2–3×10^{-3}	7×10^{-4}
	x'^2_D	1–2×10^{-4}	3×10^{-5}
$D^0 \to K^0_S\pi^+\pi^-$	y_D	2–3×10^{-3}	5×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}
Average	y_D	1–2×10^{-3}	3×10^{-4}
	x_D	2–3×10^{-3}	5×10^{-4}