Charm mixing - an update

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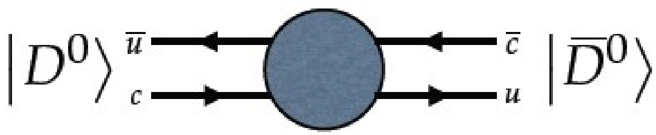
Representing the BABAR collaboration

Outline

- Charm mixing formalism
- BaBar detector & Belle detector
- Recent experimental results
- Summary

Neutral meson mixing

- Neutral D mesons (D^0 and $\overline{D}^0$) are produced as flavor eigenstates, they can mix through weak interaction



- Time evolution is governed by the Schrödinger equation:

$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0(t)\rangle \\ |\overline{D}^0(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)_{\text{Weak}} \times \begin{pmatrix}|D^0(t)\rangle \\ |\overline{D}^0(t)\rangle\end{pmatrix}$$

M and Γ are 2x2 Hermitian matrices

- Mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle, |q^2| + |p^2| = 1$

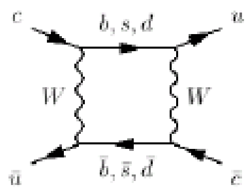
- Propagate as following:

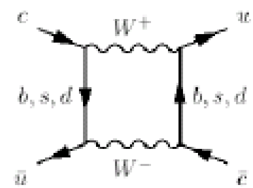
$$|D_{1,2}(t)\rangle = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}|D_{1,2}(t=0)\rangle$$

- Mixing parameters: $x \equiv \frac{m_1 - m_2}{\Gamma}, y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$

Why charm mixing is interesting

- It completes the quark mixing picture already seen in the K, B_d,B_s systems
- It provides information about processes with down-type quarks (d,s,b) in the mixing box diagram



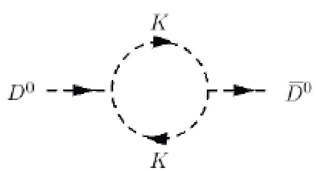


- It provides a strong constraint on new physics
  - E.Golowich, J.Hewett, S.Pakvasa, A.Petrov PRD 76, 095009(2007)
- Standard model d-type box contribution(short-distance) is very small

$$x \sim O(10^{-6}) - O(10^{-5})$$

•CKM suppression
•GIM suppression

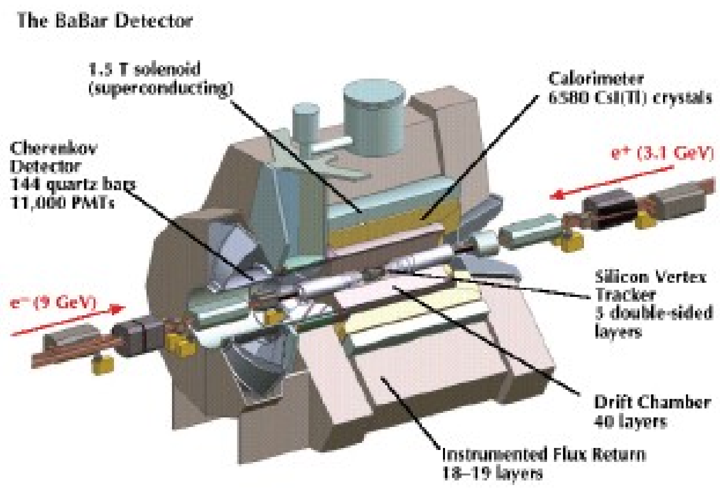
- Hadronic intermediate states(long distance contribution) hard to predict precisely:

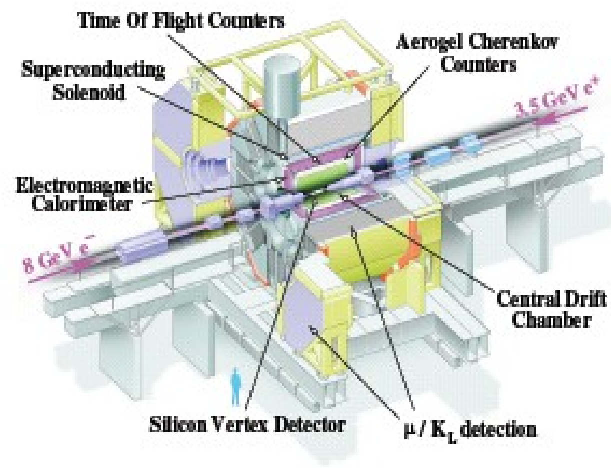


Recent calculation: $|x|\leq 0.01$, $|y|\leq 0.01$
PRD 65, 054034(2002) (Falk, Grossman, Ligeti &Petrov)
PRD 69, 114021(2004) (Falk, Grossman, Ligeti &Petrov)

- New Physics signature:
  - x>>y
  - CP violation is observed

BaBar & Belle





524.2/fb as of 03/19/2008

783.8/fb as of 03/20/2008

Operating energy mostly at $\sqrt{s} \sim 10.6$ GeV

(…plus data at Υ(3S), Υ(2S), not discussed here)

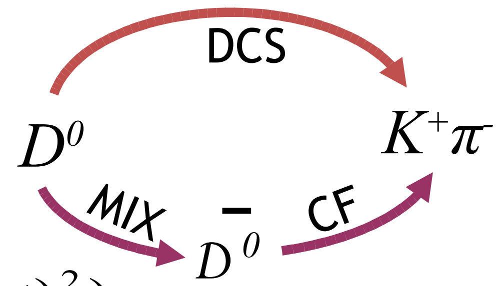
$$\sigma\ (e^+e^- \to c\bar{c}) \sim 1.3nb \ \rightarrow\ \sim 1700\text{M}\ c\bar{c}\ \text{events}$$

Experimental results of charm mixing

- Mixing analyses presented here
  - $D^0 \to K^+\pi^-$
  - $D^0 \to K^+K^-$, $\pi^+\pi^-$
  - $D^0 \to K^{(*)-} l^+ \nu$
  - $D^0 \to K^+\pi^- \pi^0$
  - $D^0 \to Ks\pi^+\pi^-$

Time dependent wrong sign hadronic decay $D^0 \rightarrow K^+\pi^-$

- Look for wrong sign decays,e.g.: $D^{*+} \rightarrow D^0\pi^+, D^0 \rightarrow K^+\pi^-$
- Two main contributions to wrong sign decays:
  - ➢ Doubly-Cabibbo-Supressed(DCS) Decay
  - ➢ Mixing then Cabibbo-Favored(CF) decay
- Distinguish between them by their time dependence



$$\Gamma_{WS}(t) = e^{-\Gamma t}(\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\, y'\Gamma t}_{\text{interference}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{mixing})$$

Assuming |x|<<1,|y|<<1 and no CPV

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

$\delta_{K\pi}$ is the relative strong phase between DCS and CF amplitudes

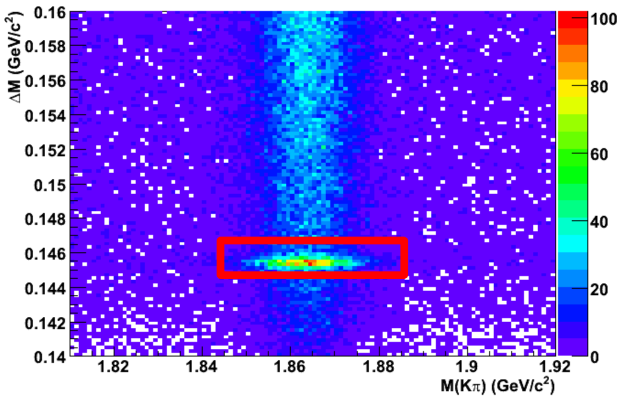
- Fitting procedure:
  - ➢ Fit 2D m(Kπ), Δm distribution to separate signal and backgrounds
  - ➢ Fit to RS proper time distribution to determine proper time signal resolution function
  - ➢ Fit to WS proper time distribution to determine x'^2 and y'

$D^0 \rightarrow K^+\pi^-$

BaBar

PRL 98: 211802(2007)

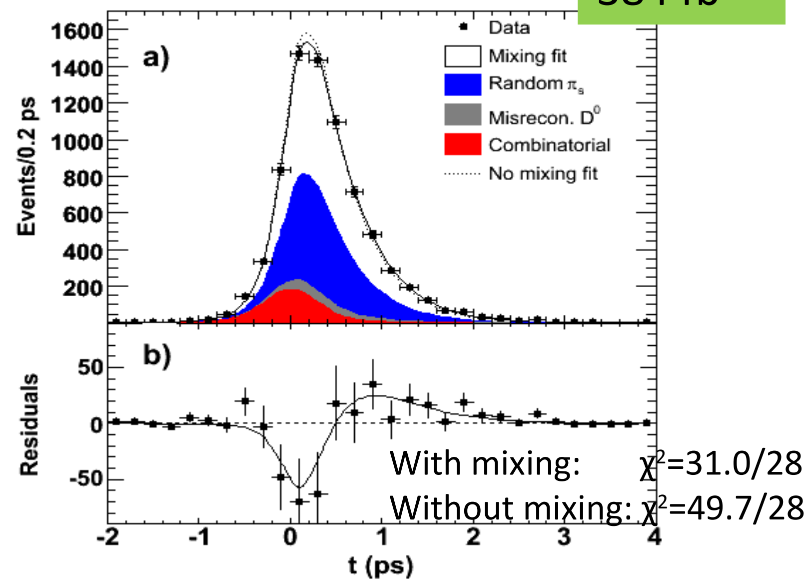
384 fb^{-1}



plot signal region:

$1.843 < m < 1.883$ GeV/c²

$0.1445 < \Delta m < 0.1465$ GeV/c²

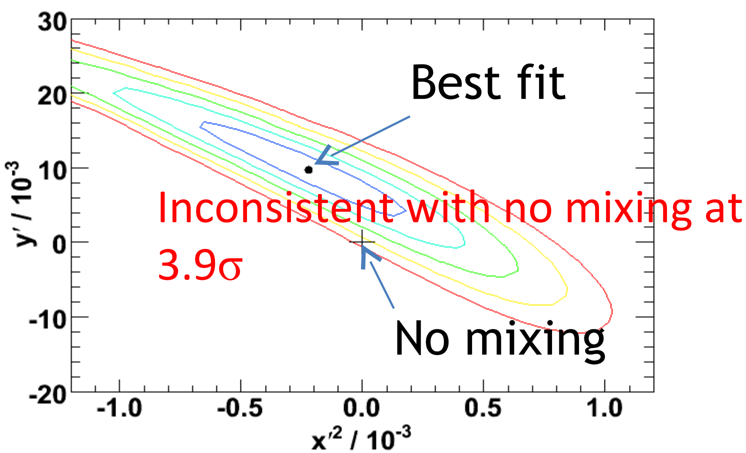


With mixing:

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

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

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



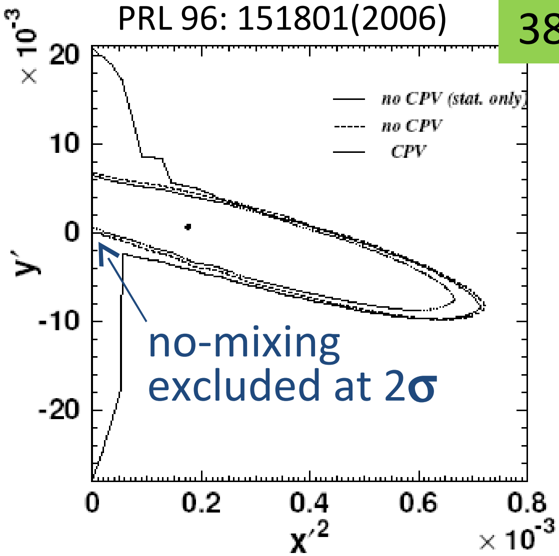
No CP violation found fitting separately D^0 and $\overline{D}^0$

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

Belle

PRL 96: 151801(2006)

384 fb^{-1}

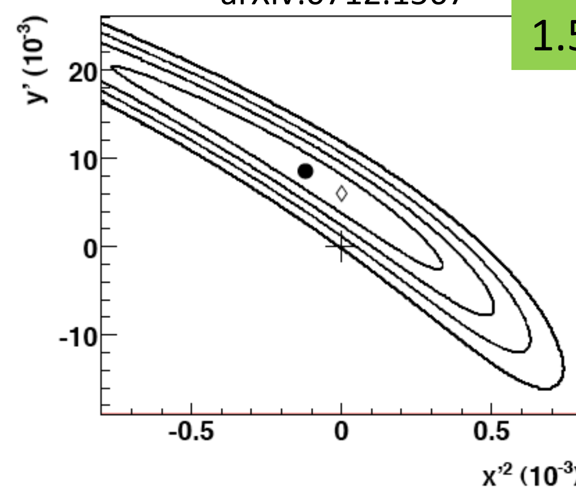


Fit case	Parameter	Fit result $(\times 10^{-3})$	95% C.L. interval $(\times 10^{-3})$
No CPV	R_D	3.64 ± 0.17	$(3.3,\ 4.0)$
	x'^2	$0.18^{+0.21}_{-0.23}$	< 0.72
	y'	$0.6^{+4.0}_{-3.9}$	$(-9.9,\ 6.8)$
	R_M	-	$(0.63 \times 10^{-5},\ 0.40)$
CPV	A_D	23 ± 47	$(-76,\ 107)$
	A_M	670 ± 1200	$(-995,\ 1000)$
	x'^2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

CDF

arXiv:0712.1567

1.5 fb^{-1}



Fit type	$R_D(10^{-3})$	$y'\ (10^{-3})$	$x'^2\ (10^{-3})$	χ^2 / d.o.f.
Unconstrained	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	19.2 / 17
Physically allowed	3.22 ± 0.23	6.0 ± 1.4	0	19.3 / 18
No mixing	4.15 ± 0.10	0	0	36.8 / 19

Evidence of mixing at 3.8σ

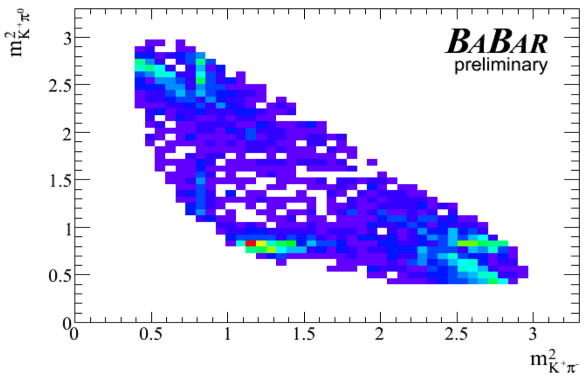
Time dependent Dalitz plot analysis $D^0 \to K^+\pi^-\pi^0$

Similar story as Kπ, except the time dependence is a function of position in the Dalitz plot

$$\Gamma_{\bar{f}}(m_{12,}m_{13},t) = e^{-\Gamma}\{|A_{\bar{f}}|^2 + |A_{\bar{f}}||\overline{A}_{\bar{f}}|[y''\cos\delta_{\bar{f}} - x''\sin\delta_{\bar{f}}](\Gamma t) + \frac{x''^2 + y''^2}{4}|\overline{A}_{\bar{f}}|^2(\Gamma t)^2\}$$

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

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



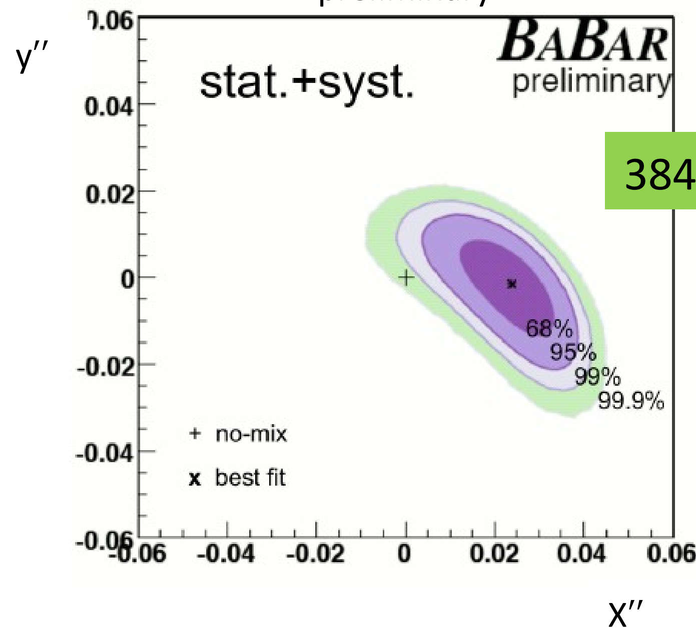
$$x'' = (2.39 \pm 0.61(stat.) \pm 0.32(syst.))\%$$

$$y'' = (-0.14 \pm 0.60(stat.) \pm 0.40(syst.))\%$$

$$R_{mix} = \frac{x''^2 + y''^2}{2} = (2.9 \pm 1.6) \times 10^{-4}$$

BaBar

preliminary



384 fb^{-1}

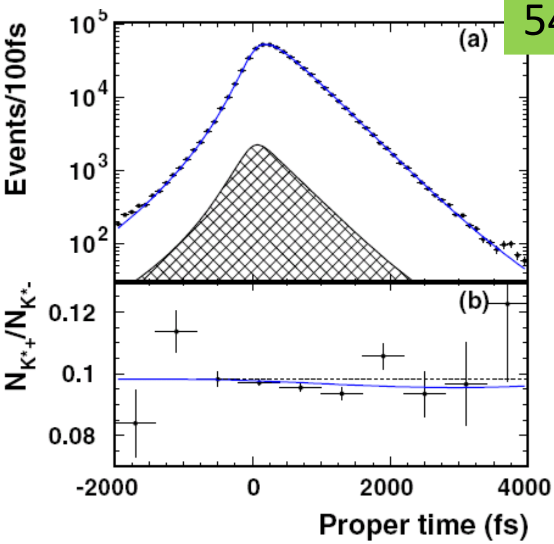
No mixing is excluded at 99% confidence level

Time dependent Dalitz plot analysis $D^0 \to K_s \pi^+ \pi^-$

- Time-dependent Dalitz plot analysis
- Determine relative phases from Dalitz plot, direct measure of x and y

Unbinned likelihood fit to Dalitz-plot variables and the decay time t

540 fb^{-1}



Assuming no CPV:

$$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$$

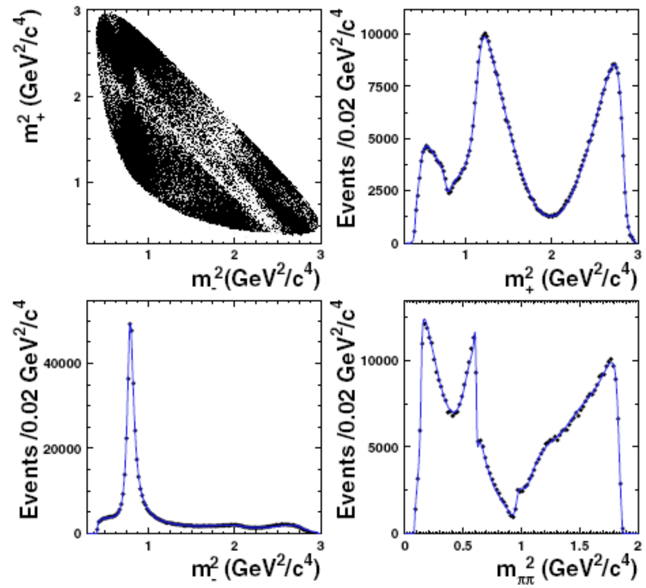
$$y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$$

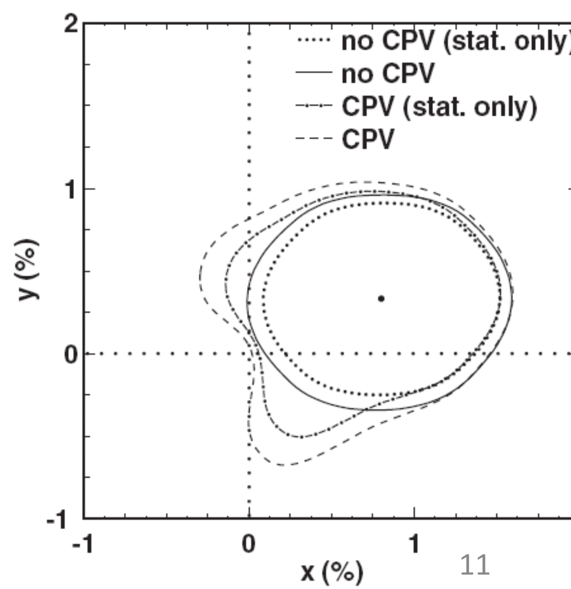
No mixing excluded at 2.2σ

No evidence for CP violation

Belle

PRL 99:131803(2007)





Charm mixing using lifetime ratio

- Measure the lifetime difference between the CP even and CP odd states

Mixture of CP odd and CP even states

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

CP even states

$$y_{CP} = y\cos\phi - \frac{1}{2} A_M x \sin\phi , A_M = |q/p|^2 - 1 , \phi \text{ is a weak phase}$$

If CP conserved, $A_M = \phi = 0$, $y_{CP} = y$

- Also search for CPV by measuring:

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^- K^+) - \tau(D^0 \to K^+ K^-)}{\tau(\overline{D}^0 \to K^- K^+) + \tau(D^0 \to K^+ K^-)} \qquad \Delta Y = -\frac{\tau(D^0/\overline{D}^0 \to K^- \pi^+)}{(\tau(D^0 \to K^+ K^-) + \tau(\overline{D}^0 \to K^+ K^-))/2} A_\Gamma$$

Lifetime ratio measurement

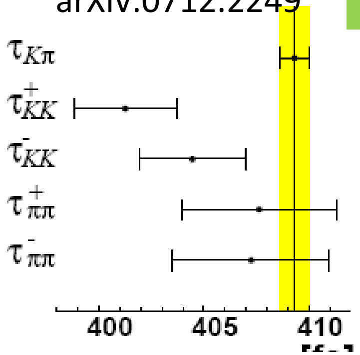
Use a charged D* tag

BaBar

preliminary

arXiv:0712.2249

384 fb^{-1}



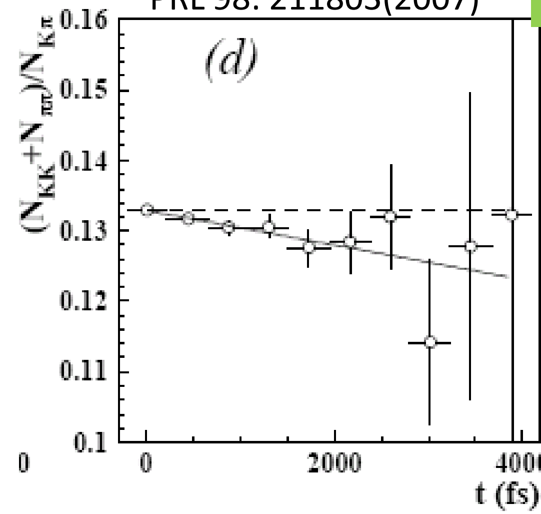
Sample	y_{CP}	ΔY
K^-K^+	$(1.60 \pm 0.46 \pm 0.17)\%$	$(-0.40 \pm 0.44 \pm 0.12)\%$
$\pi^-\pi^+$	$(0.46 \pm 0.65 \pm 0.25)\%$	$(\ \ 0.05 \pm 0.64 \pm 0.32)\%$
Combined	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

3.0σ evidence for mixing

Belle

PRL 98: 211803(2007)

540 fb^{-1}



Sample	y_{CP}	A_Γ
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	$(1.31 \pm 0.32 \pm 0.25)\%$	$(0.01 \pm 0.30 \pm 0.15)\%$

3.2σ evidence for mixing

Combining results with BaBar PRL 91, 121801(2003) with 91 fb^{-1} *(untagged D^0 sample, statistically independent)*

y_{CP}=(1.03±0.33 ±0.19) %

No evidence for CP violation

Semi-leptonic decays $D^0 \to K^{(*)} l \nu$

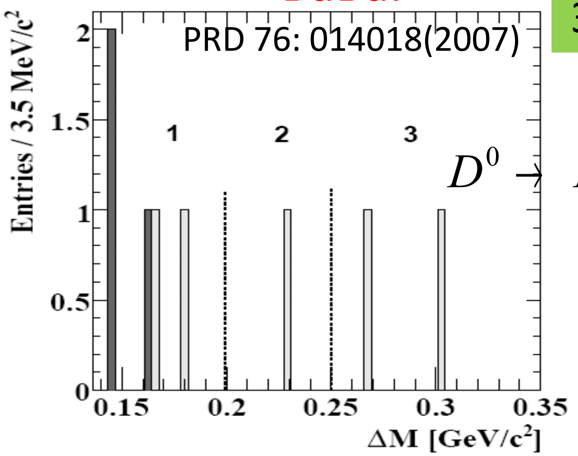
- Look for WS decay, no DCS contribution
- Missing neutrino makes D^0 reconstruction harder
- Observable: $\Delta M = M(Kl\pi\nu) - M(Kl\nu)$

$$r_{mix} = \frac{x^2 + y^2}{2}$$

Double tagging

BaBar

344 fb^{-1}



Predict 2.85 background events, observed 3

No evidence for mixing

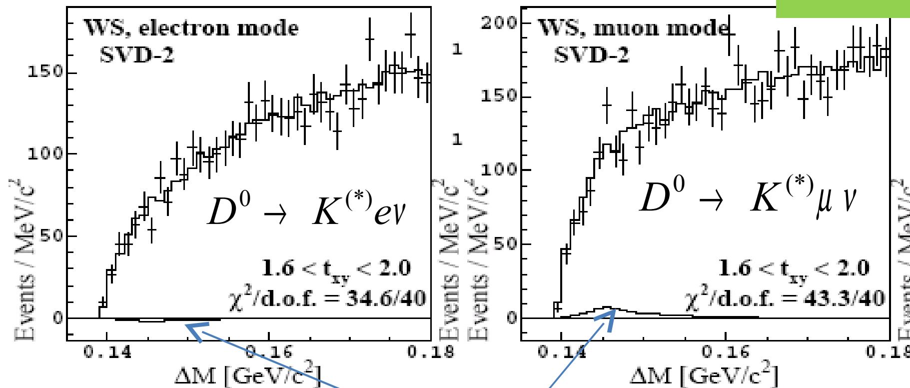
90% CL for r_{mix}: $(-13,12)\times10^{-4}$

Single tagging

Belle

arXiv:0802.2952

492 fb^{-1}



Fitted signal yield

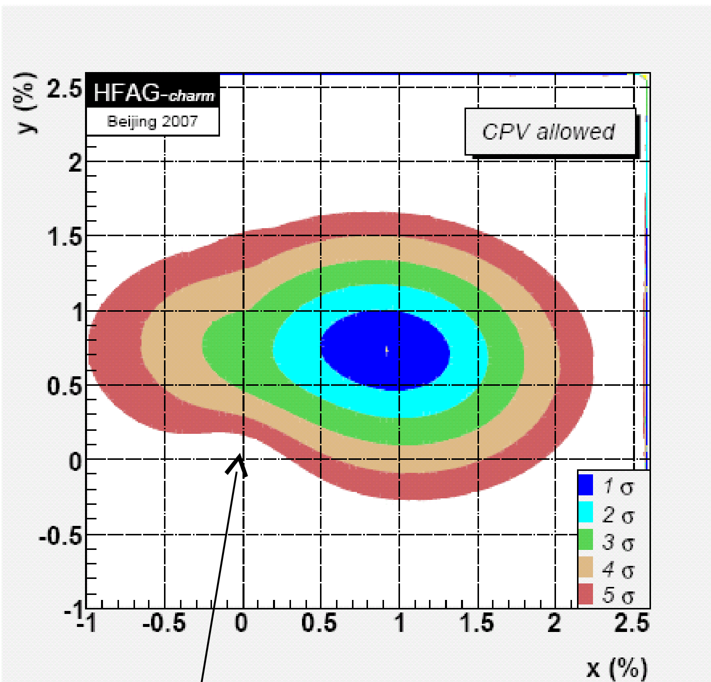
No evidence for mixing

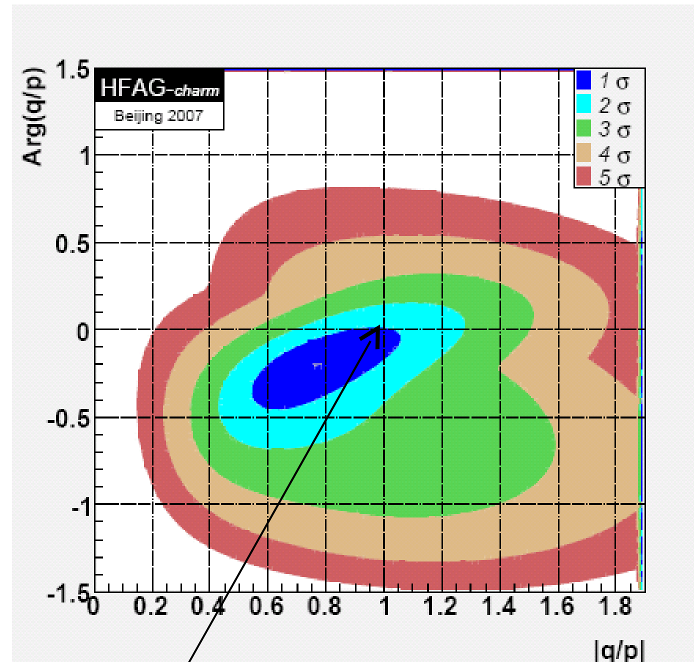
90% CL for r_{mix}: $<6.1\times10^{-4}$

World average $r_{mix} = (1.7\pm3.9)\times10^{-4}$

Heavy Flavor Averaging Group combined results

arXiv:0803.0082





No mixing point excluded at 6.7σ

No-CPV point is still allowed at 1σ

$$x_{avg} = (0.97^{+0.27}_{-0.29}) \times 10^{-2}$$

$$y_{avg} = (0.78^{+0.18}_{-0.19}) \times 10^{-2}$$

$$|q/p|_{avg} = 0.86^{+0.18}_{-0.15}$$

$$\arg(q/p)_{avg} = 0.17^{+0.14}_{-0.16}\, rad$$

Summary

- Evidence for charm mixing
  - ✓ Combined world average is inconsistent with no mixing at 6.7σ
  - ✓ Observed rate for x or y $\approx$1%, consistent with standard model expectations, although at the upper end of the range
- No evidence for CPV in charm mixing yet
- Relatively large mixing signal gives promise for finding CP violation
  - ✓ Many CPV predictions involve multiplicative factors of x and y