D^0 Mixing: One Year Later

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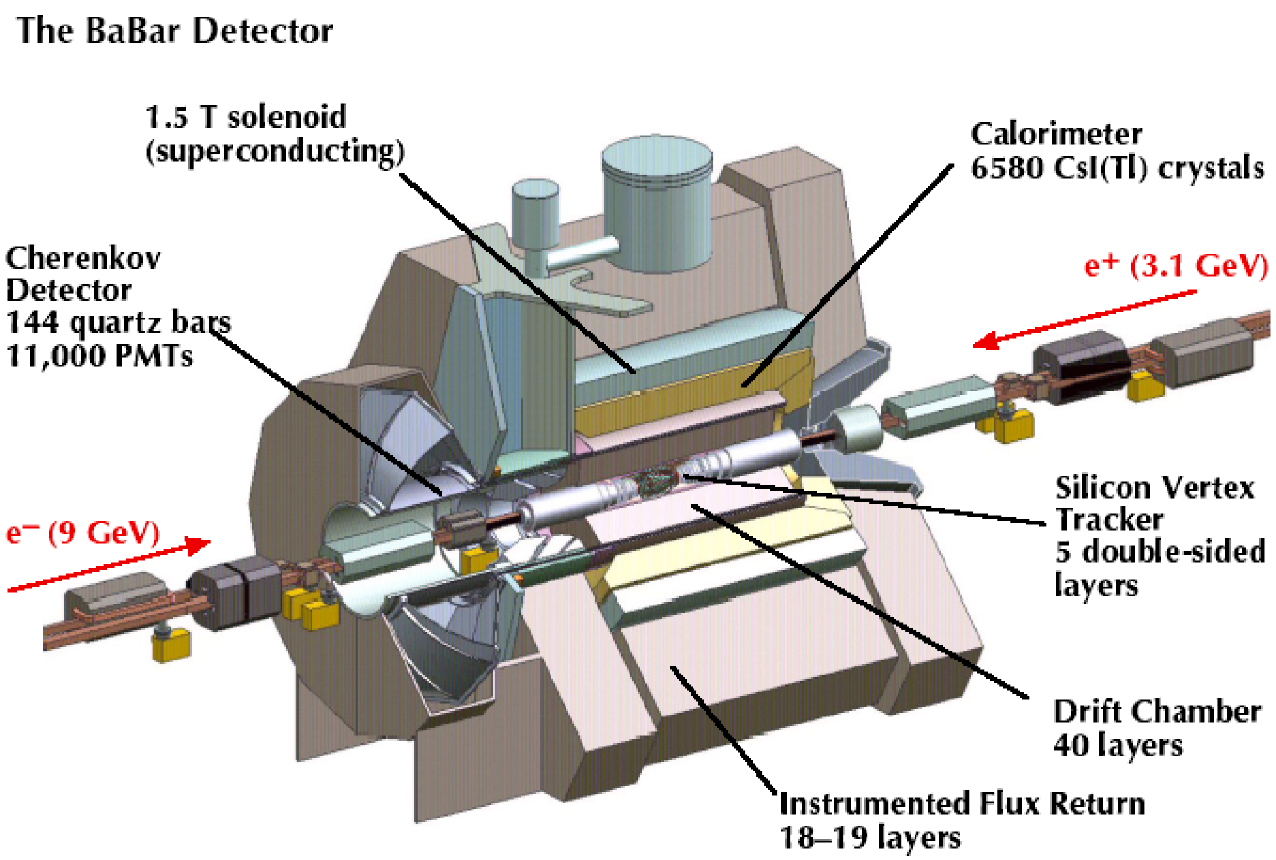
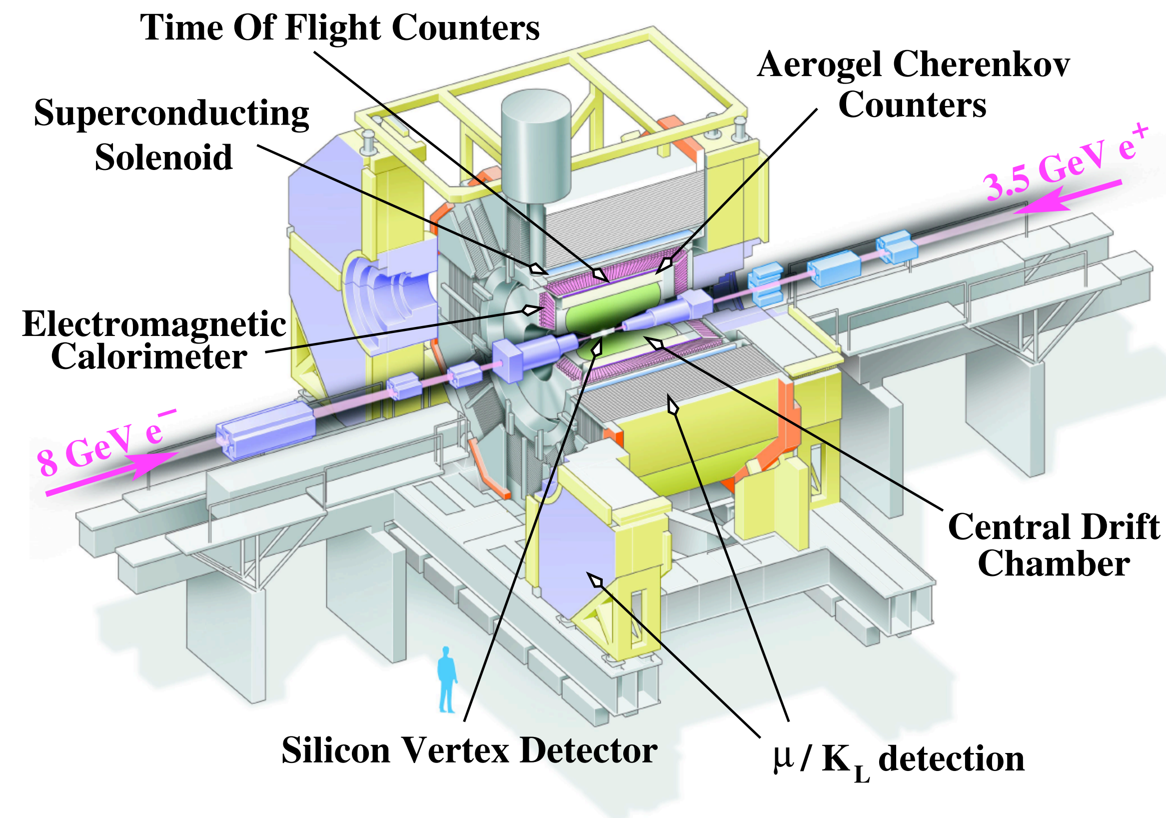
Outline

- The detectors & data samples
- Quick recap of mixing physics
- Experimental results
- Summary

BaBar & Belle





524.2/fb recorded as of 2008-03-19

783.8/fb recorded as of 2008-03-20

Operating energy: $\sqrt{s}$ ~10.6 GeV

(... plus data at Y(3S), Y(2S) -- not discussed here.)

$\sigma(e^+e^- \to c\bar{c}) \sim 1.3$ nb so combined sample contains ~ 1700M $c\bar{c}$ events

Standard mixing formalism

Mixing occurs for neutral mesons $M^0 = K^0, D^0, B^0, B_s^0$

Decompose into mass eigenstates $|M_{1,2}\rangle$:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle \quad \text{for} \ \ |q|^2 + |p|^2 = 1$$

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

... and we can invert to get $|M^0(t)\rangle$ given $m_{1,2}$, $\Gamma_{1,2}$, q/p...

General time evolution:

$$|M(t)\rangle = \frac{1}{2p}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) + e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

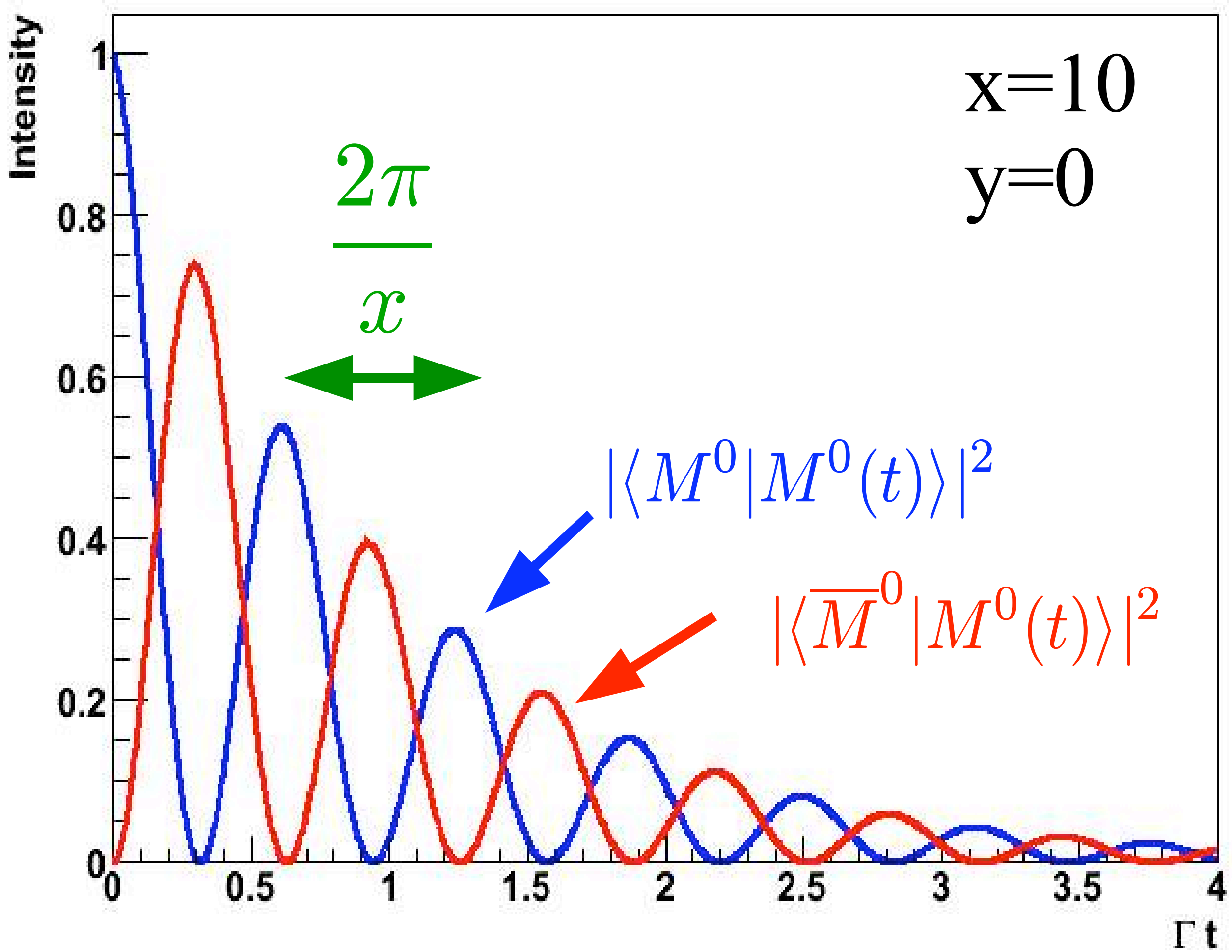
$$|\overline{M}(t)\rangle = \frac{1}{2q}\left[e^{-i(m_1 - \frac{i}{2}\Gamma_1)t}(p|M\rangle + q|\overline{M}\rangle) - e^{-i(m_2 - \frac{i}{2}\Gamma_2)t}(p|M\rangle - q|\overline{M}\rangle)\right]$$

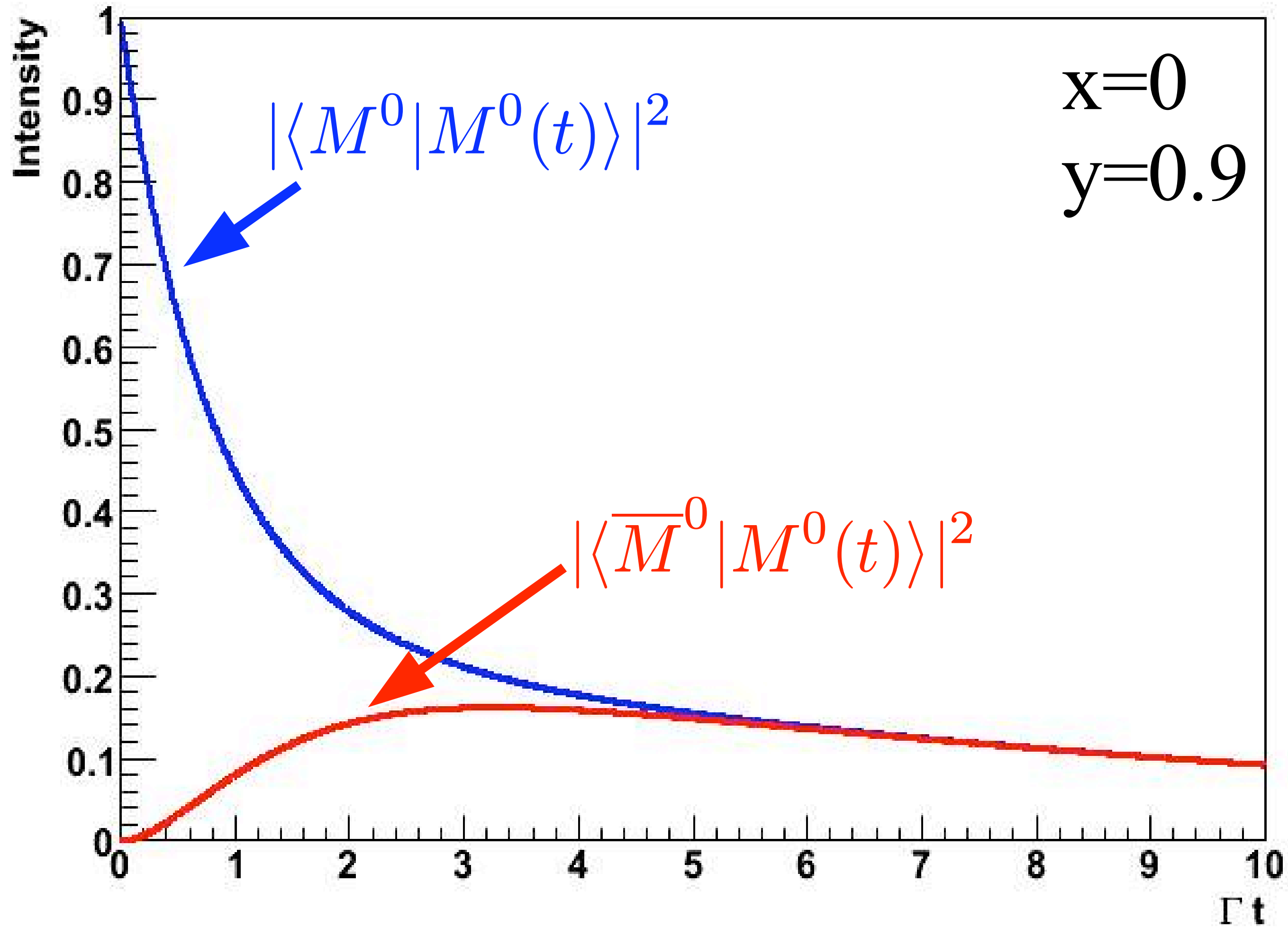
Cartoon of mixing

For convenience, define:

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2} \qquad x = \frac{m_1 - m_2}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

and $R_M = \frac{x^2 + y^2}{2}$

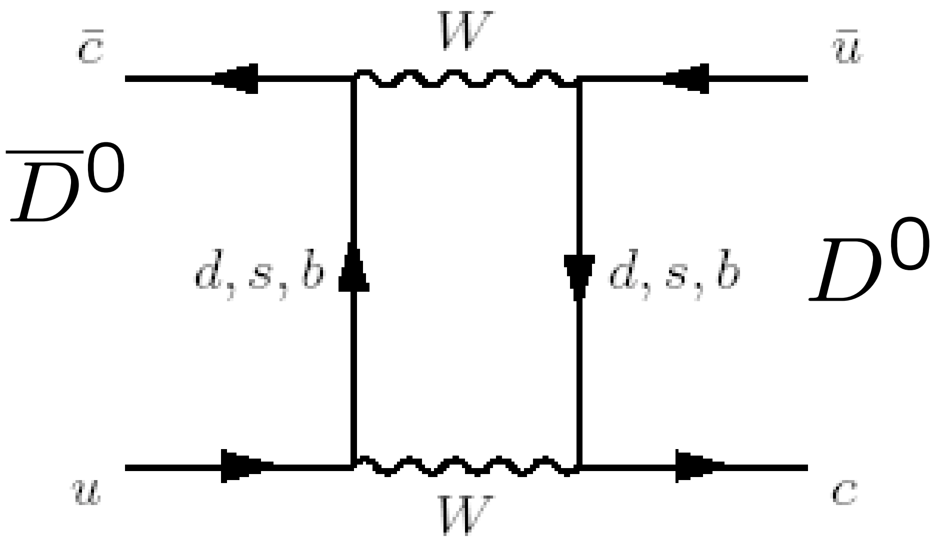




Mixing in charmed mesons

Charm mixing small compared to other mesons in SM:

Mixing via box diagram (short-range)



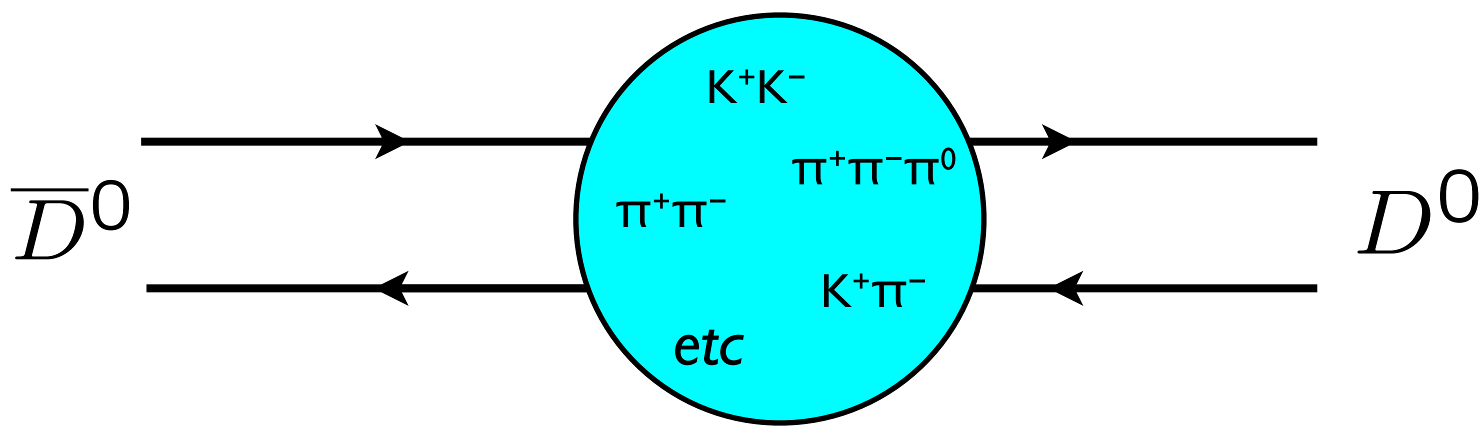
Contributes mainly to x

Intermediate b: CKM-suppressed
Intermediate d,s: GIM-suppressed

$$x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2} \sim 10^{-5}$$

Tiny!

Mixing via hadronic intermediate states (long-range)



Non-perturbative; hard to predict SM contribution.

Most predictions give x,y ~ (0.001–0.01) and |x|<|y|

Recent calculation: $|x| \leq 0.01$, $|y| \leq 0.01$ – less tiny!

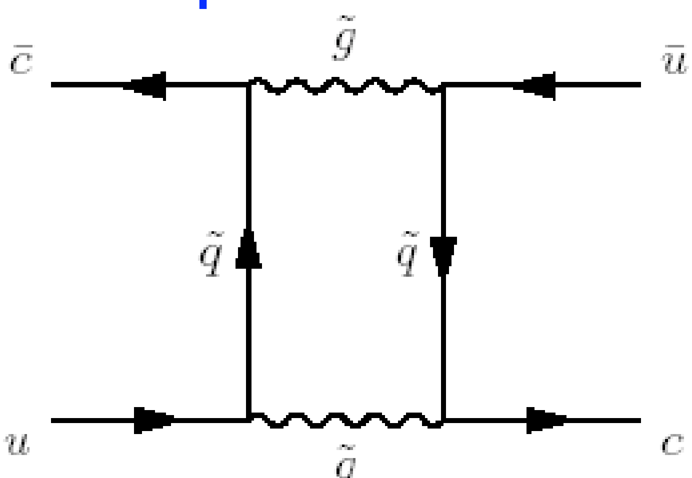
PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

New physics?

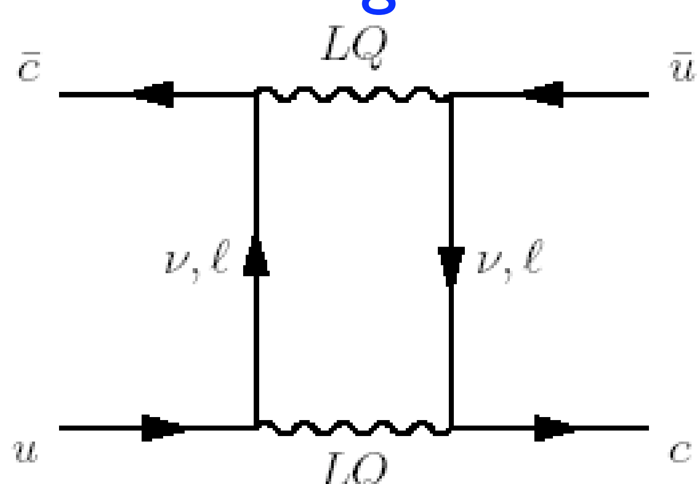
- Theoretical uncertainty in SM mixing rate => can't really observe NP by looking at mixing.
  - (... though x≫y would be a hint...)
  - Future theory input might change things.
- In the meantime, can bound NP from above
  - e.g. Golowich, Hewett, Pakvasa & Petrov (PRD76:095009,2007)
- CPV has more potential to provide a "smoking gun" -- expected to be small (typically < 10^{-3}) in SM but can be larger with NP.

Grossman, Kagan & Nir, PRD 75, 036008 (2007)

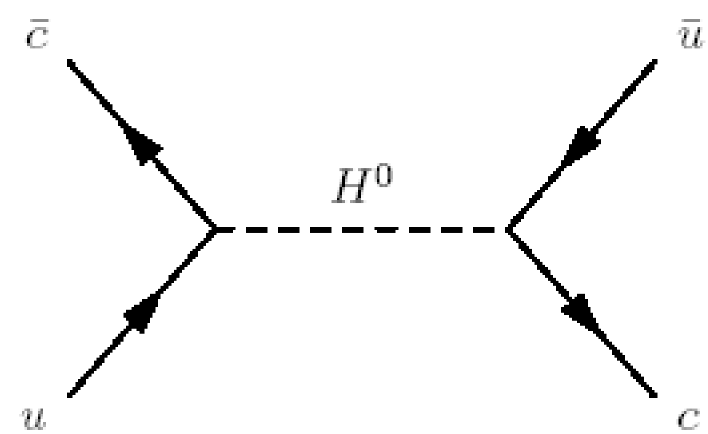
Example NP contributions to mixing:



Supersymmetry



Leptoquarks



Extended Higgs

Experimental results

Broadly, four types of measurement:

1) Lifetime difference between states of different CP
2) Time-dependence of wrong-sign hadronic decays
3) Wrong-sign semi-leptonic decays, e.g. $D^0 \rightarrow K^+ l^- \overline{\nu}_l$
4) Coherent $D^0\overline{D}^0$ production at psi(3770) -- CLEO-c
   (not covered in this talk)

Lifetime ratios: Introduction

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

$D^0 \rightarrow K^- \pi^+$: Mixture of CP states

$D^0 \rightarrow K^- K^+$: CP-even eigenstate (also $D^0 \rightarrow \pi^- \pi^+$)

y_{CP} related to y and CP parameters by:

$$y_{CP} = y \cos\phi - \frac{1}{2} A_M x \sin\phi$$

Falk et al, PRD65,054034

$A_M \neq 0$: CPV in mixing (asymmetry in R_M between D^0 and D^0)

$\cos\varphi \neq 1$: CPV in interference between mixing and decay

CP observables (A_Γ or ΔY) defined as:

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

$$\Delta Y = -\frac{\tau\left(D^0/\overline{D}^0 \rightarrow K^-\pi^+\right)}{\tau\left(D^0/\overline{D}^0 \rightarrow K^+K^-\right)} A_\Gamma$$

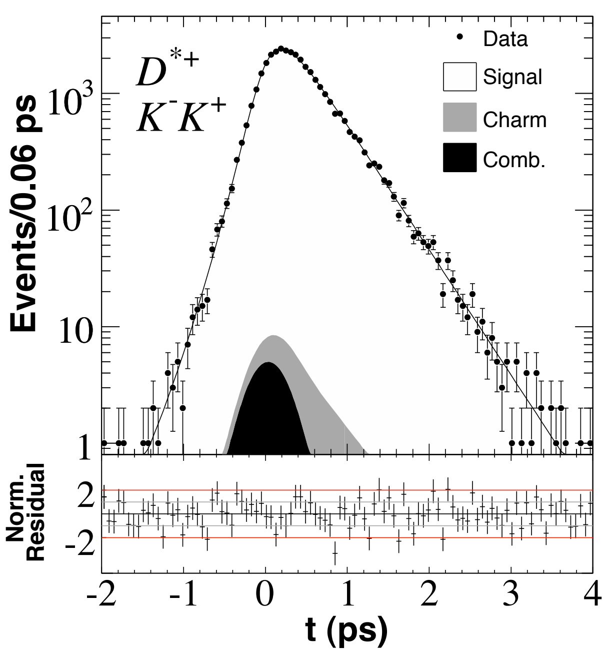
Non-zero value of y_{CP} implies mixing.
If no CP violation, y_{CP} = y.

Lifetime ratios: Method

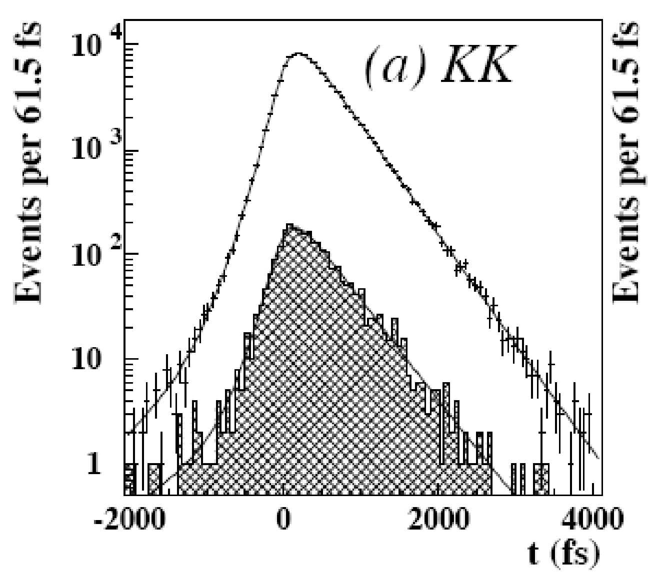
Belle & BaBar methods very similar:

- Require $D^{*+} \to D^0 \pi^+$ tag
  - ID flavour of D^0 at production for CPV measurement
  - Suppresses background
  - Modest improvement to lifetime resolution
- Use $D^0 \to K^-K^+, \pi^-\pi^+$ as signal and $K^-\pi^+$ as control
  - Many measurement systematics cancel in the ratio
- Get as clean a sample as possible
  - Background model systematics don't cancel well between modes

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



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



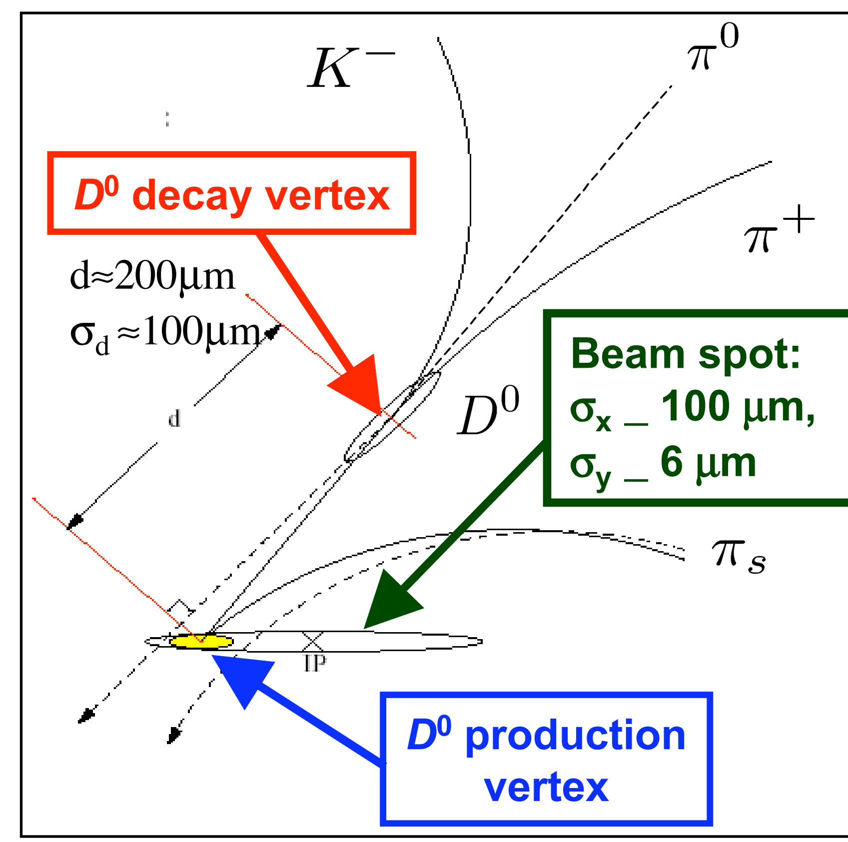
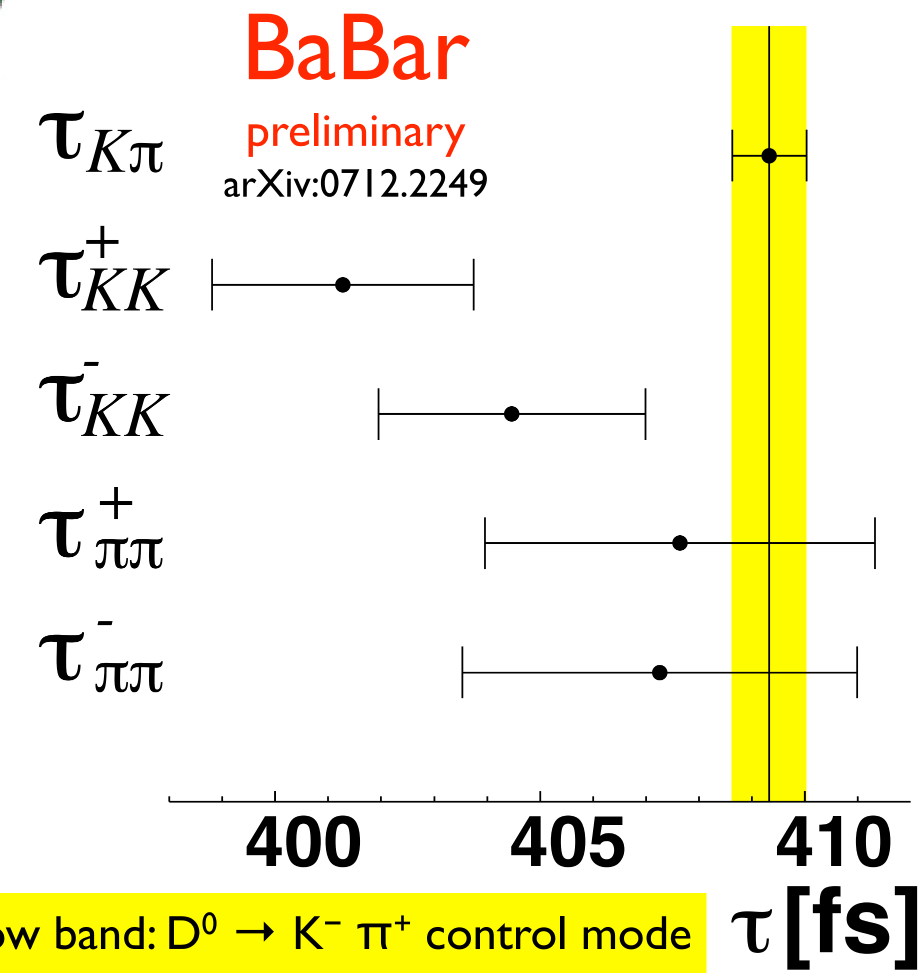
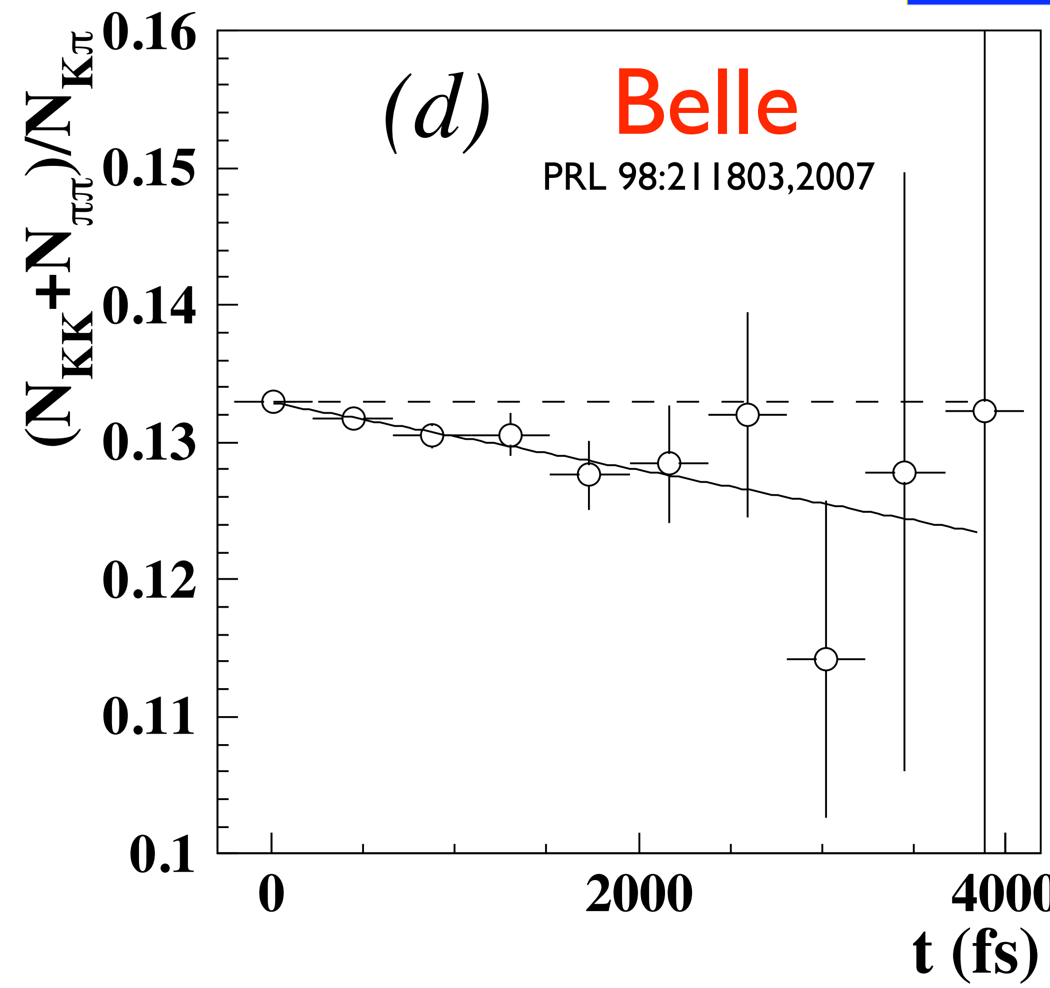


Diagram shows another D^0 decay mode

Lifetime ratios: Results





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	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

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	$(1.31 \pm 0.32 \pm 0.25)\%$	$(0.01 \pm 0.30 \pm 0.15)\%$

3.0σ evidence for mixing

No evidence for CP violation

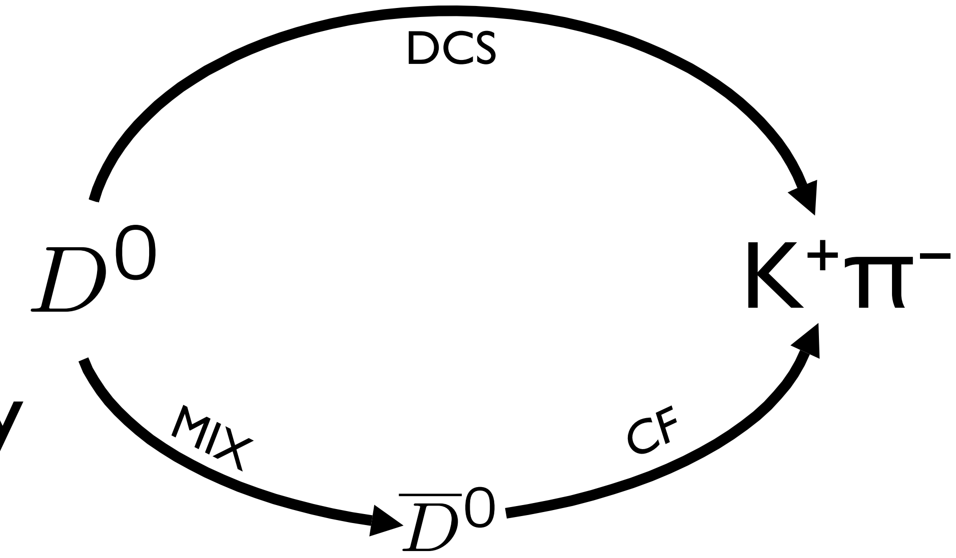
3.2σ evidence for mixing

BaBar result can be combined with statistically independent untagged sample (PRL 91, 162001(2002), 91 fb^{-1}) to obtain $y_{CP} = (1.03 \pm 0.33 \pm 0.19)\%$

Wrong-sign hadronic decays

Look for wrong-sign decays, e.g.

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



Two main contributions:

Doubly-Cabibbo-suppressed (DCS) decay

Mixing & Cabibbo-favoured (CF) decay

Distinguish them by their time dependence:

$$\Gamma_{WS}(t) = e^{-\Gamma t} \left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y' \sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{Mixing}} \right)$$

[Limit of |x| ≪ 1, |y| ≪ 1, and no CPV.]

Why x′ and y′ instead of x and y?

$x' = x \cos\delta + y \sin\delta$

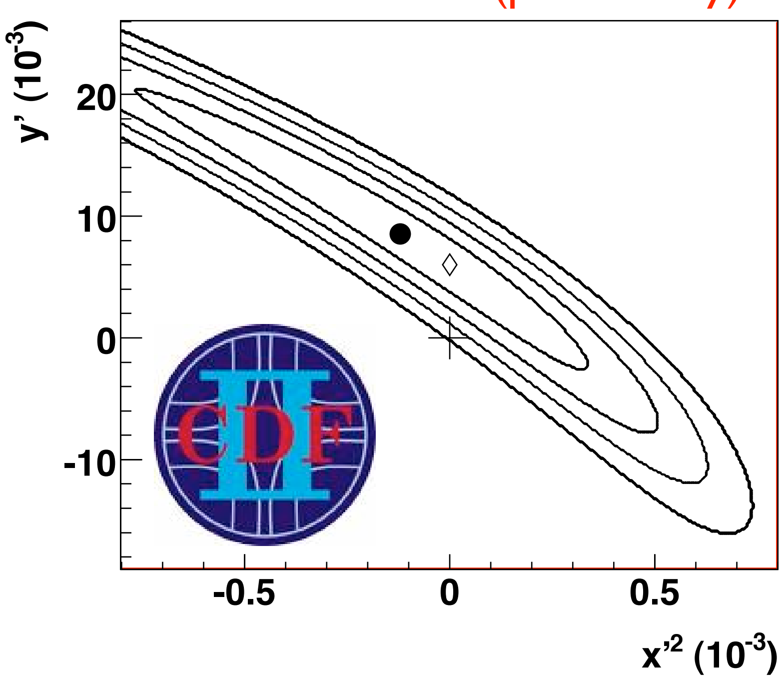
$y' = y \cos\delta - x \sin\delta$

where δ is the phase difference between DCS and CF decays and depends on the final state.

Note: $(x'^2 + y'^2)/2 = (x^2 + y^2)/2 \equiv R_M$

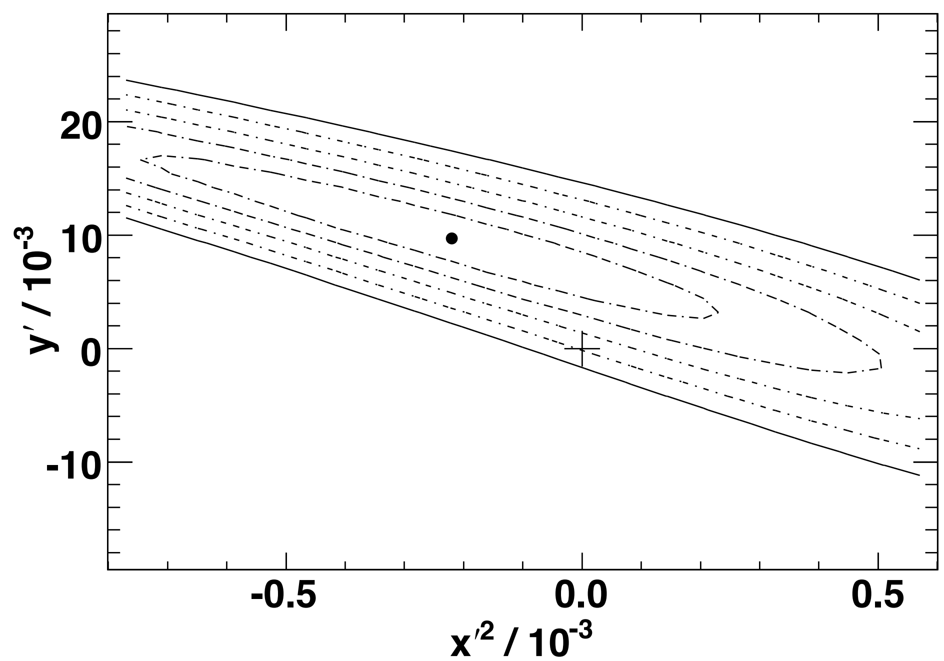
Wrong-sign $D^0 \to K^+ \pi^-$

CDF: 1.5 fb^{-1}
arXiv:0712.1567 (preliminary)



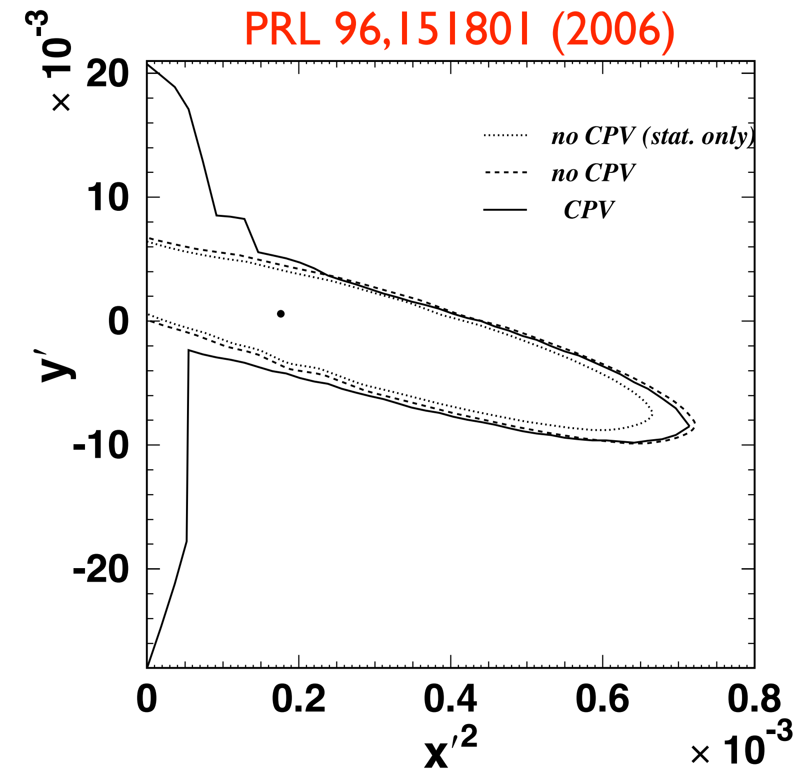
3.8σ evidence for mixing

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



3.9σ evidence for mixing

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



2.0σ evidence for mixing

x′,y′ highly correlated

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 [8]	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9
Belle [9]	3.64 ± 0.17	$0.6\ ^{+4.0}_{-3.9}$	$0.18\ ^{+0.21}_{-0.23}$	2.0

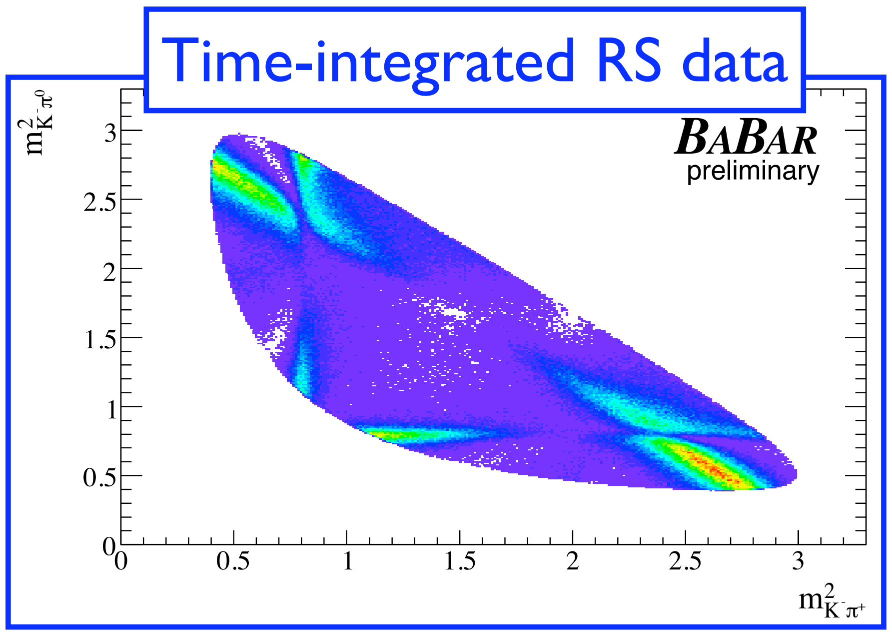
BaBar: $A_D = (-2.1 \pm 5.2 \pm 1.5)\%$
Belle: $A_D = (2.3 \pm 4.7)\%$
Belle: $A_M = 0.67 \pm 1.2$

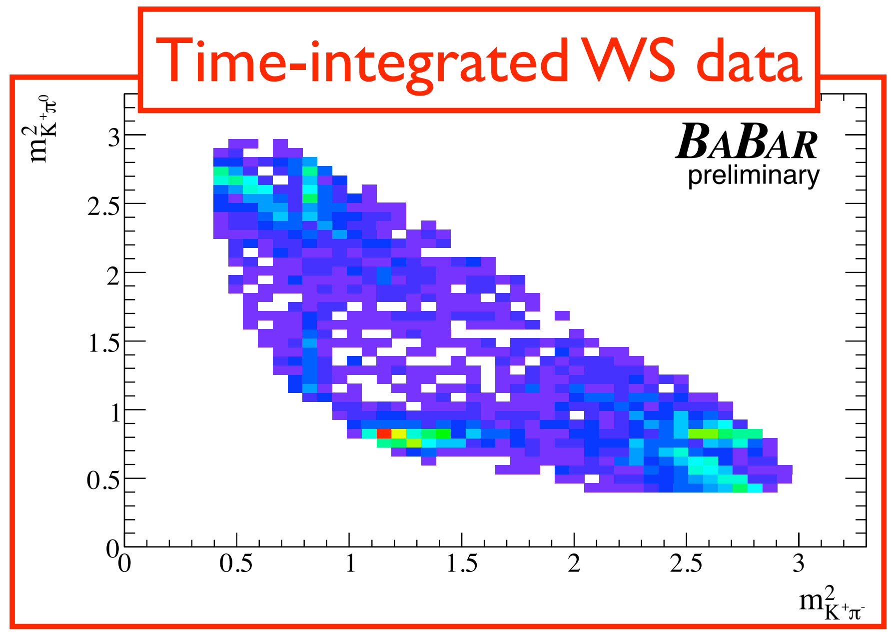
Clear evidence for mixing!
But no evidence for CP violation found.

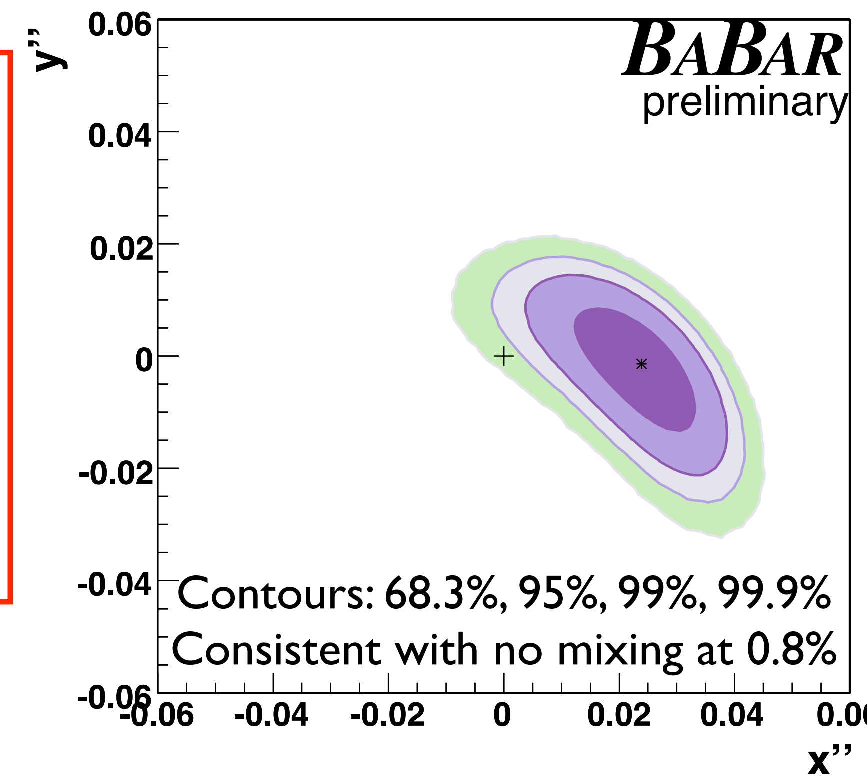
Wrong-sign $D^0 \to K^+ \pi^- \pi^0$

DCS and CF components each have a Dalitz plot.

- Get CF Dalitz model from time-independent fit to RS data
- Get DCS Dalitz model & mixing params from time-dependent fit to WS data







Mixing results:

$$x'' = (\ \ 2.39 \pm 0.61\ (\text{stat.})\ \ \pm 0.32\ (\text{syst.}))\%$$
$$y'' = (-0.14 \pm 0.60\ (\text{stat.})\ \ \pm 0.40\ (\text{syst.}))\%$$
$$R_{\text{mix}} \equiv \frac{x''^2 + y''^2}{2} = (2.9 \pm 1.6) \times 10^{-4}$$

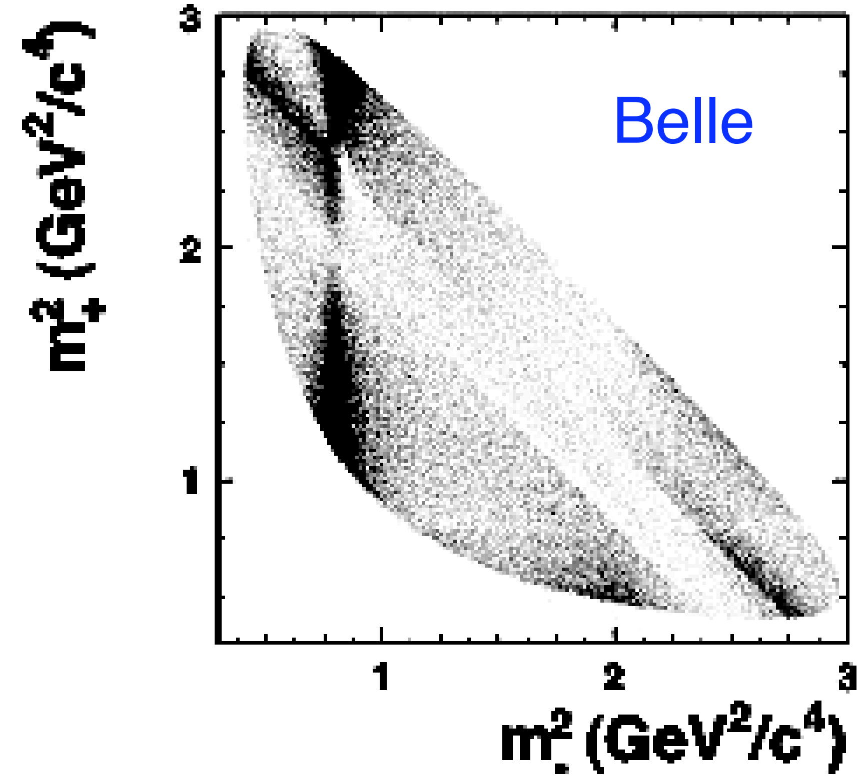
BaBar preliminary
384 fb^{-1}

[x'', y'' since phase is in general different from $D^0 \to K^+ \pi^-$]

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

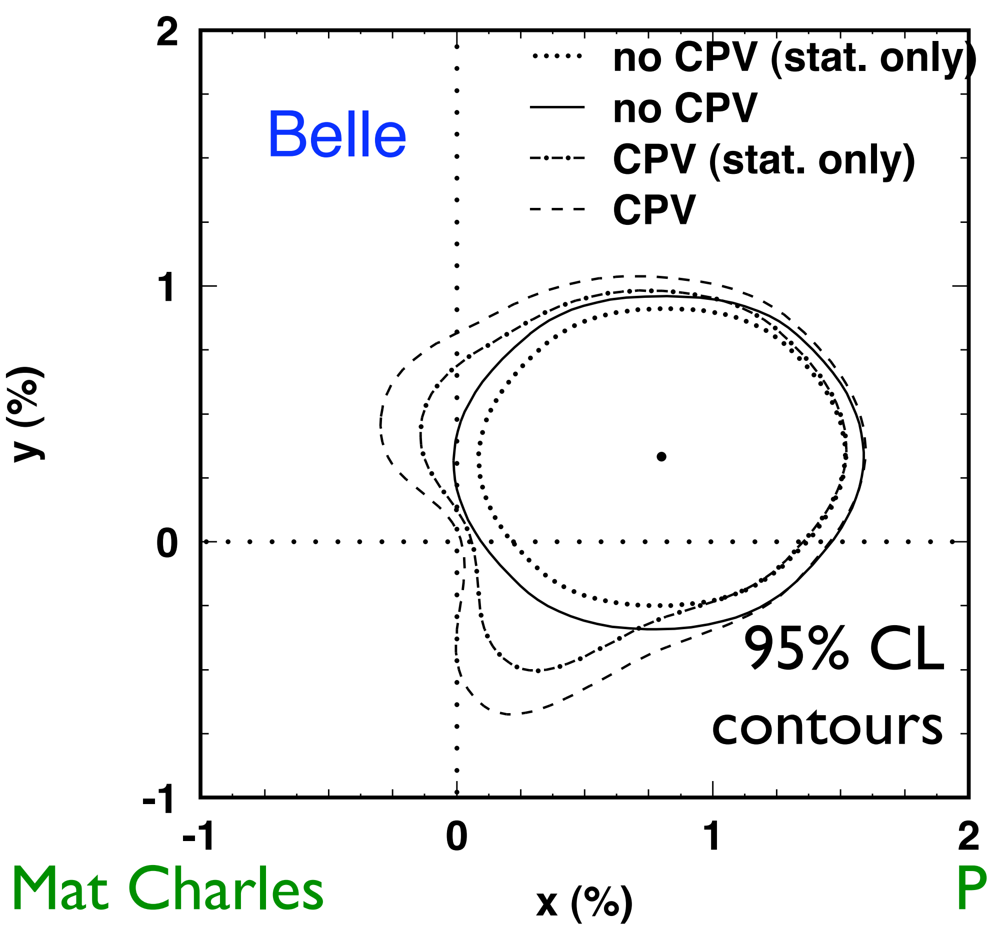
Another time-dependent Dalitz plot analysis -- but this time have:

- CF contributions (e.g. $D^0 \to K^{*-} \pi^+$)
- DCS contributions (e.g. $D^0 \to K^{*+} \pi^-$)
- CP-even contribution (e.g. $D^0 \to K_S \rho^0$)
- CP-odd contribution (e.g. $D^0 \to K_S f_0$)



... all in the same Dalitz plot, interfering.

⇒ Can measure relative phases -- and hence x, y -- directly!



Mixing results assuming no CPV:

$$x = (0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14})\%$$
$$y = (0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08})\%$$

No evidence for CPV found:

$$|q/p| = 0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$$
$$\arg(q/p) = \left(-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4}\right)^\circ$$

Belle, 540 fb⁻¹
PRL 99, 131803 (2007)

Semi-leptonic decays

Look for $D^0 \to K^{(*)+} l^- \bar{\nu}_l$

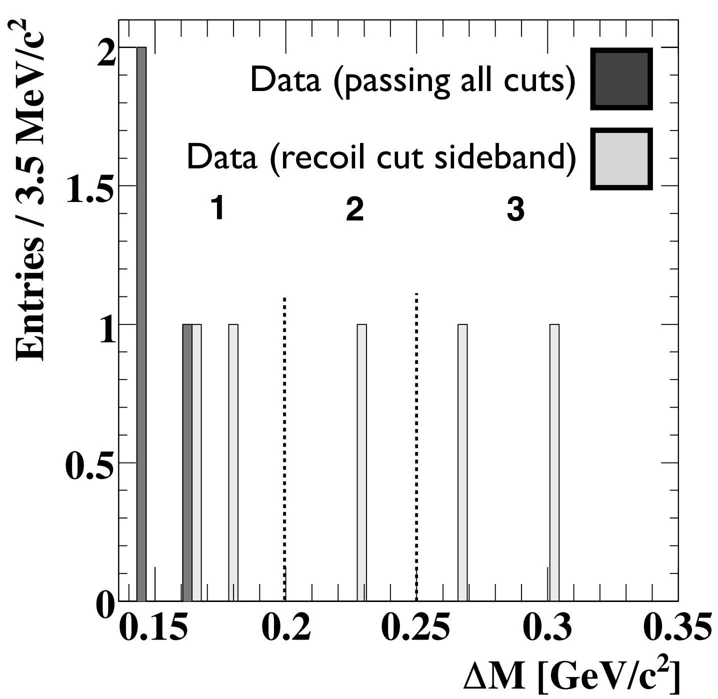
Pro: No DCS contribution! Theoretically clean

Con: Missing ν makes reconstruction/selection harder

BaBar

PRD 76:014018 (2007), 344 fb^{-1}

- Electron mode only
- Use double-tag to suppress background



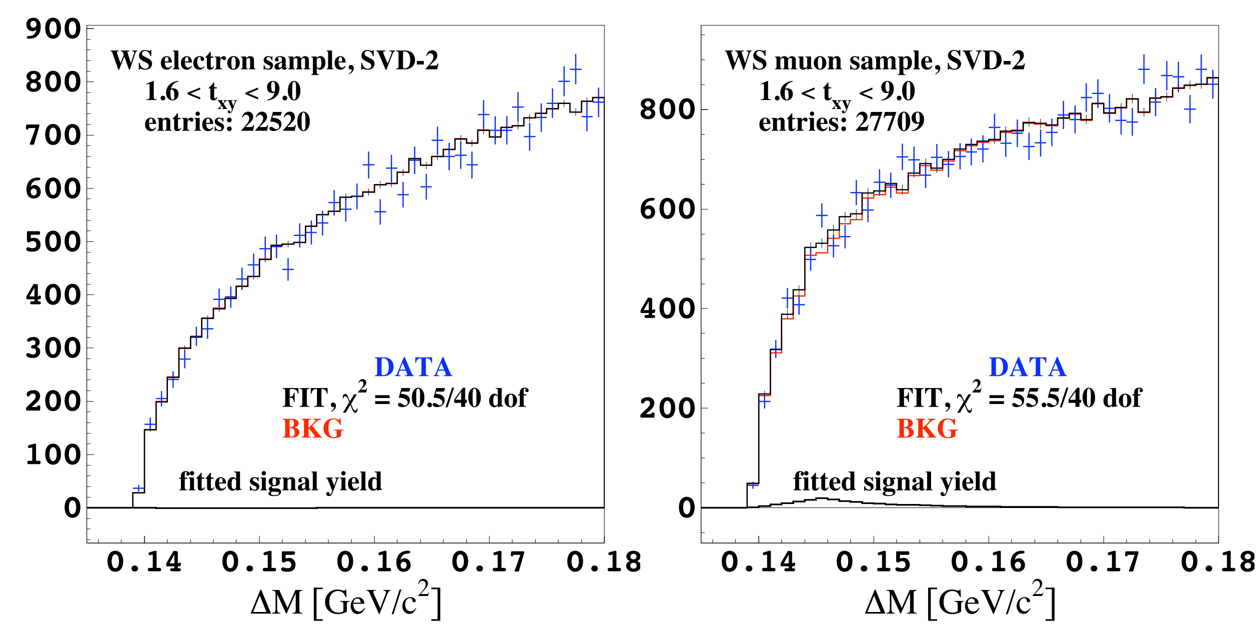
No evidence for mixing.

90% CL: R_M in (−13, +12) ×10^{-4}

Belle

arXiv:0802.2952, 492 fb^{-1} (preliminary)

- Electron & muon modes
- Kinematic constraints (E_{cm}, m_D, m_ν) improve ν reconstruction
- D^0 proper lifetime cut



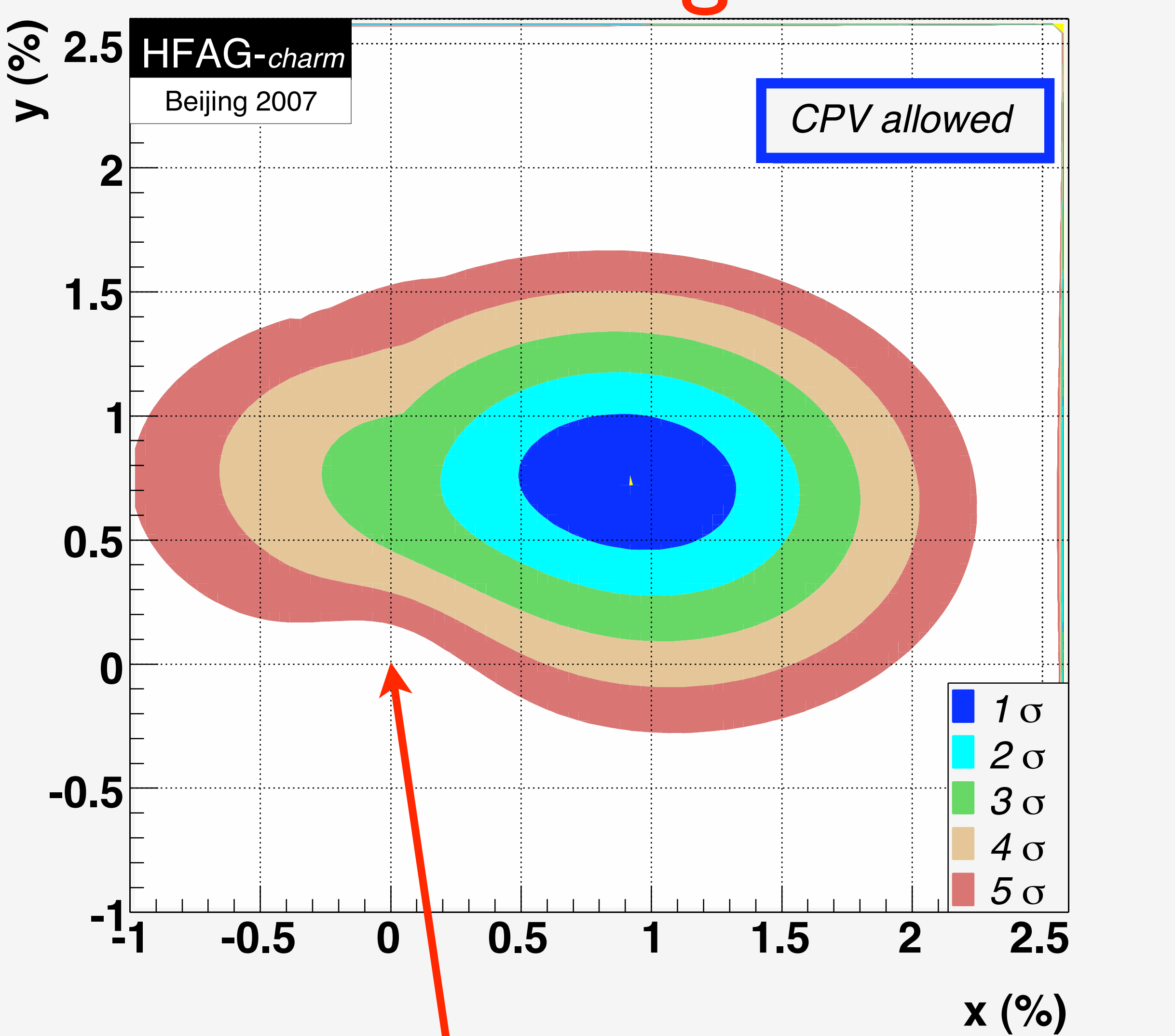
No evidence for mixing.

90% CL: $R_M < 6.1 \times 10^{-4}$

HFAG Combined results

arXiv:0803.0082

Mixing

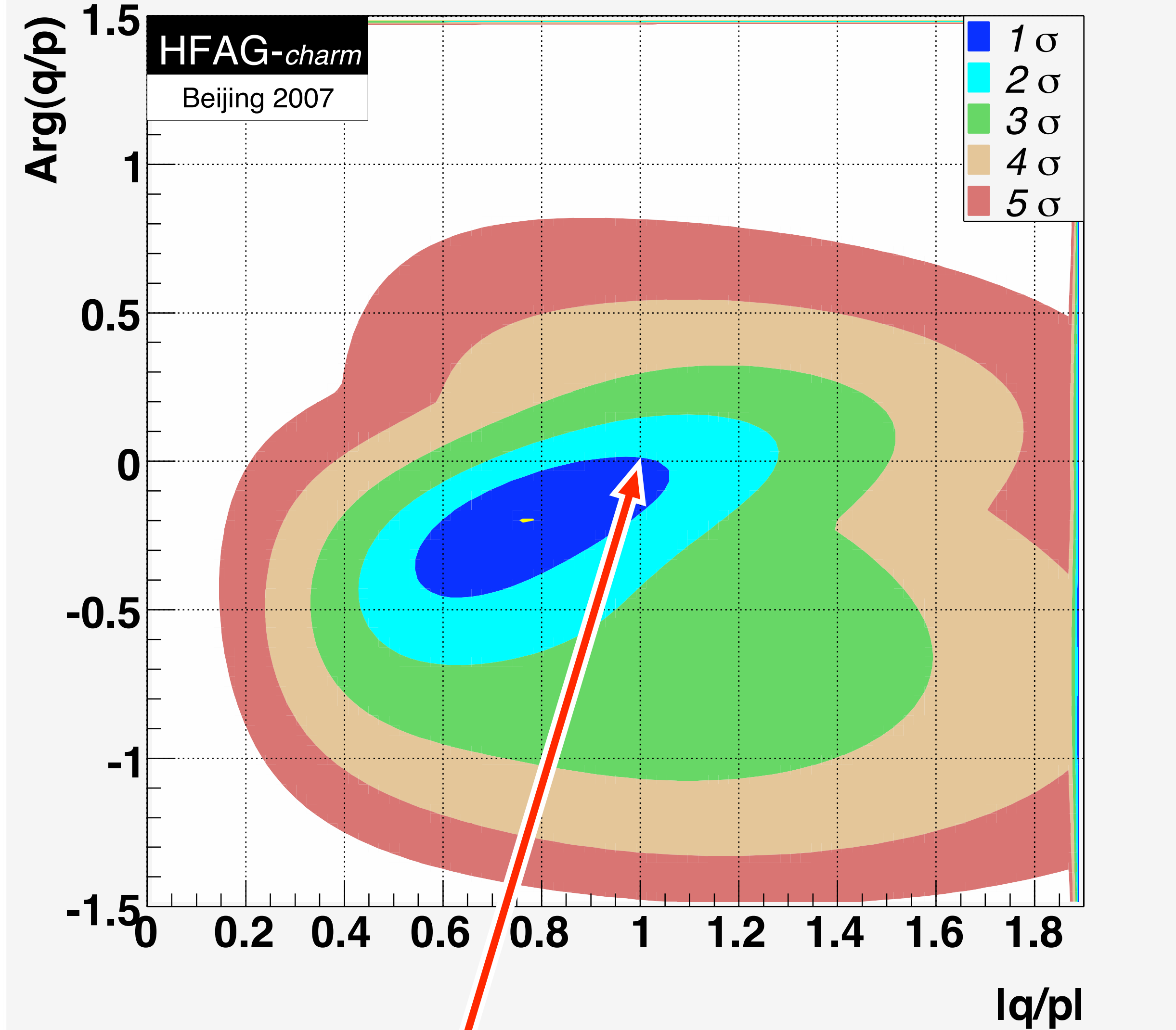


No-mixing point excluded at 6.7σ

World average: $x = (0.97^{+0.27}_{-0.29})\%$

$y = (0.78^{+0.18}_{-0.19})\%$

Indirect CP violation



No-CPV point still allowed at 1σ

World average: $|q/p| = 0.86^{+0.18}_{-0.15}$

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

Summary

- D^0 mixing now established (world avg: 6.7σ level)
  - Still large uncertainties on parameters
  - More work to do (pinning down x, y, y_{CP})
  - Still statistically limited
- Observed mixing rate consistent with SM prediction...
  - ... within large theory uncertainty...
  - ... and at upper end of expected range.
- No sign of CP violation (direct or indirect) in charm yet
  - Limits still well above SM expectations -- room for NP.

Backups

CP violation

- CP violation
  - Direct
    $$A_f = \langle f | H_D | D^0 \rangle \neq \bar{A}_f = \langle f | H_D | \bar{D}^0 \rangle$$
  - Indirect
    - In mixing
      $$r_m = \left| \frac{q}{p} \right| \neq 1$$
    - In interference between mixing and decay
      $$\phi_f = \arg\left(\frac{q}{p} \frac{\bar{A}_f}{A_f} \right) \neq 0$$

Direct CPV: Manifests as an asymmetry in time-integrated decay rate between particle & antiparticle
Indirect CPV: Manifests as an asymmetry in time-dependent decay rates (& thus time-integrated too)

CPV: WS hadronic D^0 decays

Wrong-sign hadronic D^0 decays -- time dependence goes like:

$$\frac{T^{\pm}_{\rm WS}(t)}{e^{-\Gamma t}} = \sqrt{\frac{1 \pm A_{\rm D}}{1 \mp A_{\rm D}}} R_{\rm D} + \sqrt{R_{\rm D}} \sqrt[4]{\frac{(1 \pm A_{\rm D})(1 \pm A_{\rm M})}{(1 \mp A_{\rm D})(1 \mp A_{\rm M})}} (y' \cos\varphi \mp x' \sin\varphi) \Gamma t + \sqrt{\frac{1 \pm A_{\rm M}}{1 \mp A_{\rm M}}} \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

Simplify by writing separately for D^0 (+) and $\bar{D}^0$ (−)

$$T^{\pm}_{\rm WS}(t) = e^{-\Gamma t} \left(R^{\pm}_{\rm D} + \sqrt{R^{\pm}_{\rm D}} y'^{\pm} \, \Gamma t + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\Gamma t)^2 \right)$$

i.e. $A_{\rm D} = \frac{R^{+}_{\rm D} - R^{-}_{\rm D}}{R^{+}_{\rm D} + R^{-}_{\rm D}}, \qquad A_{\rm M} = \frac{R^{+}_{\rm M} - R^{-}_{\rm M}}{R^{+}_{\rm M} + R^{-}_{\rm M}}$

Then:

- A difference between R_D^+ and R_D^- indicates CPV in decay
- A difference between (x'^+ and x'^-) or (y'^+ and y'^-) indicates indirect CPV

Advantage of expressing it this way: fit parameters ($x'^{\pm}$, $y'^{\pm}$, $R_D^{\pm}$) are well-defined even when mixing is small or zero.

CPV: Hadronic D^0 decays

Searches in time-dependent analyses

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

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

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

$$|q/p| = 0.86\,^{+0.30}_{-0.29}\,^{+0.06}_{-0.03} \pm 0.08$$

$$\arg(q/p) = \left(-14\,^{+16}_{-18}\,^{+5}_{-3}\,^{+2}_{-4}\right)^\circ$$

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

	Value	95% CL
A_D	23 ± 47	$(-76,\ 107)$
A_M	670 ± 1200	$(-995,\ 1000)$
x'^2	-	< 0.72
y'	-	$(-28,\ 21)$
R_M	-	< 0.40

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

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	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

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

$$A_\Gamma = (0.01 \pm 0.30(\text{stat.}) \pm 0.15(\text{syst.}))\%.$$

Small mixing rate ⇒ Limited sensitivity to indirect CPV

Time-integrated CPV

Search for CPV in $D^0 \to K^+K^-(\pi^0), \pi^+\pi^-(\pi^0)$

SCS = Single Cabibbo Suppressed

- CP violation in these modes is predicted to be $\mathcal{O}(10^{-5}\text{-}10^{-4})$ in SM. *Evidence of CP violation with present experimental sensitivity is a sign of Physics beyond SM.*

F. Bucella et al., Phys. Rev. **D51**, 3478 (1995)
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003)
Y. Grossman et al., Phys. Rev. **D75**, 036008 (2007)

- Time integrated CP asymmetry get contributions from the 3 different CP violation sources: decay, mixing, interference between mixing and decay.

$$a_{CP}^{f} = \frac{\Gamma\left(D^0 \to f\right) - \Gamma\left(\bar{D}^0 \to \bar{f}\right)}{\Gamma\left(D^0 \to f\right) + \Gamma\left(\bar{D}^0 \to \bar{f}\right)}; \quad \mathrm{f} = K^+K^-\left(\pi^0\right), \pi^+\pi^-\left(\pi^0\right)$$

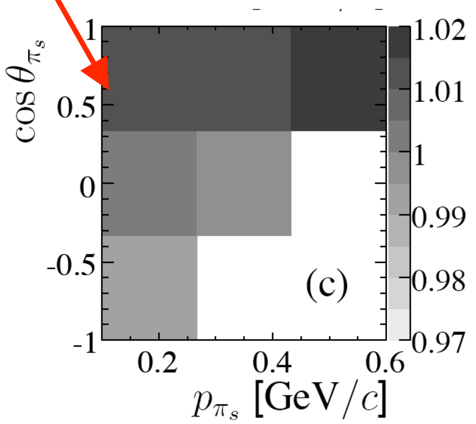
- Experimental difficulties:
  - precise determination of detector D^0 tagging asymmetry (π_{soft} reconstruction in $D^{*+} \to D^0\pi^+$ decays)
  - forward-backward (FB) asymmetry in $c\bar{c}$ production.

Time-integrated CPV

Experimental procedure

- Determine relative $D^0/\bar{D}^0$ soft pion tagging efficiency using $D^0 \to K^- \pi^+$ data

  ⇒greatly reduces systematic uncertainties



Category	Δa_{CP}^{KK}	$\Delta a_{CP}^{\pi\pi}$
2-Dim. PDF shapes	±0.04%	±0.05%
π_s correction	±0.08%	±0.08%
a_{CP} extraction	±0.09%	±0.20%
Quadrature sum	±0.13%	±0.22%

- Another thing to take into account:
  - correct for FB asymmetries A_{FB} in $e^+e^- \to c\bar{c}$ production: Z^0/γ mediated diagrams interference, high order QED diagrams interference.
  - effects are anti-symmetric in the $\cos\theta_{CM}$

A_{FB}~few %

- extract a_{CP} *(symmetric in* $\cos\theta_{CM}$ *)*

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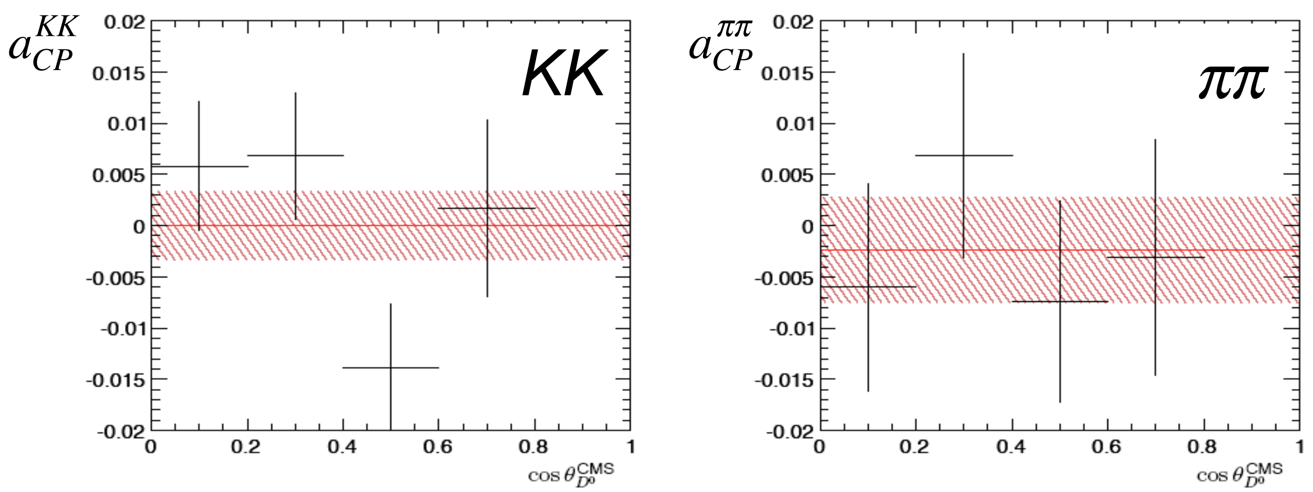
Time-integrated CPV

Search for CPV in $D^0 \to K^+K^-, \pi^+\pi^-$

arXiv:0709.2715
Data sample 385fb^{-1}



$$a_{CP}^{KK} = (\ \ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

No evidence for CPV in either modes

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Time-integrated CPV

Search for CPV in $D^0 \to K^+K^-\pi^0$, $\pi^+\pi^-\pi^0$

new

SLAC-PUB-13058

Data: 385 fb^{-1}

- Signal sample 82.5K evt for $\pi^+\pi^-\pi^0$ and 11.3K for $K^+K^-\pi^0$: *98% purity.*

•CP asymmetry evaluated with 4 different methods: 3 methods are model independent (MI).

- Difference between D^0 and $\bar{D}^0$ Dalitz plot in 2 dimensions *(MI)*
- Difference in the angular moments of D^0 and $\bar{D}^0$ *(MI)*
- Difference in Dalitz plot fit results for amplitude-phases for D^0 and $\bar{D}^0$
- Difference in phase space integrated asymmetry *(MI)*

Last method is insensitive to Dalitz plot shapes, so complements the other methods.

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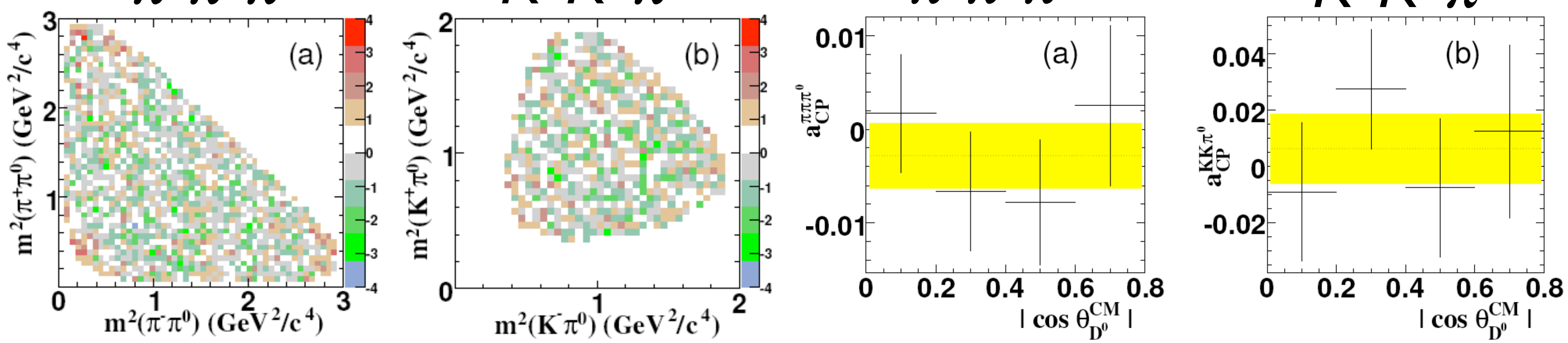
Time-integrated CPV

Search for CPV in $D^0 \to K^+K^-\pi^0,\ \pi^+\pi^-\pi^0$

BaBar preliminary

new

$\pi^+\pi^-\pi^0$ | $K^+K^-\pi^0$ | $\pi^+\pi^-\pi^0$ | $K^+K^-\pi^0$



$$\Delta = (n_{\overline{D}^0} - R \cdot n_{D^0}) \,/\, \sqrt{\sigma^2_{n_{\overline{D}^0}} + R^2 \cdot \sigma^2_{n_{D^0}}}$$

Normalized residuals. R efficiency corrected ratio of $\overline{D}^0$ wrt D^0 events.

Phase space integrated A_{CP}:

$$a_{CP}^{\pi^+\pi^-\pi^0} = (-0.31 \pm 0.41 \pm 0.17)\%$$

$$a_{CP}^{K^+K^-\pi^0} = (\ 1.00 \pm 1.67 \pm 0.25)\%$$

No evidence of CP violation at few % level in either decay modes with any of the 4 methods used to evaluate the CP asymmetry.

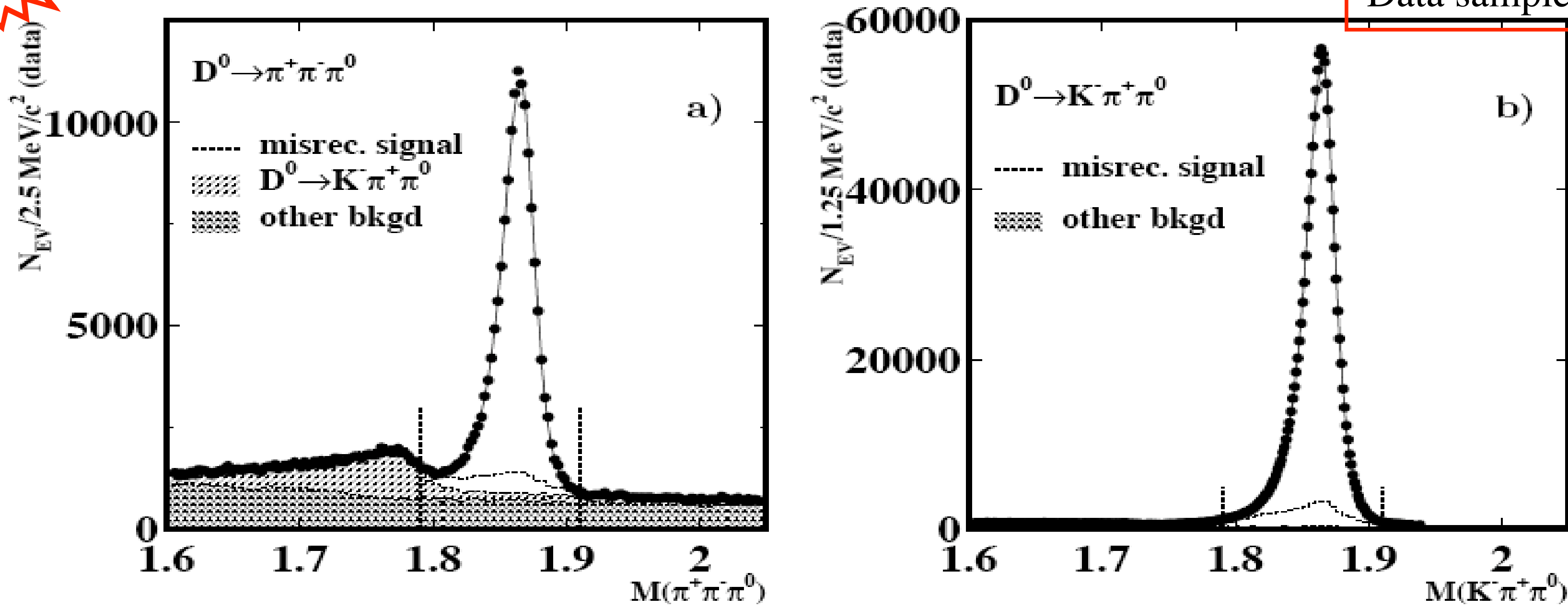
Time-integrated CPV

Search for CPV in $D^0 \to \pi^+\pi^-\pi^0$

new

$\pi^+\pi^-\pi^0$ *120K evt* — $K^-\pi^+\pi^0$ *1.2M evt*

arXiv:0801.2439
Data sample 532fb^{-1}



Systematic uncertainties on phase space integrated A_{CP}

Source	MC stat.	Tracking	Fit	K_S veto	PID	Binning	A_{fb}	Total
σ, %	0.24	1.01	0.58	0.23	0.15	0.05	0.15	1.23

$$A_{CP}(D^0 \to \pi^+\pi^-\pi^0) = (0.43 \pm 1.30)\%$$

$$\frac{\mathcal{B}(D^0 \to \pi^+\pi^-\pi^0)}{\mathcal{B}(D^0 \to K^-\pi^+\pi^0)} = 0.1012 \pm 0.0004 \pm 0.0018$$

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