Searches for mixing and *CP* violation in the D^0-$\bar{D}^0$ system:

finding the (small) crack in the Standard Model

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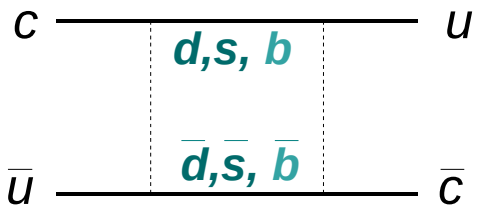
- D^0 meson mixing
- four new measurements
- summary of all measurements:
  - no *CPV*
  - allowing for *CPV*

Neutral meson mixing I:



Flavor eigenstates are not mass eigenstates:

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

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned} \qquad \begin{aligned} |D_1(t)\rangle &= |D_1\rangle\, e^{-(\Gamma_1/2+im_1)t} \\ |D_2(t)\rangle &= |D_2\rangle\, e^{-(\Gamma_2/2+im_2)t} \end{aligned}$$

$$|D^0\rangle = \frac{1}{2p}\left(|D_1\rangle + |D_2\rangle\right) \qquad |\overline{D}^0\rangle = \frac{1}{2q}\left(|D_1\rangle - |D_2\rangle\right)$$

$$\begin{aligned} |D^0(t)\rangle &= e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|D^0\rangle + \left(\frac{q}{p}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|\overline{D}^0\rangle\right\} \\ |\overline{D}^0(t)\rangle &= e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\left(\frac{p}{q}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|D^0\rangle + \cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|\overline{D}^0\rangle\right\} \end{aligned}$$

$$\overline{m} \equiv \frac{1}{2}\left(m_1+m_2\right) \qquad \overline{\Gamma} \equiv \frac{1}{2}\left(\Gamma_1+\Gamma_2\right) \qquad \Delta m \equiv m_2 - m_1 \qquad \Delta\gamma \equiv \Gamma_2 - \Gamma_1$$

Neutral meson mixing II

For $\Delta m\, t \ll 1$ and $\Delta\gamma t \ll 1$:

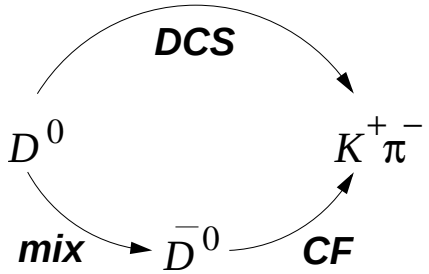
$$|\langle f|H|D^0(t)\rangle|^2 \;\propto\; e^{-\overline{\Gamma}t}\left\{1 \;+\; [\,y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\,](\overline{\Gamma}t) \;+\; |\lambda|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

$$|\langle \bar{f}|H|\overline{D}^0(t)\rangle|^2 \;\propto\; e^{-\overline{\Gamma}t}\left\{1 \;+\; \left[\,y\,\mathrm{Re}(\bar{\lambda}) - x\,\mathrm{Im}(\bar{\lambda})\,\right](\overline{\Gamma}t) \;+\; |\bar{\lambda}|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

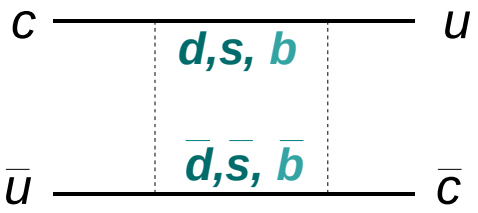
Direct ***Interference*** ***Mixing***

$$x \equiv \frac{\Delta m}{\overline{\Gamma}} \qquad y \equiv \frac{\Delta\Gamma}{2\overline{\Gamma}} \qquad \lambda \equiv \left(\frac{q}{p}\right)\frac{\mathcal{A}(\overline{D}^0 \to f)}{\mathcal{A}(D^0 \to f)} \qquad \bar{\lambda} \equiv \left(\frac{p}{q}\right)\frac{\mathcal{A}(D^0 \to \bar{f})}{\mathcal{A}(\overline{D}^0 \to \bar{f})}$$

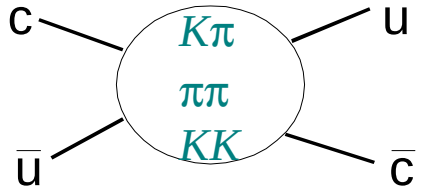
Mixing parameters *CPV enters here*



Neutral meson mixing III:



"box" diagram: Δm

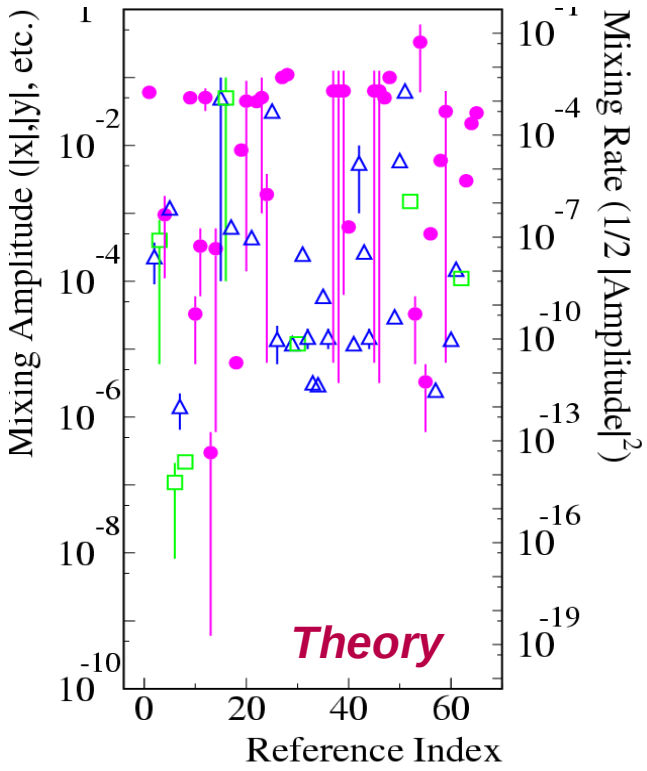


but mixing dominated by long-distance contributions (both Δm and $\Delta\Gamma$)

- *doubly-Cabibbo-suppressed w/r/t* Γ_D
- *GIM cancellation:* $V_{cd}^{*}V_{ud} + V_{cs}^{*}V_{us} + V_{cb}^{*}V_{ub} = 0$

Meson	flavors	$\Delta m/\Gamma$	$\Delta\Gamma/2\Gamma$	observed?
K^0	$\bar{s}d$	0.474	0.997	1958
B^0	$\bar{b}d$	0.77	$< 1\%$	1987
B_s^0	$\bar{b}s$	27	0.15 ± 0.07	2006
D^0	$c\bar{u}$	< 0.029	0.011 ± 0.005	March 2007

$$x \lesssim y \sim \begin{cases} 10^{-6} - 10^{-3} & \text{(short distance)} \\ 10^{-3} - 10^{-2} & \text{(long distance)} \end{cases}$$



D^0 mixing measurements


new

- **Wrong-sign semileptonic $D^0(t) \to K^+ l^- \nu$ decays**
  measures x^2+y^2, no DCS contamination


new

- **Wrong-sign hadronic $D^0(t) \to K^+\pi^-$ decays**
  measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$,
  where δ is a strong phase difference


new

- **Decays to *CP* eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$**
  measures $y\cos\phi$, where ϕ is a weak phase difference


new

- **Dalitz plot analysis of $D^0(t) \to K^0\pi^+\pi^-$ decays**
  measures x, y

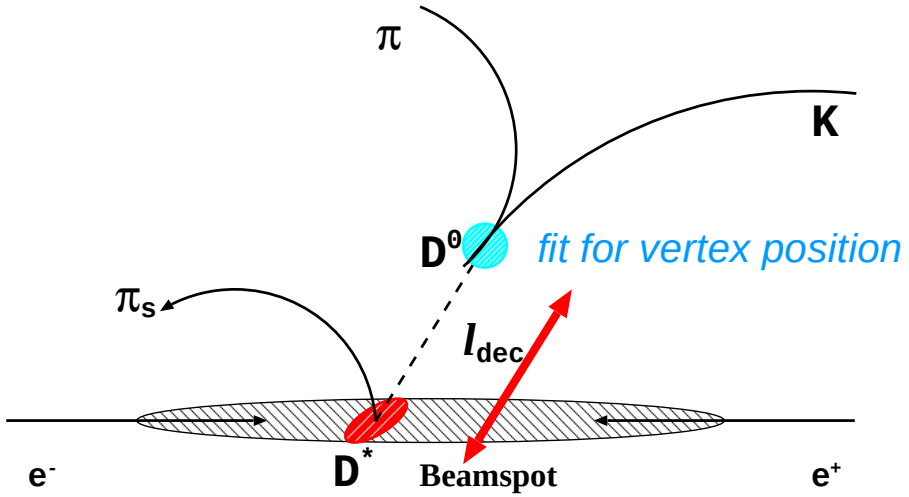
- **Wrong-sign hadronic $D^0 \to K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$ decays**
  measures x^2+y^2

- **Quantum correlations in $e^+e^- \to D^0\bar{D}^0(n\pi^0)$, $D^0\bar{D}^0\gamma(n\pi^0)$**
  measures y, $\cos\delta$

Experimental Method

- **Initial flavor of $D^0(t)$ is determined from $D^{*+} \to D^0\pi^+$ or $D^{*-} \to D^0\pi^-$**
  This also greatly reduces background: $Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi}$ only 6 MeV/c
  (very near threshold)

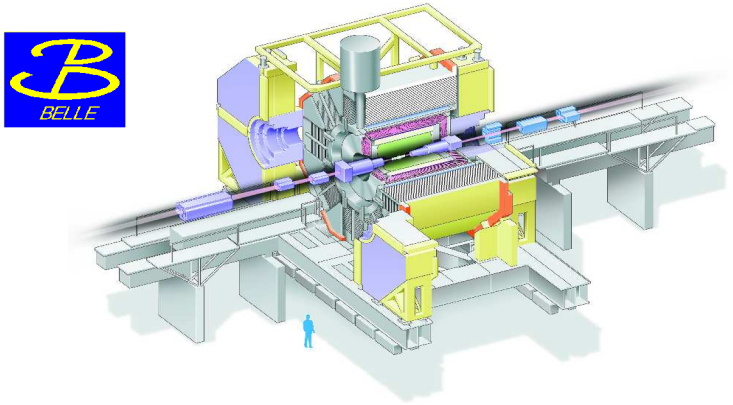
- **D^0 proper decay time $\Delta t = (l_{dec}/p) \times (m/c)$ measurement:**

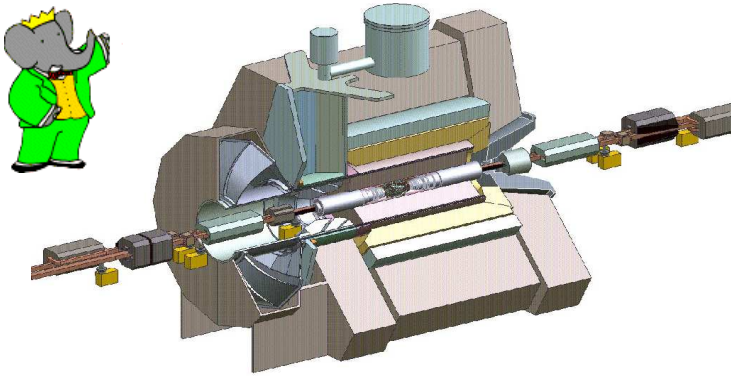


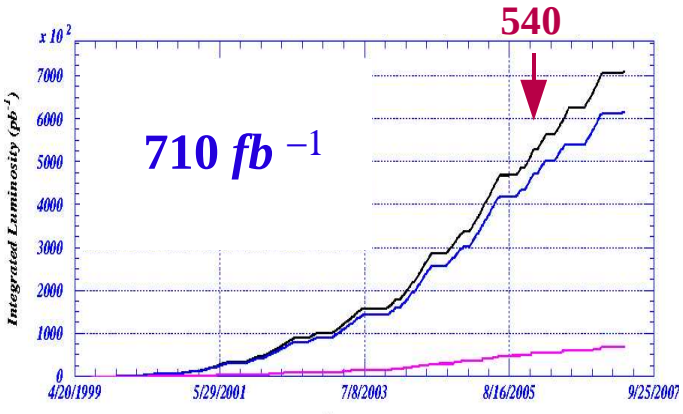
- **$p(D^*) > 2.5$ GeV to eliminate D^0's from B meson decay**
  (at $e^+e^- \to \Upsilon(4S)$ resonance, $\sigma(b\bar{b})/\sigma(\text{all}) = 1/3$)

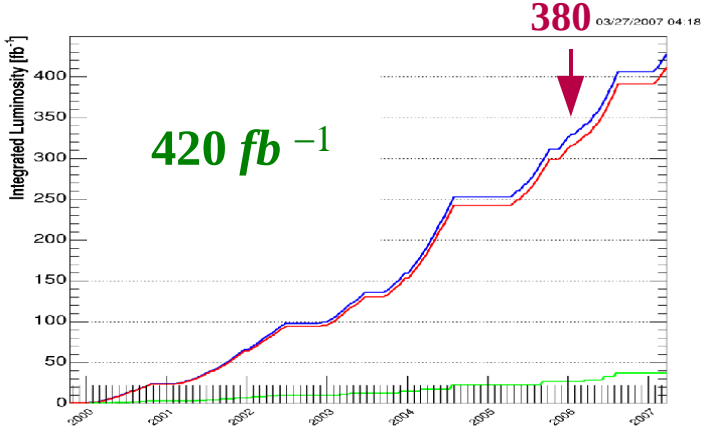
Belle (KEKB) and BaBar (PEPII)

$e^+e^- \rightarrow \Upsilon(4S) \rightarrow BB$









Detectors:

- ***Silicon strip detectors for good vertex resolution***
- ***Drift chamber for charged particle tracking and momentum measurement***
- ***Cherenkov detector (aerogel, DIRC) for K/π identification***
- ***Electromagnetic calorimeter for γ detection and electron ID***
- ***Solenoid flux return instrumented with RPCs, limited streamer tubes for μ detection***

CP eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$

Master formula: $R_{D^0(t)\to f} \propto e^{-\overline{\Gamma}t}\left\{1 + [\,y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\,](\overline{\Gamma}t)\right\}$

$$\lambda = \left(\frac{q}{p}\right)\frac{\mathcal{A}(\overline{D}^0 \to f)}{\mathcal{A}(D^0 \to f)}$$

$\boxed{D^0(t) \to K^-\pi^+}$ $\quad |\lambda| \ll 1 \Rightarrow R \propto e^{-\overline{\Gamma}t}$

$\boxed{D^0(t) \to K^+K^- \text{ (or } \pi^+\pi^-)}$ $\quad |\lambda| \approx 1 \Rightarrow R \propto e^{-\overline{\Gamma}t}(1 - y\cos\phi\,\overline{\Gamma}t)$

$$\approx e^{-\overline{\Gamma}t}\, e^{-y\cos\phi\,\overline{\Gamma}t}$$
$$= e^{-\overline{\Gamma}(1+y\cos\phi)\,t}$$

$$\Rightarrow \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} = 1 + y\cos\phi$$

So $\boxed{y\cos\phi \equiv y_{CP} = \dfrac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1}$

E791, PRL 83, 32 (1999)
FOCUS, PLB 485, 62 (2000)
CLEO, PRD 65, 092001 (2002)
Belle, PRL 88, 162001 (2002)
Babar, PRL 91, 121801 (2003)

$y_{CP} = (1.09 \pm 0.46)\%$

(world average)

Belle: $D^0(t) \to K^+K^-, \pi^+\pi^-$ with 540 fb^{-1}

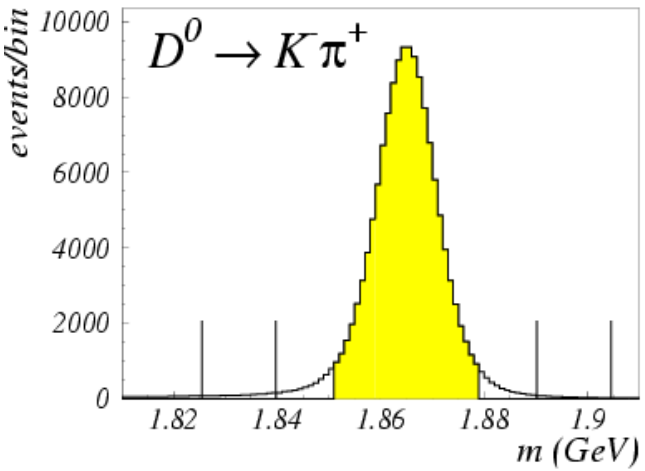
PRL 98, 211803 (2007)

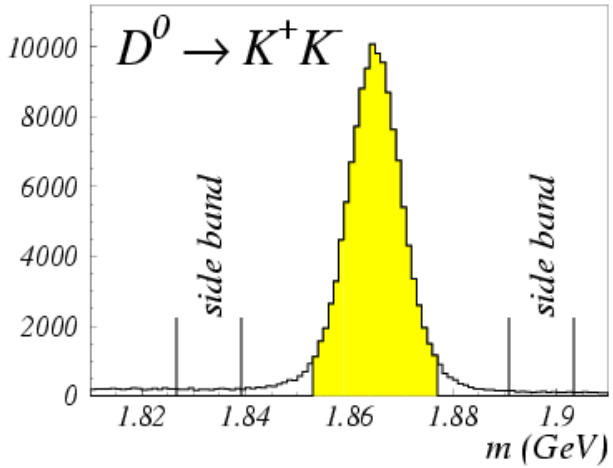
$D^{+*} \to D^0 \pi^+$
$\quad\quad \hookrightarrow K^+K^-, \pi^+\pi$

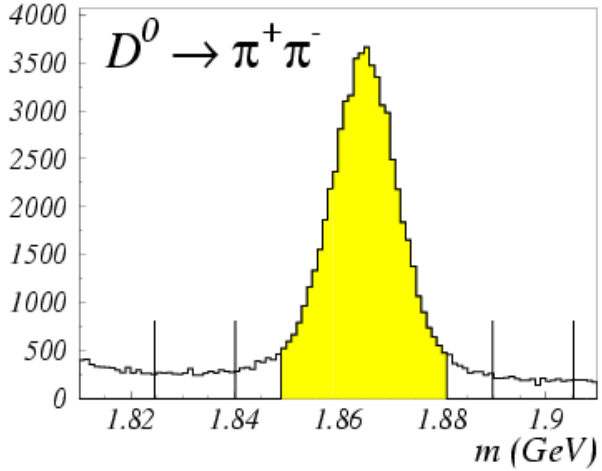
$m(D^0) = 1865$ MeV
$m(\pi^+) = 139$
$m(D^{*+}) = 2010$

} 2004 MeV

Select candidate events: **require $q = m(KK\pi) - m(D^0) - m(\pi)$ to be very small:**







1200k events
99% pure

110k events
98% pure

50k events
92% pure

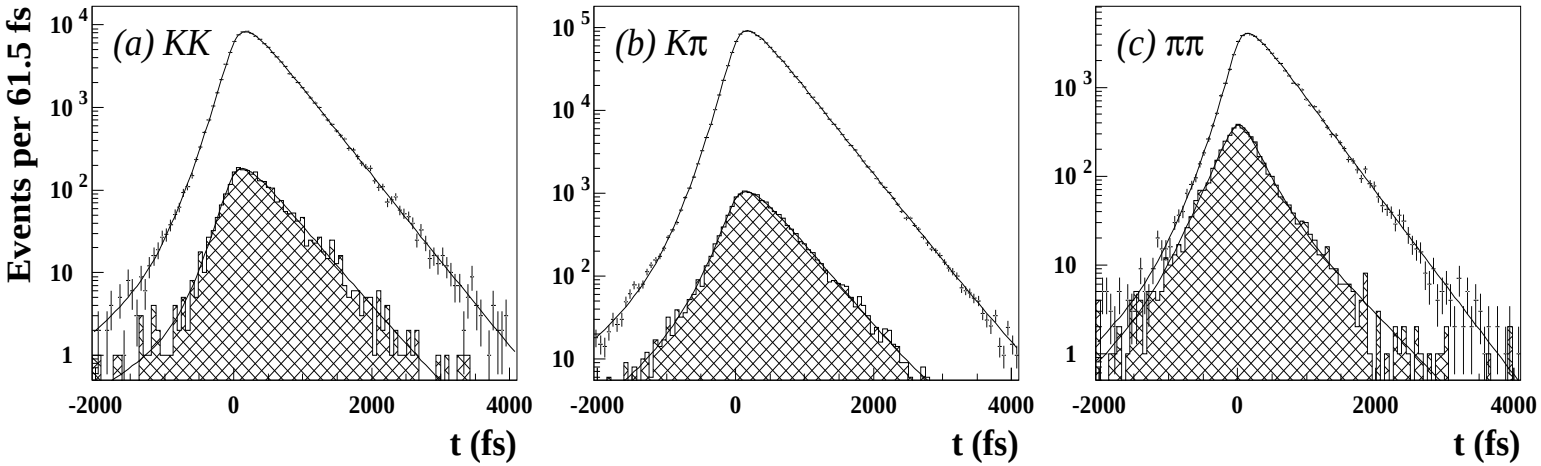
Belle: $D^0(t) \to K^+K^-, \pi^+\pi^-$ with 540 fb^{-1}

Maximum likelihood fit to decay time spectrum:

$$\frac{dN}{dt} = \frac{N}{\tau} e^{-t/\tau} \otimes R(t) + B(t)$$

resolution function

background distribution



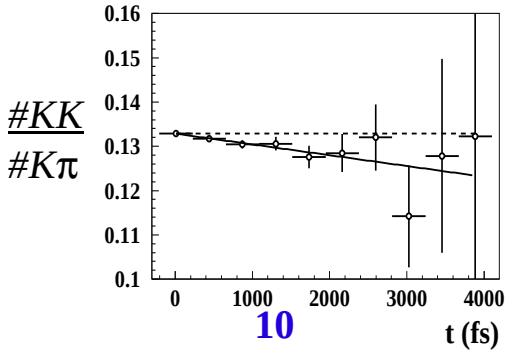
$\tau = 403.2 \pm 1.4$ fs (110k events)

$\tau = 408.6 \pm 0.7$ fs (1200k events)

$\tau = 402.5 \pm 2.2$ fs (50k events)

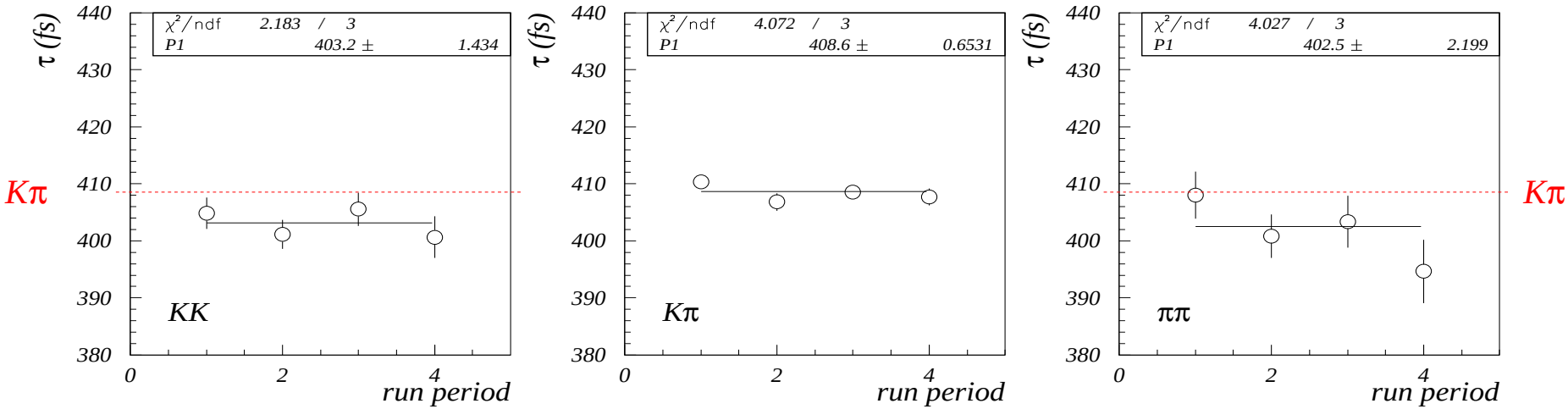
⇒ **there is a difference between *KK* and *Kπ***

(here, t0 is free for Kπ)

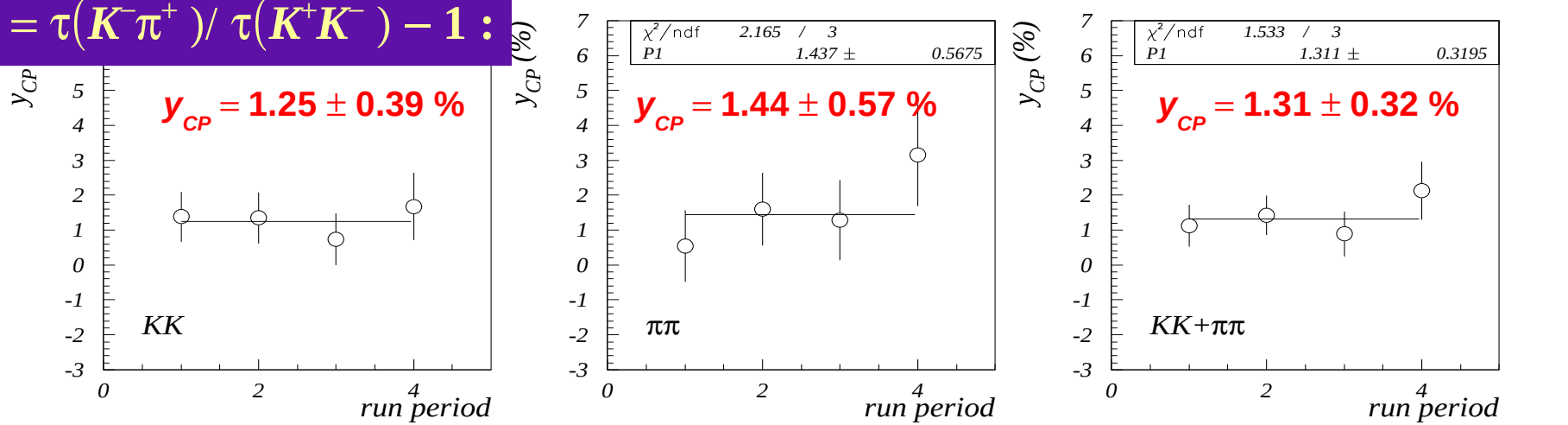


Belle: $D^0(t) \to K^+K^-, \pi^+\pi^-$ with 540 fb^{-1}

A cross-check: divide the data into sub-samples



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



Belle: $D^0(t) \to K^+K^-, \pi^+\pi^-$ with 540 fb^{-1}

Systematic errors:	y_{CP}	A_Γ
acceptance	0.12%	0.07%
equal t_0 assumption	0.14%	0.08%
mass window position	0.04%	0.003%
difference btw background and sidebands	0.09%	0.06%
difference btw final states opening angles	0.02%	
background parameterization	0.07%	0.07%
resolution function	0.01%	0.01%
analysis cuts	0.11%	0.05%
binning	0.01%	0.01%
TOTAL	**0.25%**	**0.15%**

Final result:

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

> 3 σ above zero
(first evidence for D^0-D^0 mixing)

Search for CP violation:

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

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

no evidence for CP violation

Dalitz plot analysis of $D^0(t) \to K^0 \pi^+\pi^-$

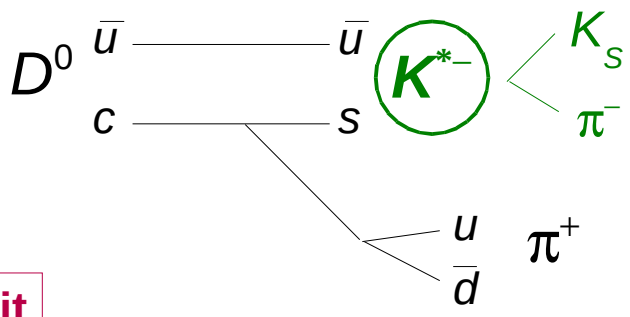
$$\langle K^0_S \pi^+\pi^- | H | D^0(t) \rangle = \frac{1}{2p}\left(\langle K^0_S \pi^+\pi^- | H | D_1(t) \rangle + \langle K^0_S \pi^+\pi^- | H | D_2(t) \rangle \right)$$
$$\equiv A_1 \, e^{-(\Gamma_1/2 + i m_1)\, t} + A_2 \, e^{-(\Gamma_2/2 + i m_2)\, t}$$

$$R(D^0(t) \to K^0_S \pi^+\pi^-) = |A_1|^2 \, e^{-\bar{\Gamma}(1+y)t} + |A_2|^2 \, e^{-\bar{\Gamma}(1-y)t} +$$
$$2e^{-\bar{\Gamma}t}\left[\mathrm{Re}(A_1 A_2^*) \cos xt - \mathrm{Im}(A_1 A_2^*) \sin xt \right]$$

$$A_n \propto \sum_j a_j \, e^{i\delta_j} \mathcal{A}^j$$

NOTE: sign of x is determined

The amplitudes A^j are functions of $m^2(K_S \pi^+)$ and $m^2(K_S \pi^-)$ and account for various intermediate states:



Each amplitude has a magnitude (a_j) and phase (δ_j)

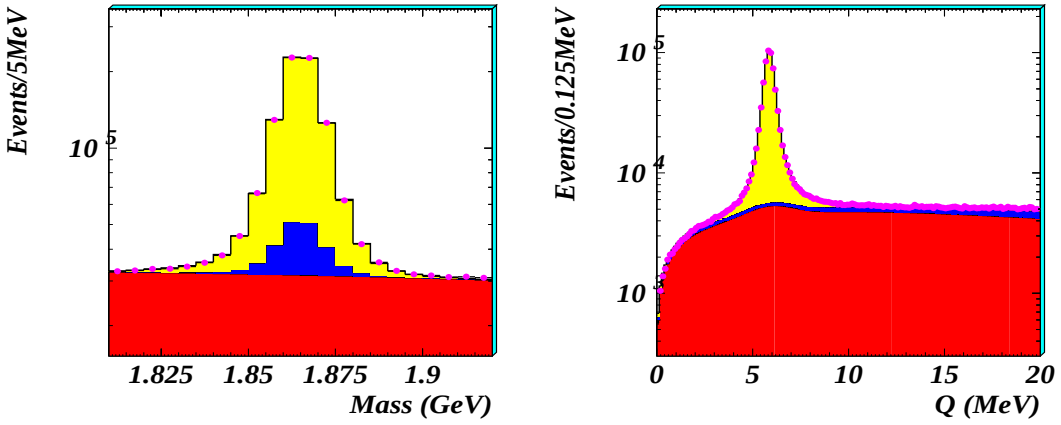
⇒ must include these parameters (36 of them) in the fit

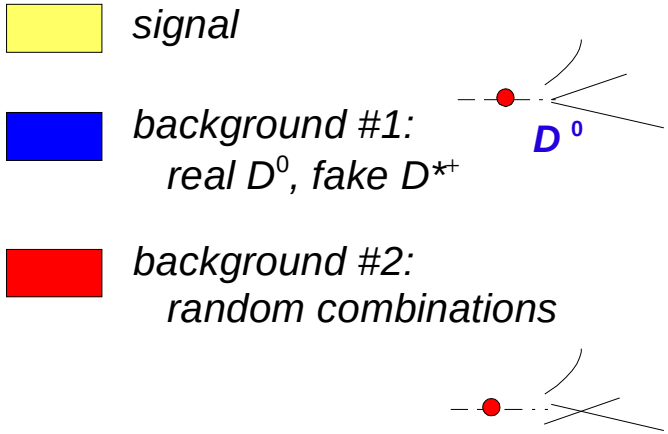
Belle: $D^0(t) \to K_S^0 \pi^+\pi^-$ with 540 fb^{-1}

arXiv:0704.1000
(submitted to PRL)

$$D^{+*} \to D^0 \pi^+$$
$$\hookrightarrow K_S \pi^+\pi$$

Select candidate events based on $m(K\pi\pi)$, $q = m(K\pi\pi\pi) - m(D^0) - m(\pi)$:

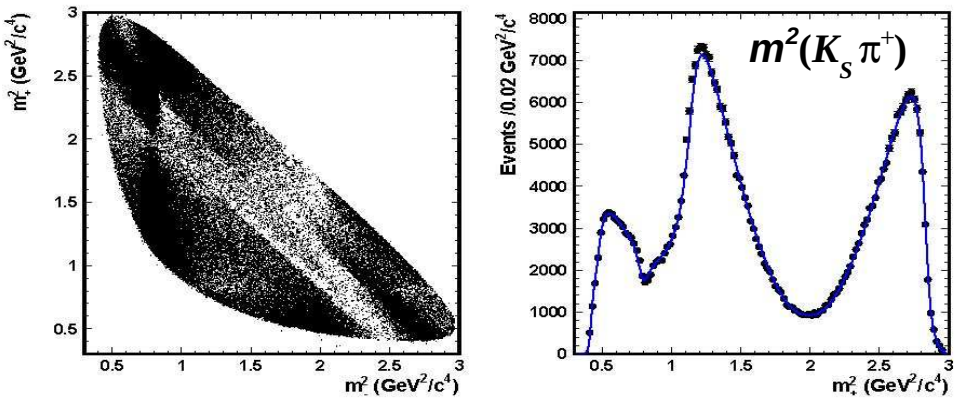




534k events

95% pure

Belle: $D^0(t) \to K_S^0 \pi^+ \pi^-$ with 540 fb^{-1}



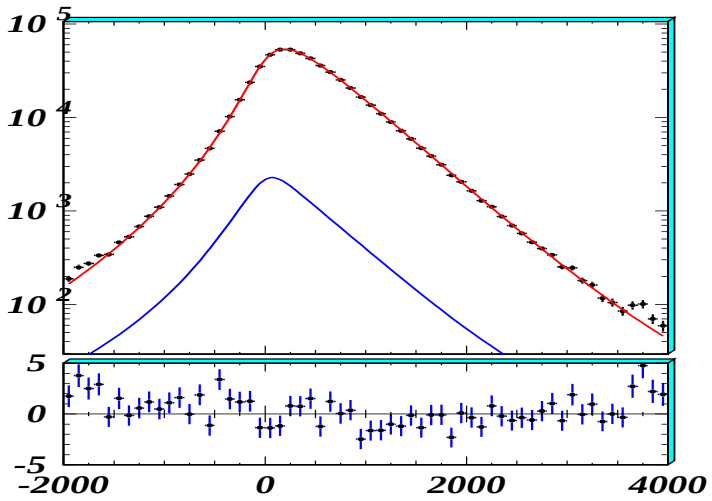
Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 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

1.19

$$\text{Fit fraction} \equiv \frac{\int |a_r \mathcal{A}_r(m_-^2, m_+^2)|^2 \, dm_-^2 \, dm_+^2}{\int |\sum_{r=1}^{n} a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2)|^2 \, dm_-^2 \, dm_+^2}$$

Belle: $D^0(t) \to K_S^0 \pi^+ \pi^-$ with 540 fb^{-1}

Time fit (in projection):



$x = (0.80 \pm 0.29)\%$ *positive*

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

$t_D = (409.9 \pm 0.9)$ fs

consistent with PDG (in fact better precision)

Largest systematic errors:	Δx (x 10^{-2})	Δy (x 10^{-2})
$p(D^*)$ cut	+0.076	–0.078
t dependence of Dalitz background	–0.056	–0.057
background timing parameters	±0.037	±0.063
decay model (form factors, variation of fixed masses & widths, K-matrix, no non-resonant comp., others)	+0.13 –0.11	+0.051 –0.066
TOTAL	**(+0.17, –0.15)**	**(+0.10, –0.15)**

Belle: $D^0(t) \to K_S^0 \pi^+\pi^-$ with 540 fb^{-1}

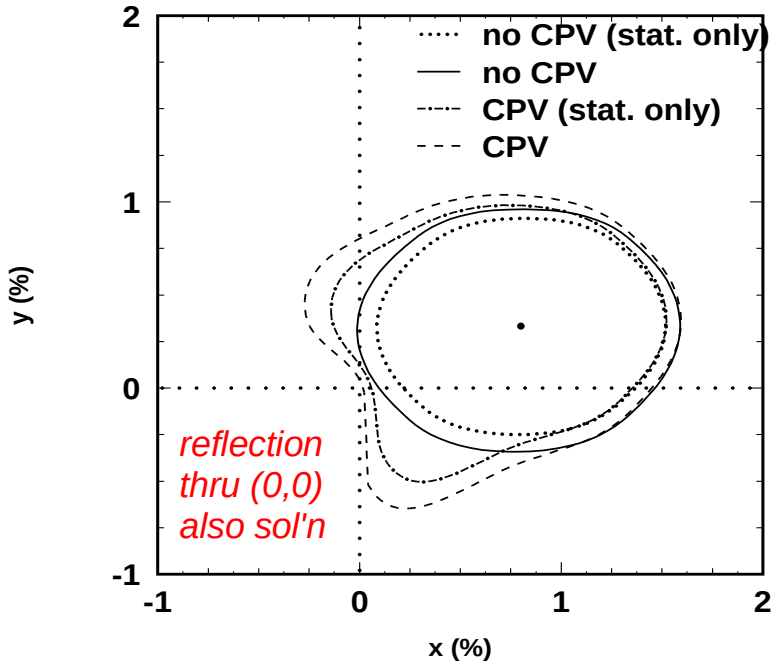
Preliminary result:

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

systematics: scale by sqrt(1+r²)
$(1/r)^2 = (\cos\theta/\Delta x)^2 + (\sin\theta/\Delta y)^2$

rise of the likelihood function at (0,0) which corresponds to no mixing:

$-2\Delta \ln \mathcal{L} = 7.33 \Rightarrow$ CL= only 2.6%



Allow for CPV:

$$e_{(1,2)} \equiv e^{-i(m_{(1,2)} - i\Gamma_{(1,2)}/2)t}$$

$$\mathcal{M}(m_-^2, m_+^2, t) = \mathcal{A}(m_-^2, m_+^2)\frac{e_1(t) + e_2(t)}{2} + \left(\frac{q}{p}\right)\overline{\mathcal{A}}(m_-^2, m_+^2)\frac{e_1(t) - e_2(t)}{2}$$

$$\overline{\mathcal{M}}(m_-^2, m_+^2, t) = \overline{\mathcal{A}}(m_-^2, m_+^2)\frac{e_1(t) + e_2(t)}{2} + \left(\frac{p}{q}\right)\mathcal{A}(m_-^2, m_+^2)\frac{e_1(t) - e_2(t)}{2}$$

CPV result: (preliminary)

$$x = (0.81 \pm 0.30\ ^{+0.13}_{-0.17})\% \qquad |q/p| = 0.86\ ^{+0.30}_{-0.29}$$
$$y = (0.37 \pm 0.25\ ^{+0.10}_{-0.15})\% \qquad \arg(q/p) = -14\ ^{+16}_{-18}$$

no dcpv →

$$|q/p| = 0.95\ ^{+0.22\ +0.10}_{-0.20\ -0.09}$$
$$\arg(q/p) = (-2\ ^{+10}_{-11} \pm 5\ )^\circ$$

Wrong-sign $D^0(t) \to K^+\pi^-$ decays

Master formula:

$$R(D^0(t)\to f) \;\propto\; e^{-\overline{\Gamma}t}\left\{1 \;+\; [\,y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\,]\,(\overline{\Gamma}t) + |\lambda|^2\frac{x^2+y^2}{4}(\overline{\Gamma}t)^2\right\}$$

for $f = K^+\pi^-$: $\quad \lambda \;\equiv\; \dfrac{q}{p}\dfrac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \;=\; \left|\dfrac{q}{p}\right|\sqrt{R_D}\,e^{i(\phi+\delta)}$ $\qquad \begin{cases} \delta & \textit{strong phase} \\ \phi & \textit{weak phase} \end{cases}$

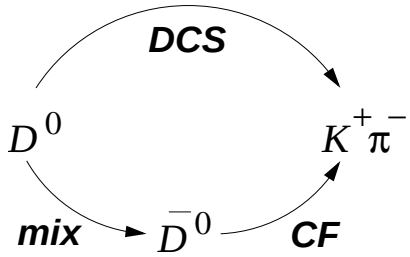
$$R(D^0\to K^+\pi^-) \;\propto\; e^{-\overline{\Gamma}t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}\,[\,y\,\cos(\phi+\delta) - x\,\sin(\phi+\delta)\,]\,(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

$$= \; e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}(y\cos\delta - x\sin\delta)(\overline{\Gamma}t) + \frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\} \qquad \left(\begin{array}{c}|q/p| = 1\\ \phi = 0\end{array}\right)$$

no CPV

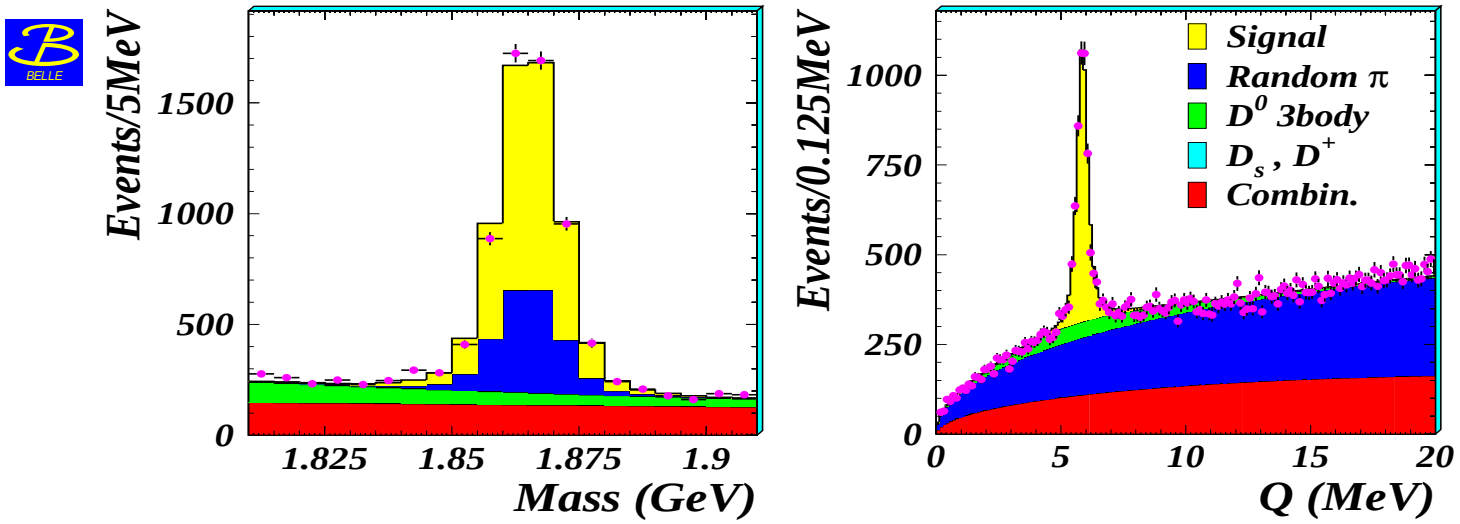
$$= \boxed{\; e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}\,y'\,(\overline{\Gamma}t) + \frac{(x'^2+y'^2)}{4}\,(\overline{\Gamma}\,t)^2\right\}}$$

$$(\; x' \equiv \; x\cos\delta + y\sin\delta \qquad\qquad y' \equiv \; y\cos\delta - x\sin\delta \;)$$



Belle $D^0(t) \to K^+\pi^-$ with 400 fb^{-1}

R.Barate *et al.* (ALEPH), PLB 436, 211 (1998)
E.M.Aitala *et al.* (E791), PRD 57, 13 (1998)
R.Godang *et al.* (CLEO), PRL 84, 5038 (2000)
J.M.Link *et al.* (FOCUS), PRL 86, 2955 (2001); PLB 618, 23 (2005)
B. Aubert *et al.* (Babar), PRL 91, 171801 (2003)
L.Zhang *et al.* (Belle), PRL 96, 151801 (2006)
new → B. Aubert *et al.* (Babar), PRL 98, 211802 (2007)



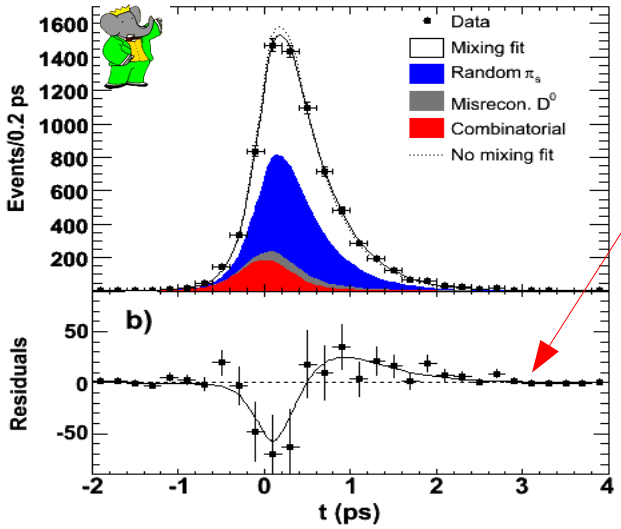
4024 events

52% purity

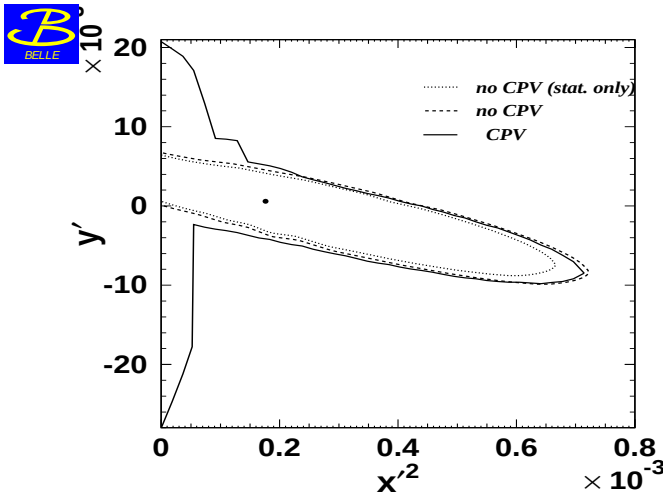
$D^0(t) \to K^+\pi^-$ (Belle and BaBar)

PRL 96, 151801 (2006)
PRL 98, 211802 (2007)

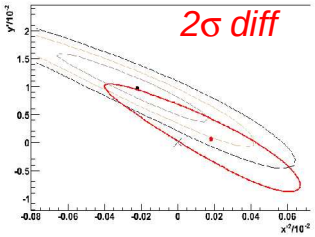
Time fit:



difference between mixing and no-mixing curves matches the no-mixing residuals



(x',y') = (0,0) has CL = 3.9%



BELLE

400 fb^{-1}

$R_D = (0.364 \pm 0.017)\%$

$x'^2 = (0.018\ ^{+0.021}_{-0.023})\%$

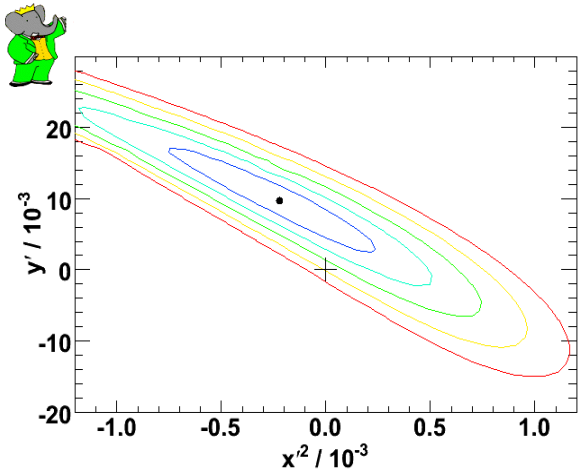
$y' = (0.06\ ^{+0.40}_{-0.39})\%$ *no CPV*

384 fb^{-1}
new
(hep-ex/0703020)

$R_D = (0.303 \pm 0.019)\%$

$x'^2 = (-0.022 \pm 0.037)\%$

$y' = (0.97 \pm 0.54)\%$ *no CPV*



(x',y') = (0,0) has CL = 0.01%

evidence for mixing

Belle $D^0(t) \to K^+\pi^-$ allowing for CPV

$$\lambda = \left(\frac{q}{p}\right)\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f} = \left|\frac{q}{p}\right|\sqrt{R_D}\, e^{i(\phi+\delta)} \qquad \bar{\lambda} = \left(\frac{p}{q}\right)\frac{\mathcal{A}_{\bar{f}}}{\overline{\mathcal{A}}_{\bar{f}}} = \left|\frac{p}{q}\right|\sqrt{\overline{R}_D}\, e^{i(-\phi+\delta)}$$

$$R_{D^0\to f} \propto e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}\left|\frac{q}{p}\right|(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2\right\}$$

$$R_{\overline{D}^0\to \bar{f}} \propto e^{-\overline{\Gamma}t}\left\{\overline{R}_D + \sqrt{\overline{R}_D}\left|\frac{p}{q}\right|(y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2\right\}$$

$A_D \equiv (R_D - \overline{R}_D)/(R_D + \overline{R}_D) \neq 0$	CPV in the decay amplitude (direct CPV)
$A_M \equiv (\lvert q\rvert^4 - \lvert p\rvert^4)/(\lvert q\rvert^4 + \lvert p\rvert^4) \neq 0$	CPV in mixing
$\phi \neq 0$	CPV in mixed/direct interference

6 total parameters; in practice, we fit for $\overline{R}_D$, R_D and

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4}(x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4}(y'\cos\phi \mp x'\sin\phi)$$

from these we calculate A_D, A_M, ϕ, x' and y' **(note sign ambiguity for $x'^{\pm}$)**

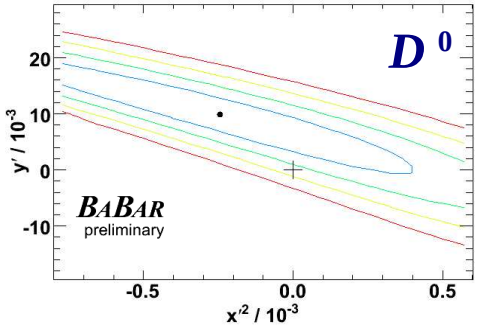
Belle $D^0(t) \to K^+\pi^-$ allowing for CPV, BaBar

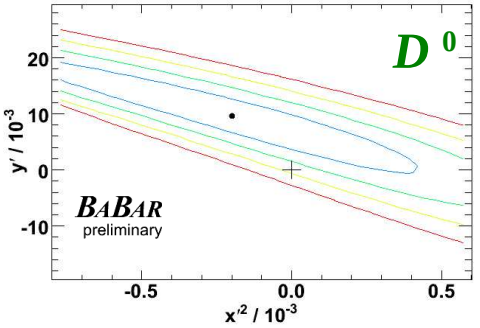
$x'^{+2} = (-0.024 \pm 0.043 \pm 0.030)\%$ $\quad y'^{+} = (0.98 \pm 0.64 \pm 0.45)\%$

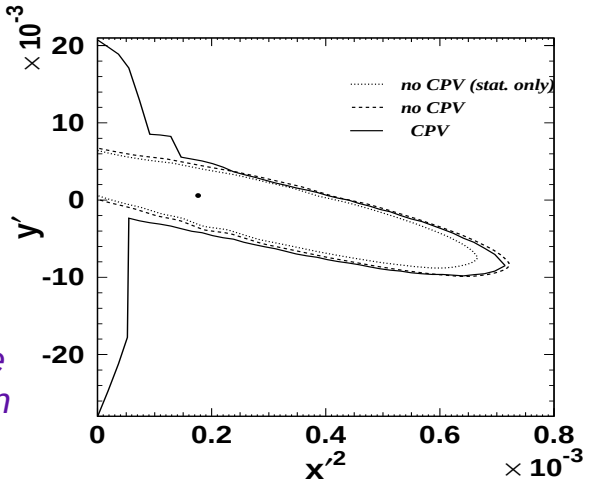
$x'^{-2} = (-0.020 \pm 0.041 \pm 0.029)\%$ $\quad y'^{-} = (0.96 \pm 0.61 \pm 0.43)\%$

$A_D = (-2.1 \pm 5.2 \pm 1.5)\%$

} no evidence of CPV



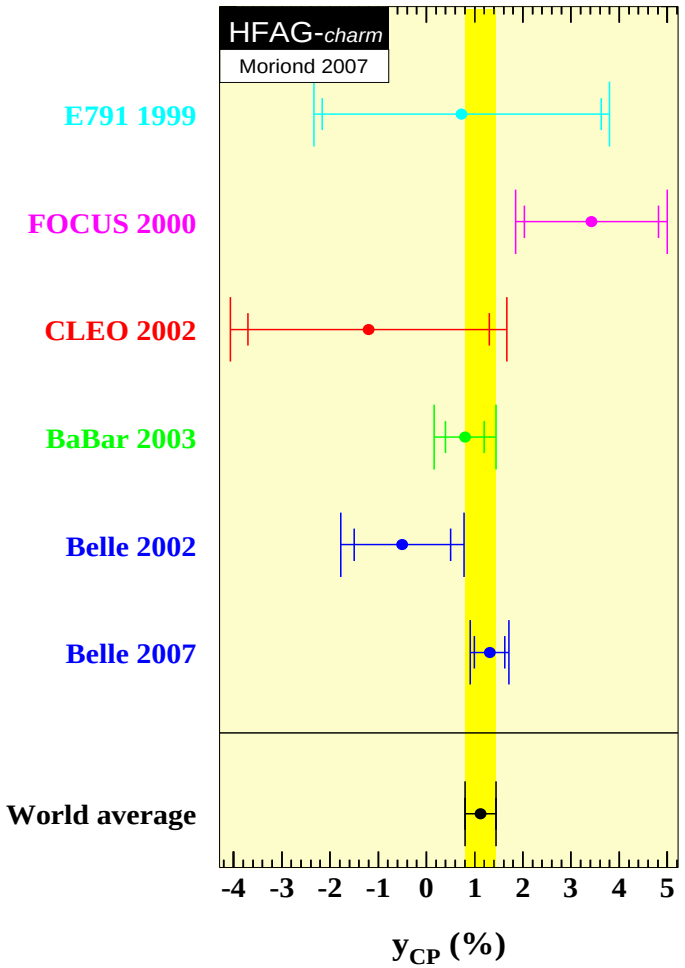


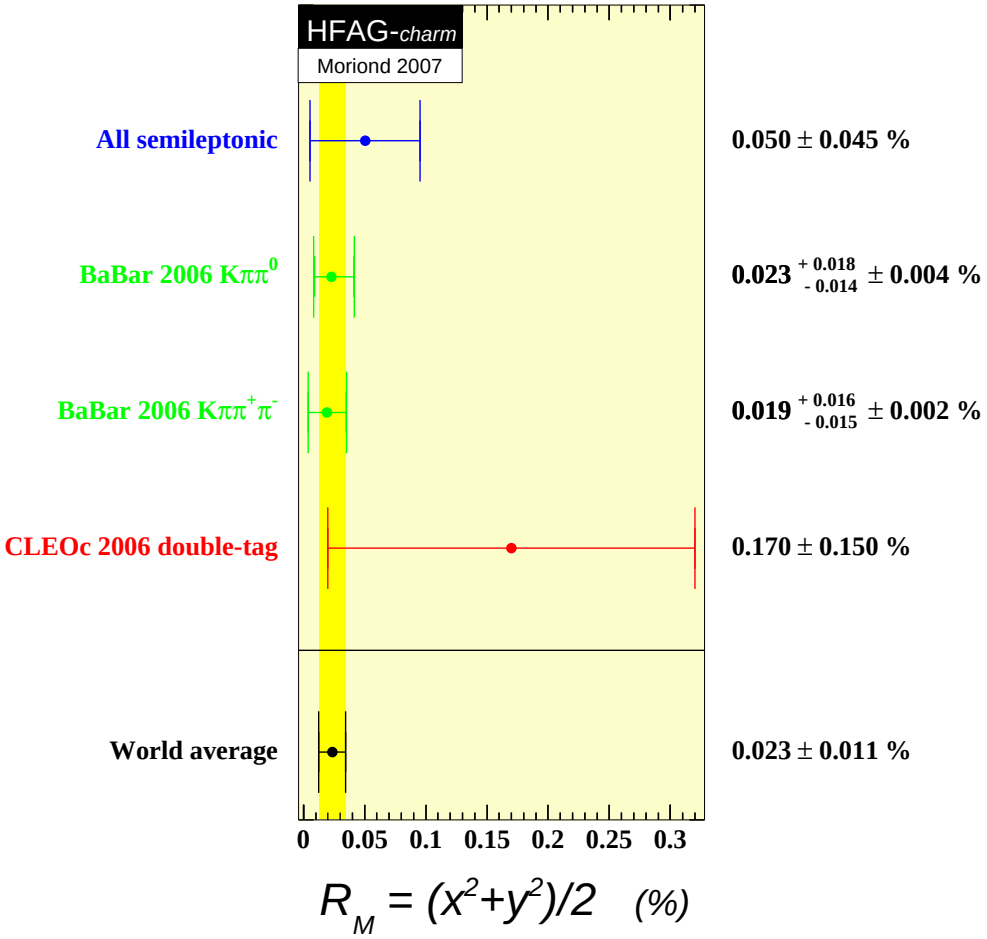


unusual contour due to 2-fold ambiguity in sign(x'$^+$)(x'$^-$)

Fit Case	Parameter	95% CL interval ($\times 10^{-3}$)
No CPV	x'^2	$x'^2 < 0.72$
	y'	$-9.9 < y' < 6.8$
	R_D	$3.3 < R_D < 4.0$
	R_M	$0.63 \times 10^{-5} < R_M < 0.40$
CPV allowed	A_D	$-76 < A_D < 107$
	A_M	$-995 < A_M < 1000$
	x'^2	$x'^2 < 0.72$
	y'	$-28 < y' < 21$
	R_M	$R_M < 0.40$

What have we learned?



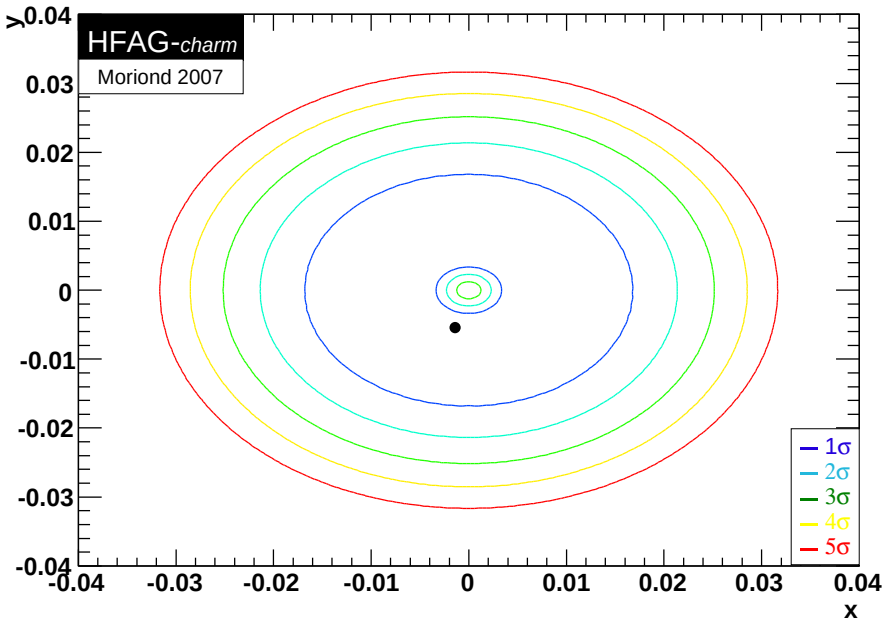


(http://www.slac.stanford.edu/xorg/hfag/charm/index.html)

Combining all measurements – no CPV

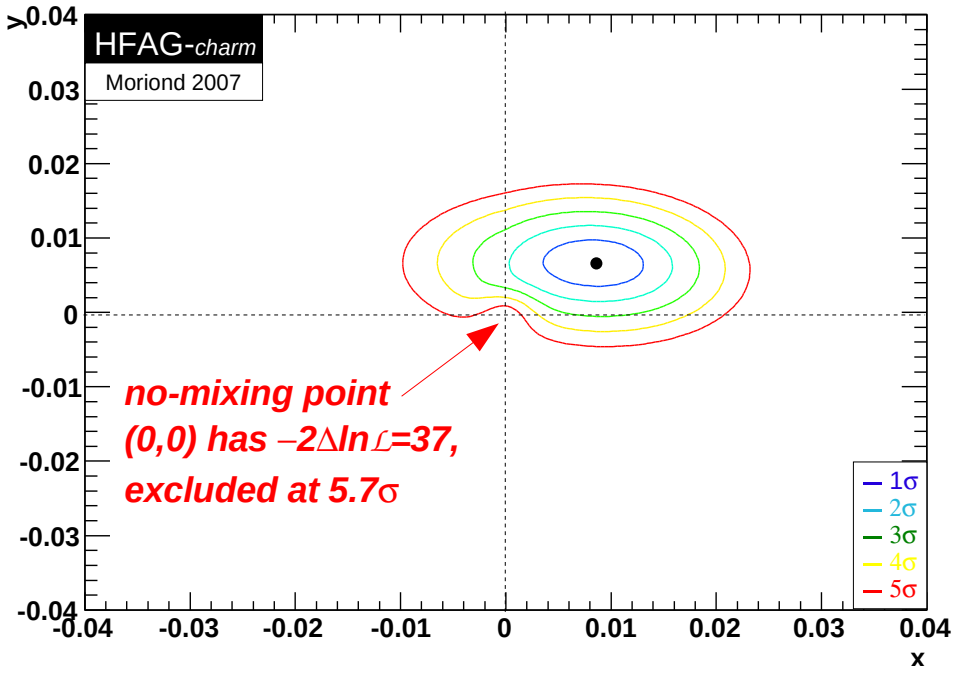
ln$\mathcal{L}(R_D, x'^2, y')$ for $D^0(t) \to K^+\pi^-$ measurements:

- *project onto (x'^2, y') plane by allowing R_D to always take its preferred value*
- *map likelihood values to (x,y,δ) volume*
- *project onto (x,y) plane by allowing δ to always take its preferred value:*



–2 ln $\mathcal{L}$

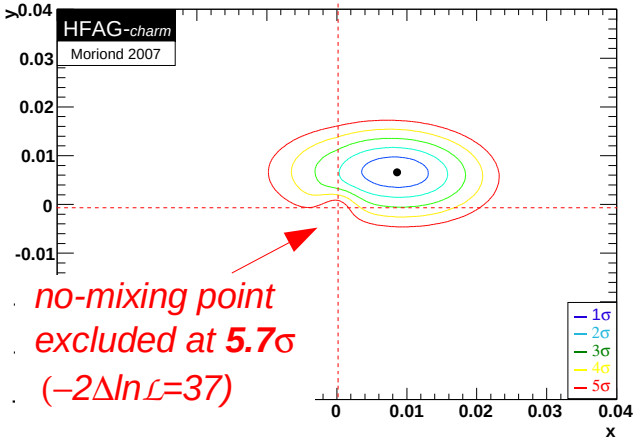
Adding –2ln $\mathcal{L}$ functions from $K^+\pi^-$, semileptonic decays, $K_S\pi^+\pi^-$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$:



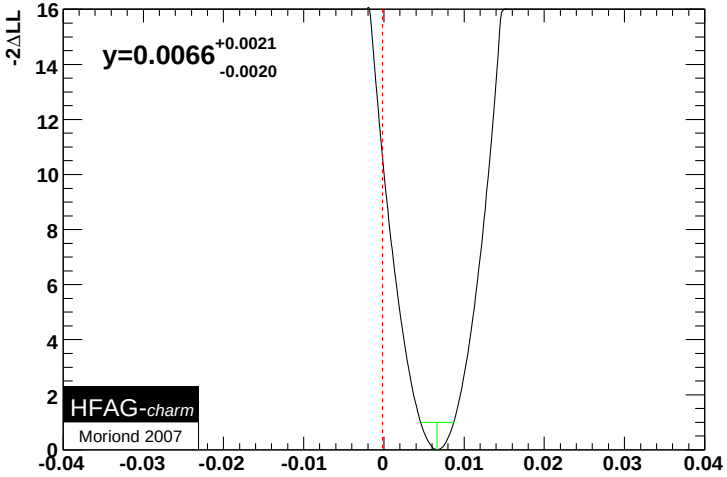
–2 ln $\mathcal{L}$

Summary (no CPV)

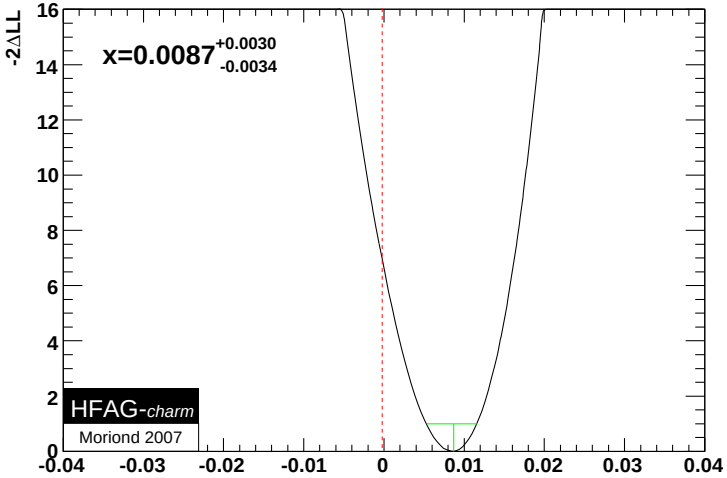
All data [semileptonic decays, $K^+\pi^-$, $K_S\pi\pi$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$]:



*no-mixing point excluded at **5.7**σ (–2Δln$\mathcal{L}$=37)*



y projection



x projection

$x = (0.87\ ^{+0.30}_{-0.34})\%$
(2.6σ above zero)

$y = (0.66 \pm 0.21)\%$
(3.2σ above zero)

Conclusions:

Evidence is consistent and convincing that D^0's mix; effect is dominated by non-perturbative processes. Unless |x|>>|y|, may be hard to identify new physics.

Since y_{CP} is positive, CP-odd state is longer-lived (like other neutral meson systems); but positive x/y implies CP-odd is lighter

No evidence for CPV (considered a true sign of NP)

Combining all measurements – allowing for CPV

$D^0(t) \to K^+ l^- \nu$, $K^+\pi\pi$, $K^+\pi\pi\pi$:

$$R_M = \frac{1}{2}(x^2 + y^2)$$

$D^0(t) \to K^+K^-$, $\pi^+\pi^-$:

$$2y_{CP} = \left(|q/p| + |p/q|\right) y\cos\phi - \left(|q/p| - |p/q|\right) x\sin\phi$$
$$2A_\Gamma = \left(|q/p| - |p/q|\right) y\cos\phi - \left(|q/p| + |p/q|\right) x\sin\phi$$

$D^0(t) \to K_S\pi^+\pi^-$:

$$x_{K^0\pi\pi} = x$$
$$y_{K^0\pi\pi} = y$$

$$|q/p|_{K^0\pi\pi} = |q/p|$$
$$\mathrm{Arg}\,(q/p)_{K^0\pi\pi} = \phi$$

$D^0(t) \to K^+\pi^-$:

$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi) \qquad A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$
$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi) \qquad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

13 observables,
7 underlying parameters
⇒ MINUIT fit

$$\frac{1}{2}\left[R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)\right] = R_D$$

$$\frac{R(D^0 \to K^+\pi^-) - \overline{R}(\overline{D}^0 \to K^-\pi^+)}{R(D^0 \to K^+\pi^-) + \overline{R}(\overline{D}^0 \to K^-\pi^+)} = A_D$$

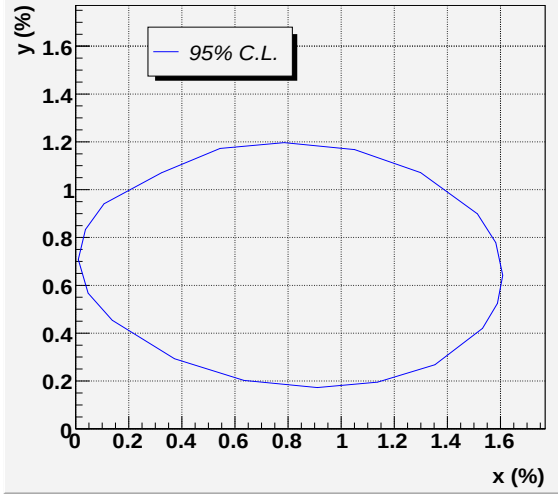
Combining all measurements – allowing CPV (cont'd)

MINUIT preliminary:

FCN= 16.25622 FROM MINOS STATUS=SUCCESSFUL 1302 CALLS 1649 TOTAL
EDM= 0.11E-04 STRATEGY= 1 ERROR MATRIX ACCURATE

EXT PARAMETER NO.	NAME	VALUE	PARABOLIC ERROR	MINOS ERRORS NEGATIVE	POSITIVE	
1	x	0.84868%	0.34165	–0.33549	0.32270	*tiny change*
2	y	0.69453%	0.16558	–0.21093	0.20730	
3	delta	0.39985	0.21088	–0.28525	0.26413	
4	Rd	0.33499%	0.13034E-01	–0.13035E-01	0.13035E-01	
5	Ad	0.40591	3.5452	–3.5477	3.5428	
6	q/p	0.87321	0.19001	–0.19976	0.23345	*no CPV (yet)*
7	phi	–0.82871E-01	0.15484	–0.19215	0.16715	

χ^2/dof = 16.2/18 = 0.90; largest contributions are from Belle/BaBar R_D difference and small "tension" between y_{CP} and $y(K_S\pi\pi)$



Wrong-sign $D^0(t) \to K^{(*)+} l^- \nu$ decays

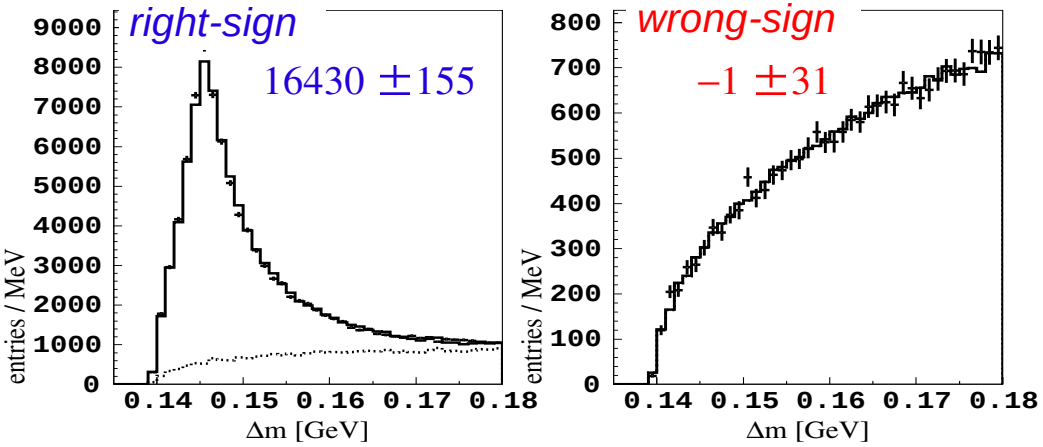
E.M.Aitala *et al.* (E791), PRL 77, 2384 (1996): 2504 RS events
B. Aubert *et al.* (Babar), PRD 70, 091102 (2004): 49620 RS events
U. Bitenc *et al.* (Belle), PRD 72, 071101 (2005): 229452 RS events
new → B. Aubert *et al.* (Babar), arXiv:0705.0704: 4780 RS events

Method: *flavor at production tagged via* $D^{*+} \to D^0 \pi^+$ *(pion charge)*
flavor at decay tagged via $D^0(t) \to K^{(*)+} l^- \nu$ *(lepton charge)*

$\Rightarrow$ *mixing signal is* $\pi^+ l^-$ *or* $\pi^- l^+$ *("wrong-sign"), normalize sens. to* $\pi^+ l^+$ *or* $\pi^- l^-$ *("right-sign")*

ν **momentum:** $P_\nu = P_{cms} - P_{\pi Ke} - P_{rest}$ $|P_{rest}|$ *adjusted to give* $(P_{cms} - P_{rest})^2 = m_{D^*}^2$
$\vec{p}_{rest}$ *direction adjusted to give* $m_\nu^2 = 0$

Fit: $\Delta m = m_{K\pi e\nu} - m_{Ke\nu}$:



$$r_D \equiv \frac{\int \mathcal{P}(D^0 \to K^+ \ell^- \bar{\nu}_\ell)\, dt}{\int \mathcal{P}(D^0 \to K^- \ell^+ \nu_\ell)\, dt} \approx \frac{x^2 + y^2}{2}$$

253 fb^{-1}

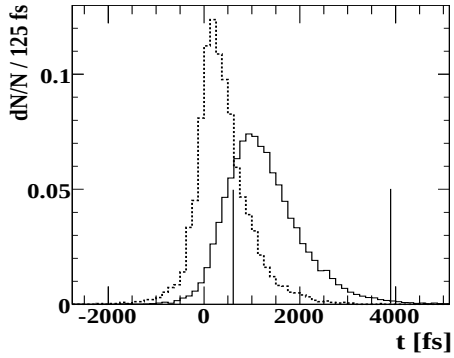
$R_M = (0.020 \pm 0.049)\%$
$< 0.10\%$ at 90% CL
$(|x|, |y| < 4.5\%)$

Wrong-sign $D^0(t) \to K^{(*)+} l^- \nu$ decays (arXiv:0705.0704)

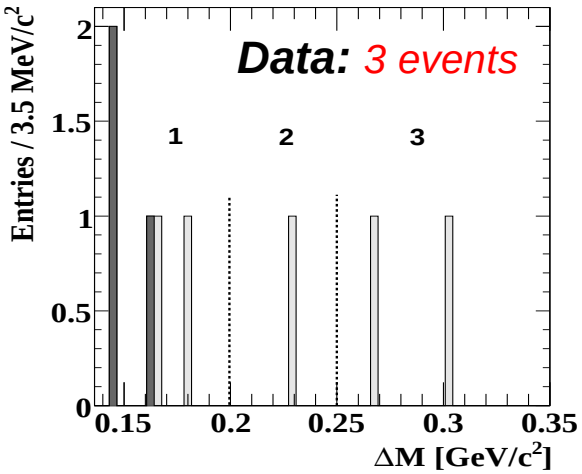
new

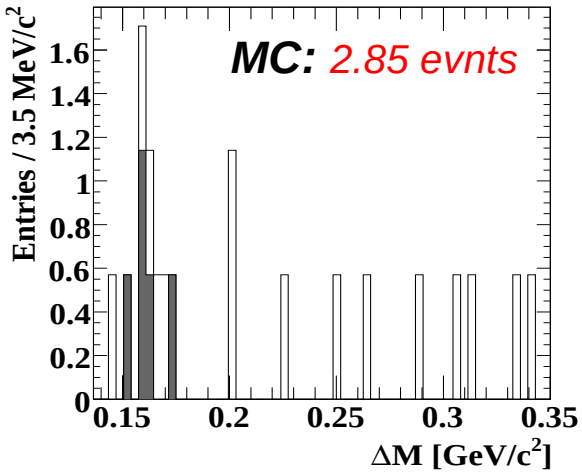
344 fb^{-1}, make many selection cuts to eliminate background:

- *Fully reconstruct D decay on opposite side ("double-tagging") 0.10 effic*
- *Neural network selection based on p_π, p_{Ke}, thrust axis, opening angles*
- *p_e > 600 MeV/c, π_s p_T and P_L selection 0.72 effic*
- *lifetime must be in the range 600 –3900 fs (1.5τ_D– 9.5 τ_D) 0.80 effic*



Determine "signal" yield by counting events; background estimate comes from MC sample:





(shaded histogram: after π_s p_T and P_L selection)

Determine confidence intervals from rise of likelihood function:

$$R_M = (0.004\ ^{+0.070}_{-0.060})\% = (-0.13, 0.12)\% \text{ at 90\% CL}$$