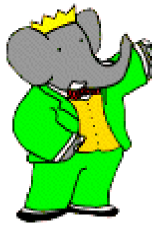
Evidence for D^0-$\bar{D}^0$ mixing:

finding the (small) crack in the Standard Model

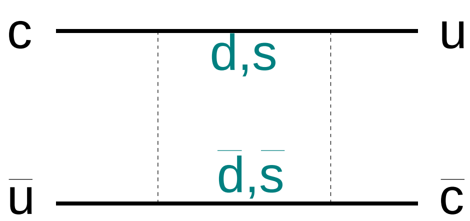


Alan Schwartz
University of Cincinnati

Joint Experiment/Theory Seminar
Fermilab
April 27th, 2007

- **neutral meson mixing**
- **D^0 meson mixing**
- **3 new D^0 measurements**
- **summary of knowledge; what have we learned?**

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

$$\langle f|H|D^0(t)\rangle \;=\; e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\mathcal{A}_f+\left(\frac{q}{p}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\bar{\mathcal{A}}_f\right\}$$

$$\langle \bar{f}|H|\overline{D}{}^0(t)\rangle \;=\; e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\left(\frac{p}{q}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\mathcal{A}_{\bar{f}}+\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\bar{\mathcal{A}}_{\bar{f}}\right\}$$

$$\mathcal{A}_f \equiv \langle f|H|D^0\rangle \qquad \bar{\mathcal{A}}_f \equiv \langle f|H|\overline{D}{}^0\rangle$$

$$\mathcal{A}_{\bar{f}} \equiv \langle \bar{f}|H|D^0\rangle \qquad \bar{\mathcal{A}}_{\bar{f}} \equiv \langle \bar{f}|H|\overline{D}{}^0\rangle$$

Since $\Delta m\, t \ll 1$ and $\Delta\gamma t \ll 1$, expand $\cos(\Delta m\, t)$, $\cosh(\Delta\gamma/2)t$, $\sin(\Delta m\, t)$, $\sinh(\Delta\gamma/2)t$:

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

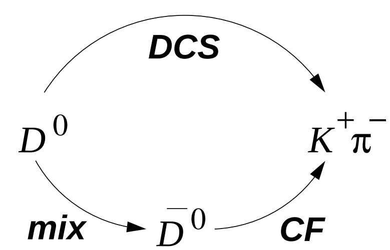
$$R(\overline{D}{}^0(t)\to \bar{f}) \;\propto\; e^{-\overline{\Gamma}t}\left\{1 \;+\; \left[\,y\,\mathrm{Re}(\bar{\lambda}) - x\,\mathrm{Im}(\bar{\lambda})\,\right](\overline{\Gamma}t) \;+\; |\bar{\lambda}|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

Direct **Interference** **Mixing**

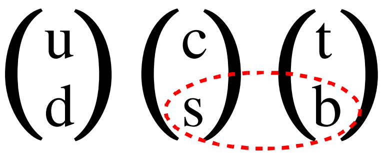
$$x \equiv \frac{\Delta m}{\overline{\Gamma}} \qquad y \equiv \frac{\Delta\Gamma}{2\overline{\Gamma}} \qquad \lambda \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \qquad \bar{\lambda} \equiv \frac{p}{q}\frac{\mathcal{A}_{\bar{f}}}{\bar{\mathcal{A}}_{\bar{f}}}$$

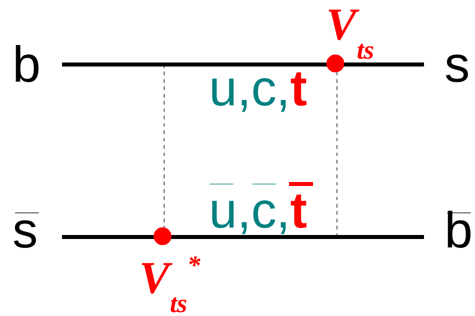
MIXING PARAM. ***CPV*** **enters here**

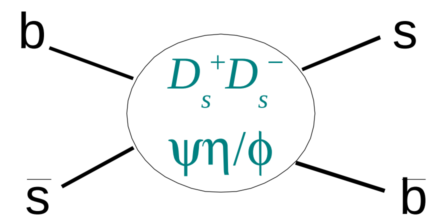
Note: $\tau = \Gamma^{-1}$



Neutral meson mixing III:







off-shell ("virtual") states: Δm on-shell states: $\Delta\Gamma$

Meson	flavors	$\Delta m/\Gamma$	$\Delta\Gamma/2\Gamma$	mixing observed?
K^0	$\bar{s}d$	0.474	0.997	yes (1958)
B^0	$\bar{b}d$	0.77	< 1%	yes (1987)
B_s^0	$\bar{b}s$	27	0.15±0.07	yes (2006)
D^0	$c\bar{u}$	< 0.029	0.011±0.005	before March'07: no after March 13: yes

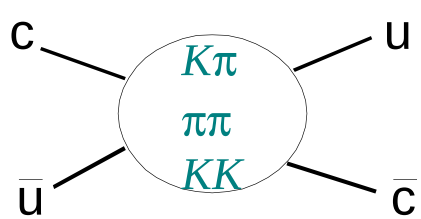
small because:

- **doubly-Cabibbo-suppressed with respect to Γ_D**
- **GIM mechanism cancellation: $V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$**

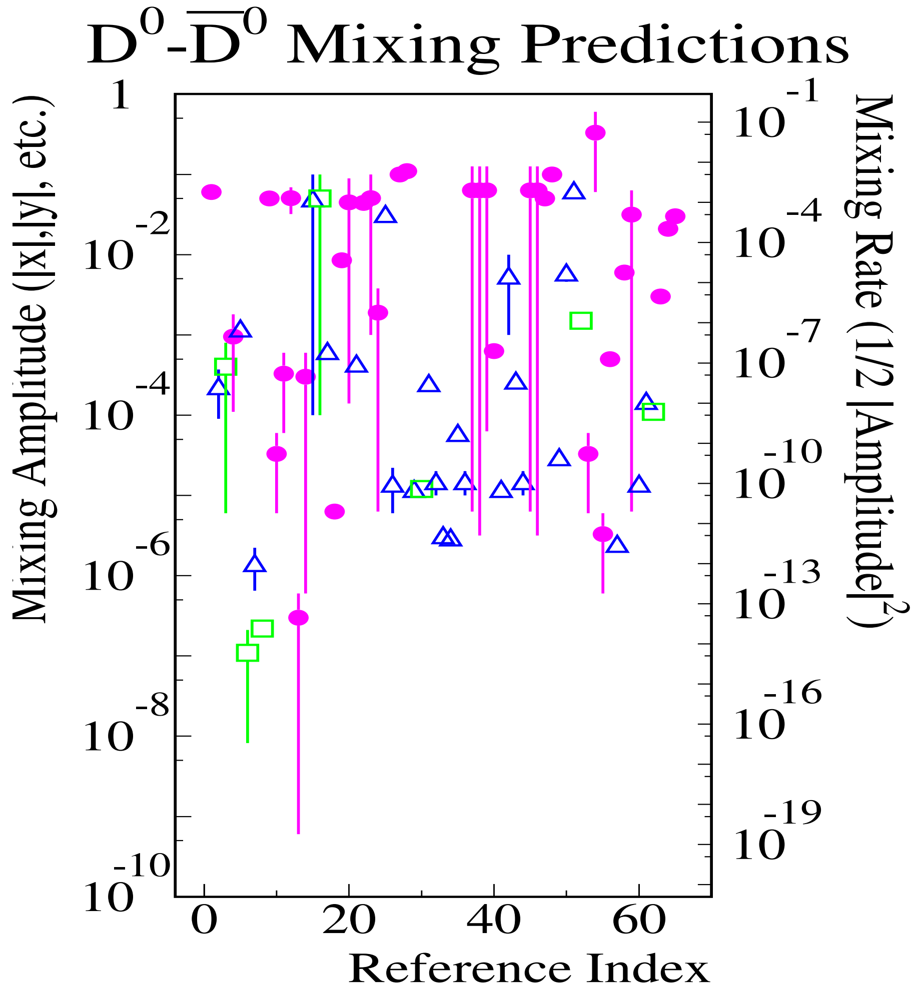
Nelson, hep-ex/9908021
Golowich, Petrov, PLB 625 (2005) 53
Bianco *et al.*, Riv.Nuov.Cim.26N7-8 (2003)

D^0 meson mixing:

Expect in SM: mixing is dominated by "long-distance" (non-perturbative) contributons



$x \lesssim y \quad \sim$	$10^{-6} - 10^{-3}$	(short distance)
	$10^{-3} - 10^{-2}$	(long distance)



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

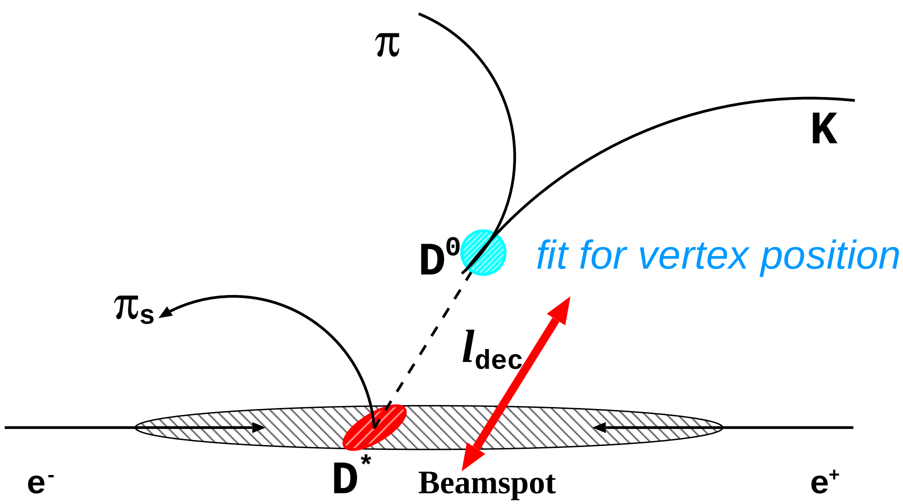
- **Wrong-sign hadronic $D^0 \to K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$ decays**
  measures x^2+y^2

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

Experimental Method

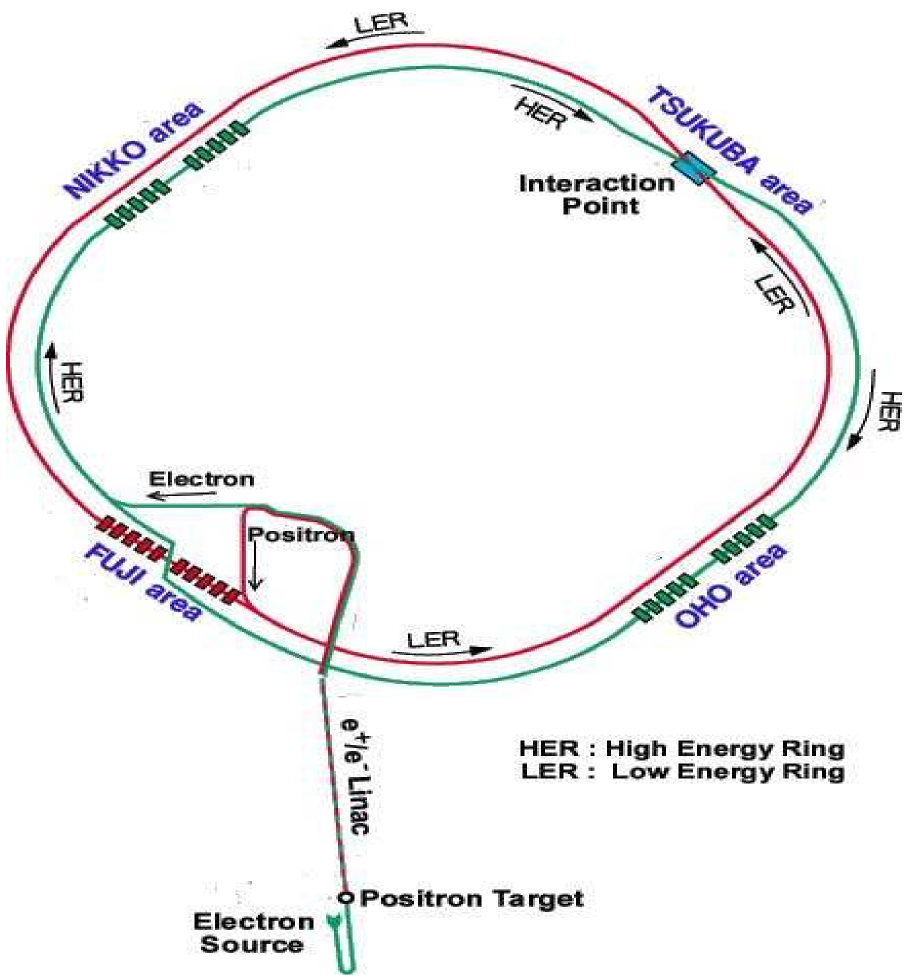
- **Initial flavor of $D^0(t)$ is determined from $D^{*+} \to D^0\pi^+$ or $D^{*-} \to D^0\pi^-$**
  This also greatly reduces background: $Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi}$ only 6 MeV/c (very near threshold)

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



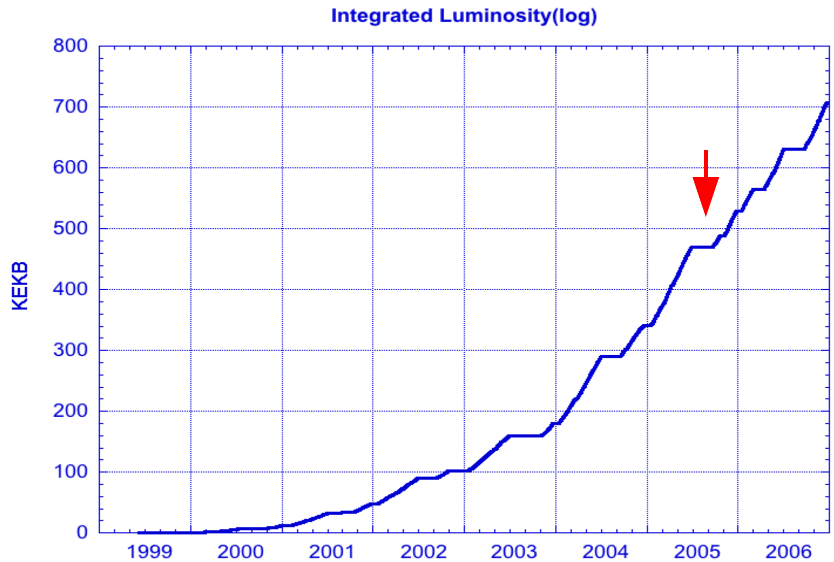
- **$p(D^*) > 2.5$ GeV to eliminate D^0's from B meson decay**
  (at $e^+e^- \to \Upsilon(4S)$ resonance, $\sigma(bb)/\sigma(\text{all}) = 1/3$)

KEKB accelerator (Tsukuba, Japan)



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

3.5 GeV on 8.0 GeV



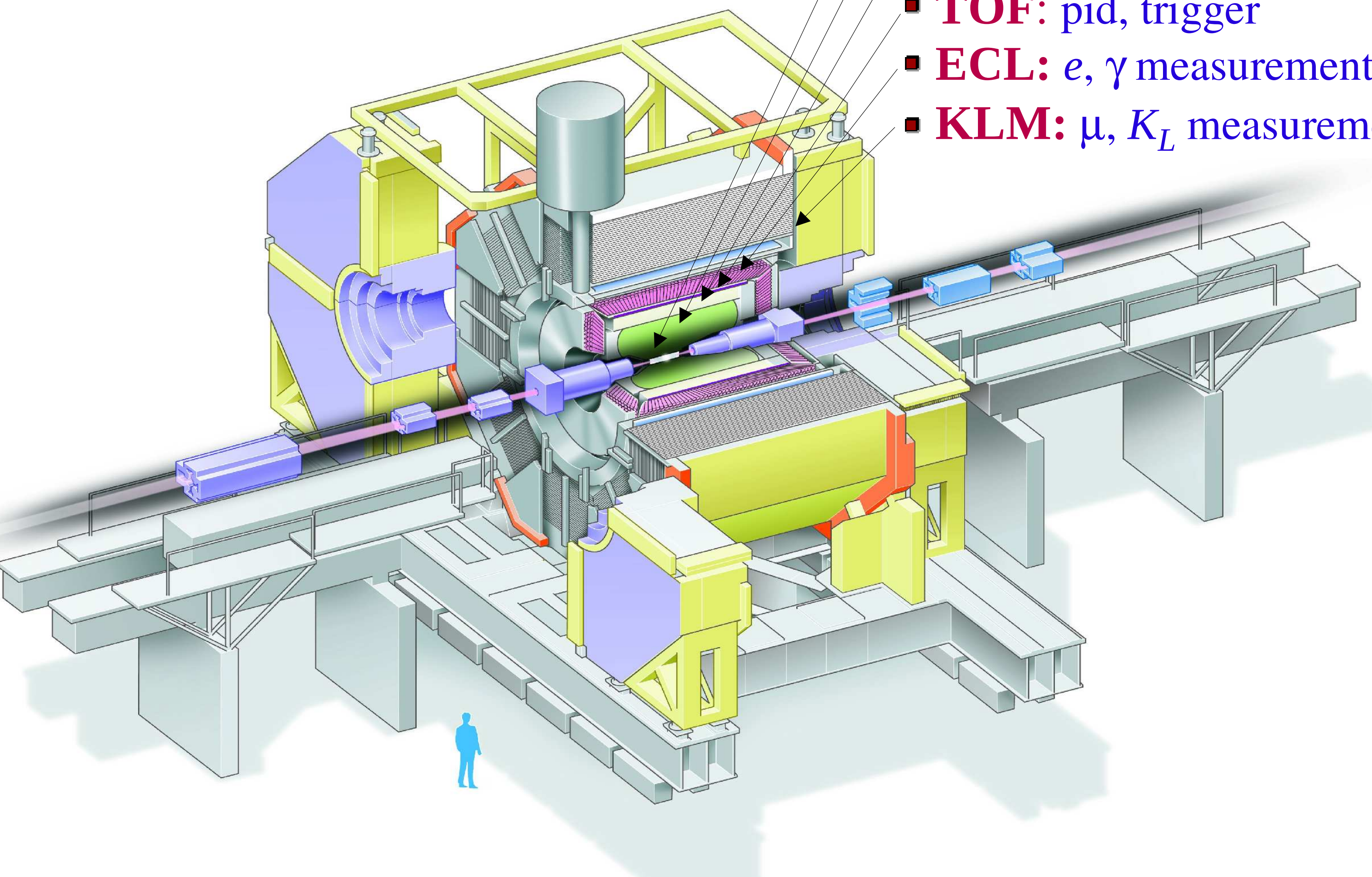
$\int L\, dt = 710\ fb^{-1}$ **(25 Dec 2006)**

L_{peak} **(max) = 1.5 x** 10^{34} $cm^{-2}\ s^{-1}$

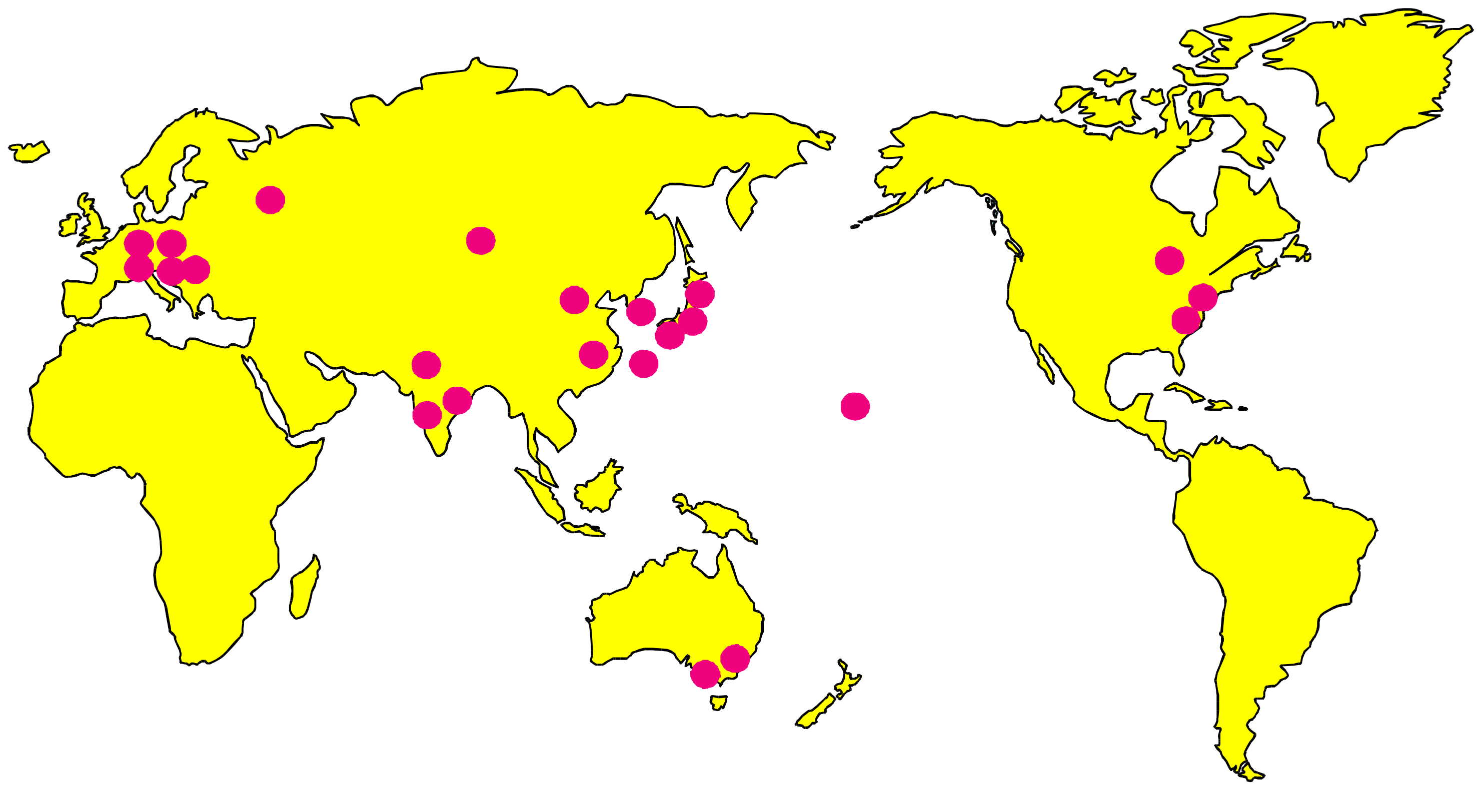
540 fb^{-1} reported here

The Belle Detector

- **SVD:** vertexing (lifetime)
- **CDC:** tracking, *dE/dx* for pid
- **ACC:** aerogel Cerenk. Counter
- **TOF**: pid, trigger
- **ECL:** *e*, γ measurement
- **KLM:** μ, K_L measurement



The Belle Collaboration



About 400 people from 59 institutions, many nations

USA: Cincinnati
Hawaii
Princeton
Virginia Tech

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

Master formula:

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

CP violation parameters:

$$\lambda \ \equiv\ \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \ =\ \left|\frac{q}{p}\right| e^{i\phi} \qquad \bar{\lambda} \ \equiv\ \frac{p}{q}\frac{\mathcal{A}_{\bar{f}}}{\bar{\mathcal{A}}_{\bar{f}}} \ =\ \left|\frac{p}{q}\right| e^{-i\phi}$$

$D^0(t) \to K^-\pi^+$ — 50% D_1 and 50% D_2 — $|\lambda| << 1 \ \Rightarrow\ \mathrm{R} \sim \mathrm{e}^{-\Gamma t}$

$D^0(t) \to K^+K^-$ (or $\pi^+\pi^-$) — pure D_1 — $\Rightarrow\ \mathrm{R} = \mathrm{e}^{-\Gamma_1 t} = \mathrm{e}^{-\Gamma(1+y)t}$

$$(\ \lambda \sim 1 \ \Rightarrow\ \mathrm{R} \sim \mathrm{e}^{-\Gamma t}(1+y\Gamma t) \sim \mathrm{e}^{-\Gamma t}\,\mathrm{e}^{y\Gamma t} = \mathrm{e}^{-\Gamma(1+y)t}\ )$$

$$\Rightarrow \quad \tau(K^-\pi^+)/\,\tau(K^+K^-) = 1 + y$$

more accurate: $y\cos\phi = \tau_{K\pi}/\tau_{KK} - 1 = y_{CP}$

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*$^{-1}$

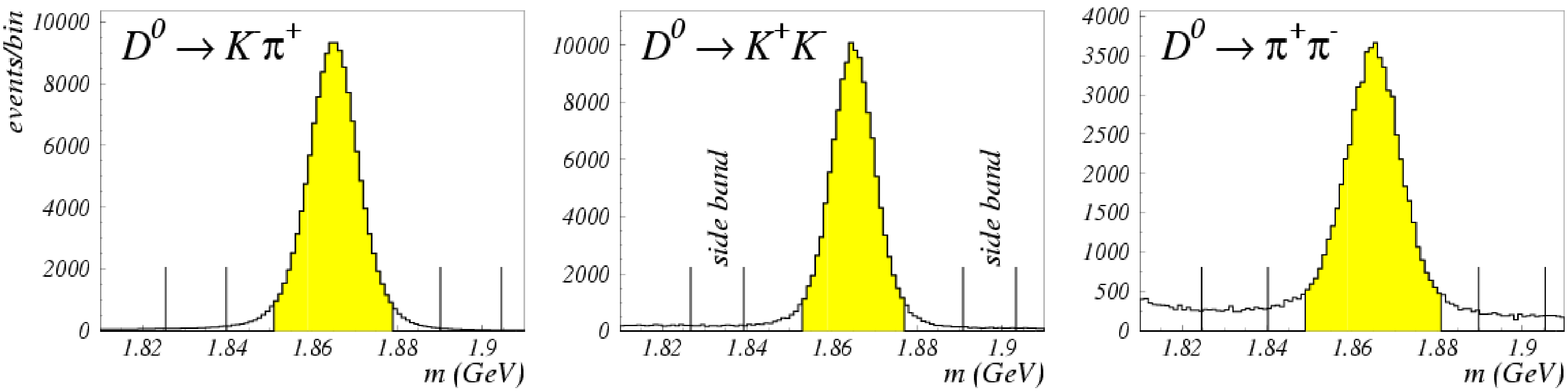
$D^{+*} \to D^0 \pi^+$

$\quad \hookrightarrow K^+K^-, \pi^+\pi$

$m(D^0) = 1865$ 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

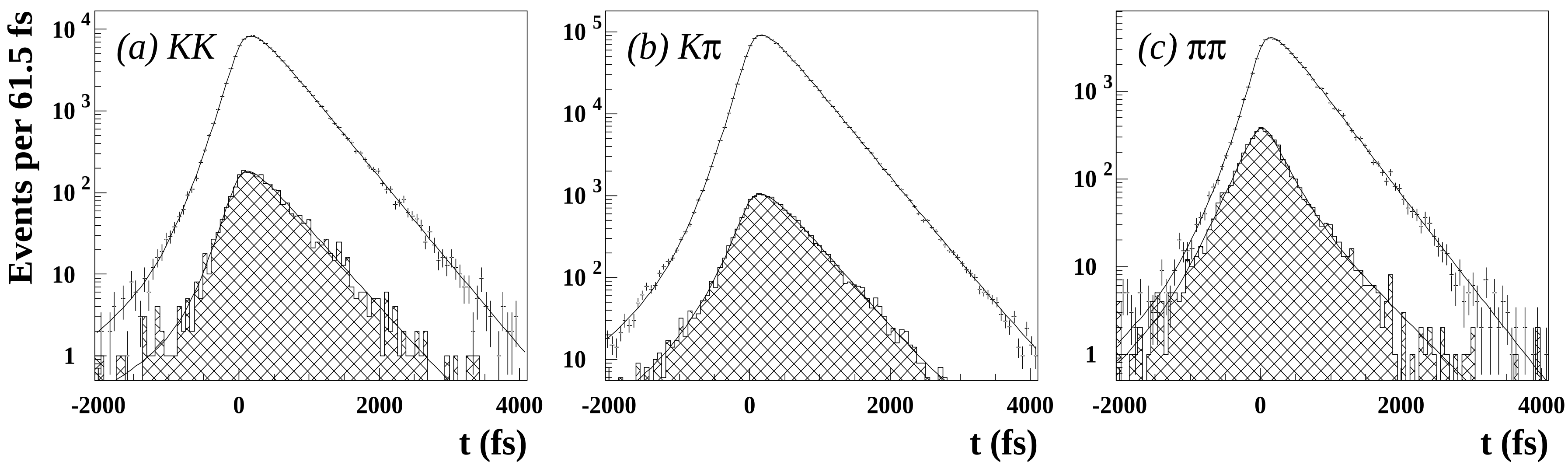
50k events
92% pure

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 = $ **404.0 ± 2.2 fs**
(110k events)

$\tau = $ **408.7 ± 0.6 fs**
(1200k events)

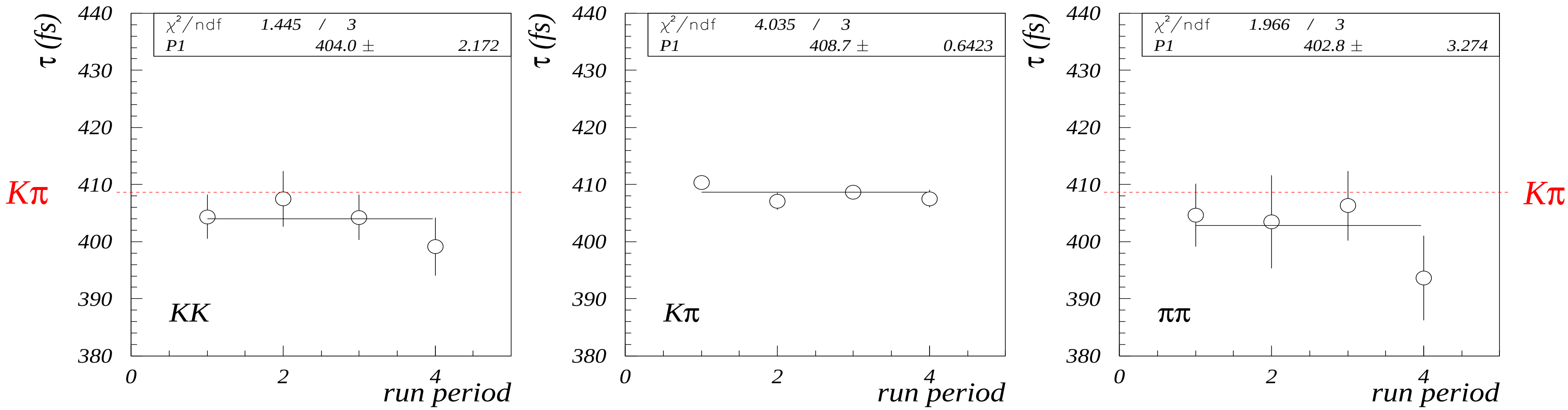
$\tau = $ **402.8 ± 3.3 fs**
(50k events)

⇒ **there is a difference between *KK* and *K*π**

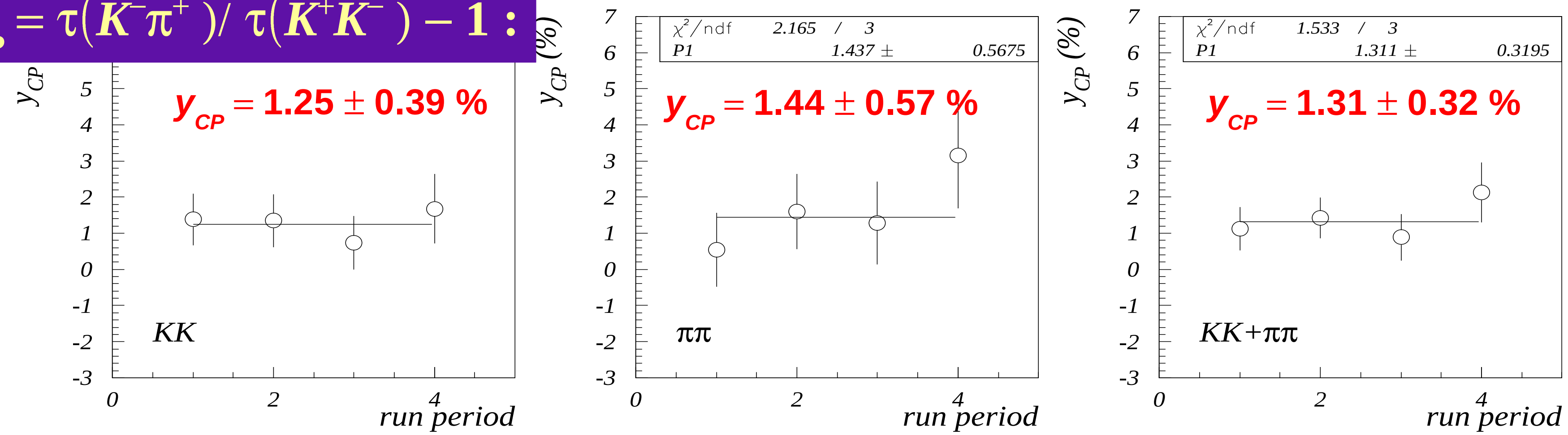
(here, t0 is free for each final state)

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

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

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

no evidence for CP violation

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

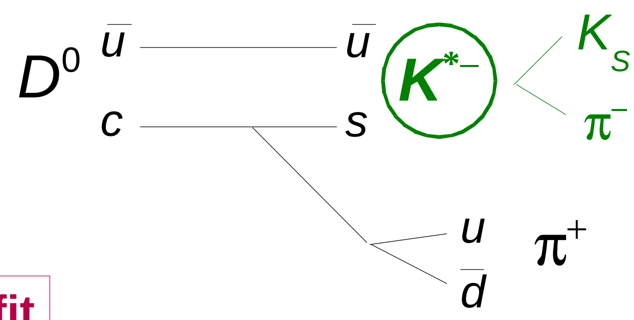
$$\langle K_S^0\pi^+\pi^-|H|D^0(t)\rangle = \frac{1}{2p}\Big(\langle K_S^0\pi^+\pi^-|H|D_1(t)\rangle + \langle K_S^0\pi^+\pi^-|H|D_2(t)\rangle\Big)$$
$$\equiv A_1\, e^{-(\Gamma_1/2+im_1)\,t} + A_2\, e^{-(\Gamma_2/2+im_2)\,t}$$

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

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

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:



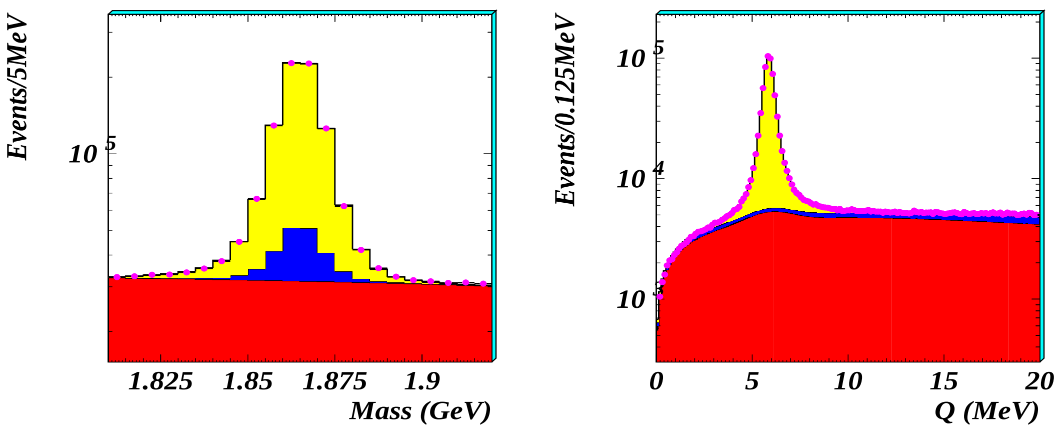
Each amplitude has a magnitude (a_j) and phase (δ_j)

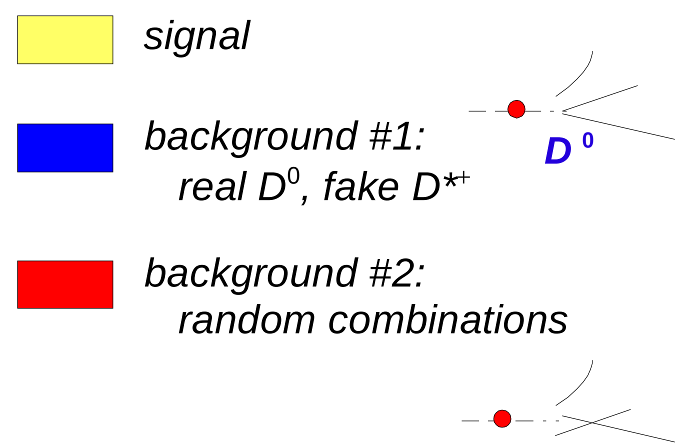
⇒ must include these parameters (34 of them) in the fit

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

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

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

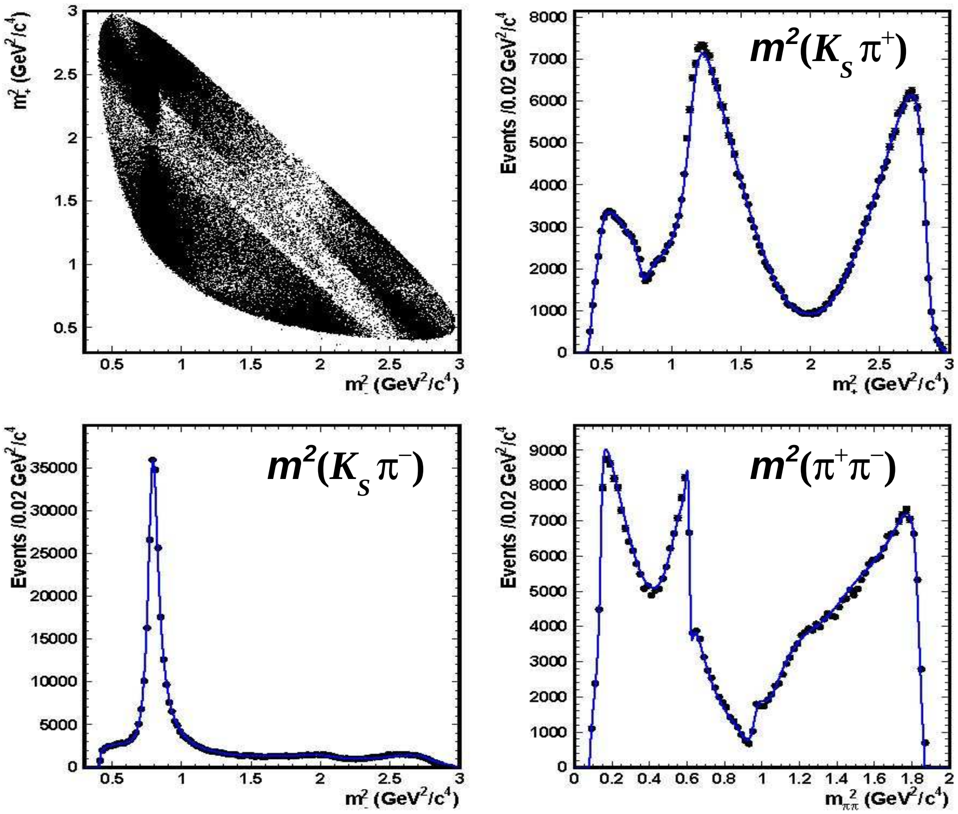




534k events

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

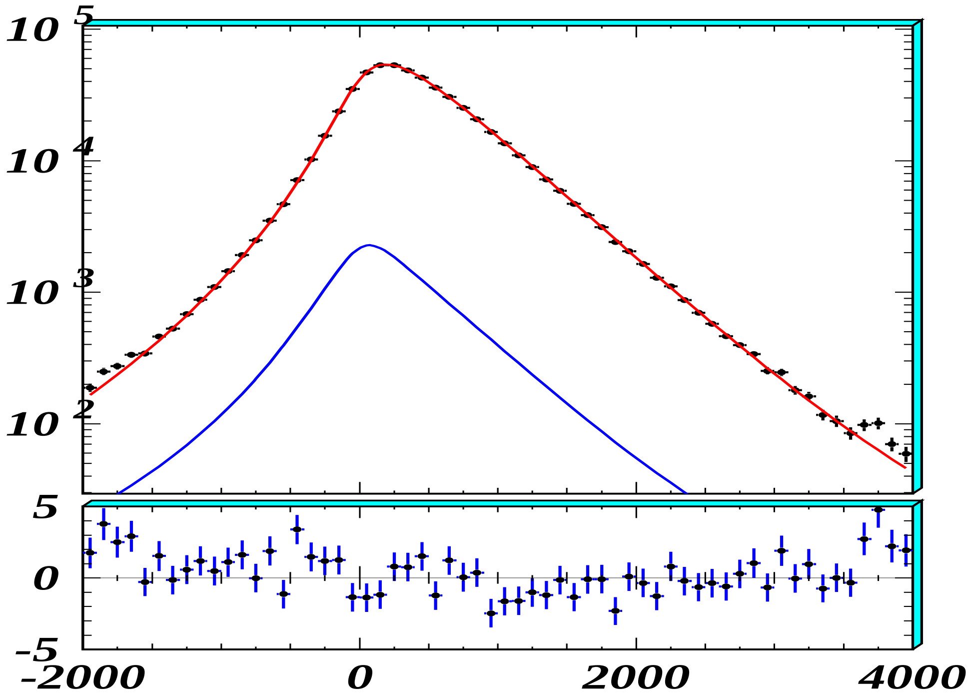
1.19

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

$\Rightarrow$ *destructive interference*

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

Time fit (in projection):



x = (0.80 ± 0.29)%

positive

y = (0.33 ± 0.24)%

t_D = (409.9 ± 0.9) fs

consistent with PDG
(in fact better precision)

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

Largest systematic errors:

	Δx ($\times 10^{-2}$)	Δy ($\times 10^{-2}$)
$p(D^*)$ 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)**

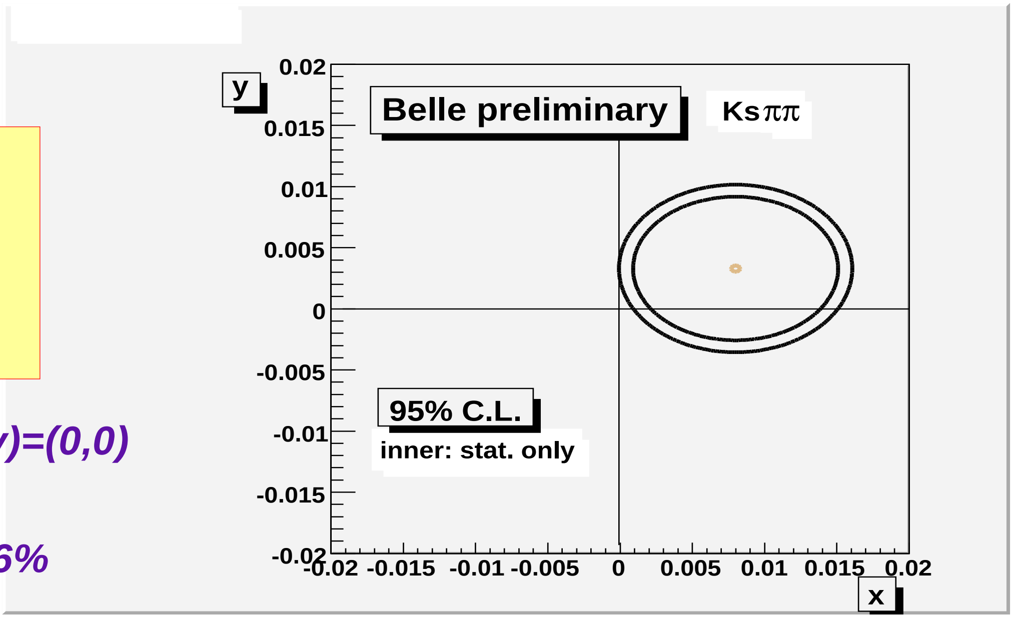
Final result:

x = (0.80 ± 0.29 ± 0.17)%

y = (0.33 ± 0.24 ± 0.15)%

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

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



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

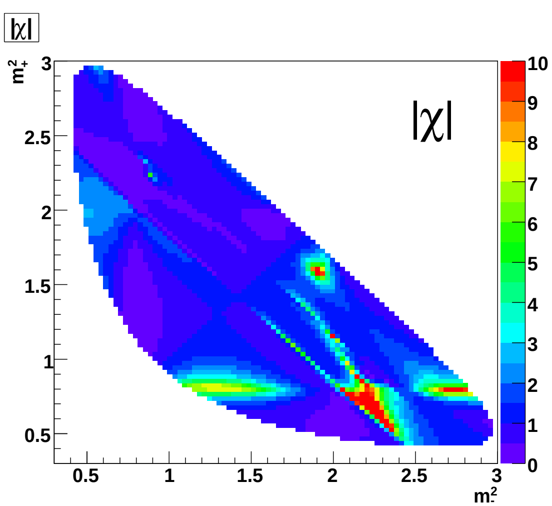
Sensitivity:

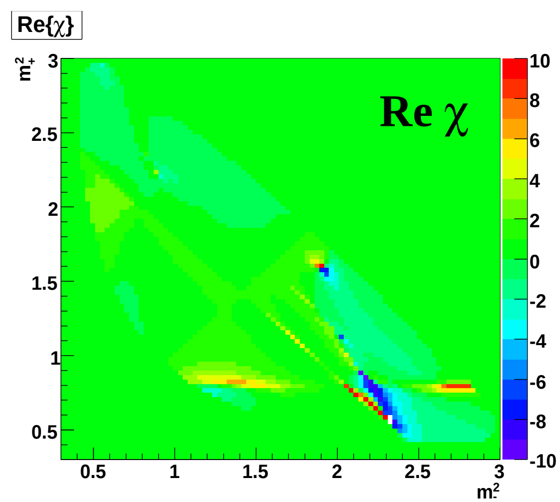
$$e_{(1,2)} \;=\; e^{-i(m_{(1,2)}-i\Gamma_{(1,2)}/2)t}$$

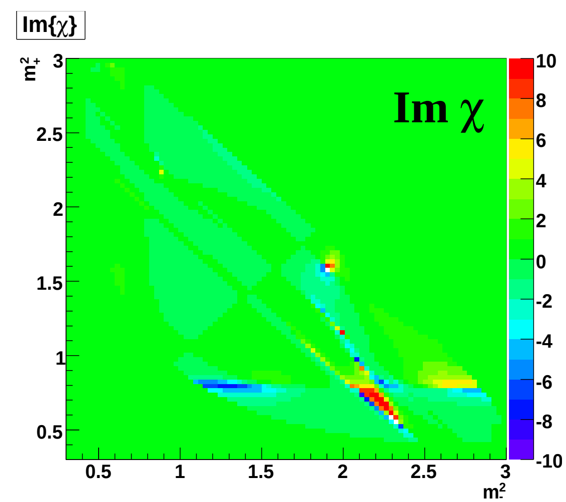
$$\begin{aligned}\mathcal{M}(m_-^2,m_+^2,t) \;&=\; \mathcal{A}(m_-^2,m_+^2)\,\frac{e_1(t)+e_2(t)}{2} \;+\; \frac{q}{p}\,\overline{\mathcal{A}}(m_-^2,m_+^2)\,\frac{e_1(t)-e_2(t)}{2}\\ &\to\; \mathcal{A}(m_-^2,m_+^2)\,\frac{e_1(t)+e_2(t)}{2} \;+\; \mathcal{A}(m_+^2,m_-^2)\,\frac{e_1(t)-e_2(t)}{2}\end{aligned}$$

Define $\chi(m_-^2,m_+^2) \;\equiv\; \dfrac{\mathcal{A}(m_+^2,m_-^2)}{\mathcal{A}(m_-^2,m_+^2)}$, then

$$|\mathcal{M}|^2 \;\approx\; |\mathcal{A}(m_-^2,m_+^2)|^2\left\{1 \;+\; [\mathrm{Im}(\chi)\,x-\mathrm{Re}(\chi)\,y]\;t+|\chi|^2\left(\frac{x^2+y^2}{4}\right)t^2\right\}\,e^{-\Gamma t}$$







⇒ ***much of sensitivity comes from the K*(890)$^+$ region and interference region between ρ(770) and ω***

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

Master formula:

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

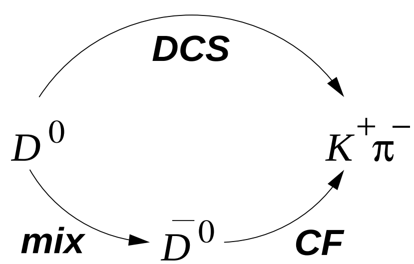
for $f = K^+\pi^-$: $\lambda \;\equiv\; \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \;=\; \left|\frac{q}{p}\right|\sqrt{R_D}\,e^{i(\phi+\delta)}$

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

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

$$= e^{-\overline{\Gamma}\,t}\left\{R_D + \sqrt{R_D}(y\cos\delta - x\sin\delta)(\overline{\Gamma}t) + \frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\} \qquad \begin{pmatrix}|q/p| = 1\\ \phi = 0\end{pmatrix} \text{ no CPV}$$

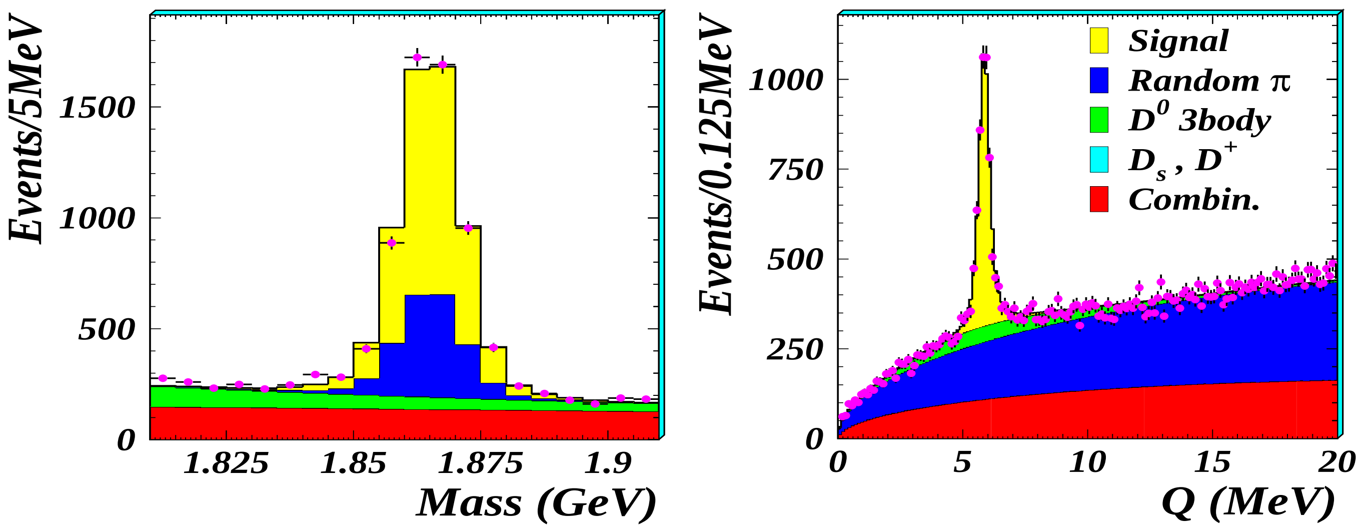
$$= e^{-\overline{\Gamma}\,t}\left\{R_D + \sqrt{R_D}\,y'\,(\overline{\Gamma}t) + \frac{(x'^2+y'^2)}{4}\,(\overline{\Gamma}\,t)^2\right\}$$



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

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), hep-ex/0703020

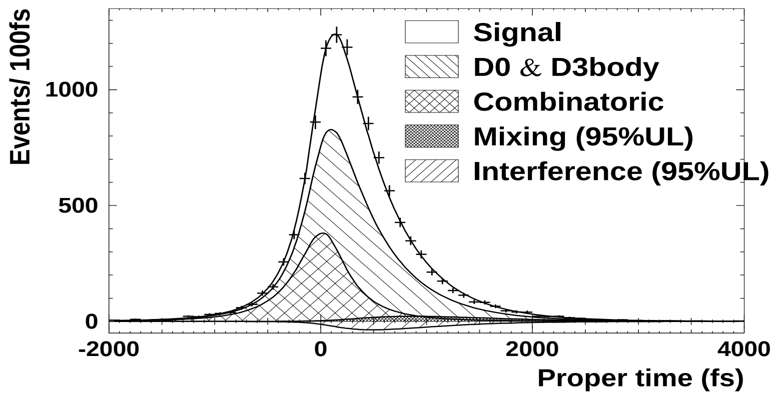


4024 events

52% purity

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

Time fit:



BELLE

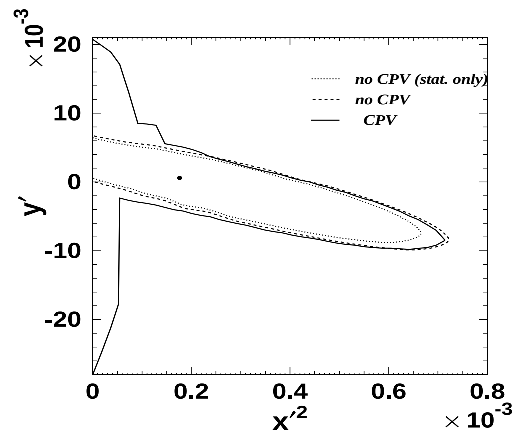
400 fb^{-1}

R_D = (0.364 ± 0.017)%

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

y' = $(0.06\ ^{+0.40}_{-0.39})$%

no CPV



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

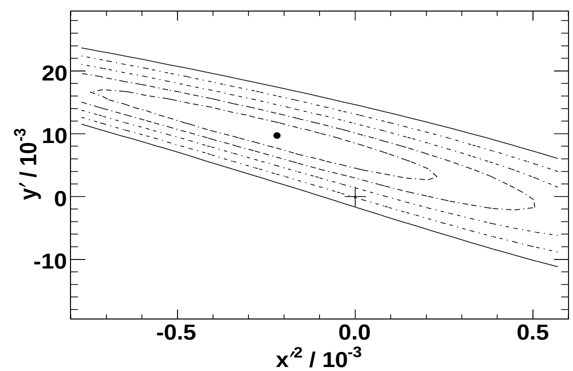
384 fb^{-1}
new

R_D = (0.303 ± 0.019)%

x'^2 = (–0.022 ± 0.037)%

y' = (0.97 ± 0.54)%

no CPV

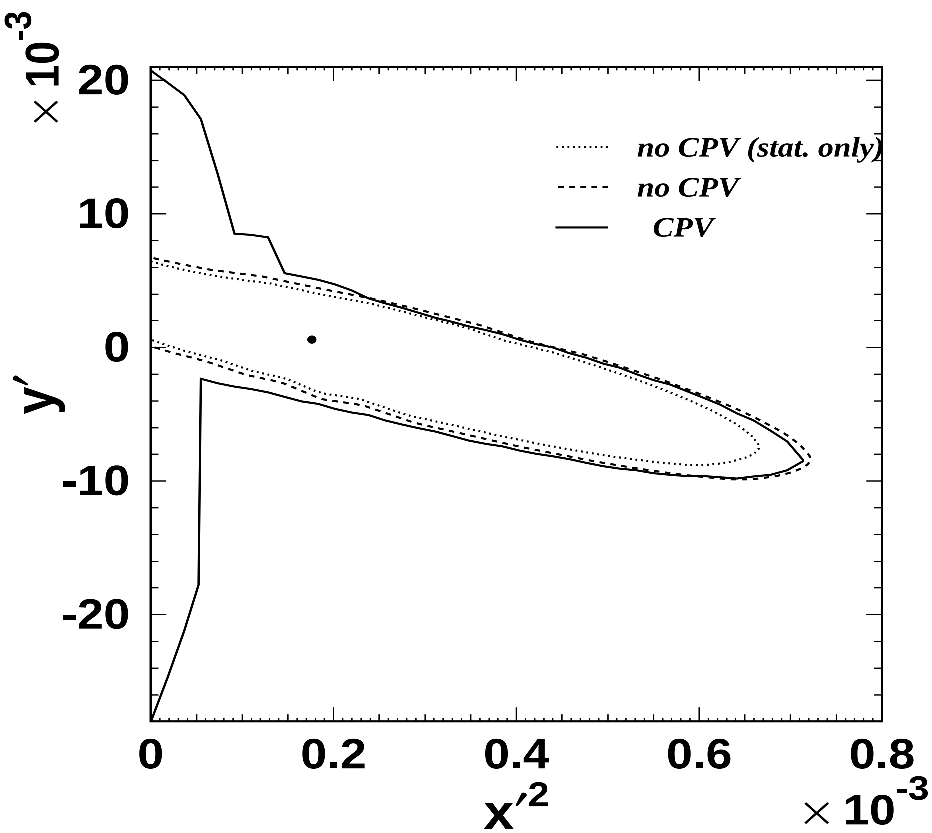


(x',y') = (0,0) has CL = 0.01%

evidence for mixing

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

Use toy MC to obtain frequentist (Feldman-Cousins) confidence region (95% CL):



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

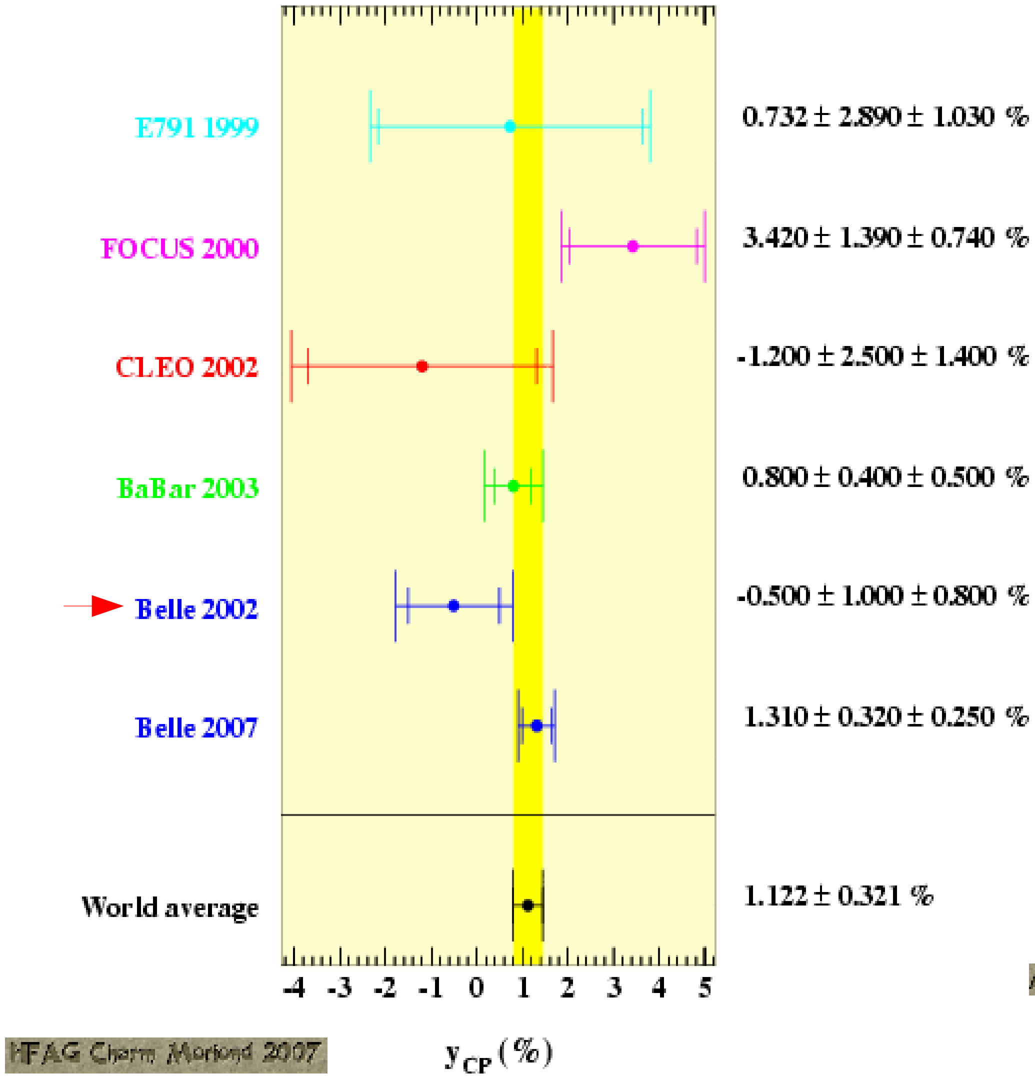
$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y' \cos\phi \mp x' \sin\phi)$$

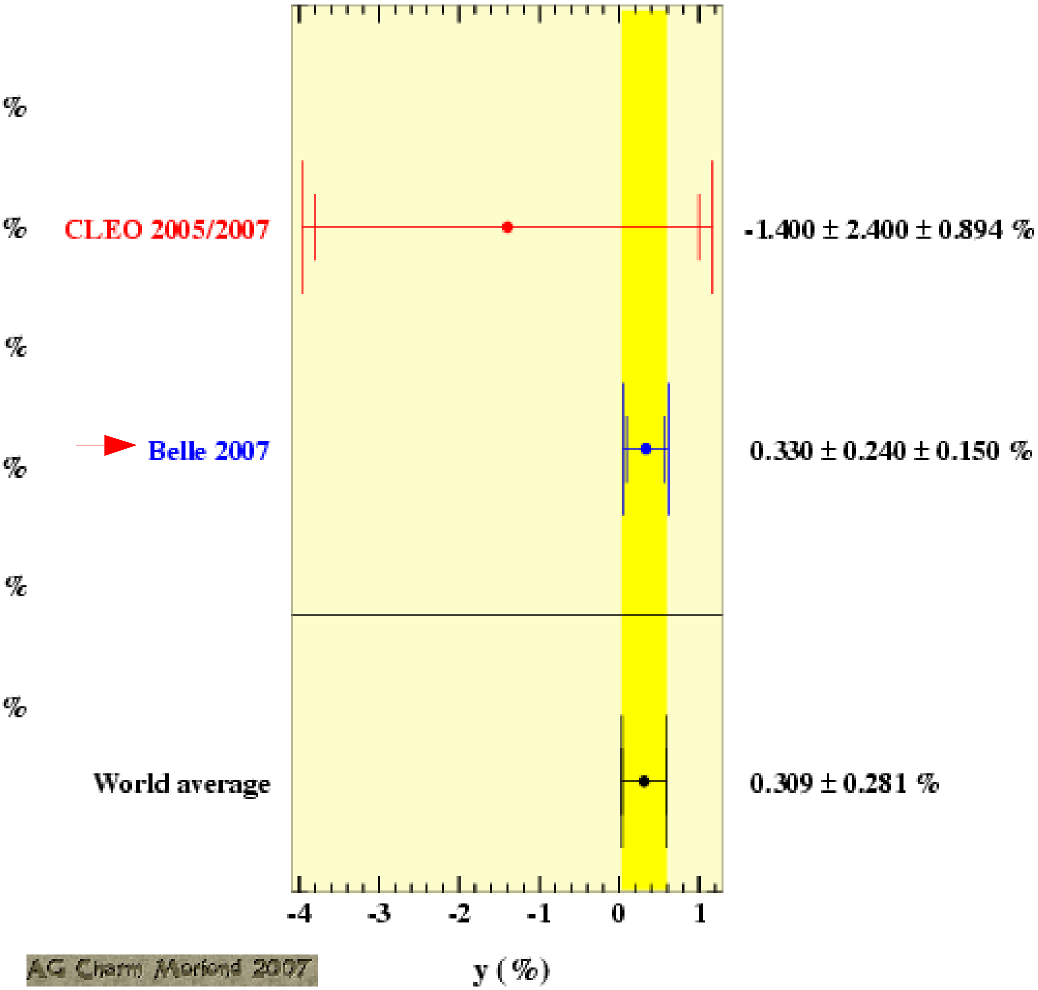
Fit Case	Parameter	95% CL interval ($\times 10^{-3}$)
No CPV	x'^2	$x'^2 < 0.72$
	y'	$-9.9 < y' < 6.8$
	R_D	$3.3 < R_D < 4.0$
	R_M	$0.63 \times 10^{-5} < R_M < 0.40$
CPV allowed	A_D	$-76 < A_D < 107$
	A_M	$-995 < A_M < 1000$
	x'^2	$x'^2 < 0.72$
	y'	$-28 < y' < 21$
	R_M	$R_M < 0.40$

unusual contour shape due to ambiguities

No *CPV*: (x'^2,y') = (0,0) has CL = 3.9% (outside 95% CL contour)

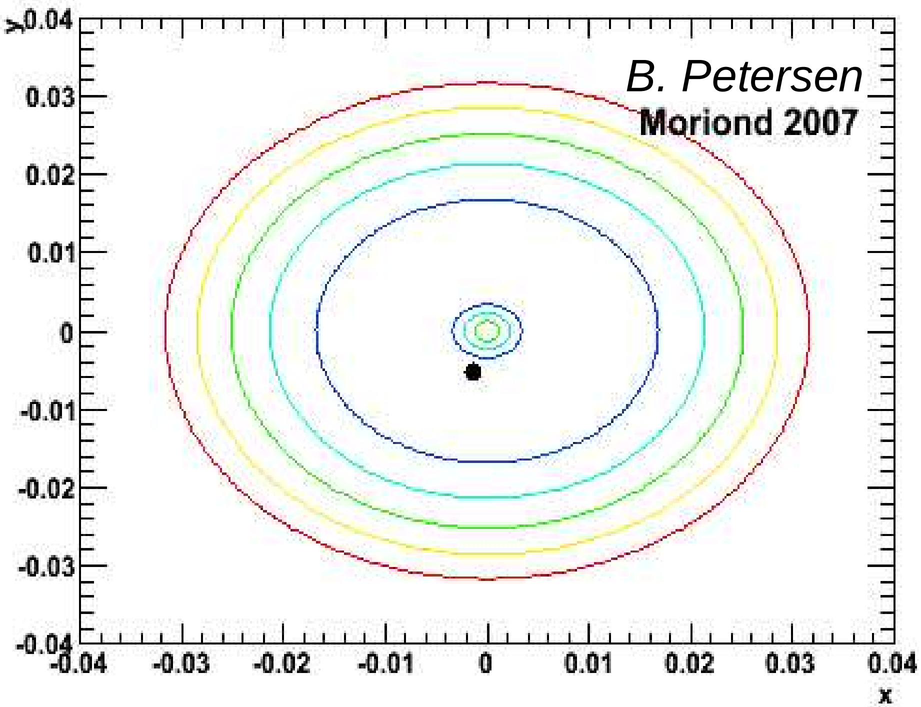
What have we learned?





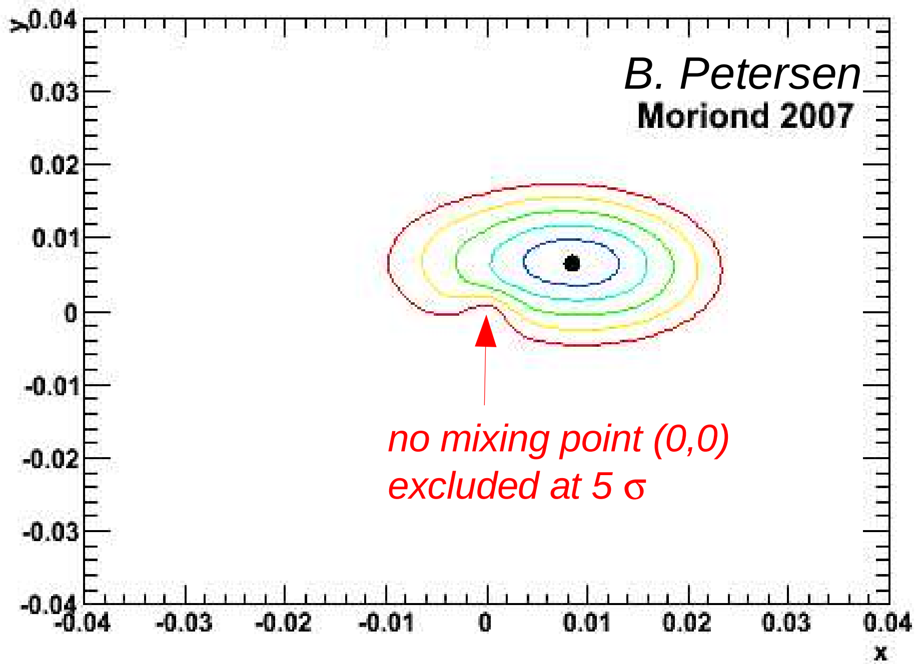
What have we learned?

All $D^0(t) \to K^+\pi^-$ measurements, allowing strong phase δ to always take its preferred value (for a given x and y):



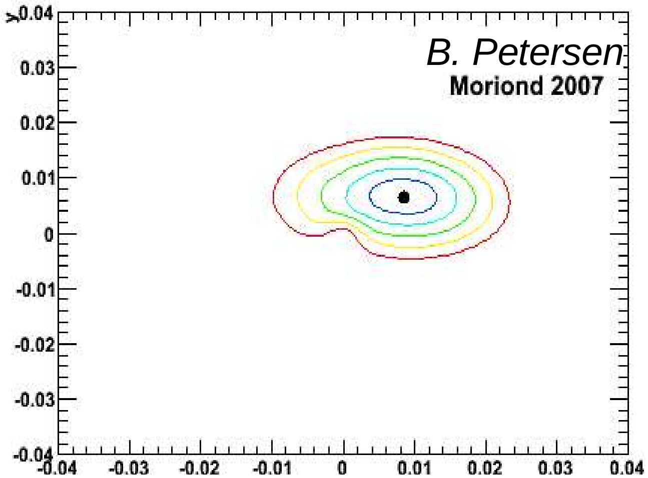
$-2 \ln \mathcal{L}$

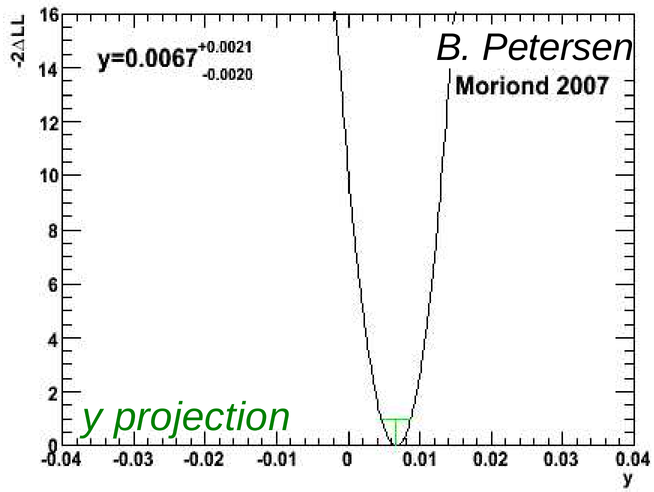
Adding $-2\ln \mathcal{L}$ functions from semileptonic decays, $K^+\pi^-$, $K_S\pi\pi$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$:



What have we learned?

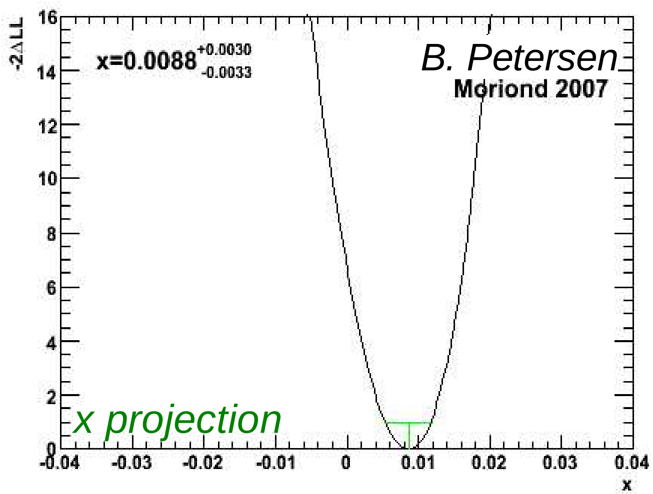
All data [semileptonic decays, $K^+\pi^-$, $K_S\pi\pi$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$]:





x = (0.88 ± 0.33)%
(2.7σ above zero)

y = (0.67 ± 0.20)%
(3.4σ above zero)



Conclusions:

Evidence is consistent and convincing that D^0's mix; affect is dominated by non-perturbative processes (y); may be new physics in x; need more data & better theoretical calculations to tell.

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