BELLE

D^0 mixing at Belle

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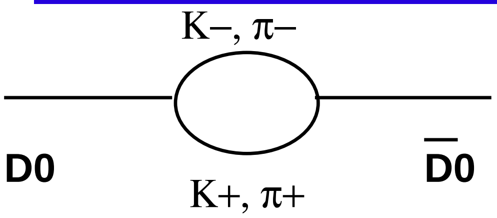
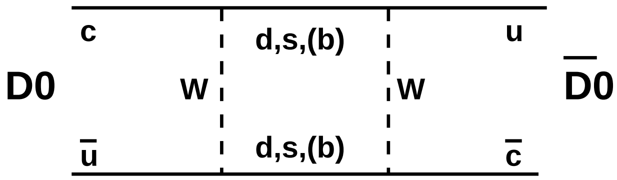
Topic

- $D^0(t) \to K^+K^- / \pi^+\pi^-$, 540 fb^{-1}
  measures y_{CP}
- $D^0(t) \to K_S{}^0\pi^+\pi^-$, 540 fb^{-1}
  measures x, y

D^0-$\overline{D}^0$ mixing



- **Only mixing via light quark intermediate states**
- **doubly-Cabibbo-suppressed with respect to Γ_D**
- **long-distance contributions**



Flavor eigenstates are not mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$

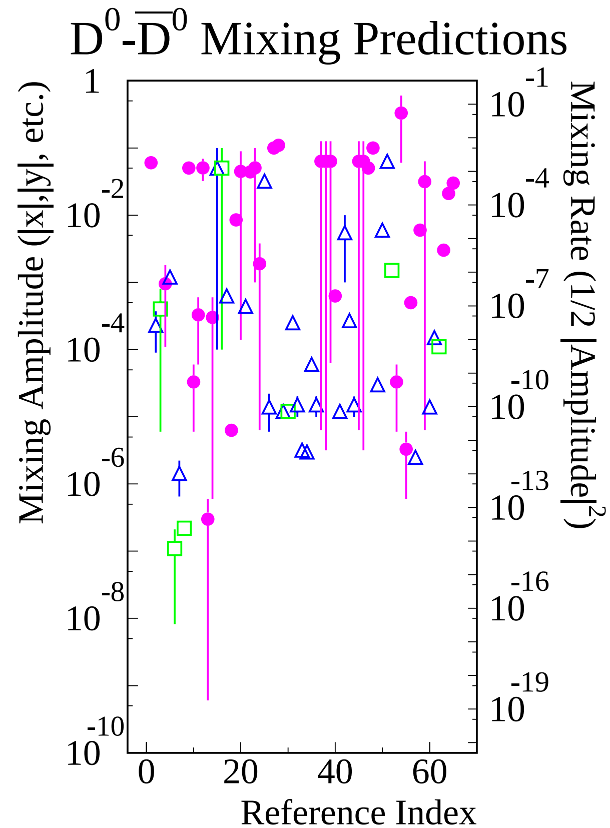
$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}\rangle \qquad e_{1,2}(t) = e^{-(\Gamma_{1,2}/2+im_{1,2})t}$$

$$|D^0(t)\rangle = |D^0\rangle\frac{e_1(t)+e_2(t)}{2} + \left(\frac{q}{p}\right)|\overline{D}^0\rangle\frac{e_1(t)-e_2(t)}{2}$$

$$|\overline{D}^0(t)\rangle = |\overline{D}^0\rangle\frac{e_1(t)+e_2(t)}{2} + \left(\frac{p}{q}\right)|D^0\rangle\frac{e_1(t)-e_2(t)}{2}$$

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

Expect in SM: $|x| \lesssim |y| \sim$ $10^{-6} - 10^{-3}$ (short distance)
$10^{-3} - 10^{-2}$ (long distance)



- If obtain $|x|>>|y|$ or *CPV* $\Rightarrow$ New Physics

Common features of analyses

- Initial flavor of D^0 is determined from $D^{*+} \to D^0\pi^+$ or $D^{*-} \to \overline{D}^0\pi^-$

  Background largely reduced: $Q = m_{K\pi\pi} - m_{K\pi} - m_\pi$ only 6 MeV (very near threshold)

- Common backgrounds:
  - Random π combined with real D^0 decays
  - Combinatorial (random combinations of tracks)

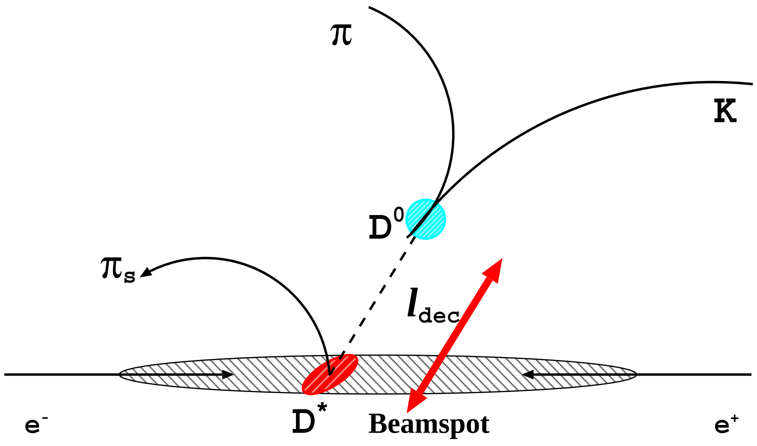
- p_{D^*} cut to eliminate D^*'s from B decays

- Signal/background yields obtained from m-Q fit

- (Unbinned) ML fit to $t = (l_{dec}/p)(m/c)$

Vertex Reconstruction

as example of $K\pi$



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

M. Staric *et al.* (Belle Collaboration), PRL 98, 211803 (2007)

- Measurement of lifetime difference between $D^0 \to K^-\pi^+$ and K^+K^-, $\pi^+\pi^-$
  - mixing parameter: $$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \approx y\cos\phi$$
  - in *CP* conservation limit: $y_{CP} = y$
- If *CP* not conserved
  - *CP* violating parameter: $$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)}$$

Previous Measurements
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)

$y_{CP} = (1.09 \pm 0.46)\%$ [***average***]

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

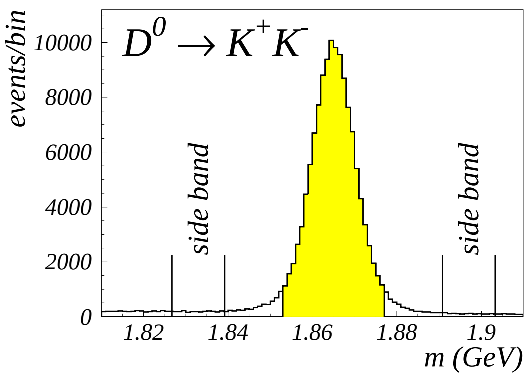
$|q/p|^2 = 1 + A_M$

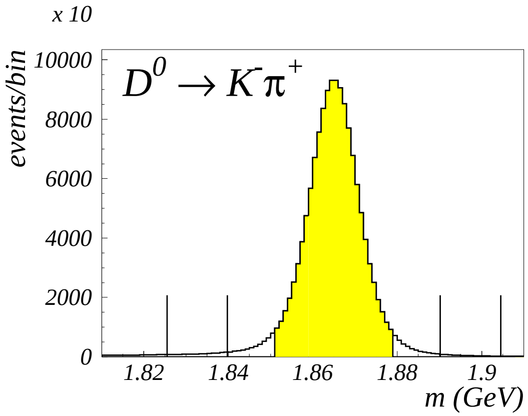
$\arg(q/p) = \phi$

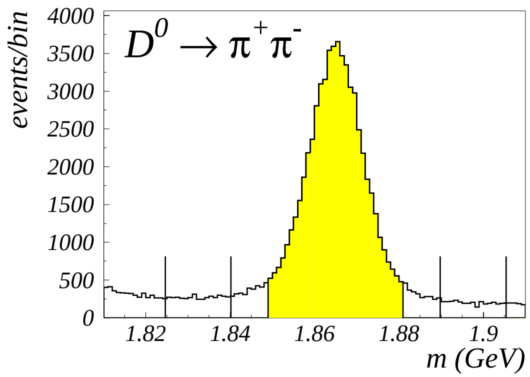
(S. Bergmann *et al.*, PLB 486, 418 (2000))

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

- Analysis cuts
  - Figure of merit: statistical error on y_{CP}
- Background estimated from sidebands in m







110k events
99% pure

1200k events
98% pure

50k events
92% pure

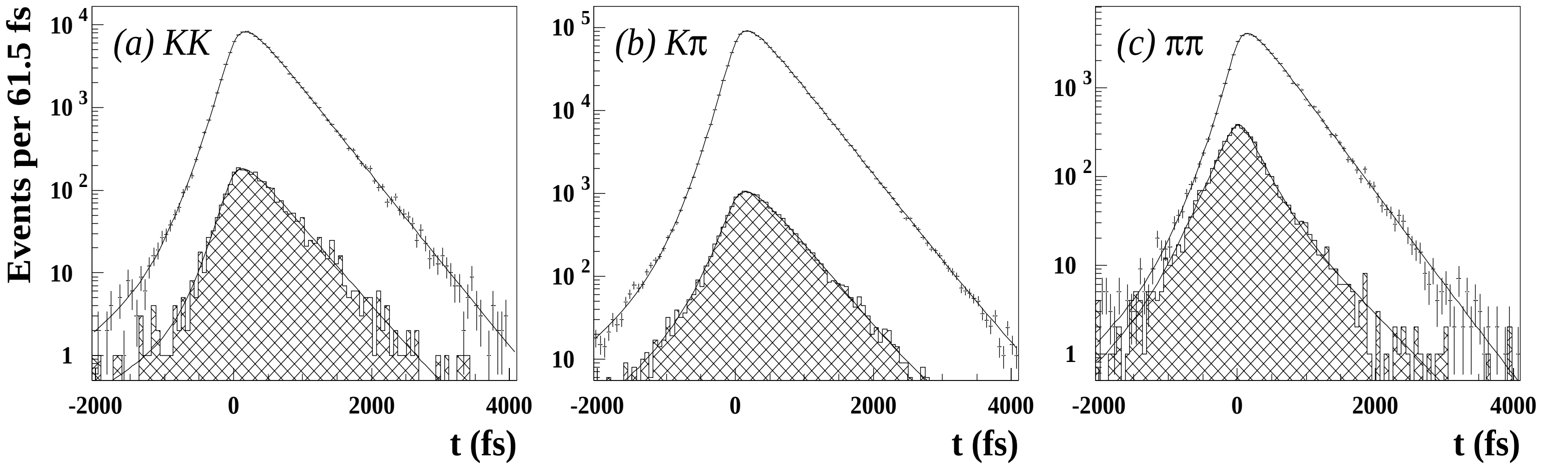
$D^0(t) \to K^+K^-, \pi^+\pi^-$, Timing fits

- Parameterization of proper decay time distribution

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

resolution function: triple Gaussian with offset t_0

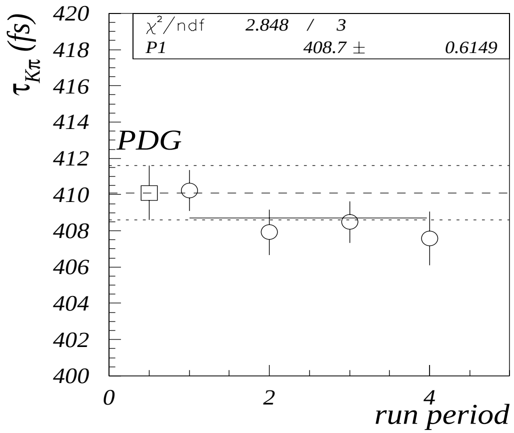
background component



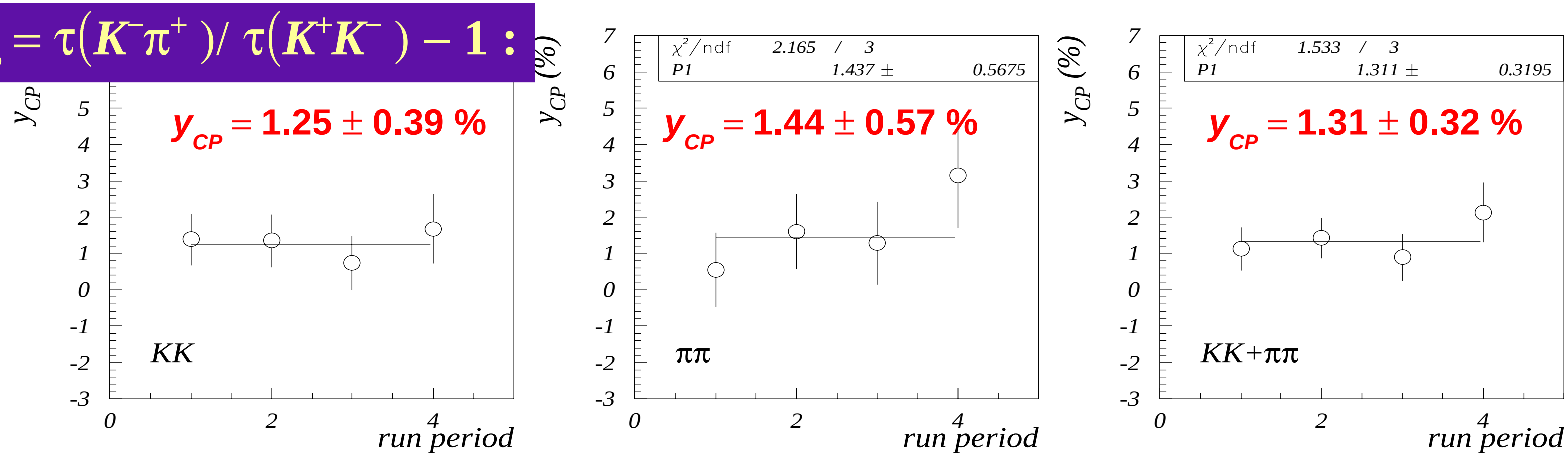
$\tau = 403.7 \pm 1.4$ fs	$\tau = 408.7 \pm 0.6$ fs	$\tau = 402.9 \pm 2.2$ fs
(110k events)	(1200k events)	(50k events)

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

Divide the data into sub-samples:



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



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

Cross-checks:

- MC test: $y_{CP}(\text{out}) - y_{CP}(\text{input}) < 0.04\%$
- Independent of $R(t)$ parameterization:

  $R(t)$ = single Gaussian: $\Delta\tau = 3.5\%$, $\Delta y_{CP} = 0.01\%$
- Exchange data sideband with background from MC

  $\Delta y_{CP} = -0.04\%$

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%**

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

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

$>$ 3 σ above zero
(first evidence for D^0-$\bar{D}^0$ mixing)

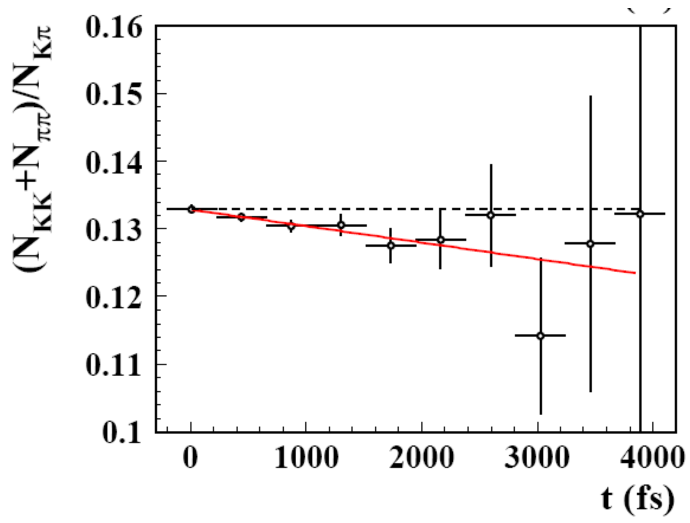
Search for CP violation:

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

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

no evidence for CP violation

There is a difference between $K^-\pi^+$ and K^-K^+



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

L.M.Zhang *et al.* (Belle Collaboration), arXiv:0704.1000v2 (submitted to PRL)

- Difference decays identified through Dalitz plot
  - CF: $D^0 \to K^{*-}\pi^+$ DCS: $D^0 \to K^{*+}\pi^-$ CP: $D^0 \to \rho^0 K_S^0$
- Formula

$$|f\rangle = |K_S^0 \pi^+ \pi^-\rangle$$

$$\langle f|H|D^0(t)\rangle = \langle f|H|D^0\rangle \frac{e_1(t)+e_2(t)}{2} + \left(\frac{q}{p}\right)\langle f|H|\overline{D}^0\rangle \frac{e_1(t)-e_2(t)}{2}$$

$$\langle f|H|\overline{D}^0(t)\rangle = \langle f|H|\overline{D}^0\rangle \frac{e_1(t)+e_2(t)}{2} + \left(\frac{p}{q}\right)\langle f|H|D^0\rangle \frac{e_1(t)-e_2(t)}{2}$$

$$\langle f|H|D^0\rangle = \mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2) + a_{\rm NR} e^{i\phi_{\rm NR}}$$

$$\langle f|H|\overline{D}^0\rangle = \overline{\mathcal{A}}(m_-^2, m_+^2) = \sum_r \bar{a}_r e^{i\bar{\phi}_r} \mathcal{A}_r(m_+^2, m_-^2) + \bar{a}_{\rm NR} e^{i\bar{\phi}_{\rm NR}}$$

$$\text{where} \quad \mathrm{m}_\pm^2 \equiv \mathrm{m}^2(\mathrm{K_S^0}\pi^\pm)$$

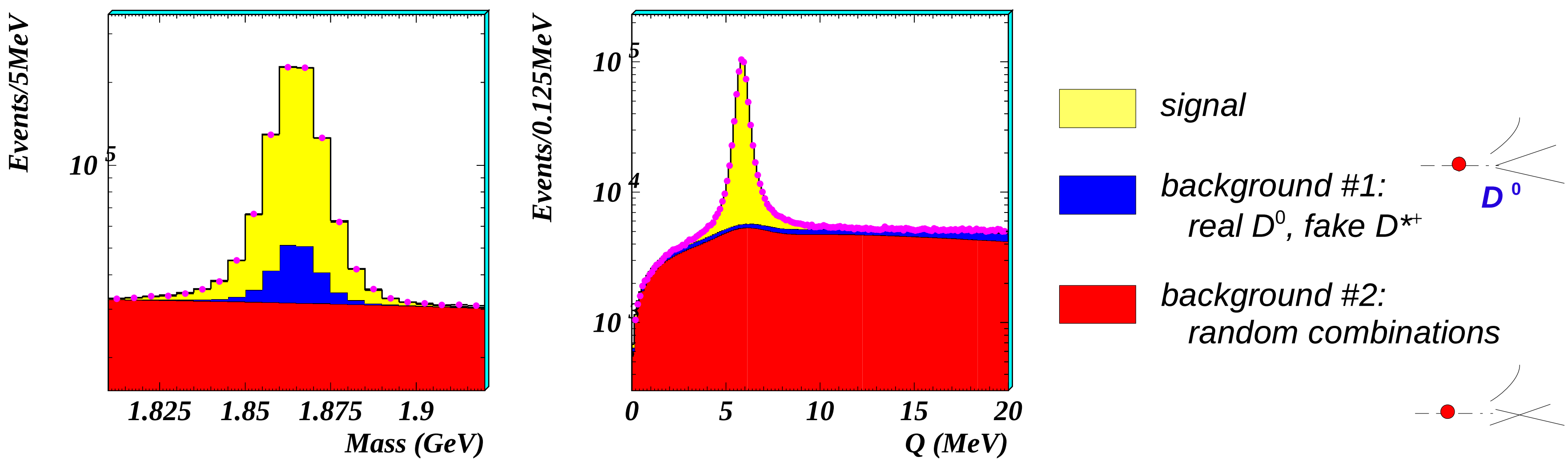
$$|\langle f|H|D^0(t)\rangle|^2 \equiv |A_1\, e_1(t) + A_2\, e_2(t)|^2$$

$$= |A_1|^2 e^{-\overline{\Gamma}(1+y)t} + |A_2|^2 e^{-\overline{\Gamma}(1-y)t} + 2e^{-\overline{\Gamma}t}\left[\mathrm{Re}(A_1 A_2^*)\cos(x\overline{\Gamma}t) + \mathrm{Im}(A_1 A_2^*)\sin(x\overline{\Gamma}t)\right]$$

- $\Longrightarrow$ fit $\{m_-^2,\ m_+^2,\ t\}$ together

$D^0(t) \to K_S^0 \pi^+ \pi^-$, Data distribution

- Reconstruction
  - K_S^0 reconstruction
  - D^0 decay vertex from $\pi^+ \pi^-$
  - D^0 mass constraint for $K_S^0 \pi^+ \pi^-$
  - $p_{D^*} > 2.5$ GeV/c



534k events

95% pure

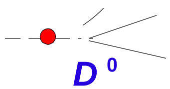
$D^0(t) \to K_S^0 \pi^+ \pi^-$, Fit PDFs

PDFs:

signal

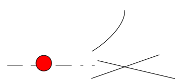
- theoretical function convolved with time and Dalitz plot resolution functions

background #1: real D^0, fake D^{*+}



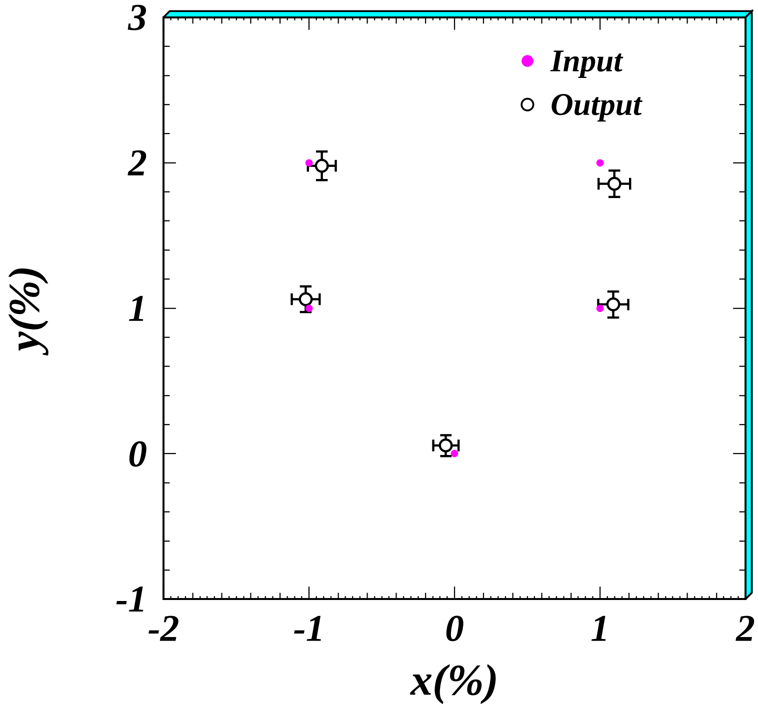
- contains wrong-taged $\overline{D}^0$ events (fraction 0.452±0.005)
- Sum of D^0 and $\overline{D}^0$ signal PDFs

background #2: random combinations



- production of Dalitz-plot and decay time PDFs

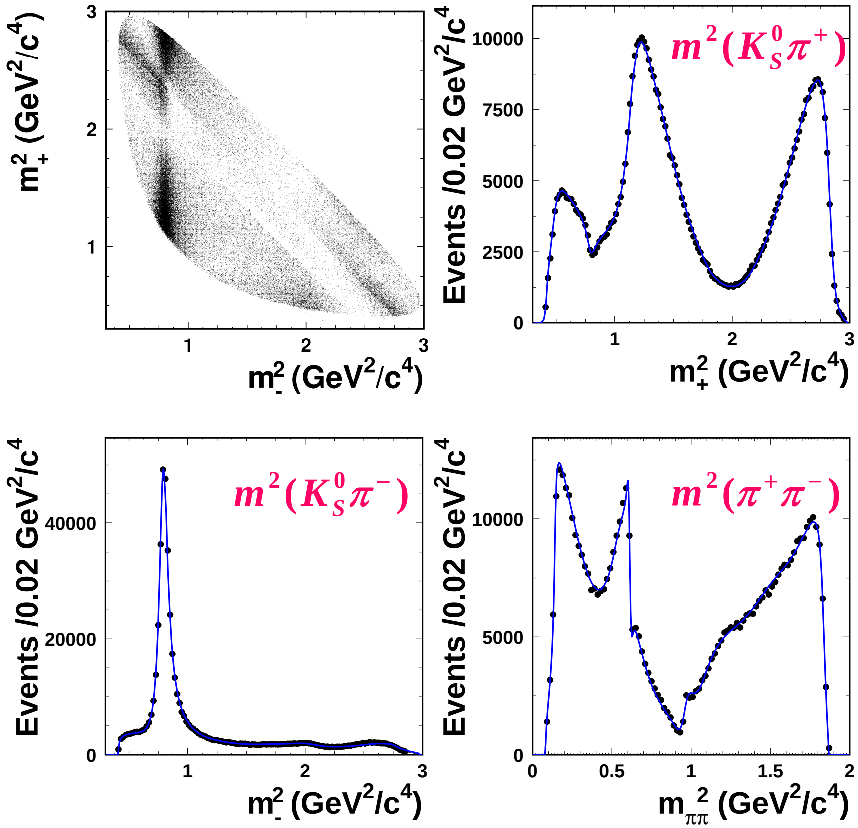
Full Geant MC test (x10 datasize)



Free parameters are x, y, $R(t)$, τ_D and Dalitz-plot parameters (a_r, ϕ_r)

$D^0(t) \to K_S{}^0\pi^+\pi^-$, No-CPV fit

Fit (1): No CPV ($a_r = \overline{a}_r$, $\phi_r = \overline{\phi}_r$, $q/p = 1$)



Resonance	Amplitude	Phase (°)	Fit fraction
$K^*(892)^-$	1.629 ± 0.006	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.8	0.0724
$K_2^*(1430)^-$	0.87 ± 0.02	-47.3 ± 1.2	0.0133
$K^*(1410)^-$	0.65 ± 0.03	111 ± 4	0.0048
$K^*(1680)^-$	0.60 ± 0.25	147 ± 29	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.3	0.0054
$K_0^*(1430)^+$	0.541 ± 0.019	91.8 ± 2.1	0.0047
$K_2^*(1430)^+$	0.276 ± 0.013	-106 ± 3	0.0013
$K^*(1410)^+$	0.33 ± 0.02	-102 ± 4	0.0013
$K^*(1680)^+$	0.73 ± 0.16	103 ± 11	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0007	115.1 ± 1.1	0.0063
$f_0(980)$	0.380 ± 0.004	-147.1 ± 1.1	0.0452
$f_0(1370)$	1.46 ± 0.05	98.6 ± 1.8	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.2	0.0180
$\rho(1450)$	0.72 ± 0.04	41 ± 7	0.0024
σ_1	1.39 ± 0.02	-146.6 ± 0.9	0.0914
σ_2	0.267 ± 0.013	-157 ± 3	0.0088
NR	2.36 ± 0.07	155 ± 2	0.0615

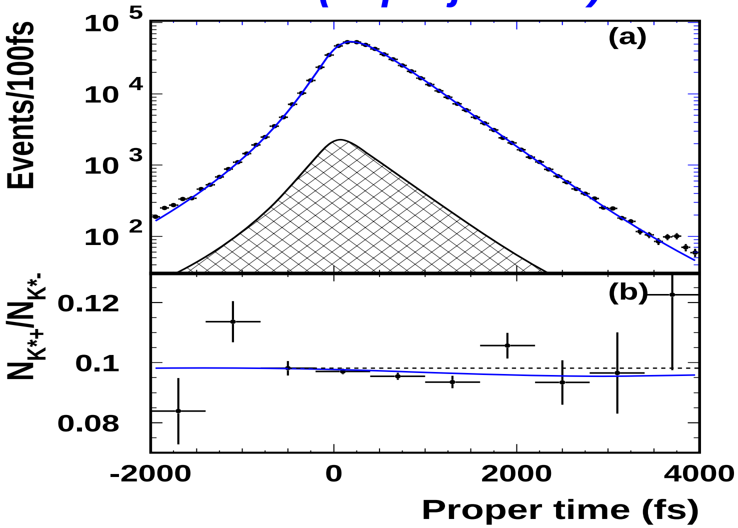
1.19

18 quasi-two-body resonances consistent with PRD 73, 112009 (2006) (ϕ_3 measurement)

$$\text{Fit Fraction} \equiv \frac{\int |a_r \mathcal{A}_r(m_-^2, m_+^2)|^2 \, dm_-^2 \, dm_+^2}{\int |\mathcal{A}(m_-^2, m_+^2)|^2 \, dm_-^2 \, dm_+^2}$$

$D^0(t) \to K_S^0\pi^+\pi^-$, No-CPV fit

Time fit (in projection)



τ_D = 409.9 ± 1.0 fs
(consistent with PDG)

$$x = (0.80 \pm 0.29 \pm 0.16)\%$$
$$y = (0.33 \pm 0.24 \pm 0.14)\%$$

(most stringent limit on x)

CLEO, PRD **72**, 012001 (2005):
$x = (1.8 \pm 3.4 \pm 0.6)\%$
$y = (-1.4 \pm 2.5 \pm 0.9)\%$

Main systematic errors	Δx(%)	Δy(%)
p_{D^*} cut	+0.076	−0.078
BG Dalitz - t correlation	$^{+0.016}_{-0.056}$	$^{+0.044}_{-0.057}$
Eff. Par.	+0.004	−0.009
BG t par.s	±0.037	±0.063
M_r & Γ_r err.s	±0.020	±0.010
Form factor	−0.031	+0.006
No q^2 dependence	−0.051	−0.041
K-Matrix model	±0.073	±0.058
No NR	−0.015	+0.003
No $K^*(1680)^+$	−0.003	−0.008
No $\rho(1450)$	−0.005	−0.006
$K_0^*(1430)^+$ bias	−0.103	+0.001
$K_2^*(1430)^+$ bias	+0.069	−0.025
$K^*(1410)^\pm$ bias	−0.016	−0.009
TOTAL	$^{+0.13}_{-0.16}$	$^{+0.10}_{-0.14}$

$D^0(t) \to K_S^0\pi^+\pi^-$, CPV fits

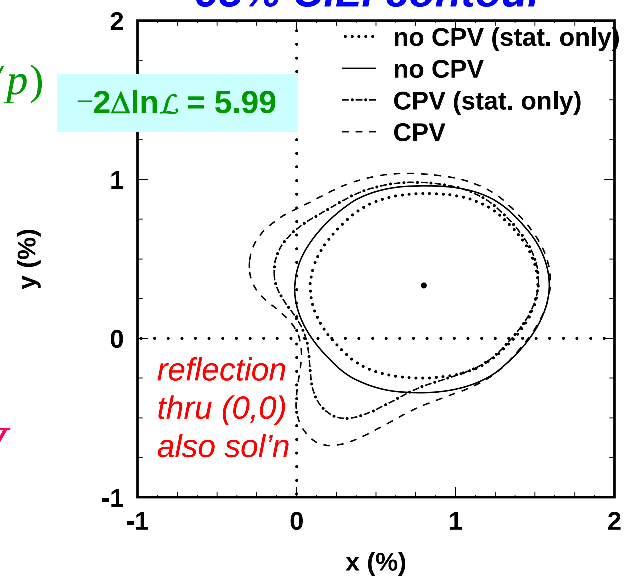
Fit (2): Allow for CPV ($a_r \neq \bar{a}_r$, $\phi_r \neq \bar{\phi}_r$, $q/p \neq 1$)

Two solutions: $\{x, y, \phi\}$ and $\{-x, -y, \phi+\pi\}$, where $\phi = \arg(q/p)$

$$
\begin{aligned}
x &= (0.81 \pm 0.30 \pm 0.17)\% \\
y &= (0.37 \pm 0.25 \pm 0.15)\% \\
|q/p| &= 0.86^{+0.30}_{-0.29}{}^{+0.10}_{-0.09} \\
\phi &= (-14^{+16}_{-18} \pm 5)^\circ
\end{aligned}
$$

- a_r, ϕ_r consistent with $\bar{a}_r, \bar{\phi}_r \Rightarrow$ no direct CPV
- $|q/p|$ $\phi \Rightarrow$ consistent with CP conservation

95% C.L. contour



Including systematics by rescaling factor $\sqrt{1+r^2}$
r = syst./stat. errors

No mixing point (0,0) corresponds to
$-2\Delta\ln\mathcal{L}=7.33 \Rightarrow$ CL = only 2.6%

Fit (3): No Direct CPV ($a_r = \bar{a}_r$, $\phi_r = \bar{\phi}_r$) :

further constrain →

$$
\begin{aligned}
|q/p| &= 0.95^{+0.22}_{-0.20} \\
\phi &= (-2^{+10}_{-11})^\circ
\end{aligned}
$$

Summary

- Two recent Belle measurements of D^0 mixing parameters presented
- Evidence for D^0 mixing found in decays to *CP* eigenstates

$$y_{CP} = 1.31 \pm 0.32 \pm 0.25\ \%\ (3.2\sigma)$$

- The most sensitive measurement of x up to now from time-dependent Dalitz-plot analysis :

$$x = 0.80 \pm 0.29 \pm 0.16\ \%\ (2.4\sigma)$$

- CPV search: no evidence found

BACKUP

$D^0(t) \to K_S^0\pi^+\pi^-$, Sensitive region for mixing

$$|\langle f|H|D^0(t)\rangle|^2 \approx |\mathcal{A}(m_-^2, m_+^2)|^2 \times \left\{1 + [\mathrm{Im}(\chi)x - \mathrm{Re}(\chi)y](\overline{\Gamma}t) + |\chi|^2 \frac{x^2+y^2}{4}(\overline{\Gamma}t)^2\right\}$$

x* and *y* modulated *by $\chi = \frac{q}{p}\frac{\overline{\mathcal{A}}(m_-^2, m_+^2)}{\mathcal{A}(m_-^2, m_+^2)}$

No CPV: $\chi = \frac{\mathcal{A}(m_+^2, m_-^2)}{\mathcal{A}(m_-^2, m_+^2)}$