D^0 mixing at Belle

Marko Starič
J. Stefan Institute, Ljubljana, Slovenia

19-25 July 2007
HEP 2007, Manchester, England

- Introduction
- Decays to CP eigenstates (lifetime difference measurement)
- Self-conjugate decays (time-dependent Dalitz plot analysis)
- Conclusions

Introduction

- Mixing between a neutral heavy-flavoured meson and its anti-particle is possible, if flavour eigenstates are not the same as mass eigenstates (masses m_1, m_2, widths Γ_1, Γ_2)

$$|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

- Time evolution is governed by mass and lifetime differences

$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

- A D^0 at $t = 0$ evolves as:

$$|D^0(t)\rangle = e^{-(\Gamma/2+im)t}[\cosh(\frac{y+ix}{2}\Gamma t)|D^0\rangle + \frac{q}{p}\sinh(\frac{y+ix}{2}\Gamma t)|\overline{D}^0\rangle]$$

- Since D^0 mixing is small ($|x|, |y| \ll 1$) expand to the lowest order in x, y. The decay rate of initially produced D^0 to a final state $|f\rangle$ is:

$$\frac{dN_{D^0\to f}}{dt} \propto |\langle f|\mathcal{H}|D^0(t)\rangle|^2 = e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- Decay time distribution of different final states sensitive to different combinations of mixing parameters x and y.

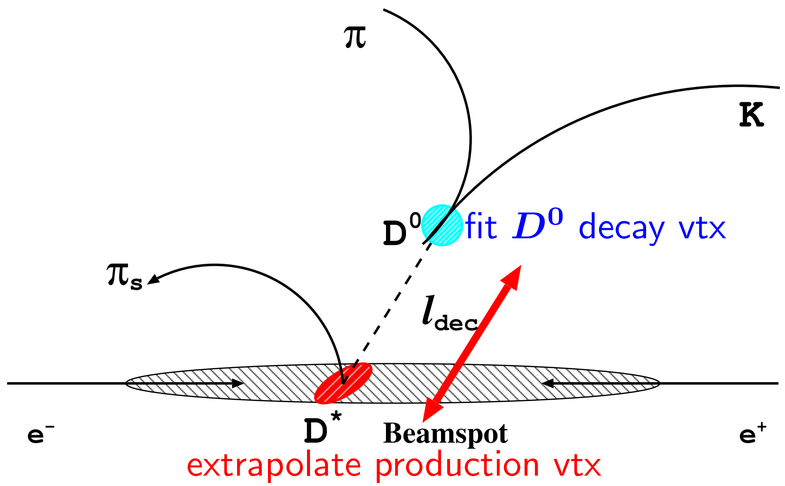
Experimental method

- $D^{*+} \to \pi^+ D^0$
  - ▷ tag the flavor of $D^0/\overline{D}^0$ at production
  - ▷ background suppression

- D^0 proper decay time t measurement:

$$t = \frac{l_{dec}}{c\beta\gamma}\,, \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$

  σ_t ... decay-time uncertainty
  (from vtx cov. matrices)



- Measurements performed at $\Upsilon(4S)$
  - ▷ to reject D^{*+} from B decays: $p^{CMS}_{D^{*+}} > 2.5\ GeV/c$
- Observables:

$$m = m(K\pi)$$
$$q = m(K\pi\pi_s) - m(K\pi) - m_\pi$$

Decays to CP eigenstates $K^+K^-,\ \pi^+\pi^-$

PRL 98, 211803 (2007)

- Measurement of lifetime difference between $D^0 \to K^-\pi^+$ and $K^+K^-, \pi^+\pi^-$
  - ▷ mixing parameter: $y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$
  - ▷ in CP conservation limit: $y_{CP} = y = \Delta\Gamma/2\Gamma$
- If CP not conserved, difference in lifetimes of $D^0/\overline{D}^0 \to K^+K^-, \pi^+\pi^-$
  - ▷ CP violating parameter: $A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$
  - ▷ $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$
  - ▷ $A_\Gamma = \frac{1}{2}A_M y \cos\phi - x\sin\phi$

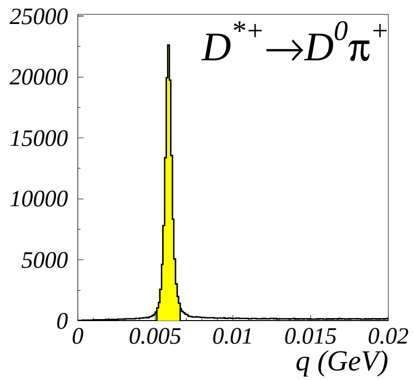
(S. Bergmann et.al., PLB 486, 418 (2000))

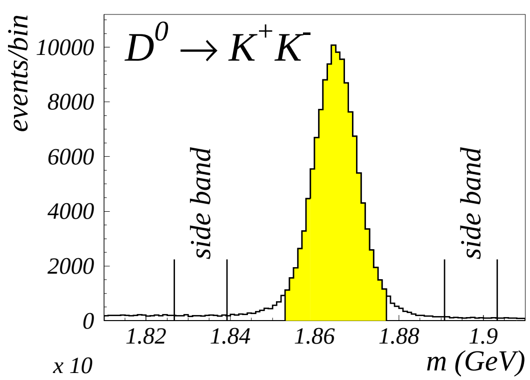
$D^0 \to K^+K^-,\ \pi^+\pi^-$ (540 fb^{-1})

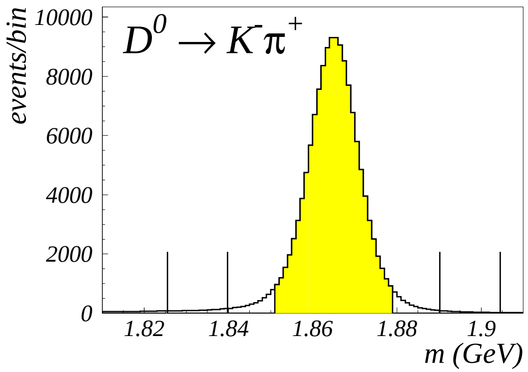
Event Selection

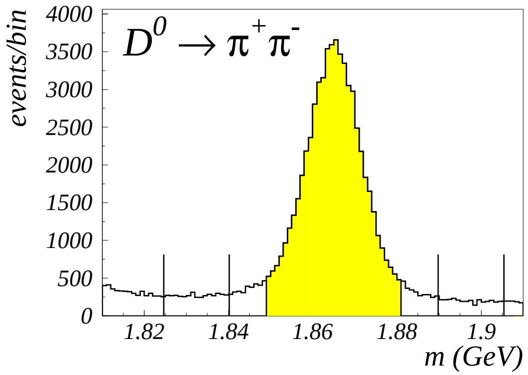
- Reconstruction
  - ▷ K and π selection
  - ▷ vertex fits
  - ▷ $p^*(D^{*+}) > 2.5$ GeV/c
- Analysis cuts
  - ▷ Δm, Δq, σ_t
  - ▷ optimized on tuned Monte Carlo
  - ▷ figure of merit: statistical error on y_{CP}

σ_t/τ_{PDG}	$\Delta m/\sigma_m$	Δq (MeV)
0.90	2.30	0.80









- Background estimated from sidebands in m
  - ▷ side band position optimized
- Signal yields (purities) entering the measurement

channel	KK	$K\pi$	$\pi\pi$
signal	110K	1.2M	50K
purity	98%	99%	92%

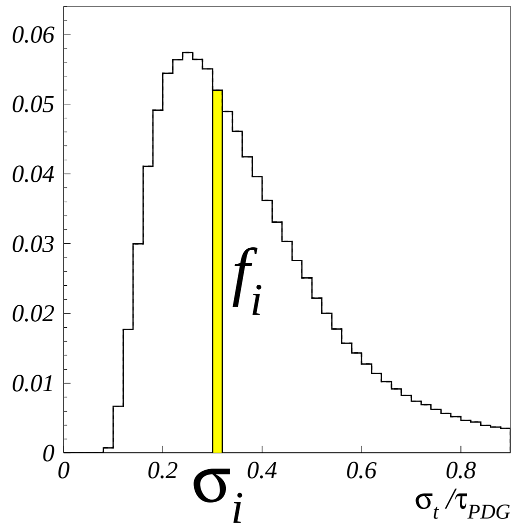
Lifetime fit

- Parameterization of proper decay time distribution

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

- Resolution function
  - ▷ constructed from normalized distribution of event proper time uncertainty σ_t
  - ▷ ideally, σ_t of event represents uncertainty with Gaussian p.d.f
  - ▷ examining pulls $\to$ p.d.f.=sum of 3 Gauss.

σ_t distribution for $D^0 \to K^-\pi^+$



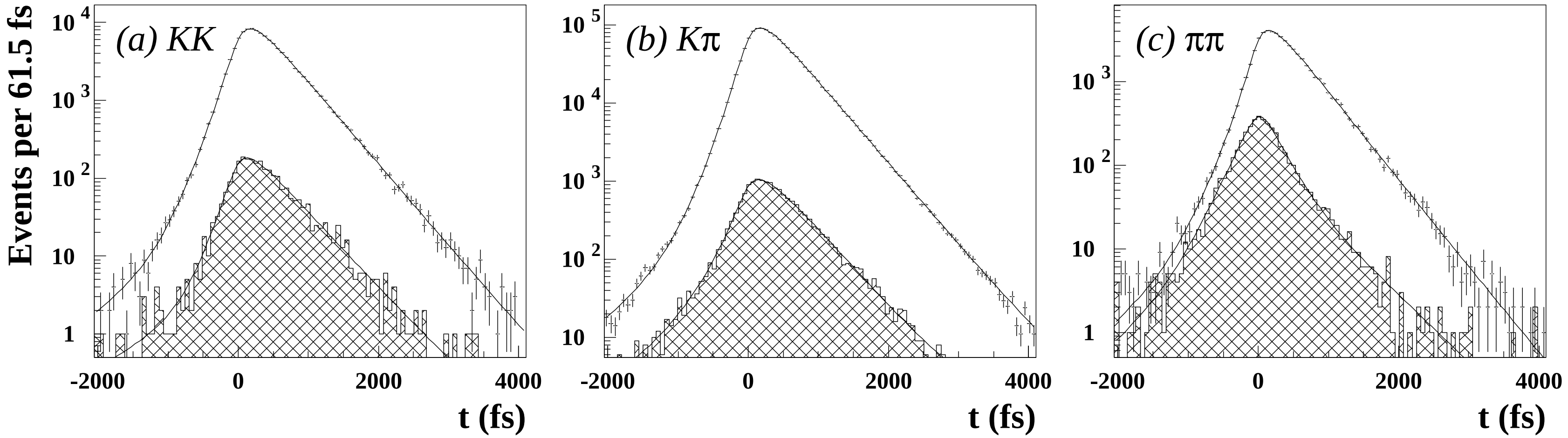
$$R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t; \sigma_{ik}, t_0)\ , \qquad \sigma_{ik} = s_k \sigma_k^{pull} \sigma_i$$

- $R(t)$ studied in detail with $D^0 \to K\pi$ and special MC samples
  - also in changing running conditions (two different SVD, small misalignments)

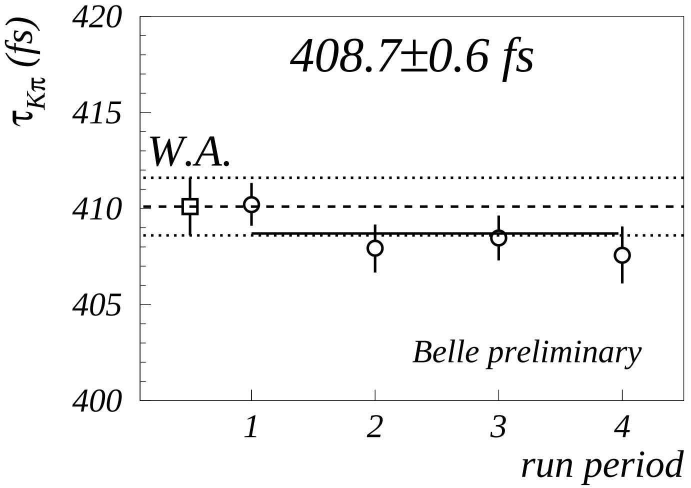
Marko Starič
J. Stefan Institute, Ljubljana, Slovenia

Simultaneous $KK/\pi\pi/K\pi$ binned likelihood fit

quality of fit: $\chi^2 = 1.084$ (289)



$D^0 \to K\pi$ lifetime very stable in slightly different running periods



$D^0 \to K^+K^-,\ \pi^+\pi^-$ *(540 fb^{-1})*

Cross-checks

- MC: $y_{CP}(\mathrm{out}) - y_{CP}(\mathrm{input}) < 0.04\%$ for large range of input values
- y_{CP} independent of resolution function parameterization:
  $R(t) =$ single Gaussian: $\Delta\tau = 3.5\%$, $\Delta y_{CP} = 0.01\%$
- Exchanging data side band with signal window background from tuned MC:
  $\Delta y_{CP} = -0.04\%$

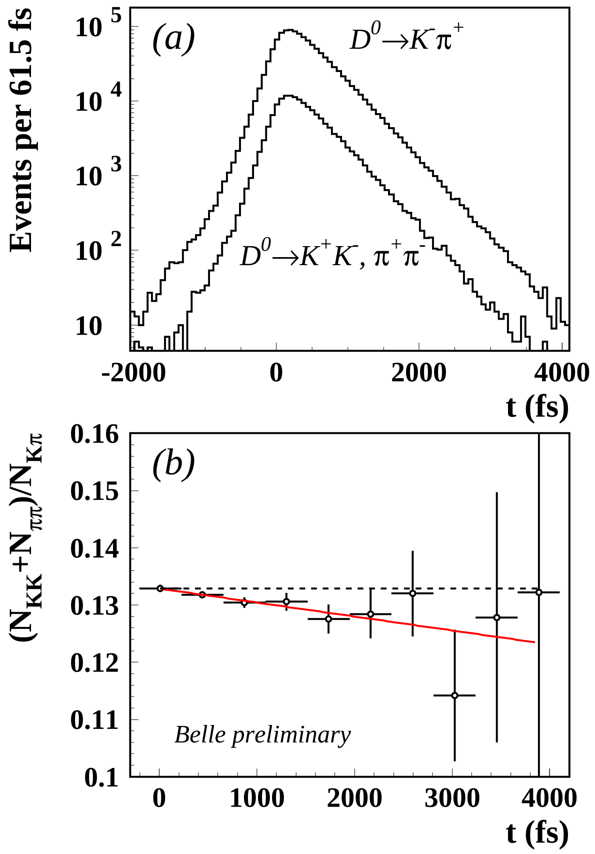
Systematics

source	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 side bands	0.09%	0.06%
difference btw. final states in opening angle	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%

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

Results

	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	−0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15



Evidence for $D^0 - \overline{D}^0$ mixing
(regardless of possible CPV)

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

$> 3\sigma$ above zero (4.1σ stat. only)

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

no evidence for CP violation

Self-conjugate decays $K_s^0\,\pi^+\pi^-$

arXiv:hep-ex/0704.1000v2 (submitted to PRL)

- Different decays identified through Dalitz plot analysis
  - CF: $D^0 \to K^{*-}\pi^+$
  - DCS: $D^0 \to K^{*+}\pi^-$
  - CP: $D^0 \to \rho^0 K_s^0$
- Matrix element is Dalitz space dependent; for initially produced $|D^0\rangle$:

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

  where $m_\pm^2 = m^2(K_s^0\pi^\pm)$ and $e_{1,2}(t) = e^{-i(m_{1,2}-i\Gamma_{1,2}/2)t}$

- Amplitudes $\mathcal{A}(\overline{\mathcal{A}})$ for $D^0(\overline{D}^0)$ decays parameterized as a sum of quasi-two-body amplitudes + non-resonant contribution
- Decay rate $dN/dt \propto |\mathcal{M}(m_-^2, m_+^2, t)|^2$ contains terms

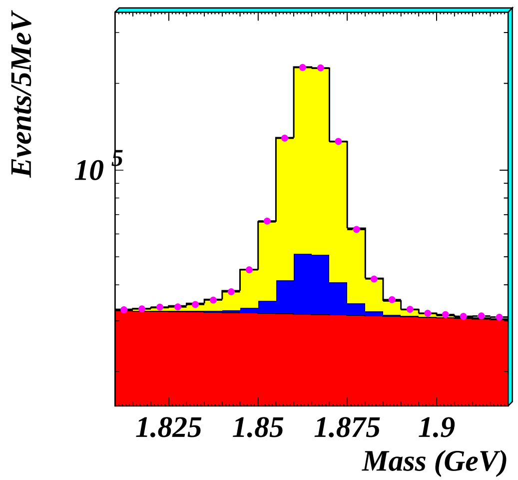
  $\exp(-\Gamma t)\cos(x\Gamma t)$, $\exp(-\Gamma t)\sin(x\Gamma t)$, $\exp[-(1\pm y)\Gamma t]$

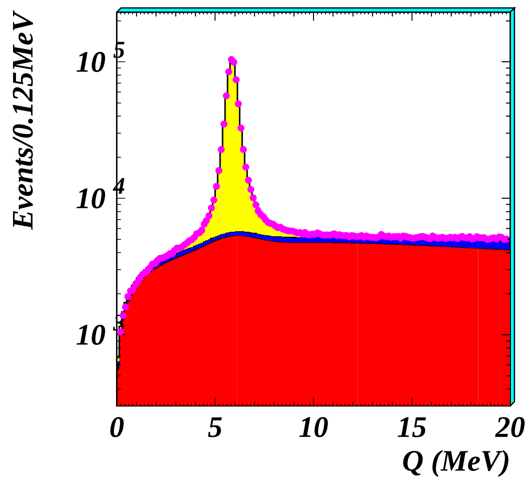
- With time-dependent Dalitz plot analysis both mixing parameters (x and y) can be measured.

Event Selection

- Reconstruction
  - K_s^0 reconstruction and π selection
  - D^0 decay vertex from π^+, π^-
  - D^0 mass kinematic constraint for $m(K_s, \pi^+, \pi^-)$
  - $p^*(D^{*+}) > 2.5$ GeV/c
- Signal yields and purity

signal	purity
534000	95%

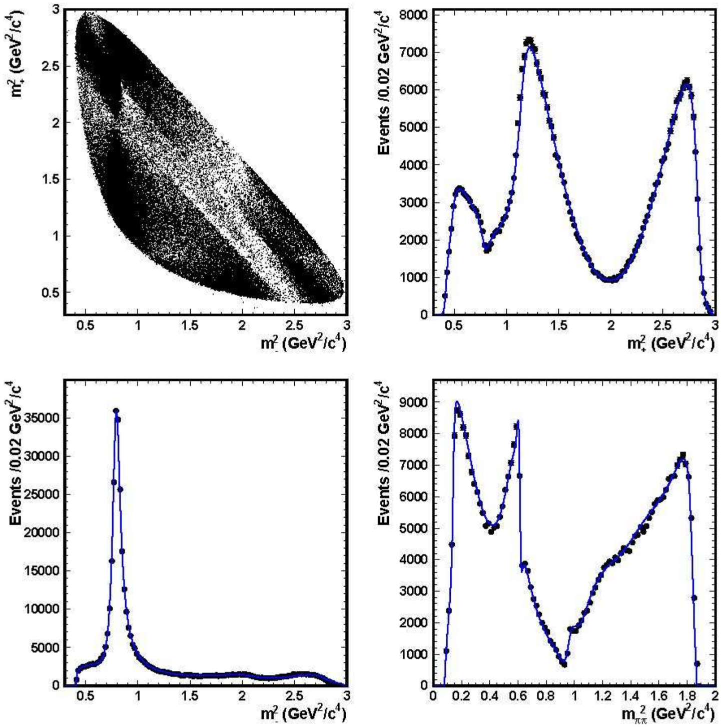




- Combinatorial
- Random π_s
- Signal

$D^0 \to K_s^0\,\pi^+\pi^-$ Dalitz (540 fb^{-1})

Dalitz projection of fit



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

- Dalitz model: 18 different (BW) resonances and a non-resonant contribution
- Results (amplitudes, phases) in agreement with PRD73, 112009 (2006) (measurement of $\phi_3(\gamma)$)
- To test the scalar $\pi\pi$ contributions, K-matrix formalism is also used

$D^0 \to K_s^0 \pi^+\pi^-$ Dalitz (540 fb^{-1})

Results

Assuming CP conservation

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

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

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

$x = 1.8 \pm 3.4 \pm 0.6\%$

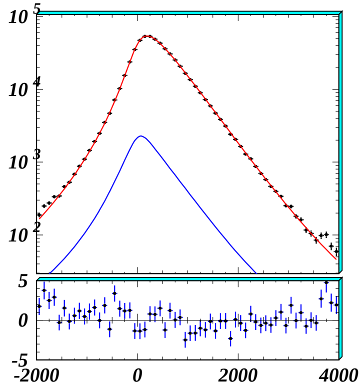
$y = -1.4 \pm 2.5 \pm 0.9\%$

Search for CP violation

- Dalitz plot fit separately for D^0 and $\overline{D}^0$
- fit parameters consistent for both samples
  $\to$ no direct CPV
- parameters $|q/p|$ and $\phi = \arg(q/p)$ consistent with CP conservation

$$|q/p| = 0.86^{+0.30+0.10}_{-0.29-0.09} \qquad \phi = (-14^{+16+5}_{-18-5})^{\circ}$$

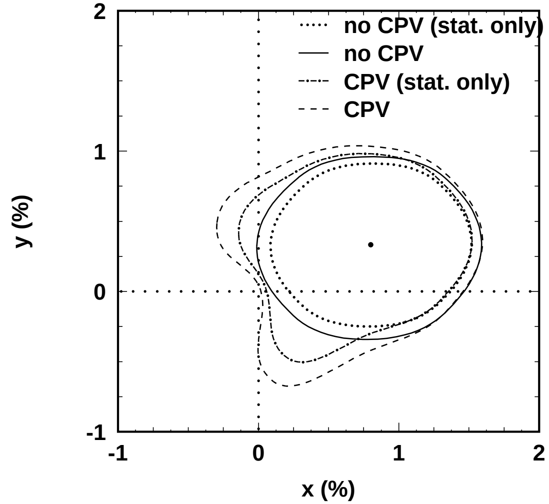
Time projection of fit



$$\tau = 409.9 \pm 0.9 \text{ fs}$$

$\to$ consistent with PDG

95% C.L. contours



Conclusions

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

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

- From time-dependent Dalitz plot analysis the most sensitive measurement of x up to now:

$$x = 0.80 \pm 0.29^{+0.13}_{-0.16} \ \% \ (2.4\sigma)$$

- CPV search: no evidence found

Backup slide: $D^0 \to K_s^0 \pi^+\pi^-$ Dalitz

- Systematics

Experimental

Source	Δx (%)	Δy (%)
Event selection	$^{+0.076}_{-0.001}$	$^{+0.018}_{-0.078}$
Dalitz dep. effi.	$+0.004$	-0.009
Background	$^{+0.041}_{-0.068}$	$^{+0.077}_{-0.086}$
Total	$^{+0.09}_{-0.07}$	$^{+0.08}_{-0.12}$

Model dependence

Source	Δx (%)	Δy (%)
$M\&\Gamma$ errors	± 0.020	± 0.010
$F_r = F_D = 1$	-0.031	$+0.006$
$\Gamma(q^2) = \mathrm{const.}$	-0.051	-0.041
K-Matrix	± 0.073	± 0.058
No NR	-0.015	$+0.003$
No $K^*(1680)^+$	-0.003	-0.008
No $\rho(1450)$	-0.005	-0.006
$K_0^*(1430)$ DCS/CF	-0.103	$+0.001$
$K_2^*(1430)$ DCS/CF	$+0.069$	-0.025
$K^*(1410)$ DCS/CF	-0.016	$+0.009$
Total	$^{+0.10}_{-0.14}$	$^{+0.06}_{-0.08}$