D-Mixing and search for CPV at Belle

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- Introduction
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- Conclusions

Introduction

Mixing

- Flavor eigenstates $\neq$ mass eigenstates (with $m_{1,2}$, $\Gamma_{1,2}$)

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

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

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

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

- $|x|, |y| \ll 1$:

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

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

CP violation

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

- $q/p \neq 1 \ \Rightarrow$ indirect CP violation
- $q/p = |q/p| \cdot e^{i\phi}$:
  - ▷ $|q/p| \neq 1 \ \Rightarrow$ CP violation in mixing
  - ▷ $\phi \neq 0(\pi) \ \Rightarrow$ CP violation in interference of decays w/ and w/o mixing
- $|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\bar{D}^0 \to \bar{f})|^2 \ \Rightarrow$ direct CP violation

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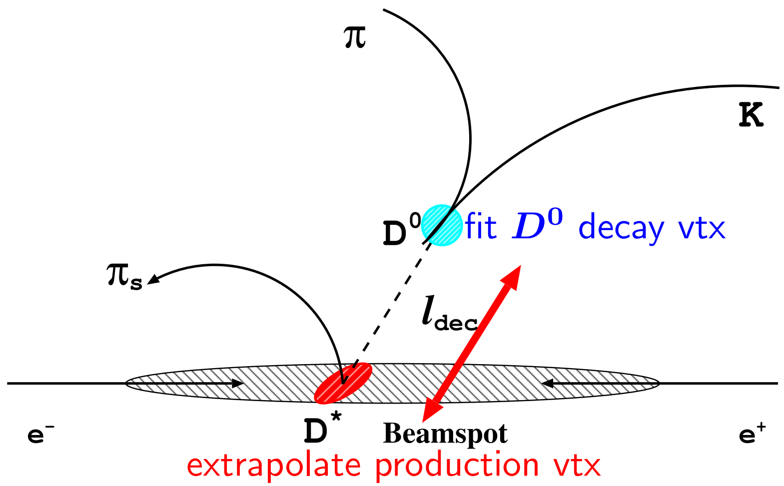
Experimental method

- $D^{*+} \to \pi^+ D^0$
  - ▷ flavor tagging by π_{slow} charge
  - ▷ 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:

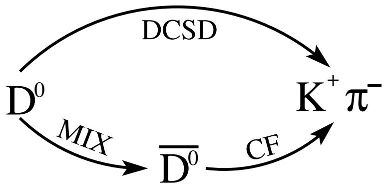
$$m = m(K\pi)$$

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

Wrong Sign decays $K^+\pi^-$

PRL 96, 151801 (2006)

- Wrong sign (WS) final state:
  via doubly Cabibbo suppressed decay (DCS) or via mixing



- Proper decay time distribution of WS events (assuming negligible CPV)

$$\frac{dN}{dt} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

DCS, interference, mixing

R_D ratio of DCS/CF decay rates
$x' = x\cos\delta + y\sin\delta$
$y' = y\cos\delta - x\sin\delta$
δ strong phase between DCS and CF

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

- Search for CPV
  - ▷ Fit D^0 and $\bar{D}^0$ samples separately $\Rightarrow R_D^{\pm},\ x'^{2\pm},\ y'^{\pm}$
- CPV in DCS decays:

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

- CPV in mixing and interference $\to$ by solving 4 equations for 4 unknowns:

$$x'^{\pm} = (1 \pm \frac{1}{2}A_M) \cdot (x' \cos\phi \pm y' \sin\phi)$$
$$y'^{\pm} = (1 \pm \frac{1}{2}A_M) \cdot (y' \cos\phi \mp x' \sin\phi)$$

$\to x',\ y',\ \phi,\ |q/p| = 1 + \frac{1}{2}A_M$

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

Results

- DCS/CF ratio:

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

- Mixing:

$$x'^2 = (0.18^{+0.21}_{-0.23}) \times 10^{-3}$$
$$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$$

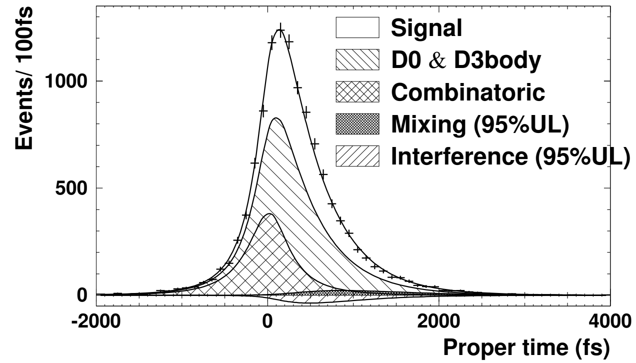
$\rightarrow$ no mixing point at 2σ

- Search for CPV:

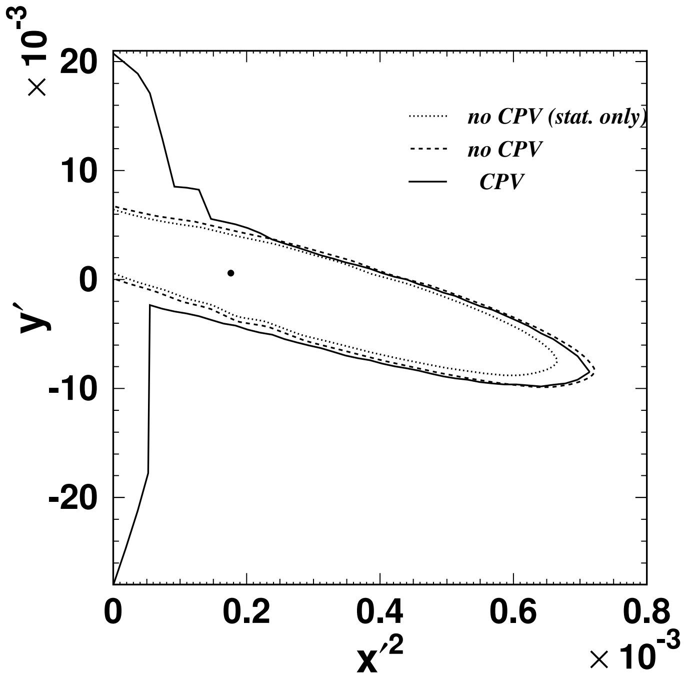
$$A_D = (2.3 \pm 4.7)\%$$
$$A_M = 0.67 \pm 1.2$$
$$|\phi| = 0.16 \pm 0.44$$

$\rightarrow$ consistent with no CPV

Unbinned fit to time distributions



95% C.L. contours



Decays to CP-even 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))

PLB 670, 190 (2008)

- Measurement of CP-violating asymmetry A_{CP}

$$A_{CP}^f = \frac{\mathcal{B}(D^0 \to f) - \mathcal{B}(\bar{D}^0 \to \bar{f})}{\mathcal{B}(D^0 \to f) + \mathcal{B}(\bar{D}^0 \to \bar{f})}$$

$$A_{CP}^f = a_d^f + a_{\rm ind} = a_d^f - A_\Gamma$$

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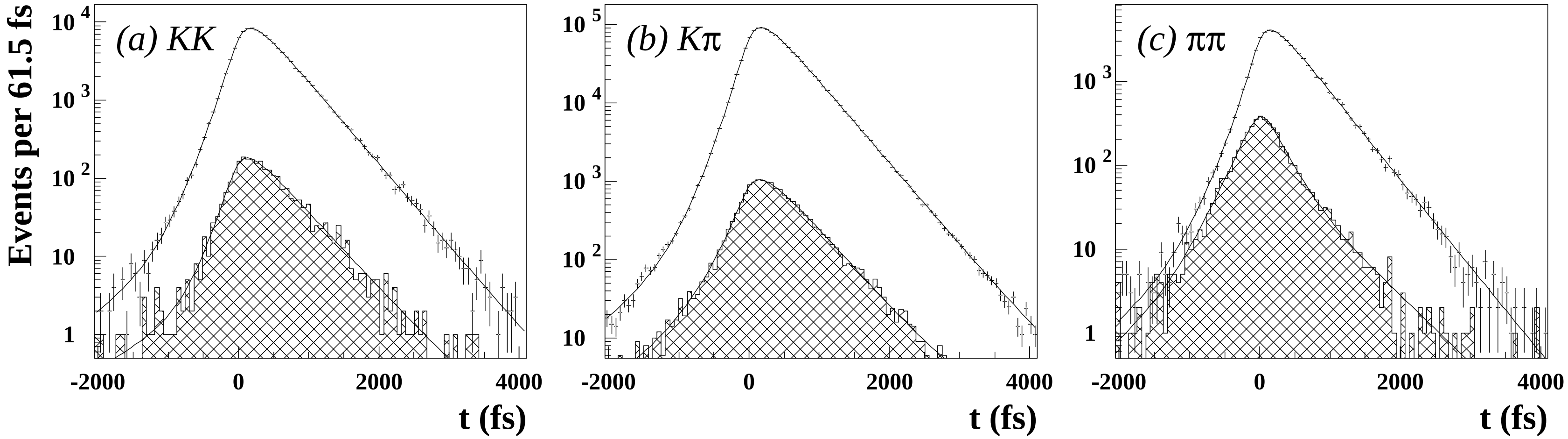
$D^0 \to K^+K^-,\ \pi^+\pi^-$ (540 fb^{-1})

- Data samples: signal yields (purities)

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

- Background estimated from sidebands in m
- Resolution function: decay mode and run period dependent
- Simultaneous $KK/\pi\pi/K\pi$ binned maximum likelihood fit

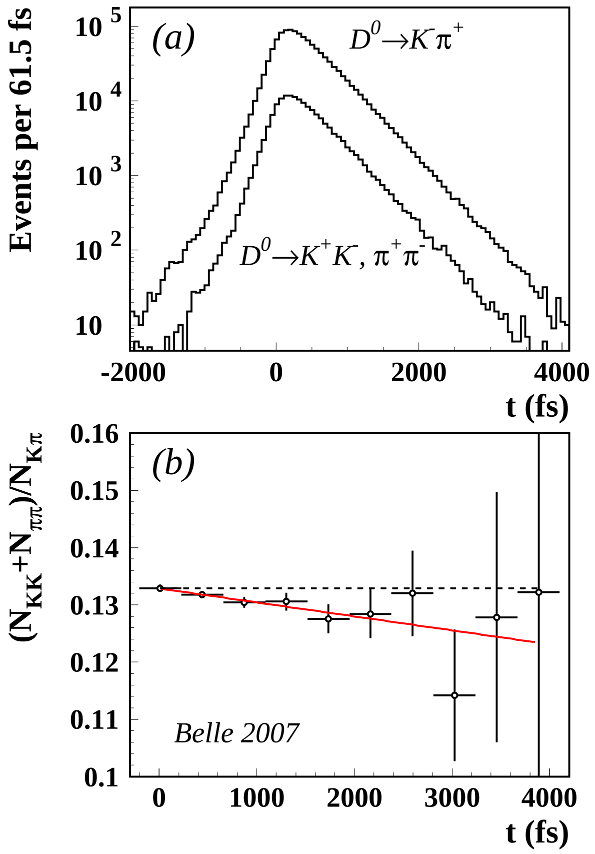


quality of fit: $\chi^2 = 1.084$ (289)

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

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

Search for CP-violating asymmetry A_{CP}

- Measured asymmetry

$$A^{reco} = A_{FB}^{D^{*+}} + A_{CP}^{f} + A_{\epsilon}^{\pi}$$

- Asymmetry of slow pion efficiency (A_ϵ^π) can be measured using tagged and untagged $D^0 \to K^-\pi^+$

$$\begin{aligned} A_{\rm rec}^{\rm tag} &= A_{FB} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi} + A_{\epsilon}^{\pi} \\ A_{\rm rec}^{\rm untag} &= A_{FB} + A_{CP}^{K\pi} + A_{\epsilon}^{K\pi} \end{aligned}$$

- Efficiency corrected asymmetry:

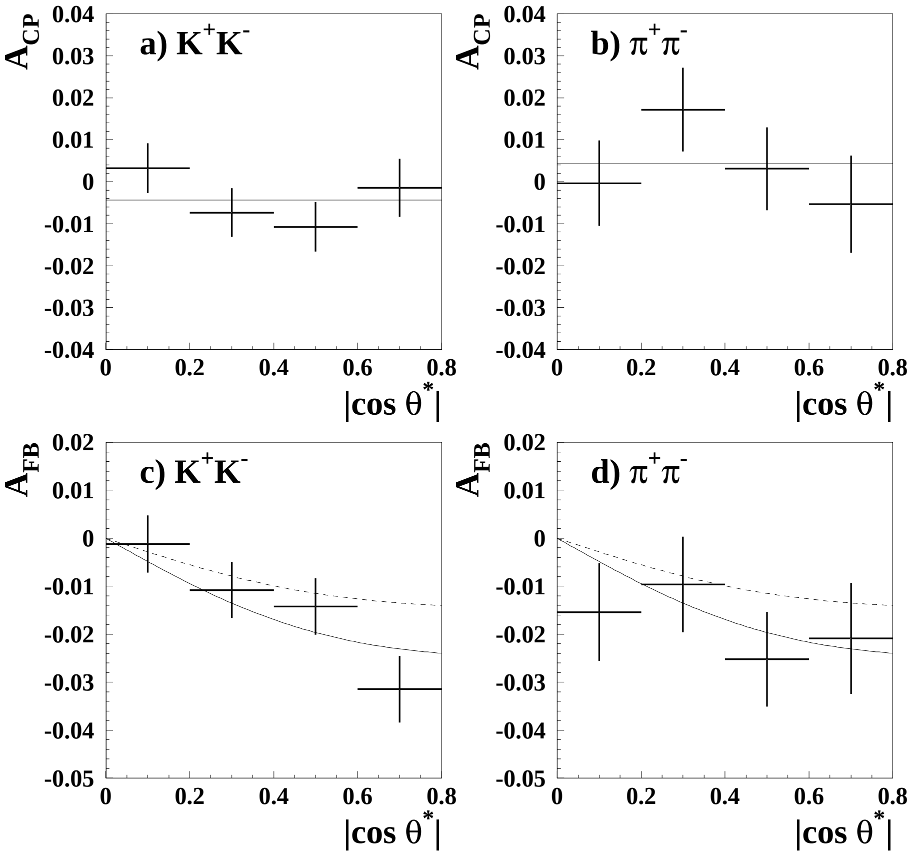
$$A_{corr}^{reco} = A^{reco} - A_{\epsilon}^{\pi} = A_{FB} + A_{CP}^{f}$$

- Forward-backward asymmetry is an odd function of $\cos\theta^*$
- A_{CP} and A_{FB} are then obtained by adding/subtracting bins at $\pm\cos\theta^*$:

$$A_{CP} = \frac{A_{corr}^{reco}(\cos\theta^*) + A_{corr}^{reco}(-\cos\theta^*)}{2}$$

$$A_{FB} = \frac{A_{corr}^{reco}(\cos\theta^*) - A_{corr}^{reco}(-\cos\theta^*)}{2}$$

Results



$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$
$$A_{CP}^{\pi\pi} = (+0.43 \pm 0.52 \pm 0.12)\%$$

→ consistent with no CPV

Direct CPV: $a_d^f = A_{CP}^f + A_\Gamma$

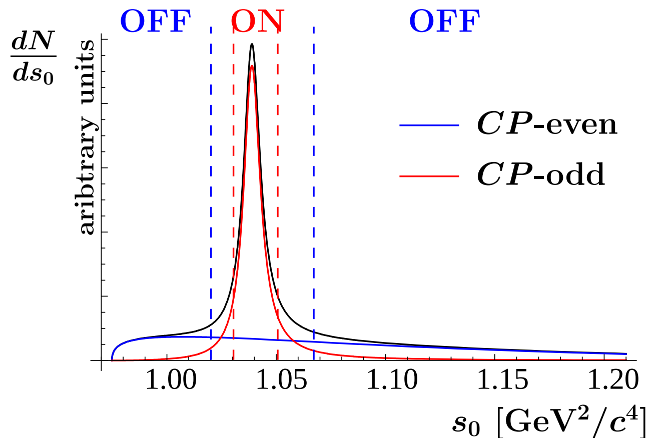
$$a_d^{KK} = (-0.42 \pm 0.42 \pm 0.19)\%$$
$$a_d^{\pi\pi} = (+0.44 \pm 0.60 \pm 0.19)\%$$

→ no sign of direct CPV

Decays to CP-odd eigenstate ϕK_s^0

to be submitted to PRD

- Measurement of lifetime difference between CP-even and CP-odd eigenstates



- $m(K^+K^-)$ dependent CP mixture:
  - ▹ peak region: mainly CP-odd ($\phi(1020)$)
  - ▹ sideband: mainly CP-even ($a_0(980)$)
- Decay rate (no CPV):

$$\frac{dN}{dt} \propto a_1(s_0)e^{-\frac{t}{\tau}(1+y)} + a_2(s_0)e^{-\frac{t}{\tau}(1-y)}$$

- By measuring effective lifetimes in the peak region (ON) and in sideband (OFF)

$$y_{CP} = \frac{1}{f_{ON} - f_{OFF}} \cdot \frac{\tau_{ON} - \tau_{OFF}}{\tau_{ON} + \tau_{OFF}}$$

f_{ON}, f_{OFF} CP-even fractions, obtained from Dalitz model

- Topologically equal events in ON and OFF regions → reduced effects of resolution function.

$D^0 \to \phi K_s^0$ (673 fb^{-1})

- Untagged data sample used to increase statistics

region	ON	OFF
signal	72k	62k
purity	97%	91%

- Background estimated from sidebands in (m_{D^0}, m_{K_s}) plane
- $f_{ON},\ f_{OFF}$ from fit to $m(K^+K^-)$ using 8-resonance Dalitz model
- $\tau_{ON},\ \tau_{OFF}$ determined from mean proper decay times of all events and background events:

$$\tau_R = \frac{<t>^R - (1-p^R) <t>_b^R}{p^R}, \quad R = \{ON, OFF\}$$

Results

$y_{CP} =$ (0.11±0.61±0.52) %

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

PRL 99, 131803 (2007)

- Different decays identified through Dalitz plot analysis

  CF: $D^0 \to K^{*-}\pi^+$
  DCS: $D^0 \to K^{*+}\pi^-$
  CP: $D^0 \to \rho^0 K_s^0$

  $\to$ relative phases can be determined (unlike $D^0 \to K^+\pi^-$)

- Matrix element is Dalitz space dependent:

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

  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 parametrized 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

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

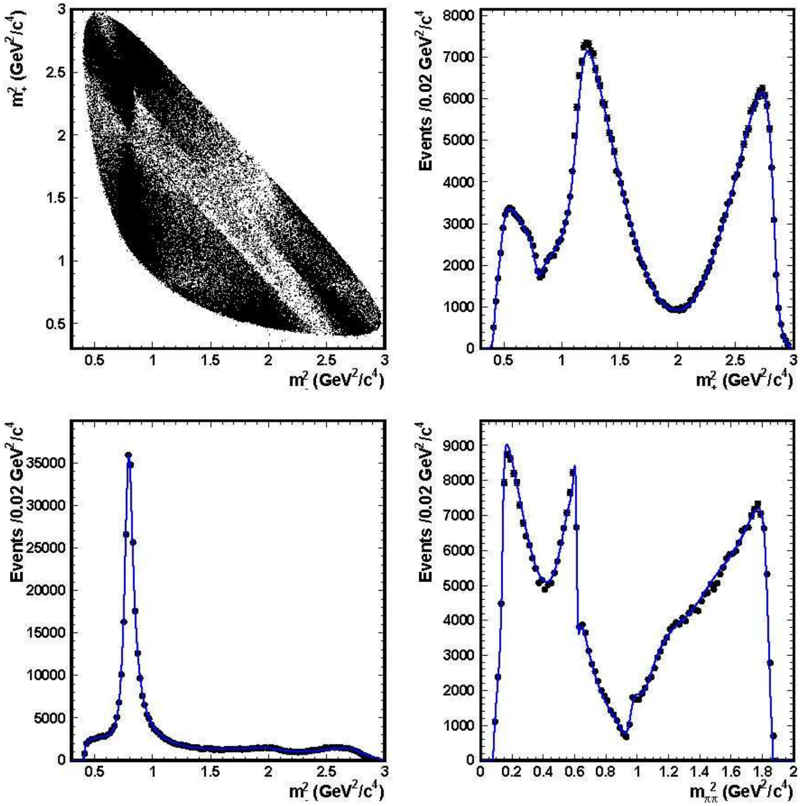
- With time-dependent Dalitz plot analysis both mixing parameters (x and y) can be measured.

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

- Signal yield and purity

signal	purity
534000	95%

- Dalitz projection of a 3D fit (unbinned max. likelihood)



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

Results

Assuming CP conservation

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

$$y = 0.33 \pm 0.24^{+0.10}_{-0.14}\ \%$$

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

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

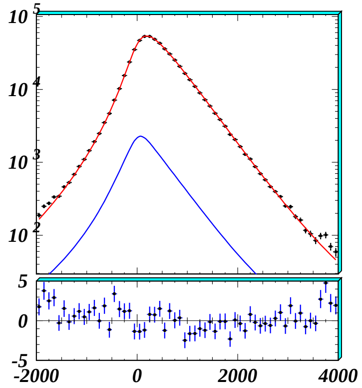
Search for CP violation

- 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

$$|q/p| = 0.86^{+0.30+0.10}_{-0.29-0.09}$$

$$\phi = (-0.24^{+0.28}_{-0.30} \pm 0.09)$$

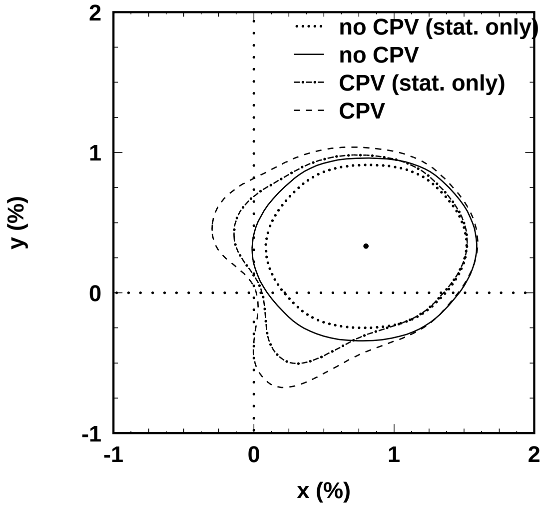
Time projection of fit



$\tau = 409.9 \pm 0.9$ fs

$\to$ consistent with PDG

95% C.L. contours



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Conclusions

- Measurements of D-mixing at Belle from recent years as well as searches for CPV have been presented.
- In 2007 the first evidence for D-mixing found in decays to CP eigenstates.
- From time-dependent Dalitz plot analysis the most sensitive measurement of x up to now.
- CPV: no evidence found so far.
- Till the end of Belle data taking (next spring) expect to reach 1 ab^{-1}
  - ▷ these measurements will be updated
  - ▷ planned to analyse also other perspective decay modes ($\pi^+\pi^-\pi^0$, $K_s^0K^+K^-$, $K^+\pi^-\pi^0$, ...)

Statistical method

- y_{CP} and A_Γ can be determined from mean of the timing distributions (e.g. without fitting the data), and the error from r.m.s
- Assumptions:
  - ▷ timing distribution is a convolution of exponential with some resolution function + some background
  - ▷ resolution function offsets of final states are the same and small

$$P(t) = p\frac{1}{\tau}e^{-t/\tau} * R_s(t) + (1-p)B(t) \quad \Rightarrow \quad <t>= p(\tau + t_0) + (1-p) <t>_b$$

$$\tau + t_0 = \frac{<t> -(1-p) <t>_b}{p} =<t>_s$$

- In lifetime difference t_0 cancels, thus if $t_0 \ll \tau$

$$y_{CP} = \frac{<t>_{K\pi} - <t>_{KK}}{<t>_{KK}}$$

- Result with this method for $D^0 \to K^+K^-, \pi^+\pi^-$:

$$y_{CP} = (1.35 \pm 0.33_{stat})\ \%$$

Systematics of $D^0 \to K^+K^-, \pi^+\pi^-$

source	y_{CP}	A_Γ
Acceptance	0.12%	0.07%
Equal t_0	0.14%	0.08%
Mass window position	0.04%	0.003%
Signal/sideband background differences	0.09%	0.06%
Opening angle distributions	0.02%	
Background distribution $B(t)$	0.07%	0.07%
(A)symmetric resolution function	0.01%	0.01%
Selection variation	0.11%	0.05%
Binning of t distribution	0.01%	0.01%
Sum in quadrature	0.25%	0.15%

Systematic uncertainties in A_{CP}

Source	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$
Signal counting	0.04%	0.06%
Slow pion corrections	0.10%	0.10%
A_{CP} extraction	0.03%	0.04%
Sum in quadrature	0.11%	0.12%

Systematics of $D^0 \to \phi K_s^0$

Source	Systematic error (%)
Resolution function offset difference $t_0^{\rm OFF} - t_0^{\rm ON}$	± 0.38
Estimation of $\langle t \rangle_b$	± 0.10
$D^0 \to K^+ K^- \pi^+ \pi^-$ background	± 0.07
Selection of sideband	± 0.05
Variation of selection criteria	± 0.30
Fitting procedure	± 0.10
Proper decay time range and binning	± 0.07
Dalitz model	± 0.01
Total	± 0.52

Backup slide

Systematics of $D^0 \to K_s^0 \pi^+\pi^-$ Dalitz

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	$^{+0.10}_{-0.14}$	$^{+0.06}_{-0.08}$

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