Evidence for Mixing of Neutral D Mesons

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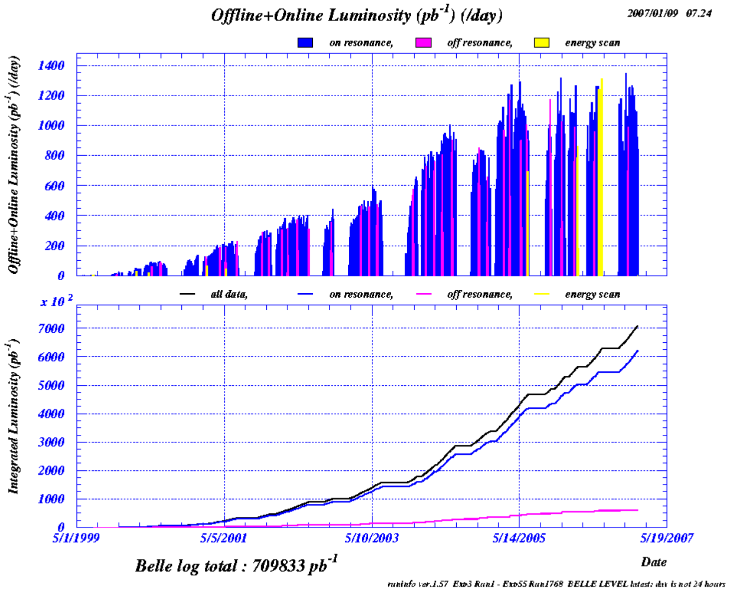
representing Belle collaboration

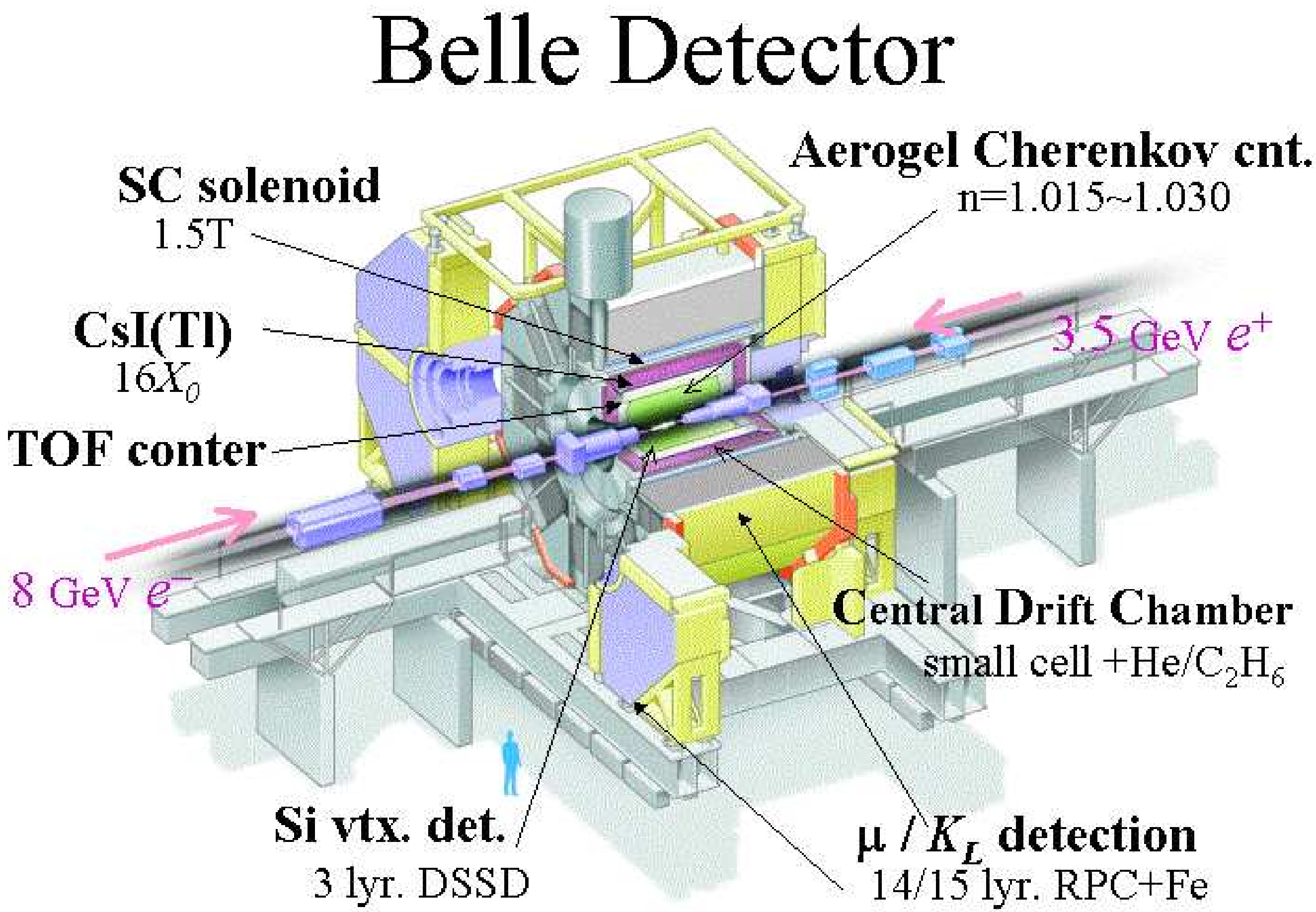
April 2007
DESY seminar

- Belle experiment
- D-mixing formalism/experimental
- 4 measurements

Belle experiment

- KEK, Tsukuba, Japan
- KEKB: asymmetric e^+e^- collider at $\Upsilon(4s)$ (B-factory)
  $e^+(3.5GeV) \rightarrow\leftarrow e^-(8GeV)$
- Continuous injection
- Peak luminosity: $\mathcal{L} = 1.7 \cdot 10^{34}/cm^2/s$
- Integrated luminosity: $\int \mathcal{L} dt = 710 fb^{-1}$

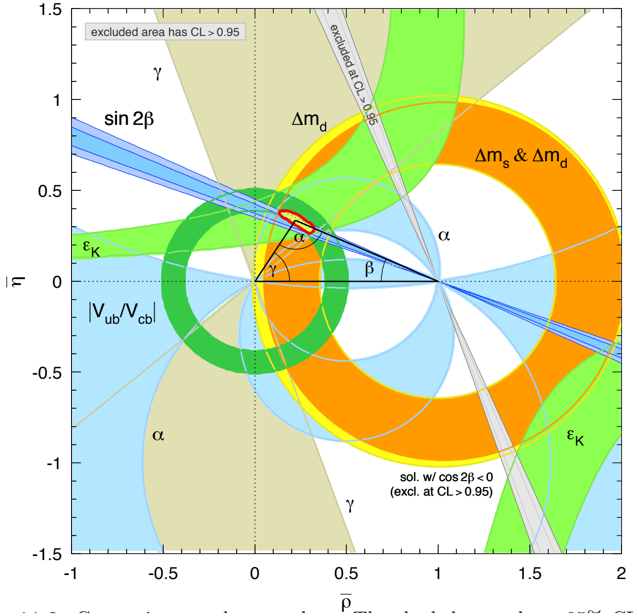




- Tracking: $\sigma(p_T)/p_T = 0.2\%\sqrt{p_T^2 + 2.5}$
- PID: $\epsilon(K^\pm) \approx 85\%$, $\epsilon(\pi^\pm \rightarrow K^\pm) \leq 10\%$ for $p < 3.5\ GeV/c$

Physics at Belle

- Main goal: study of CPV in B-meson decays
  observed in 2001
  since then many precise measurements performed



- Various results in charm physics (production: $\sigma(c\bar{c}) \approx \sigma(B\bar{B})$)
  among others - search for D-mixing
- Mixing observed in K^0, B^0_d and B^0_s (2006)
- D-mixing has not been observed since many years

Phenomena of Mixing

- Mixing: transition of particles to anti-particles (and vice versa)
- Possible for neutral particles when flavour eigenstates not the same as mass eigenstates (masses m_1, m_2, widths Γ_1, Γ_2)

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

- $p/q \neq 1$ sign for CP violation
- Time evolution governed by mass and lifetime differences

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

- Time evolution given by

$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{pmatrix} = (\hat{M} - i\frac{\hat{\Gamma}}{2})\begin{pmatrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{pmatrix}$$

- Solution:

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

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

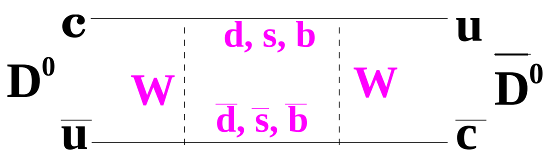
D-mixing in Standard Model

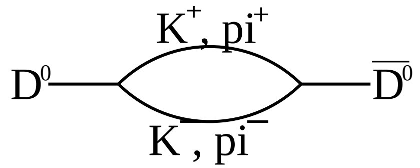
- Mixing in the SM governed by box diagrams
- Mixing in D^0 system is rare process:

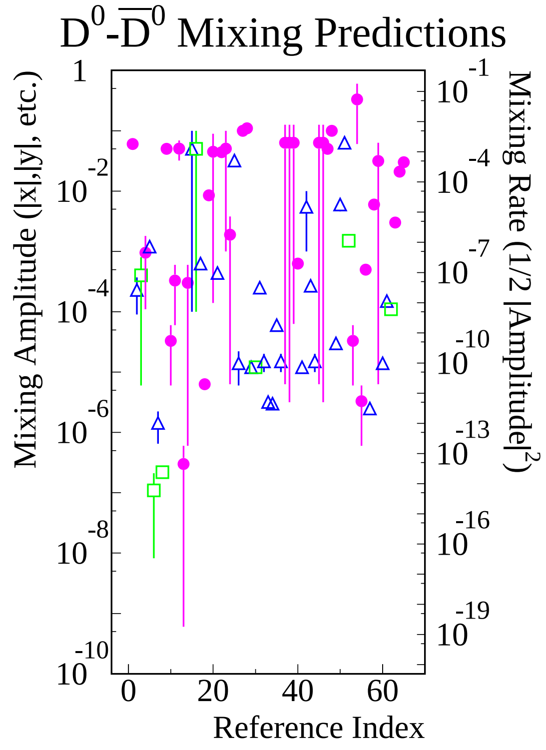
D mixing	B mixing
intermediate down-type quarks	intermediate up-type quarks
SM: b quark contribution is negligible due to V_{ub}	SM: t quark contribution is dominant
$\Delta M \approx m_s^2 - m_d^2$ (small)	$\Delta M \approx m_t^2$ (sizable)
sensitive to long distance QCD	described by local Lagrangian

(from P. Ball's talk at Moriond EW 2007)

- D prefers to decay rather than mix
  - ▷ off-shell intermediate states very relevant
  - ▷ outdo short-distance box diagram
- Long distance effects difficult to predict
- Largest predictions: $|x|,\ |y| \sim \mathcal{O}(10^{-2})$







H.Nelson, hep-ex/9909

Experimental method

- Since D mixing is small ($|x|, |y| \ll 1$) expand to the lowest order in x, y

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

- Determine the rates of wrong-sign decays, compare to right-sign

Right-Sign (RS)	Wrong-Sign (WS)
$D^0 \to \|f\rangle$	$D^0 \to \bar{D}^0 \to \|\bar{f}\rangle$
($D^0 \to K^-\pi^+$)	($D^0 \to K^+\pi^-$)

- WS decay rate

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

- Measurement:
  - ▷ tag the flavour at production
  - ▷ reconstruct wrong-sign decays
  - ▷ measure proper decay time distribution
  - ▷ use right-sign decays for normalization

Some measurement strategies

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

- Wrong-sign semileptonic decays ($D^0 \to K^+\ell^-\nu$)

  WS only via mixing: $\langle \bar{f}|\mathcal{H}|D^0\rangle = 0$

  measures time integrated mixing rate

$$R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}$$

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

  WS via doubly Cabibbo suppressed (DCS) decays or mixing

  interference between DCS and mixing (strong phase δ)

  measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$

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

  $\langle \bar{f}|\mathcal{H}|D^0\rangle = \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle$

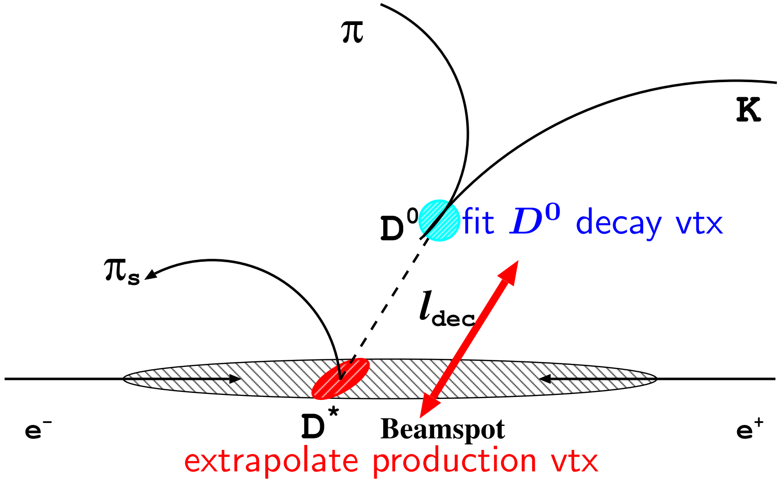
  measures y

- Dalitz plot time dependent analysis ($D^0 \to K^0\pi^+\pi^-$)

  measures x and y

Measurement technics

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



- D^0 proper decay time t measurement:

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

- Measurements performed at $\Upsilon(4s)$
  - ▷ to reject D^{*+} from B decays:

$$p_{D^{*+}}^{CMS} > 2.5\ GeV/c$$

To be presented

Measurements to be presented in this talk

- $D^0 \to K^+ e^- \nu$ (published)
- $D^0 \to K^+ \pi^-$ (published)
- $D^0 \to K_s^0 \pi^+ \pi^-$ Dalitz (preliminary)
- $D^0 \to K^+ K^-, \ \pi^+ \pi^-$ (preliminary)

$D^0 \to K^+ e^- \nu$ (253 fb^{-1})

PRD (RC) 72, 071101 (2005)

- WS charge combination only via mixing

	flavor at production		flavor at decay	
No mixing	$D^{*+} \to \pi^+ D^0$		$D^0 \to K^- e^+ \nu$	RS
Mixing	$D^{*+} \to \pi^+ D^0$	$D^0 \to \bar{D}^0$	$\bar{D}^0 \to K^+ e^- \nu$	WS

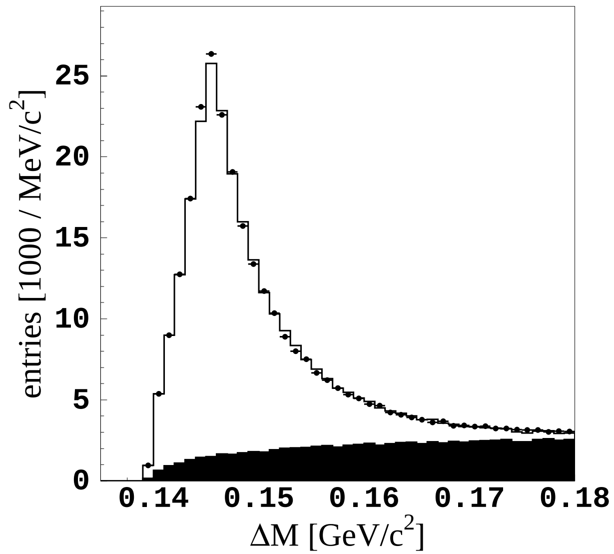
- Mixing parameter R_M measured directly

$$R_M = \frac{x^2 + y^2}{2} = \frac{N_{WS}}{N_{RS}} \frac{\epsilon_{RS}}{\epsilon_{WS}} \approx \frac{N_{WS}}{N_{RS}}$$

- Observable: $\Delta M = M(\pi K e \nu) - M(K e \nu)$
- Neutrino reconstruction:
  - ▷ Four-momentum conservation:
    $P_\nu = P_{CMS} - P_{\pi K e} - P_{rest}$
  - ▷ Kinematic constrains:
    $m^2_{D^{*+}}, \quad |P_\nu|^2 = 0$

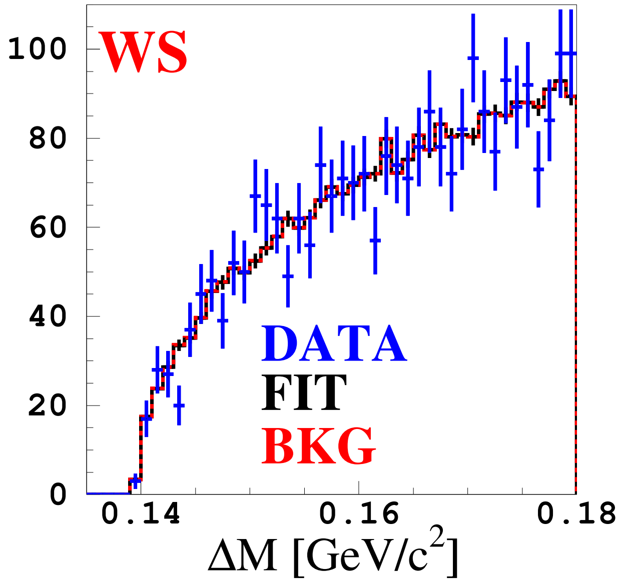
  (resolution impr.: 55 MeV $\to$ 7 MeV)
- ΔM shape:
  - ▷ signal - from MC
  - ▷ background - from data (evt. mixing)

RS events

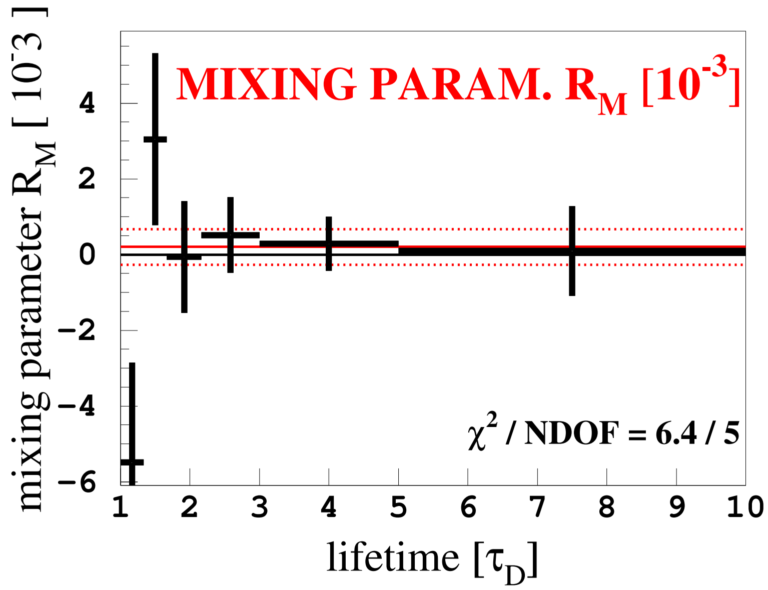


- Fit of WS data performed in bins of proper decay time to increase sensitivity (since RS and WS signals differ in proper decay time distributions)

example of a fit in one bin



measured R_M in bins of decay time

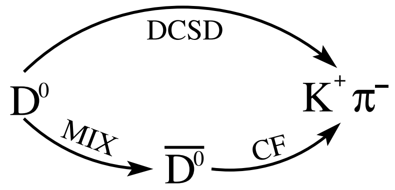


$$R_M < 1.2 \times 10^{-3} \quad @\ 95\%\ C.L.$$

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

PRL 96, 151801 (2006)

- WS final state: via DCS decay or mixing



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

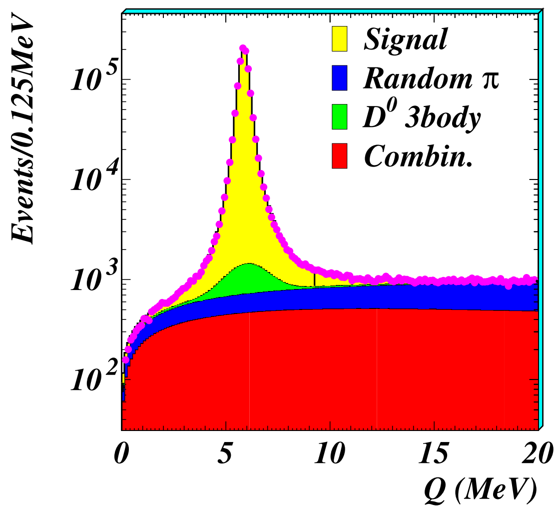
$$\frac{dN}{dt} \propto [R_D + y'\sqrt{R_D}(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2]e^{-\Gamma t}$$

DCS interference mixing

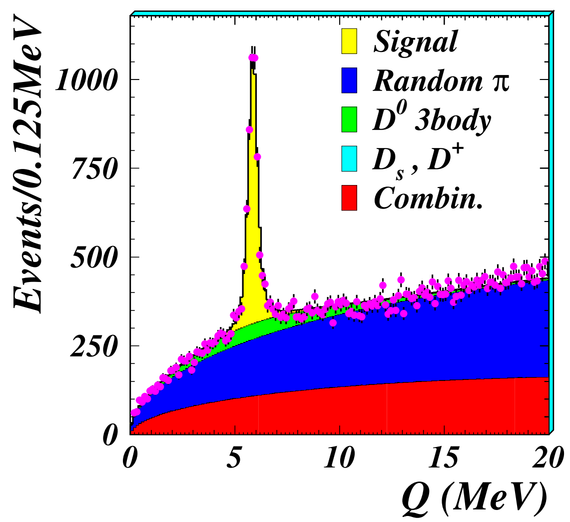
R_D ratio of DCS/CF decay rates
$x' = x\cos\delta + y\sin\delta$
$y' = y\cos\delta - x\sin\delta$
δ strong phase between DCS and CF

- Observables:
  $M = M(K\pi)$
  $Q = M(K\pi\pi_s) - M(K\pi) - m_\pi$

RS events

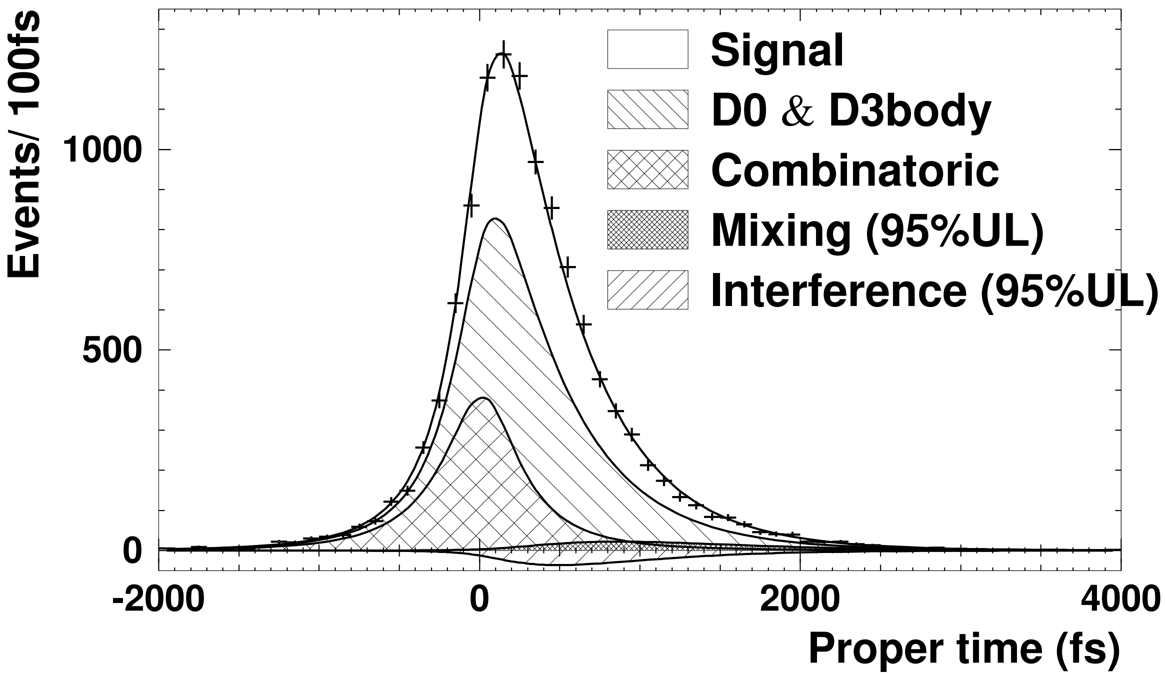


WS events



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

- 2D M-Q fit first to obtain:
  - ▷ $R_{WS} = \frac{N_{WS}}{N_{RS}} = (0.375 \pm 0.008)\%$
  - ▷ signal and background fractions (M, Q and σ_t dependent)
  - $\rightarrow$ used in the proper decay time fit of WS events
- Proper decay time fit of WS events:
  - ▷ unbinned max. likelihood fit in 4σ (M, Q) window
  - ▷ resolution function parameters determined from RS data



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

Results

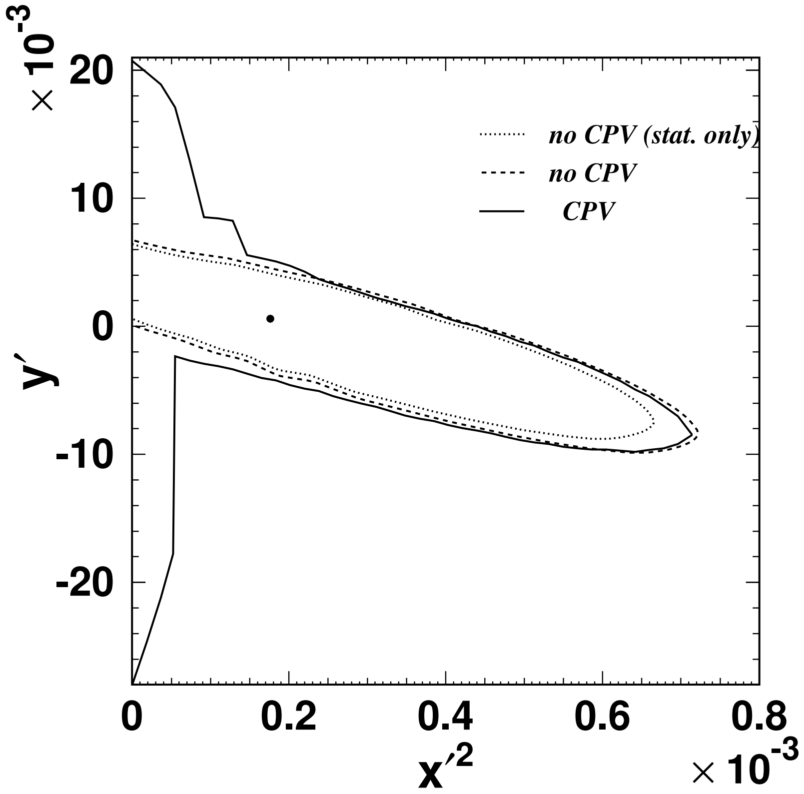
- Assuming CP conservation

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

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

$$y' = (0.6^{+4.0}_{-3.9}) \times 10^{-3}$$

- CP asymmetries consistent with 0
  $\to$ no evidence for CPV



$$R_M < 0.40 \times 10^{-3} \quad @ \; 95\% \; C.L.$$

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

hep-ex/0704.1000

- 3-body decay modes:
  amplitudes $A(D^0 \to f)$ and $\bar{A}(\bar{D}^0 \to \bar{f})$ depend on Dalitz variables.
- Dalitz space dependent matrix element is for negligible CPV

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

where $m_\pm$ is defined with the D^* tag

$$m_\pm = \begin{cases} m(K_s, \pi^\pm) & D^{*+} \to D^0\pi^+ \\ m(K_s, \pi^\mp) & D^{*-} \to \bar{D}^0\pi^- \end{cases}$$

and time dependent functions with

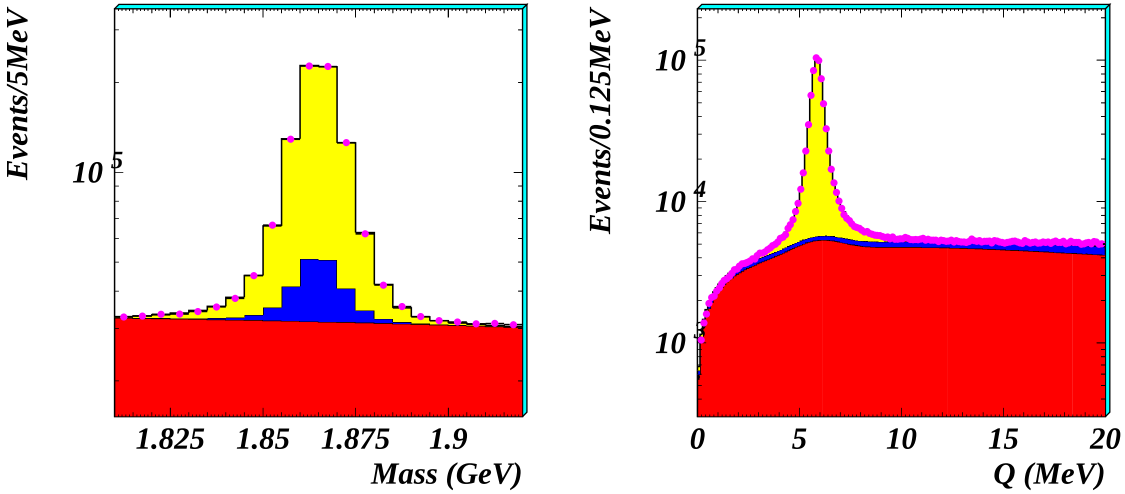
$$e_{1,2}(t) = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}$$

- $|M(m_-^2, m_+^2, t)|^2$ thus includes x and y
- The only measurement sensitive directly to x

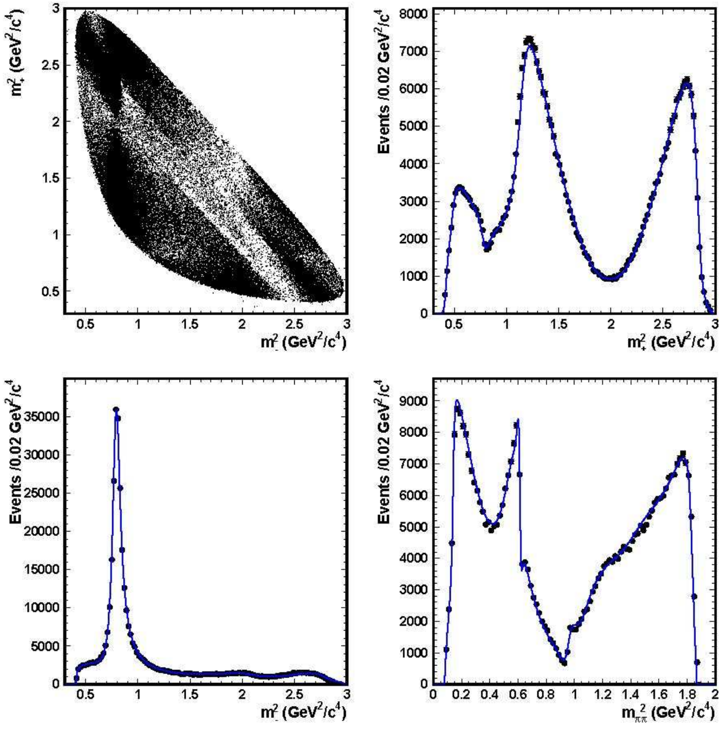
Event Selection

- 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%



Dalitz fit

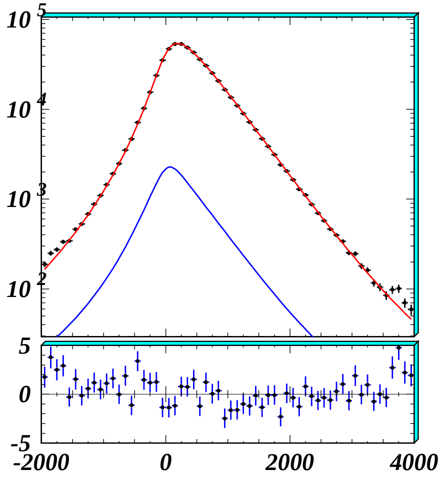


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 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: 13 different (BW) resonances and a non-resonant contribution
- Results with this refined model consistent with the analysis performed for the Belle ϕ_3 measurement, PRD73, 112009 (2006)
- 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})

Time fit (in projection)



Results (preliminary)

$$x = 0.80 \pm 0.29 \pm 0.17 \text{ \%}$$

$$y = 0.33 \pm 0.24 \pm 0.15 \text{ \%}$$

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

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

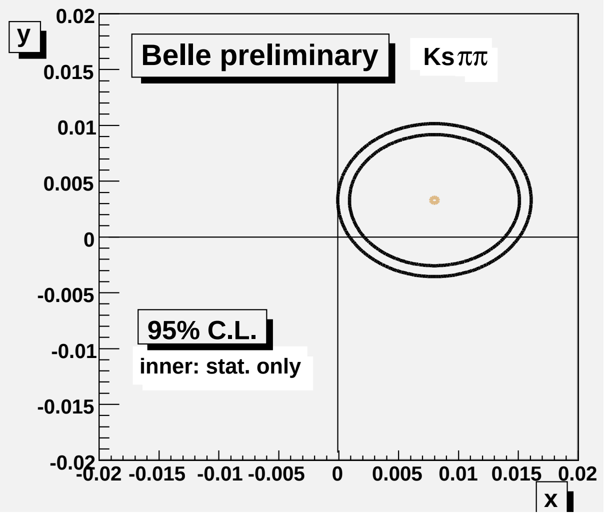
Systematics

Largest contributions ($\times 10^{-4}$)

x	y	
$^{+14.6}_{-13.6}$	$^{+7.8}_{-8.8}$	Model dependence
$^{+8.5}_{-6.8}$	$^{+6.6}_{-11.6}$	Time fit

Total ($\times 10^{-4}$)

x	y
$^{+16.9}_{-15.2}$	$^{+10.2}_{-14.6}$



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

hep-ex/0704036

- 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: $y_{CP} = y = \Delta\Gamma/\Gamma$
- If CP not conserved, difference in lifetimes of $D^0/\bar{D}^0 \to K^+K^-, \pi^+\pi^-$
  - ▷ CP violating parameter: $A_\Gamma = \frac{\hat{\Gamma}(D^0 \to KK) - \hat{\Gamma}(\bar{D}^0 \to KK)}{\hat{\Gamma}(D^0 \to KK) + \hat{\Gamma}(\bar{D}^0 \to KK)}$
- Existing measurements:

  E.M.Aitala et al., PRL 83, 32 (1999); E791

  J.M.Link et al., PLB 485, 62 (2000); Focus

  S.E.Csorna et al., PRD 65, 092001 (2002); Cleo

  K.Abe et al., hep-ex/0308034 (2003); Belle (preprint)

  B.Aubert et al., PRL 91, 121801 (2003); (BaBar)

average

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

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

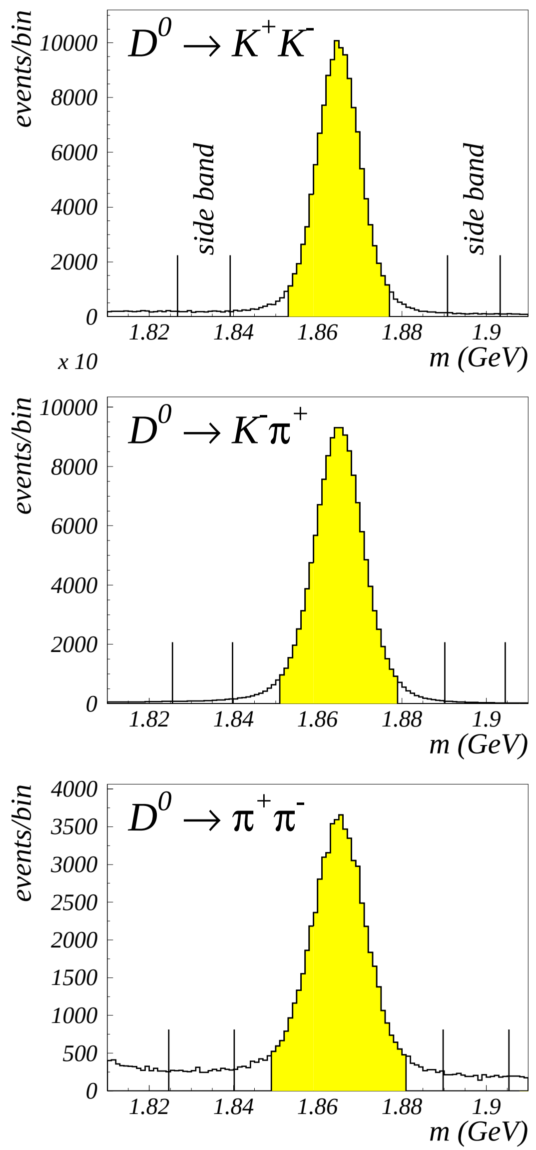
Event Selection

- 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%



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

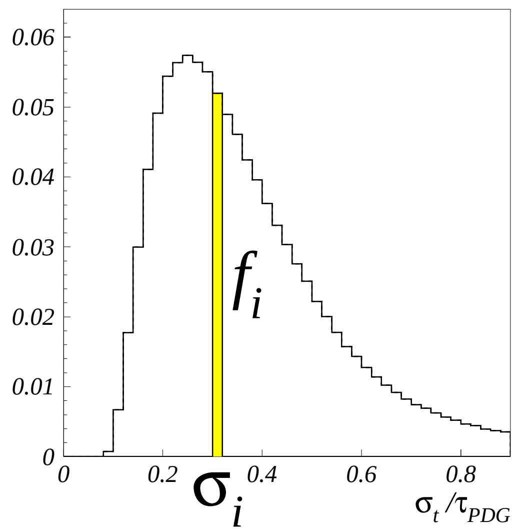
Lifetime fit

- 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 → p.d.f.=sum of 3 Gauss.

σ_t distribution



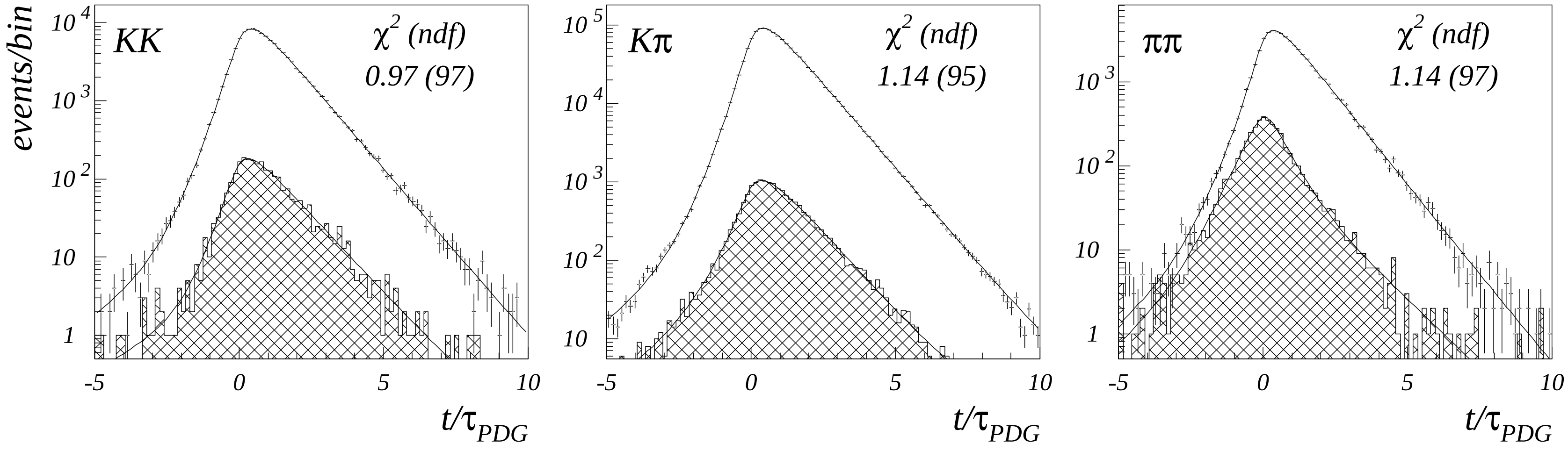
$$R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t; \sigma_{ik}, t_0)\ , \qquad \sigma_{ik} = s_k \sigma_k^{pull} \sigma_i$$

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

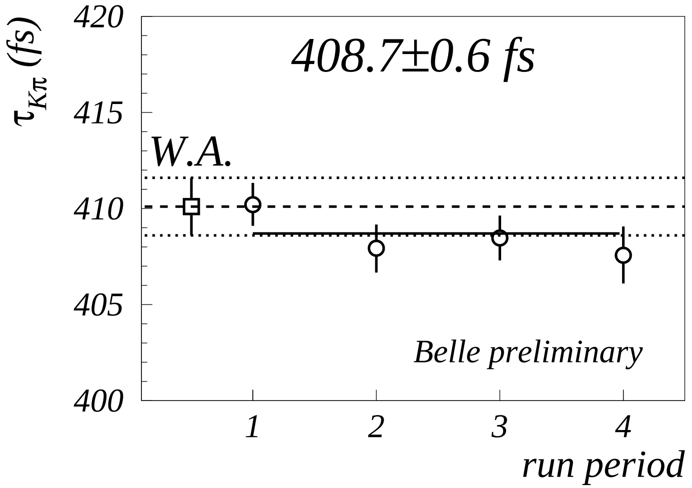
$D^0 \to K^+K^-,\ \pi^+\pi^-$ (540 fb^{-1})

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



Cross-checks

- MC: y_{CP}(out) - y_{CP}(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%

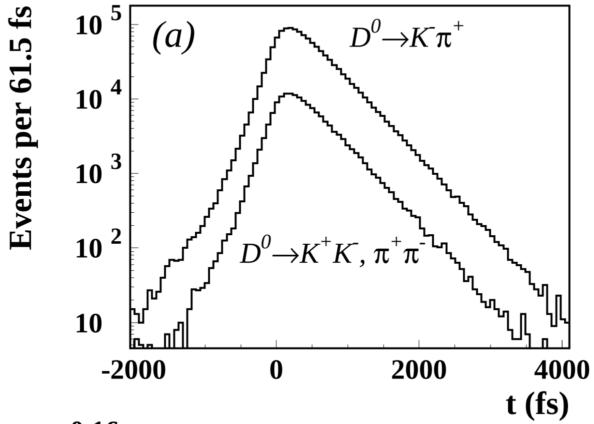
Systematics

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 (preliminary)

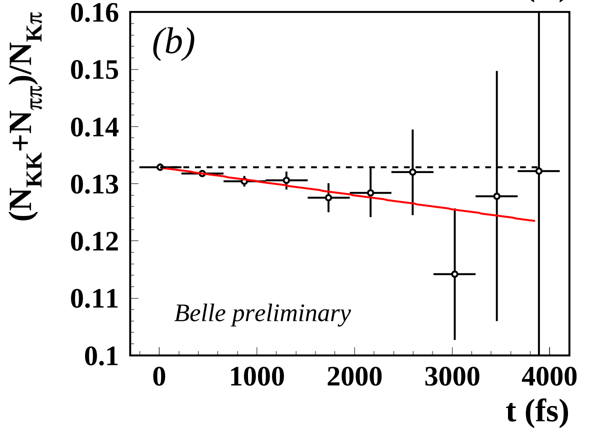
	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	-0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15



Belle preliminary (540 fb^{-1})

y_{CP} = 1.31±0.32±0.25 %

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



A_Γ = 0.01±0.30±0.15 %

no evidence for CP violation

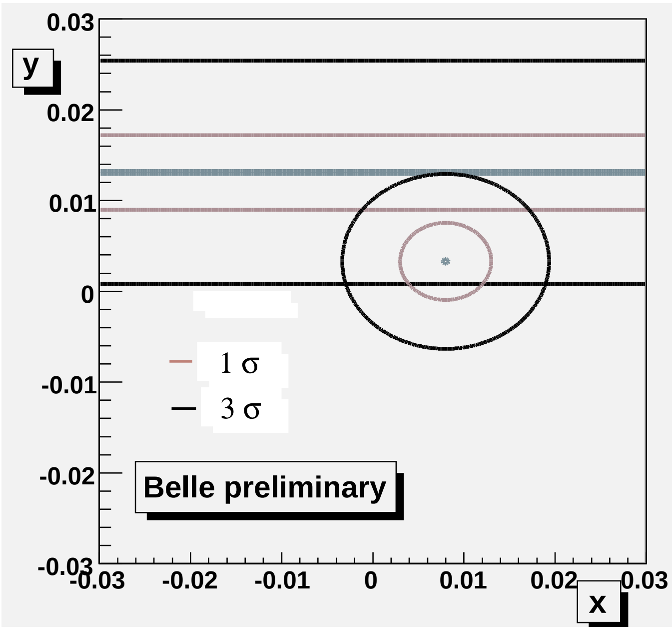
Conclusions

- Several measurements of D^0 mixing parameters presented
- Best sensitivity on x from t-dependent Dalitz analysis:

$$x = 0.80 \pm 0.29 \pm 0.17\ \%\ (2.4\sigma)$$

- First evidence of non-zero y_{CP}:

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

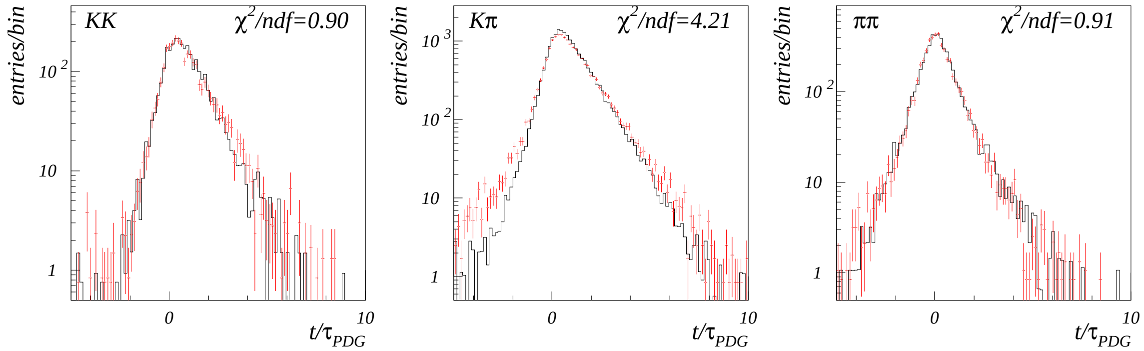


Backup slide: X-checks for y_{CP}

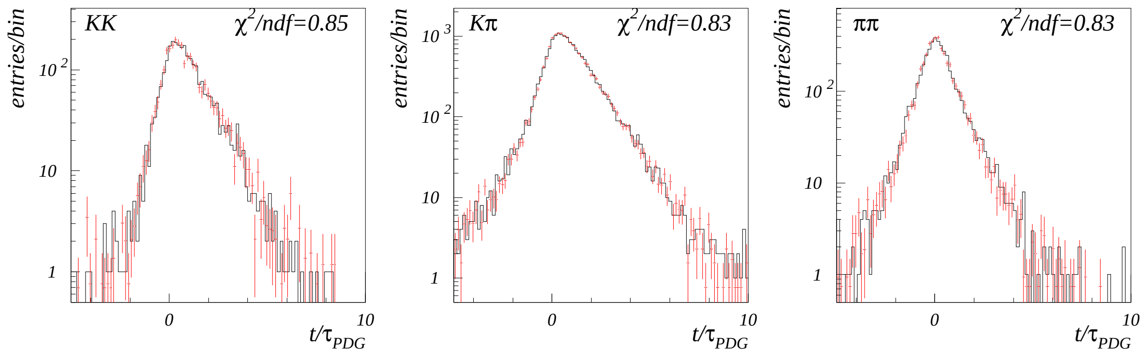
Background

- A comparison of timing distributions

MC signal region background - MC side bands



DATA side bands - MC side bands



- Difference to result, if using background from tuned MC

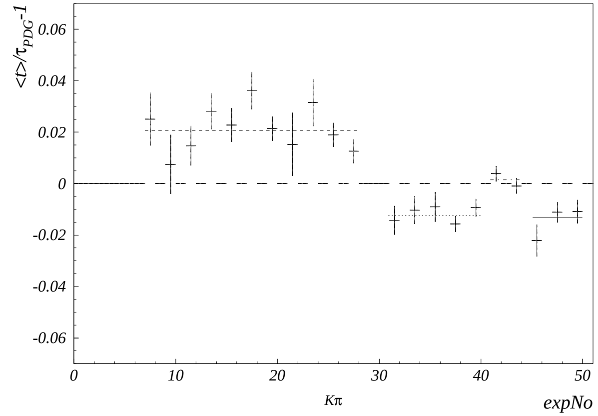
	KK	$\pi\pi$	$KK+\pi\pi$
Δy_{CP}	-0.10%	$+0.09\%$	-0.04%

Run periods

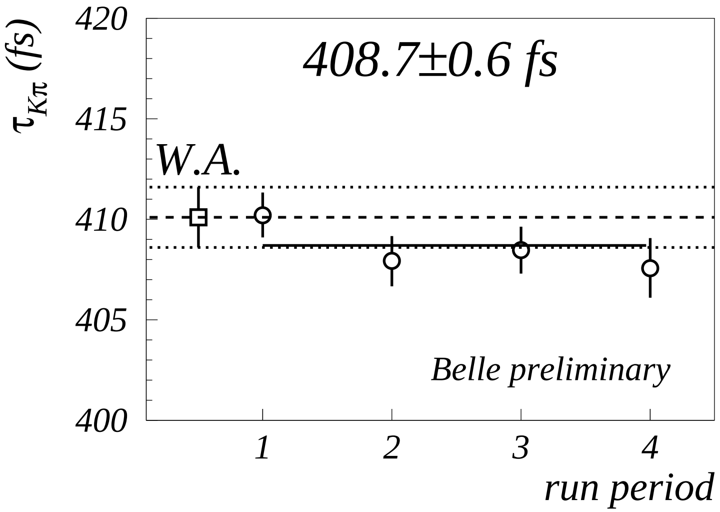
$$P(t) = \frac{1}{\tau} e^{-t/\tau} * R(t) \quad \Rightarrow \quad < t >= \tau + t_0$$

- By inspecting $< t >$ of $K\pi$, four different running conditions clearly visible
- Attributed to small SVD misalignments

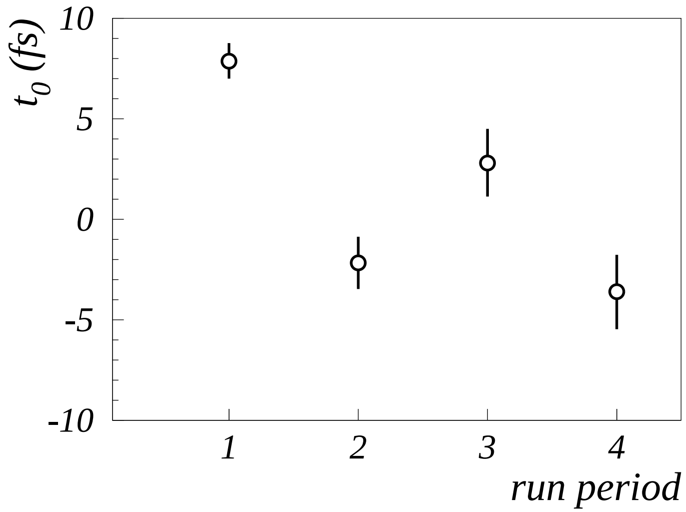
“mean” of $K\pi$ timing distr.



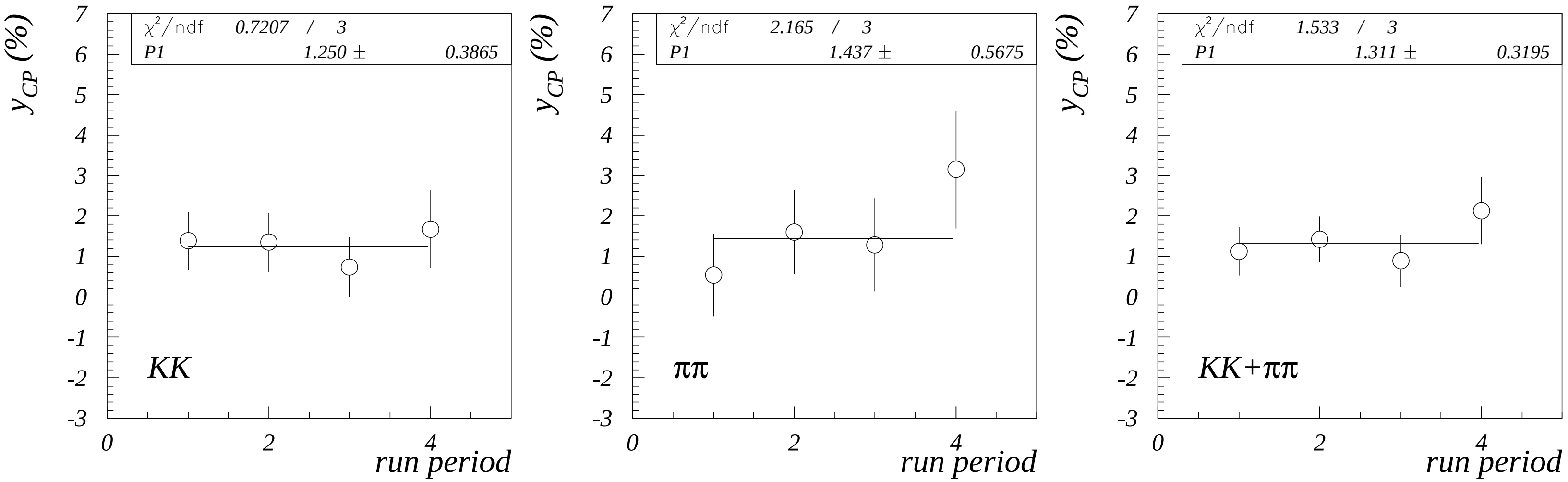
fitted $K\pi$ lifetimes



fitted r.f. offsets



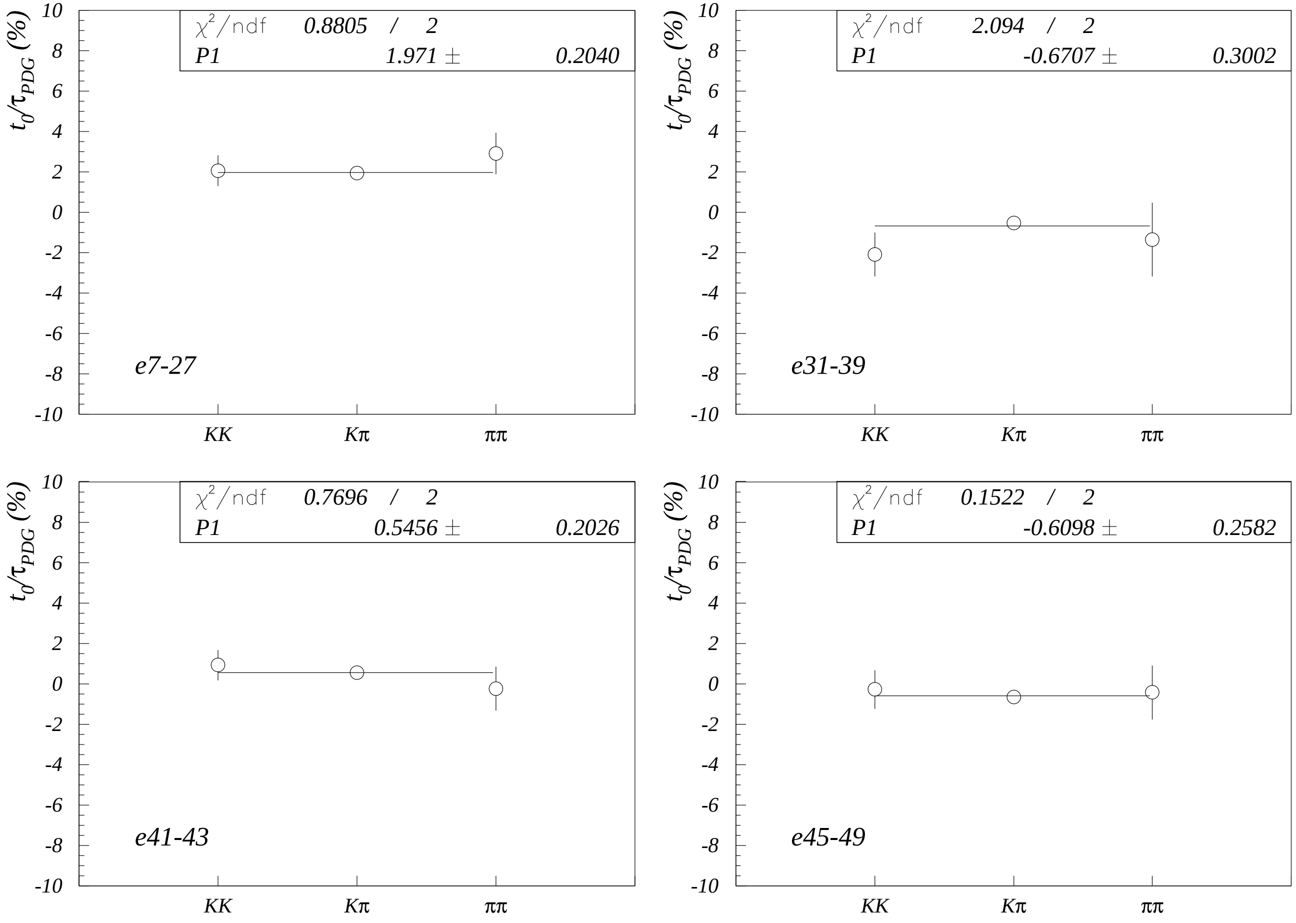
Measured y_{CP} versus run periods



$\Rightarrow y_{CP}$ consistent between run periods

Backup slide: X-checks for y_{CP}

Test for equal t_0 assumption for each of the run periods

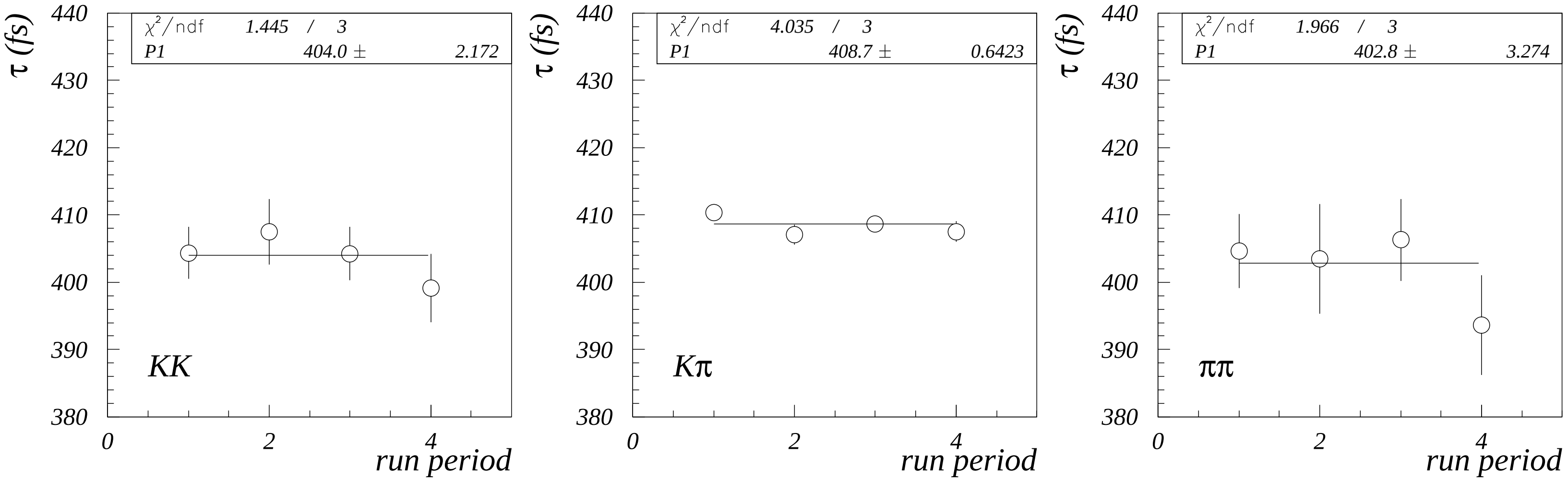


$\Rightarrow t_0$ is final state independent

Backup slide: X-checks for y_{CP}

Fitted lifetimes of KK, $K\pi$, $\pi\pi$

- Results for t_0 being free for each of the final states



$\Rightarrow$ lifetimes consistent between different run periods

	KK	$K\pi$	$\pi\pi$
τ (fs)	404.0±2.2	408.7±0.6	402.8±3.3
χ^2/ndf	0.48	1.35	0.66

$\Rightarrow$ lifetimes of KK and $\pi\pi$ consistent (and smaller than $K\pi$)

$y_{CP} = 1.25 \pm 0.48$ % (central value similar, error 50% larger)

Backup slide: X-checks for y_{CP}

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

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

Comparison of Belle and BaBar measurements in $D^0 \to K^+\pi^-$