Search for D^0 - $\bar{D}^0$ mixing at Belle and BaBar

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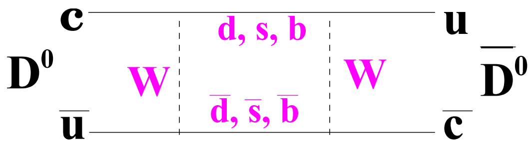
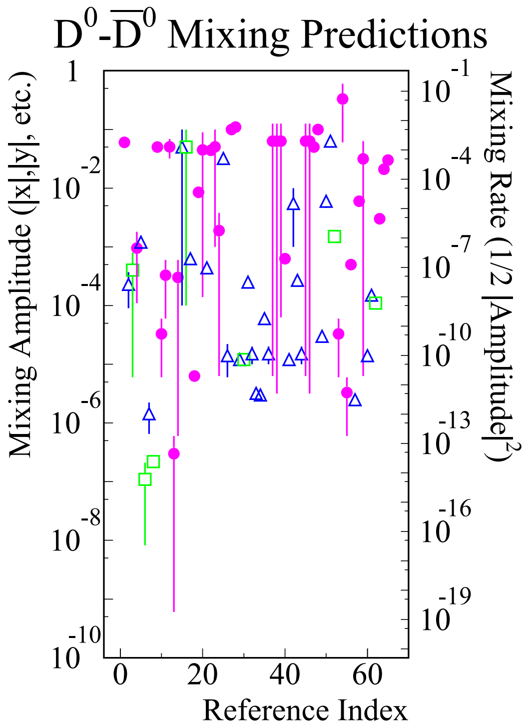
Introduction

- Mixing observed in K^0, B_d^0 and B_s^0 (2006), not yet in D^0 system
- D^0 mixing in the SM governed by box diagrams
- Effective GIM suppression
  $\rightarrow$ mixing in D^0 system rare process



- Non-perturbative effects difficult to predict



- Mixing: flavor eigenstates not mass eigenstates:
  $|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
  with masses m_1, m_2 and widths Γ_1, Γ_2.
- Mixing governed by

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

- Time integrated mixing rate

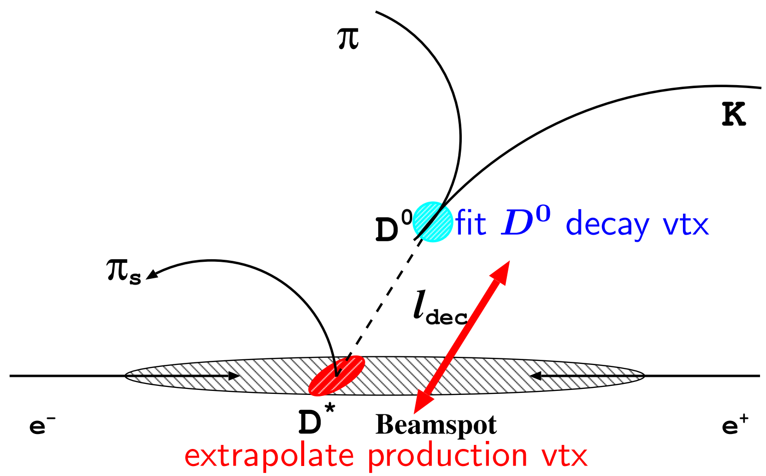
$$R_M = \frac{x^2 + y^2}{2}$$

Experimental method

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

- D^0 proper decay time t measurement:
  - ▷ to disentangle DCS decays
  - ▷ to increase sensitivity

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



- Measurements performed in e^+e^- collisions at $\sqrt{s} \approx 10$ GeV (B-factories)
  - ▷ to reject D^{*+} from B decays:

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

Semileptonic decays

Measurement in semileptonic decays $D^0 \to Ke\nu$ (Belle, 253 fb^{-1})
PRD (RC) 72, 071101 (2005)

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

New measurement from BaBar, 344 fb^{-1}

- Double tag
  $D^{*+} \to D^0\pi^+$, semil. and hadronic (fully rec.)
  Several hadronic tagging modes
- $\Delta M = m(K\pi e) - m(Ke)$, NN selection
- RS ΔM distrib.;
  For WS cut on decay time to increase sensitivity
- WS events (dark grey)
  2.9 expected, 3 observed

$$-1.3 \times 10^{-3} < R_M < 1.2 \times 10^{-3} \quad @\ 90\%\ C.L.$$

ΔM RS events

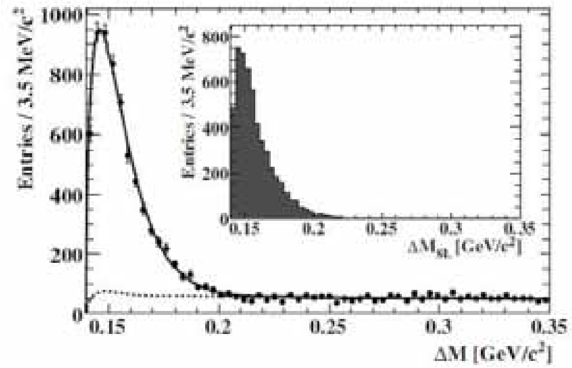
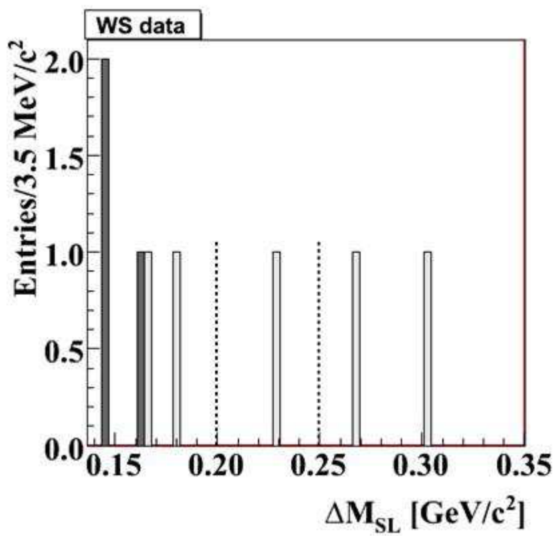


FIG. 6: RS data ΔM distribution. The main plot shows the RS data (points) before imposing the double-tagged kinematic selection, and the projections of the total fit PDF (solid line) and the background PDF (dashed line). The inset plot shows the RS ΔM distribution after the double-tagged kinematic selection is applied.

ΔM WS events



Measurements

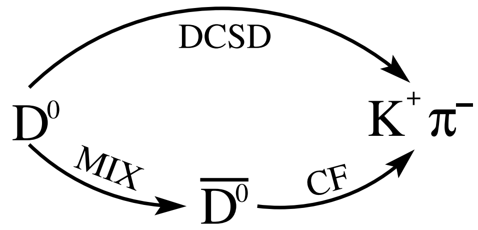
Measurements to be presented in this talk

- $D^0 \to K^+\pi^-$ (Belle)
- $D^0 \to K^+\pi^-\pi^0,\ K^+\pi^-\pi^+\pi^-$ (BaBar)
- $D^0 \to K_s^0\,\pi^+\pi^-$ Dalitz (Belle preliminary)
- $D^0 \to K^+K^-,\ \pi^+\pi^-$ (Belle preliminary)

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

PRL 96, 151801 (2006)

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



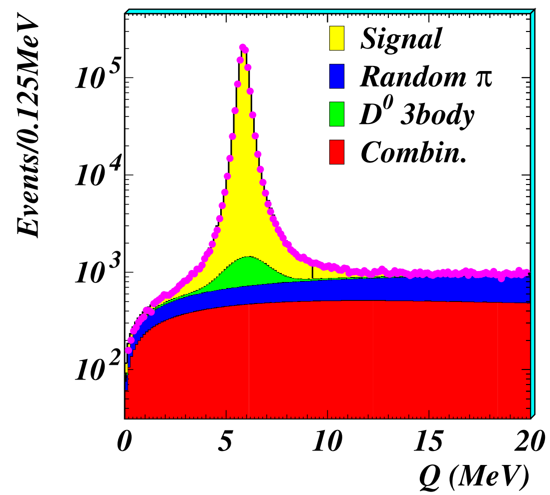
- Proper decay time distribution of WS events (assuming negligible CPV)

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

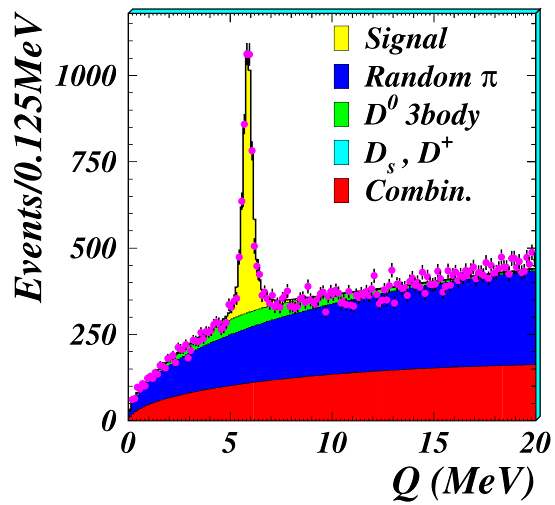
DCS interference mixing

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

RS events



WS events



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

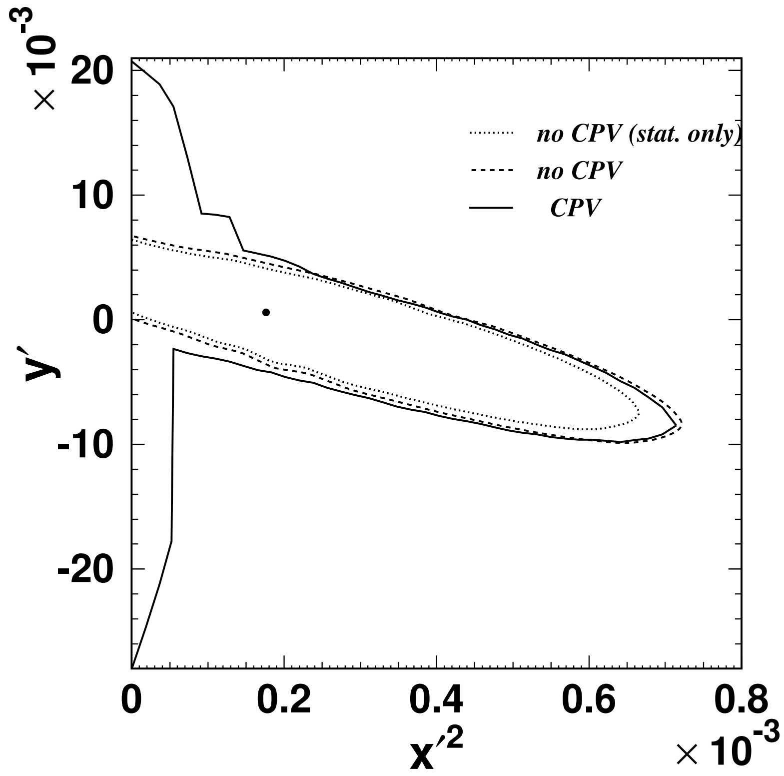
Unbinned fit to time distribution

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
  $\rightarrow$ no evidence for CPV



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

$D^0 \to K^+\pi^-\pi^0,\ K^+\pi^-\pi^+\pi^-$ (BaBar, 230 fb^{-1})

PRL 97, 221803 (2006)
hep-ex/0607090

- WS final state: again via DCS decay or mixing
- Proper decay time distribution of WS events for more than 2 body decays (assuming negligible CPV)

$$\frac{dN}{dt} \propto [\widetilde{R}_D + \alpha\widetilde{y}'\sqrt{\widetilde{R}_D}(\Gamma t) + \frac{\widetilde{x}'^2 + \widetilde{y}'^2}{4}(\Gamma t)^2]e^{-\Gamma t}\ , \qquad 0 \leq \alpha \leq 1$$

with

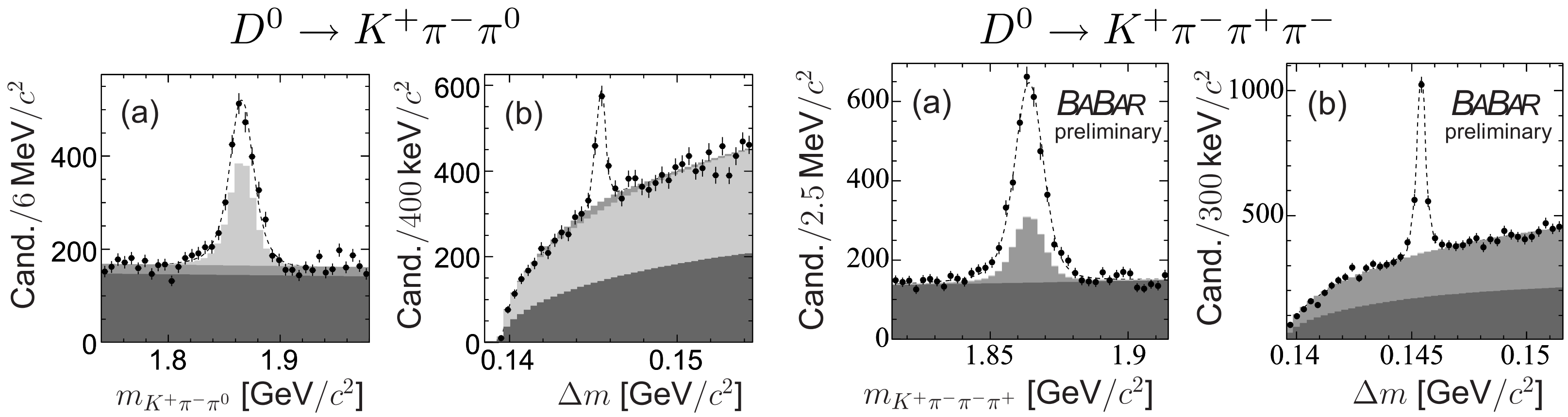
$$\widetilde{x}' = x\cos\widetilde{\delta} + y\sin\widetilde{\delta}$$
$$\widetilde{y}' = y\cos\widetilde{\delta} - x\sin\widetilde{\delta}$$

Mixing rate

$$R_M = \frac{\widetilde{x}'^2 + \widetilde{y}'^2}{2} = \frac{x^2 + y^2}{2}$$

- For $K\pi\pi^0$ phase-space selection to suppress K^{*+} and K^{*0}

$D^0 \to K^+\pi^-\pi^0,\ K^+\pi^-\pi^+\pi^-$ (BaBar, 230 fb^{-1})

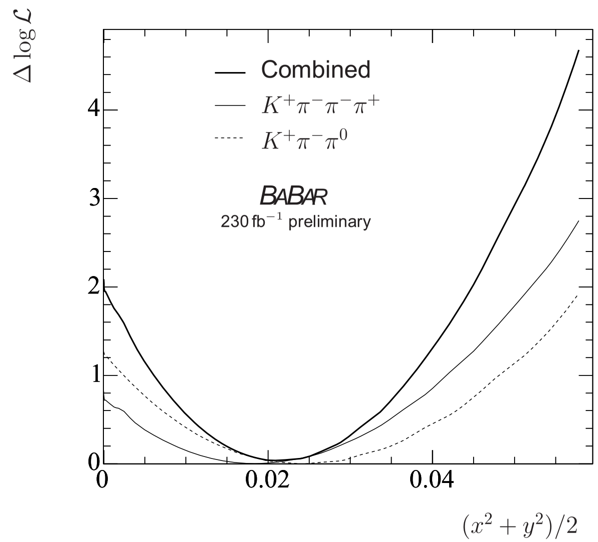


Results

- Assuming CP conservation
- Upper limits (95% C.L.)

$K\pi\pi^0 \quad R_M < 0.054\%$

$K3\pi \quad R_M < 0.048\%$



Combined result

$$R_M < 0.42 \times 10^{-3} \quad @\ 95\%\ C.L.$$

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

- 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

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

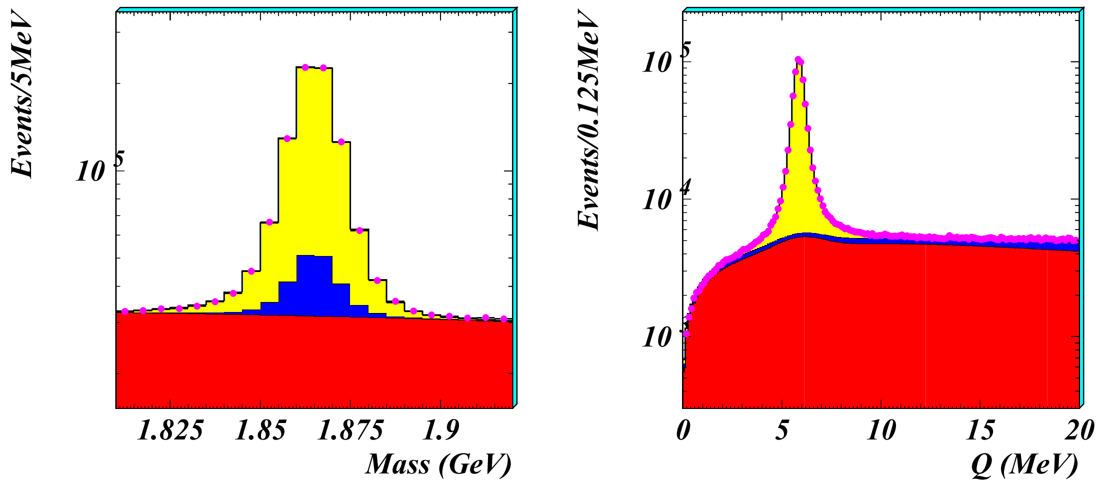
- $|M(m_-^2, m_+^2, t)|^2$ thus includes x and y
- The only measurement sensitive directly to x

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

Event Selection

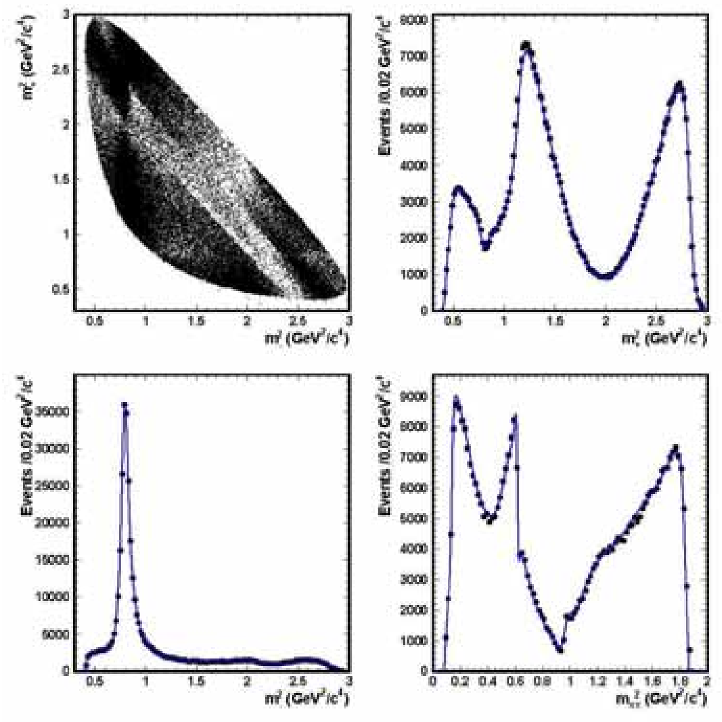
- Reconstruction
  - ▷ K_s^0 reconstruction and π selection
  - ▷ D^0 decay vertex from π^+, π^-
  - ▷ D^0 mass kinematic constraint for $m(K_s, \pi^+, \pi^-)$
  - ▷ $p^*(D^{*+}) > 2.5$ GeV/c
- Signal yields and purity

signal	purity
534000	95%



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

Dalitz fit

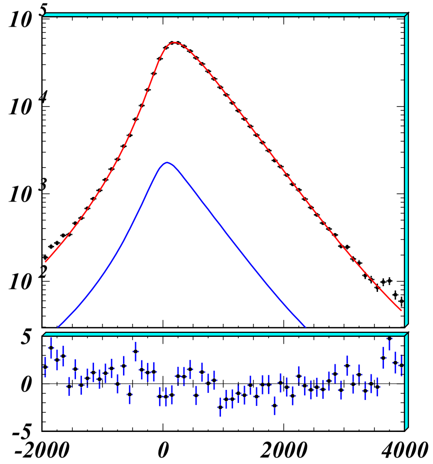


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 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 (Belle, 540 fb^{-1})

Time fit (in projection)



Results (preliminary)

$x = 0.80 \pm 0.29 \pm 0.17$ %

$y = 0.33 \pm 0.24 \pm 0.15$ %

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

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

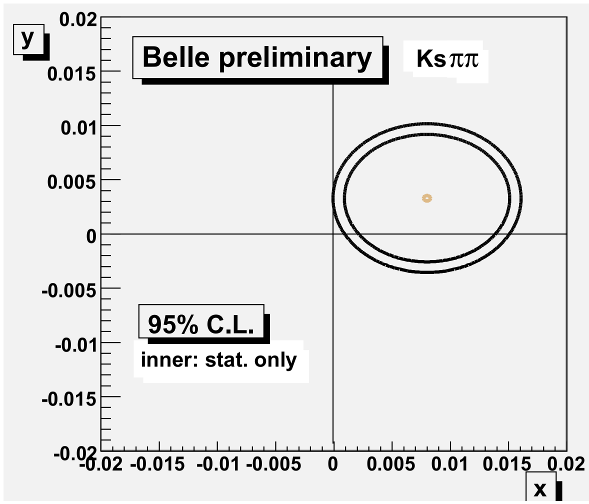
Systematics

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



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

- 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

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

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

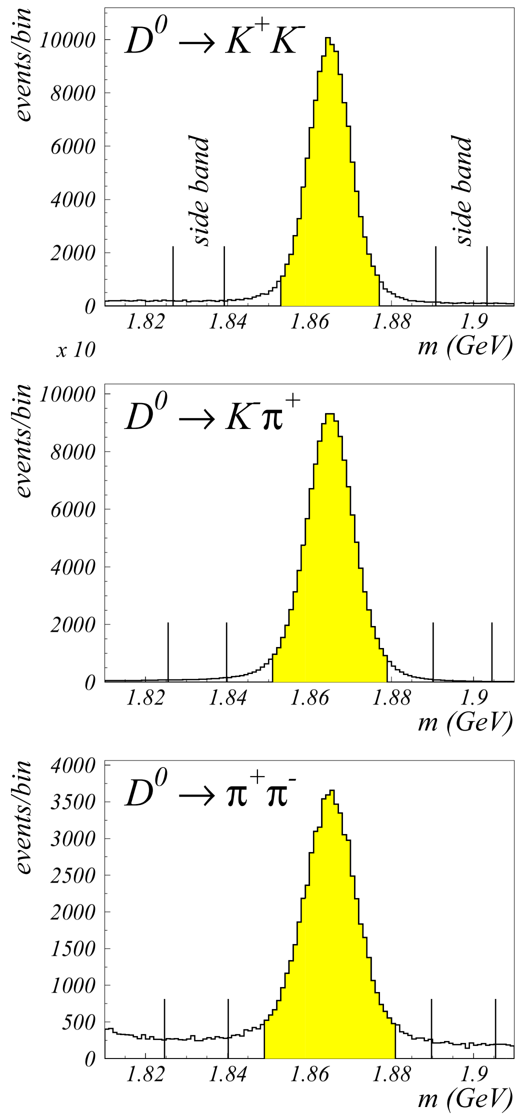
Event Selection

- 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 purity	110K 98%	1.2M 99%	50K 92%



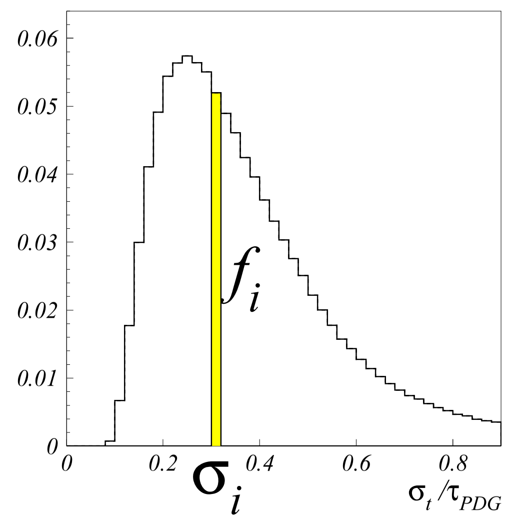
$D^0 \to K^+K^-,\ \pi^+\pi^-$ *(Belle, 540 fb^{-1})*

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 $\to$ p.d.f.=sum of 3 Gauss.



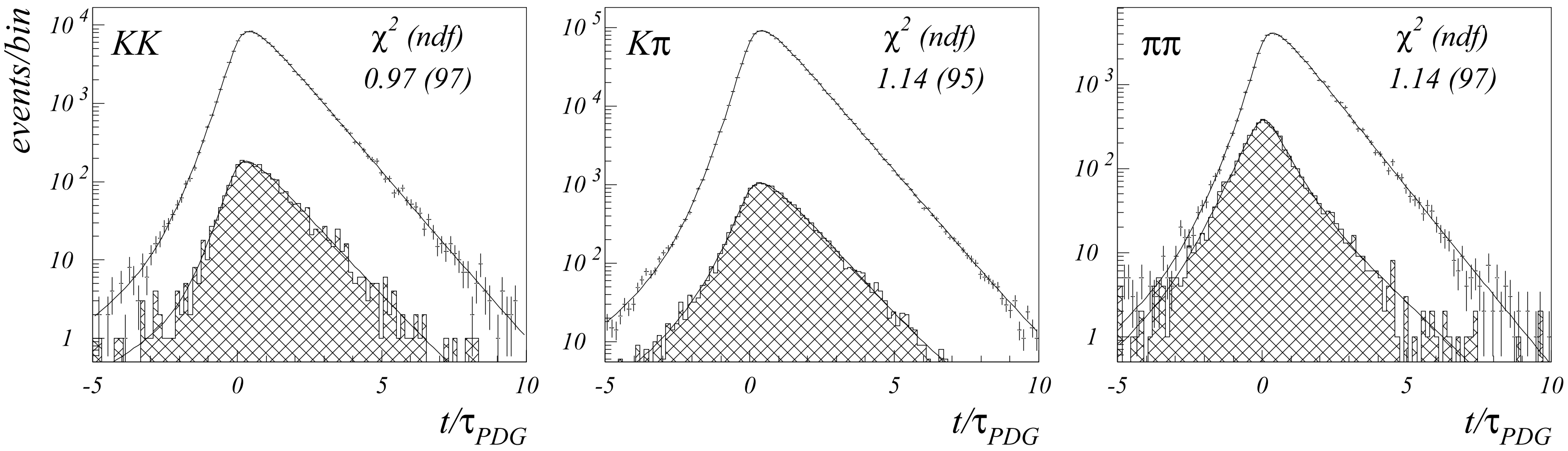
$$R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t; \sigma_{ik}, t_0)\ , \qquad \sigma_{ik} = s_k \sigma_k^{pull} \sigma_i$$

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

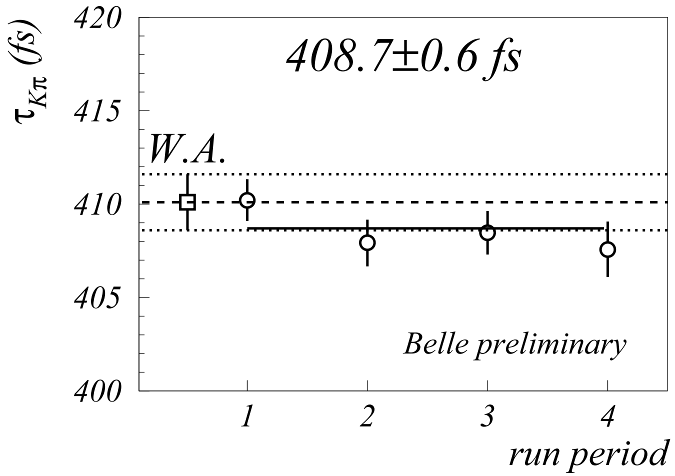
$D^0 \to K^+K^-,\ \pi^+\pi^-$ (Belle, 540 fb^{-1})

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

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



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



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

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%

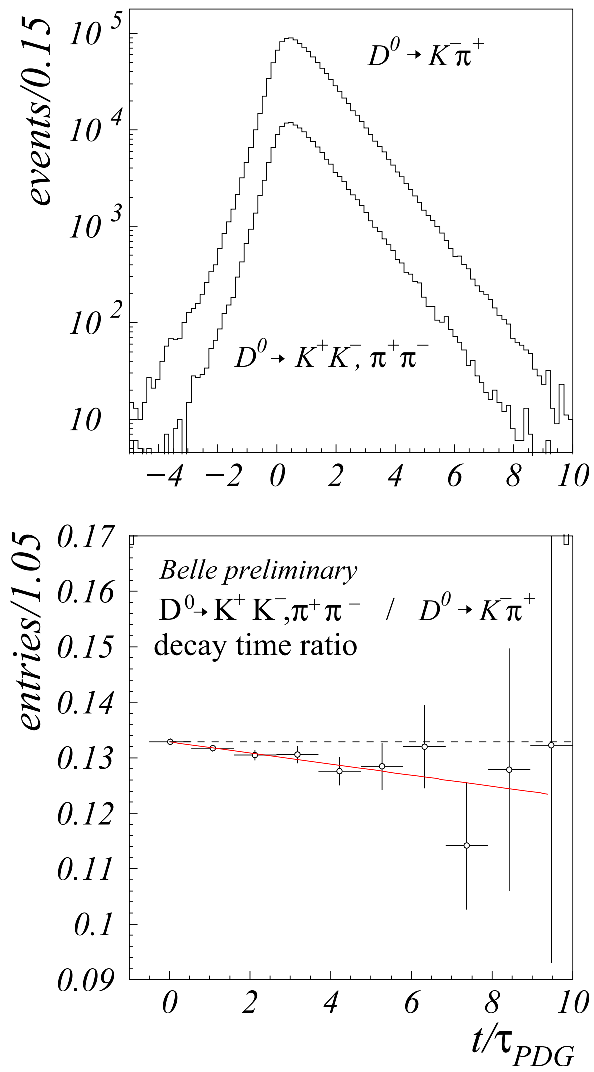
Systematics

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%

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

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

$> 3\sigma$ above zero
(4.1σ stat. only)
first evidence for $D^0 - \bar{D}^0$ mixing

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

no evidence for CP violation

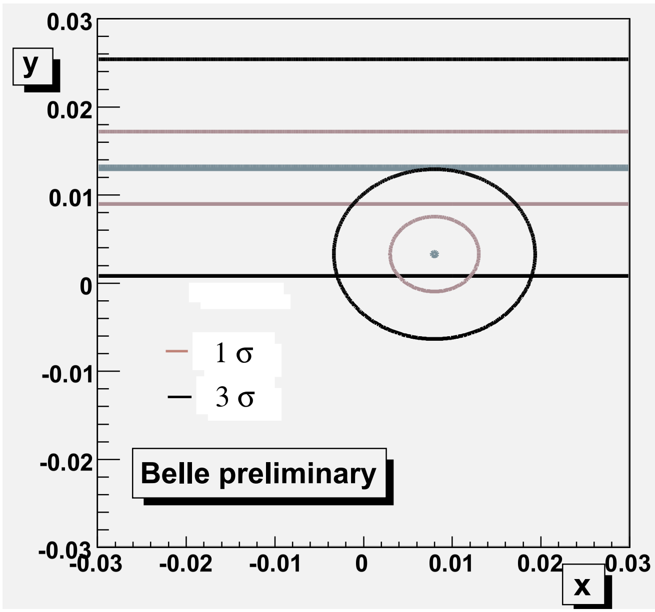
Conclusions

- 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}:

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

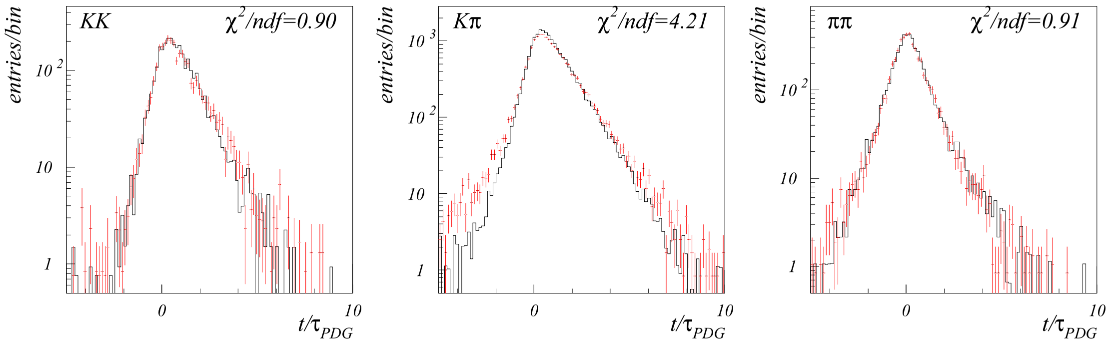


Backup slide: X-checks for y_{CP}

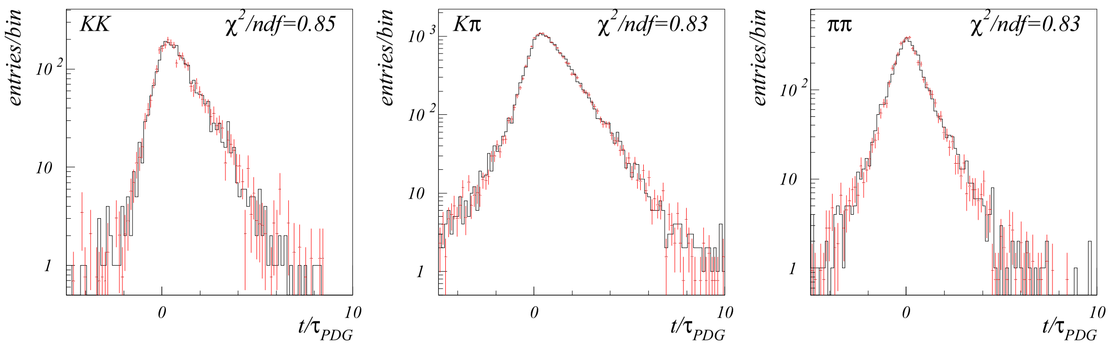
Background

- A comparison of timing distributions

signal region background - side bands



side bands DATA - side bands tuned MC



- Difference to result, if using background from tuned MC

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

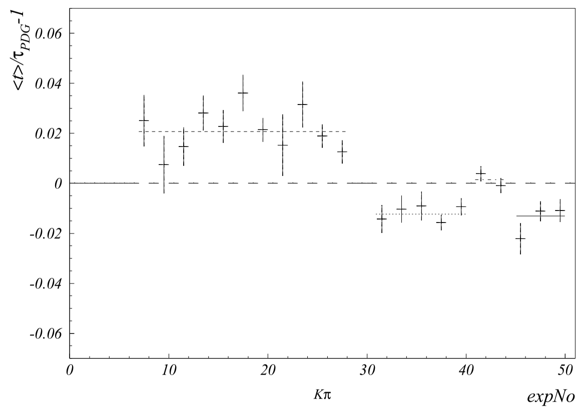
Backup slide: X-checks for y_{CP}

Run periods

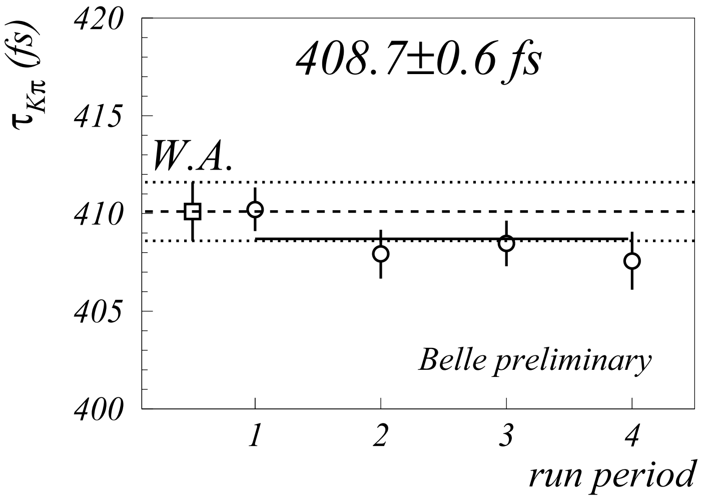
$$P(t) = \frac{1}{\tau} e^{-t/\tau} * R(t) \quad \Rightarrow \quad \langle t \rangle = \tau + t_0$$

- By inspecting $\langle t \rangle$ of $K\pi$, four run periods with different resolution function offsets (t_0) found
- Attributed to small SVD misalignments

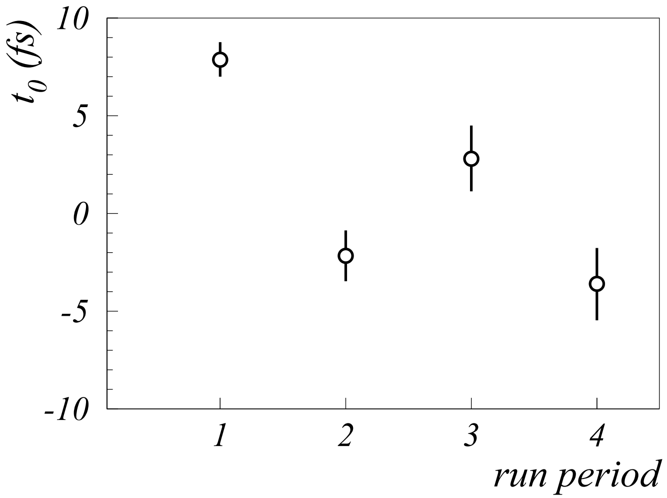
“mean” of $K\pi$ timing distr.



fitted $K\pi$ lifetimes

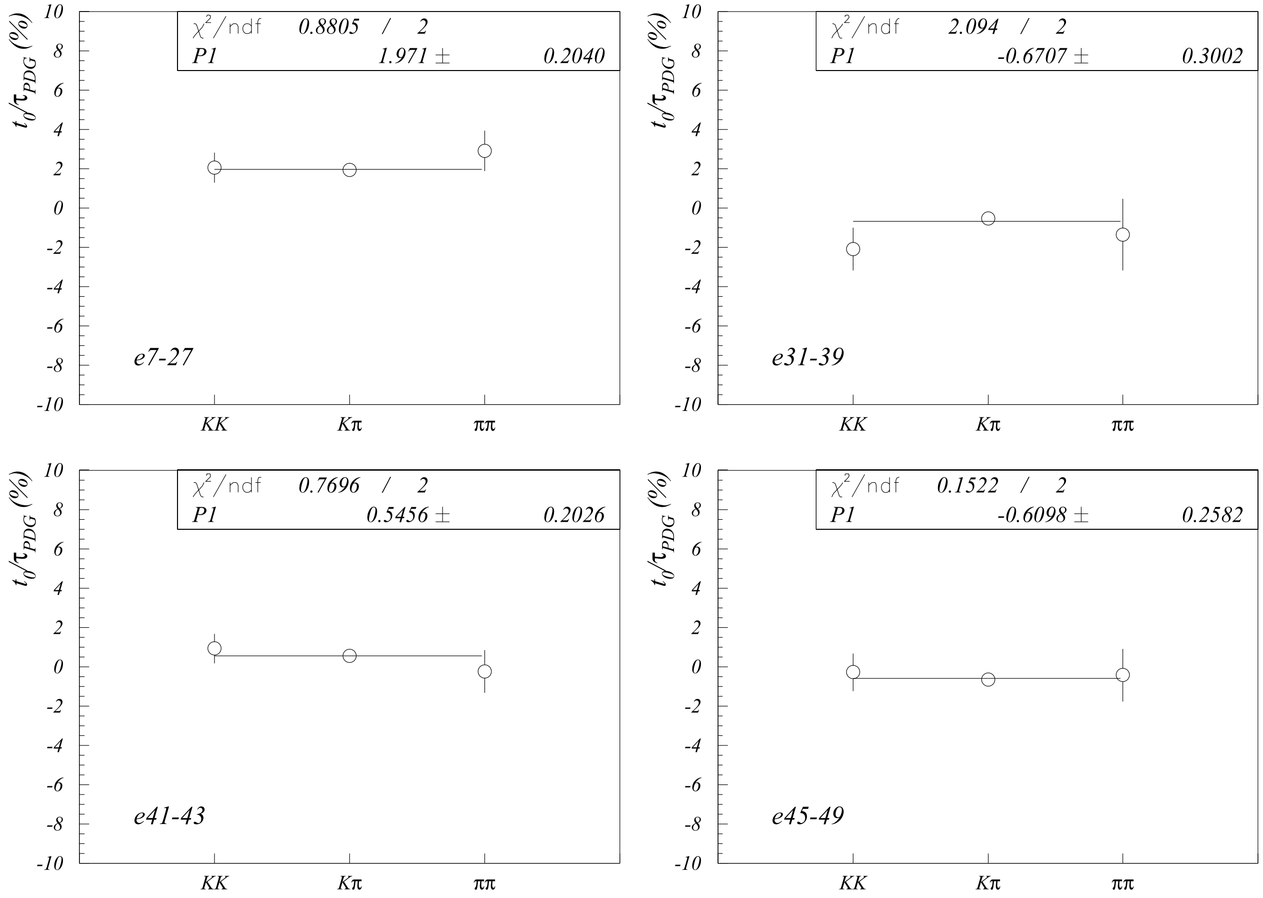


fitted r.f. offsets



Backup slide: X-checks for y_{CP}

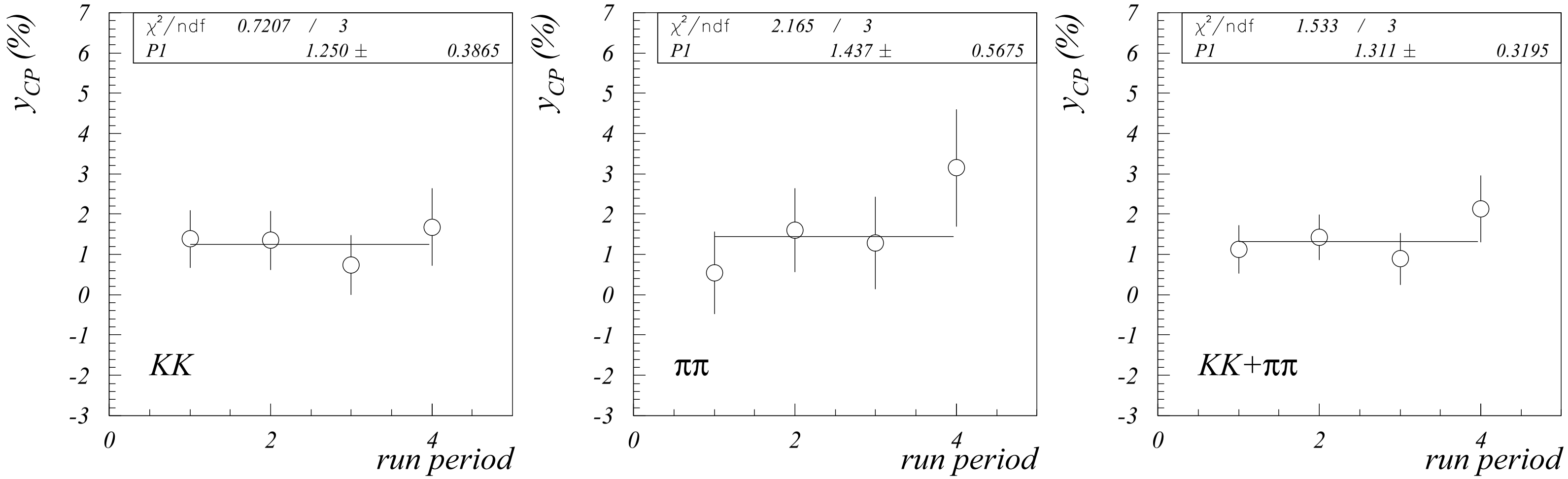
Test for equal t_0 assumption



⇒ t_0 is final state independent

Backup slide: X-checks for y_{CP}

Measured y_{CP} versus run periods

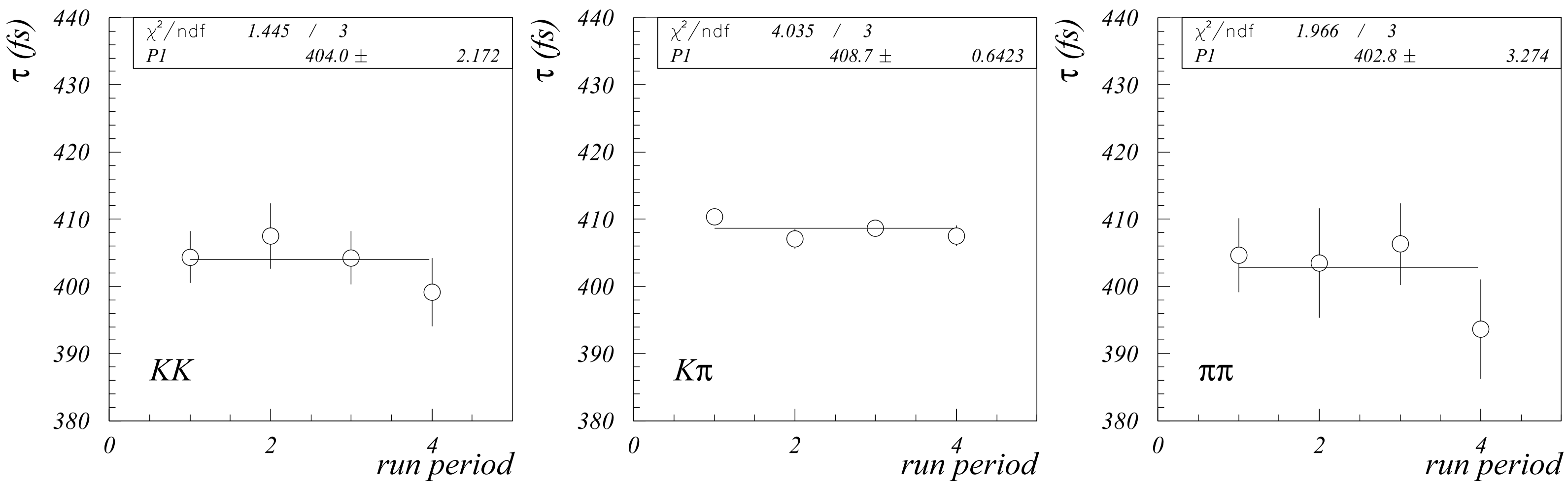


⇒ y_{CP} consistent between run periods

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 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 $t_0 \ll \tau$

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

- Result from this method

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