D^0 mixing in decays to CP eigenstates

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- Introduction
- Measurement giving the first evidence for D mixing
- Prospects for future
- Conclusions

Introduction

Mixing

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

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

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

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

with

$$x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

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

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

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

Decays to CP eigenstates

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

$p/q = 1 \;\Rightarrow$ CP conservation:

- $|D_{1,2}\rangle$ are CP-odd (1) and CP-even (2) eigenstates
  - ▷ with decays to CP eigenstates we measure Γ_1 or Γ_2
  - ▷ time distribution is exactly exponential
- Decays to non-CP eigenstates ($D^0 \to K^-\pi^+$ most suitable):
  - ▷ time distribution is exponential only in the approximation
  - ▷ lifetime is $\tau = 1/\Gamma$; $\Gamma = \frac{\Gamma_1+\Gamma_2}{2}$
- Measurement of lifetime difference between decays to non-CP and CP eigenstates
  - ▷ mixing parameter: $y_{CP} = \frac{\tau(non\!-\!CP)}{\tau(CP)} - 1$
  - ▷ in CP conservation limit: $y_{CP} = \pm y = (\Gamma_2 - \Gamma_1)/2\Gamma$
  - ▷ sign depends on CP eigenvalue: CP-even (+), CP-odd (-)

Decays to CP eigenstates

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

$p/q \neq 1 \ \Rightarrow$ CP violation:

- Time distribution is exponential only approximately
  - ▷ approximation very good, since mixing and CPV are small
- Difference also in lifetimes of $D^0/\overline{D}^0 \to CP$-eigenstates
  - ▷ CP violating parameter: $A_\Gamma = \frac{\tau(\overline{D}^0\to CP)-\tau(D^0\to CP)}{\tau(\overline{D}^0\to CP)+\tau(D^0\to CP)}$
- With $p/q = (1+\frac{A_M}{2})e^{i\phi}$ and $A_M, x, y \ll 1$:
  - ▷ $y_{CP} = (\pm y)\cos\phi - \frac{1}{2}A_M(\pm x)\sin\phi$
  - ▷ $A_\Gamma = \frac{1}{2}A_M(\pm y)\cos\phi - (\pm x)\sin\phi$
  - ▷ sign depends on CP eigenvalue: CP-even (+), CP-odd (-)
- Notes:
  - ▷ we assumed no direct CPV
  - ▷ we used phase convention $CP|D^0\rangle = -|\overline{D}^0\rangle$

Some decays suitable for measurement

- Criteria:
  - branching fraction
  - possibility to fit decay vertex (min. two charged tracks)
  - narrow resonances (CP-odd decays)
- CP-even decays:

  $D^0 \to K^+K^- \quad Br = 0.38\%$

  $D^0 \to \pi^+\pi^- \quad Br = 0.14\%$
- CP-odd decays:

  $D^0 \to K_s^0\omega;\ \omega \to \pi^+\pi^-\pi^0 \quad Br = 0.68\%$

  $D^0 \to K_s^0\phi;\ \phi \to K^+K^- \quad Br = 0.15\%$
- Some drawbacks of CP-odd decays:
  - ▷ smaller efficiency (K_s^0, π^0 reconstruction)
  - ▷ contribution of other resonances (interference!)

    $\longrightarrow$ different CP states; non-CP states
  - ▷ large differences in kinematics of particles used for vertex fit and $K^-\pi^+$

    $\longrightarrow$ large differences in resolution functions

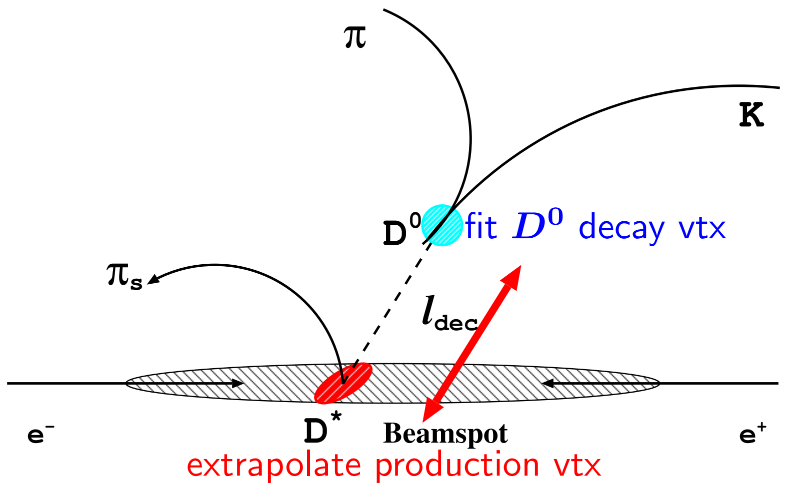
Experimental method

- $D^{*+} \to \pi^+ D^0$
  - ▷ 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:

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

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

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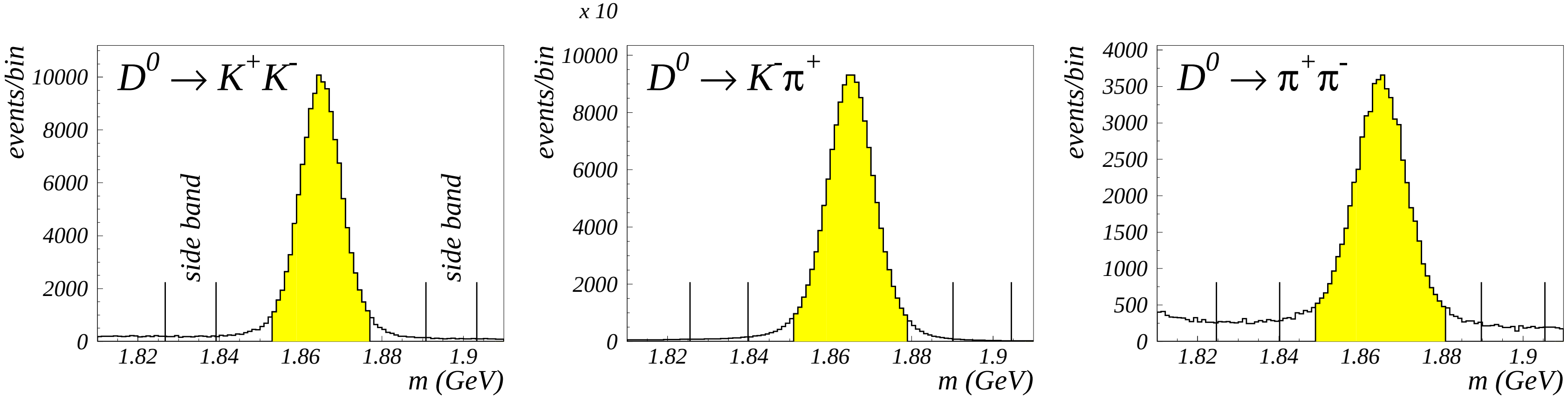
Event Selection

- Selection criteria optimized on tuned Monte Carlo
  figure of merit: statistical error on y_{CP}
- Background estimated from sidebands in m
- Signal yields (purities)

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



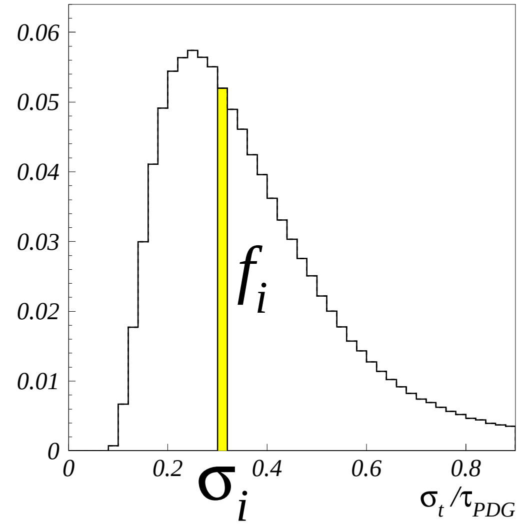
Lifetime fit

- Parametrization 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 for $D^0 \to K^-\pi^+$



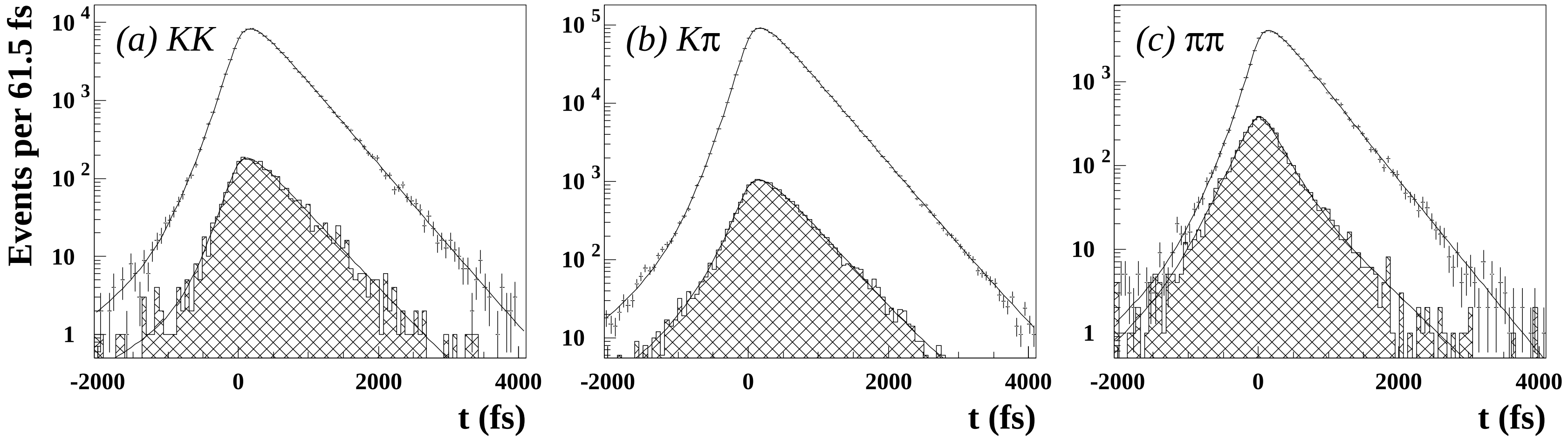
$$R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t; \sigma_{ik}, t_0) \,, \qquad \sigma_{ik} = s_k \sigma_k^{pull} \sigma_i$$

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

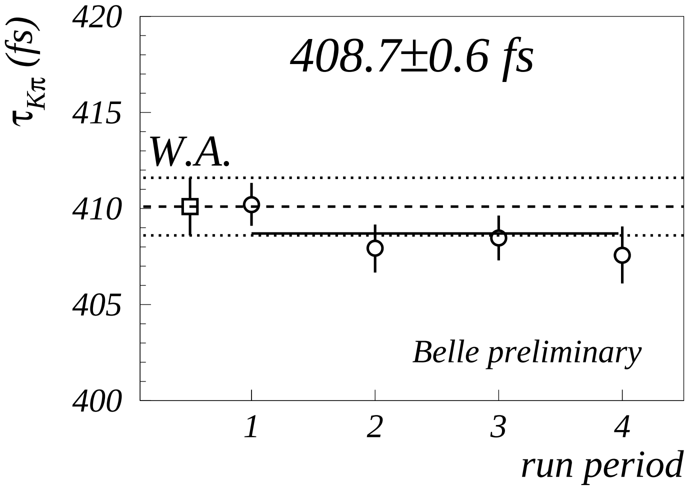
Belle measurement in $D^0 \to K^+K^-, \pi^+\pi^-$ (540 fb^{-1})

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

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



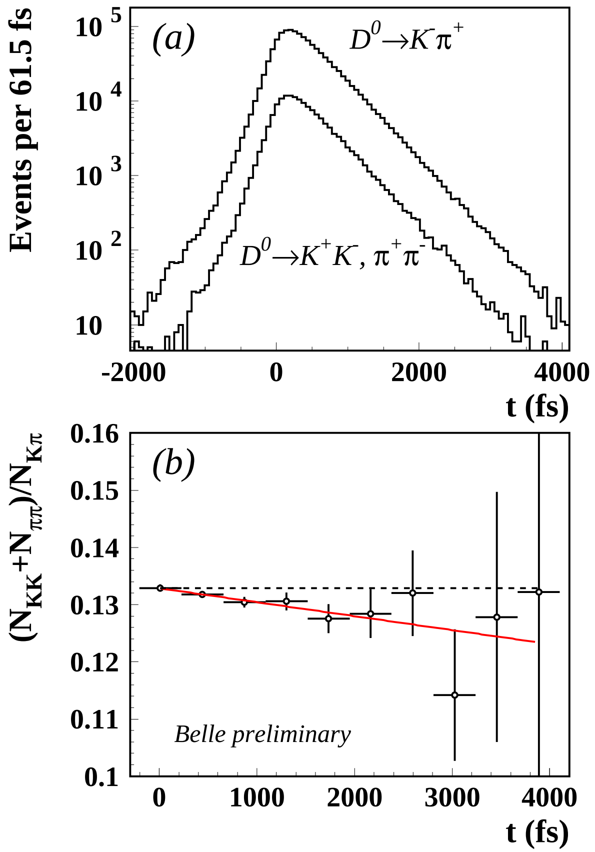
$D^0 \to K\pi$ lifetime very stable in slightly different running periods



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

Prospects for $D^0 \to K^+K^-, \pi^+\pi^-$ *(several ab^{-1})*

Systematics of Belle measurement (540 fb^{-1})

source	y_{CP}	A_Γ	scales with
Acceptance	0.12%	0.07%	MC stat.
Equal t_0 assumption	0.14%	0.08%	
M window position	0.04%	0.003%	
Signal/sideband background difference	0.09%	0.06%	MC, RD stat.
Opening angle distributions	0.02%		RD stat.
Background statistical fluctuations	0.07%	0.07%	RD stat.
(A)symmetric resolution function	0.01%	0.01%	
Selection variation	0.11%	0.05%	RD stat.
Binning of t distribution	0.01%	0.01%	
Total	0.25%	0.15%	

- ▷ contributions scaling with statistics 0.20%
- ▷ Equal t_0 assumption 0.14% equal to stat. error at 3 ab^{-1}
- ▷ M window position 0.04% equal to stat. error at 35 ab^{-1}

Systematics due to equal t_0 assumption the only one critical

Prospects for $D^0 \to K^+K^-, \pi^+\pi^-$ (several ab^{-1})

Equal t_0 assumption

- t_0 = resolution function offset; assumed the same for K^+K^-, $K^-\pi^+$, $\pi^+\pi^-$
- The widths of r.f. may differ slightly (free fit parameters)
- Ideally, $t_0 = 0$
- MC (ideal detector alignment) shows some small offsets ($|t_0|/\tau \approx 0.2\%$), but are the same (consistent) for the three final states
- RD show larger offsets - different in different running periods (up to 2% in both directions), but consistent between final states
- In one of the running period the resolution function was found to be also slightly asymmetric
- Asymmetric parametrization

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

with

$$x_1 = t_0 - \frac{w_2}{w_1 + w_2} \Delta t \; , \quad x_2 = t_0 + \frac{w_1}{w_1 + w_2} \Delta t \; , \quad x_3 = t_0$$

and free parameters: t_0, Δt, s_1, s_2, s_3 (for symmetric: $\Delta t = 0$)

Prospects for $D^0 \to K^+K^-, \pi^+\pi^-$ (several ab^{-1})

- By introducing small vertex detector misalignments (within the current alignment precision!) we were able to reproduce with MC the offsets and asymmetry seen in RD
- Example: enlarging the radius of the second superlayer by 15 μm results in $t_0/\tau = 0.8\%$ and slightly asymmetric r.f.
- Note that current alignment precision satisfies completely the requirements needed for CPV measurements in B meson sector (much smaller statistics!)

To conclude:

- Detector resolution function and corresponding systematic uncertainties studied in details and well understood
- The systematics due to equal t_0 assumption can be reduced by improving the alignment precision
- Systematic uncertainties seems will not be dominating the precision of y_{CP} and A_Γ measurements with several ab^{-1} expected in the near future at Belle.

Conclusions

- Measurements of D^0 mixing in decays to CP eigenstates discussed.
- CP-even final states (K^+K^-, $\pi^+\pi^-$) are more favourite than CP-odd.
- Evidence for D^0 mixing found in decays to CP-even eigenstates $K^+K^-, \pi^+\pi^-$

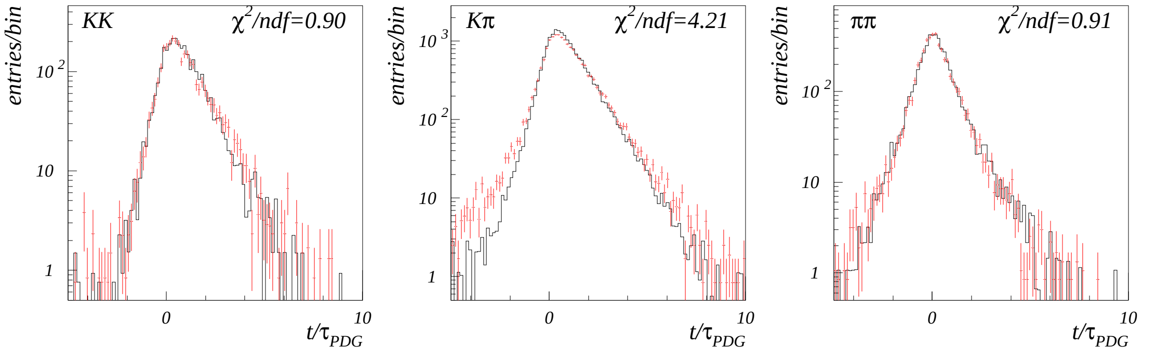
$$y_{CP} = 1.31 \pm 0.32 \pm 0.25 \text{ \% } (3.2\sigma)$$

- CPV search: no evidence found.
- Prospects for future measurements also discussed; with improved vertex detector alignment precision, I think, systematics will not dominate the precision of measurement with an order-of-magnitude increased data statistics.

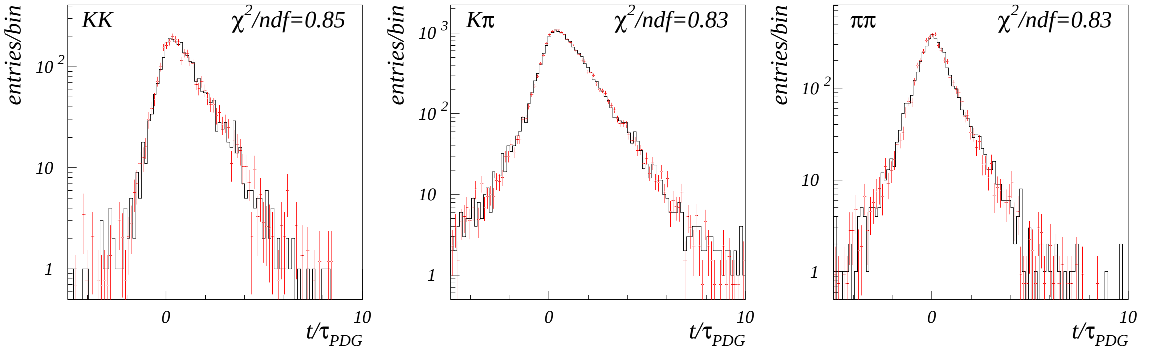
Background

- A comparison of timing distributions

MC signal region background - MC side bands



DATA side bands - MC side bands



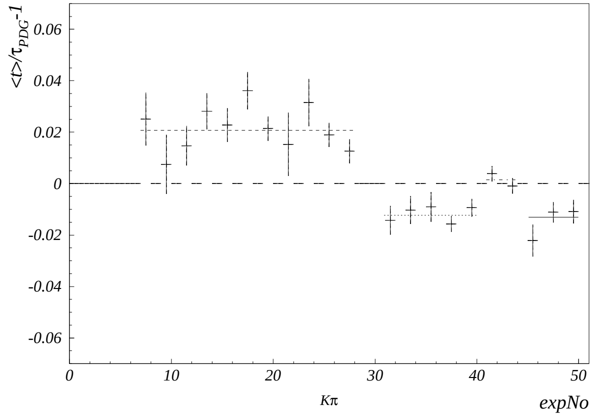
- Difference to result, if using background from tuned MC

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

Backup slide: X-checks for y_{CP}

Run periods

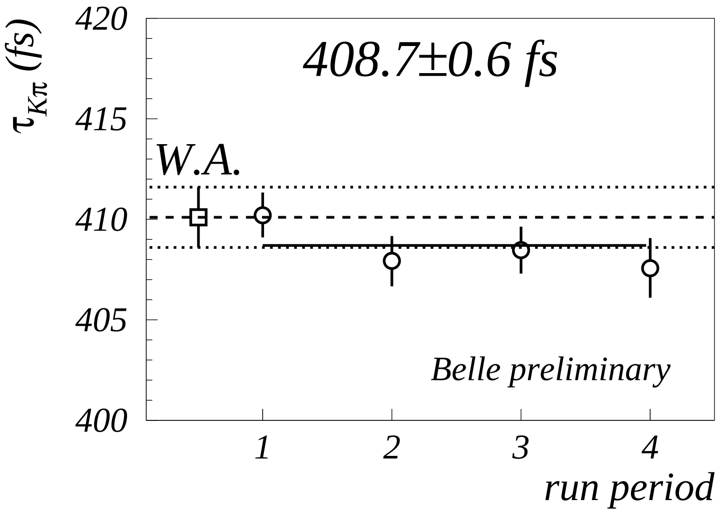
"mean" of $K\pi$ timing distr.



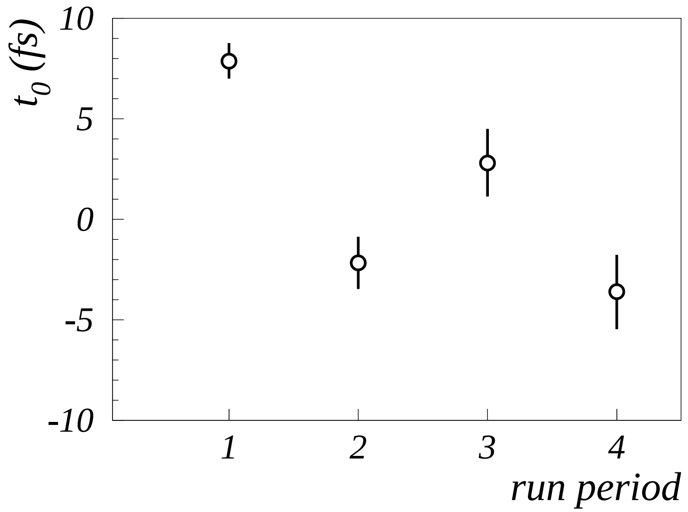
$$P(t) = \frac{1}{\tau} e^{-t/\tau} * R(t) \quad \Rightarrow \quad < t >= \tau + t_0$$

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

fitted $K\pi$ lifetimes

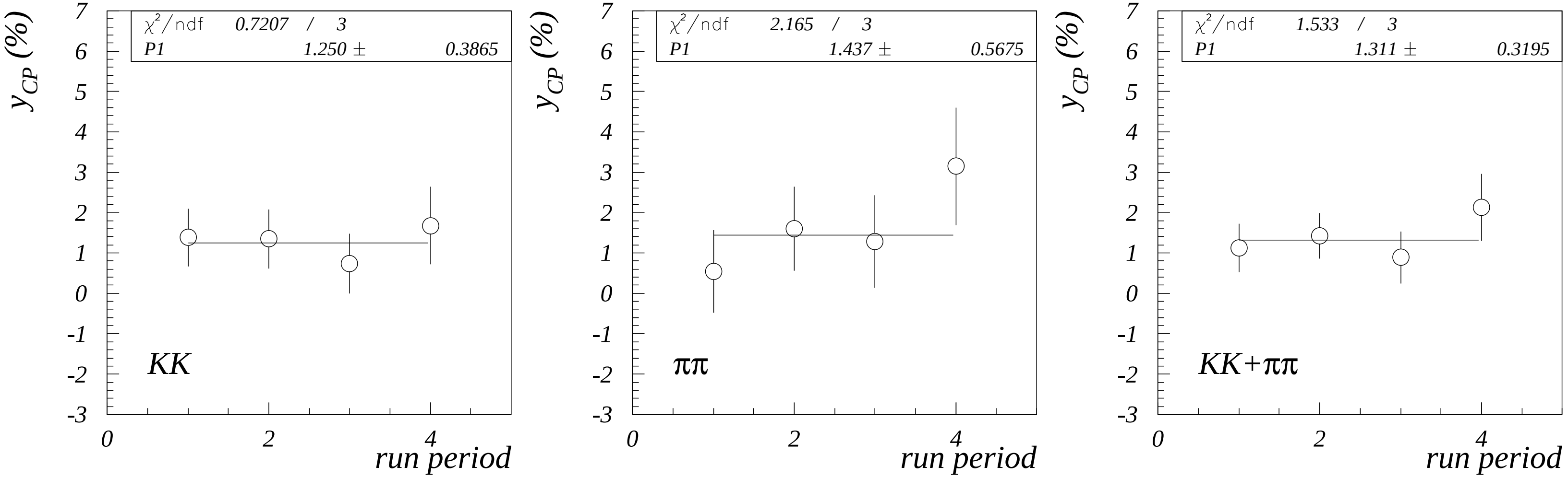


fitted r.f. offsets



Backup slide: X-checks for y_{CP}

Measured y_{CP} versus run periods



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

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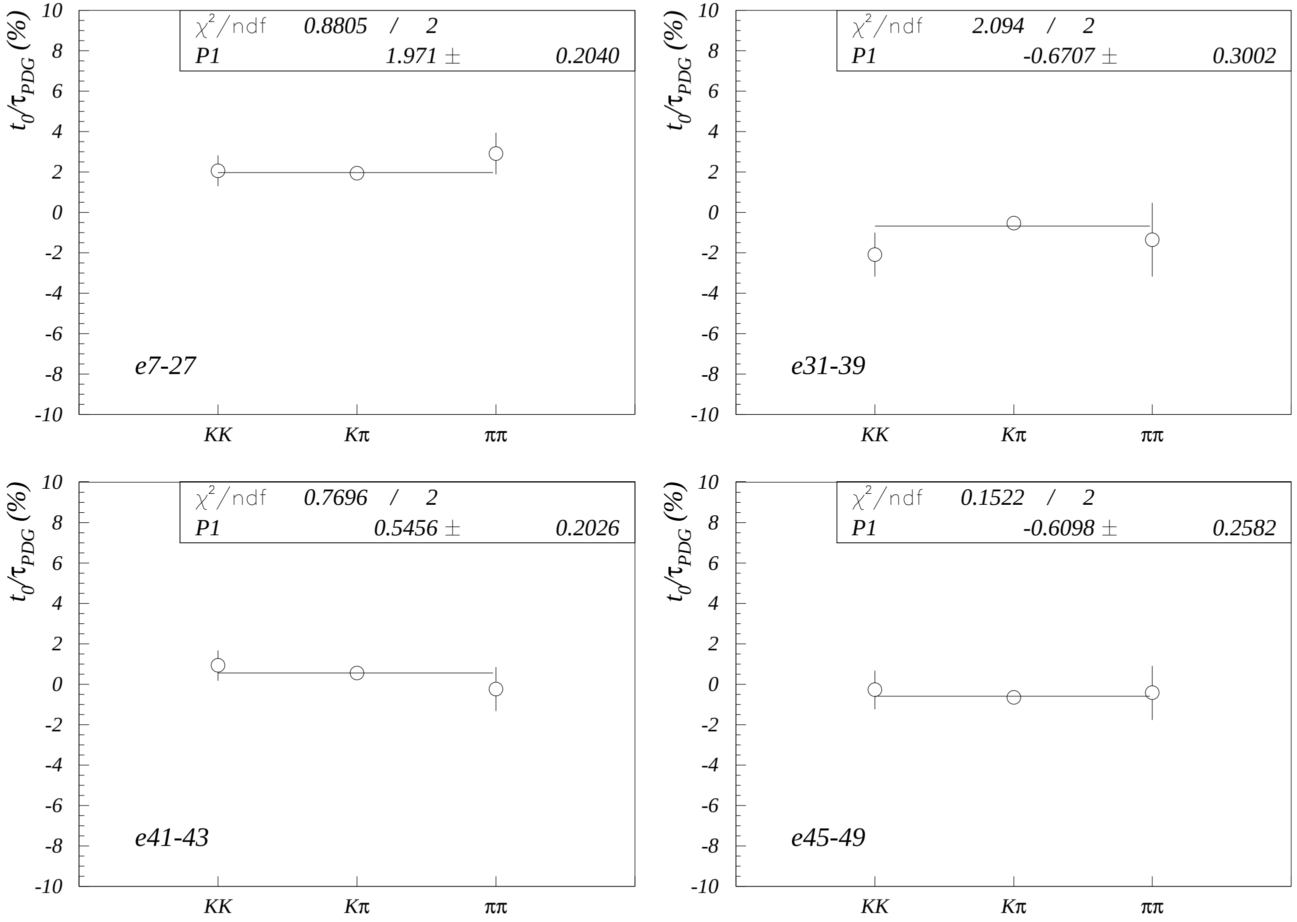
Test for equal t_0 assumption for each of the run periods

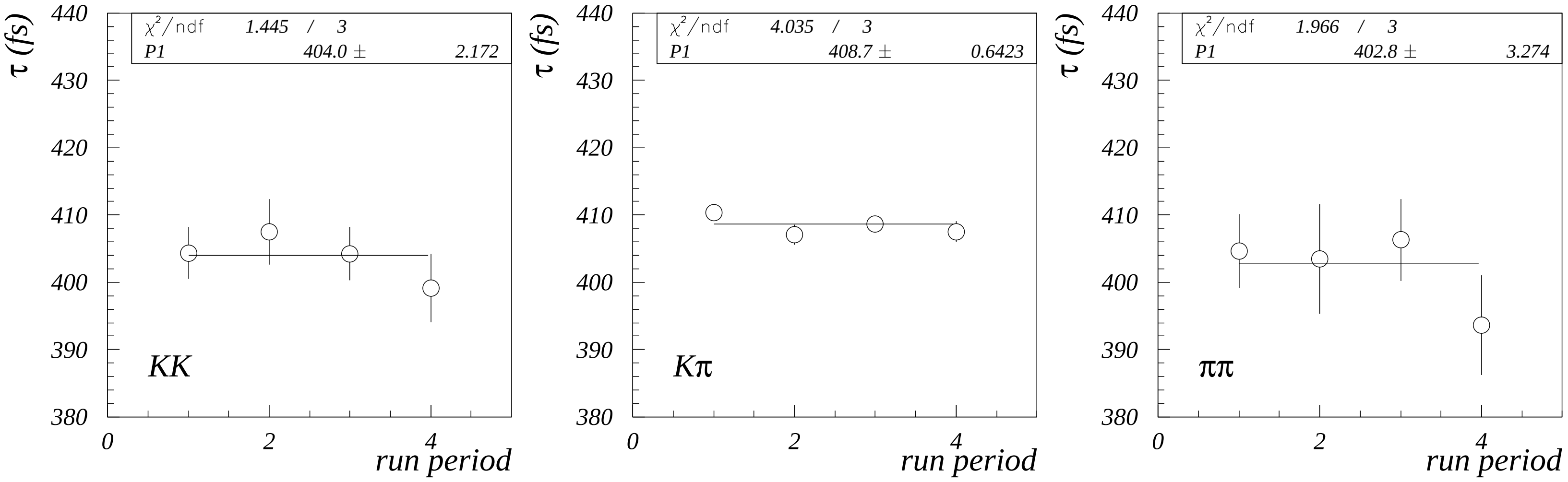


$\Rightarrow t_0$ is final state independent

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

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