New Belle results on $D^0 - \overline{D}^0$ mixing

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Outline

- Introduction
- Updated measurement in $D^0 \to K^+K^-, \pi^+\pi^-$ (976 fb^{-1})
- Conclusions

Mixing formalism

- Flavor eigenstates $\neq$ mass eigenstates: $|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$
  - $p/q \neq 1 \Rightarrow$ *CP* violation (CPV)
- Time evolution of a $D^0 - \overline{D^0}$ system

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

with $\hat{M}$ and $\hat{\Gamma}$ being hermitian

- Solutions:

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

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

- Mixing parameters:

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

D^0 mixing

- Since D^0 mixing is small ($|x|, |y| \ll 1$):

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

- Time dependent decay rates of $D^0 \to f$:

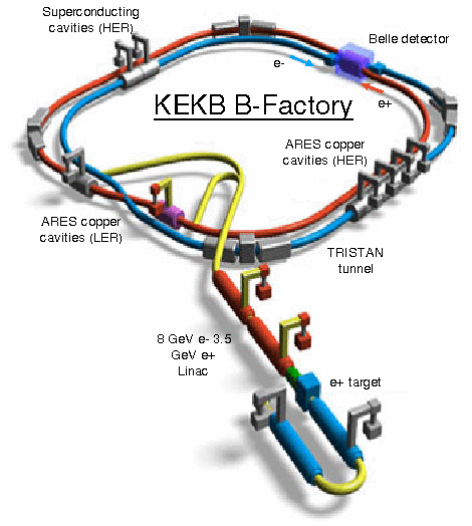
$$\frac{dN_{D^0\to f}}{dt} \propto |\langle f|\mathcal{H}|D^0(t)\rangle|^2 = e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- Exponential decay modulated with x and y
  - x and y can be obtained from measured time dependence of $\frac{dN_{D^0\to f}}{dt}$
- Shape is final state dependent
  - different final states sensitive to different combinations of x and y

Charm production at Belle

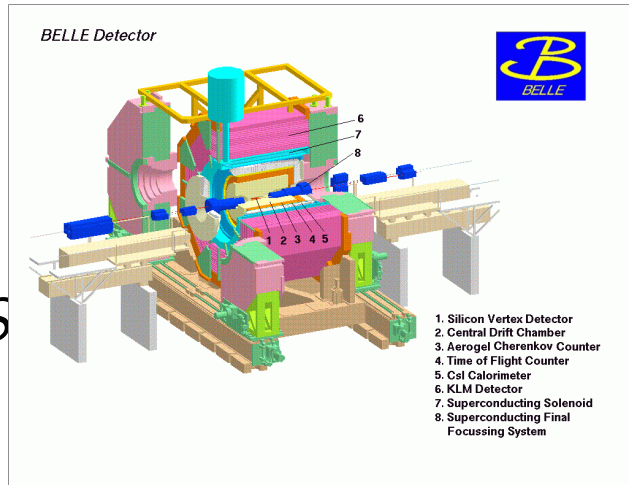
B-factories are also charm-factories: $\sigma_{c\bar{c}} \approx \sigma_{b\bar{b}}$

KEKB B-factory



- Asymmetric e^+e^- collider
- primarily at $\Upsilon(4S)$
- also $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), \Upsilon(5S$
- $\int \mathcal{L} dt = 1 \text{ ab}^{-1}$

Belle detector



- Charm production $\sigma_{c\bar{c}} \sim 1 \text{ nb} \longrightarrow \sim 10^9$ charm events at Belle
- Easy to reject D mesons from B decays using simple kinematic cuts:
  - $p^*_D > 2.5 \text{ GeV/c}$ at $\Upsilon(4S)$
  - $p^*_D > 3.1 \text{ GeV/c}$ at $\Upsilon(5S)$

Belle II will collect 50 times more (talk by A. Schwartz)

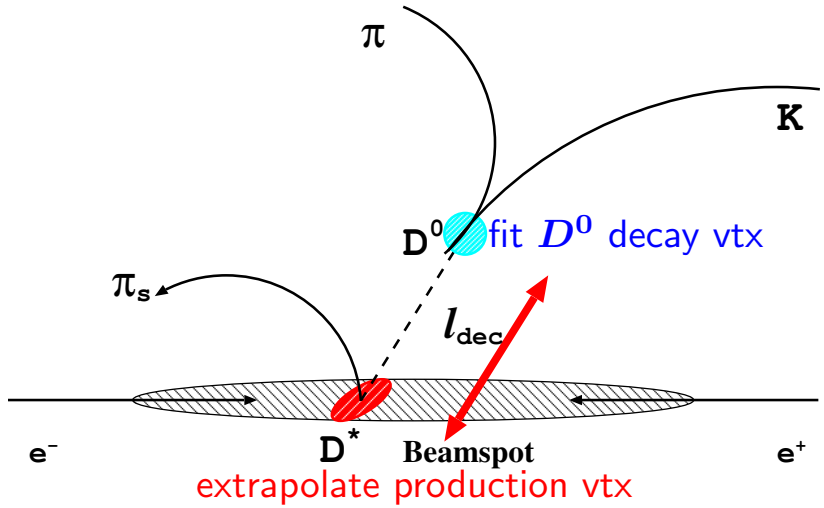
Experimental method

- Usually using $D^{*+} \to \pi^+ D^0$
  - flavor tagging by π_{slow} charge
  - background suppression

- D^0 proper decay time measurement:

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

  - decay time uncertainty σ_t calculated from vtx err. matrices



- To reject D^{*+} from B decays: $p^{CMS}_{D^{*+}} > 2.5\ (3.1)\ \mathrm{GeV/c}$
- Observables:
  - $m = m(K\pi)$
  - $q = m(K\pi\pi_s) - m(K\pi) - m_\pi$

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

- Measurement of lifetime difference btw. $D^0 \to K^-\pi^+$ and $D^0 \to K^+K^-, \pi^+\pi^-$
- Timing distributions are exponential (if CP is conserved)
  - mixing parameter: $\boxed{y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1}$
  - if CP conserved: $y_{CP} = y$
- If CP violated $\to$ difference in lifetimes of $D^0/\overline{D^0} \to K^+K^-, \pi^+\pi^-$
  - lifetime asymmetry: $\boxed{A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}}$
  - $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$
  - $A_\Gamma = \frac{1}{2}A_M y\cos\phi - x\sin\phi$

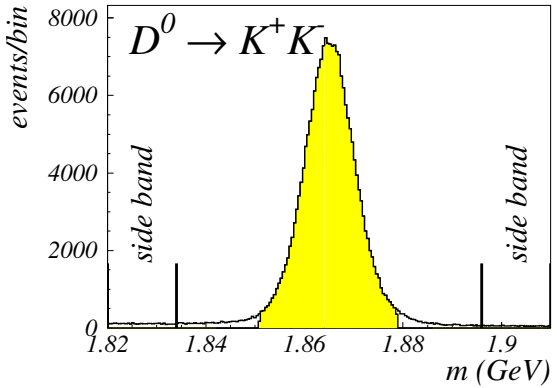
(S. Bergmann et.al., PLB 486, 418 (2000))

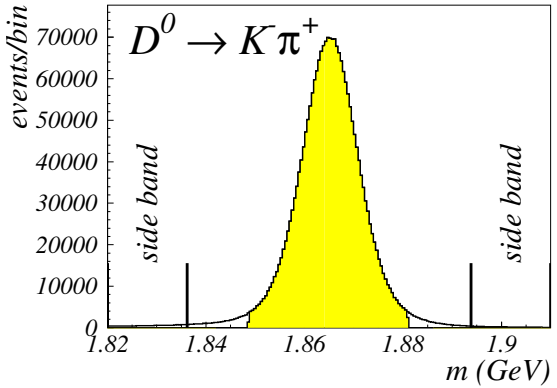
$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

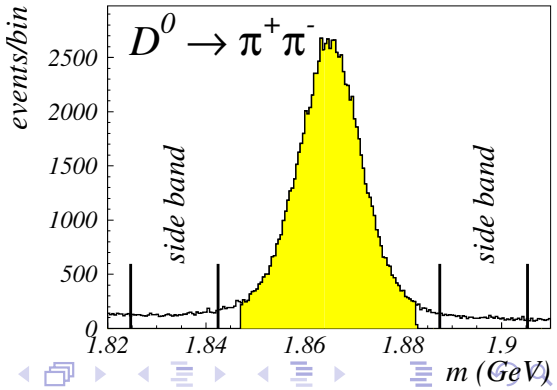
Event Selection

- Reconstruction
  - K and π selection
  - vertex fits
  - $p^*(D^{*+}) > 2.5(3.1)$ GeV/c
- Analysis cuts: Δm, Δq, σ_t
  - optimized on tuned Monte Carlo
  - figure of merit: statistical error on y_{CP}
- Background estimated from sidebands in m
  - sideband position optimized
- Signal yields (purities) entering the measurement

channel	KK	$K\pi$	$\pi\pi$
yield	242k	2.61M	114k
purity	98.0%	99.7%	92.9%



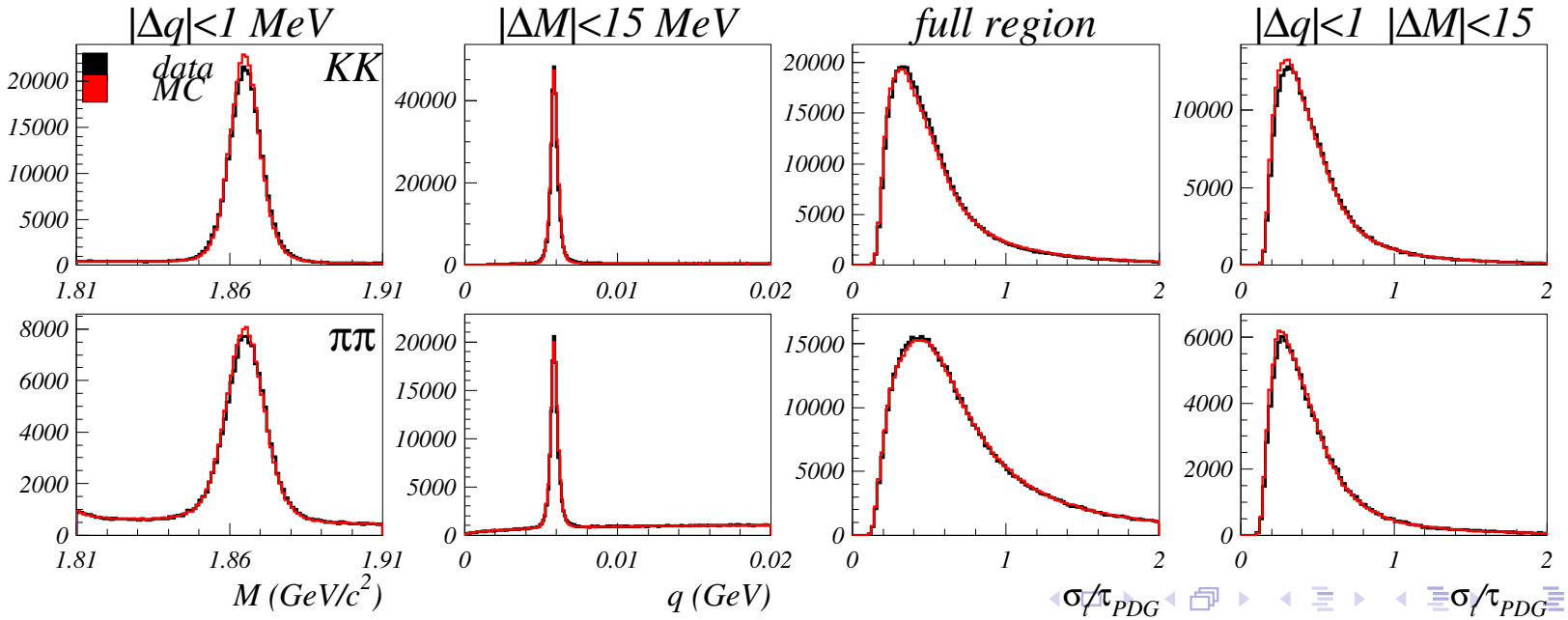




$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

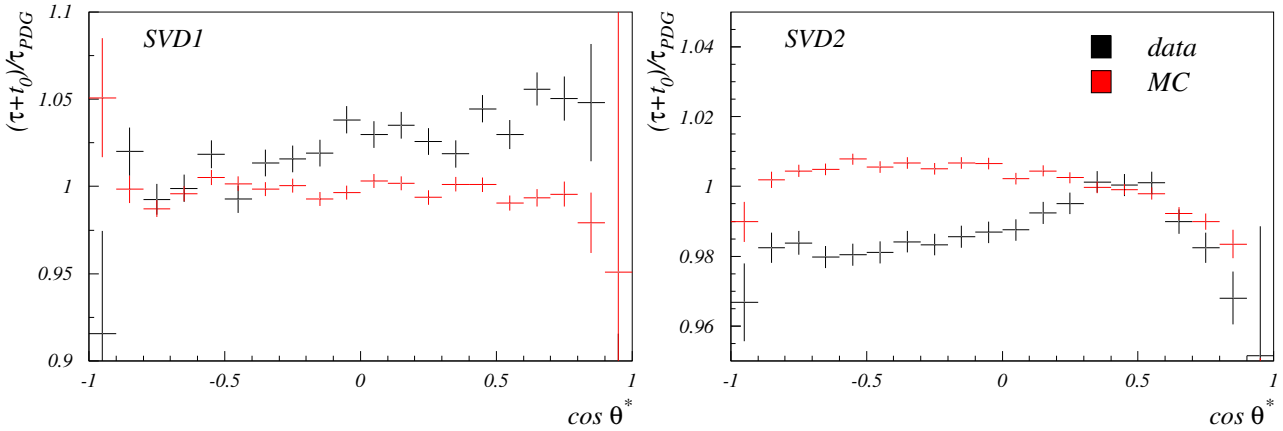
Monte Carlo tuning

- MC used for cut optimization and sideband position selection
- Very good agreement with data in shapes of M, q and σ_t distributions
- However, signal/background fractions differ by 10% - 20% $\to$ tuning needed
- Correction factors obtained from 2D fit to $M - q$ data distributions
  - MC shapes used for different event types



$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Mean proper decay time as a function of $\cos\theta^*$ for $D^0 \to K^-\pi^+$

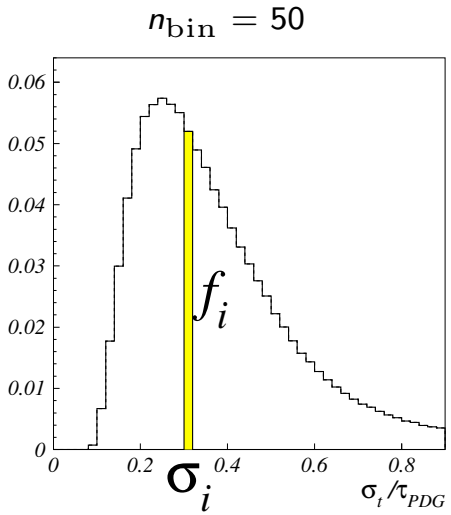


- Disagreement between data and MC of up to 5% of lifetime
  - due to different resolution function offsets
  - attributed to SVD misalignments
- Measurement therefore performed in bins of $\cos\theta^*$
  - 20 bins
  - additional cut: $|\cos\theta^*| < 0.9$ (1% events lost)

$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Resolution function (for binned fit)

- Constructed from normalized distribution of σ_t
  - Using 2 or 3 Gaussian PDF for each σ_t bin
- PDF parameters determined in each $\cos\theta^*$ bin by fitting the distribution of pulls $(t - t_{\mathrm{gen}})/\sigma_t$
  - widths σ_k^{pull}, fractions w_k



$$R(t) = \sum_{i=1}^{n_{\mathrm{bin}}} f_i \sum_{k=1}^{n_g} w_k G(t; \mu_i, \sigma_{ik})$$

$$\sigma_{ik} = s_k \sigma_k^{\mathrm{pull}} \sigma_i \qquad \mu_i = t_0 + a(\sigma_i - \sum_{j=1}^{n} f_j \sigma_j)$$

- Free parameters:
  - width scaling factors: s_k, $k = 1, \ldots, n_g$ ($n_g = 2$ or 3)
  - resolution function offset: t_0
  - slope to model asymmetry: a

$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Proper decay time distribution

- Parameterization

$$f(t) = \frac{N}{\tau} \int e^{-t'/\tau} R(t - t') dt' + B(t)$$

- Free parameters: N, τ, s_k, t_0, a
- Sideband subtracted σ_t distribution used to construct $R(t)$

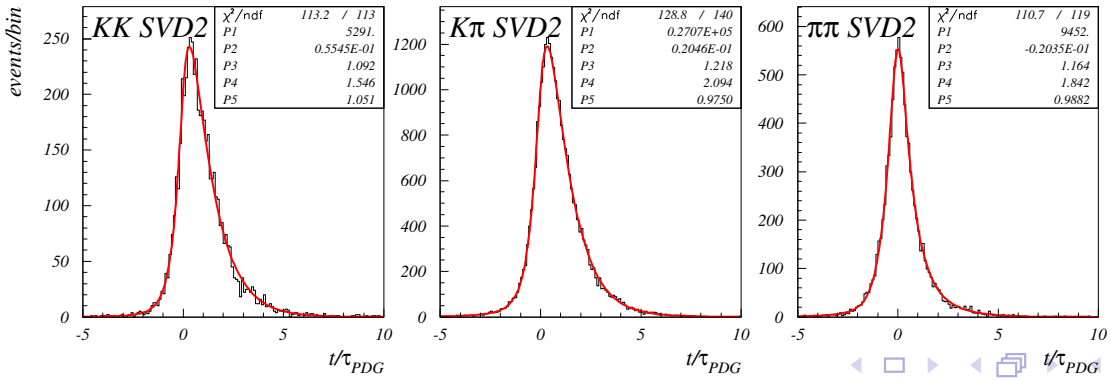
$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Background

- Two lifetime components (zero and non-zero lifetime)

$$B(t) = N_b \int [f\,\delta(t') + (1-f)\frac{1}{\tau_b} e^{-t'/\tau_b}] R_b(t-t')dt'$$

- Background resolution function:
  - symmetric ($a = 0$) with $n_g = 3$ and $s_3 = s_2$
- Fraction f is $\cos\theta^*$ dependent, fixed from tuned-MC
- Free parameters t_0, s_1, s_2, τ_b
  - determined by fit to sideband distributions summed over $\cos\theta^*$ bins
  - $B(t)$ is still $\cos\theta^*$ dependent due to σ_t distribution, f and N_b



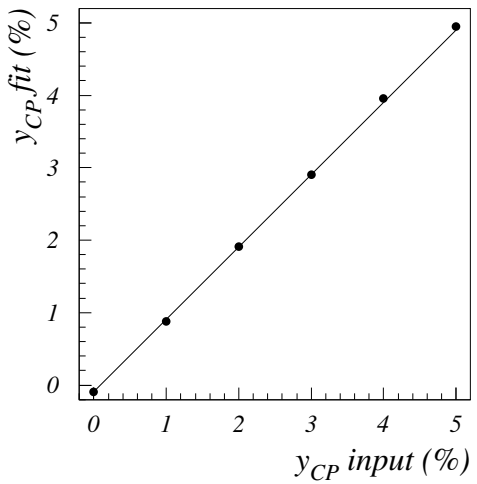
$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Simultaneous fit

- Decay modes fitted simultaneously in each $\cos\theta^*$ bin
  - binned maximum likelihood fit
- Shared parameters:
  - y_{CP}, A_Γ (KK and $\pi\pi$)
  - t_0, a (all decay modes)
  - s_1, s_2, s_3 (up to an overall scaling factor)

- Fit x-checked with generic MC (6×data statistics)
  - $y_{CP} = (-0.02 \pm 0.08)\%$, $A_\Gamma = (-0.00 \pm 0.08)\%$
    $\to$ consistent with zero
  - $\tau_{K\pi} = (411.30 \pm 0.18)$ fs
    $\to$ consistent with generated lifetime (411.6 fs)
- Linearity x-checked with MC re-weighted to different y_{CP}
  - no bias found

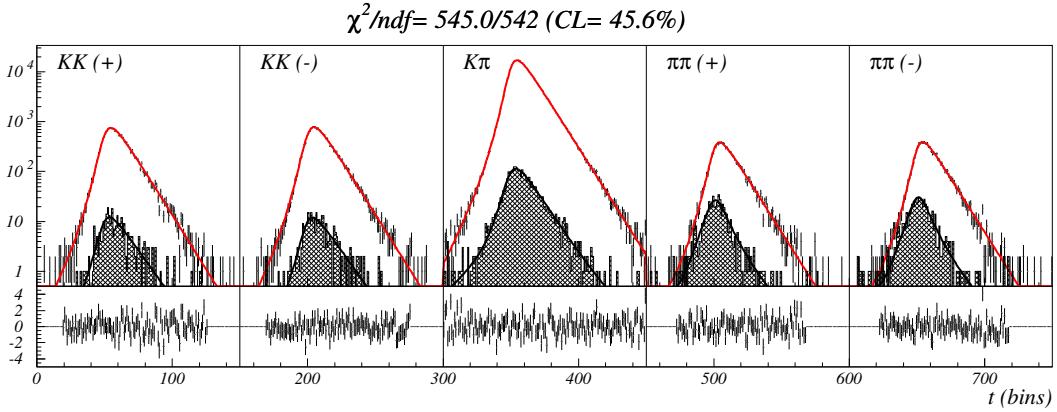
Linearity



$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

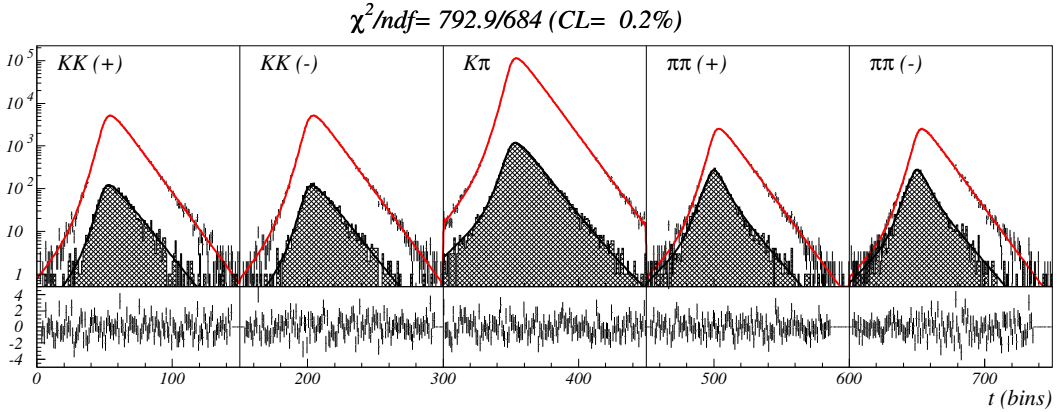
Sum of histograms and fitted functions over $\cos\theta^*$ bins

SVD1



3-layer SVD
153 fb^{-1}

SVD2

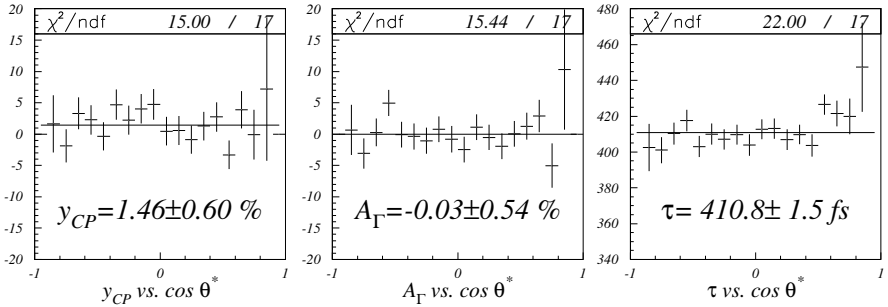


4-layer SVD
823 fb^{-1}

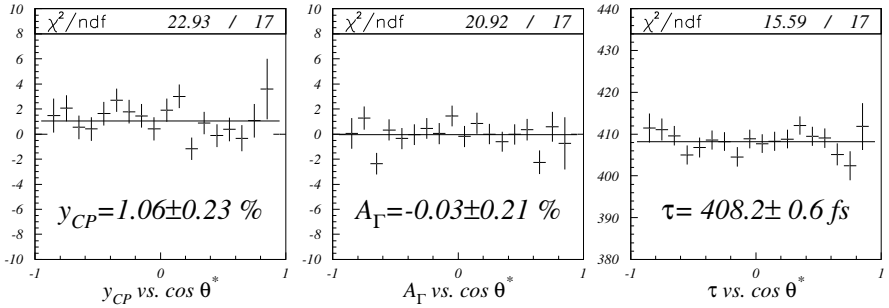
- Minos status: successful for all fits (2×18 fits)
- Confidence levels of fits above 5% (except one with CL=3.3%)

$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

SVD1



SVD2



sample	y_{CP} (%)	A_Γ (%)	τ (fs)
SVD1	1.46 ± 0.60	-0.03 ± 0.54	410.81 ± 1.50
SVD2	1.06 ± 0.23	-0.03 ± 0.21	408.23 ± 0.58
SVD1+SVD2	1.11 ± 0.22	-0.03 ± 0.20	408.56 ± 0.54

- y_{CP} at $5.1\sigma_{\mathrm{stat}}$
- A_Γ consistent with zero
- $\tau_{K\pi}$ consistent between SVD1 and SVD2 within 1.6σ and consistent with PDG within 1σ

$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Systematics

source	Δy_{CP} (%)	ΔA_Γ (%)
acceptance	0.050	0.044
SVD misalignments	0.060	0.041
mass window position	0.007	0.009
background	0.059	0.050
resolution function	0.030	0.002
binning	0.021	0.010
sum in quadrature	0.11	0.08

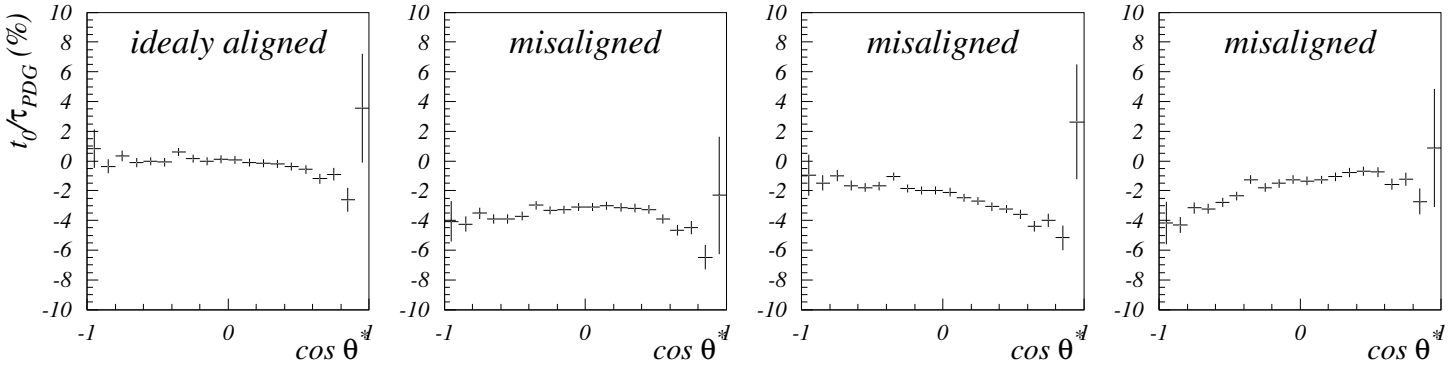
SVD misalignments:

- Studied with misaligned signal MC:
  - different local and different global misalignments simulated
- Found to affect resolution function considerably (especially t_0)
- Effect very similar for KK, $K\pi$ and $\pi\pi$
  - small impact on y_{CP}, A_Γ, large impact on $\tau_{K\pi}$

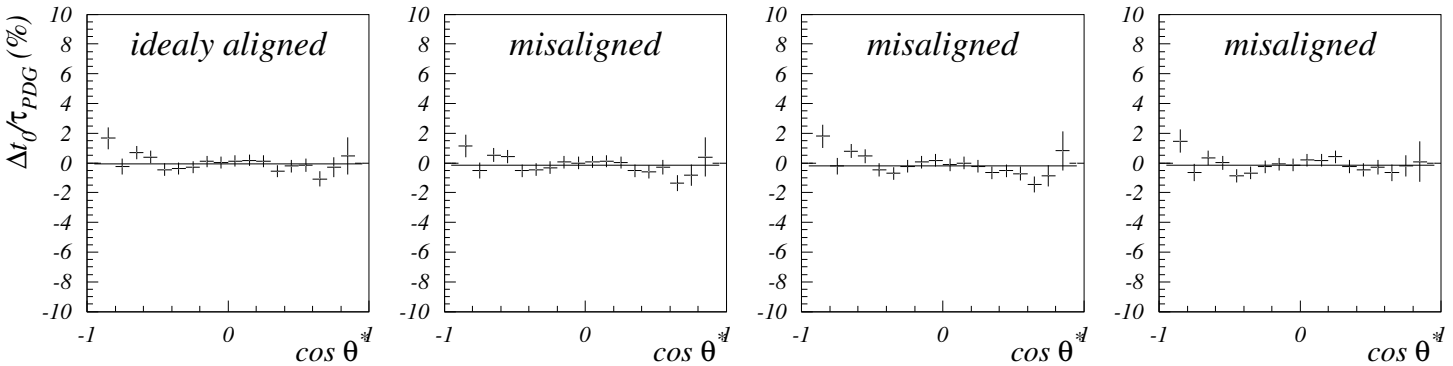
$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

SVD misalignments

- Impact on resolution function offset t_0 (shown for $K\pi$)



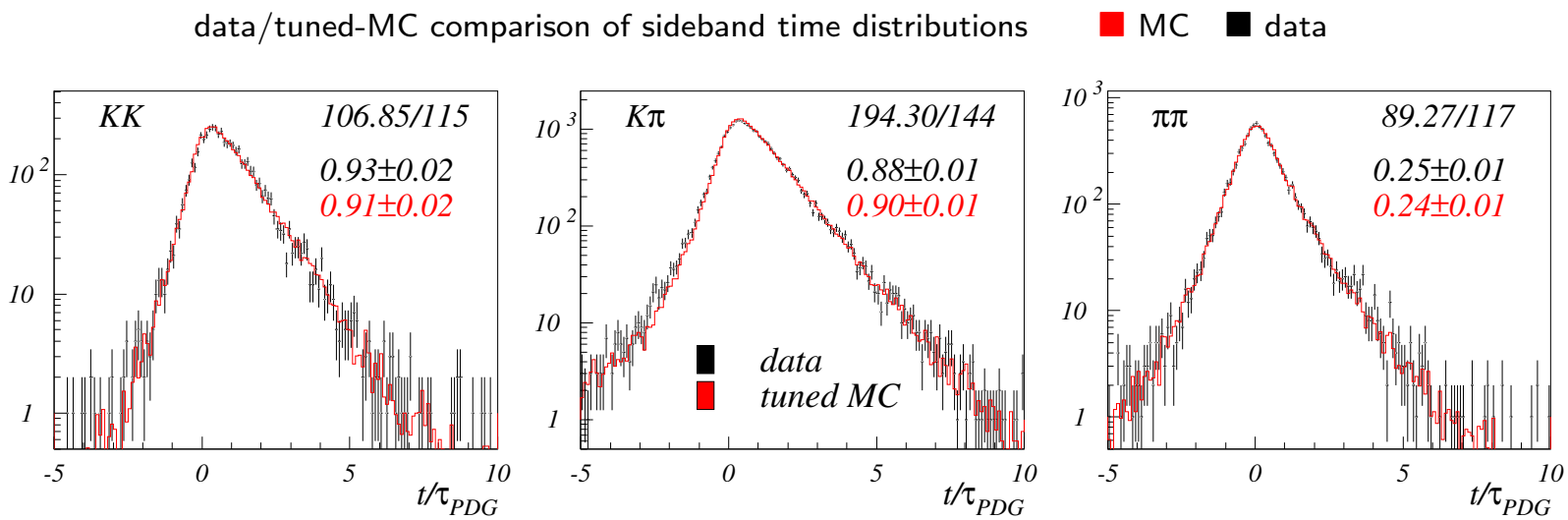
- Impact on the difference of resolution function offsets $t_0^{KK} - t_0^{K\pi}$



$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Background

- The second largest source of sistematics; two contributions
  - statistical fluctuations of sideband distribution
    $\to$ propagate to 0.051% (y_{CP}) and 0.050% (A_Γ)
  - approximation of signal-window background with sideband
    $\to$ estimated from tuned MC (0.029% y_{CP}, 0.007% A_Γ)
- To validate second point:
  - data/tuned-MC sideband time distributions in good agreement

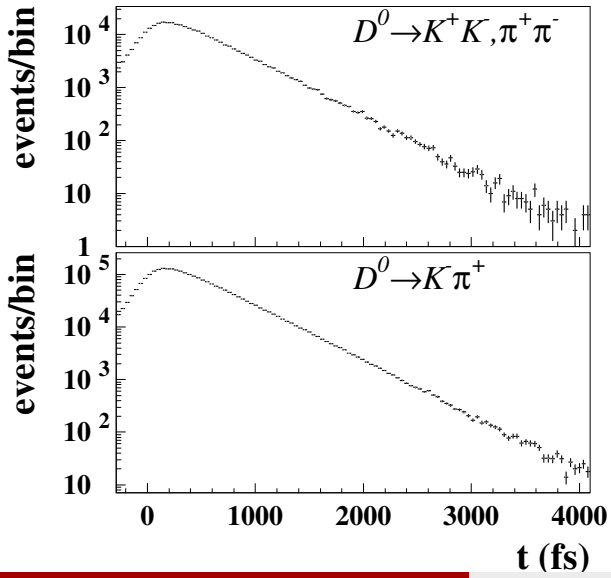


$D^0 \to K^+K^-, \pi^+\pi^-$ (update with 976 fb^{-1})

Results (preliminary)

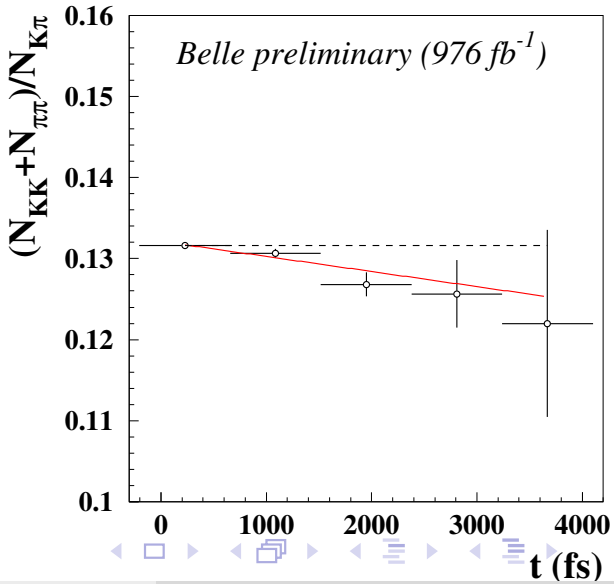
$$\begin{aligned} y_{CP} &= (+1.11 \pm 0.22 \pm 0.11)\% \\ A_\Gamma &= (-0.03 \pm 0.20 \pm 0.08)\% \end{aligned}$$

- y_{CP} is at 4.5σ when both errors are combined in quadrature and at 5.1σ if only statistical error is considered
- A_Γ is consistent with no indirect CP violation.



divide distributions

$\longrightarrow$



Conclusions

- The measurement of $D^0 - \overline{D}^0$ mixing in $D^0 \to K^+K^-, \pi^+\pi^-$ decays has been updated with the full Belle data of 976 fb^{-1}
- We measure $y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$
  - the most sensitive and the most significant measurement of any mixing parameter up to now
  - consistent with our previous measurement on 540 fb^{-1}, where we found the first evidence for $D^0 - \overline{D}^0$ mixing
  - consistent also with BaBar measurements in these decays
- We also measure $A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$
  - consistent with no indirect CP violation
  - the most stringent limits on A_Γ up to now