SEARCH FOR CP VIOLATION IN $D^0 \to KK, \pi\pi, K\pi$ AND $D^0 \to \pi^0\pi^0$

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on behalf of the Belle Collaboration

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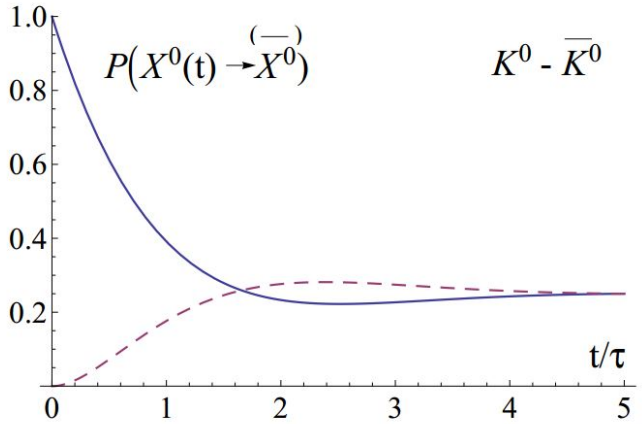
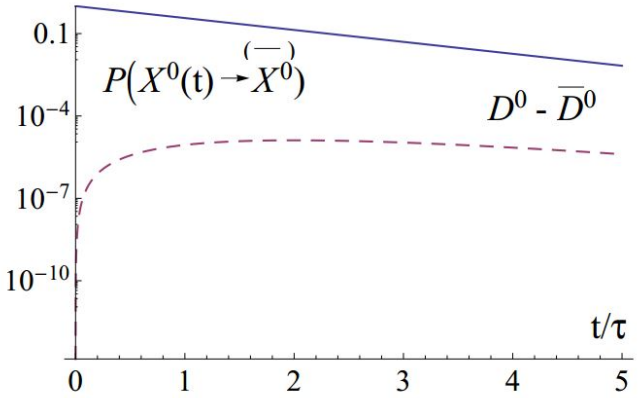
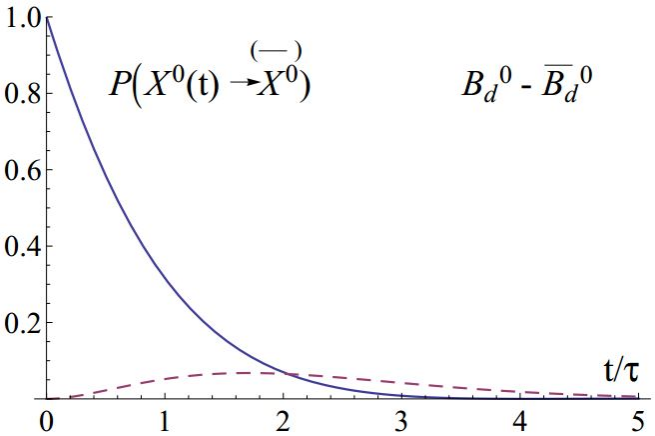
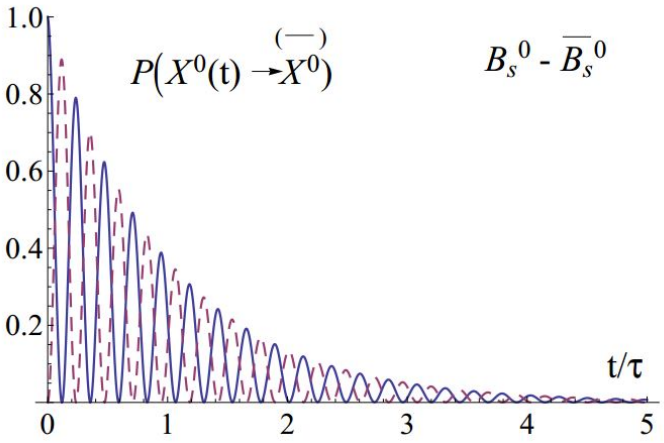
$D^0 - \overline{D}^0$ mixing

- mixing in D^0 meson system considerably smaller than in K^0, B^0









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

- mixing parameters $x = \Delta m/\Gamma, y = \Delta\Gamma/2\Gamma$
- if $p \neq q \to |D^0_{1,2}\rangle$ not CP eigenstates $\to$ CPV

From mixing to CPV

From mixing arises a difference in effective lifetime of CP eigenstates (KK, $\pi\pi$) and flavour eigenstates (Kπ):

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^+K^-)} - 1 = \\ = y\cos(\phi) - \frac{1}{2}A_M x \sin(\phi) \overset{\text{no CPV}}{=} y \tag{1}$$

$$\phi = arg(p/q) \overset{\text{no CPV}}{=} 0$$
$$A_M = |q/p| - |p/q| \overset{\text{no CPV}}{=} 0$$

Difference in effective lifetimes of CP eigenstates of $D^0, \overline{D}^0$ gives a non-zero asymmetry:

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} = \\ = \frac{1}{2}A_M y\cos(\phi) - x\sin(\phi) \overset{\text{no CPV}}{=} 0 \tag{2}$$

SM CPV in charm $\mathcal{O}(10^{-3})$ $\rightarrow$ anything larger indicates NP.

TIME-DEPENDENT ANALYSIS

- measure only indirect CPV - common to all D^0 decay modes
- get y_{CP}, A_Γ from measurements of proper decay time

Updated analysis:

- twice as large data sample: 976 fb^{-1}
  ($\Upsilon(4S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(5S)$)
- improved analysis method - take into account
  - two different configurations of SVD
  - polar angle dependence
- final results are shown here

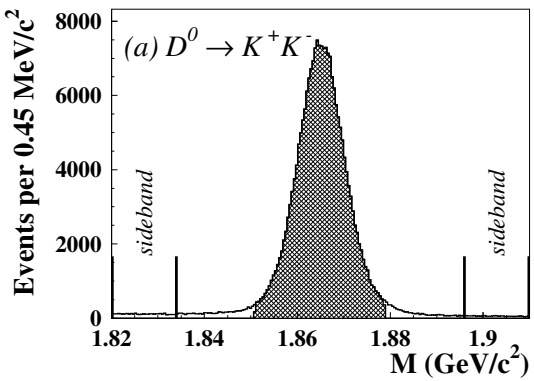
$D^0 \to KK, \pi\pi, K\pi$

Selection

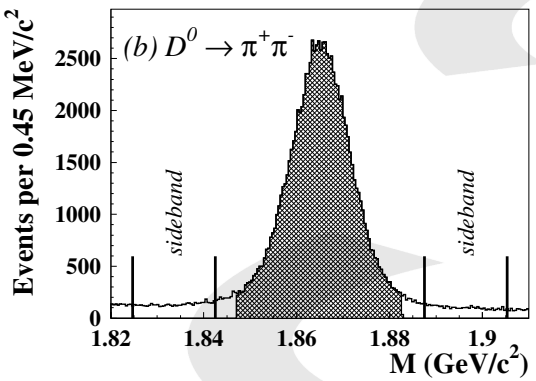
Flavour tag	$D^{*+} \to D^0 \pi_S^+$
vertex fit	p value $> 10^{-3}$
$p_{CMS}(D^{*+})$	> 2.5 GeV (3.1 GeV for $\Upsilon(5S)$)
window in m(D^0)	$2.25\sigma_M (\sigma_M \approx 6-8$ MeV)
window in q	0.66 MeV (SVD1), 0.82 MeV (SVD2)
σ_t	$<$ 440 fs (SVD1), 370 fs (SVD2)

Table: Selection criteria.

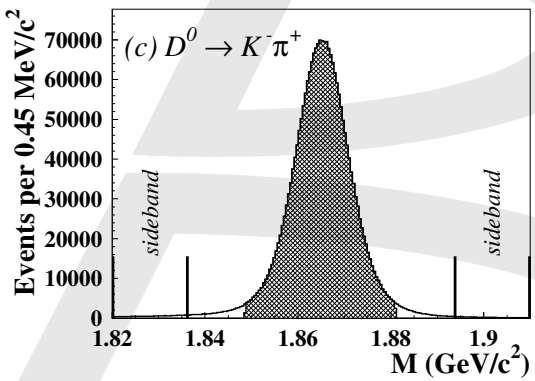
Optimisation: minimal statistical error on y_{CP}.



Signal yield: 242×10^3



Signal yield: 114×10^3



Signal yield: 2.61×10^6

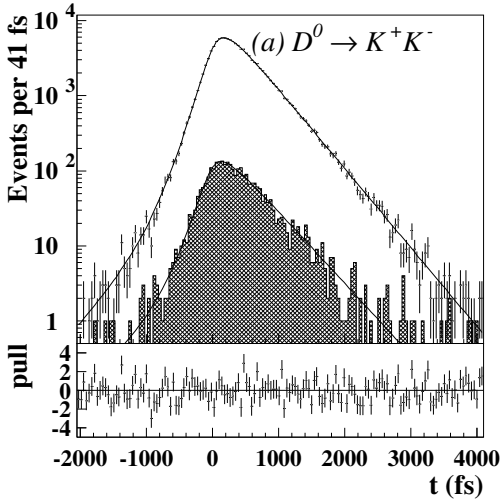
- Proper decay time t distribution:

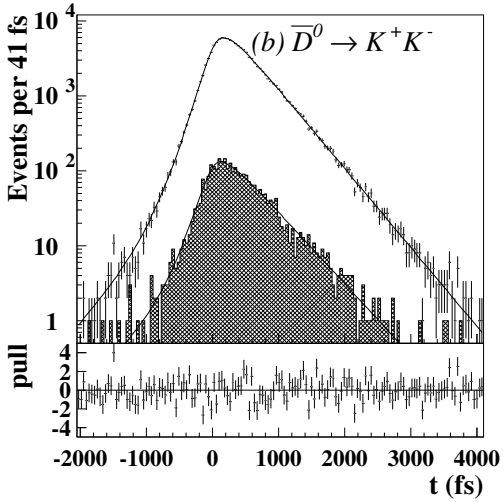
$$F(t) = \frac{N}{\tau} \int e^{-t'/\tau} R(t - t') dt' + B(t)$$

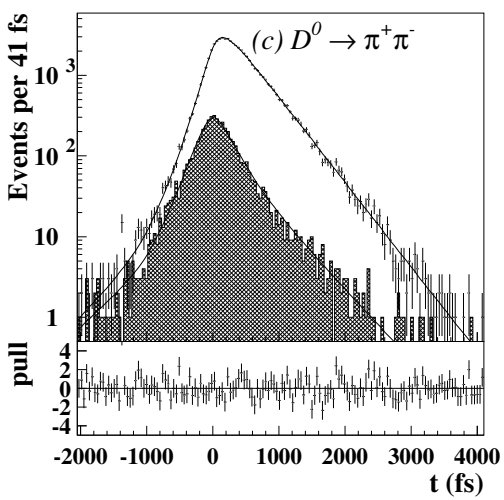
- Perform simultaneous binned maximum likelihood fit to all 3 channels (KK, $\pi\pi$, $K\pi$), separately for SVD1,2.
- $\cos(\theta^*)$ dependence $\to$ perform fit in bins of $\cos(\theta^*)$.
- Combine results from all bins with least squares fit to constant to obtain the final result.
- Fit tested on MC, linearity tests show no bias.

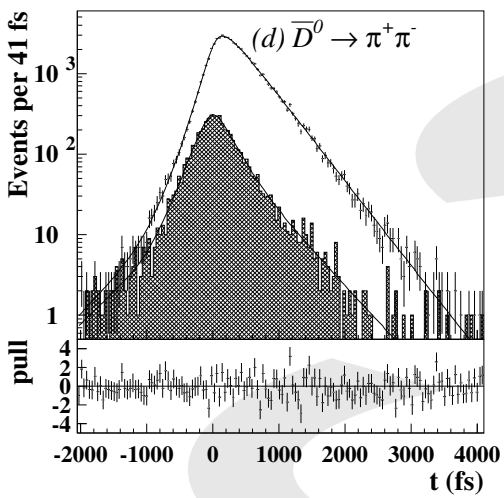
$D^0 \to KK, \pi\pi, K\pi$

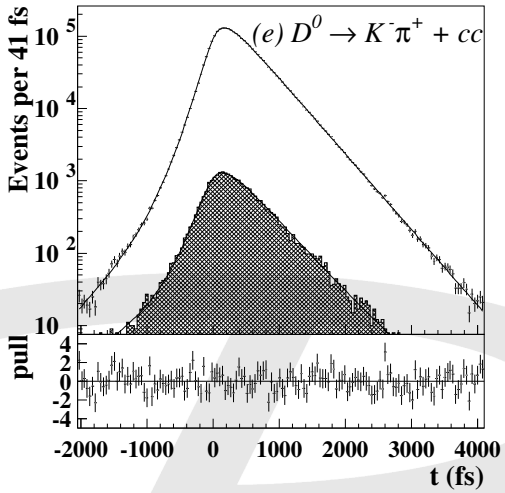
Lifetime fit











Systematics and result

Source	Δy_{CP} (%)	ΔA_γ (%)
SVD misalignment	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	0.066
Total	0.092	0.066

Table: Systematic uncertainties.

FINAL RESULT:

$$A_\Gamma = [-0.03 \pm 0.20(stat.) \pm 0.07(syst.)]\%$$
$$y_{CP} = [1.11 \pm 0.22(stat.) \pm 0.09(syst.)]\%$$

consistent with no CPV

4.7σ significance

TIME-INTEGRATED ANALYSIS

- measure direct + indirect CPV
- asymmetry due to a difference in time-integrated decay rates of $D^0 \to f, \overline{D}^0 \to \overline{f}$:

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \overline{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \overline{f})}$$

Experimentally measured quantity:

$$A_{raw} = \frac{N(D^0 \to f) - N(\overline{D}^0 \to \overline{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \overline{f})} = \\ = A_{CP} + A_{FB} + A_{\pi_s^+}$$

- get A_{CP} from extracted signal yields and corrections for detector-induced asymmetries and asymmetries in production

DETECTOR-INDUCED ASYMMETRY

- due to different reconstruction efficiencies for π_S^+, π_S^-
- determined from tagged and untagged $D^0 \to K\pi$ decays
- evaluated in bins of $p_{\pi_S}, \theta_{\pi_S}$

PRODUCTION ASYMMETRY

- forward-backward asymmetry in production of D^{*+} and and D^{*-} ($\gamma - Z^0$ interference and higher order QED effects in $e^+e^- \to c\bar{c}$)
- assumed same for all charm mesons
- odd function of θ^*, correct for using:

$$A_{CP} = \frac{1}{2}[A_{rec}^{corr}(\cos\theta^*) + A_{rec}^{corr}(-\cos\theta^*)] \text{ and}$$

$$A_{FB} = \frac{1}{2}[A_{rec}^{corr}(\cos\theta^*) - A_{rec}^{corr}(-\cos\theta^*)]$$

where A_{rec}^{corr} is after $A_{\pi_S^+}$ correction

$D^0 \to KK, \pi\pi$

Selection and A_{CP} extraction

	all	KK	Kπ	$\pi\pi$
Flavour tag	$D^{*+} \to D^0 \pi_S^+$			
vertex fit	p value $> 10^{-3}$			
$p_{CMS}(D^{*+})$ [GeV]	> 2.5 (3.1 for $\Upsilon(5S)$)			
window in m(D^0) [MeV]		17.8	17.8	17.2
window in q [MeV]		1.00	1.85	0.90

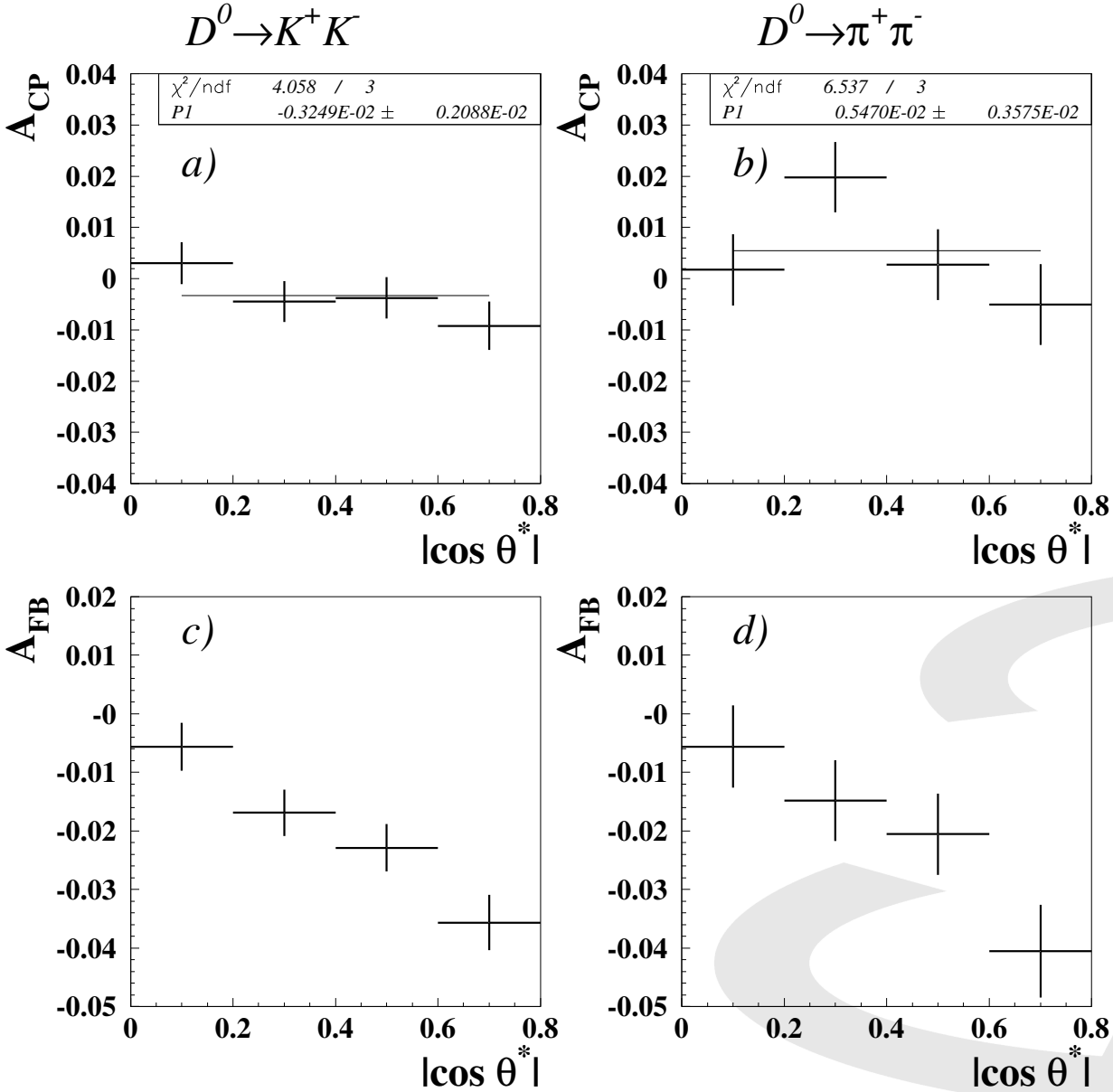
Table: Selection criteria.

Optimisation: minimal error on asymmetry (σ_A).

- Extract signal yield from signal window via background subtraction.
- Determine background from 2 sidebands $\pm$20 MeV from m(D^0_{nom}).
- Limit to $|\cos\theta^*| < 0.8$ to decrease A_{π_S}-related systematics.
- A_{CP} extracted via fit to constant.

$D^0 \to KK, \pi\pi$

A_{CP} fit



Systematics and result

	A_{CP}^{KK} (%)	$A_{CP}^{\pi\pi}$ (%)	ΔA_{CP} (%)
Signal counting method	0.055	0.023	0.037
π_S correction	0.065	0.067	0.014
A_{CP} extraction method	0.06	0.050	0.051
Total	0.085	0.087	0.064

Table: Systematic uncertainties.

FINAL RESULT:

$$A_{CP}^{KK} = [-0.32 \pm 0.21(stat.) \pm 0.09(syst.)]\%$$
$$A_{CP}^{\pi\pi} = [0.55 \pm 0.36(stat.) \pm 0.09(syst.)]\%$$
$$\Delta A_{CP} = [-0.87 \pm 0.41(stat.) \pm 0.06(syst.)]\%$$

Results consistent with no CPV.

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TIME-INTEGRATED ANALYSIS

Flavour tag	$D^{*+} \to D^0\pi_S^+$
$p_{CMS}(D^{*+})$	> 2.5 GeV (3.1 GeV for $\Upsilon(5S)$)
mass window $m(D^0)$	(1.758, 1.930) GeV
mass window Δm	(0.14, 0.16) GeV

Table: Selection criteria.

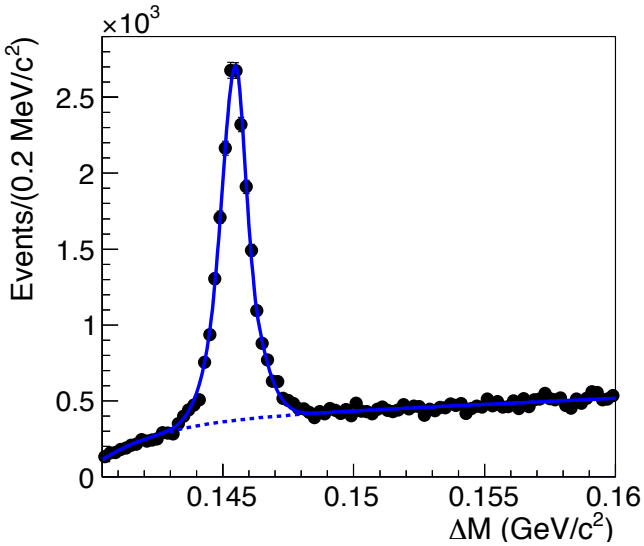
Optimisation: minimal error on A_{rec}.

- Fit $\Delta m = m(D^{*+}) - m(D^0)$ simultaneously for $D^0, \overline{D}^0$.
- Perform fit in bins of $(\cos(\theta^*), p_T^{\pi_S}, \cos(\theta^{\pi_S}))$.
- Obtain average via a χ^2 fit on values in bins of $\cos(\theta^*)$.
- Procedure tested and confirmed on MC.

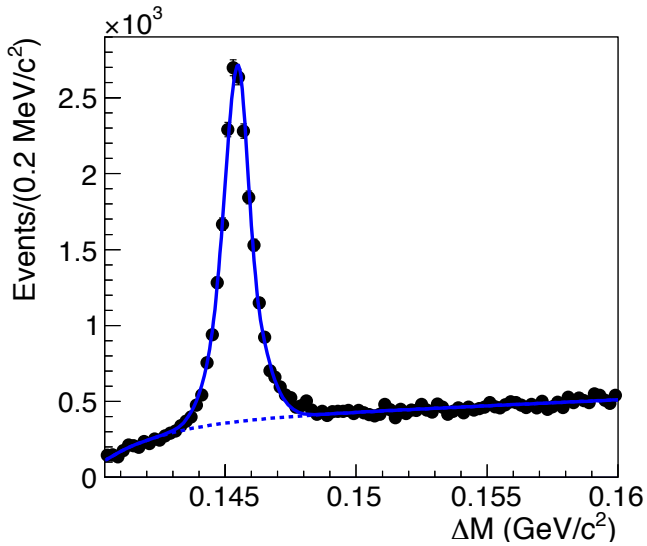
$D^0 \to \pi^0\pi^0$

Δm fit and asymmetries fit

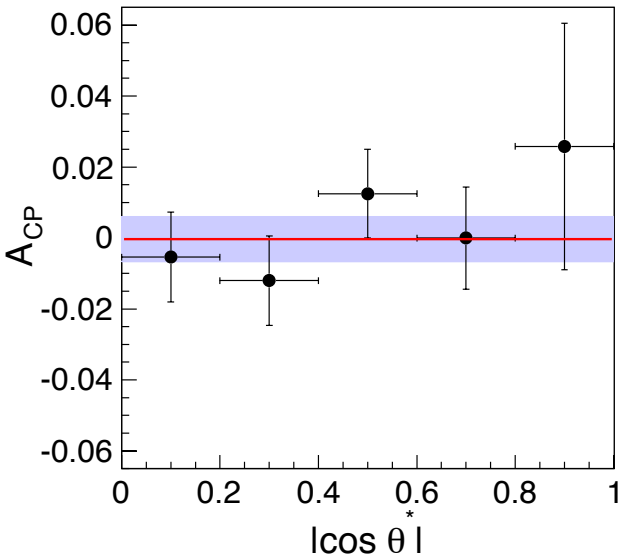
D^0

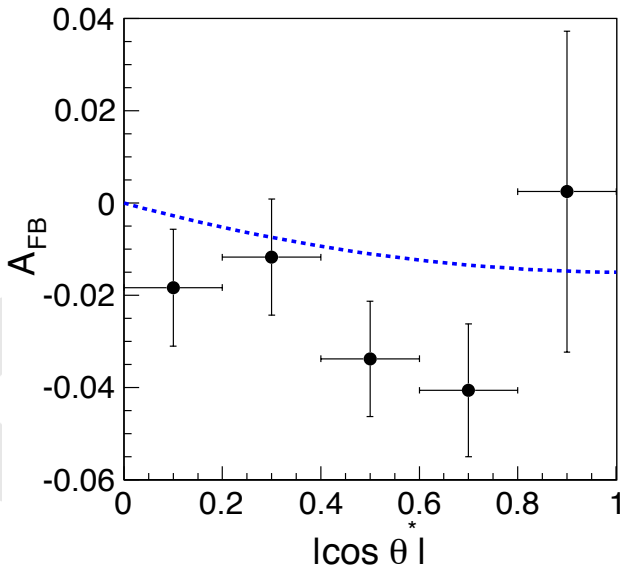


$\overline{D}^0$



Signal yield: 34460 ± 273





Systematics and result

signal shape	0.03
π_S correction	0.07
A_{CP} extraction method	0.07
Total	0.10

Table: Systematic uncertainties.

FINAL RESULT:

$$A_{CP} = [-0.03 \pm 0.64(stat.) \pm 0.10(syst.)]\%$$

Result consistent with no CPV.

Summary and conclusion

- We have searched for CP violation in decays of $D^0 \to KK, \pi\pi, K\pi$ and $D^0 \to \pi^0\pi^0$.
- Results are consistent with no CPV (direct or indirect).
- Here Belle story finishes... for Belle II prospects, see talk by Marko Starič (Friday).