Search for CP violation in D^0 decays at B factories

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- Introduction
- Time dependent searches
- Time integrated searches
- Conclusions

Formalism

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

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

- $q/p \neq 1 \Rightarrow$ indirect CP violation
- $q/p = |q/p| \cdot e^{i\phi}$:
  - $|q/p| \neq 1 \Rightarrow$ CP violation in mixing
  - $\phi \neq 0(\pi) \Rightarrow$ CP violation in interference of decays w/ and w/o mixing
- $|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\bar{D}^0 \to \bar{f})|^2 \Rightarrow$ direct CP violation

Experimental techniques

- Time-dependent analysis:
  - difference in proper decay time distributions of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - $\to$ measure indirect CPV
- Time-integrated analysis:
  - difference in time-integrated decay rates of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - $\to$ measure direct+indirect CPV

To be presented

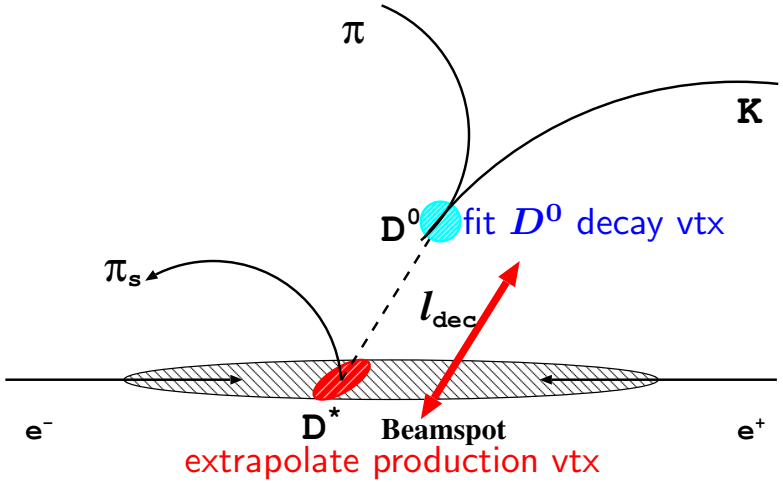
- Searches with time-dependent analysis:
  (measure mixing and indirect CPV)
  - $D^0 \to K^+\pi^-$ (Belle 2006, BaBar 2007)
  - $D^0 \to K^+K^-, \pi^+\pi^-$ (Belle 2007, BaBar 2007)
  - $D^0 \to K^0_s\pi^+\pi^-$ (Belle 2007)
  - $D^0 \to K^+\pi^-\pi^0$ (BaBar 2008)
- Searches with time-integrated analysis:
  (measure CPV asymmetries A_{CP})
  - $D^0 \to K^+K^-, \pi^+\pi^-$ (BaBar 2008, Belle 2008)
  - $D^0 \to \pi^+\pi^-\pi^0$ (Belle 2008, BaBar 2008)
  - $D^0 \to K^+K^-\pi^0$ (BaBar 2008)
  - $D^0 \to K^+\pi^-\pi^0$ (Belle 2005)
  - $D^0 \to K^+\pi^-\pi^+\pi^-$ (Belle 2005)

Experimental method

- Hints:
  - ▷ tag the flavor at production
  - ▷ measure proper decay time distribution
- $D^{*+} \to D^0 \pi^+$
  - ▷ flavor tagging by π_{slow} charge
  - ▷ considerable 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:

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

$D^0 \to K^+\pi^-$ *(time-dependent)*

- Proper decay time distribution

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

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)

- Fit D^0 and $\bar{D}^0$ samples separately $\Rightarrow R_D^{\pm},\ x'^{2\pm},\ y'^{\pm}$
- CPV in DCS decays:

$$A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

- CPV in mixing and interference $\to$ by solving 4 equations for 4 unknowns:

$$x'^{\pm} = (1 \pm \frac{1}{2}A_M)\cdot(x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = (1 \pm \frac{1}{2}A_M)\cdot(y'\cos\phi \mp x'\sin\phi)$$

$\to x',\ y',\ \phi,\ |q/p| = 1 + \frac{1}{2}A_M$

Results

- Belle, PRL 96, 151801 (2006), 400 fb^{-1}:

$$A_D = (2.3 \pm 4.7)\%$$
$$A_M = 0.67 \pm 1.2$$
$$|\phi| = 0.16 \pm 0.44$$

$\to$ consistent with no CPV

- BaBar, PRL 98, 211802 (2007), 384 fb^{-1}:

$$A_D = (-2.1 \pm 5.2 \pm 1.5)\%$$
$$x'^{2+} = (-0.24 \pm 0.43 \pm 0.30) \times 10^{-3} \qquad y'^{+} = (9.8 \pm 6.4 \pm 4.5) \times 10^{-3}$$
$$x'^{2-} = (-0.20 \pm 0.41 \pm 0.29) \times 10^{-3} \qquad y'^{-} = (9.6 \pm 6.1 \pm 4.3) \times 10^{-3}$$

$\to$ consistent with no CPV

$D^0 \to K^+K^-,\ \pi^+\pi^-$ *(time-dependent)*

- Measure lifetime difference btw. D^0 and $\bar{D}^0$

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to f_{CP}) - \tau(D^0 \to f_{CP})}{\tau(\overline{D}^0 \to f_{CP}) + \tau(D^0 \to f_{CP})}\,, \qquad f_{CP} = K^+K^-,\ \pi^+\pi^-$$

- Expressed with indirect CPV parameters:

$$A_\Gamma = \tfrac{1}{2}A_M y\cos\phi - x\sin\phi\,, \qquad (|q/p| = 1 + \tfrac{1}{2}A_M)$$

Results

- Belle, PRL 98, 211803 (2007), 540 fb^{-1}:

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

$\to$ consistent with no CPV

- BaBar, arXiv:0712.2249v1 (2007), 384 fb^{-1}:

$$A_\Gamma = (0.26 \pm 0.36 \pm 0.08)\%$$

$\to$ consistent with no CPV

$D^0 \to K^0_s \pi^+ \pi^-$ *(time-dependent)*

- Time-dependent Dalitz analysis separately for D^0 and $\bar{D}^0$

  $\to \quad x,\ y,\ |q/p|,\ \phi$

Results

- Belle, PRL99, 131803 (2007), 540 fb^{-1}:

  $|q/p| = 0.86 \pm 0.30 \pm 0.09$

  $\phi = -0.24 \pm 0.30 \pm 0.09$

  $\to$ consistent with no CPV

$D^0 \to K^+\pi^-\pi^0$ *(time-dependent)*

- Time-dependent Dalitz analysis separately for D^0 and $\bar{D}^0$

  $\to \quad x''^{\pm},\ y''^{\pm}$

Results

- BaBar, arXiv:0807.4544v1 (2008), 384 fb^{-1}:

$$x''^{+} = (2.53^{+0.54}_{-0.63} \pm 0.39)\% \quad y''^{+} = (-0.05^{+0.63}_{-0.67} \pm 0.50)\%$$
$$x''^{-} = (3.55^{+0.73}_{-0.83} \pm 0.65)\% \quad y''^{-} = (-0.54^{+0.40}_{-1.16} \pm 0.41)\%$$

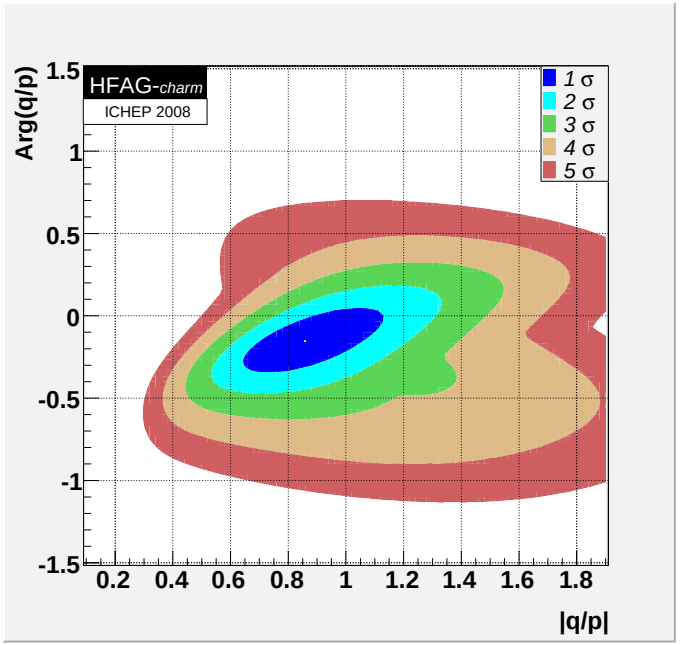
$\to$ consistent with no CPV

Summary (time-dependent)

- Sensitivity (using Belle results, 540 fb^{-1}):

decay	$\lvert q/p\rvert$	ϕ (rad)	
$K^+\pi^-$	0.52	0.38	(scalled to 540 fb^{-1})
$K^+K^-,\ \pi^+\pi^-$	0.25		(assuming $\phi = 0 \Rightarrow \lvert q/p\rvert = 1 + A_\Gamma / y_{CP}$)
$K^0_s\pi^+\pi^-$	0.31	0.31	

- HFAG average (includes also data from other experiments)



$$|q/p| = 0.86^{+0.17}_{-0.15}$$

$$\phi = -0.15 \pm 0.13$$

no CPV point at $\sim 1\sigma$

Time-integrated searches

- Measure CP-violating asymmetry A_{CP}

$$A_{CP} = \frac{\mathcal{B}(D^0 \to f) - \mathcal{B}(\bar{D}^0 \to \bar{f})}{\mathcal{B}(D^0 \to f) + \mathcal{B}(\bar{D}^0 \to \bar{f})}$$

Principle of measurement

- Initial flavor tagged by the charge of π from $D^{*+} \to D^0\pi^+$
- Number of reconstructed decays:

$$N^{reco} = N^{prod}_{D^{*+}} \cdot \mathcal{B}(D^{*+} \to D^0\pi^+) \cdot \mathcal{B}(D^0 \to f) \cdot \epsilon_f \cdot \epsilon_\pi$$

- Contributions to asymmetry in N^{reco}:
  - production (A_{FB})
  - branching fractions (A_{CP})
  - efficiencies (A_ϵ)
- If $A_{FB}, A_{CP}, A_\epsilon \ll 1$:

$$A^{reco} = A^{D^{*+}}_{FB} + A^f_{CP} + A^f_\epsilon + A^\pi_\epsilon$$

Time-integrated searches

$$A^{reco} = A_{FB} + A^{f}_{CP} + A^{f}_{\epsilon} + A^{\pi}_{\epsilon}$$

- Asymmetry of slow pion efficiency (A^{π}_{ϵ}) can be measured using tagged and untagged $D^0 \to K^-\pi^+$ (BaBar, PRL100, 061803 (2008))

$$\begin{aligned} A^{\rm tag}_{\rm rec} &= A_{FB} + A^{K\pi}_{CP} + A^{K\pi}_{\epsilon} + A^{\pi}_{\epsilon} \\ A^{\rm untag}_{\rm rec} &= A_{FB} + A^{K\pi}_{CP} + A^{K\pi}_{\epsilon} \end{aligned}$$

- Asymmetry of $D^0 \to f$ efficiency (A^{f}_{ϵ}):
  - ▷ is zero for K^+K^-, $\pi^+\pi^-$
  - ▷ other decays: A^{f}_{ϵ} determined with MC (systematics!)
- Efficiency corrected asymmetry:

$$A^{reco}_{corr} = A^{reco} - A^{f}_{\epsilon} - A^{\pi}_{\epsilon} = A_{FB} + A^{f}_{CP}$$

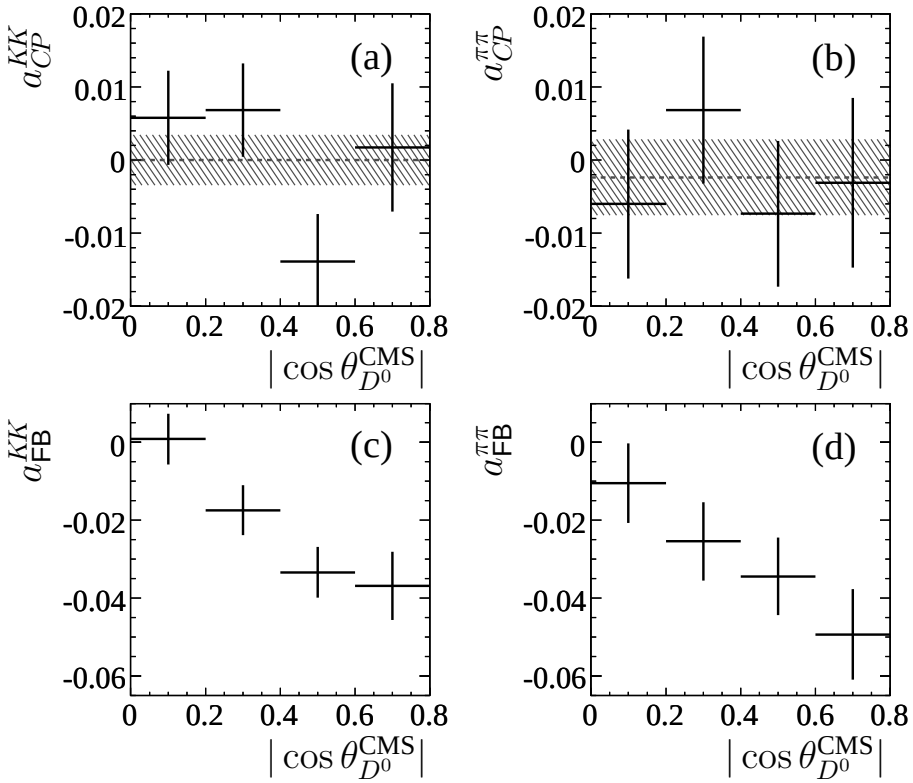
- Forward-backward asymmery is an odd function of $\cos\theta^*$
- A_{CP} and A_{FB} are then obtained by adding/subtracting bins at $\pm\cos\theta^*$:

$$A_{CP} = \frac{A^{reco}_{corr}(\cos\theta^*) + A^{reco}_{corr}(-\cos\theta^*)}{2}$$

$$A_{FB} = \frac{A^{reco}_{corr}(\cos\theta^*) - A^{reco}_{corr}(-\cos\theta^*)}{2}$$

$D^0 \to K^+K^-,\ \pi^+\pi^-$ *(time-integrated)*

BaBar, PRL100, 061803 (2008), 386 fb^{-1}



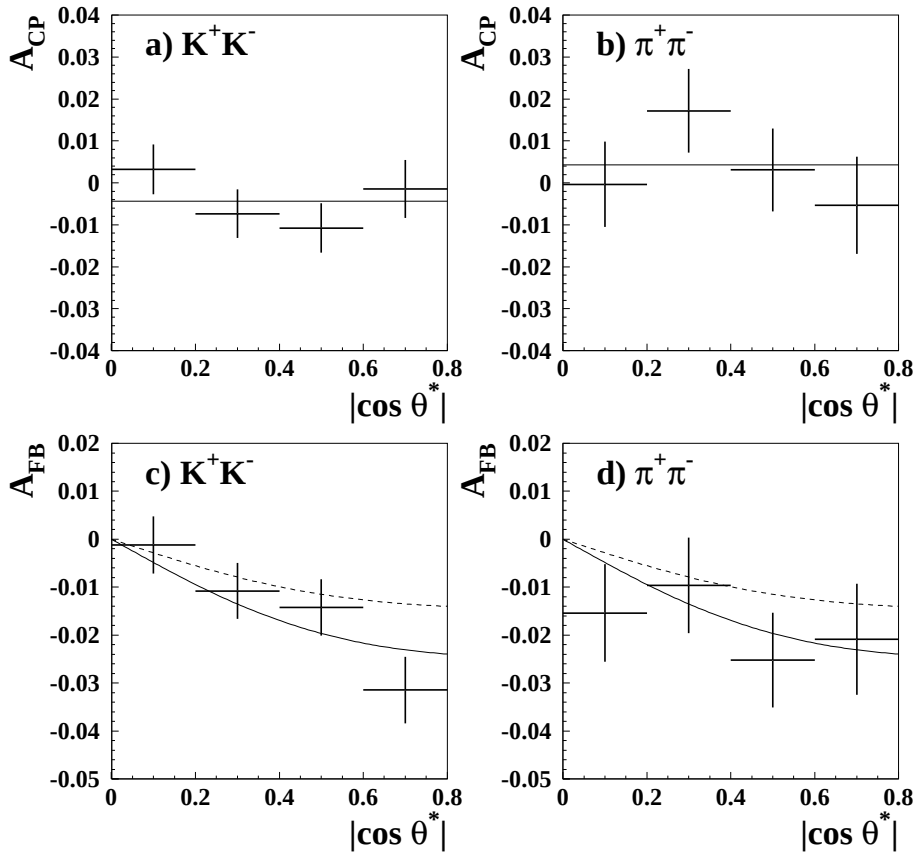
$$A_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\%$$

$$A_{CP}^{\pi\pi} = (-0.24 \pm 0.52 \pm 0.22)\%$$

consistent with no CPV

$D^0 \to K^+K^-,\ \pi^+\pi^-$ *(time-integrated)*

Belle, arXiv:0807.0148 (2008), 540 fb^{-1}



$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$

$$A_{CP}^{\pi\pi} = (+0.43 \pm 0.52 \pm 0.12)\%$$

consistent with no CPV

Direct CPV

- By combining A_{CP} and A_Γ one can obtain the direct CPV contribution (errors are uncorrelated because different observables used to extract them)
- Y. Grossman, L. Kagan and Y. Nir, PRD75, 036008 (2007):
  - $A_{CP}^f = a_d^f + a_{\rm ind}^f$
  - decays to CP eigenstate: $a_{\rm ind} = -A_\Gamma$

$$\Rightarrow \quad a_d^f = A_{CP}^f + A_\Gamma$$

exp.	a_d^{KK} (%)	$a_d^{\pi\pi}$ (%)
BaBar	$+0.26 \pm 0.50 \pm 0.15$	$+0.02 \pm 0.63 \pm 0.23$
Belle	$-0.42 \pm 0.42 \pm 0.19$	$+0.44 \pm 0.60 \pm 0.19$
average	-0.12 ± 0.35	0.24 ± 0.46

$\to$ no sign of direct CPV

shown in black $\to$ my calculations

Other decay modes (time-integrated)

- 3 and 4 body decays studied
- Dalitz plot dependent efficieny corrections used (obtained from MC)
  - larger systematics
- All searches consistent with no CPV

Belle, $D^0 \to \pi^+\pi^-\pi^0$ (532 fb^{-1})
PLB662, 102 (2008)

BaBar, $D^0 \to \pi^+\pi^-\pi^0,\ K^+K^-\pi^0$ (Dalitz analysis, 385 fb^{-1})
arXiv:0802.4035v1 (2008)

Belle, $D^0 \to K^+\pi^-\pi^0,\ K^+\pi^-\pi^+\pi^-$ (281 fb^{-1})
PRL95, 231801 (2005)

decay	A_{CP} (%)	experiment
$D^0 \to \pi^+\pi^-\pi^0$	$+0.43 \pm 0.41 \pm 1.23$	Belle
$D^0 \to \pi^+\pi^-\pi^0$	$-0.31 \pm 0.41 \pm 0.17$	BaBar (Dalitz)
$D^0 \to K^+K^-\pi^0$	$+1.00 \pm 1.67 \pm 0.25$	BaBar (Dalitz)
$D^0 \to K^+\pi^-\pi^0$	-0.6 ± 5.3	Belle
$D^0 \to K^+\pi^-\pi^+\pi^-$	-1.8 ± 4.4	Belle

Conclusions

- Many D^0 decay modes have been searched at B-factories (Belle, BaBar) for CP violation.
- No evidence has been found.
- The most stringent constrains obtained from decays to CP eigenstates ($K^+K^-,\ \pi^+\pi^-$) and, by using Dalitz analysis, from decays to charge conjugate states ($K^0_s\pi^+\pi^-,\ \pi^+\pi^-\pi^0$).
- Several CP asymmetries measured to $\pm 0.25\%$.
- Average of CPV parameters $|q/p|$ and ϕ consistent with no CPV to ± 0.15.