Direct CPV in charm decays at Belle and prospects for Belle II

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Outline

- Introduction
- Time-integrated CPV searches
  - $D^0 \to K^+K^-,\ \pi^+\pi^-$
  - $D^0 \to \pi^0\pi^0$
  - $D^+ \to K_S^0\pi^+$
  - $D^+ \to K_S^0K^+$
  - many more from recent years
- Prospects for Belle II
- Conclusions

CP violation

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

Two kinds:

- $q/p \neq 1 \;\Rightarrow$ 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

Indirect CPV

- D^0 only, common to all decay modes

Direct CPV

- All three species (D^0, D^+, D_s^+), decay mode dependent

CP violation

Experimental techniques

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

Time-integrated analysis

- Asymmetry in time-integrated decay rates: $A^f_{CP} = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$
- Charged D mesons: $A^f_{CP} = a^f_{\rm dir}$
- Neutral D mesons: $A^f_{CP} = a^f_{\rm dir} + a_{\rm ind}$
  - indirect CPV is universal: $a_{\rm ind} \equiv -A_\Gamma$ (neglecting terms with y_{CP})
  - world average: $A_\Gamma = (-0.014 \pm 0.052)\%$ (HFAG, June-2014)

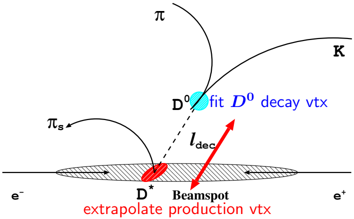
D^0 flavor tag

- Usually using $D^{*+} \to D^0 \pi^+_{\rm slow}$
  - flavor tagging by $\pi_{\rm slow}$ charge
  - provides also considerable background suppression
- Observables:
  - D^0 invariant mass: $M \equiv m(K\pi)$
  - D^{*+} mass difference: $\Delta M \equiv m(K\pi\pi_{\rm slow}) - m(K\pi)$ or $Q \equiv \Delta M - m_\pi$

- Measurements performed mainly at $\Upsilon(4S)$
  - D^{*+} from B decays can be completely rejected with

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

  - similar requirement used also when reconstructing charged D mesons
- IP constrained refit of $\pi_{\rm slow}$ to improve ΔM resolution



Time-integrated measurements (A_{CP})

- Asymmetry in time-integrated decay rates of $D^0 \to f$ and $\overline{D}^0 \to \overline{f}$

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

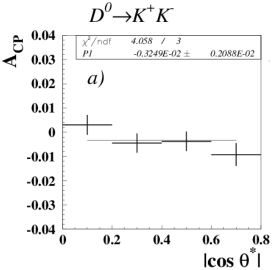
- Raw asymmetry

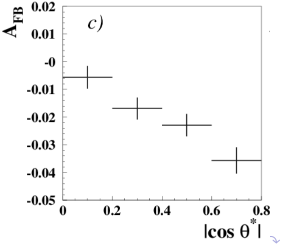
$$A_{\rm raw} = \frac{N - \overline{N}}{N + \overline{N}} = A_D + A_\epsilon^f + A_{CP}^f$$

  - A_D production asymmetry
  - A_ϵ^f asymmetry in efficiencies
- Production asymmetry at B-factory
  - odd function of CMS polar angle $A_D \equiv A_{FB}(cos\theta^*)$
  - can easily be disentangled

$$A_{CP} = \frac{A_{\rm raw}^{\rm cor}(cos\theta^*) + A_{\rm raw}^{\rm cor}(-cos\theta^*)}{2}$$

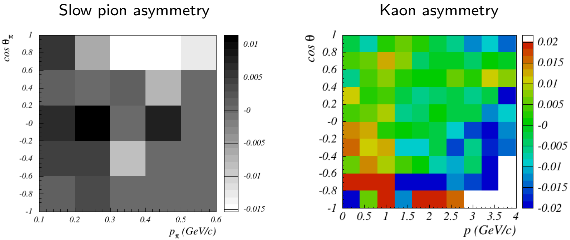
$$A_{FB} = \frac{A_{\rm raw}^{\rm cor}(cos\theta^*) - A_{\rm raw}^{\rm cor}(-cos\theta^*)}{2}$$





Detection asymmetries A_ϵ^f

- Asymmetries in detection efficiencies can be measured with sufficient precision using CF decays (direct CPV is very unlikely)
  - must be performed in bins of relevant phase-spaces
  - requires production asymmetries to be known
    $\rightarrow$ at B-factory: $A_D \equiv A_{FB}(cos\theta^*)$
- Slow pions: from tagged and untagged $D^0 \rightarrow K^-\pi^+$ decays
- Kaons: from decays $D^0 \rightarrow K^-\pi^+$ and $D_s^+ \rightarrow \phi\pi^+$
- Pions: from decays $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^0$

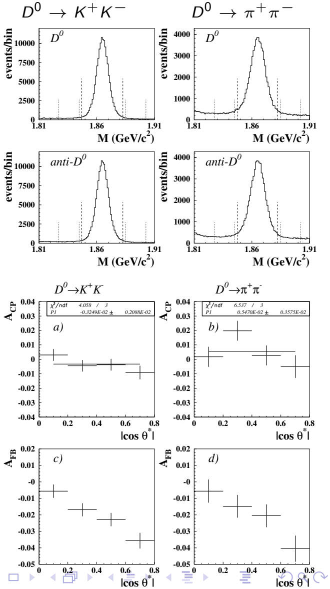


A_{CP} in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (976 fb^{-1})

arXiv:1212.1975 (2012)

- Flavor tag with $D^{*+} \to D^0\pi^+$
- Raw asymmetry:
  $A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon^{\pi_{\rm slow}}$
- Slow pion asymmetry corrected by event weighting:
  $$w_{D^0} = 1 - A_\epsilon^{\pi_{\rm slow}}(p_{\pi_s}, \cos\theta_{\pi_s})$$
  $$w_{\overline{D}^0} = 1 + A_\epsilon^{\pi_{\rm slow}}(p_{\pi_s}, \cos\theta_{\pi_s})$$
- $D^0/\bar{D}^0$ yields then determined in $\cos\theta^*$ bins using sideband subtraction method.
- Results consistent with no CPV:

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



A_{CP} in $D^0 \to \pi^0\pi^0$ and $D^0 \to K_S^0\pi^0$ (966 fb^{-1})

PRL 112, 211601 (2014)

- Flavor tag with $D^{*+} \to D^0\pi^+$
- Raw asymmetry:

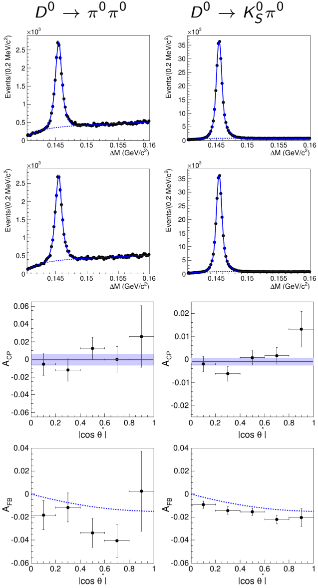
  $A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon^{\pi_{\rm slow}} \; (+ \, A_{\rm mat}^{K^0})$

  - Last term due to different strong interactions of $K^0/\bar{K}^0$ in detector material $A_{\rm mat}^{K^0} = -0.11\%$, PRD 84, 111501 (2011)
- $D^0/\bar{D}^0$ yields from fit to ΔM distributions in bins of $(\cos\theta^*, p_T^{\pi_s}, \cos\theta^{\pi_s}) \to 10\times7\times8$
- Results consistent with no CPV:

$$A_{CP}^{\pi^0\pi^0} = (-0.03 \pm 0.64 \pm 0.10)\%$$
$$A_{CP}^{K_S^0\pi^0} = (-0.21 \pm 0.16 \pm 0.07)\%$$

- Modes with K_S^0:
  - CPV due to K^0-mixing: -0.34%,

  PRL 109, 021601 (2012); 109, 119903(E) (2012)



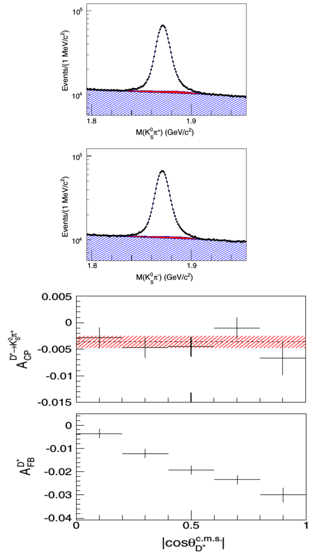
A_{CP} in $D^+ \to K_S^0\pi^+$ (977 fb^{-1})

PRL 109, 021601 (2012)

- Raw asymmetry:
  $A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon^\pi + A_{\rm mat}^{K^0}$
- Pion and K^0-material asymmetries corrected by event weighting
- Corrected asymmetry then determined in $\cos\theta^*$ bins using simultaneous fit to $M(K_S^0\pi^+)$ and $M(K_S^0\pi^-)$ distributions.
- Result:

$$A_{CP}^{K_S^0\pi^+} = (-0.363 \pm 0.094 \pm 0.067)\%$$

  - 3.2σ away from zero
  - consistent with expected CPV due to K^0-mixing $(-0.345 \pm 0.008)\%$
  - no evidence for CPV in charm sector



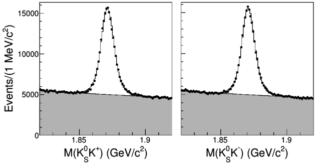
A_{CP} in $D^+ \to K_S^0 K^+$ $(977\ \text{fb}^{-1})$

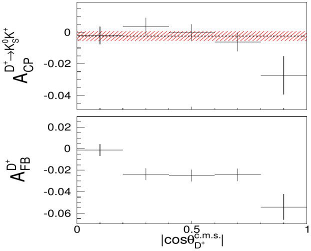
JHEP 02, 98 (2013)

- Raw asymmetry:
  $A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon^K + A_{\rm mat}^{K^0}$
- Kaon and K^0-material asymmetries corrected by event weighting
- Corrected asymmetry then determined in $\cos\theta^*$ bins using simultaneous fit to $M(K_S^0 K^+)$ and $M(K_S^0 K^-)$ distributions.
- Result:

$$A_{CP}^{K_S^0 K^+} = (-0.25 \pm 0.28 \pm 0.14)\%$$

  - consistent with zero
  - consistent also with expected CPV due to K^0-mixing $(-0.345 \pm 0.008)\%$
  - no evidence for CPV in charm sector





Time-integrated measurements: Summary

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	paper
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	arXiv:1212.1975 (2012)
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	arXiv:1212.1975 (2012)
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	PRL 112, 211601 (2014)
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	PRL 112, 211601 (2014)
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL 106, 211801 (2011)
$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL 106, 211801 (2011)
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	PLB 662, 102 (2008)
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	PRL 95, 231801 (2005)
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	PRL 95, 231801 (2005)
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	PRL 108, 071801 (2012)
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL 107, 221801 (2011)
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL 107, 221801 (2011)
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	PRL 109, 021601 (2012)
$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	JHEP 02, 98 (2013)
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL 104, 181602 (2010)
$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL 104, 181602 (2010)

Prospects at Belle II

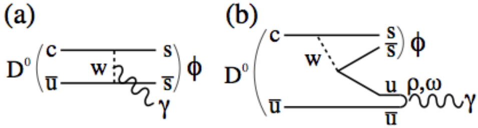
- Belle measurements extrapolated to 50 ab^{-1}
- Systematic uncertainties primarily scale with integrated luminosity, with one exception:
  - A_{CP} of modes with K_s^0: asymmetry of $K^0/\overline{K}^0$ interactions in material (PRD 84, 111501 (2011)), $\sigma_{\text{ired}} \approx 0.02\%$
- Extrapolation:

$$\sigma_{BelleII} = \sqrt{(\sigma_{stat}^2 + \sigma_{sys}^2)\frac{\mathcal{L}_{Belle}}{50\ \text{ab}^{-1}} + \sigma_{\text{ired}}^2}$$

Time-integrated measurements: Prospects

mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	Belle II at 50 ab^{-1}
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	± 0.03
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	± 0.05
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	± 0.09
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	± 0.03
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	± 0.07
$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	± 0.09
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	± 0.13
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	± 0.40
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	± 0.33
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	± 0.04
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	± 0.14
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	± 0.14
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	± 0.03
$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	± 0.05
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	± 0.29
$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	± 0.05

Direct CPV in $D^0 \to \phi\gamma, \rho^0\gamma$



- Direct CPV in radiative decays can be enhanced to exceed 1% (G. Isidori and J. F. Kamenik, PRL 109, 171801 (2012))
  - $D^0 \to \phi\gamma$: A_{CP} up to 2%
  - $D^0 \to \rho^0\gamma$: A_{CP} up to 10%
- $D^0 \to \phi\gamma$: first observation by Belle with 78 fb^{-1} (PRL 92, 101803 (2004))
  - measured yield: $27.6^{+7.4+0.5}_{-6.5-1.0}$
    $\Rightarrow$ relative error on yield 25% (as would be the error on A_{CP})
- A_{CP} sensitivity at 50 ab^{-1}: $\approx$ 1%

Conclusions

- *CP* violation was searched in many decay modes using time-integrated approach
  - no evidence found for CPV in the charm sector
  - can see CPV due to K^0-mixing in $D^+ \to K_S^0 \pi^+$ decay
- Prospects for these measurements at Belle II were also discussed
  - in some cases the sensitivity would reach a 0.03% level.