CP violation in charm decays at Belle

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for the Belle Collaboration

Introduction

- CP violation in charm decays
  : Very small in the Standard Model (SM), <O(0.1%)
  : CP violation of O(1%) would signal new physics

CP violation in charm decays
provides a unique probe
to search for beyond the SM

Contents

- Introduction
- y_{CP} and indirect CP Violation (CPV)
  - y_{CP} and A_Γ from CP even ($D^0 \to h^+h^-$) and mixed ($D^0 \to K^-\pi^+$) states, where $h=\{K,\pi\}$
- Direct CPV
  - Method
  - $D^0 \to h^+h^-$ and ΔA_{CP}
  - $D^+ \to K_s K^+$
- Summary

y_{CP} and A_{Γ}
with $D^0 \rightarrow h^+h^-$ and $D^0 \rightarrow K^-\pi^+$
at Belle

y_{CP} and A_Γ from $D^0 \to h^+h^-$ and $D^0 \to K^-\pi^+$

- $\boxed{y_{CP}} \equiv \dfrac{\hat{\Gamma}(D^0 \to \text{eigenstate}) + \hat{\Gamma}(\overline{D}^0 \to \text{eigenstate})}{2\Gamma} - 1$

  (Γ : average width and $\hat{\Gamma}$: effective decay width)

  $\cong \dfrac{1}{2}\left[\left(R_m + R_m^{-1}\right) y \cos\phi - \left(R_m - R_m^{-1}\right) x \sin\phi\right]$ (No direct CPV, where $R_m = |q/p|$)

  $\cong y$ (No CPV)

  - Experimental observable: $\boxed{y_{CP} = \dfrac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1}$

  If CP is conserved,

  $D^0 \to h^+h^-$: CP even

  $D^0 \to K^-\pi^+$: Equal mixture of CP even and odd

  $\Rightarrow \dfrac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1 = \boxed{y}$

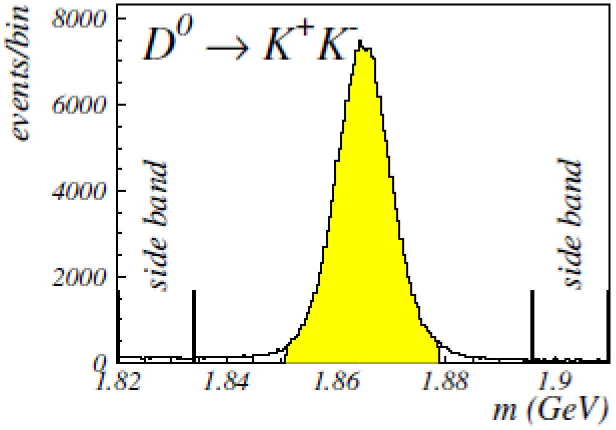
- $\boxed{A_\Gamma} = \dfrac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}{2\Gamma} = \dfrac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{2\tau}$

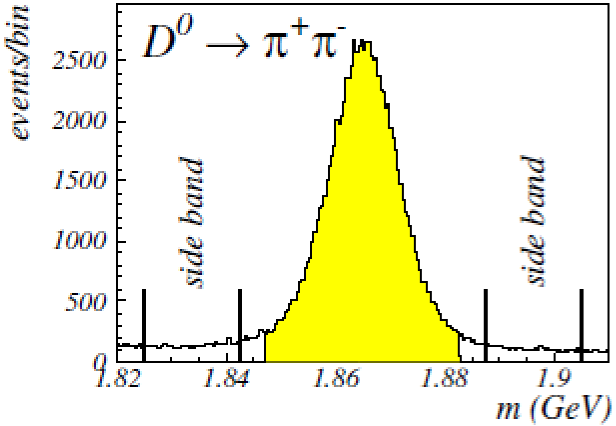
  $\cong \dfrac{1}{2}\left[\left(R_m - R_m^{-1}\right) y \cos\phi - \left(R_m + R_m^{-1}\right) x \sin\phi\right]$ without direct CPV

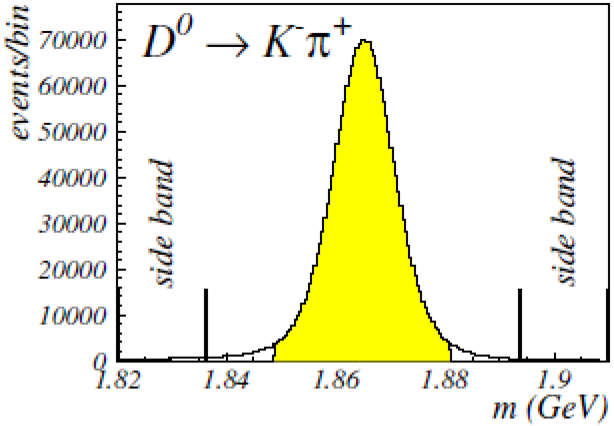
  $= 0$ without CPV

Signal yields

Belle preliminary
using 976 fb^{-1}





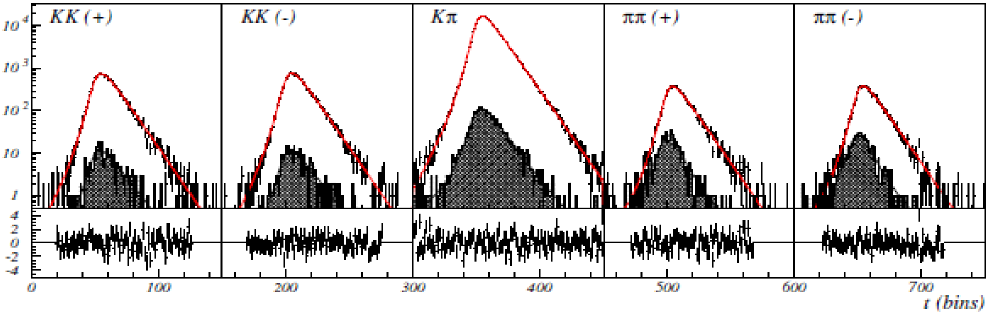


channel	$D^0 \to K^+K^-$	$D^0 \to \pi^+\pi^-$	$D^0 \to K^-\pi^+$
yield	242k	114k	2.61M
purity	98.0%	92.9%	99.7%

- D^{*+} tagged yields
- yellow regions : for the measurements
- sidebands regions: for the background parameterization

Decay time distributions & y_{CP}, A_Γ, and τ extraction from simultaneous fit

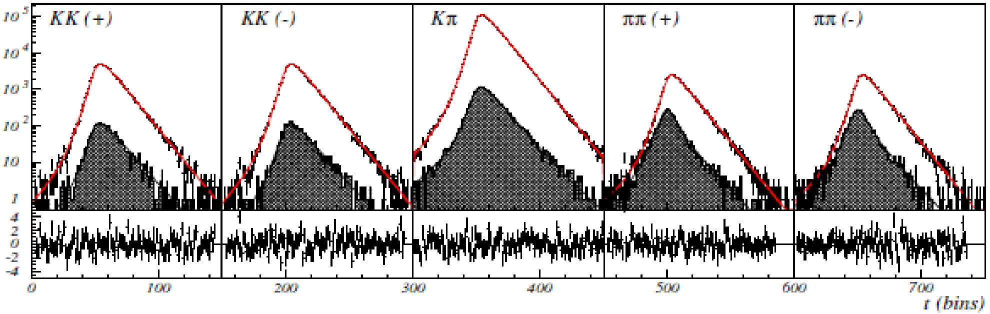
Belle preliminary using 976 fb^{-1}



3-layer SVD $153\ \mathrm{fb}^{-1}$

Integrated over the phase space

$\chi^2/ndf = 792.9/684$ (CL= 0.2%)



4-layer SVD $823\ \mathrm{fb}^{-1}$

Simultaneous fit to the 5 modes

mode	flavor	lifetime
KK	D^0	$\tau\frac{1-A_\Gamma}{y_{CP}+1}$
KK	$\overline{D^0}$	$\tau\frac{1+A_\Gamma}{y_{CP}+1}$
$K\pi$	both	τ
$\pi\pi$	D^0	$\tau\frac{1-A_\Gamma}{y_{CP}+1}$
$\pi\pi$	$\overline{D^0}$	$\tau\frac{1+A_\Gamma}{y_{CP}+1}$

- $y_{CP} = \dfrac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^+h^-)} - 1 \;\Rightarrow \tau(D^0 \to h^+h^-) = \dfrac{\tau(D^0 \to K^-\pi^+)}{(y_{CP}+1)}$
- $A_\Gamma = \dfrac{\tau(\overline{D}^0 \to h^+h^-) - \tau(D^0 \to h^+h^-)}{2\tau}$

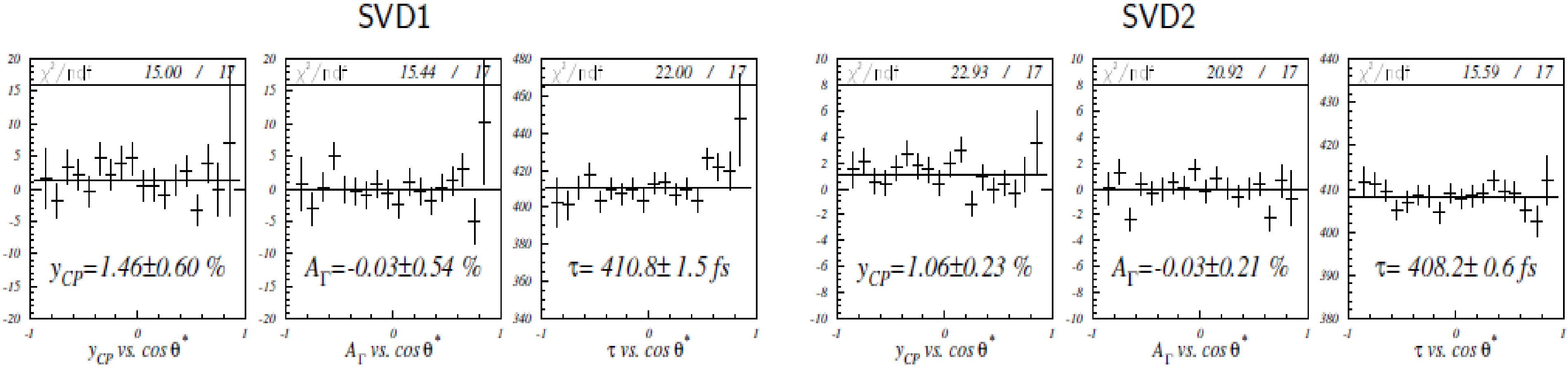
$$\Rightarrow \tau(\overline{D}^0 \to h^+h^-) = (1+A_\Gamma)\tau(D^0 \to K^-\pi^+),$$

$$\tau(D^0 \to h^+h^-) = (1-A_\Gamma)\tau(D^0 \to K^-\pi^+)$$

Fit results : y_{CP} , A_Γ , and τ

Belle preliminary using 976 fb^{-1}

- Obtained as a function of the polar angle of D^{*+} at the c.m.s.



- y_{CP} =(+1.11±0.22±0.11)% : 4.5σ away from zero
- A_Γ =(-0.03±0.20±0.08)% : No indirect CPV
- $\tau(D^0 \rightarrow K^-\pi^+)$=(408.56±0.54) fs : consistent with PDG

Direct CPV at Belle

1) Method
2) $D^0 \rightarrow h^+h^-$ and ΔA_{CP}
3) $D^+ \rightarrow K_sK^+$

Direct CPV : Method (1)

- $A_{CP}^{D\to f} \equiv \dfrac{\Gamma(D\to f)-\Gamma(\bar{D}\to \bar{f})}{\Gamma(D\to f)+\Gamma(\bar{D}\to \bar{f})}$, Γ : partial decay width
- $A_{rec}^{D\to f} = \dfrac{N_{rec}^{D\to f} - N_{rec}^{\bar{D}\to \bar{f}}}{N_{rec}^{D\to f} + N_{rec}^{\bar{D}\to \bar{f}}} \approx A_{CP}^{D\to f} + A_{prod}^{D} + A_{\varepsilon}^{f}$

, $A_{CP}^{D\to f}$: CPV from $D\to f$, independent of any kinematic variables

, A_{prod}^{D} : production asymmetry, A_{FB}^{D} for Belle and it depends on $\cos\theta_D^{\text{c.m.s.}}$

, A_{ε}^{f} : final state particle detection asymmetry, usually depends on $(p_{Tf}^{lab}, \cos\theta_f^{lab})$

1)Remove A_{ε}^{f} using CPV free resonance data in which particle misidentification free

then, we have $A_{rec}^{D\to f_{corr}} \equiv A_{CP}^{D\to f} + A_{FB}^{D}$ only

2)Using antisymmetry of A_{FB}^{D} in $\cos\theta_D^{\text{c.m.s.}}$, extract $A_{CP}^{D\to f}$ in bins of $\cos\theta_D^{\text{c.m.s.}}$

$$* \; A_{CP}^{D\to f} = \left\{A_{rec}^{D\to f_{corr}}(\cos\theta_D^{c.m.s.}) + A_{rec}^{D\to f_{corr}}(-\cos\theta_D^{c.m.s.})\right\}/\,2$$

$$* \; A_{FB}^{D} = \left\{A_{rec}^{D\to f_{corr}}(\cos\theta_D^{c.m.s.}) - A_{rec}^{D\to f_{corr}}(-\cos\theta_D^{c.m.s.})\right\}/\,2$$

Direct CPV : Method (2)

- Final states with neutral kaon requires additional works

1) $K^0(\bar{s}d)$ and $\overline{K}^0(s\bar{d})$

$\rightarrow \sigma(K^0 N) \neq \sigma(\overline{K}^0 N)$ as $\sigma(K^+ N) \neq \sigma(K^- N)$, N : nuclei

$\rightarrow$ PRD 84, 111501(R) (2011) reported the effect,

referred the effect to as A_D, dilution asymmety,

it can be as large as $\sim 0.3\%$ depending on kaon momentum,

$\rightarrow A_D$ should be corrected for the final state with neutral kaons

2) Unavoidable CPV in neutral kaon system : $A_{CP}^{\overline{K}^0} = (-0.332 \pm 0.006)\%$

$\rightarrow$ Should be subtracted to get CPV in change in charm : $A_{CP}^{\Delta C}$

$\rightarrow$ Take into account for experimental dependency

according to Grossman and Nir (JHEP, 04 (2012) 002)

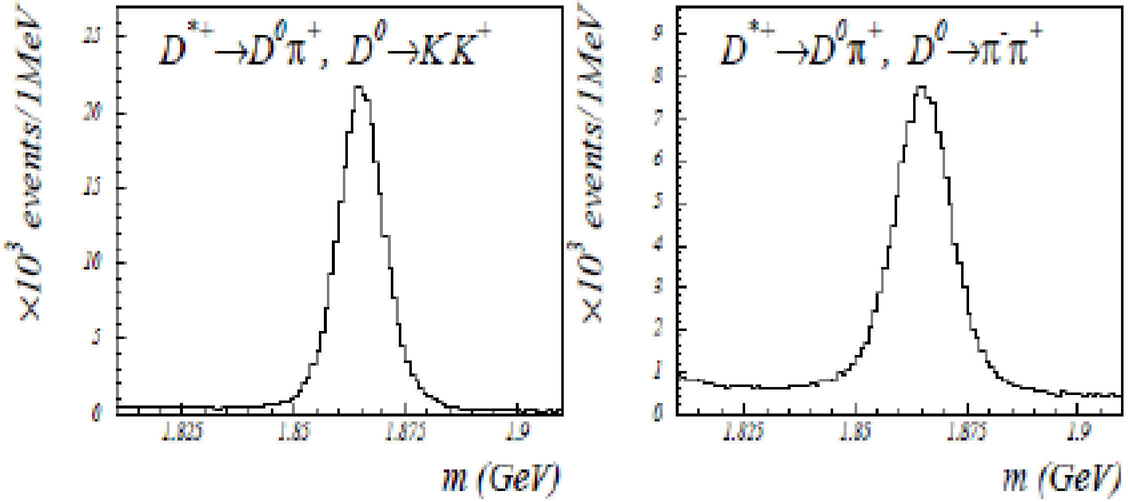
(referring to Grossman - Nir correction)

Direct CPV: $D^0 \to h^+ h^-$ and $\Delta A_{CP}, h \in \{K, \pi\}$ (1)

- Both are Singly Cabibbo Suppressed decays :
  SM expects DCPV~O(0.1%)
- Can also generate indirect CPV induced by D^0 mixing,
- But, ΔA_{CP} (A_{CP} difference between the two decays) reveals significant DCPV according to universality of indirect CPV in charm decays (ICPV from each decay ~cancels out at Belle)
- Each decay includes asymmetries other than A_{CP},
  But, unwanted asymmetries cancel out in ΔA_{CP} measurement

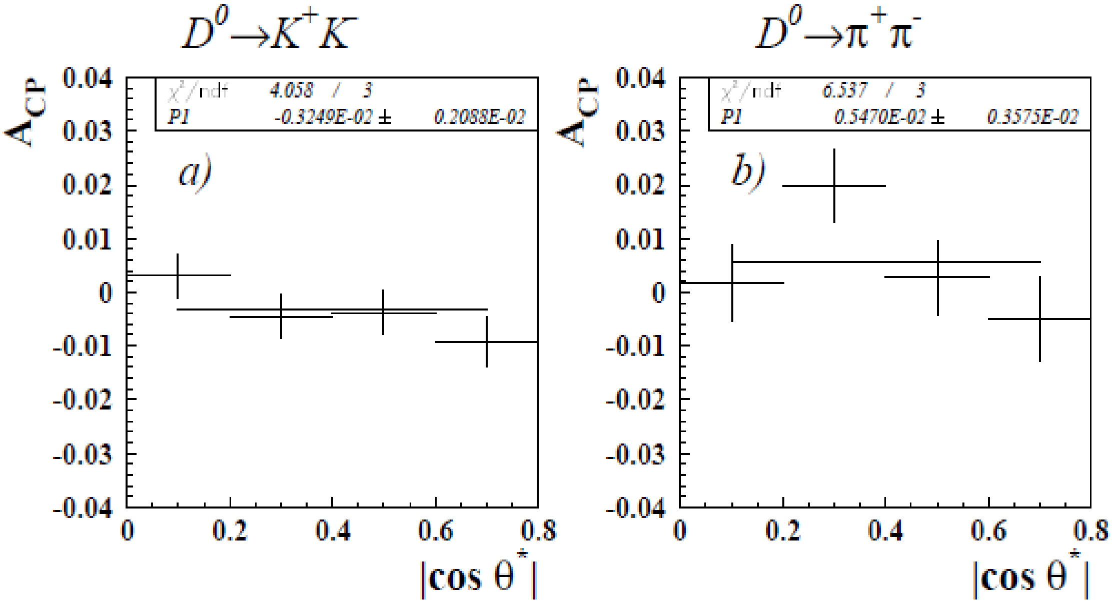
- $A_{rec}^{D^{*+}\to D^0\pi_s^+\to K^+K^-\pi_s^+} = A_{CP}^{D^0\to K^+K^-} + A_{FB}^{D^{*+}} + A_{\varepsilon}^{\pi_s^+} \to$ Eq.(1)
- $A_{rec}^{D^{*+}\to D^0\pi_s^+\to \pi^+\pi^-\pi_s^+} = A_{CP}^{D^0\to \pi^+\pi^-} + A_{FB}^{D^{*+}} + A_{\varepsilon}^{\pi_s^+} \to$ Eq.(2)
- $\Delta A_{CP} \equiv A_{CP}^{D^0\to K^+K^-} - A_{CP}^{D^0\to \pi^+\pi^-} =$ Eq.(1) – Eq.(2)

Direct CPV: $D^0 \to h^+h^-$ and ΔA_{CP}, $h \in \{K, \pi\}$ (2)



Belle preliminary
using 976 fb^{-1}

yield
$D^0 \to K^+K^-$ ~282k
$D^0 \to \pi^+\pi^-$ ~123k



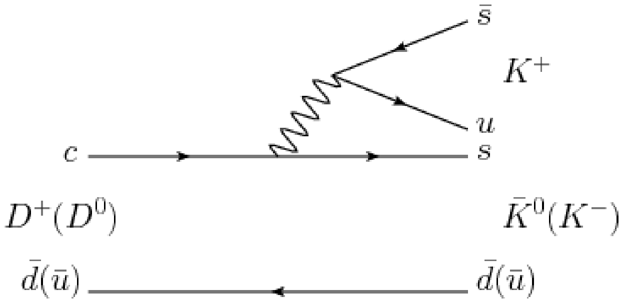
$A_{CP}^{D^0 \to K^+K^-}$	(-0.32±0.21±0.09)%
$A_{CP}^{D^0 \to \pi^+\pi^-}$	(+0.55±0.36±0.09)%
ΔA_{CP}	(-0.87±0.41±0.06)%

- $A_{CP}^{D^0 \to K^+K^-}$: best sensitivity
- ΔA_{CP} : 2.1σ away from zero

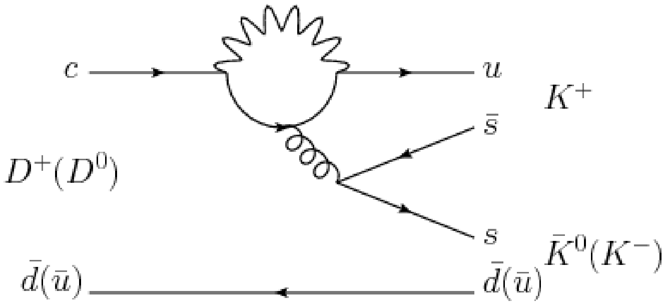
Direct CPV : $D^+ \to K^0_S K^+$ (1)

- Singly Cabibbo Suppressed, thus SM expects O(0.1%) DCPV : $A_{CP}^{\Delta C} \sim O(0.1\%)$
- CPV in K⁰ system : $A_{CP}^{\bar{K}^0} = (-0.332 \pm 0.006)\%$
- A_{CP} in the final state, $A_{CP}^{D^+ \to K^0_S K^+} = A_{CP}^{\Delta C} + A_{CP}^{\bar{K}^0}$
- Shares the same tree and penguin diagrams with $D^0 \to K^+ K^-$, neglecting helicity suppressed decays, annihilation and W-exchange,

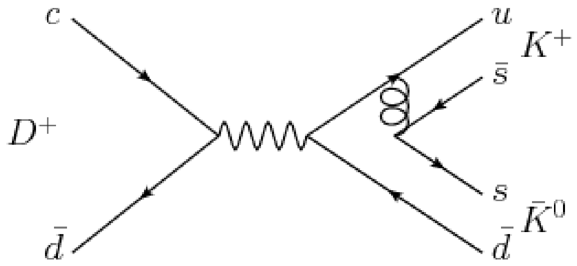
  DCPV from $D^+ \to K^0_S K^+$ and $D^0 \to K^+ K^-$ expected to be ~same
- Helps to pin down the origin of the ΔA_{CP} measurements, though the tension is rather released recently



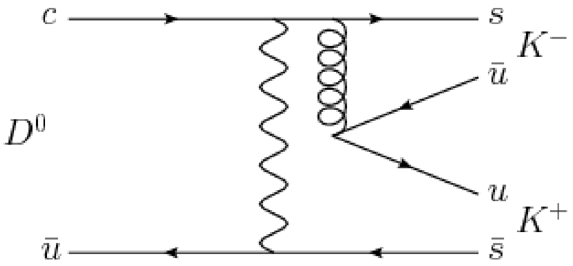
(a)



(b)



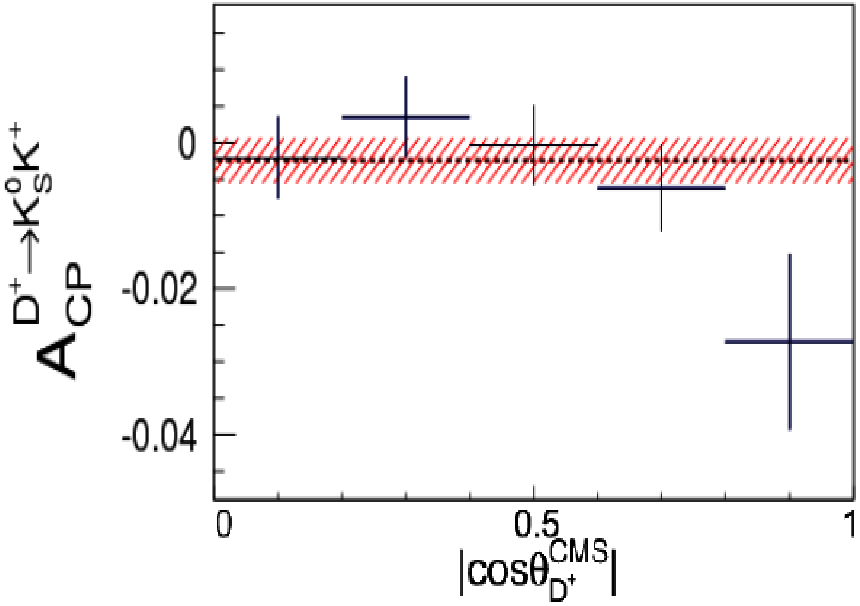
(c)

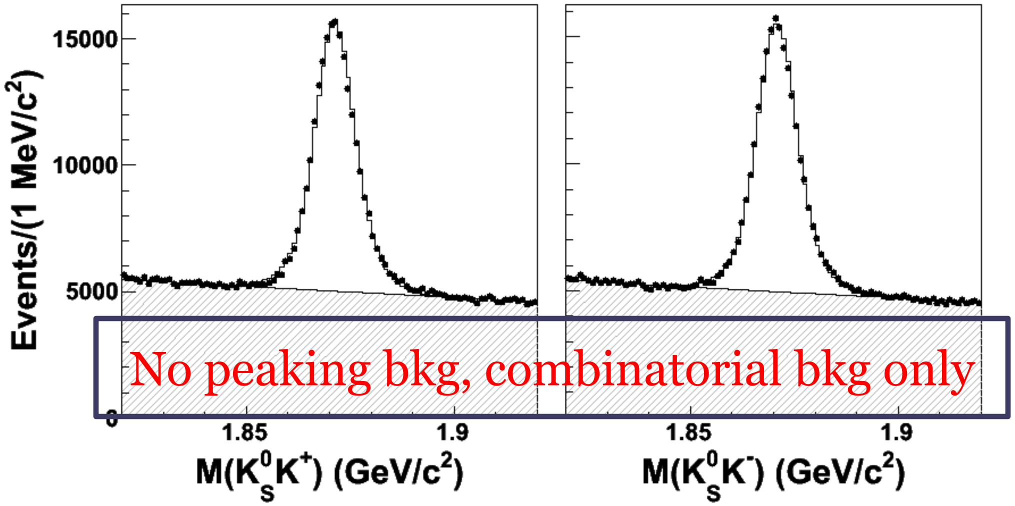


(d)

Direct CPV : $D^+ \to K_S^0 K^+$ (2)

same method used in
PRL 104, 181602 (2010),
update of the PRL with the
entire data sample
→JHEP 02 (2013) 098





No peaking bkg, combinatorial bkg only

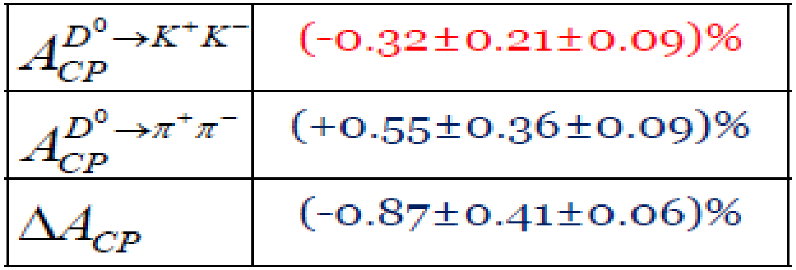
- $A_{CP}^{D^+\to K_S^0 K^+}$ = (-0.25±0.28±0.14)%
- After the Grossman-Nir correction, A_{CP} in intrinsic charm

using 977 fb^{-1}
~277k signals

$A_{CP}^{D^+\to \overline{K}^0 K^+}$ = (+0.08±0.28±0.14)%

Summary

- CP violation in charm decays at Belle
  - y_{CP} and indirect CPV
    - $y_{CP}=(+1.11\pm0.22\pm0.11)\%$
    - $A_\Gamma=(-0.03\pm0.20\pm0.08)\%$
  - Direct CPV
    - No direct CPV found



$A_{CP}^{D^0\to K^+K^-}$	$(-0.32\pm0.21\pm0.09)\%$
$A_{CP}^{D^0\to \pi^+\pi^-}$	$(+0.55\pm0.36\pm0.09)\%$
ΔA_{CP}	$(-0.87\pm0.41\pm0.06)\%$

$$A_{CP}^{D^+\to K_S^0K^+} = (-0.25\pm0.28\pm0.14)\%$$

$$A_{CP}^{D^+\to \overline{K}^0K^+} = (+0.08\pm0.28\pm0.14)\%$$

- Obtaining A_{ε}^{f} from CPV free resonance data : depends on f

– Assume the same A_{FB} for all charmed mesons

1)charged π : $D^+ \rightarrow \boxed{K^-\pi^+}\pi^+$ and $D^0 \rightarrow \boxed{K^-\pi^+}\pi^0$

2)charged K : $D^0 \rightarrow K^-\boxed{\pi^+}$ and $D_s^+ \rightarrow \phi\boxed{\pi^+}$

3)soft charged π : $D^{*+} \rightarrow D^0\pi_s^+ \rightarrow \boxed{K^-\pi^+}\pi_s^+$ and $D^0 \rightarrow \boxed{K^-\pi^+}$

A_ε^π measurement

- $D^+ \to K^-\pi_h^+\pi_l^+ \; (p_{T\pi_h^+}^{lab} > p_{T\pi_l^+}^{lab})$ and $D^0 \to K^-\pi^+\pi^0$ samples: $>$ 10 times of $D^+ \to K_S^0\pi^+$
- $A_{rec}^{D^+\to K^-\pi_h^+\pi_l^+} = A_\varepsilon^{K^-}(p_{TK^-}^{lab}, \cos\theta_{K^-}^{lab}) + A_\varepsilon^{\pi_h^+}(p_{T\pi_h^+}^{lab}, \cos\theta_{\pi_h^+}^{lab}) + A_\varepsilon^{\pi_l^+}(p_{T\pi_l^+}^{lab}, \cos\theta_{\pi_l^+}^{lab}) + A_{FB}^{D^+}(\cos\theta_{D^+}^{CMS})$
- $A_{rec}^{D^0\to K^-\pi^+\pi^0} = A_\varepsilon^{K^-}(p_{TK^-}^{lab}, \cos\theta_{K^-}^{lab}) + A_\varepsilon^{\pi^+}(p_{T\pi^+}^{lab}, \cos\theta_{\pi^+}^{lab}) + A_{FB}^{D^0}(\cos\theta_{D^0}^{CMS})$

- Assume $A_{FB}^{D^0} = A_{FB}^{D^+}$ and

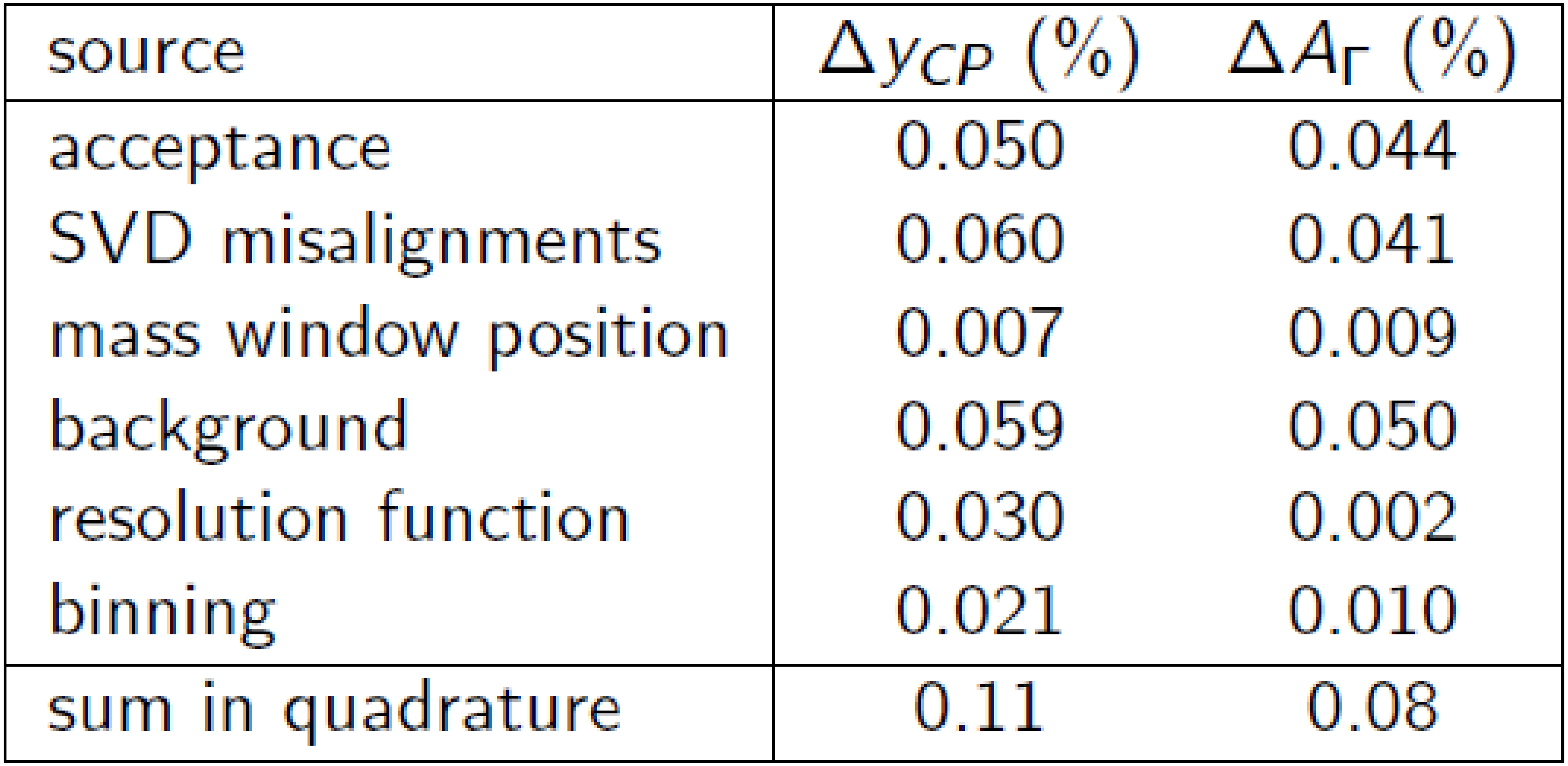
we can measure $A_\varepsilon^{\pi_h^+}(p_{T\pi_h^+}^{lab}, \cos\theta_{\pi_h^+}^{lab})$ by subtracting $A_{rec}^{D^0\to K^-\pi^+\pi^0}$ from $A_{rec}^{D^+\to K^-\pi_h^+\pi_l^+}$ in 5-D

$$A_{rec}^{D^+\to K^-\pi_h^+\pi_l^+} - A_{rec}^{D^0\to K^-\pi^+\pi^0} =$$

$$\cancel{A_\varepsilon^{K^-}(p_{TK^-}^{lab}, \cos\theta_{K^-}^{lab})} + A_\varepsilon^{\pi_h^+}(p_{T\pi_h^+}^{lab}, \cos\theta_{\pi_h^+}^{lab}) + \cancel{A_\varepsilon^{\pi_l^+}(p_{T\pi_l^+}^{lab}, \cos\theta_{\pi_l^+}^{lab})} + \cancel{A_{FB}^{D^+}(\cos\theta_{D^+}^{CMS})} -$$

$$\cancel{A_\varepsilon^{K^-}(p_{TK^-}^{lab}, \cos\theta_{K^-}^{lab})} - \cancel{A_\varepsilon^{\pi^+}(p_{T\pi^+}^{lab}, \cos\theta_{\pi^+}^{lab})} - \cancel{A_{FB}^{D^0}(\cos\theta_{D^0}^{CMS})} = A_\varepsilon^{\pi_h^+}(p_{T\pi_h^+}^{lab}, \cos\theta_{\pi_h^+}^{lab})$$

- Actually correction procedure is quite nontrivial



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