Direct CP Violation in charm at Belle

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for the Belle Collaboration

Introduction (1)
CP Violation (CPV) in the SM

$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Wolfenstein parameterization; Expanding in λ (λ~0.23) ⇒

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

$$+O(\lambda^4)$$

- CPV ← non-zero η in the CKM Matrix

1. Direct CPV : CPV in decay rate (this talk)
2. Indirect CPV : CPV induced by mixing (For mixing and indirect CPV results, see talk by Tao Peng)

Introduction (2)
Direct CP Violation (DCPV)

- $A_{CP}^{D\to f} \equiv \frac{\Gamma(D\to f)-\Gamma(\overline{D}\to \bar{f})}{\Gamma(D\to f)+\Gamma(\overline{D}\to \bar{f})} \propto \sin(\phi_1^W-\phi_2^W)\sin(\delta_1^{FSI}-\delta_2^{FSI})$

$, \Gamma(D\to f) = \left|A(D\to f)_1 + A(D\to f)_2\right|^2$: partial decay width

$, A(D\to f)_1 = A_1 e^{i\phi_1^W} e^{i\delta_1^{FSI}}$

$, A(D\to f)_2 = A_2 e^{i\phi_2^W} e^{i\delta_2^{FSI}}$

- Need two different decays with final state interactions ; not only different weak phases $(\phi_1^W \neq \phi_2^W)$ but also different strong phases $(\delta_1^{FSI} \neq \delta_2^{FSI})$

Introduction (3)
DCPV in charm decays

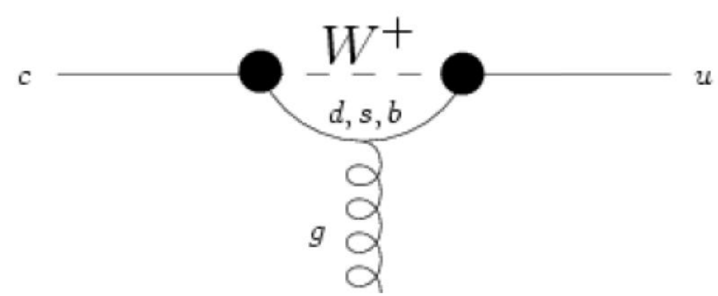
$$\begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix}$$

Wolfenstein parameterization; Expanding in λ (λ~0.23)

$$\begin{bmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{bmatrix}$$

Most of Charm decays

- Cabibbo Favored (CF) and Doubly Cabibbo Suppressed (DCS) decays governed by the 2x2 Cabibbo sub-matrix, which has no CP violating weak phase → No CPV in the SM
- Vub enters via a quantum loop in Singly Cabibbo Suppressed (SCS) decays → DCPV expected to be ~O(0.1%) in the SM



- DCPV of O(1%) in charm decays could signal new physics (NP)

Contents

Introduction (already given)

- $A_{CP}^{D^+ \to K_S^0 \pi^+}$
- $A_{CP}^{D^0 \to h^+ h^-}$ and ΔA_{CP}, $h \in \{K, \pi\}$
- These measurements

use the full data sample collected

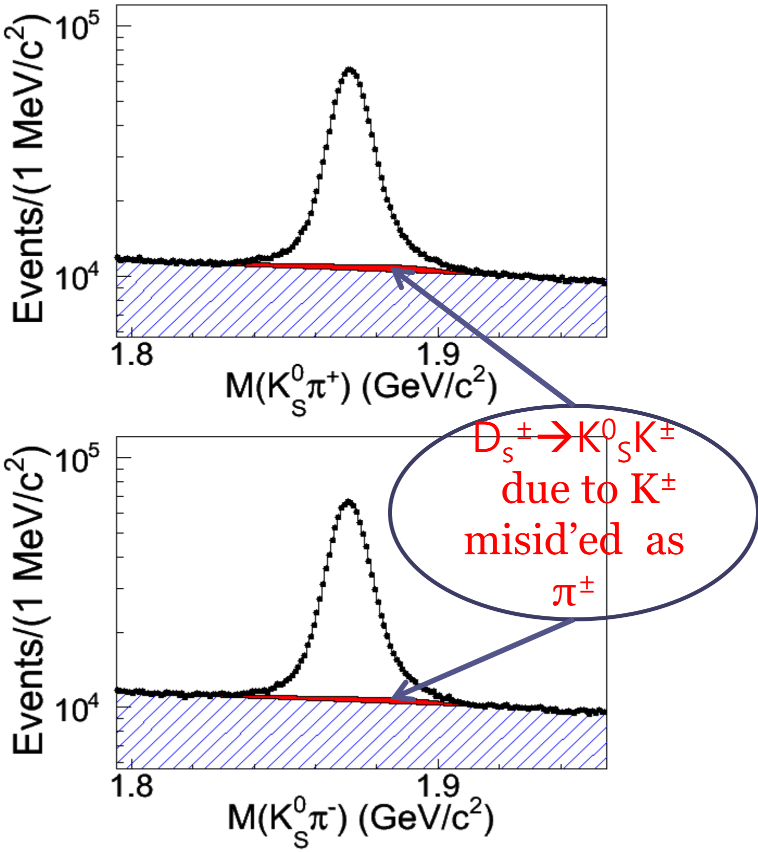
by Belle during the last decade

$D^+ \to K_S^0\pi^+$ (1) (arXiv:1203.6409)

- Final state : coherent sum of CF ($D^+ \to \overline{K}^0\pi^+$) and DCS ($D^+ \to K^0\pi^+$) decays, thus No SM CPV in these decays : $A_{CP}^{\Delta C}$
- CPV in K^0 system : (-0.332±0.006)% ($A_{CP}^{\overline{K}^0}$)
- A_{CP} in the final state,

$$A_{CP}^{D^+\to K_S^0\pi^+} = A_{CP}^{\Delta C} + A_{CP}^{\overline{K}^0}$$

- Significant CPV ≠ -0.332% could signal existence of new physics!!
- Unknown new phase from NP may appear in interference between the CF and DCS decays →could generate O(1%) DCPV in $D^+ \to K_S^0\pi^+$ decay
- Using the full data (1S, 2S, 3S, 4S, 5S, and near 4S), ~1.74 M reconstructed decays



$D^+ \to K_S^0 \pi^+$ (2) (arXiv:1203.6409)

- $A_{rec}^{D^+ \to K_S^0 \pi^+} = \frac{N_{rec}^+ - N_{rec}^-}{N_{rec}^+ + N_{rec}^-}, \quad N_{rec}^{\pm} = N_{rec}^{D^\pm \to K_S^0 \pi^\pm}, \ K_S^0 \to \pi^+ \pi^-$

  $= A_{CP}^{D^+}$ (CPV from intrinsic D^+ decay, independent of any kinematic variables)

  $+ A_{CP}^{\overline{K}^0}$ (CPV in K^0 system, depends on K_S^0 decay time (Grossman and Nir, JHEP 4 (2012), 2)

  $+ A_{FB}^{D^+}$ (production asymmetry, odd function of $\cos\theta_{\mathrm{D}^+}^{\mathrm{CMS}}$)

  $+ A_{\varepsilon}^{\pi^+}$ ($\pi^\pm$ detection asymmetry, depends on ($p_{T\pi^+}^{lab}, \cos\theta_{\pi^+}^{lab}$)

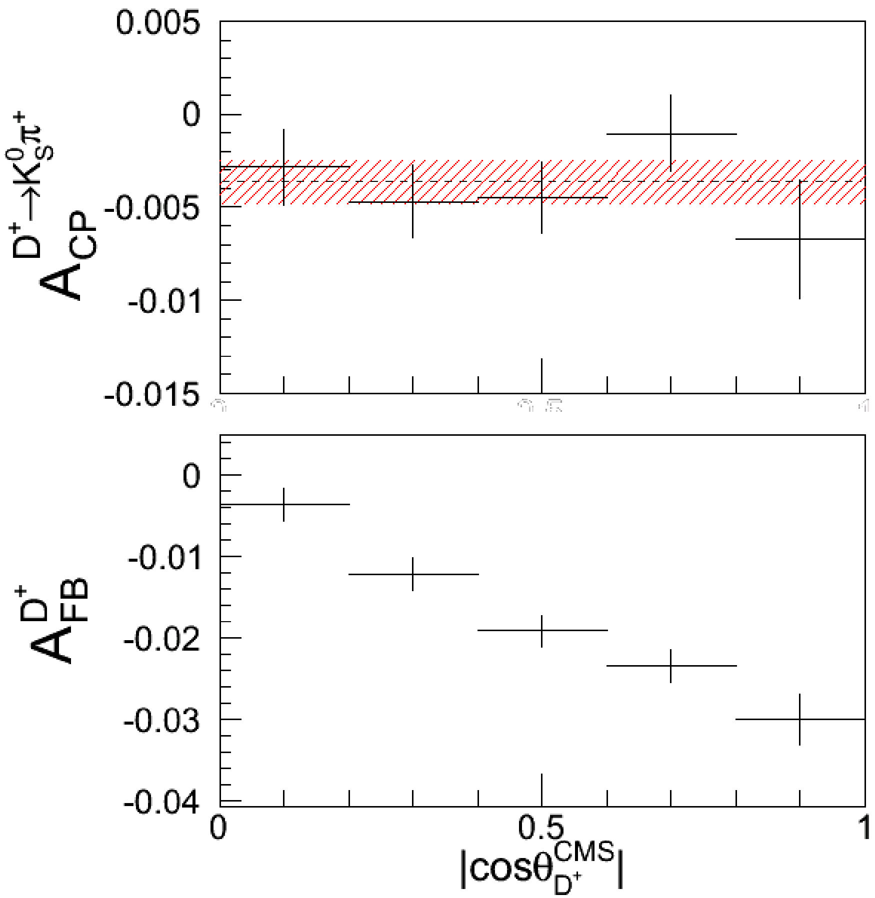
  : Correct using CPV free CF decays, $D^+ \to K^- \pi^+ \pi^+$ and $D^0 \to K^- \pi^+ \pi^0$)

  $+ A_D$ (Dilution asymmetry from different interactions between $\sigma(NK^0)$ and $\sigma(N\overline{K}^0)$

  depends on $p_{K_S^0}^{lab}$: Correction needed according to PRD 84, 111501 (2011))

- After correcting for $A_{\varepsilon}^{\pi^+}$ and A_D, $A_{rec}^{D^+ \to K_S^0 \pi^+_{corr}} = A_{CP}^{D^+ \to K_S^0 \pi^+} + A_{FB}^{D^+}$, ($A_{CP}^{D^+ \to K_S^0 \pi^+} = A_{CP}^{D^+} + A_{CP}^{\overline{K}^0}$)
- Using the antisymmetry of $A_{FB}^{D^+}$ in $\cos\theta_{\mathrm{D}^+}^{\mathrm{CMS}}$, $A_{CP}^{D^+ \to K_S^0 \pi^+}$ extracted in $\cos\theta_{\mathrm{D}^+}^{\mathrm{CMS}}$ bins

$D^+ \to K_S^0 \pi^+$ (3) (PRL accepted)



- $A_{CP}^{D^+ \to K_S^0 \pi^+}$ = (-0.363±0.094±0.067)%
- Highest sensitivity in charm sector ever
- 3.2σ away from zero
- First evidence for CPV in charm decays from a single decay mode !
- Measured asymmetry consistent with CPV in K^0 mixing

$D^+ \to K_S^0 \pi^+$ (4) (PRL accepted)

- A_{CP} in K^0 with correction for K_S^0 decay time acceptance,

$A_{CP}^{\overline{K}^0}$ = (-0.332±0.006)%x(1.040±0.005)=(-0.345±0.008)%

- A_{CP} in intrinsic D^+ decay : subtracting A_{CP} in K^0,

$A_{CP}^{\Delta C}$ = (-0.018±0.094±0.068)%

- New world average of $A_{CP}^{D^+ \to K_S^0 \pi^+}$

Experiment	$A_{CP}^{D^+ \to K_S^0 \pi^+}$(%)
FOCUS	-1.6 ± 1.5 ± 0.9
CLEO	-1.3 ± 0.7 ± 0.3
BaBar	-0.44 ± 0.13 ± 0.10
Belle	-0.363 ± 0.094 ± 0.067
Average	-0.41 ± 0.09

4.6σ away from zero, Consistent with expected CPV in K^0 system

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

- Both are SCS decays : Expect O(0.1%) DCPV in the SM
- Can also generate indirect CPV induced by mixing,
- But, A_{CP} difference between the two decays reveals ~DCPV only according to universality of indirect CPV in charm decays

- $A_{CP}^{D^0 \to K^+ K^-} = (-0.43 \pm 0.30 \pm 0.11)\%,$

  $A_{CP}^{D^0 \to \pi^+ \pi^-} = (+0.43 \pm 0.52 \pm 0.12)\%,$

  $\Delta A_{CP} = (-0.86 \pm 0.60 \pm 0.07)\%$

→ Belle with 540 fb^{-1} (PLB 670, 190 (2008))

- Update A_{CP} in each decay mode with the full data sample
  Also report ΔA_{CP} between the two decays

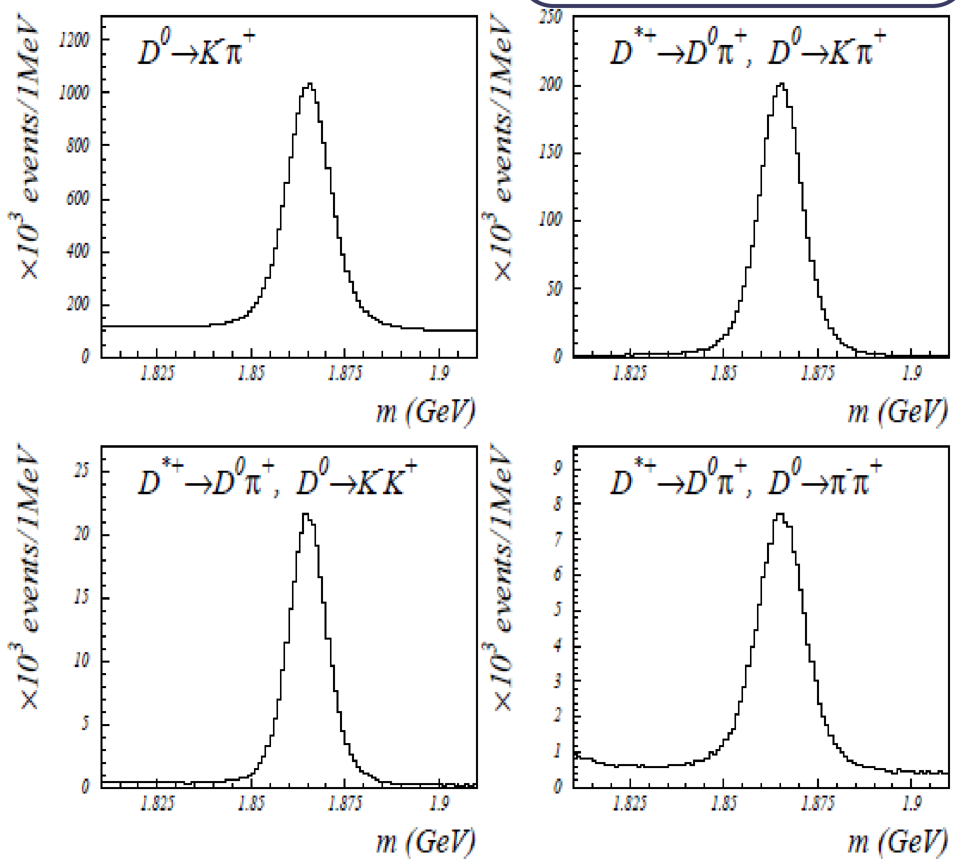
$A_{CP}^{D^0 \to h^+h^-}$ and ΔA_{CP}, $h \in \{K, \pi\}$ (2)

- A_{CP} extracting similar to that for $D^+ \to K_S^0 \pi^+$ (the same method in previous measurement with 540 fb^{-1})
- Unwanted asymmetries corrected properly
  - -slow pion detection : using CPV free CF decays, untagged (top left) and tagged $D^0 \to K^-\pi^+$ (top right);
    Integrated $A_\varepsilon^{\pi_s} = (+0.17 \pm 0.07)\%$
  - -A_{FB} : using the antisymmetry of A_{FB}^D in $\cos\theta_D^{CMS}$
  - -Subtract these unwanted asymmetries in ΔA_{CP} measurement

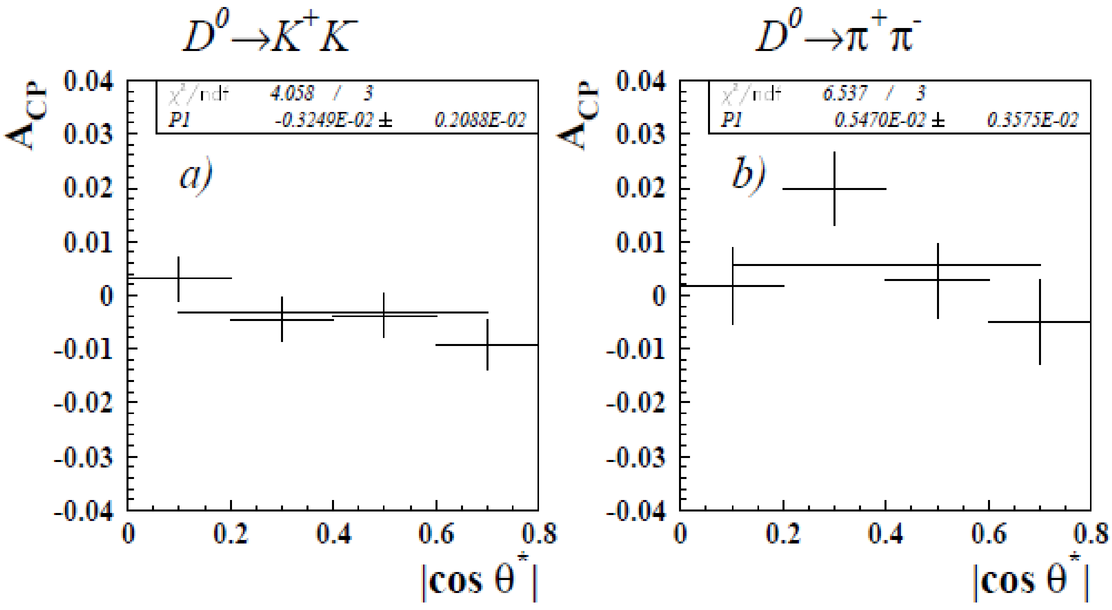
Belle preliminary

Signal yields, purities ($\Delta M < 15$ MeV, $\Delta q < 1$ MeV)

mode	yield	purity
KK	282k	97%
$\pi\pi$	123k	88%
$K\pi$	3.1M	99%
$K\pi$ untag.	14.7M	82%



$A_{CP}^{D^0 \to h^+ h^-}$ and ΔA_{CP}, $h \in \{K, \pi\}$ (3)



	976 fb^{-1} 540 fb^{-1}
$A_{CP}^{D^0 \to K^+ K^-}$	(-0.32±0.21±0.09)% (-0.43±0.30±0.11)%
$A_{CP}^{D^0 \to \pi^+ \pi^-}$	(+0.55±0.36±0.09)% (+0.43±0.52±0.12)%
ΔA_{CP}	(-0.87±0.41±0.06)% (-0.86±0.60±0.07)%

Belle preliminary

- Each A_{CP} : consistent with our previous measurement,
- ΔA_{CP} : 2.1σ away from zero
- Modest improvement in systematics,

  Statistics of $D^0 \to K^- \pi^+$ control samples

  : scale with integrated luminosity in two places

  Signal counting (choices of signal and sideband regions)

  : does not scale with integrated luminosity

$A_{CP}^{D^0\to h^+h^-}$ and ΔA_{CP}, $h \in \{K, \pi\}$ (4)

Experiment	$A_{CP}^{D^0\to K^+K^-}$ (%)	$A_{CP}^{D^0\to \pi^+\pi^-}$ (%)	ΔA_{CP} (%)
BaBar PRL 100, 061803 (2008)	0.00±0.34±0.13	-0.24±0.52±0.22	N.A.
LHCb PRL 108,111602 (2012)	N.A.	N.A.	-0.82±0.21±0.11
CDF	-0.24±0.22±0.09 PRD 85,012009 (2012) with 6.0 fb^{-1}	+0.22±0.24±0.11 PRD 85,012009 (2012) with 6.0 fb^{-1}	-0.62±0.21±0.10 CHARM (2012) with 9.6 fb^{-1}
Belle preliminary (2012)	-0.32±0.21±0.09	+0.55±0.36±0.09	-0.87±0.41±0.06

- $A_{CP}^{D^0\to K^+K^-}$ is the most sensitive and ΔA_{CP} is consistent with others
- Now, new world average from LHCb, CDF, and Belle ;
  ΔA_{CP}=(-0.74±0.15)% ~4.9σ away from zero
- SM or BSM ? many speculations
- Need complementary measurements from other decays,
  for example, A_{CP} in $D^+ \to K_S^0 K^+$ and $D^+ \to \pi^+\pi^0$ etc.…

Summary

- Report the first evidence for CPV in the decay $D^+ \to K_S^0\pi^+$

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

  → 3.2σ away from zero

  A_{CP} in intrinsic charm decay after removing the K⁰ mixing contribution (also neglecting DCS decay contribution)

  $A_{CP}^{D^+\to \overline{K}^0\pi^+}$ = (-0.018±0.094±0.068)%

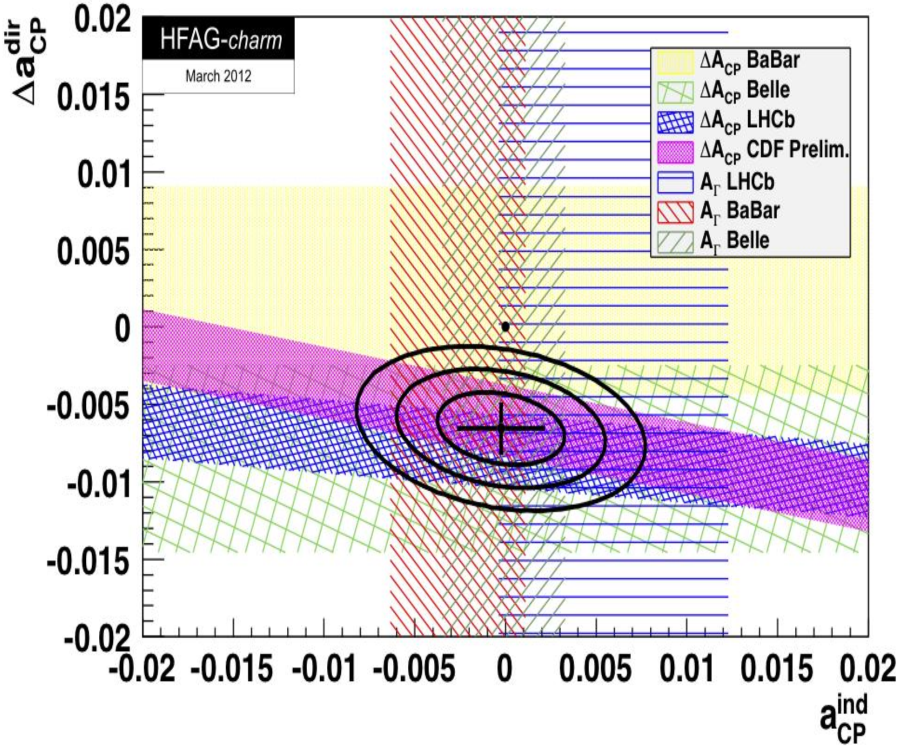
- Update $A_{CP}^{D^0\to K^+K^-}$ and $A_{CP}^{D^0\to \pi^+\pi^-}$,

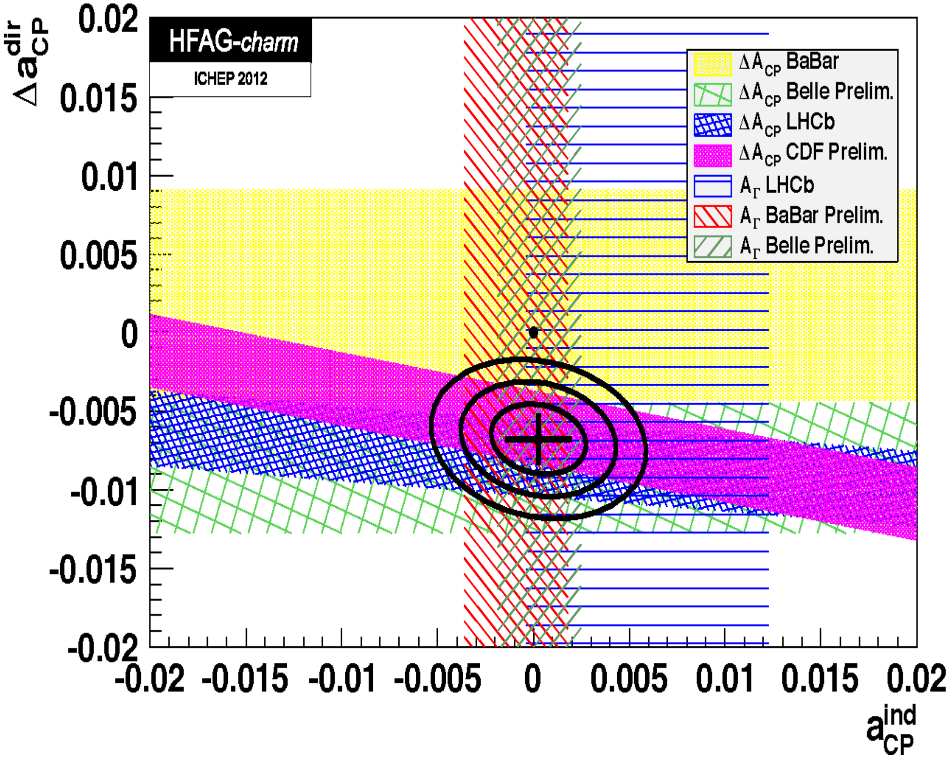
  $A_{CP}^{D^0\to K^+K^-}$ is the most sensitive measurement to date

  Our ΔA_{CP} value consistent with LHCb and CDF results

$A_{CP}^{D^0\to K^+K^-}$	(-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)%

Thanks to Marco Gersabeck from HFAG



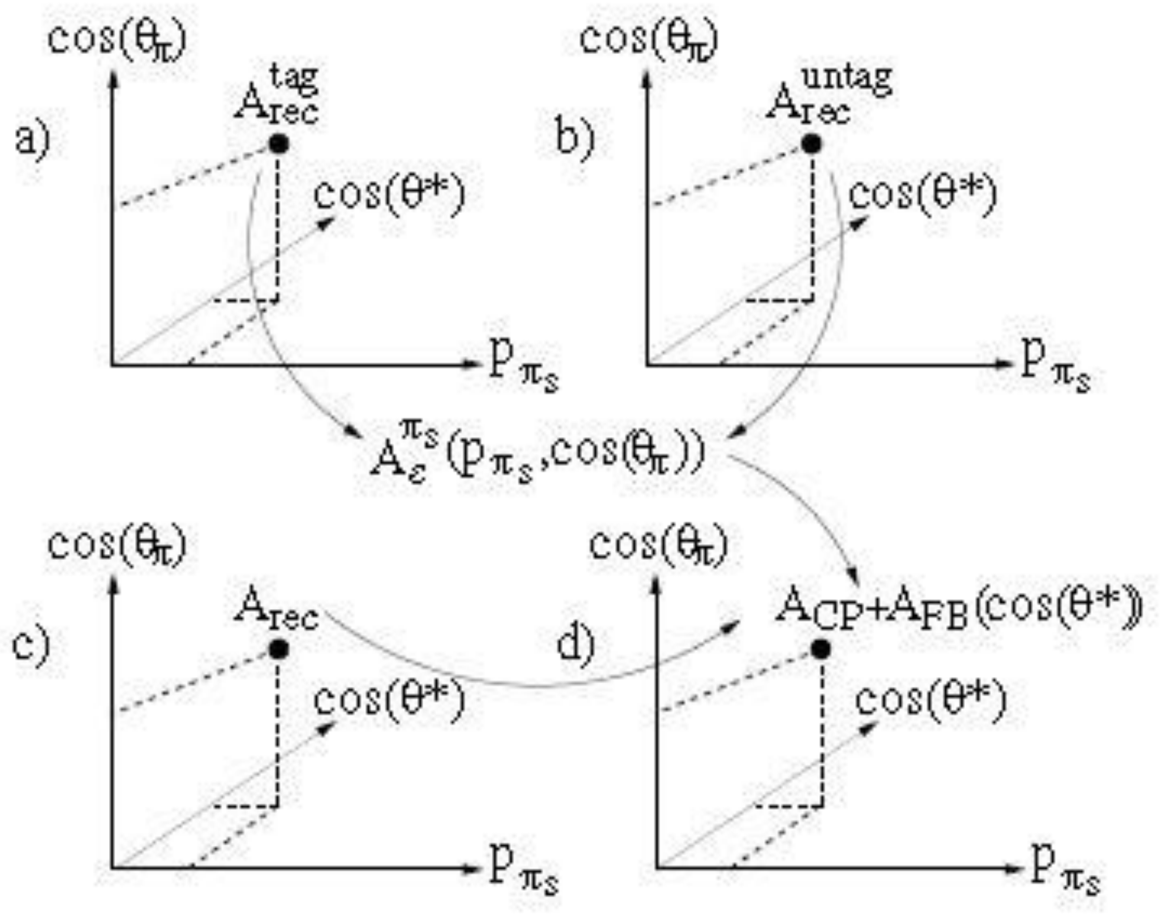


HFAG March 2012
without the latest BaBar A_Γ
No CPV hypothesis : 6.15×10^{-5}
Δa_{CP}(dir)=(-0.656±0.154)%
a_{CP}(ind)=(-0.025±0.231)%

HFAG ICHEP 2012
with Belle preliminary,
No CPV hypothesis : 1.98×10^{-5}
Δa_{CP}(dir)=(-0.678±0.147)%
a_{CP}(ind)=(-0.027±0.163)%

Thank you
for
your attention !!

Slow pion asymmetry correction



A_ε^π measurement

- Use two VERY large and CPV free resonance samples to measure $A_\varepsilon^{\pi^+}$
- $D^+ \to K^-\pi_h^+\pi_l^+$ $(p_{T\pi_h^+}^{lab} > p_{T\pi_l^+}^{lab})$ 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 no CPV in Cabibbo favored decays
- 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

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

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

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

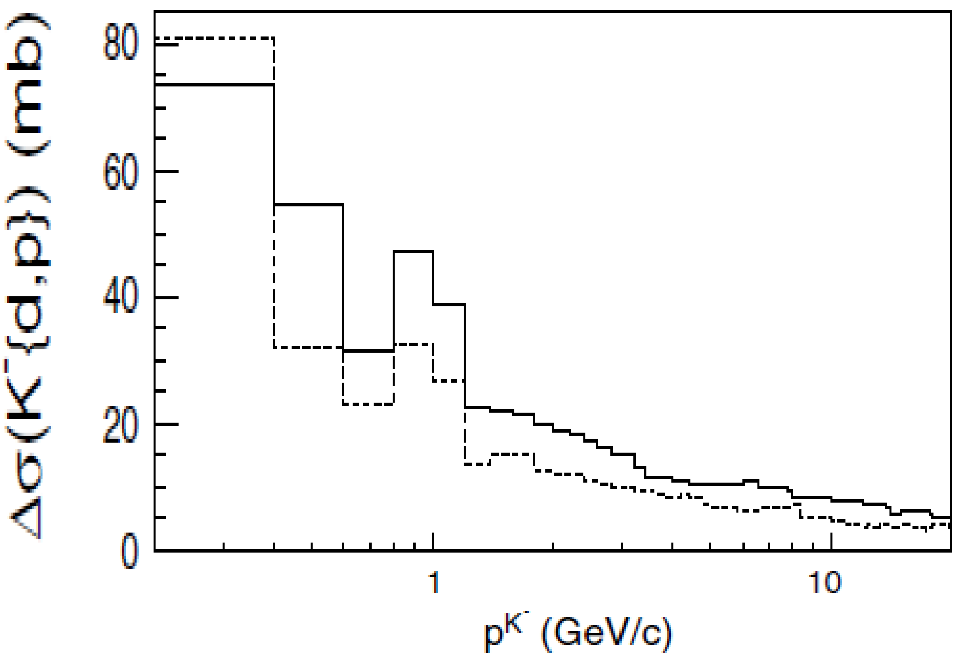
- Actually correction procedure is quite nontrivial

Using the antisymmetry of $A_{FB}^{D}(\cos\theta_D^{CMS})$

$$* A_{CP}^{D\to K_S^0 X^+} = \left\{ A_{rec}^{D\to K_S^0 X_{corr}^+}(\cos\theta_D^{CMS}) + A_{rec}^{D\to K_S^0 X_{corr}^+}(-\cos\theta_D^{CMS}) \right\} / 2$$

$$* A_{FB}^{D} = \left\{ A_{rec}^{D\to K_S^0 X_{corr}^+}(\cos\theta_D^{CMS}) - A_{rec}^{D\to K_S^0 X_{corr}^+}(-\cos\theta_D^{CMS}) \right\} / 2$$

Asymmetry due to K^0-K^0bar material effects (we call it A_D)



- $\sigma(K^+N) \neq \sigma(K^-N)$
  dot : proton, line : deuteron
- Assuming isospin symmetry
  $\sigma(K^0N) \neq \sigma(K^0barN)$
  → This is the origin of the effect

- A_D was naively calculated and assigned as systematics in Belle PRL 104, 181602 (2010)
- Getting more data, this became one of the dominant systematics for Acp($D^+ \rightarrow K^0_S\pi^+$)
- A few colleagues and myself went through this effect in detail,
  the result is available in PRD 84, 111501 (2011)

Experiment-dependent SM expectation of Acp due to K^0_S

- A_{CP} in the final states with K_S^0, $D \to K_S^0 X$, $K_S^0 \to \pi^+\pi^-$

$$A_{CP}^{D\to K_S^0 X} \equiv \frac{\Gamma(D \to K_S^0 X)\Gamma(K_S^0 \to \pi^+\pi^-) - \Gamma(\overline{D} \to K_S^0 \overline{X})\Gamma(K_S^0 \to \pi^+\pi^-)}{\Gamma(D \to K_S^0 X)\Gamma(K_S^0 \to \pi^+\pi^-) + \Gamma(\overline{D} \to K_S^0 \overline{X})\Gamma(K_S^0 \to \pi^+\pi^-)}$$

$$= A_{CP}^{D} + A_{CP}^{K_S^0}$$

- $A_{CP}^{K_S^0}$: A_{CP} due to K_S^0 is known to be $(-0.332 \pm 0.006)\%$,
- Grossman and Nir (arXiv:1110.3790) pointed out

$A_{CP}^{K_S^0}$ should be estimated with experimental dependency

$$\because A_{CP}^{K_S^0} \equiv \frac{\int_0^\infty \Gamma_{\pi\pi}(t) - \overline{\Gamma}_{\pi\pi}(t)dt}{\int_0^\infty \Gamma_{\pi\pi}(t) + \overline{\Gamma}_{\pi\pi}(t)dt}, \quad t : K_S^0 \text{ decay time}$$

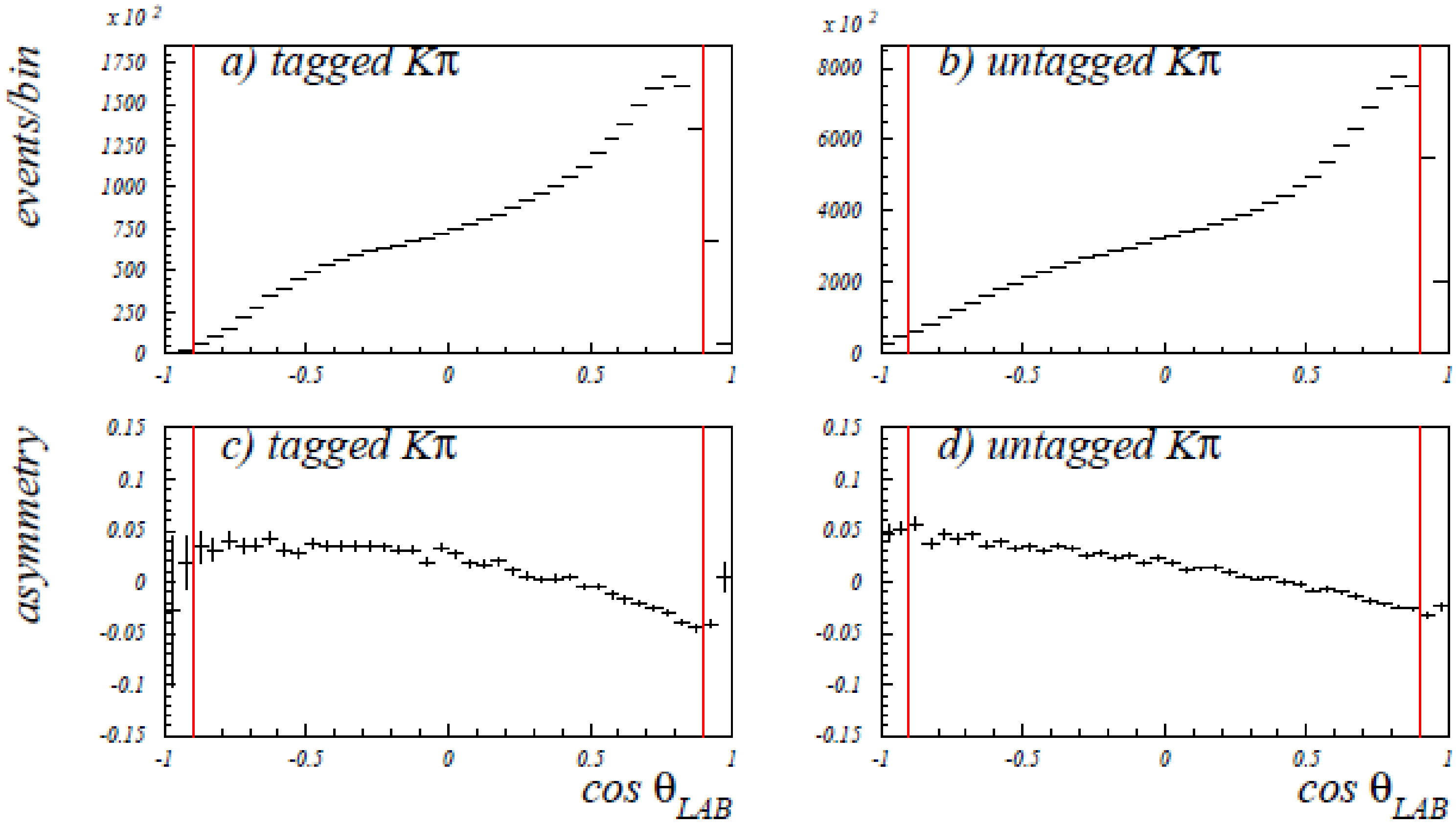


Figure 7: Polar angle distribution of the reconstructed $D^0 + \overline{D}^0$ signal events (in lab) for (a) the tagged $K\pi$ sample, (b) for the non-tagged $K\pi$ sample, and corresponding asymmetries (c) for tagged, (d) for non-tagged sample. Vertical lines indicate the cut introduced to reduce systematics.