International workshop on e^+e^- collisions
from Phi to Psi 2013

CHARM MIXING AND CP VIOLATION AT B-FACTORIES

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Outline

- Introduction
- Indirect CPV and mixing in two-body decays
- Direct CPV
  - $D^{\pm} \rightarrow K_S^0 K^{\pm}$, $D_s^{\pm} \rightarrow K_S^0 K^{\pm}$, $D_s^{\pm} \rightarrow K_S^0 \pi^{\pm}$ analysis
  - $D^0 \rightarrow h^+ h^-$ and ΔA_{CP}
  - $D^{\pm} \rightarrow K^+ K^- \pi^{\pm}$ analysis
- Summary and outlook

Flavor mixing in the charm sector

- Mass eigenstate ≠ flavor eigenstate

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

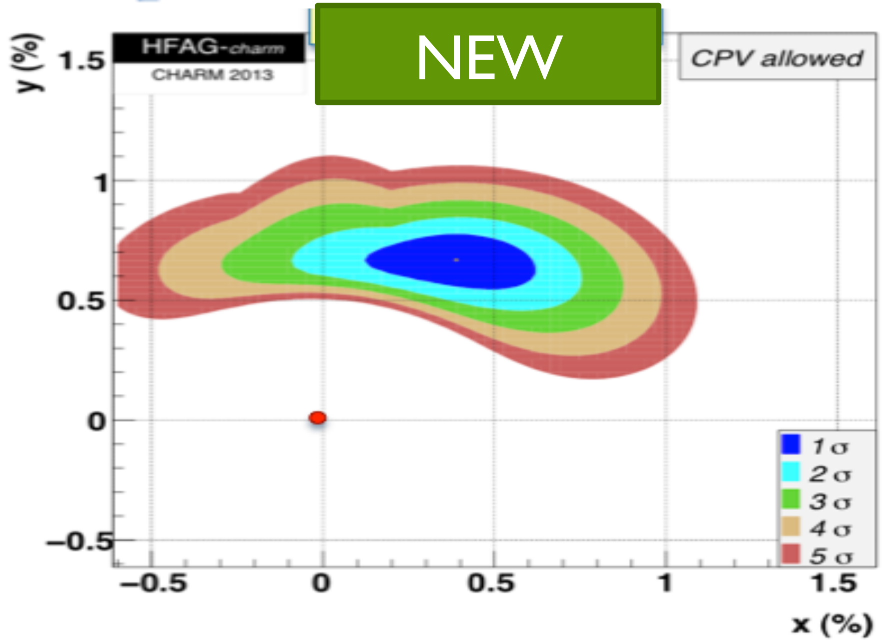
- $m_{1,2}$ and $\Gamma_{1,2}$ are mass and width of $D_{1,2}$ and $\Gamma_D = (\Gamma_1 + \Gamma_2)/2$

- Mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma_D}, \quad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D}$$

- Short distance contributions are GIM and CKM suppressed in the Standard Model.

- Long distance contributions are dominant but affected by large uncertainties.



- Mixing in the D^0 system is well established, significance ~10 σ (*Int.J.Mod.Phys. A21 (2006) 5686-5693*).
- Standard Model (SM) predictions affected by large uncertainties: $x_{theo}, y_{theo} \sim O(10^{-2}\text{-}10^{-7})$.
- Measurements of *x* and *y* are at the upper limit of SM, New Physics may contribute in short-distance diagrams.

CP violation in the charm sector

- CP Violation in decay to final states f and $\bar{f}$ $\quad |A_f| \neq |\bar{A}_{\bar{f}}|$

  Two amplitudes with different weak and strong phases

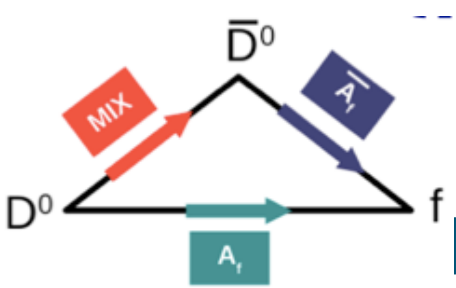
$$A_{CP} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

- CP violation in mixing if $r_m = |q/p| \neq 1$

  Probability of $D^0 \rightarrow \bar{D}^0$ is different than CP conjugate $\bar{D}^0 \rightarrow D^0$

$$A_M = \frac{R_M^2 - R_M^{-2}}{R_M^2 + R_M^{-2}}, \qquad R_M = \frac{q}{p}$$

- CP violation in the *interference* between the decay with and without mixing if $\phi_f \neq 0$



$$\lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f} = \left| \frac{\bar{A}_f}{A_f} \right| exp[i(\delta_f + \phi_f)]$$

strong + weak phase

Why search for CPV in charm decays?

- CPV in charm decays is expected to be very small in the Standard Model (SM), at the level of 0.1% or below.

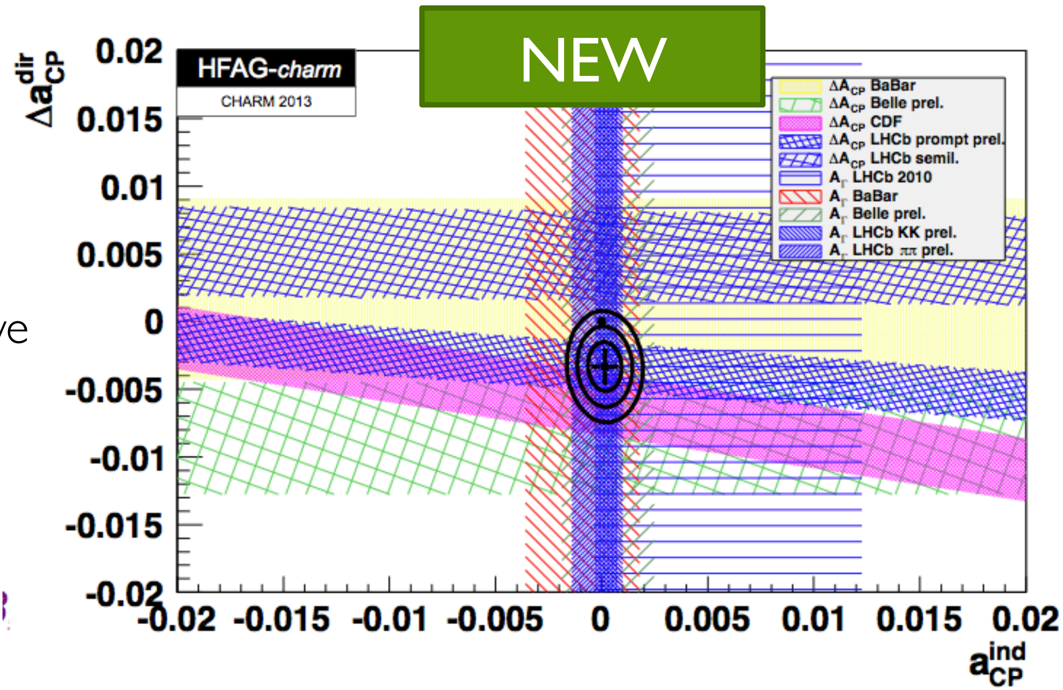
- CP-violating asymmetries in charm decays provide a unique probe for physics beyond the Standard Model (SM).

- New Physics can enhance CP violating observables.

- Recent results from LHCb and CDF have renewed the interest for searching new physics in the charm sector:

$$a_{CP}^{\text{ind}} = (0.015 \pm 0.052)\%$$

$$\Delta a_{CP}^{\text{dir}} = (-0.333 \pm 0.120)\%$$



Current data consistent with no CPV at 2.0σ

Is this an observation of new physics? No straightforward answer, could be SM or NP.

Indirect CPV and mixing in two-body decays

- Perform a fit to different D^0 decay modes from:

  - "flavor tagged" at production according to the pion charge $D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+, K^+K^-$ and $\pi^+\pi^-$ — BaBar and Belle
  - "flavor untagged" $D^0 \to K^-\pi^+, K^+K^-$ only for y_{CP} measurement. Four times statistics wrt "flavor tagged" sample. Lower purity. — BaBar

- Experimentally we measure the lifetimes of CP-even and CP-mixed eigenstates.

$$\tau^+ = \tau(D^0 \to h^+h^-)$$
$$\bar{\tau}^+ = \tau(\bar{D}^0 \to h^+h^-)$$
$$\tau_D = \tau(D^0 \to K^\mp\pi^\pm)$$
$$h^\pm = K^\pm, \pi^\pm$$

Mixing: $$y_{CP} = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} + \frac{1}{\bar{\tau}^+}\right) - 1$$

CP Violation: $$\Delta Y = \frac{\tau_D}{2}\left(\frac{1}{\tau^+} - \frac{1}{\bar{\tau}^+}\right)$$

$$\text{if CP conserved} \Rightarrow y_{CP} \equiv y \quad \textit{and} \quad \Delta Y = 0$$

Reconstruction technique

- Measure D^0 proper time, *t*, and its error σ_t, by reconstructing D^0 momentum and 3D flight length *L*: Requires a precision vertex detector and a significant flight path.

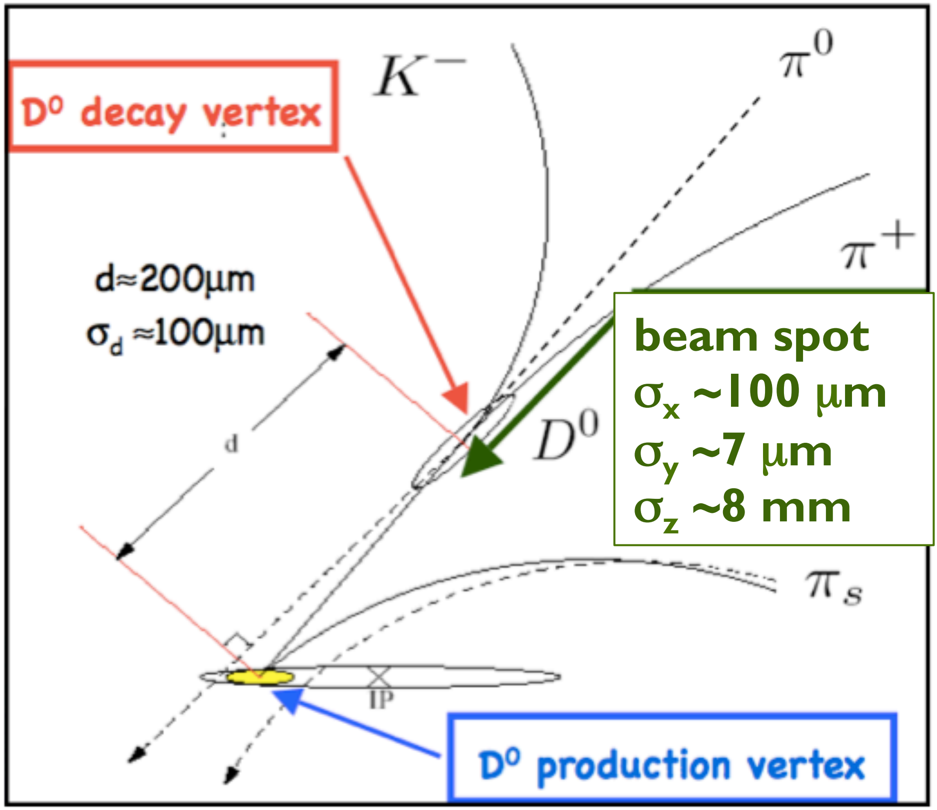
Tagged Candidates $D^* \rightarrow D^0\pi_s$, sample purities > 98%

- Slow pion reconstructed and D^0 decays selected with two dimensional cut [m(D^0), q]

$$q = (M_D^* - M(h^+h^-) - m_\pi)c^2$$

Untagged $D^0 \rightarrow K^+K^-$, $K^\mp\pi^\pm$ candidates with sample purities ~ 75%.

- Statistically independent samples used in BaBar analysis to improve sensitivity of y_{CP} and Δy.



Selection of signal events

- remove D from B decays, $p_{CM}(D^0)$ > 2.5 GeV/c
- Vertex fit requirements, Particle ID using Cherenkov detectors.

PRD 87, 012004 (2013)

BaBar lifetime ratio analysis

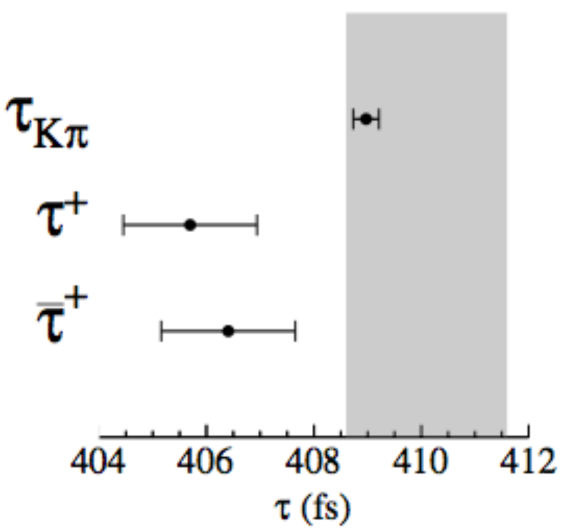
- BaBar uses independent datasets of tagged and untagged decays with full dataset 468 fb^{-1}. Simultaneous fit to all decays both tagged and untagged to measure the lifetime.

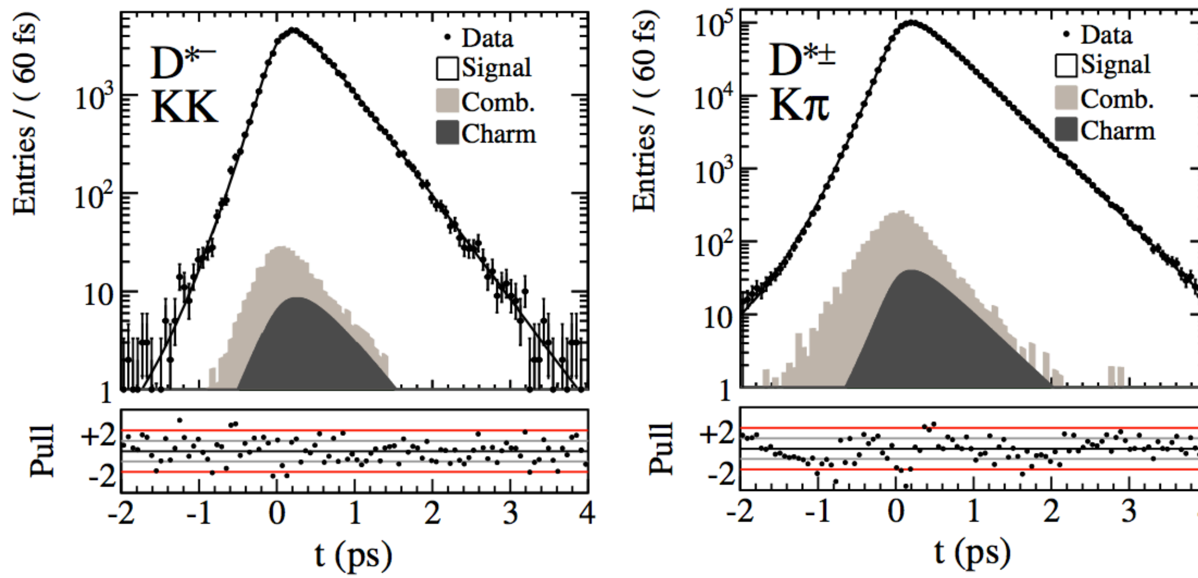
Flavor tagged

$D^{*+} \to D^0\pi_s^+; D^0 \to K^+K^-$

$D^{*+} \to D^0\pi_s^+; D^0 \to \pi^+\pi^-$

$D^{*+} \to D^0\pi_s^+; D^0 \to K^-\pi^+, K^+\pi^-$





$$y_{CP} = [0.72 \pm 0.18(stat) \pm 0.12(syst)]\%$$

$$\Delta Y = [0.09 \pm 0.26(stat) \pm 0.06(syst)]\%$$

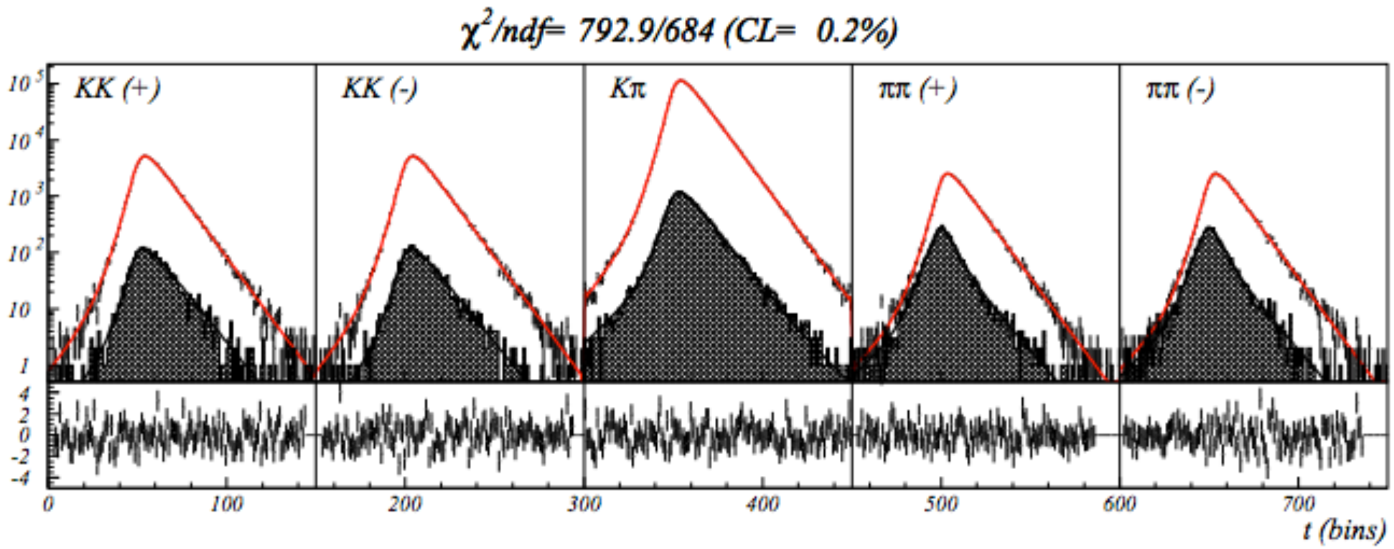
- no-mixing hypothesis excluded at 3.3 σ level
- no CPV observed

arXiv: 1212.3478

Belle lifetime ratio analysis

- Belle uses tagged decays.
- Full dataset 976 fb^{-1}

$$D^{*+} \to D^0 \pi_s^+; D^0 \to K^+K^-$$
$$D^{*+} \to D^0 \pi_s^+; D^0 \to \pi^+\pi^-$$
$$D^{*+} \to D^0 \pi_s^+; D^0 \to K^-\pi^+, K^+\pi^-$$

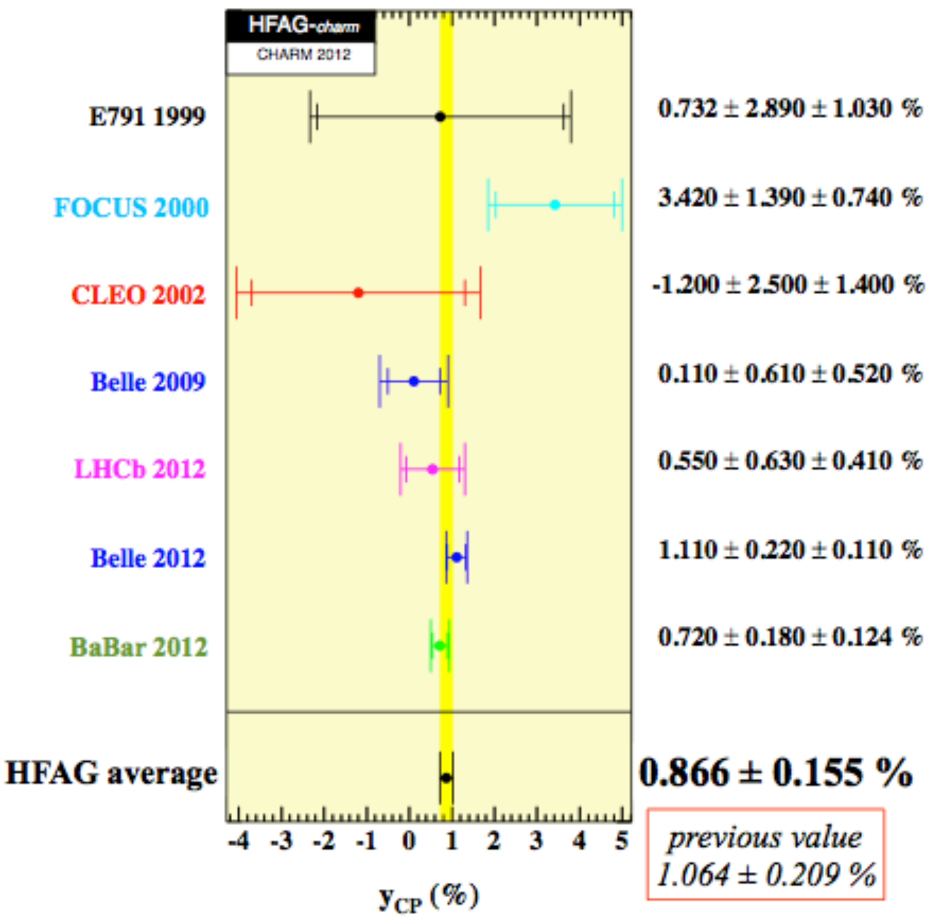


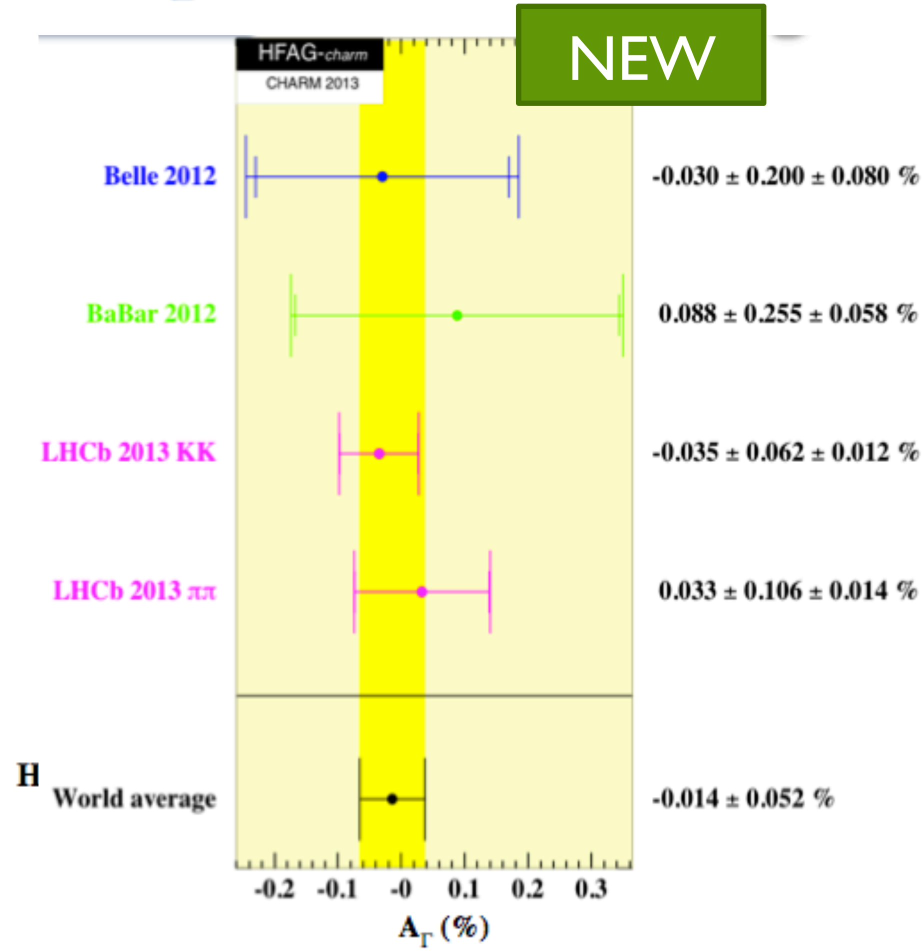
- Many systematics cancel in the relative lifetime measurements.

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%,$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%,$$

Evidence for mixing at 4.5 σ - no CPV observed

New HFAG averages for y_{CP} and A_{Γ}





Including new BaBar and Belle results: significant improvement in the uncertainty and lower value for y_{CP}

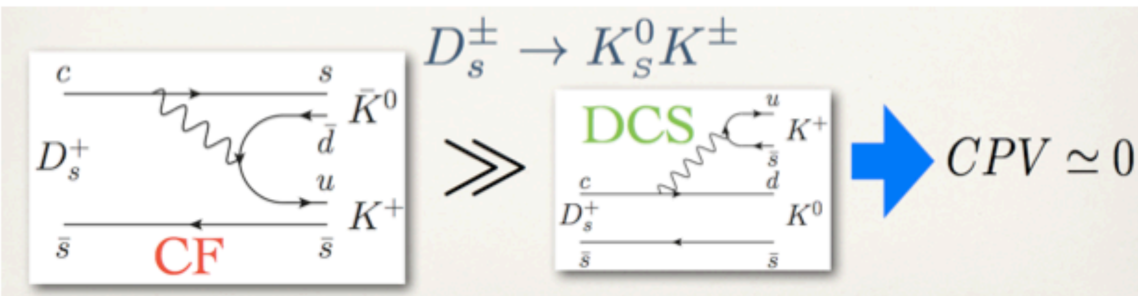
Direct CPV in D decays with a K_S in the final state

- CP asymmetry in charm decays with a K_S in the final state is expected to be (±0.332±0.006)% whether a K^0 or a $\bar{K}^0$ is produced, due to CPV in K^0-$\bar{K}^0$ mixing.
- Sizable difference from this value would indicate CP violation in the $|\Delta C|=1$ transition (very small in the SM) indicating possible new physics effects.

$$A_{CP} = \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)} = A^{\Delta C}_{CP} + A^{\bar{K}^0}_{CP}$$

$h = (\pi, K)$

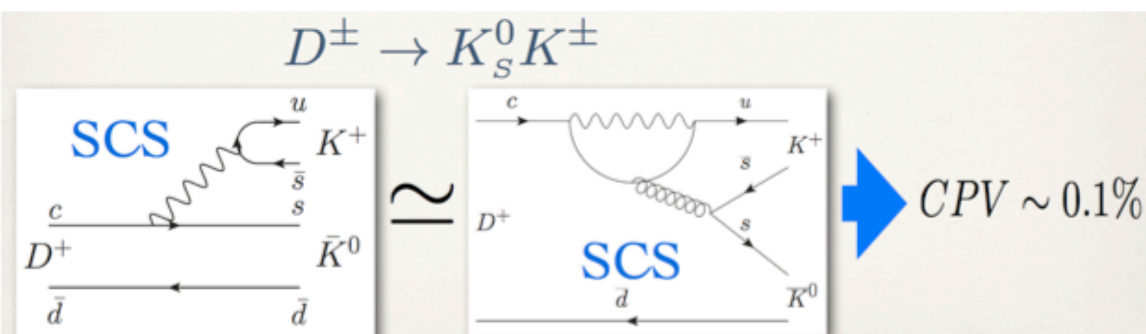
$A^{\bar{K}^0}_{CP}$ → **(-0.332±0.006)%**



$D_s^\pm \to K_s^0 K^\pm$

$D^\pm \to K_s^0 \pi^\pm$

Proceed through CF and DCS.
single phase and no SM CPV



$D_s^\pm \to K_s^0 \pi^\pm$

$D^\pm \to K_s^0 K^\pm$

CP asymmetry generated from interference of tree-level and penguin-level amplitudes.

Direct CPV in D decays with a K_S in the final state

The reconstructed asymmetry at B-factories

$$A_{rec} = A_{CP} + A_{FB}(cos\theta^*_D) + A^h_\epsilon(p^{lab}_h, cos\theta^{lab}_h)$$

$$A_{CP} = \frac{\Gamma(D^+_{(s)} \to K^0_S h^+) - \Gamma(D^-_{(s)} \to K^0_S h^-)}{\Gamma(D^+_{(s)} \to K^0_S h^+) + \Gamma(D^-_{(s)} \to K^0_S h^-)}$$

CPV from the decay of the charm meson - what we want to measure + CPV in the K^0 system, depends on the K_S^0 lifetime [Grossman and Nir, JHEP 4 (2012), 2]

$$A_{FB}(cos\theta^*_D)$$

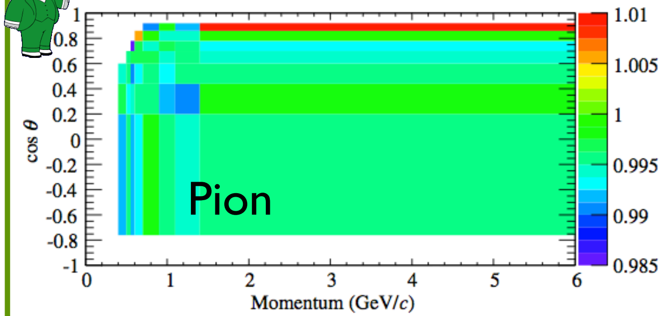
Production asymmetry of the D meson, odd as a function of the D meson polar angle in the center-of-mass. Extract directly by measuring reconstructed asymmetry in intervals of the $\cos\theta^*_D$

$$A^h_\epsilon(p^{lab}_h, cos\theta^{lab}_h)$$

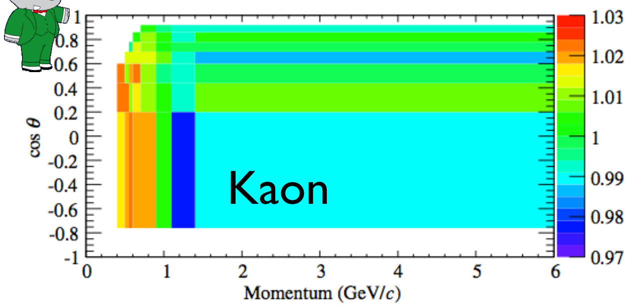
Detection induced component for the $\pi^\pm$ or the $K^\pm$. Corrected from the detection efficiency measured from high-statistics control samples.

Detector induced and F/B asymmetries

- Use a data-driven method to determine charge asymmetry in track reconstruction. Use tracks from $e^+e^- \to \Upsilon(4S) \to B\bar{B}$, which are free from any physics induced asymmetry.



$\sigma(\text{Ratio}) \simeq 0.005$



$\sigma(\text{Ratio}) \simeq 0.01$

Use track quality cuts, reject tracks identified as protons or electrons,

$$\text{Ratio} = \frac{\epsilon^+(\vec{p})}{\epsilon^-(\vec{p})} = \frac{N^+_{rec}(\vec{p})}{N^-_{rec}(\vec{p})}$$

$$N_{\text{rec}}(\vec{p}) = N_{\text{recOnPeak}}(\vec{p}) - N_{\text{recOffPeak}}(\vec{p}) \cdot \frac{\mathcal{L}_{\text{OnPeak}}}{\mathcal{L}_{\text{OffPeak}}}$$

- Fwd/Bwd asymmetry in $c\bar{c}$ production
- virtual photon interference with virtual Z^0
- Odd in $\cos\theta^*$, used to decouple from A_{CP} (constant)

$$A_{FB}(\cos\theta^*_D) = \frac{A(+|\cos\theta^*_D|) - A(-|\cos\theta^*_D|)}{2}$$

$$A_{CP}(\cos\theta^*_D) = \frac{A(+|\cos\theta^*_D|) + A(-|\cos\theta^*_D|)}{2}$$

A_{CP} results

PRD 87, 052012 (2013)

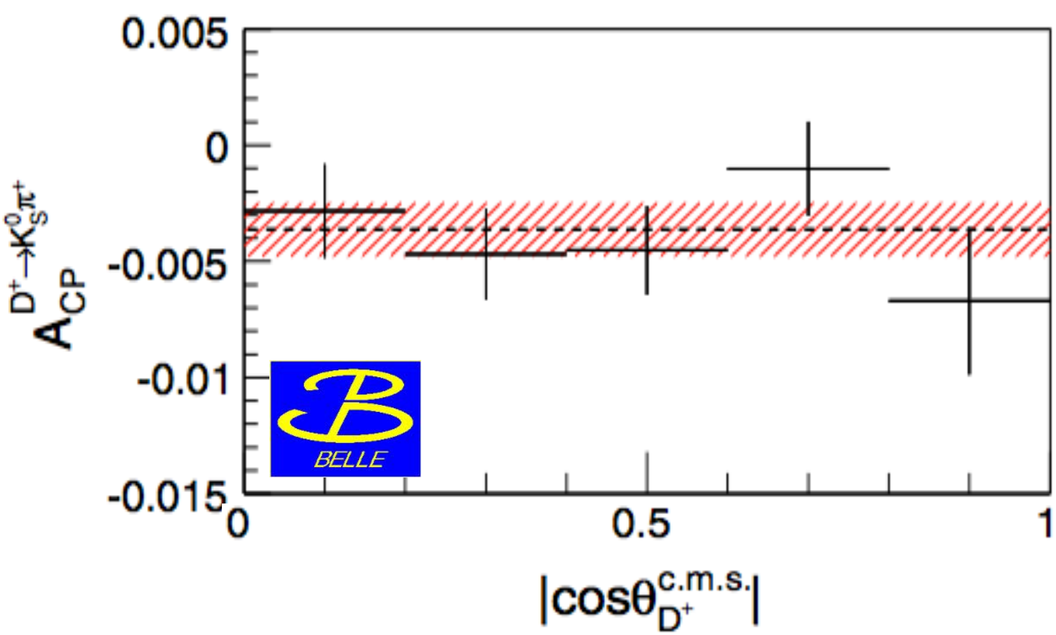
	$D^{\pm} \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S K^{\pm}$	$D^{\pm}_s \to K^0_S \pi^{\pm}$
A_{CP} value from the fit	$(0.16 \pm 0.36)\%$	$(0.00 \pm 0.23)\%$	$(0.6 \pm 2.0)\%$
Bias Corrections			
Toy MC experiments	$+0.013\%$	-0.01%	$-$
PID selectors	-0.05%	-0.05%	-0.05%
$K^0_S - K^0_L$ interference	$+0.015\%$	$+0.014\%$	-0.008%
A_{CP} corrected value	$(0.13 \pm 0.36 \pm 0.25)\%$	$(-0.05 \pm 0.23 \pm 0.24)\%$	$(0.6 \pm 2.0 \pm 0.3)\%$
A_{CP} contribution from $K^0 - \overline{K}^0$ mixing	$(-0.332 \pm 0.006)\%$	$(-0.332 \pm 0.006)\%$	$(0.332 \pm 0.006)\%$
A_{CP} value (charm only)	$(0.46 \pm 0.36 \pm 0.25)\%$	$(0.28 \pm 0.23 \pm 0.24)\%$	$(0.3 \pm 2.0 \pm 0.3)\%$

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

PRL109,021601(2012)

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

JHEP 1302, 098 (2013)



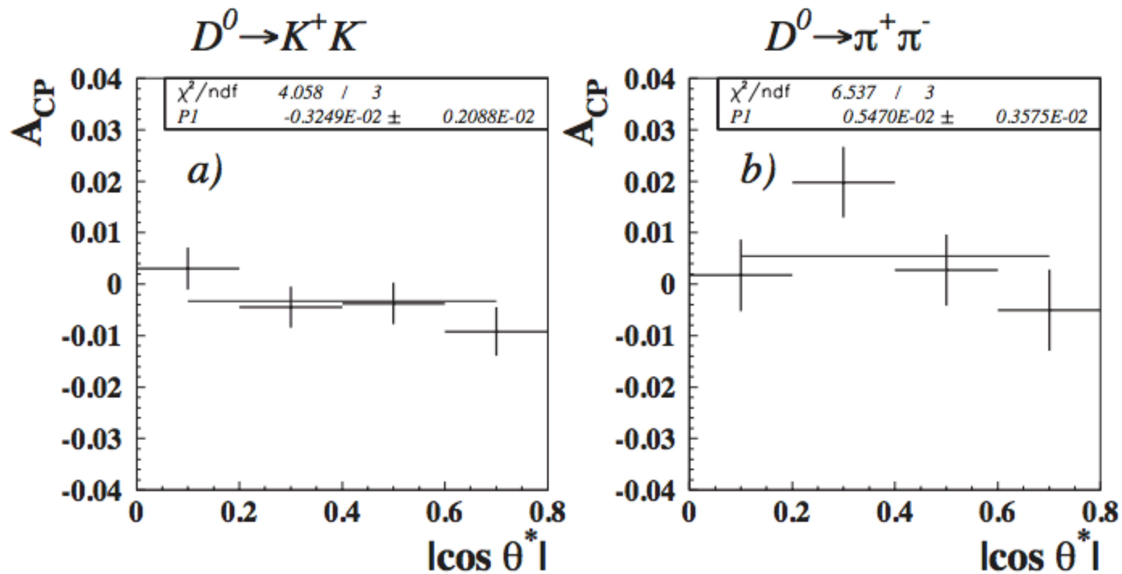
D^0 decays to CP-even eigenstates K^+K^-, $\pi^+\pi^-$

- For final CP eigenstate, indirect CP violation is universal. Difference in time-integrated CP asymmetry separates non-universal direct CP contribution.

$$\Delta A_{CP}^{direct} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

Belle (ICHEP 2012 976 fb^{-1})
[arXiv: 1212.5320]

ΔA_{CP} = -0.87 ± 0.41 ± 0.06



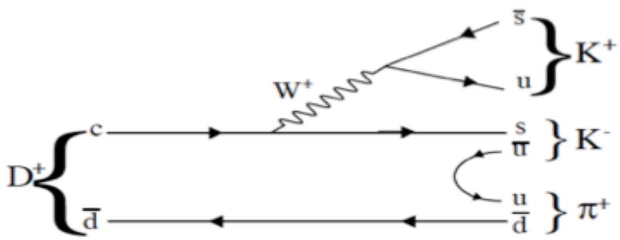
LHCb D^0 production modes : (1) inclusive semileptonic b-hadron decays (2) direct production of charm $D^{*+} \rightarrow D^0\pi_s$

Measurement (1): ΔA_{CP} = (0.49 ± 0.30 ± 0.14)% [arXiv 1303.2614]

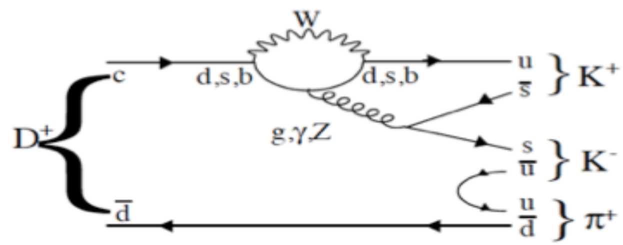
Measurement (2): ΔA_{CP} = (-0.34 ± 0.15 ± 0.10)% [LHCb-CONF-2013-003]

Direct CPV search in Dalitz plot decays $D^+ \rightarrow K^+K^-\pi^+$

- SCS decays can exhibit direct CP asymmetries due to interference between tree-level transition and $|\Delta C|=1$ penguin-level transition.

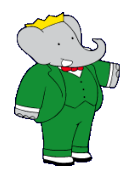


Tree level diagram

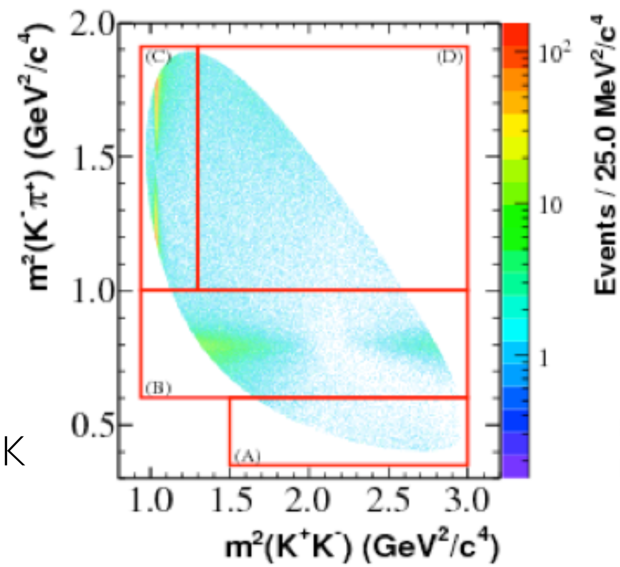


Penguin diagram

- CP asymmetry can be localized in a specific part of the Dalitz plot or integrated over the entire phase space.



- Search for CPV using 5 different approaches
  - 1) phase space integrated CP asymmetry A_{CP}
  - 2) A_{CP} in 4 different regions of Dalitz plot (A, B, C, D)
  - 3) comparison of the binned D^+ and D^- Dalitz plots
  - 4) comparison of Legendre polynomial moment distributions for K^+K^- and $K^-\pi^+$ systems
  - 5) comparison of parameterized fits to Dalitz plot distributions



Direct CPV search in Dalitz plot decays

- Belle uses a complementary approach.

- Belle uses larger dataset of SCS and CF decays to search for CP violation in $D_{(s)}^{+} \rightarrow \Phi \pi^{+}$

$$A_{CP}^{D_{(s)}^{+}\rightarrow\phi\pi^{+}} = \frac{\Gamma(D_{(s)}^{+} \rightarrow \phi\pi^{+}) - \Gamma(D_{(s)}^{-} \rightarrow \phi\pi^{-})}{\Gamma(D_{(s)}^{+} \rightarrow \phi\pi^{+}) + \Gamma(D_{(s)}^{-} \rightarrow \phi\pi^{-})}$$

- Measures the asymmetry difference between the SCS decay $D^{+} \rightarrow \Phi \pi^{+}$ and the CF decay $D_{s}^{+} \rightarrow \Phi \pi^{+}$

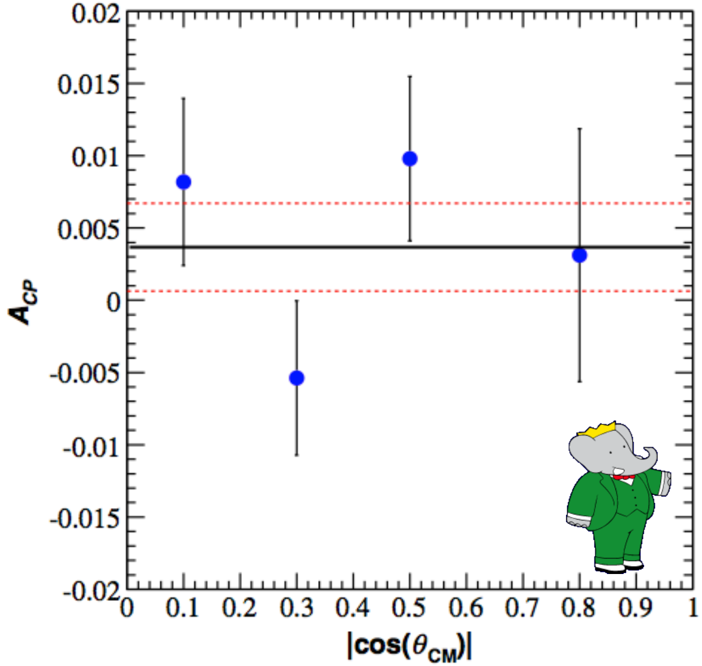
$$\Delta A_{rec} = \frac{N(D^{+})-N(D^{-})}{N(D^{+})+N(D^{-})} - \frac{N(D_{s}^{+})-N(D_{s}^{-})}{N(D_{s}^{+})+N(D_{s}^{-})}$$

- Where the second term is expected to have negligible A_{CP}

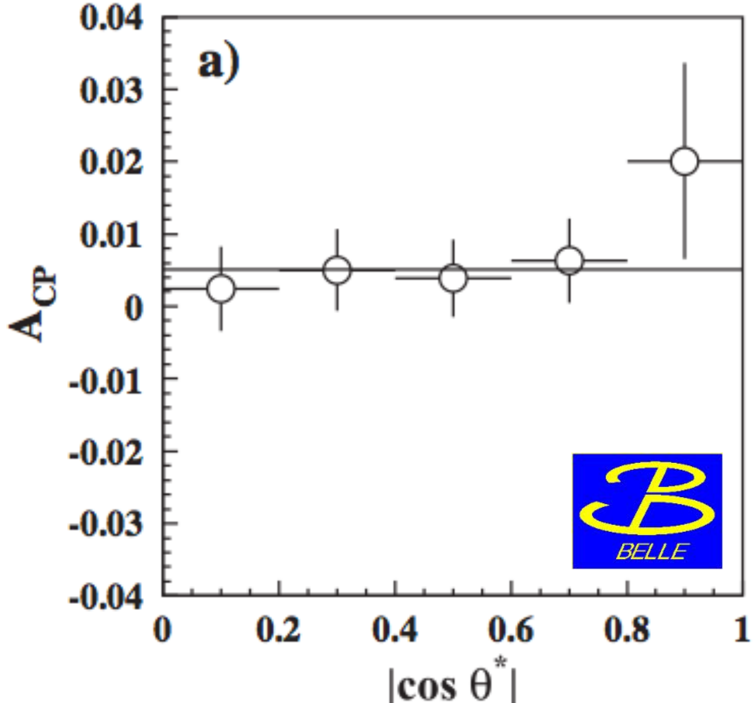
- The asymmetry difference cancels the detector-induced asymmetry and other systematics effects.

Direct CPV search in Dalitz plot decays

BaBar [PRD 87, 052010 (2013)]
A_{CP} = (0.37 ± 0.30 ± 0.15)%



Belle [PRL 108, 071801 (2012)]
$A_{CP}(D^{\pm}\rightarrow\varphi\,\pi^{\pm})$ = (0.51 ± 0.28 ± 0.05)%

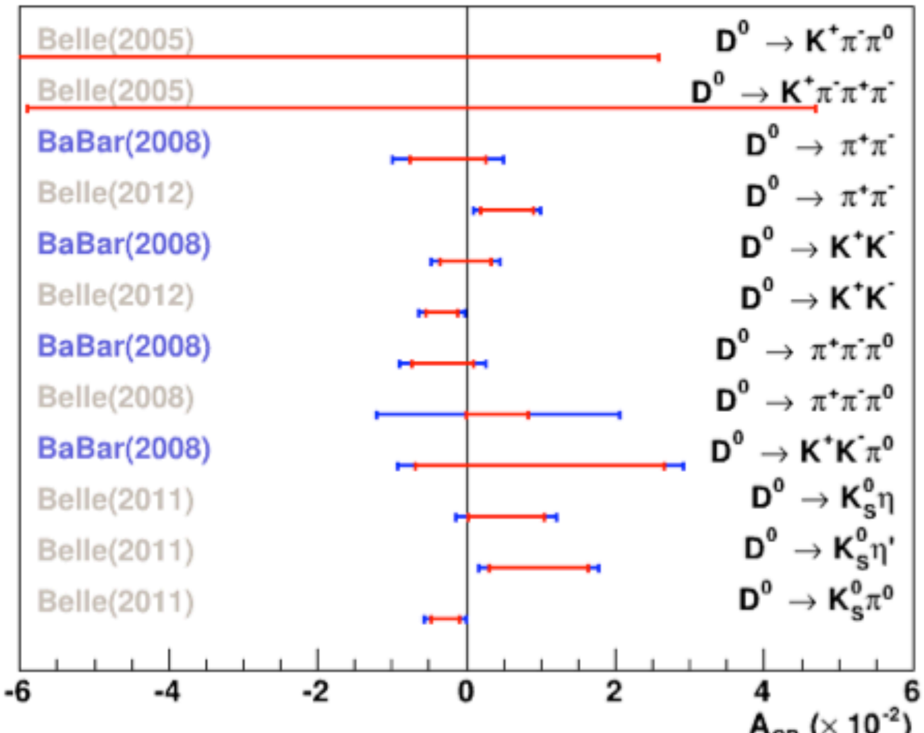


- No evidence of CP violation measured as a function of the center-of-mass polar angle of D^+ meson.

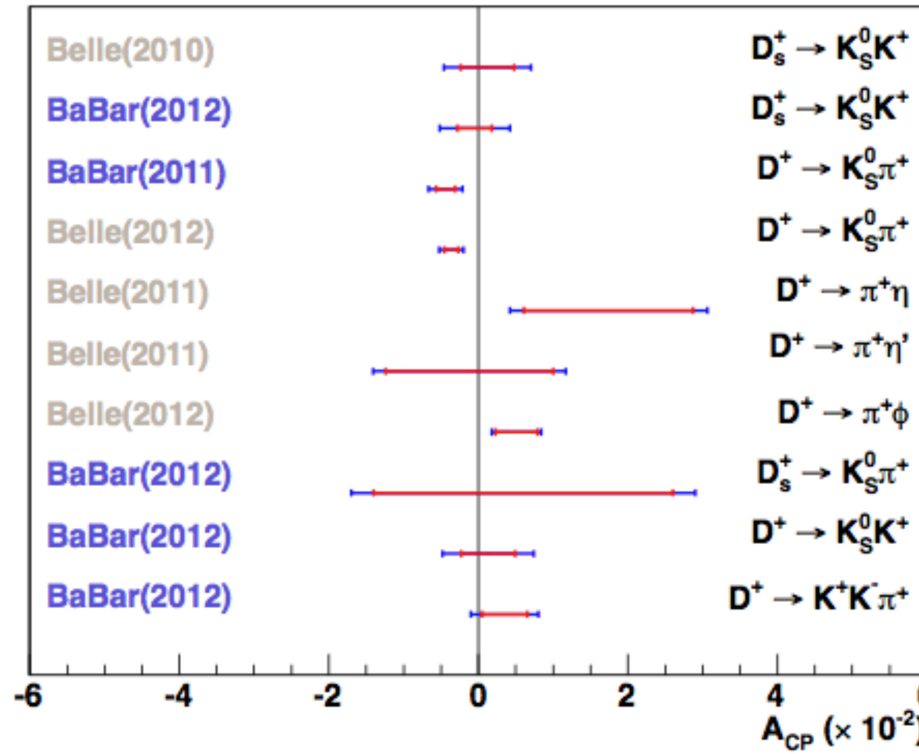
Summary and conclusions

Time-integrated CPV measurements at the B factories

D^0 modes: direct + indirect CPV



$D_{(s)}^+$ modes: direct CPV



- At the B factories was found evidence of CP violation in $D^+ \to K_S^0 \pi^+$ decays as expected in the SM. Systematic errors kept under control below the 10^{-3} level.

Summary and conclusions

- Searching for CPV in charm decays allows to probe for new physics and puts stringent constraints on new models.
- The current data samples from the B-factories are being used effectively to complete many analyses of mixing and CP violation in Charm decays.
- Evidence for mixing at 5 σ for individual B-factory results. All consistent with no CP violation.
- Direct CP Violation in Charm decays not observed at the e^+e^- collider experiments.
- Hints of CP violation in charm sector - cannot rule out SM or NP.

Thanks

D meson hadronic decays

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

➡ Cabibbo-favored

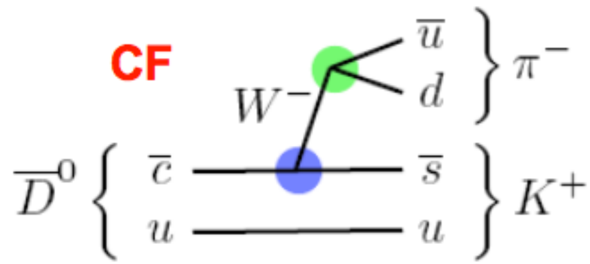
- examples: $D^0 \rightarrow K^- \pi^+$, $D^+ \rightarrow K^- \pi^+ \pi^+$
- $A_T \sim |V_{cs} V_{ud}|$

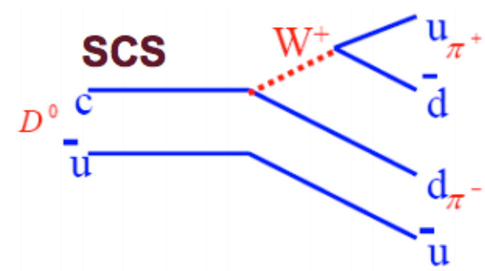
➡ singly Cabibbo-suppressed (SCS)

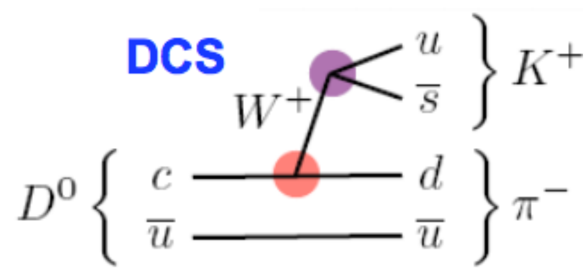
- examples: $D^0 \rightarrow K^+ K^-$, $D^0 \rightarrow \pi^+ \pi^-$, $D^+ \rightarrow K^+ K^- \pi^+$
- $A_T \sim |V_{cd} V_{ud}|$, $|V_{cs} V_{us}|$

➡ doubly Cabibbo-suppressed (DCS)

- $D^0 \rightarrow K^+ \pi^-$
- $A_T \sim |V_{cd} V_{us}|$







$$\mathrm{CF: BR}(D^0 \rightarrow K^- \pi^+) = (3.89 \pm 0.05)\%$$

$$\mathrm{SCS: BR}(D^0 \rightarrow \pi^+ \pi^-) = (1.397 \pm 0.026) \times 10^{-3}$$

$$\mathrm{DCS: BR}(D^0 \rightarrow K^+ \pi^-) = (1.48 \pm 0.07) \times 10^{-4}$$

Indirect CPV and mixing in two-body decays

- Mixing and CP violation observables are obtained from the partial widths of the decays:

$$D^0(\bar{D}^0) \to h^+h^-, h^\pm = K^\pm, \pi^\pm$$

Mixing

$$y_{CP} = \frac{\Gamma^+ + \bar{\Gamma}^+}{2\Gamma} - 1$$

CP Violation

$$\Delta Y = \frac{\Gamma^+ - \bar{\Gamma}^+}{2\Gamma}$$

$$\Delta Y = (1 + y_{CP})A_\Gamma \qquad A_\Gamma = \frac{\Gamma^+ - \bar{\Gamma}^+}{\Gamma^+ + \bar{\Gamma}^+}$$

CP Eigenstates

Γ^+ is the width of the decay to $D^0 \to \mathrm{CP}^+$

$\bar{\Gamma}^+$ is the width of the decay to $\bar{D}^0 \to \mathrm{CP}^+$

Indirect CPV and mixing in two-body decays

$$\text{if CP conserved} \Rightarrow y_{CP} \equiv y \quad \textit{and} \quad \Delta Y = 0$$

Experimental assumptions:

(i) small mixing (|x|, |y| << 1) proper time distributions are exponential with corresponding effective lifetimes to very good approximation.

(ii) not sensitive to direct CPV and weak phase does not depend on final state → KK and $\pi\pi$ share the same common effective lifetime. [PRD 80, 076008 (2009)]

Belle time-integrated $D^0 \rightarrow K^+\pi^- \pi^+ \pi^-$

New result, 791 fb-1

arXiv:1307.5935

$D^0 \rightarrow K^+\pi^- \pi^+ \pi^-$ "wrong-sign" decays are due to both a doubly-Cabibbo suppressed amplitude and mixing:

Normalize to Cabibbo-favored $D^0 \rightarrow K^-\pi^+ \pi^+ \pi^-$ decays

$$R_{\rm WS} = \frac{\Gamma(D^0 \rightarrow K^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \rightarrow K^-\pi^+\pi^-\pi^+)} = R_D + \alpha y' \sqrt{R_D} + \frac{1}{2}(x^2 + y^2)$$

$$(y' = y\cos\delta - x\sin\delta)$$

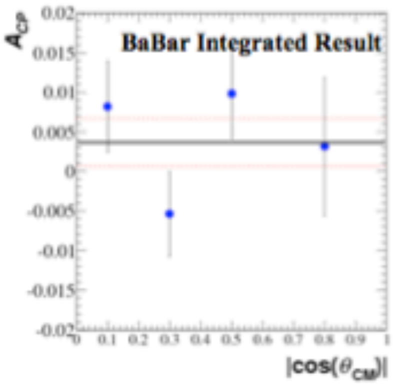
$$\Rightarrow \quad R_{\rm WS} = (0.324 \pm 0.008 \pm 0.007)\%$$
$$B_{D^0 \rightarrow K^+\pi^-\pi^+\pi^-} = (2.61 \pm 0.06\,^{+0.09}_{-0.08}) \times 10^{-4}$$

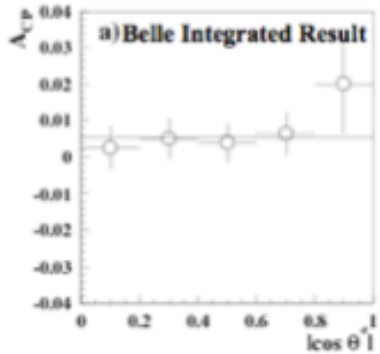
Take coherence factor α and strong phase δ from CLEOc:

$$R_D = (0.327\,^{+0.019}_{-0.016})\%$$

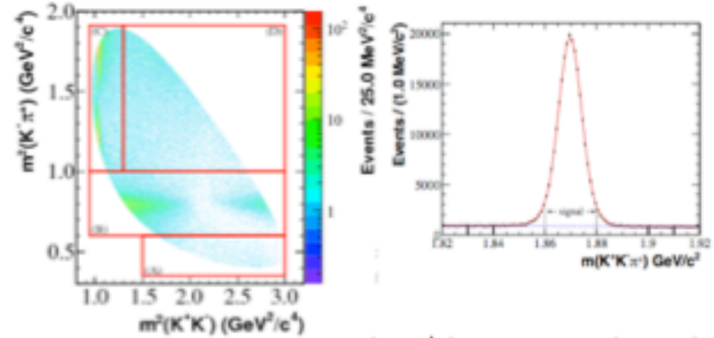
Direct CPV search in Dalitz plot decays

Asymmetry in bins of production angle. [BaBar/Belle]





Localized CP Asymmetry [BaBar/Belle]

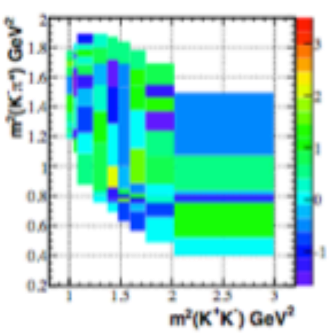


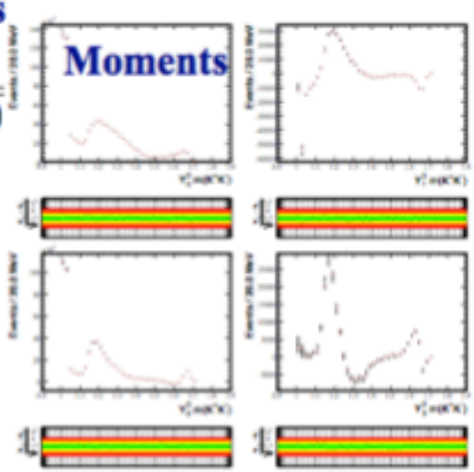
$$A_{CP} = \frac{N(D^+) - RN(D^-)}{N(D^+) + RN(D^-)}$$

Model Independent Techniques [BaBar]

Normalized Residuals

$$\Delta \equiv \frac{n(D^+) - Rn(D^-)}{\sqrt{\sigma^2(D^+) + R^2\sigma^2(D^-)}}$$





Dalitz Plot Analysis [BaBar]