Charm Mixing and *CP* Violation

A. C. dos Reis, on behalf of the LHCb collaboration,

including results from Belle.

What is new since FPCP 2013

$D^0 - \overline{D}^0$ oscillations and *CP*V:

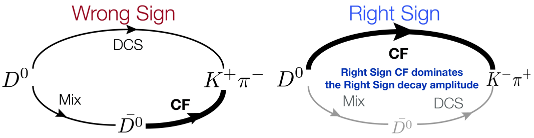
- $D^0 - \overline{D}^0$ mixing and *CP*Vsearch with WS $D^0 \to K\pi$ (Belle, LHCb, 3 fb^{-1})
- A_Γ from $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ (LHCb 1 fb^{-1})
- Mixing from time-dependent $D^0 \to K^0_S\pi^+\pi^-$ Dalitz plot analysis (Belle)

Searches for *CP* violation in time-integrated rates:

- ΔA_{CP} from $\overline{B} \to D^0\mu^- X$ (LHCb, 3 fb^{-1})
- $D^0 \to \pi^-\pi^+\pi^-\pi^+ / K^+K^-\pi^-\pi^+$ (LHCb, 1 fb^{-1})
- $D^+ \to \pi^-\pi^+\pi^+$ (LHCb, 1 fb^{-1})
- $D^+_{(s)} \to K^0_S h^+$ (LHCb, 3 fb^{-1}, preliminary)

$D^0 - \overline{D}^0$ oscillations and CPV — $D^0 \to K\pi$

Measurements of time-dependent ratio of WS-to-RS decay rates:



Assuming $|x|, |y| \ll 1$ and no CP violation, and defining

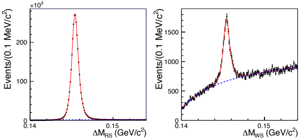
$$\frac{A_{K^+\pi^-}}{\overline{A}_{K^+\pi^-}} = -\sqrt{R_D}\, e^{-i\delta_{K\pi}}, \qquad y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}, \qquad x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi},$$

($\delta_{K\pi}$ = strong phase between $\overline{A}_{K^+\pi^-}$ and $A_{K^+\pi^-}$)

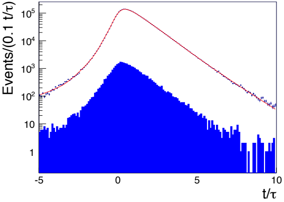
the time-dependent ratio of WS $D^0 \to K^+\pi^-$ and RS $\overline{D^0} \to K^+\pi^-$ decay is

$$R(t) = \frac{\Gamma(D^0(t) \to K^+\pi^-)}{\Gamma(\overline{D}^0(t) \to K^+\pi^-)} \approx \underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\, y'\, \Gamma t}_{\text{interf.}} + \underbrace{\frac{x'^2 + y'^2}{4} (\Gamma t)^2}_{\text{mixing}}.$$

$D^0 - \overline{D}^0$ oscillations from Belle



11.5×10^3 WS and
2.98×10^6 RS decays.



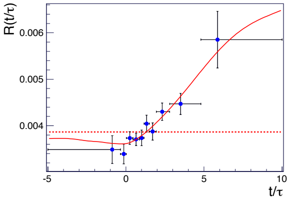
Flavour tag with $D^{*+} \to D^0\pi_s^+$

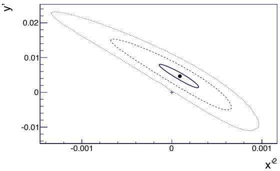
CP conservation assumed.

Small DCS contribution to the RS yield neglected.

Proper time resolution is comparable to the D^0 lifetime.

Resolution function (sum of 4 Gaussians) included in the PDF, with free parameters.





Data divided into 10 bins of D^0 decay proper time.

$R_D(\times 10^{-3}) = 3.53 \pm 0.13$

$y'(\times 10^{-3}) = 4.6 \pm 3.4$

$x'^2(\times 10^{-3}) = 0.09 \pm 0.22$

No-mixing hypothesis excluded at 5.1σ

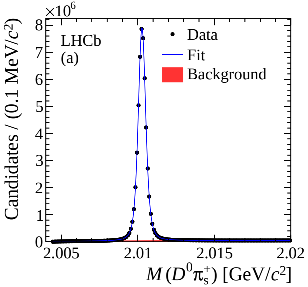
Belle - PRL **112** (2014) 111801

$D^0 - \overline{D}^0$ oscillations and CPV search – LHCb (3 fb^{-1})

Allowing for CPV: simultaneous fit to $R^+(t)$ and $R^-(t)$, for initially produced D^0 and $\overline{D}^0$, producing two sets of parameters: (R_D^+, x'^{2+}, y'^+) and (R_D^-, x'^{2-}, y'^-).

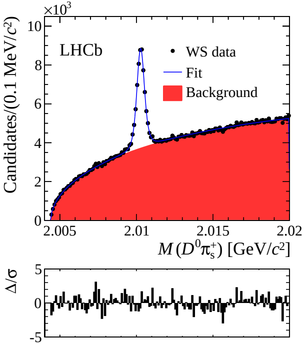
$R_D^+ \neq R_D^-$: direct CPV; $(x'^{2+}, y'^+) \neq (x'^{2-}, y'^-)$: mostly indirect CPV.

$$x'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (x' \cos\phi \pm y' \sin\phi) \qquad y'^{\pm} = \left|\frac{q}{p}\right|^{\pm 1} (y' \cos\phi \mp x' \sin\phi),$$



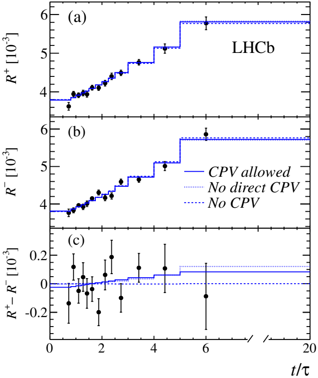
20x more data than Belle.

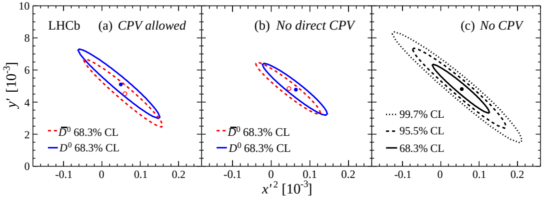
Decay time resolution: $\sigma_t \sim 0.1\tau_D$



PRL **111** (2013) 251801

$D^0 - \overline{D}^0$ oscillations and *CPV* search – LHCb (3 fb^{-1})





Fit type	Parameter	Fit result
CPV	$R_D^+ (\times 10^{-3})$	$3.545 \pm 0.082 \pm 0.048$
	$y'^+ (\times 10^{-3})$	$5.1 \pm 1.2 \pm 0.7$
	$x'^{2+} (\times 10^{-5})$	$4.9 \pm 6.0 \pm 3.6$
	$R_D^- (\times 10^{-3})$	$3.591 \pm 0.081 \pm 0.048$
	$y'^- (\times 10^{-3})$	$4.5 \pm 1.2 \pm 0.7$
	$x'^{2-} (\times 10^{-5})$	$6.0 \pm 5.8 \pm 3.6$
no *CPV*	$R_D (\times 10^{-3})$	$3.545 \pm 0.058 \pm 0.033$
	$y' (\times 10^{-3})$	$4.8 \pm 0.8 \pm 0.5$
	$x'^2 (\times 10^{-5})$	$5.5 \pm 4.2 \pm 2.6$

Direct *CPV*: nonzero intercept.
$A_D = (-0.7 \pm 1.9)\%$

Slope of $R^+ - R^-$: 5% of R^+, R^- slopes and consistent with zero.

No indication of direct or indirect *CPV*.

PRL **111** (2013) 251801

Indirect CPV search in D^0 decays to CP eigenstates $(K^+K^-, \pi^+\pi^-)$

The time-dependent rates of decays to CP eingestates, assuming no direct CPV, are approximated by single exponentials, $\Gamma(D^0(t) \to f) \propto \exp[-\hat{\Gamma}_{D^0 \to f}\, t]$:

$$\hat{\Gamma}_{D^0 \to h^+h^-} = \Gamma_D \left[1 + \left|\frac{q}{p}\right| (y \cos\phi - x \sin\phi)\right],$$

$$\hat{\Gamma}_{\overline{D}^0 \to h^+h^-} = \Gamma_D \left[1 + \left|\frac{p}{q}\right| (y \cos\phi + x \sin\phi)\right],$$

$$\hat{\Gamma}_{D^0 \to K^-\pi^+} = \hat{\Gamma}_{\overline{D}^0 \to K^+\pi^-} = \Gamma_D, \qquad \phi = \arg(\lambda_{hh}) = \arg(q/p) \quad (\phi_{hh} = 0).$$

Any difference between $\hat{\Gamma}_{D^0 \to h^+h^-}$ and $\hat{\Gamma}_{D^0 \to K\pi}$ $\to$ mixing.

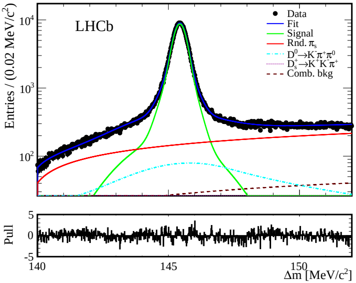
$$y_{CP} = \frac{\hat{\Gamma}_{D^0 \to h^+h^-} + \hat{\Gamma}_{\overline{D}^0 \to h^+h^-}}{2\Gamma_D} - 1.$$

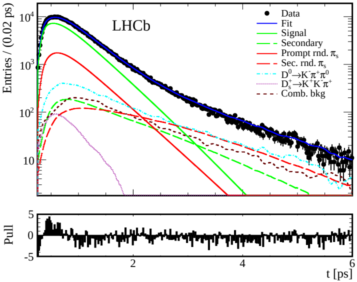
Any difference between $\hat{\Gamma}_{D^0 \to h^+h^-}$ and $\hat{\Gamma}_{\overline{D}^0 \to h^+h^-}$ $\to$ indirect CPV.

$$A_\Gamma \equiv \frac{\hat{\Gamma}(D^0 \to h^+h^-) - \hat{\Gamma}(\overline{D}^0 \to h^+h^-)}{\hat{\Gamma}(D^0 \to h^-h^+) + \hat{\Gamma}(\overline{D}^0 \to h^+h^-)} \simeq \left(\frac{1}{2} A_m y \cos\phi - x \sin\phi\right),$$

$$A_m = \frac{|q/p|^2 - |p/q|^{-2}}{|q/p|^2 + |p/q|^{-2}}.$$

$\overline{D}^0 \to K^+K^-$: Δm and proper time fit.





3.11×10^6 $D^0 \to K^+K^-$
1.06×10^6 $D^0 \to \pi^+\pi^-$

Measurement of $A_\Gamma(K^+K^-)$ and $A_\Gamma(\pi^+\pi^-)$ using $D^{*+} \to D^0\pi^+$.

The nominal A_Γ measurement: effective lifetimes extracted from a simultaneous two-stage fit to eight subsamples (mag. polarity x run period x D flavour).

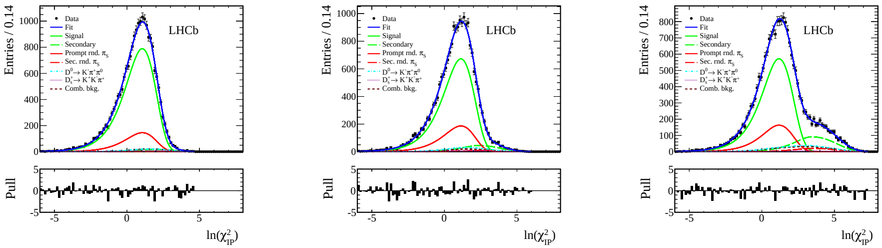
Cross-check: divide data into equally populated bins of decay time t, compute the ratio of $\overline{D}^0$ to D^0 in each bin, then extract A_Γ from a χ^2 fit it to

$$R(t) \approx \frac{N_{\overline{D}^0}}{N_D^0}\left(1 + \frac{2A_\Gamma}{\tau_{KK}}t\right)\frac{1 - e^{\Delta t/\tau_{\overline{D}^0}}}{1 - e^{\Delta t/\tau_{D^0}}}$$

PRL **112** (2014) 041801

Background from secondary D controled using impact parameter wrt primary vertex.

0.25 – 0.37 ps 0.74 – 0.78 ps 1.55 – 1.80 ps



LHCb

$$A_\Gamma(KK) = (-0.035 \pm 0.062 \pm 0.012)\%$$

$$A_\Gamma(\pi\pi) = (+0.033 \pm 0.106 \pm 0.014)\%$$

LHCb - PRL **112**, 041801 (2014).

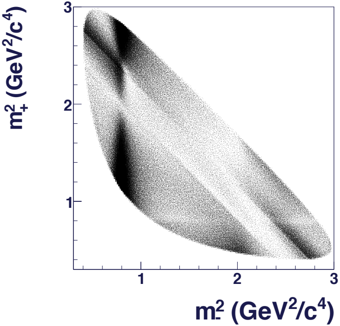
BaBar and Belle

$$A_\Gamma(KK) = (-0.03 \pm 0.20 \pm 0.08)\%$$

$$\Delta Y = (+0.09 \pm 0.26 \pm 0.06)\%$$

Belle - arXiv:1212.3479,
BaBar - PRD **87**, 012004.

No indication of indirect *CPV*.



Belle - arXiv:1404.2412

Mixing parameters x, y can be directly accessed in a time-dependent Dalitz plot analysis of $D^0 \to K^0_S\pi^+\pi^-$.

3 types of contributions: $K^{*-}\pi^+$ (CF); $K^{*+}\pi^-$ (DCS); $K^0_S\rho^0$ ("CP eigenstate"), eliminating the dependence on the relative strong phase between the CF and DCS decays.

Time-dependent decay amplitudes:

$$\mathcal{M}(s_+, s_-, t) = A(s_+, s_-)g_+(t) + \frac{q}{p}\overline{A}(s_+, s_-)g_-(t),$$

$$\overline{\mathcal{M}}(s_+, s_-, t) = \overline{A}(s_+, s_-)g_+(t) + \frac{p}{q}A(s_+, s_-)g_-(t).$$

$$A(s_+, s_-) = \sum a_k e^{i\delta_k} A_k(s_+, s_-), \qquad s_\pm = m^2(K^0_S\pi^\pm)$$

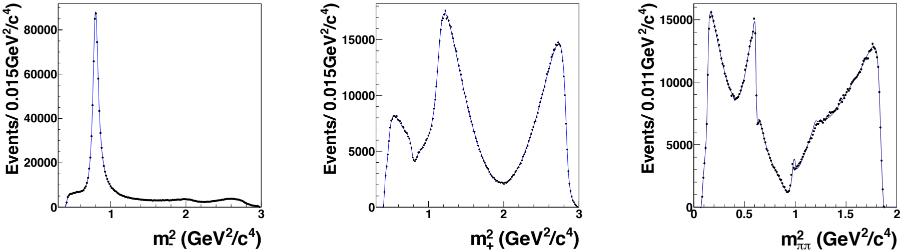
Assuming no direct CPV, $\overline{A}(s_+, s_-) = A(s_-, s_+)$.

Dependence on (x, y) appears when the decay amplitude $\mathcal{M}(s_+, s_-, t)$ is squared:

$$d\Gamma(s_+, s_-, t) = \frac{1}{32(2\pi)^3 M_D}|\mathcal{M}(s_+, s_-, t)|^2 ds_+ ds_-.$$

Decay model: 14 resonances, K-matrix for $\pi\pi$ S-wave, effective range (LASS) for $K^0_S\pi$ S-wave (40 free parameters), but only an approximate solution found.

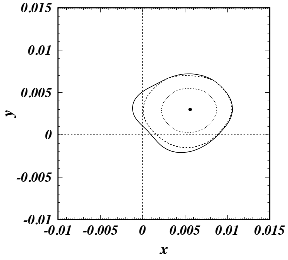
Mixing from time-dependent $D^0 \to K_S^0 \pi^+ \pi^-$ — Belle



Belle - arXiv:1404.2412

$\chi^2/\text{ndof} = 1.207 \;\to\; CL = 10^{-60}$!

no *CP*V	
$x(\%)$	$0.56 \pm 0.19 \,^{+0.07}_{-0.13}$
$y(\%)$	$0.30 \pm 0.15 \,^{+0.05}_{-0.08}$
*CP*V allowed	
$x(\%)$	$0.56 \pm 0.19^{+0.07}_{-0.11}$
$y(\%)$	$0.30 \pm 0.15^{+0.05}_{-0.09}$
$\lvert q/p \rvert$	$0.90^{+0.16}_{-0.15}\,^{+0.08}_{-0.07}$
$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3 \,^{+3}_{-4}$



Mixing significance at 2.5σ.

No indication of mixing-induced *CP*V

Time-integrated CP asymmetry in D^0 decays to a CP eigenstate f $(f = K\overline{K}, \pi\pi)$:

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} \simeq a_{CP}^{\rm dir}(f) + \frac{\langle t \rangle}{\tau} a_{CP}^{\rm ind},$$

$a_{CP}^{\rm dir}(f) \Rightarrow |\,\mathcal{A}(D^0 \to f)\,| \neq |\,\mathcal{A}(\overline{D}^0 \to f)\,|$;

$a_{CP}^{\rm ind} \Rightarrow$ CPV in mixing and/or in interference between mixing and decay: universal, to a good approximation. Depends on the experimental decay-time acceptance.

In the SM, $a_{CP}^{\rm dir}(K^-K^+)$ and $a_{CP}^{\rm dir}(\pi^-\pi^+)$ are expected to have opposite signs:

$$\begin{aligned}\Delta A_{CP} &\equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) \\ &= a_{CP}^{\rm dir}(K^-K^+) - a_{CP}^{\rm dir}(\pi^-\pi^+) + \frac{\Delta\langle t \rangle}{\tau} a_{CP}^{\rm ind} \\ &\simeq \Delta a_{CP}^{\rm dir} - \frac{\Delta\langle t \rangle}{\tau} A_\Gamma .\end{aligned}$$

ΔA_{CP}: cancellation of systematics and production/detection asymmetries; higher sensitivity to CPV.

ΔA_{CP} from $\overline{B} \to D^0\mu^- X$ decays – (LHCb, 3 fb^{-1})

- D^0 flavour is tagged by the muon sign in $\overline{B} \to D^0\mu^- X$.
- Statistically independent from the prompt $D^* \to D^0\pi^+$ sample.

$$A_{\rm raw} = \frac{\Gamma(D^0 \to f)\varepsilon(\mu^-)\mathcal{P}(D^0) - \Gamma(\overline{D}^0 \to f)\varepsilon(\mu^+)\mathcal{P}(\overline{D}^0)}{\Gamma(D^0 \to f)\varepsilon(\mu^-)\mathcal{P}(D^0) + \Gamma(\overline{D}^0 \to f)\varepsilon(\mu^+)\mathcal{P}(\overline{D}^0)} \simeq A^f_{CP} + A^\mu_D + A^B_{\mathcal{P}}$$

$$\Delta A_{CP} = A_{\rm raw}(K^-K^+) - A_{\rm raw}(\pi^-\pi^+) \simeq A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$

Using the CF decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$ and $D^+ \to K^0_S\pi^+$, A^μ_D and $A^B_{\mathcal{P}}$ are determined, allowing the measurement of the invididual asymmetries.

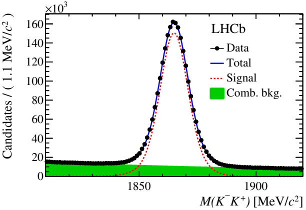
$$A_{\rm raw}(K^-\pi^+) = A^\mu_D - A^B_{\mathcal{P}} - A_D(K^-\pi^+)$$

$$A_{CP}(K^-K^+) = A_{\rm raw}(K^-K^+) - A_{\rm raw}(K^-\pi^+) - A_D(K^-\pi^+)$$

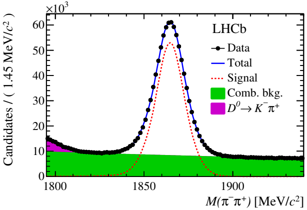
Very small difference in the average decay time between K^-K^+ and $\pi^-\pi^+$:

$$\frac{\Delta\langle t\rangle}{\tau} = 0.014 \pm 0.004 \quad \Longrightarrow \quad \Delta A_{CP} \simeq \Delta a^{\rm dir}_{CP}$$

Raw asymmetries determined from a simultaneous fit of eight data subsets
(2011 x 2012, MagUp x MagDown, D^0 x $\overline{D}^0$)



2.14×10^6 $D^0 \to K^- K^+$



7.67×10^5 $D^0 \to \pi^- \pi^+$

Detection asymmetries studied as a function of particle momentum.

Small differences in the kinematics of the final states accounted by a weighting procedure.

Statistics comparable to prompt analysis (1 fb^{-1}).

Systematic uncertainties (%)

source of uncertainties	ΔA_{CP}	$A_{CP}(KK)$
Production asymmetry	0.03	0.03
Detection asymmetry	0.02	0.06
Background from real D^0	0.03	0.03
Background from fake D^0	0.07	0.07
Total	0.08	0.10

Asymmetry diluted by wrong flavor tag:

$$\Delta A_{CP} = (1 - 2\omega)\,[A_{\rm raw}(KK) - A_{\rm raw}(\pi\pi)]$$

$$A_{CP}(KK) = (1 - 2\omega)\,[A_{\rm raw}(KK) - A_{\rm raw}(K\pi)] + (1 - 2R)A_D(K\pi)$$

$$\Delta A_{CP} \;\to\; \omega = (0.988 \pm 0.006)\%,$$

$$A_{CP}(KK) \;\to\; \omega = (0.791 \pm 0.006)\%.$$

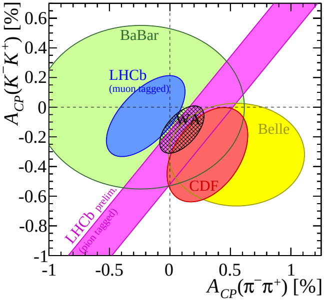
arXiv:1405.2797

This measurement (arXiv:1405.2797):

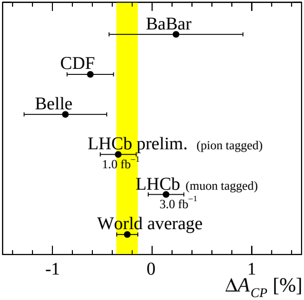
$$A_{CP}(KK) = (-0.20 \pm 0.19 \pm 0.10)\%, \qquad A_{CP}(\pi\pi) = (-0.06 \pm 0.15 \pm 0.10)\%,$$

$$\Delta A_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%.$$

Overview of *CP* measurements:
68% CL contours



New world average
(neglecting indirect *CP*V).



New world averages:

$$A_{CP}(KK) = (-0.15 \pm 0.11)\%, \qquad A_{CP}(\pi\pi) = (+0.10 \pm 0.12)\%,$$

$$\Delta A_{CP} = (-0.25 \pm 0.11)\%.$$

HFAG averages, as in May 28, 2014

April 28, 2013:

$$\langle x \rangle = (0.49^{+0.17}_{-0.18})\%$$

$$\langle y \rangle = (0.74 \pm -0.09)\%$$

$$|q/p| = 0.91^{+0.11}_{-0.09}$$

$$\phi(^\circ) = -29.6^{+8.9}_{-7.5}$$

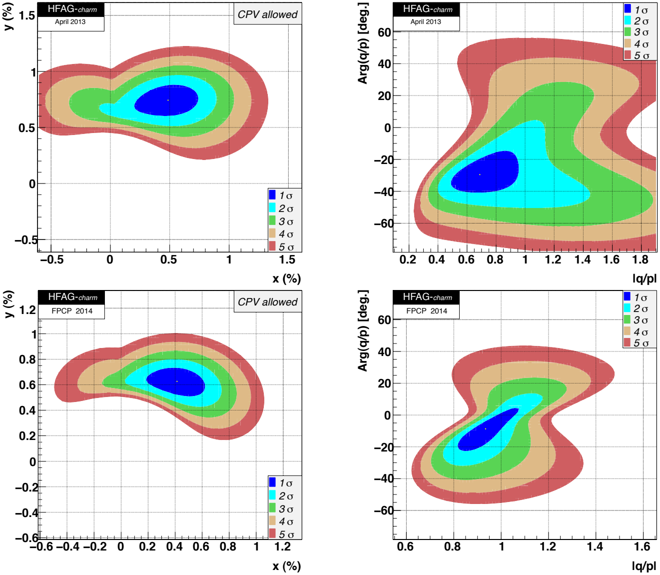
May 28, 2014:

$$\langle x \rangle = (0.41^{+0.14}_{-0.15})\%$$

$$\langle y \rangle = (0.63^{+0.08}_{-0.07})\%$$

$$|q/p| = 0.93^{+0.08}_{-0.09}$$

$$\phi(^\circ) = 8.7^{+9.1}_{-8.8}$$



to appear soon at http://www.slac.stanford.edu/xorg/hfag/charm

In the SM, direct *CPV* in DCS decays is not possible. A relation between the four mixing parameters sets stringent bounds on the values of ϕ and $|q/p|$:

$$\tan\phi = \frac{x}{y}\left[\frac{1-|q/p|^2}{1+|q/p|^2}\right]$$

Chiuchini *et al.*, PLB 655, 162
Kagan and Sokoloff, PRD 80, 076008

$$|q/p| = 1.007 \pm 0.014, \quad \phi(^\circ) = -0.03 \pm 0.10$$

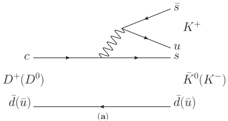
HFAG also fits for the underlying theory parameters

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma_D}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma_D}, \quad \phi_{12} \equiv \arg\left(\frac{M_{12}}{\Gamma_{12}}\right):$$

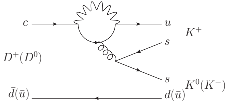
$$x_{12} = (0.43 \pm 0.14)\%, \quad y_{12} = (0.60 \pm 0.07)\% \quad \phi_{12} = (0.9 \pm 1.6)^\circ$$

Direct CPV searches in charged D mesons are a natural complement to the A_{CP} measurements with neutral D.

$D^+ \to K^0_S K^+$ and $D^+_{(s)} \to K^0_S \pi^+$ have similar amplitudes than $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$:



(a)

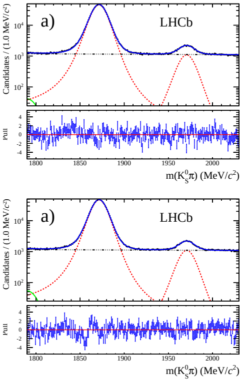


(b)

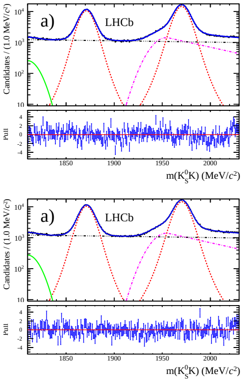
3-body decays offer unique opportunities:

- local effects may be larger than phase-space integrated ones (e.g. large asymmetries observed in charmless $B^+ \to h_1^- h_2^+ h_3^+$, see Bediaga's talk);
- local *CP* asymmetries may change sign across the phase space;
- the pattern of local *CP* asymmetries brings additional info on the underlying dynamics (other than a single number).
- the main strategy is to perform a direct, model-independent comparison between $D^+_{(s)}$ and $D^-_{(s)}$ Dalitz plots.

$D^+_{(s)} \to K^0_S \pi^+$



$D^+_{(s)} \to K^0_S K^+$



PRELIMINARY

$1.0 \times 10^6 \; D^+ \to K^0_S K^+$,
$1.2 \times 10^5 \; D^+_s \to K^0_S \pi^+$.

Three observables,

$\mathcal{A}_{CP}^{D^+ \to K^0_S K^+}, \; \mathcal{A}_{CP}^{D^+_s \to K^0_S \pi^+}, \; \mathcal{A}_{CP}^{DD}$.

four asymmetry measurements:

$\mathcal{A}_{\rm meas}^{D^+_{(s)} \to K^0_S h^+}, \quad h = K, \pi$ (CF),

and $\mathcal{A}_{\rm meas}^{D^+_s \to \phi\pi^+}$ (control channel).

$$\mathcal{A}_{\rm meas}^{D^+_{(s)} \to K^0_S h^+} \approx \mathcal{A}_{CP}^{D^+ \to K^0_S h^+} + \mathcal{A}_{\rm prod}^{D^+_{(s)}} + \mathcal{A}_{\rm det}^{h^+} + \mathcal{A}_{K^0},$$

$$\mathcal{A}_{CP}^{D^+ \to K^0_S K^+} \approx \left[\mathcal{A}_{\rm meas}^{D^+ \to K^0_S K^+} - \mathcal{A}_{\rm meas}^{D^+_s \to K^0_S K^+}\right] - \left[\mathcal{A}_{\rm meas}^{D^+ \to K^0_S \pi^+} - \mathcal{A}_{\rm meas}^{D^+_s \to \phi\pi^+}\right] - \mathcal{A}_{K^0},$$

$$\mathcal{A}_{CP}^{D^+_s \to K^0_S \pi^+} \approx \mathcal{A}_{\rm meas}^{D^+_s \to K^0_S \pi^+} - \mathcal{A}_{\rm meas}^{D^+_s \to \phi\pi^+} - \mathcal{A}_{K^0}.$$

LHCb-PAPER-2014-18, in preparation

Search for direct CPV in $D^+_{(s)} \to K^0_S h^+$ — (LHCb, 3 fb^{-1})

$D^+_{(s)}$ production and hadron detection asymmetries cancel in the observable

$$A_{CP}^{\mathcal{DD}} = [\mathcal{A}_{\rm meas}^{D_s^+ \to K^0_S \pi^+} - \mathcal{A}_{\rm meas}^{D_s^+ \to K^0_S K^+}] - [\mathcal{A}_{\rm meas}^{D^+ \to K^0_S \pi^+} - \mathcal{A}_{\rm meas}^{D^+ \to K^0_S K^+}] - \mathcal{A}_{K^0}$$

$\mathcal{A}_{K^0}$ is the combined effect of $K^0-\overline{K}^0$ mixing, CPV and $\sigma(K^0N) \neq \sigma(\overline{K}^0N)$.

Only K^0_S with short decay time are used: small contribution from CPV and $K^0-\overline{K}^0$ mixing. $\mathcal{A}_{K^0}$ dominated by $\sigma(K^0N) \neq \sigma(\overline{K}^0N)$.

Weighting is used to equalise small differences in kinematic distributions.

Fiducial cuts remove small portions of phase space with large raw asymmetries.

Preliminary results:

$$A_{CP}^{D^+ \to K^0_S K^+} = (+0.03 \pm 0.17 \pm 0.14)\%$$
$$A_{CP}^{D_s^+ \to K^0_S \pi^+} = (+0.38 \pm 0.46 \pm 0.17)\%$$
$$A_{CP}^{\mathcal{DD}} = (+0.41 \pm 0.49 \pm 0.26)\%$$

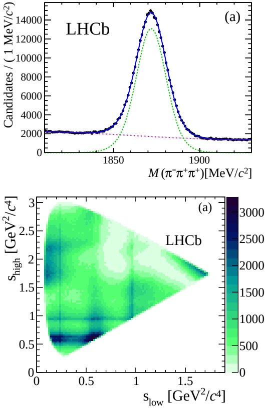
LHCb-PAPER-2014-18, in preparation

Direct, model-independent comparison between D^+ and D^- Dalitz plots.

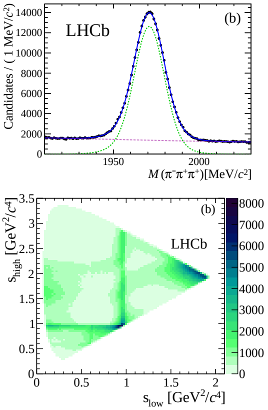
Bined and unbinned analysis, using the CF $D_s^+ \to \pi^-\pi^+\pi^+$ as control channel.

Unbinned analysis use the k-Nearest neighbour technique.

2.68×10^6 $D^+ \to \pi^-\pi^+\pi^+$



2.70×10^6 $D_s^+ \to \pi^-\pi^+\pi^+$



Binned analysis:

- the combined $D^\pm$ Dalitz plot is divided into bins;
- in each bin compute

$$S_{CP}^i = \frac{N_i(D^+) - \alpha N_i(D^-)}{\sqrt{\alpha[\sigma_i^2(D^+) + \sigma_2^i(D^-)]}},$$

$$\alpha = \frac{\sum_i N_i(D^+)}{\sum_i N_i(D^-)}$$

- from the S_{CP}^i values extract a *p*-value for the no *CPV* hypothesis,

$$\chi^2 = \sum_i (S_{CP}^i)^2$$

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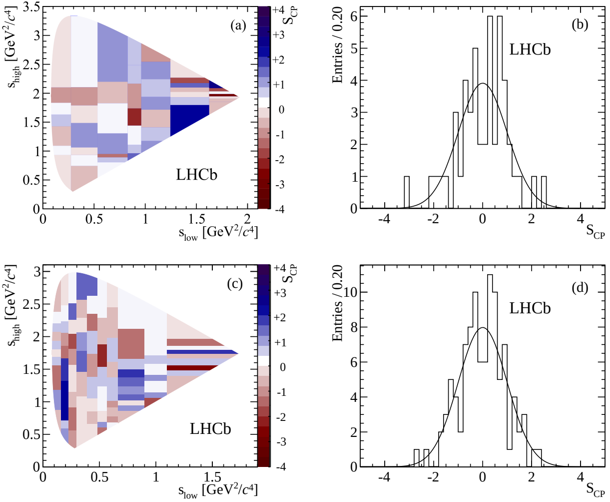
Search for direct *CPV* in $D^+ \to \pi^-\pi^+\pi^+$ — (LHCb, 1 fb^{-1})



In the absence of *CPV*, S^i_{CP} distribution is a Gaussian ($\mu = 0, \sigma = 1$).

Different binning schemes (adaptative/uniform) tested.

bins	χ^2	p-value (%)
20	14.0	78.1
30	28.2	50.6
40	28.5	89.2
50	26.7	99.5
100	89.1	75.1

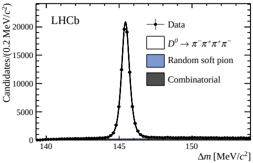
Consistent results obtained with the unbinned analysis.

No evidence for *CPV*.

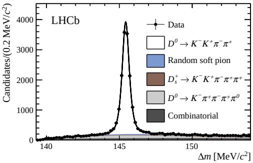
PLB **718** (2014) 585.

Search for direct CPV in $D^0 \to K^-K^+\pi^-\pi^+ / \pi^-\pi^+\pi^-\pi^+$ — (LHCb, 1 fb^{-1})

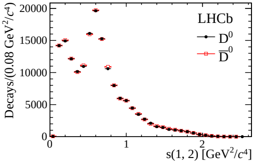
3.3×10^5 $D^0 \to \pi^-\pi^+\pi^-\pi^+$



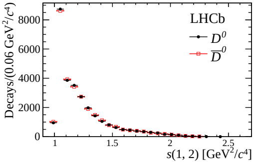
5.7×10^4 $D^0 \to K^-K^+\pi^-\pi^+$



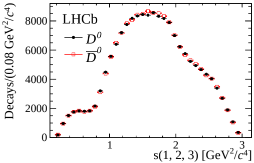
$m^2(\pi^-\pi^+)$



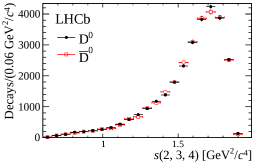
$m^2(K^-K^+)$



$m^2(\pi^-\pi^+\pi^+)$



$m^2(K^+\pi^+\pi^-)$



PLB **726** (2013) 623.

Same method and strategy as in $D^+ \to \pi^-\pi^+\pi^+$.

Particle-antiparticle asymmetry studied with the control channel $D^0 \to K^-\pi^+\pi^-\pi^+$.

Different partitions of the 5-dimensional phase space.

$D^0 \to K^-K^+\pi^-\pi^+$

bins	χ^2	p-value (%)
16	22.7	9.1
32	28.2	9.1
64	75.7	13.1

$D^0 \to \pi^-\pi^+\pi^-\pi^+$

bins	χ^2	p-value (%)
64	68.8	28.8
128	130.0	41.0
256	246.7	61.7

No indication of CPV.

Charm mixing is well established: a great experimental achievement!

$x \approx y \sim 0.5\%$: How should we interpret it? Is it SM driven?
Could new physics be hidden here?

No evidence for *CP*V in charm: a remaining experimental challenge!

Experimental sensitivity now at $\mathcal{O}(10^{-3})$ and improving.
Interpretation of a *CP*V signal would not be easy.

Charm mixing and *CP*V now in the precision era:
A lively field, plenty of opportunities

The prize worths the effort!

Backup slides

Charm mixing and CPV: formalism and notation

Mass eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$, eigenvalues: $\lambda_{1,2} = m_{1,2} - i\Gamma_{1,2}/2$

The dimensionless parameters governing mixing:

$$x \equiv \frac{m_1 - m_2}{\Gamma} = \frac{\Delta m}{\Gamma}, \qquad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}.$$

Amplitudes for D decay to a final state f:

$$A_f = A(D \to f), \quad \overline{A}_{\bar{f}} = A(\overline{D} \to \bar{f}), \qquad A_{\bar{f}} = A(D \to \bar{f}), \quad \overline{A}_f = A(\overline{D} \to f).$$

The master equations for time-dependent decay rates:

$$\Gamma[D^0(t) \to f] = \frac{1}{2}\, e^{-\tau}\, |A_f|^2 \,[\, (1 + |\lambda_f|^2) \cosh(y\tau) + (1 - |\lambda_f|^2) \cos(x\tau) + 2\mathrm{Re}(\lambda_f) \sinh(y\tau) - 2\mathrm{Im}(\lambda_f) \sin(x\tau)\,],$$

$$\Gamma[\overline{D}^0(t) \to f] = \frac{1}{2}\, e^{-\tau}\, |\bar{A}_f|^2 \,[\, (1 + |\lambda_f^{-1}|^2) \cosh(y\tau) + (1 - |\lambda_f^{-1}|^2) \cos(x\tau) + 2\mathrm{Re}(\lambda_f^{-1}) \sinh(y\tau) - 2\mathrm{Im}(\lambda_f^{-1}) \sin(x\tau)\,]$$