Charm Mixing and CP Violation

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Including results from CDF, Belle and BaBar

FPCP 2013

20/5/13

CP violation in charm is usually seen as a portal
to NP due to the smallness of SM "background".

SM predictions: very difficult due to long-distance processes.
SM CP asymmetries would be as large as $\mathcal{O}(10^{-2})$.

Most promising: searches for direct CPV in hadronic decays.

The quest for CPV in charm continues:

asymmetry in rates of 2- and quasi-2-body CS decays;
asymmetry in regions of phase space of multi-body CS decays;
in a longer term, CP asymmetries in DCS decays.

CPV in charm is an important missing piece of the SM.

Outline

Searches for CP violation in time-integrated rates:

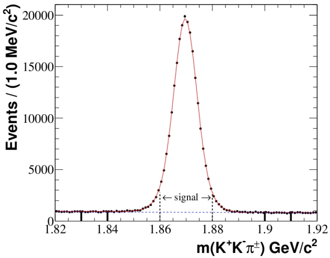
- $D^+ \to K^- K^+ \pi^+$ (BaBar)
- $D^+ \to \phi\pi^+$, $D^+_{(s)} \to K^0_s h^+$ (LHCb, BaBar, Belle)
- $D^0 \to K^+ K^-$ and $D^0 \to \pi^+\pi^-$ (LHCb, Belle, CDF)

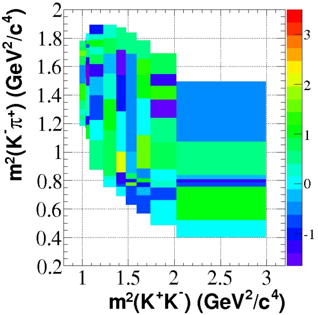
$D^0 - \overline{D}^0$ oscillations:

- Observation of $D^0 - \overline{D}^0$ oscillations with WS $D^0 \to K\pi$ (LHCb)

Search for direct CPV in $D^+ \to K^- K^+ \pi^+$ – BaBar

2.23×10^5 candidates (476 fb^{-1})





A comprehensive study using three different methods:

Asymmetry in total rate:

$$A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$$

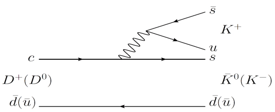
Model-independent search over the Dalitz plot:

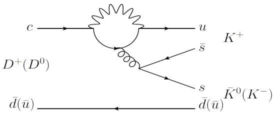
p-value = 72% for no CPV.

Model-dependent search (simultaneous fit to the D^+ and D^- Dalitz plots):

no indication of CPV in relative phases and magnitudes.

PRD 87,052010 (2013)





Similar diagrams for $D^+ \to K^0_s K^+$, $D^0 \to K^- K^+$; penguin amplitude may be enhanced by new particles.

JHEP 02 (2013) 098, PRD 87,052012 (2013)

$D^+ \to K^0_s \pi^+$: direct CPV is allowed from interference between CF and DCS amplitudes, but expected to be negligible in SM.

$D^+_s \to K^0_s \pi^+$: CS decay, similar diagrams as $D^+ \to K^0_s K^+$.

The *CP* asymmetry in $D^+_{(s)} \to K^0_s h^+$ includes the effect of $K^0 - \overline{K}^0$ mixing:

$$A_{CP}^{D^+_{(s)} \to K^0_s h^+} \equiv \frac{\Gamma(D^+_{(s)} \to \overline{K}^0 h^+)\Gamma(\overline{K}^0 \to \pi^+\pi^-) - \Gamma(D^-_{(s)} \to K^0 h^-)\Gamma(K^0 \to \pi^+\pi^-)}{\Gamma(D^+_{(s)} \to \overline{K}^0 h^+)\Gamma(\overline{K}^0 \to \pi^+\pi^-) + \Gamma(D^-_{(s)} \to K^0 h^-)\Gamma(K^0 \to \pi^+\pi^-)}$$

$$= \frac{A_{CP}^{D^+_{(s)} \to \overline{K}^0 h^+} + A_{CP}^{\overline{K}^0}}{1 + A_{CP}^{D^+ \to \overline{K}^0 h^+} A_{CP}^{\overline{K}^0}} \simeq A_{CP}^{D^+_{(s)} \to \overline{K}^0 h^+} + A_{CP}^{\overline{K}^0}$$

A_{CP} is obtained from the asymmetry in signal yields:

$$A_{\rm raw}^{D^+_{(s)}\to K^0_s h^+} = \frac{N_{D^+_{(s)}} - N_{D^-_{(s)}}}{N_{D^+_{(s)}} + N_{D^-_{(s)}}} = A_{CP}^{D^+_{(s)}\to K^0_s h^+} + A_{FB}^{D^+_{(s)}}(\cos\theta^*_D) + A_{\rm det}^{K^+} + A_{\rm det}^{K^0}.$$

Detector-induced asymmetries determined by a data-driven method:

- $A_{\rm det}^{K^+}$ determined from the CF (no CPV) $D^0 \to K^-\pi^+$ and $D^+_s \to \phi\pi^+$ decays:

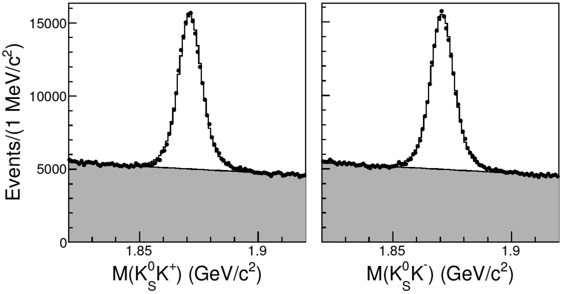
$$A_{\rm raw}^{D^0\to K^-\pi^+} = A_{FB}^{D^0} + A_{\rm det}^{K^+} + A_{\rm det}^{\pi^+}, \qquad A_{\rm raw}^{D^+_s\to\phi\pi^+} = A_{FB}^{D^+_s} + A_{\rm det}^{\pi^+},$$

$$A_{\rm det}^{K^+} = A_{\rm raw}^{D^0\to K^-\pi^+} - A_{\rm raw}^{D^+_s\to\phi\pi^+} \qquad (\text{assuming } A_{FB}^{D^0} = A_{FB}^{D^+_s})$$

- forward-backward asymmetry A_{FB} is an odd function of $\cos\theta^*_D$,

$$A_{FB}^{D^+_{(s)}} = \frac{1}{2}\left[A_{\rm raw}^{K^0_s h^+}(+\cos\theta^*_D) - A_{\rm raw}^{K^0_s h^+}(-\cos\theta^*_D)\right]$$

- the detection asymmetry due to differences in $K^0 - \overline{K}^0$ interactions with matter is estimated numerically in PRD 84, 111501 $\to A_{\rm det}^{K^0} \approx 0.1\%$



Belle - 977 fb^{-1}

276 x 10^3 $D^+ \to K^0_s K^+$

1738 x 10^3 $D^+ \to K^0_s \pi^+$

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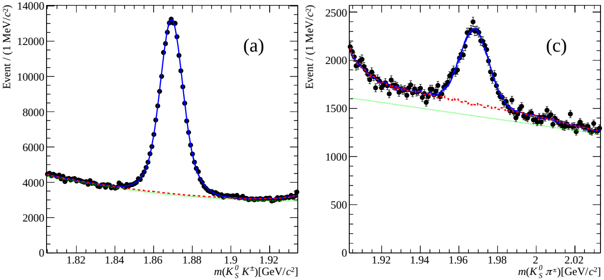


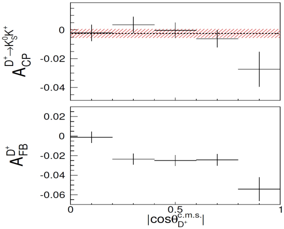
BaBar - 469 fb^{-1}

159 x 10^3 $D^+ \to K^0_s K^+$

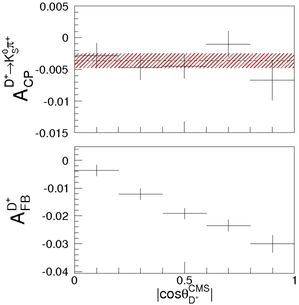
14 x 10^3 $D^+_s \to K^0_s \pi^+$

PRD 87,052012 (2013)

$D^+ \to K^0_s K^+$ (Belle)



$D^+ \to K^0_s \pi^+$ (Belle)



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

$$A_{CP}(D^+ \to \overline{K}^0 \pi^+) = (-0.024 \pm 0.094 \pm 0.067)\%$$

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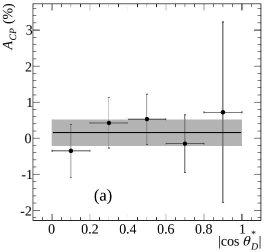
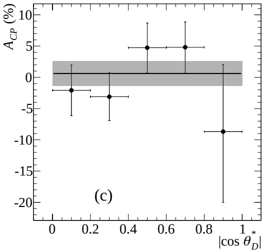
$D^+ \to K^0_s K^+$ (BaBar)



$D^+_s \to K^0_s \pi^+$ (BaBar)



$$A_{CP}(D^+ \to \overline{K}^0 K^+) = (+0.46 \pm 0.36 \pm 0.25)\%$$

$$A_{CP}(D^+_s \to \overline{K}^0 \pi^+) = (+0.3 \pm 2.0 \pm 0.3)\%$$

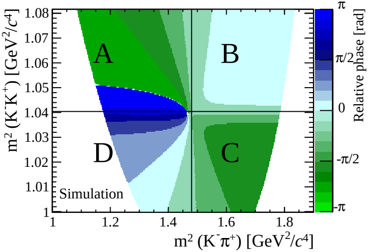
PRD 87,052012 (2013)

Look for direct CPV in the ϕ region of the $D^+ \to K^- K^+ \pi^+$ Dalitz plot:

$$A_{CP}(D^+ \to \phi\pi^+) = A_{\rm raw}(D^+ \to \phi\pi^+) - A_{\rm raw}(D^+ \to K_s^0\pi^+) + A_{CP}(K^0 - \overline{K}^0)$$

A complementary observable, sensitive to asymmetries that change sign (according to the strong phase variation along the "ϕ" band $(1.00 < m_{K^-K^+} < 1.04$ GeV/c^2):

$$A_{CP|S} = \frac{1}{2}(A^A_{\rm raw} + A^C_{\rm raw} - A^B_{\rm raw} - A^D_{\rm raw})$$



A concurrent measurement:

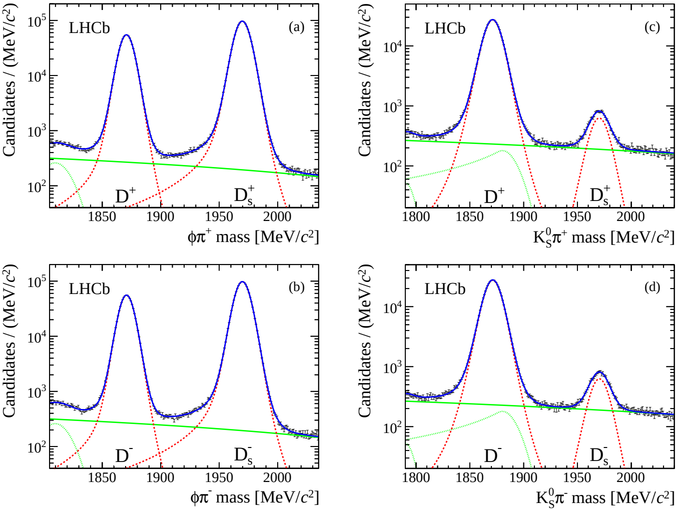
$$A_{CP}(D_s^+ \to K_s^0\pi^+) = A_{\rm raw}(D_s^+ \to K_s^0\pi^+) - A_{\rm raw}(D_s^+ \to \phi\pi^+) + A_{CP}(K^0 - \overline{K}^0)$$

$A_{CP}(K^0/\overline{K}^0)$ is the correction for CPV in the neutral kaon system,

$$A_{CP}(K^0 - \overline{K}^0) = (-0.028 \pm 0.028)\%$$

arXiv:1303.4906

Search for direct CPV in $D^+ \to \phi\pi^+$ and $D_s^+ \to K_s^0\pi^+$ – LHCb



1.6×10^6 $D^+ \to \phi\pi^+$

3.0×10^6 $D_s^+ \to \phi\pi^+$

1.1×10^6 $D^+ \to K_s^0\pi^+$,

2.5×10^4 $D_s^+ \to K_s^0\pi^+$

arXiv:1303.4906

2011 data set
(1.0 fb^{-1}@ 7 TeV)

Hardware trigger (L0) decision based on K_s^0 and ϕ daughter tracks

All tracks must have been detected in the vertex finder (VELO).

Signal yields measured in 12 bins of p_T and η for each charge and magnet polarity.

Systematic uncertainties

arXiv:1303.4906

Source	A_{CP} (D^+) [%]	A_{CP} (D_s^+) [%]	$A_{CP}\|_S$ [%]
Triggers	0.114	0.114	n/a
D_s^+ control sample size	n/a	n/a	0.169
Kaon asymmetry	0.031	0.002	0.009
Binning	0.035	0.035	n/a
Resolution	0.007	0.006	0.056
Fitting	0.033	0.033	n/a
Kaon CP violation	0.028	0.028	n/a
Fiducial effects	0.022	0.022	n/a
Backgrounds	0.008	n/a	0.007
D from B	0.003	0.015	0.003
Regeneration	0.010	0.010	n/a
Total	0.133	0.130	0.178

$$A_{CP}(D^+ \to \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%,$$
$$A_{CP}|_S(D^+ \to \phi\pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%,$$
$$A_{CP}(D_s^+ \to K_s^0\pi^+) = (+0.61 \pm 0.83 \pm 0.13)\%.$$

No evidence for CPV.

Search for time-integrated CPV in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$

Time-dependent CP asymmetry for D^0 decays to a CP eigenstate f:

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

$a_{CP}^{\rm dir}(f) \;\Rightarrow\; |<f|\mathcal{H}_{\Delta F=1}|D^0>| \;\neq\; |<f|\mathcal{H}_{\Delta F=1}|\overline{D}^0>|;$

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

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

Experiment	$\Delta A_{CP}(\%)$	reference
LHCb	-0.82$\pm$0.21 $\pm$ 0.11	PRL 108 (2012) 111602
CDF	-0.62$\pm$0.21 $\pm$ 0.10	PRL 109 (2012) 111801
Belle	-0.87$\pm$0.41 $\pm$ 0.06	arXiv:1212.1975 (prelim.)
BaBar	+0.24$\pm$0.62 $\pm$ 0.26	PRL 100 (2008) 061803

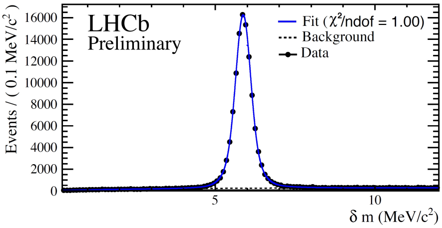
Agreement with no CP violation $\Rightarrow$ $CL = 2.0 \times 10^{-5}$

Analysis strategy: the sign of the soft π^+ from $D^{*+} \to D^0 \pi_s^+$ tags the D^0 flavor.

$$A_{\mathrm{raw}}(f) = \frac{N(D^{*+} \to D^0 \pi_s^+) - N(D^{*-} \to \overline{D}^0 \pi_s^-)}{N(D^{*+} \to D^0 \pi_s^+) + N(D^{*-} \to \overline{D}^0 \pi_s^-)}.$$

- To first order, $A_{\mathrm{raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s^+) + A_P(D^{*+})$.
- $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$, and $A_D(\pi_s^+)$, $A_P(D^{*+})$ independent of f:

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



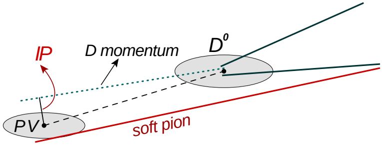
A subsample of $D^{*+} \to D^0(K^-K^+)\pi_s^+$.

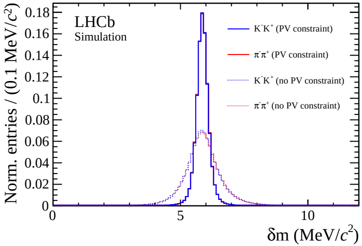
Signal yields from 2011 data :

2.2 million $D^0 \to K^-K^+$;
0.7 million $D^0 \to \pi^-\pi^+$.

$\Delta\langle t\rangle/\tau = (11.19 \pm 0.13 \pm 0.17)\%$

LHCb-CONF-2013-003



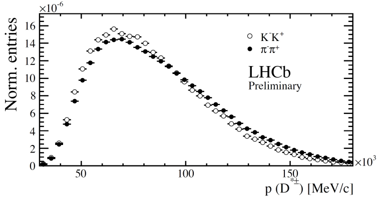


LHCb-CONF-2013-003

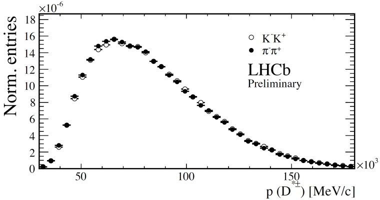
- Fiducial requirements to exclude kinematic regions with large π_s^+ detection asymmetry.
- IP requirement reduces contamination from D^0 originated from b-hadron decays.
- Weighting procedure to adjust kinematic distributions of the K^-K^+ and $\pi^-\pi^+$ final states.
- Data divided into several disjoint samples (magnet polarity and hardware trigger).
- Signal yields extracted from a fit to $\delta m \equiv m(h^+h^-\pi^+) - m(h^+h^-) - m(\pi^+)$.
- Constrain the D^{*+} vertex to coincide with the PV substantially improves δm resolution.

ΔA_{CP} from prompt $D^{*+} \to D^0 \pi_s^+$ – (LHCb, 1 fb^{-1})

D^{*+} momentum before weighting.

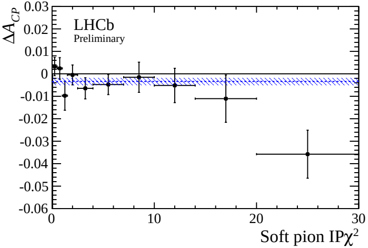


D^{*+} momentum after weighting.



Systematic uncertainties

source	Uncertainty(%)
Fiducial cut	0.02
Peaking Background	0.04
Fit model	0.03
Multiple candidates	0.01
Weighting	0.01
Soft pion IP$_{\chi^2}$	0.08
Total	0.10



$$\Delta A_{CP} = (-0.34 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%$$

LHCb-CONF-2013-003

D^0 flavor is tagged by the muon sign in $B \to D^0 \mu^- X$.

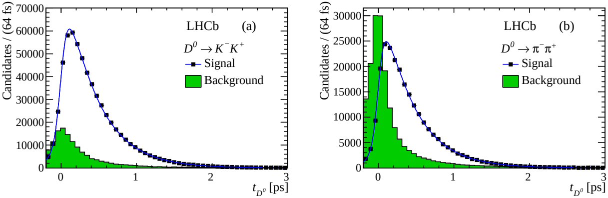
Lower rate partially compensated by a higher trigger efficiency.

Statistically independent from the prompt D^* sample.

Different trigger composition and systematics involved.

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

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

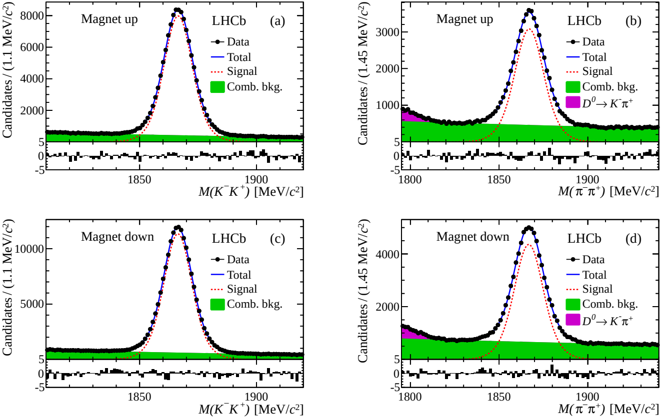


$$\frac{\Delta\langle t\rangle}{\tau} = 0.018 \pm 0.007$$

$$\Delta A_{CP} \simeq \Delta a^{\rm dir}_{CP}$$

arXiv:1303.2614

ΔA_{CP} from semileptonic B decays – (LHCb, 1 fb^{-1})



arXiv:1303.2614

Raw asymmetries determined from a simultaneous fit of four data subsets.

5.6 x 10^5 $D^0 \to K^-K^+$

2.2 x 10^5 $D^0 \to \pi^-\pi^+$

Differences in the kinematics of the two final states are accounted by a weighting procedure.

Systematic uncertainties (%)

Production asymmetry	0.03
Detection asymmetry	0.05
Background from real D^0	0.02
Background from fake D^0	0.12
Total	**0.14**

Wrong flavor tag dilutes the observed asymmetry:

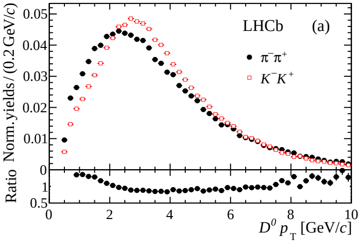
$$A_{\rm raw} \approx (1-2\omega)(A^f_{CP} + A^\mu_D + A^B_{\mathcal{P}}) - \Delta\omega,$$

$$\omega = (\omega^+ + \omega^-)/2 = (0.982 \pm 0.012)\%,$$

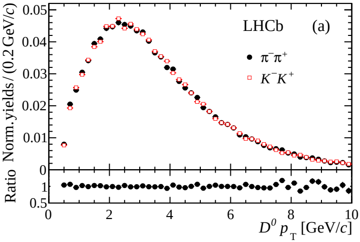
$$\Delta\omega = \omega^+ - \omega^- = (0.006 \pm 0.021)\%.$$

ΔA_{CP} from semileptonic B decays – (LHCb, 1 fb^{-1})

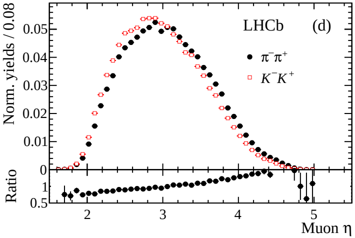
D^0 p_T before weighting



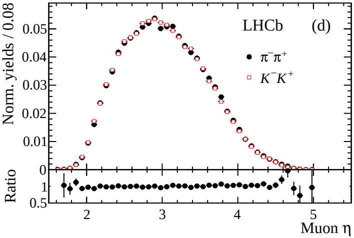
D^0 p_T after weighting



Muon η before weighting



Muon η after weighting



arXiv:1303.2614

ΔA_{CP} results from LHCb – 2011 data (1 fb^{-1}@ 7 TeV):

$B \to D^0 \mu^- X$ $(+0.49 \pm 0.30(stat) \pm 0.14(syst))\%$ arXiv:1303.2614

Prompt D^* $(-0.34 \pm 0.15(stat) \pm 0.10(syst))\%$ LHCb-CONF-2013-003

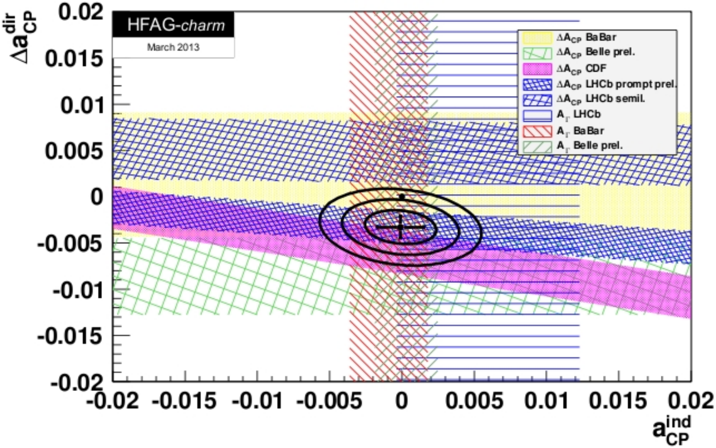
Combination $(-0.15 \pm 0.16)\%$

No evidence for CPV.

ΔA_{CP} – HFAG average

$$\Delta a_{CP}^{\mathrm{dir}} = (-0.329 \pm 0.121)\%, \qquad \Delta a_{CP}^{\mathrm{ind}} = (-0.010 \pm 0.162)\%$$

Agreement with NO CPV hypothesis - CL = 2.1 x 10^{-2}.

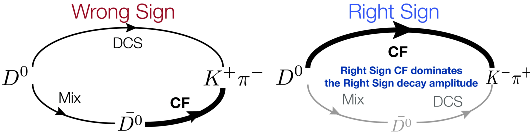


No evidence of CPV in *D* decays.

Observation of $D^0 - \overline{D^0}$ oscillations – LHCb

Measurements of time-dependent "wrong-sign" decay rates:

exploits interference between mixing and DCS decay amplitudes.



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

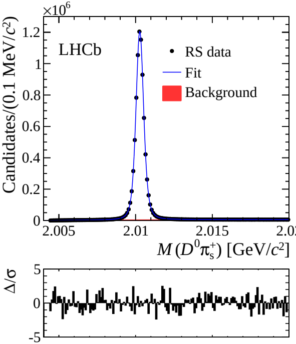
$$\frac{\overline{A}_{K^-\pi^+}}{A_{K^-\pi^+}} = -\sqrt{R_D}\, e^{-i\delta}, \qquad y' = y\cos\delta - x\sin\delta, \qquad x' = x\cos\delta + y\sin\delta,$$

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

the time-dependent decay rate of "wrong sign" $D^0 \to K^+\pi^-$ decay is

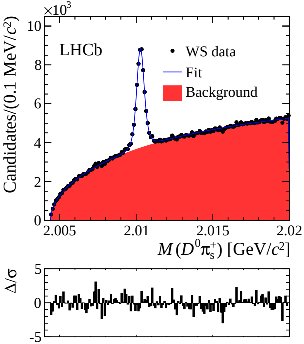
$$\frac{\Gamma(D^0(t)\to K^+\pi^-)}{\Gamma(D^0(t)\to K^-\pi^+)} = R(t) \approx \underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\, y'\Gamma t}_{\text{interf.}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{mixing}}.$$

2011 data – 1.0 fb^{-1} at 7 TeV



$D^{*+} \to D^0(K^-\pi^+)\pi_s^+$

8.4 x 10^6 decays



$D^{*+} \to D^0(K^+\pi^-)\pi_s^+$

3.6 x 10^4 decays

PRL 110 (2013) 101802

Charge of soft pion π_s^+ tags the flavor of the D^0.

Background of WS data dominated by real D^0 associated to a random π.

Contamination from $B \to D^0 X$ reduced by IP requirements on D^0 and π_s^+.

D^0 and π_s^+ required to form a vertex constrained to PV.

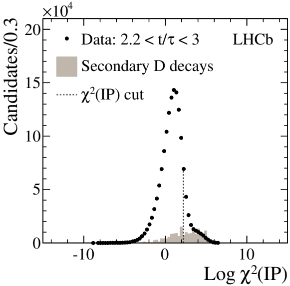
Data divided into 13 D^0 decay time bins with similar number of candidates.

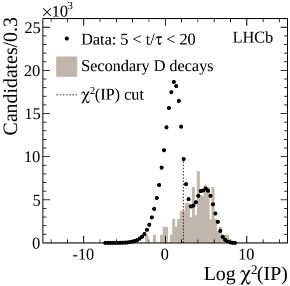
RS and WS yields determined in each decay time bin using fits to $M(D^0\pi_s^+)$.

Most systematics affecting the determination of yields as a function of decay time cancel in the ratio between WS and RS.

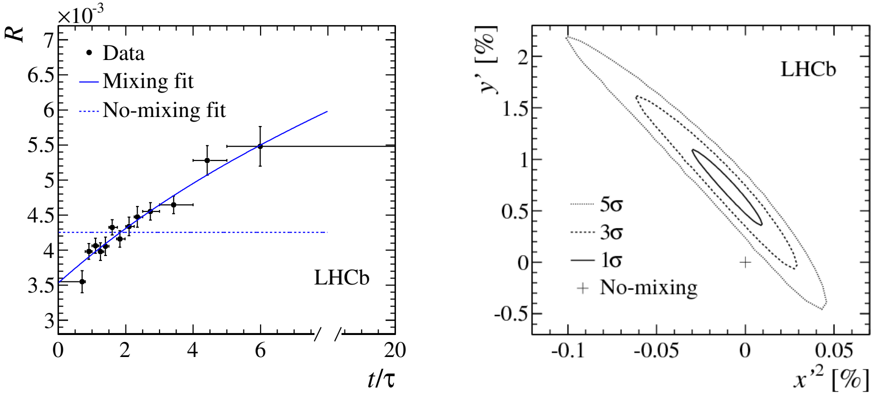
Doubly misidentified RS events correspond to (0.4$\pm$0.2)% of WS signal.

Residual (2.7$\pm$0.2)% contamination from secondary D^0 survives the IP cut.





Observation of $D^0 - \overline{D^0}$ oscillations – LHCb



Fit type	Parameter	Fit result (10^{-3})
Mixing	R_D	3.52 ± 0.15
	y'	7.2 ± 2.4
	x'^2	-0.09 ± 0.13
No mixing	R_D	4.25 ± 0.04

No mixing hypothesis excluded at 9.1σ

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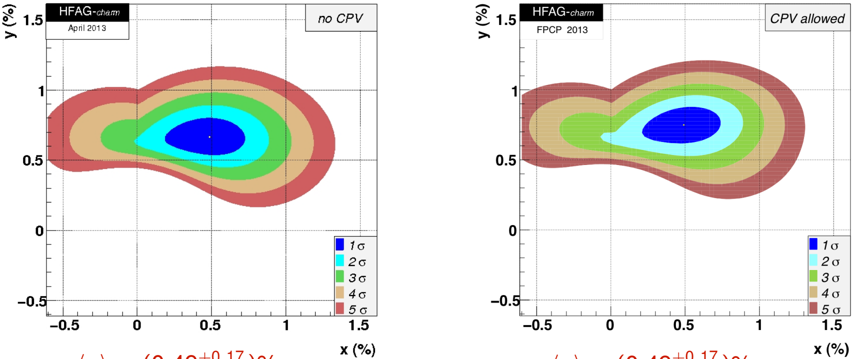


$\langle x \rangle = (0.49^{+0.17}_{-0.18})\%$ $\langle x \rangle = (0.49^{+0.17}_{-0.18})\%$

$\langle y \rangle = (0.66 \pm 0.09)\%$ $\langle y \rangle = (0.74 \pm 0.09)\%$

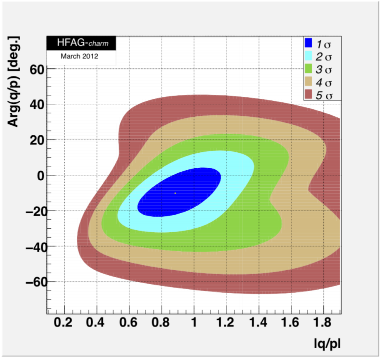
http://www.slac.stanford.edu/xorg/hfag/charm

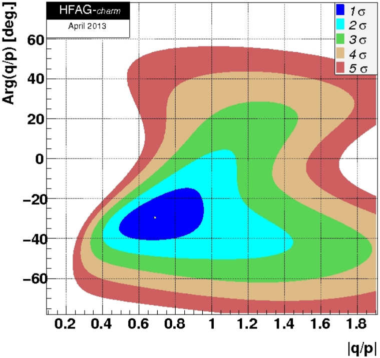
Latest results on "WS" $D^0 \to K\pi$ decay.

Exp.	R_D (10^{-3})	y' (10^{-3})	x'^2 (10^{-3})
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13
Belle	3.64 ± 0.17	$0.6^{+4.0}_{-3.9}$	$0.18^{+0.21}_{-0.23}$
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37
CDF	3.51 ± 0.35	4.3 ± 4.3	0.08 ± 0.18

$D^0 - \overline{D^0}$ oscillations – new HFAG averages

http://www.slac.stanford.edu/xorg/hfag/charm





Although there is no new data on $|q/p|$ and ϕ, contour plots have changed significantly due to correlations with new y' and x' measurements.

Enormous progress in last six years:

Charm mixing is now well established:

$x \approx y$, well within SM expectations;

no evidence for CPV in mixing;

stringent limits on NP scale.

Observation of CPV in charm remains a challenge:

there is still the LHCb 2012 data (2 fb^{-1}).

Sensitivity of CPV searches approaching SM expectations:

LHCb entered a new precision era of Flavor Physics .

All observations are compatible with SM expectations.

Backup slides

Updated LHCb result from 1.0 fb^{-1}:

$$\Delta A_{CP} = (-0.34 \pm 0.15(\text{stat}) \pm 0.10(\text{syst}))\%$$

Differences from previous result:

1) New reconstruction changed the selected signal events (600 fb^{-1}):

a) 15% of signal events no longer selected;
b) 17% (K^-K^+) and 34% ($\pi^-\pi^+$) new events selected:

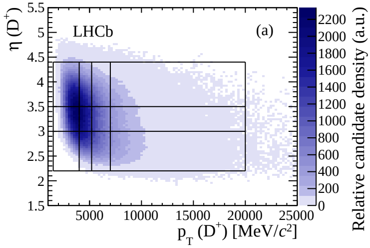
ΔA_{CP}: (-0.82$\pm$0.21)% $\to$ (-0.55$\pm$0.21)%.

2) Including new data (+ 400 fb^{-1}) : $\Delta A_{CP} = (-0.55 \pm 0.21) \;\to\; (-0.45 \pm 0.16)\%$.

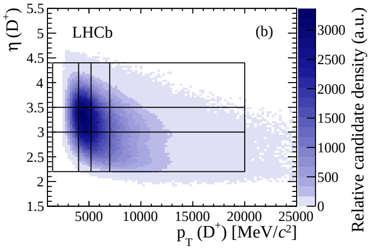
3) Constraining the soft pion and the D^0 to originate from a primary vertex:
ΔA_{CP}: (-0.45$\pm$0.16)% $\to$ (-0.34$\pm$0.15)%.

2012 data set (2 fb^{-1}) currently being analysed.

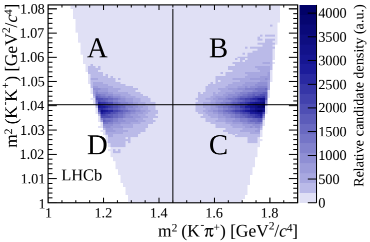
$D^+ \to \phi\pi^+$



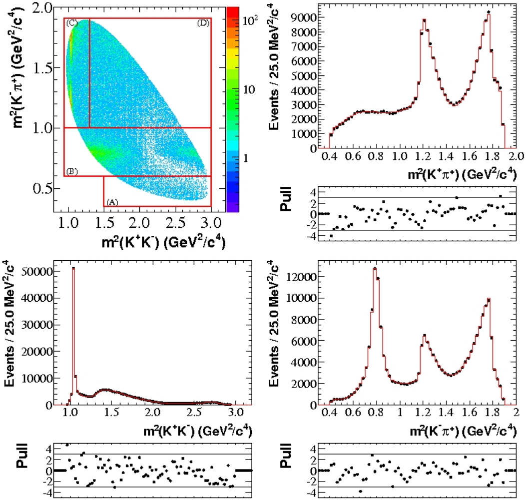
$D_s^+ \to K_s^0\pi^+$



$D^+ \to \phi\pi^+$

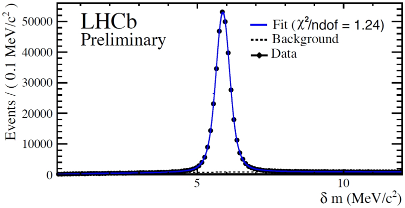


Search for direct CPV in $D^+ \to K^- K^+ \pi^+$ – BaBar

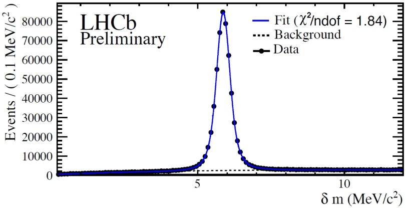


$D^{*+} \to D^0(K^- K^+)\pi_s^+$ signals

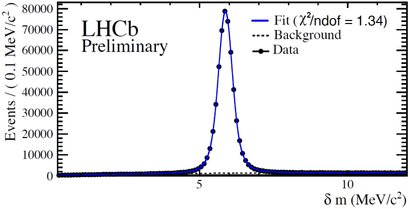
Magnet Up TOS



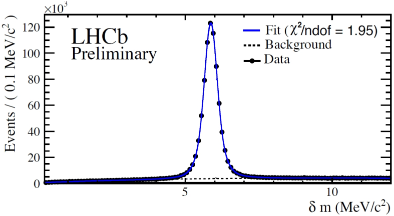
Magnet Up TIS



Magnet Down TOS

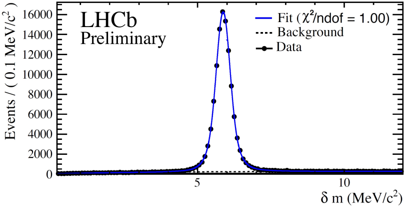


Magnet Down TIS

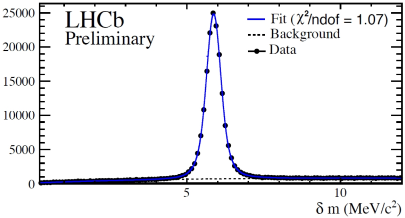


$D^{*+} \to D^0(\pi^- \pi^+)\pi_s^+$ signals

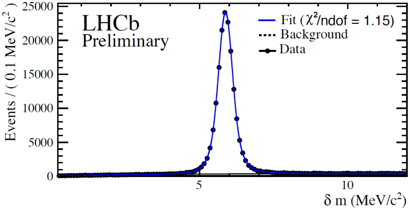
Magnet Up TOS



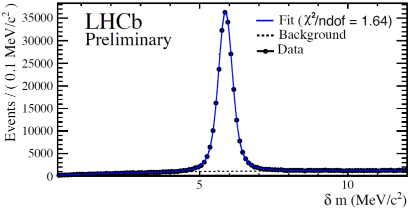
Magnet Up TIS



Magnet Down TOS

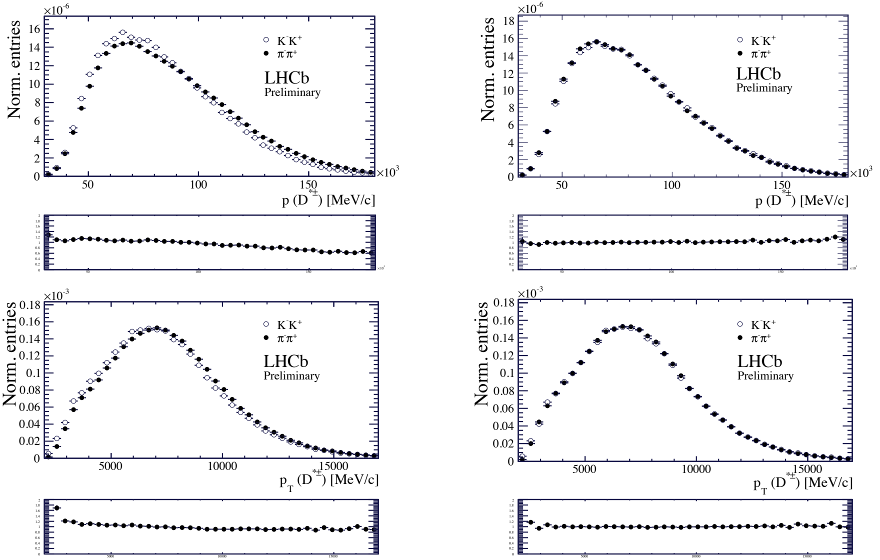


Magnet Down TIS

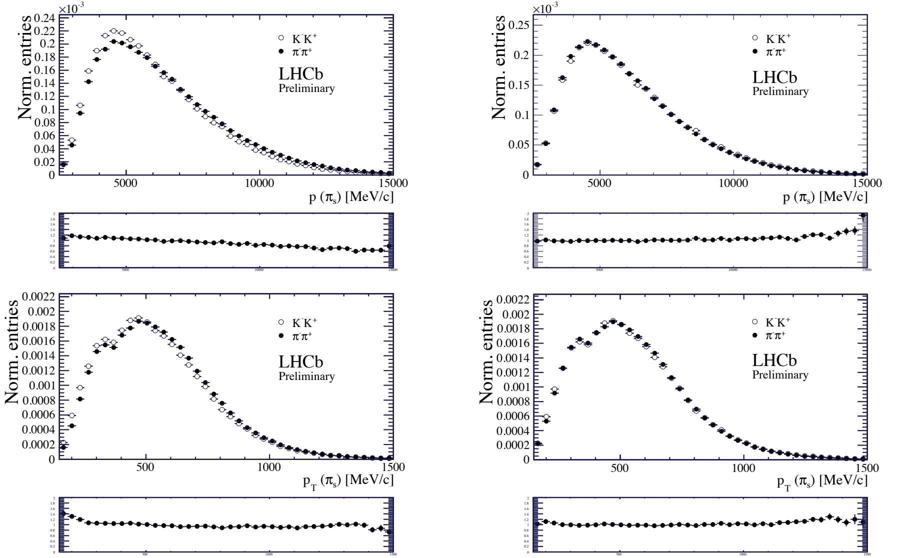


ΔA_{CP} from prompt $D^{*+} \to D^0 \pi_s^+$ – (LHCb, 1 fb^{-1})

D^{*+} kinematic distributions before (left) and after (right) weighting.



Soft pion kinematic distributions before (left) and after (right) weighting.



y_{CP} – lifetime difference between CP-even and CP-mixed final states

Different lifetimes in D^0 decays: unambiguous manifestation of oscillations.

Time-dependent rate for the $D^0 \to K^-K^+$ and $D^0 \to K^-\pi^+$:

$$\begin{aligned}
\Gamma(D^0(t) \to K^-K^+) &= e^{-\Gamma t}|A_{K^-K^+}|^2\left[1 - \left|\frac{q}{p}\right|(y\cos\phi - x\sin\phi)\Gamma t\right] \\
\Gamma(\overline{D}^0(t) \to K^-K^+) &= e^{-\Gamma t}|A_{K^-K^+}|^2\left[1 - \left|\frac{p}{q}\right|(y\cos\phi + x\sin\phi)\Gamma t\right] \\
\Gamma(D^0(t) \to K^-\pi^+) &= e^{-\Gamma t}|A_{K^-\pi^+}|^2
\end{aligned}$$

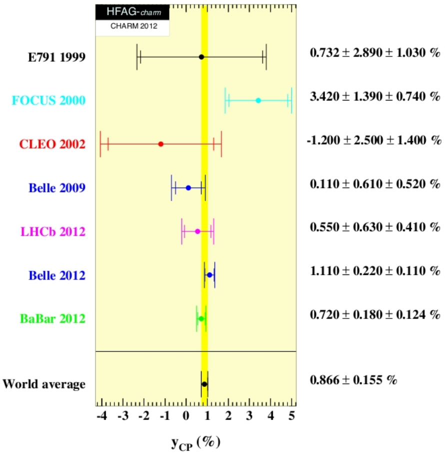
Ratio between *CP*-even and *CP*-mixed lifetimes:

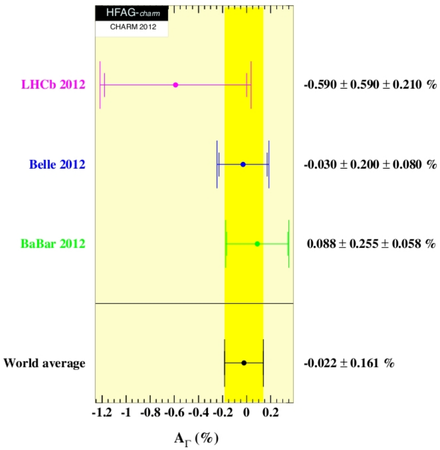
$$y_{CP} = \frac{\Gamma_+ - \Gamma_-}{2\Gamma} \simeq \frac{\tau(K^-\pi^+)}{\langle\tau(K^-K^+)\rangle} - 1 = y\cos\phi - \frac{1}{2}A_m\, x\sin\phi, \qquad A_m = 1 - \left|\frac{q}{p}\right|^2$$

If there is no CPV in mixing, $|q/p| = 1$ and $\phi = 0$,

$$y_{CP} = y, \qquad A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^-K^+)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^-K^+)} = 0$$

http://www.slac.stanford.edu/xorg/hfag/charm





$\langle y_{CP} \rangle = (0.866 \pm 0.155)\%$ $\langle A_\Gamma \rangle = (-0.022 \pm 0.161)\%$

Time evolution of neutral D mesons:

$$i\frac{d}{dt}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix} = \begin{pmatrix} M_{11} - \frac{i}{2}\Gamma_{11} & M_{12} - \frac{i}{2}\Gamma_{12} \\ M_{12}^* - \frac{i}{2}\Gamma_{12}^* & M_{22} - \frac{i}{2}\Gamma_{22} \end{pmatrix}\begin{pmatrix} D^0 \\ \overline{D}^0 \end{pmatrix},$$

CPT invariance:
$M_{11} = M_{22}, \ \Gamma_{11} = \Gamma_{22}.$

Mass eingenstates:

$$|D_1\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}\left(p|D^0\rangle + q|\overline{D}^0\rangle\right), \qquad |D_2\rangle = \frac{1}{\sqrt{|p|^2 + |q|^2}}\left(p|D^0\rangle - q|\overline{D}^0\rangle\right),$$

Parameters governing mixing:

$$x \equiv \frac{m_2 - m_1}{\Gamma} = \frac{\Delta m}{\Gamma},$$

$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma} = \frac{\Delta\Gamma}{2\Gamma},$$

$$\Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

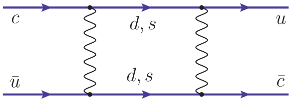
Parameters governing CPV:

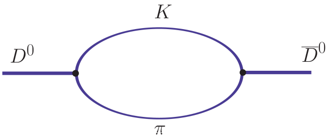
$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f} = -\eta_{CP}\left|\frac{q}{p}\right|\left|\frac{\overline{A}_f}{A_f}\right|e^{i\phi},$$

$$A_f \equiv \langle f|\mathcal{H}|D^0\rangle, \qquad \overline{A}_f \equiv \langle f|\mathcal{H}|\overline{D}^0\rangle,$$

$$\frac{q}{p} = \sqrt{\frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}}$$

In the SM $D^0 - \overline{D^0}$ oscillations are slow and have two mechanisms,





Short distance box amplitudes:

- GIM+CKM suppression, negligible contribution from b ($|\mathbf{V}_{ub}\mathbf{V}_{cd}| \sim \mathcal{O}(\lambda^5)$);
- contribute only to Δm;
- Where NP could manifest.

long distance amplitudes:

- dominant mechanism, but not calculable from first principles;
- contribute to both Δm and $\Delta\Gamma$;
- hardly sensitive to NP.

SM predictions (still rather uncertain): $x, y \sim \mathcal{O}(10^{-2} - 10^{-3})$.

$D^0 - \overline{D^0}$ oscillations driven by the first two generations:

negligible CPV in mixing.