Time-dependent measurements of CP violation in charm

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Charm mixing:

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

$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

CP violation:

CPV in mixing

$$\left|\frac{q}{p}\right| \neq 1$$

$$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$$

$$a_{CP}^{ind} = -\frac{A_m}{2}\, y\cos\phi + x\sin\phi$$

CPV in decay

$$\left|\frac{\bar{A}_{\bar{f}}}{A_f}\right|^{\pm 2} \approx 1 \pm A_d \qquad a_{CP}^{dir} \approx -\frac{1}{2}A_d$$

CPV in interference

$$\lambda_f = \left|\frac{q}{p}\right|\left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$

$$Im(\lambda_f) \neq 0$$

- In the Standard Model CP violation is expected to be small.
- Significant enhancements are an indication of New Physics.

A_Γ

Asymmetry of D^0 and $\bar{D}^0$ decay rates to a CP eigenstate, K^+K^- or $\pi^+\pi^-$:

$$A_\Gamma(KK) = \frac{\hat{\Gamma}\left(D^0 \to K^+K^-\right) - \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)}{\hat{\Gamma}\left(D^0 \to K^+K^-\right) + \hat{\Gamma}\left(\bar{D}^0 \to K^+K^-\right)} \approx \frac{A_m + A_d}{2} y \cos\phi - x \sin\phi$$

In the SM:

- $\sim 10^{-4}$ Bigi et al. JHEP 06 (2011) 089
- Roughly final state independent Kagan and Sokoloff, Phys. Rev. D 80 (2009) 07600

$$\Delta A_\Gamma = A_\Gamma(KK) - A_\Gamma(\pi\pi) \approx \Delta A_d y \cos\phi + (A_m + A_d) y \Delta\cos\phi - x\Delta\sin\phi$$

Large A_Γ or final state dependence is indicative of New Physics.

y_{CP}

In mixing parameter y is defined as:

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

Introducing CP violation into mixing one can finds:

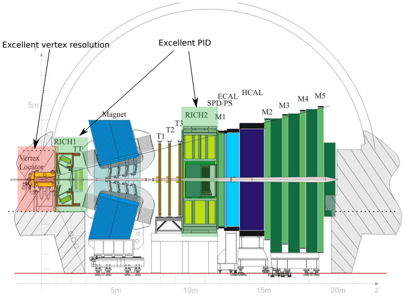
$$y_{CP} = \frac{\hat{\Gamma}\left(D^0 \to K^+K^-\right)}{\hat{\Gamma}\left(D^0 \to K^-\pi^+\right)} - 1 \approx \left(1 - \frac{1}{8}A_m^2\right) y\cos\phi - \frac{1}{2}A_m x \sin\phi$$

- In the limit of no CP violation $y_{CP} \to y$
- Can be seen as a mixing measurement
- Deviation of y_{CP} from y indicates CP violation in mixing
- From the Heavy Flavour Averaging Group (HFAG)
  - $y = 0.67^{+0.07}_{-0.08}\%$
  - $y_{CP} = (0.866 \pm 0.155)\%$

M Gersabeck et al. 2012 J. Phys. G: Nucl. Part. Phys. 39 045005

LHCb

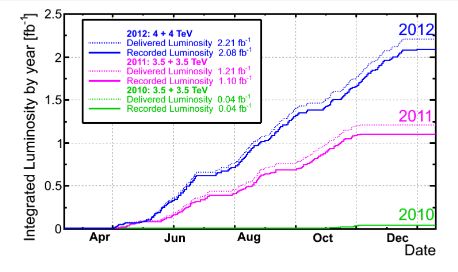
- Forward spectrometer.
- Acceptance $2 < \eta < 5$



- 3 level trigger:
  - L0 hardware selects events with high p_T particles.
  - Two layers of software triggers.
- Output at $\sim$ 5kHz

Data set

- 2011: $1fb^{-1}$ at 7TeV
- 2012: $2fb^{-1}$ at 8TeV



LHCb

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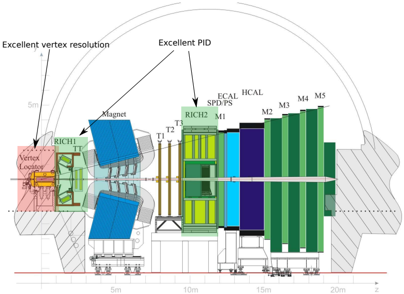

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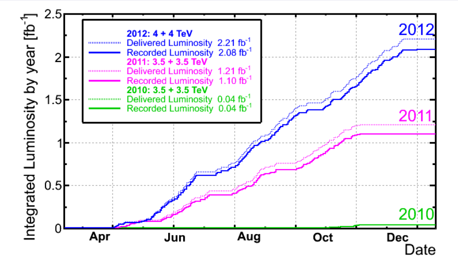


Charm

$$\sigma_{b\bar{b},acc} = 75.3 \pm 14.1\mu\text{b at 7TeV}$$
Phys. Lett. B694 209-216
$$\sigma_{c\bar{c},acc} = 1419 \pm 134\mu\text{b at 7TeV}$$
Nucl. Phys. B871, 1-20

- A_Γ paper has been published by PRL. PRL 112 (2014) 041801
- Due to the large $K^-\pi^+$ data set the y_{CP} analysis is to follow.

$1fb^{-1}$ of pp collisions collected in 2011.

- Data split into 8 samples; D^0, $\overline{D}^0$, magnet polarity, July TS.

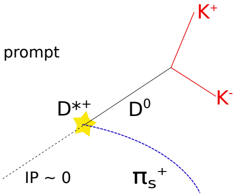
Channel	No. of candidates
$D^0 \to K^-\pi^+$	34.1 million
$D^0 \to K^+K^-$	4.8 million
$D^0 \to \pi^+\pi^-$	1.6 million

Measure effective lifetimes of D^0 decaying to K^+K^-, $\pi^+\pi^-$ and $K^-\pi^+$ to extract y_{CP} and A_Γ ('unbinned method') - presented here.
Additionally use an alternative method ('binned method') to ascertain A_Γ- see backup.

Tagging and backgrounds

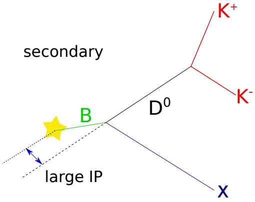
Prompt:

- Look for the decay $D^{*+} \to D^0 \pi_s^+$.
- Charge on π_s^+ signifies D^0 flavour.



Prompt backgrounds:

- Random π_s^+ - mis-tag:
  - Separated out by fit of difference between D^{*+} and D^0 masses, Δm.
- D^0 from B decays - secondaries:
  - $\ln(\mathrm{IP}\chi^2)$ used as a discriminating variable.



Extract mean effective lifetimes of D^0 ($\bar{D}^0$) by means of a fit to D^0 decay times.

- Acceptance biases due to the selection corrected for using the "swimming" method. JHEP 04 (2012) 129

Two stage fit process:

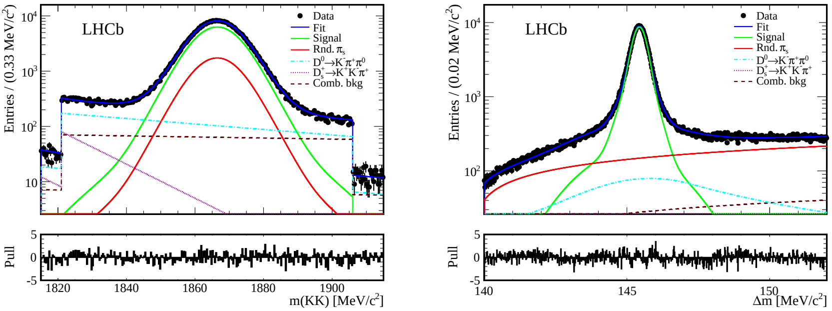
- Fit m_{D^0} and Δm simultaneously to separate signal and background.
- Mis-reconstructed background shapes in K^+K^- taken from simulation.
- Simultaneous fit to D^0 decay time and $\ln(\mathrm{IP}\chi^2)$ to extract the prompt signal mean lifetime.

A_Γ - Mass fit

- Unbinned maximum likelihood fit to D^0 mass and Δm to determine signal and backgrounds.

- Separate out:
  - Random π_s^+
  - Combinatoric
  - Mis-reconstructed decays in the $K^+ K^-$ final state

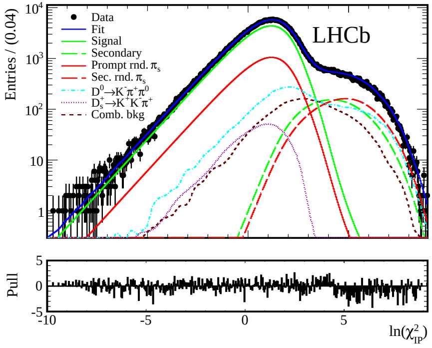
$$\overline{D}^0 \to K^+K^-$$



PRL 112 (2014) 041801

A_Γ - $\ln(\mathrm{IP}\chi^2)$ fit

$\overline{D}^0 \to K^+K^-$



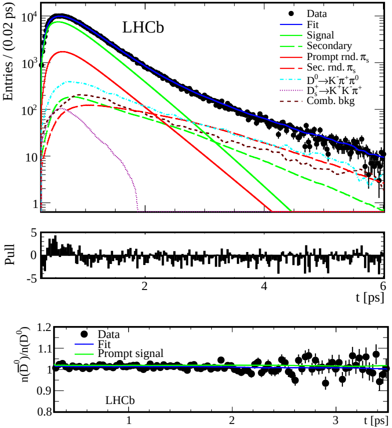
PRL 112 (2014) 041801

The $\ln(\mathrm{IP}\chi^2)$ fit is used to separate prompt and secondary signal and random π_s^+ .

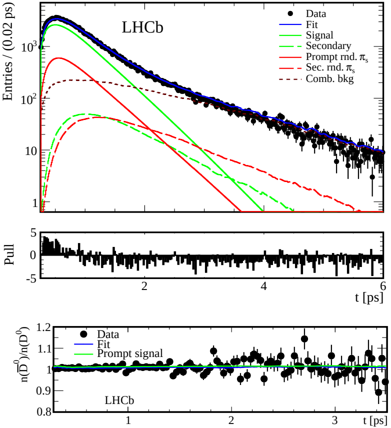
- Prompt and secondary signal and π_s^+ background are described by parametric PDFs.
- Their fit parameters are allowed to evolve in time.
- Secondary components show significant time dependence.
- Background PDFs are constructed by applying kernel density estimators to sPlots.

A_Γ - Result

$\bar{D}^0 \to K^+K^-$



$\bar{D}^0 \to \pi^+\pi^-$



$$A_\Gamma(KK) = (-0.35 \pm 0.62_{stat} \pm 0.12_{syst}) \times 10^{-3}$$
$$A_\Gamma(\pi\pi) = (0.33 \pm 1.06_{stat} \pm 0.14_{syst}) \times 10^{-3}$$

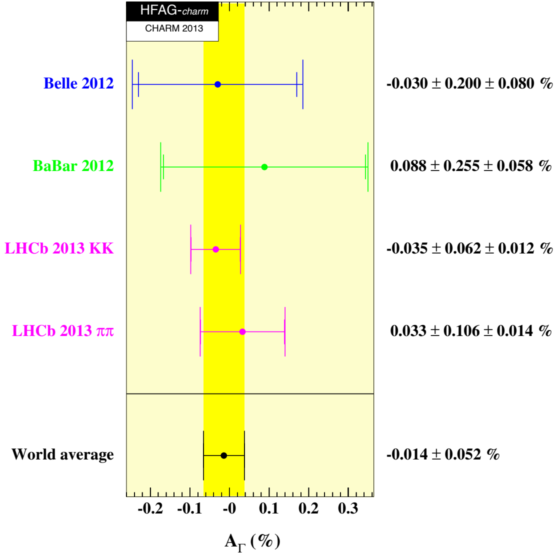
PRL 112 (2014) 041801

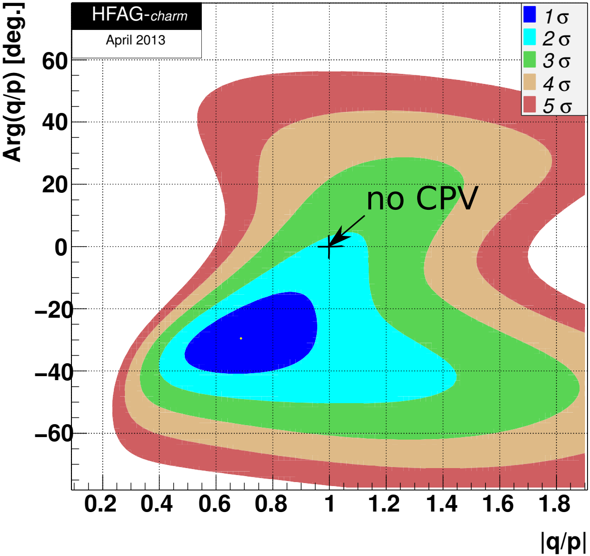
A_Γ - Cross checks and systematics

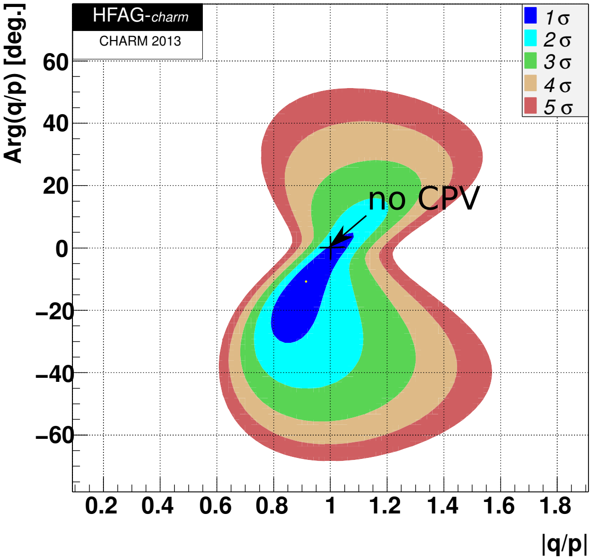
Several cross checks were carried out:

- D^0 lifetime measured using the $K^-\pi^+$ data; $\tau = (412.9 \pm 0.1) fs$, compared to the PDG value of $\tau = (410.1 \pm 1.5) fs$.
- Null tests.
- Checked dependencies on kinematics, number of PVs in the event, trigger selections etc.
- Simulations with varying configurations.

Effect	A_Γ $(K^+K^-)\times 10^{-3}$	A_Γ $(\pi^+\pi^-)\times 10^{-3}$
Mis-reconstructed bkg.	± 0.02	± 0.00
Charm from B	± 0.07	± 0.07
Other backgrounds	± 0.02	± 0.04
Acceptance function	± 0.09	± 0.11
Total	± 0.12	± 0.14


HFAG-charm
CHARM 2013
Belle 2012
-0.030 ± 0.200 ± 0.080 %
BaBar 2012
0.088 ± 0.255 ± 0.058 %
LHCb 2013 KK
-0.035 ± 0.062 ± 0.012 %
LHCb 2013 ππ
0.033 ± 0.106 ± 0.014 %
World average
-0.014 ± 0.052 %
-0.2
-0.1
-0
0.1
0.2
0.3
A_Γ (%)


HFAG-charm
April 2013
1σ
2σ
3σ
4σ
5σ
no CPV
Arg(q/p) [deg.]
60
40
20
0
–20
–40
–60
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
|q/p|


HFAG-charm
CHARM 2013
1 σ
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no CPV
Arg(q/p) [deg.]
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0.6
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1
1.2
1.4
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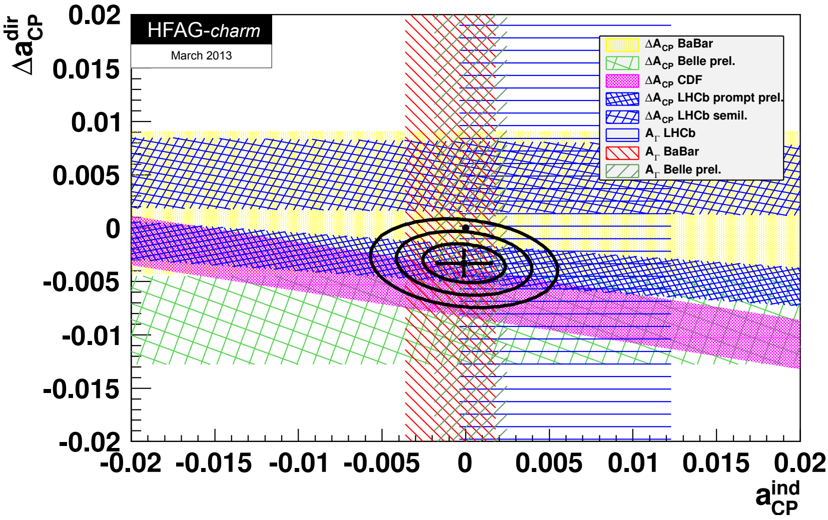
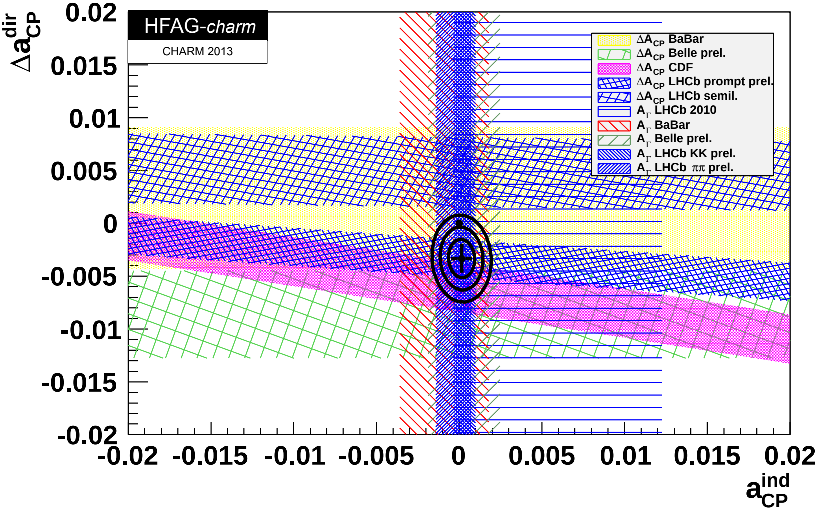
|q/p|

HFAG fit results



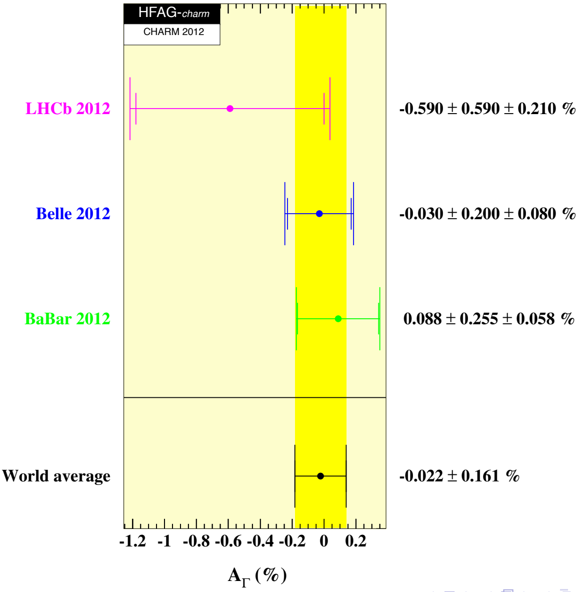
HFAG fit results



Conclusions

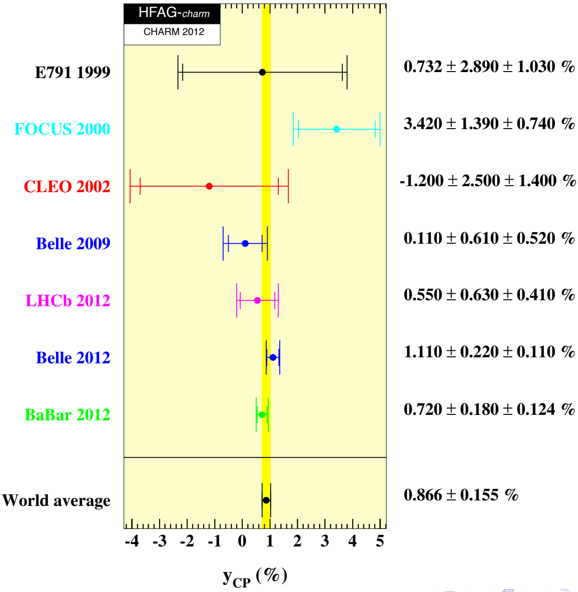
- We have made the most accurate measurement of CP violation in charm mixing to date.
- No CP violation or final state dependence has been found at this level of precision.
- y_{CP} result is to follow shortly.
- $2fb^{-1}$ of 2012 data still to be analysed.

Backup



HFAG-charm
CHARM 2012
LHCb 2012
-0.590 ± 0.590 ± 0.210 %
Belle 2012
-0.030 ± 0.200 ± 0.080 %
BaBar 2012
0.088 ± 0.255 ± 0.058 %
World average
-0.022 ± 0.161 %
-1.2 -1 -0.8 -0.6 -0.4 -0.2 0 0.2
A_Γ (%)

y_{CP} competition



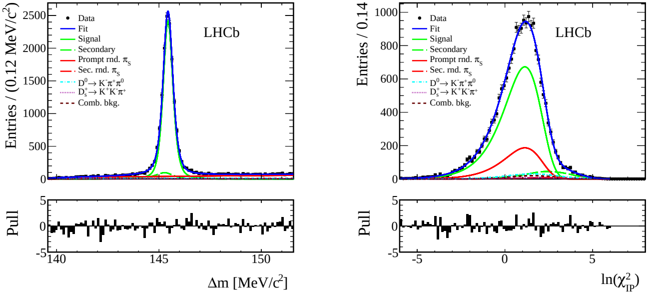
A_Γ - Binned method

Use an alternative method to measure A_Γ. Measure the ratio of D^0 and $\overline{D}^0$ yields in bins of decay time.

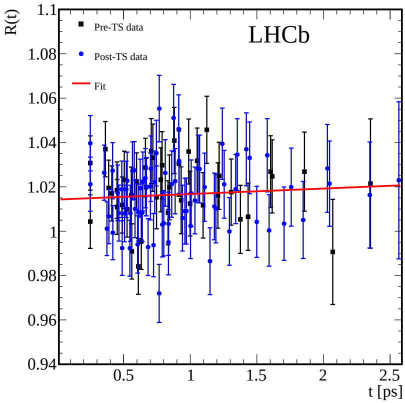
$$R(t, t+\Delta t) \approx \frac{N_{\overline{D}^0}}{N_{D^0}} \left(1 + \frac{2A_\Gamma}{\tau_{KK}} t\right) \frac{1 - e^{\frac{-\Delta t}{\tau_{\overline{D}^0}}}}{1 - e^{\frac{-\Delta t}{\tau_{D^0}}}}$$

- Fit m_{D^0}, Δm, and $\ln(\mathrm{IP}\chi^2)$ to find yields.
- Plot ratio as function of decay time and fit.

$\overline{D}^0 \to K^+K^-$, 0.74ps-0.78ps



$K^+ \ K^-$



The binned results are consistent with those from the unbinned fit.