Measurements of CP violation and mixing in charm decays at LHCb

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19 February 2015

Mixing:

- Charm mixing discovered through a combination of measurements in 2007: BABAR (PRL 98:211802 (2007)), Belle (PRL 98:211803 (2007)), CDF (PRL 100, 121802 (2008))
- Now well established.

CP Violation:

- CP violation in charm not yet observed.
- LHCb has collected very large samples of charm decays to look for CP violation in mixing and decay.

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

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

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

CPV in decay

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

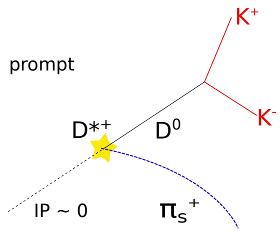
CPV in interference

$$\lambda_f = \left|\frac{q}{p}\right| \left|\frac{\bar{A}_f}{A_f}\right| e^{i\phi}$$
$$\phi \neq 0$$

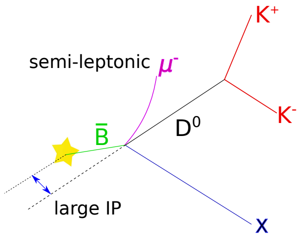
- In the Standard Model CP violation in charm is expected to be small.
- Significant enhancements are an indication of New Physics.

We can tag the initial D^0 flavour in two ways:

- Prompt:
  - D^{*+} produced at the interaction point.
  - Look for the decay $D^{*+} \to D^0 \pi_s^+$.
  - Slow-pion π_s^+ denotes D^0 flavour.
  - Fit difference between D^{*+} and D^0 mass, Δm, to ascertain correctly tagged candidates.
  - Background from B decays.

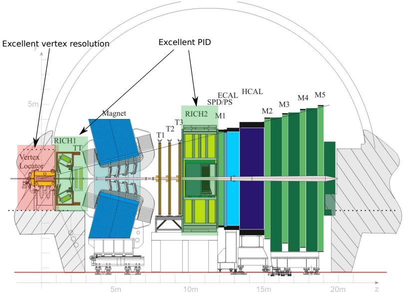


- Semi-leptonic:
  - Search for the decay $\overline{B} \to D^0 \mu^- X$.
  - μ charge signifies D^0 flavour.
  - Completely independent of the prompt sample.



LHCb

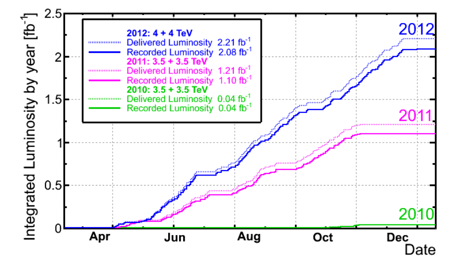
- Forward spectrometer.
- Acceptance $2 < \eta < 5$



- 3 level trigger:
  - L0 hardware selects events with high p_T particles.
  - Two layers of software triggers.
- Charm output at $\sim$ 2kHz

Data set

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



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

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:

- Roughly final state independent

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

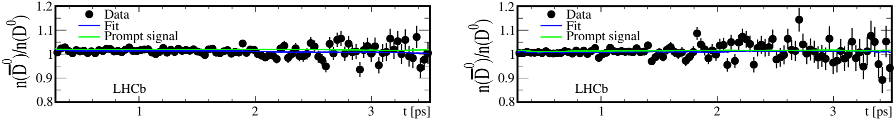
Large A_Γ or final state dependence is indicative of New Physics.

A_Γ - Prompt

PRL 112 (2014) 041801

- 1fb^{-1} of *pp* collisions collected in 2011.
- Measure effective lifetime of D^0 decaying to K^-K^+ and $\pi^+\pi^-$.

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



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

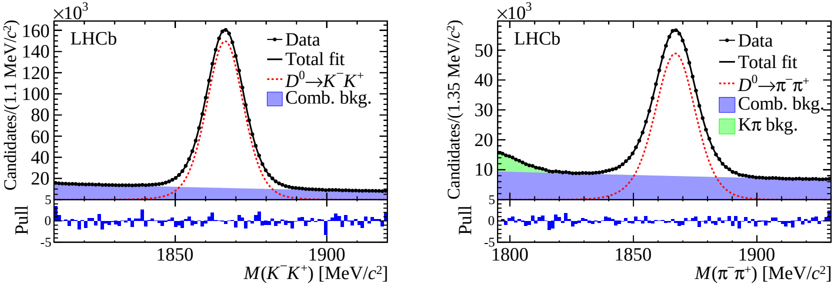
Most precise measurement to date.

arXiv:1501.06777 , submitted to JHEP

A_Γ has been measured using D from semi-leptonic B decays

- Full $3\,\text{fb}^{-1}$ run 1 data set.
- Fit the invariant mass of D^0 and $\overline{D}^0$ to ascertain their yields in bins of proper time, t.
- Fit the time evolution of the asymmetry of the yields to ascertain A_Γ:

$$A_{CP}(t) \approx A_{CP}^{dir} - A_\Gamma \frac{t}{\tau}.$$



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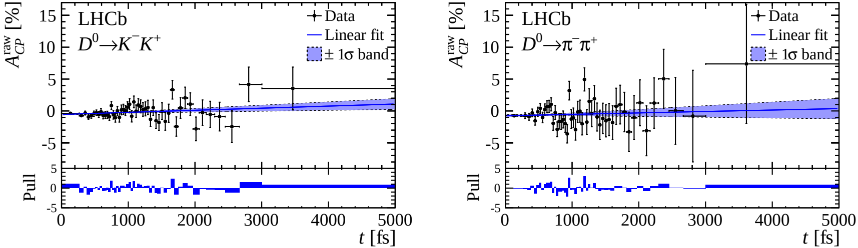


$$A_\Gamma(KK) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$$
$$A_\Gamma(\pi\pi) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$$

Consistent with the prompt analysis and CP symmetry.

ΔA_{CP}

Time-integrated asymmetries for final states f: K^+K^- and $\pi^+\pi^-$.

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}$$

Measured asymmetry:

$$A_{raw} = \frac{N(D^0 \to f) - N(\bar{D}^0 \to f)}{N(D^0 \to f) + N(\bar{D}^0 \to f)}$$

The measured quantity includes production and measurement asymmetries:

$$A_{raw} = A_{CP} + A^{prod} + A^{det}$$

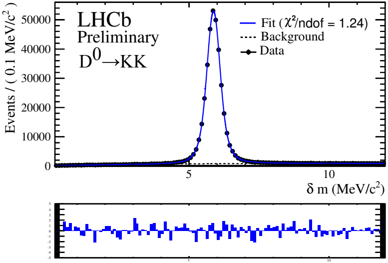
- Taking the difference cancels detection and production asymmetries.
- To a good approximation this is a measure of direct CP violation.

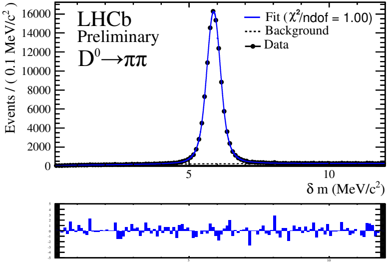
$$\Delta A_{CP} = A_{KK} - A_{\pi\pi} \approx \Delta a_{CP}^{dir}\left(1 + y_{CP}\frac{\langle \bar{t} \rangle}{\tau}\right) + a_{CP}^{ind}\frac{\Delta\langle t \rangle}{\tau}$$

LHCb has both prompt and semi-leptonic analyses - they are completely independent.

LHCb-CONF-2013-003

Full 1fb^{-1} 2011 data set.
Fit $\delta m = m(h^+h^-\pi_s^+) - m(h^+h^-) - m(\pi_s^+)$ to extract signal yield; K^+K^- on left, $\pi^+\pi^-$ on right.



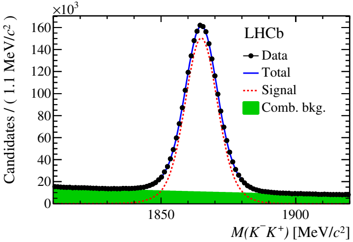


$$\Delta A_{CP} = (-0.34 \pm 0.15_{stat} \pm 0.10_{syst})\%$$

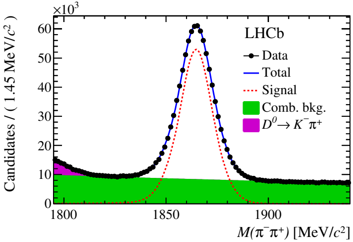
Preliminary

JHEP 1407 (2014) 041

Fit mass distributions to ascertain yields of each decay mode:



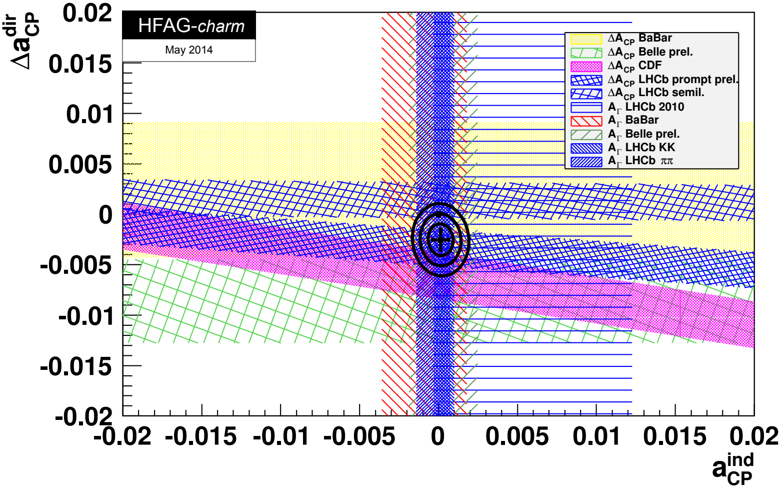
$D^0 \to K^- K^+$



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

$$\Delta A_{CP} = (+0.14 \pm 0.16_{stat} \pm 0.08_{sys})\%$$
$$A_{CP}(K^- K^+) = (-0.06 \pm 0.15_{stat} \pm 0.10_{sys})\%$$
$$A_{CP}(\pi^+ \pi^-) = (-0.20 \pm 0.19_{stat} \pm 0.10_{sys})\%$$

Consistent with CP conservation. First individual charm asymmetry measurement at LHCb; most precise to date.



$$a_{CP}^{ind} = (0.013 \pm 0.052)\%$$
$$\Delta a_{CP}^{dir} = (-0.253 \pm 0.104)\%$$

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Test for time-integrated *CP* symmetry in $D^0 \to \pi^+\pi^-\pi^0$ decays using the 'energy test' method.

- $2\,\text{fb}^{-1}$ 2012 data set, prompt D^0.
- Model-independent method.

Define a test statistic T, that compares the distances between events in the Dalitz plane:

$$T = \sum_{i,j>i}^{n} \frac{\psi_{ij}}{n(n-1)} + \sum_{i,j>i}^{\bar{n}} \frac{\psi_{ij}}{\bar{n}(\bar{n}-1)} - \sum_{i,j}^{n,\bar{n}} \frac{\psi_{ij}}{n\bar{n}}$$

where

$$\psi_{ij} = \exp^{-d_{ij}^2/2\sigma^2} .$$

d_{ij} is the length of the displacement vector for the three mass combinations , $\Delta\vec{x}_{ij}$

$$\Delta\vec{x}_{ij} = \begin{pmatrix} m_{12}^{2,j} - m_{12}^{2,i} \\ m_{23}^{2,j} - m_{23}^{2,i} \\ m_{13}^{2,j} - m_{13}^{2,i} \end{pmatrix}$$

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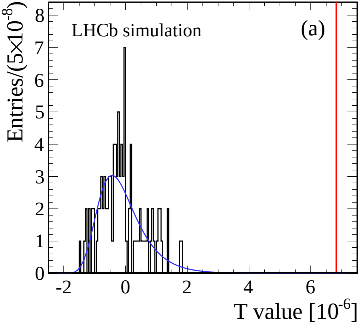
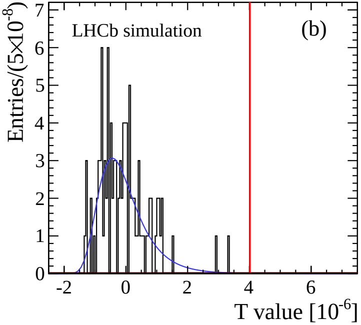
Test CP symmetry by comparing the measured value of T (red) with the distribution of T for randomly tagged samples (blue) and calculating a p-value for CP symmetry.

For example introducing CP violation in the ρ^+ resonance, tested on simulation:

2% CP violation in the amplitude



1° phase difference



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

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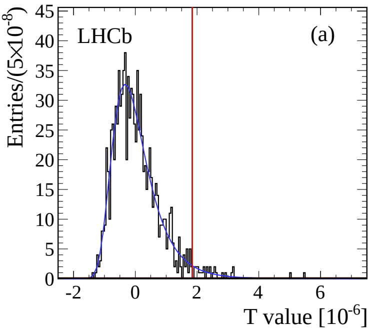
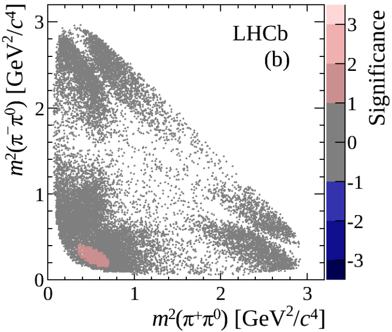
Result



Visualisation of local asymmetry



Consistent with CP symmetry
p-value: $(2.6 \pm 0.5)\%$

Best-sensitivity to CP violation in this mode; data sample roughly eight times larger than previous most sensitive search.

First CP violation measurement with π^0 at LHCb.

Conclusion

- LHCb has made several of the most precise measurements of CP violation in charm.
- A_Γ has been measured using prompt and semi-leptonic data.
  - The prompt result is the most precise to date.
  - Semi-leptonic result is consistent with the prompt.
  - Prompt 2012 analysis is to follow.
- Presented the most precise measurements of the time-integrated CP asymmetries $A_{CP}(K^-K^+)$ and $A_{CP}(\pi^+\pi^-)$.
- Improved the constraints on charm CP violation parameters.
- Presented the most precise measurement of CP violation in $D^0 \to \pi^+\pi^-\pi^0$ decays.
- Expect further improvements in precision with data from run 2.

All results so far are consistent with CP conservation in charm.