

## Measurements of mixing and indirect $CP$ violation in two-body charm decays at LHCb

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The large dataset of charm decays collected by LHCb in the first data-taking period (Run 1) of the Large Hadron Collider (LHC), facilitates precision measurements of charm mixing and of the Charge-Parity ( $CP$ ) symmetry. Of particular interest are two-body decays due to their large branching fractions and the abundance of Cabibbo favoured (CF) control modes, suppressed modes and  $CP$  eigenstates. The observable  $A_\Gamma$ , which is predominantly a measure of indirect  $CP$  violation, is accessed through the singly Cabibbo suppressed decays  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$ . The results are  $A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$  and  $A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$ , where the first uncertainty is statistical, and the second systematic. These measurements show no evidence of  $CP$  violation and improve on the precision of the previous best measurements by nearly a factor of two. The interference between possible decay mechanisms of the doubly Cabibbo suppressed (DCS)  $D^0 \rightarrow K^+\pi^-$  and  $\bar{D}^0 \rightarrow K^-\pi^+$  decays gives access to the charm system mixing parameters and provides a test of various  $CP$  violation hypotheses. The results are consistent with the no  $CP$  violation hypothesis.

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## 1. Introduction

Violation of the symmetry under the combined operations of charge conjugation and parity ( $CP$ ) was discovered in flavour-changing interactions of the  $s$  quark [1], and later observed also in processes involving the  $b$  quark [2, 3]. However,  $CP$  violation ( $CPV$ ) has not yet been observed in the charm system. Here the Standard Model (SM) predicts  $CP$  violation at a level below  $10^{-3}$  [4, 5], and thus is sensitive to potentially small effects of physics beyond the SM.

Charm hadrons are the only systems involving up-type quarks where  $CP$  violation effects are expected to be observable. This provides an important opportunity to detect new physics effects that might leave down-type quarks unaffected.

This report details two measurements made by LHCb using the full Run 1 dataset. Both measurements use  $3 \text{ fb}^{-1}$  of proton-proton ( $pp$ ) collision data,  $1 \text{ fb}^{-1}$  of which was collected at a  $pp$  centre-of-mass energy,  $\sqrt{s} = 7 \text{ TeV}$  in 2011, while the remaining  $2 \text{ fb}^{-1}$  was collected at  $\sqrt{s} = 8 \text{ TeV}$  in 2012.

## 2. Measurement of the $CP$ violation observable $A_\Gamma$

A sensitive probe of  $CP$  violation in the charm sector is given by decays of  $D^0$  mesons into  $CP$  eigenstates  $f$ , where  $f = \pi^+\pi^-$  or  $f = K^+K^-$ . The time-integrated  $CP$  asymmetries and the charm mixing parameters  $x \equiv (m_2 - m_1)/\Gamma$  and  $y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)$  [6], where the subscripts denote the mass eigenstates  $|D_{1,2}\rangle$ , are known to be small [7, 8, 9]. As a result, the time-dependent  $CP$  asymmetry of each decay can be approximated as

$$A_{CP}(t) \equiv \frac{\Gamma(t; D^0 \rightarrow f) - \Gamma(t; \bar{D}^0 \rightarrow f)}{\Gamma(t; D^0 \rightarrow f) + \Gamma(t; \bar{D}^0 \rightarrow f)} \simeq a_{\text{dir}}^f - A_\Gamma \frac{t}{\tau_D}, \quad (2.1)$$

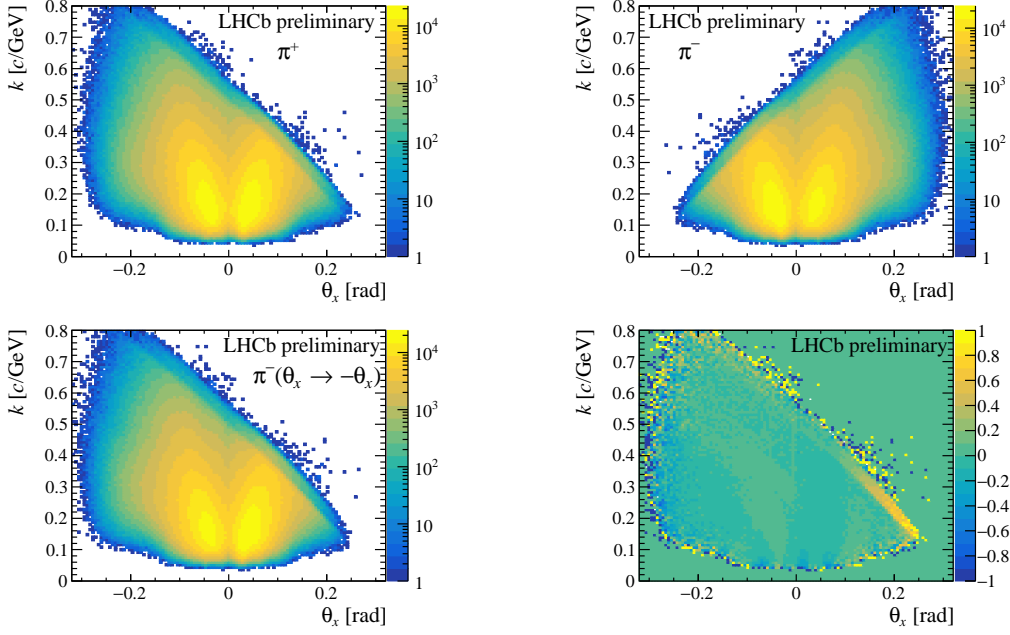
where  $\Gamma(t; D^0 \rightarrow f)$  and  $\Gamma(t; \bar{D}^0 \rightarrow f)$  indicate the time-dependent decay rates of a  $D^0$  or  $\bar{D}^0$  decaying to a final state  $f$  at time  $t$ ,  $\tau_D$  is the average lifetime of the  $D^0$  meson,  $a_{\text{dir}}^f$  is the asymmetry related to direct  $CP$  violation and  $A_\Gamma$  is the asymmetry between the  $D^0$  and  $\bar{D}^0$  effective decay widths:

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \rightarrow f} - \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}{\hat{\Gamma}_{D^0 \rightarrow f} + \hat{\Gamma}_{\bar{D}^0 \rightarrow f}}. \quad (2.2)$$

The effective decay width  $\hat{\Gamma}_{D^0 \rightarrow f}$ , is related to the time dependent decay rate by

$$\Gamma(t; D^0 \rightarrow f) \propto \exp(-t\hat{\Gamma}_{D^0 \rightarrow f}) := \exp(-t/\hat{\tau})$$

Two different methods are used to perform the measurement of  $A_\Gamma$ , based on Eq. (2.1) and Eq. (2.2), respectively. The first method, based on Eq. (2.1), is similar to that used in the previous LHCb measurement [10] but now provides the most precise results. It uses a fit to the yield asymmetry between  $D^0$  and  $\bar{D}^0$  decays, binned in decay time to determine  $A_\Gamma$ . The other method, based on Eq. (2.2), was also used in the previous LHCb measurement [10] and uses a maximum likelihood fit to the decay time distributions to extract the effective decay widths directly for both  $D^0$  and  $\bar{D}^0$  decays. The charge of the ‘‘soft’’ pion from the  $D^{*+} \rightarrow D^0\pi^+$  ( $D^{*-} \rightarrow \bar{D}^0\pi^-$ ) decay is used to identify, or ‘‘tag’’ the flavour of the  $D^0$  ( $\bar{D}^0$ ) meson at production in both methods. The two methods are now described in turn.



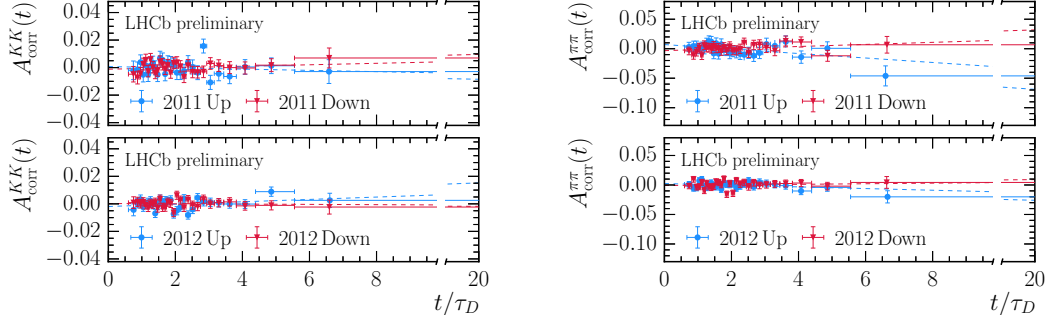
**Figure 1:** The distributions of (top left) the  $(k, \theta_x)$  space for positive pions, (top right) for negative pions, and (bottom left) for negative pions with the  $\theta_x$  component reflected about  $\theta_x = 0$ . Also shown is (bottom right) the ratio,  $R$  of the positive pion space and the reflected negative pion space.

## 2.1 Binned yield asymmetry

A background subtraction is used to remove combinatorial background and fake  $D^{*+}$  candidates, which are reconstructed with the wrong soft pion. The mass difference  $\Delta m = m(D^{*+}) - m(D^0)$  is used, as the signal peaks in this distribution while randomly chosen pions and combinatorial background have a rising distribution with a threshold at the pion mass. The signal and sideband regions defined for the subtraction are  $[144.45, 146.45]$  MeV and  $[149, 154]$  MeV, respectively. An irreducible background of  $D^{*+}$  mesons produced in  $b$ -hadron decays, known as “secondary” decays is mostly removed by the selection cut  $\ln(\chi_{IP}^2(D^0)) < 2$ , where  $\chi_{IP}^2$  is the difference between the  $\chi^2$  of the reconstructed primary interaction vertex with and without the considered particles. A systematic is assigned for residual contamination of secondaries.

A momentum dependent charge-detection asymmetry of pions is known to cause a time-dependent detection asymmetry. This is due to a correlation between momentum and decay-time. A correction is applied to the data to account for this effect. A space  $Q = (k, q_s \theta_x, \theta_y)$  is defined, where  $k = 1/\sqrt{p_x^2 + p_y^2}$  is proportional to the curvature of the soft pion track in the magnetic field,  $q_s$  is the sign of the soft pion charge and  $\theta_x = \arctan(p_x/p_z)$  ( $\theta_y = \arctan(p_y/p_z)$ ) is the emission angle in the bending (vertical) plane. The  $(k, \theta_x)$  projection of these spaces are shown in Fig. 1. These should be identical for pions from  $D^{*+}$  and  $D^{*-}$  decays, modulo a sign. Small differences are seen between these spaces in the ratio  $R = Q_{\pi^+}/Q_{\pi^-(\theta_x \rightarrow -\theta_x)}$  which is also shown. The data are corrected by reweighting such that  $R = 1$ .

The asymmetry in the number of  $D^0$  and  $\bar{D}^0$  signal candidates determined from the background



**Figure 2:** The corrected yield asymmetries in bins of decay time for (left)  $D^0 \rightarrow K^+K^-$  and (right)  $D^0 \rightarrow \pi^+\pi^-$ . The top frames show the data taken in 2011, while the bottom frames show the data taken in 2012. The two colours denote the polarity of the magnet when the data was taken. Overlaid is a linear fit to each distribution, the slope of which is equal to  $-A_\Gamma$ .

subtracted  $\Delta m$  fits in bins of decay time is shown for the  $K^+K^-$  and  $\pi^+\pi^-$  final states in Fig. 2. The slope of a linear fit to the distributions is  $-A_\Gamma$ .

The final results with the full 2011 and 2012 data samples, which are the world's best measurements of these quantities, are  $A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$  and  $A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$ , where the first uncertainty is statistical and the second is systematic. The results for  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  are consistent and show no evidence of CP violation. Assuming that only indirect CP violation contributes to  $A_\Gamma$  [5], and accounting for correlations between the systematic uncertainties, the two values obtained with this method can be averaged to yield a single value of  $A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$ , which shows no indication of CPV.

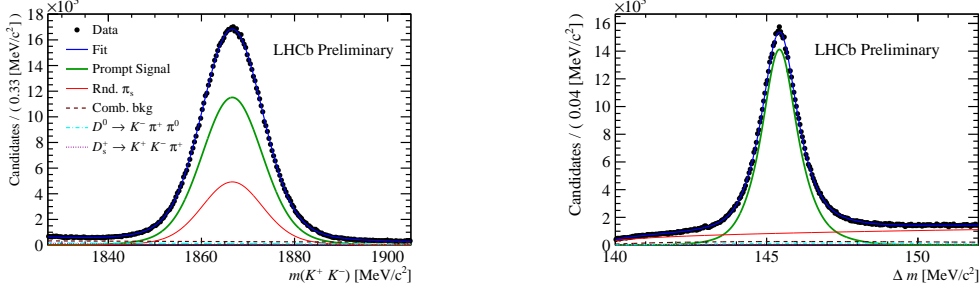
## 2.2 Unbinned maximum likelihood fit

The other method employs a two stage maximum likelihood fit to extract the effective decay times,  $\hat{\tau}$  of the  $D^0$  and  $\bar{D}^0$  decays, which is related to the effective decay width as  $\hat{\tau} = 1/\hat{\Gamma}_{D^0 \rightarrow f}$ . The data is split into three data-taking periods to account for known differences in the detector alignment and calibration after detector interventions. In the first stage, fits to the  $D^0$  mass and  $\Delta m$  spectra, as in Fig. 3, are used to determine yields of signal decays and both combinatorial and partially reconstructed backgrounds. In the second stage, the decay time is fitted along with  $\ln(\chi_{\text{IP}}^2(D^0))$  (Fig. 4) to separate secondary background and determine the effective decay time.

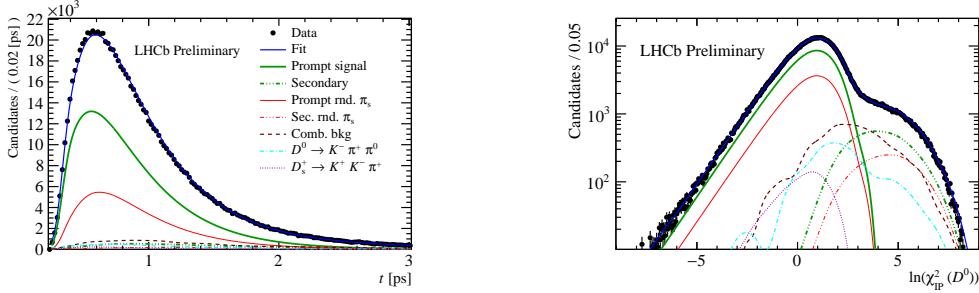
Biases on the decay-time distribution, introduced by the selection criteria and detection asymmetries, are accounted for through per-candidate acceptance functions. These acceptance functions are parametrised by the decay-time intervals within which a candidate would pass the event selection if its decay time could be varied. The acceptance functions are determined using a data-driven method [11].

The method is validated by measuring an asymmetry consistent with zero from the control channel,  $A_\Gamma(K^-\pi^+) = (-0.07 \pm 0.15) \times 10^{-3}$  in the 2012 data sample. The largest source of systematic uncertainty for this method with  $K^+K^-$  ( $\pi^+\pi^-$ ) is  $0.08 \times 10^{-3}$  ( $0.10 \times 10^{-3}$ ), due to the uncertainty in modelling the contamination from secondary (combinatorial) background. The results from the 2012 data sample are  $A_\Gamma(K^+K^-, 2012) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}$  and

$A_\Gamma(\pi^+\pi^-, 2012) = (0.03 \pm 0.79 \pm 0.16) \times 10^{-3}$ . These results are then combined with results from Ref. [10] to yield full Run 1 measurements:  $A_\Gamma(K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}$  and  $A_\Gamma(\pi^+\pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3}$ , which are consistent with no CPV and with the results of the first method.



**Figure 3:** Distributions of (left)  $m(K^+K^-)$  and (right)  $\Delta m$  for the  $D^0 \rightarrow K^+K^-$  selected candidates from one of the three data-taking periods. The maximum likelihood fit results are overlaid.



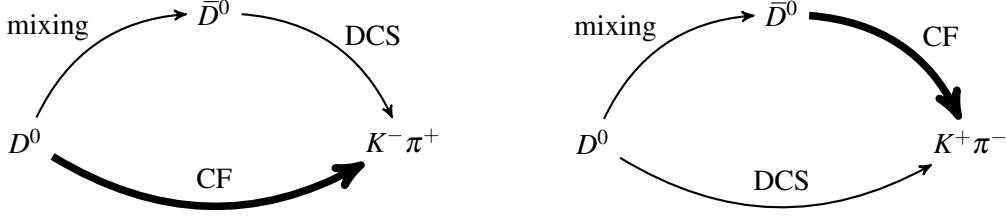
**Figure 4:** Distribution of (left) decay-time and (right)  $\ln(\chi_{\text{IP}}^2(D^0))$  for the  $D^0 \rightarrow K^+K^-$  candidates from one of the three data-taking periods. The unbinned maximum likelihood fit results are overlaid.

### 3. CP hypothesis fits to $R^\pm(t)$

The right sign (RS) decay  $D^0 \rightarrow K^- \pi^+$  and the highly suppressed wrong sign (WS) decay  $D^0 \rightarrow K^+ \pi^-$  and their complex conjugates, can proceed through two different mechanisms, as shown in Fig. 5. The interference between these diagrams gives access to the full complement of mixing and CPV terms. The ratio of the number of wrong sign to right sign candidates against time, for negligible direct CPV and small  $x$  and  $y$ , is defined as,

$$\frac{WS^\pm(t)}{RS^\pm(t)} := R^\pm(t) \approx R_D^\pm + \sqrt{R_D^\pm} y'^{\pm} \Gamma t + \frac{x'^{\pm 2} + y'^{\pm 2}}{4} (\Gamma t)^2, \quad (3.1)$$

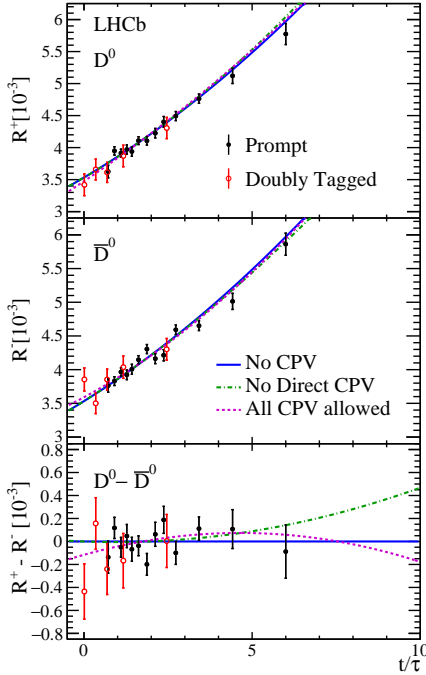
where  $R_D^+ = |A_{\bar{f}}/A_f|^2$ ,  $R_D^- = |\bar{A}_f/\bar{A}_{\bar{f}}|^2$ .  $A_f$  denotes the transition amplitude  $D^0 \rightarrow K^- \pi^+$  and  $\bar{A}_f$  denotes the transition amplitude of  $\bar{D}^0 \rightarrow K^- \pi^+$ , while  $\bar{A}_{\bar{f}}$  denotes  $\bar{D}^0 \rightarrow K^+ \pi^-$  and  $A_{\bar{f}}$  denotes  $D^0 \rightarrow K^+ \pi^-$ . The parameters  $x'$  and  $y'$  are  $x$  and  $y$  rotated by the relative strong phase between the DCS and CF amplitudes  $\bar{A}_f$  and  $A_f$  and  $\Gamma$  is the average decay width between the two  $D^0$  mass eigenstates. The sign indicates the flavour,  $D^0$  or  $\bar{D}^0$ , and thus the measurement becomes a simple counting experiment of the four possible decays which are used to compute two ratios. Fits to the  $\Delta m$  distributions are used to count the number of signal events.



**Figure 5:** Mechanisms of the decays  $D^0 \rightarrow K^\pm \pi^\mp$ . (left) The right sign decay can proceed through a CF decay or the  $D^0$  can mix into a  $\bar{D}^0$  and undergo a DCS decay, which is a highly suppressed path. (right) The wrong sign decay can proceed through a suppressed mixing process then a CF decay, or through a DCS decay.

Two techniques are used to determine the flavour of the initial meson. A previous LHCb publication uses a single soft pion to tag the flavour with the decay  $D^{*+} \rightarrow D^0 \pi^+$  [7]. A complimentary measurement uses both the soft pion from the  $D^{*+}$  decay and the muon in  $\bar{B} \rightarrow D^{*+} \mu^- X$  to doubly tag the flavour [12].

Three mixing hypotheses are tested in fits to the difference  $R^+ - R^-$ ,  $CP$  symmetry ( $R^+ = R^-$ ),  $CP$  symmetry in decay amplitudes ( $R_D^+ = R_D^-$ ) and all  $CP$  allowed. Fig. 6 shows the fits to these hypotheses and the values of the resulting fit parameters. The data are consistent with all three hypothesis including the no CPV hypothesis.



Parameter	DT + Prompt	
	No CPV	
$R_D [10^{-3}]$	$3.533 \pm 0.054$	$3.568 \pm 0.067$
$x'^2 [10^{-4}]$	$0.36 \pm 0.43$	$0.55 \pm 0.49$
$y'^+ [10^{-3}]$	$5.23 \pm 0.84$	$4.8 \pm 0.9$
$\chi^2/\text{ndf}$	96.6/111	86.4/101
Parameter	No direct CPV	
	$R_D [10^{-3}]$	$3.533 \pm 0.054$
$(x'^+)^2 [10^{-4}]$	$0.49 \pm 0.50$	$0.64 \pm 0.56$
$y'^+ [10^{-3}]$	$5.14 \pm 0.91$	$4.8 \pm 1.1$
$(x'^-)^2 [10^{-4}]$	$0.24 \pm 0.50$	$0.46 \pm 0.55$
$y'^- [10^{-3}]$	$5.32 \pm 0.91$	$4.8 \pm 1.1$
$\chi^2/\text{ndf}$	96.1/109	86.0/99
Parameter	All CPV allowed	
	$R_D^+ [10^{-3}]$	$3.474 \pm 0.081$
$(x'^+)^2 [10^{-4}]$	$0.11 \pm 0.65$	$0.49 \pm 0.70$
$y'^+ [10^{-3}]$	$5.97 \pm 1.25$	$5.1 \pm 1.4$
$R_D^- [10^{-3}]$	$3.591 \pm 0.081$	$3.591 \pm 0.090$
$(x'^-)^2 [10^{-4}]$	$0.61 \pm 0.61$	$0.60 \pm 0.68$
$y'^- [10^{-3}]$	$4.50 \pm 1.21$	$4.5 \pm 1.4$
$\chi^2/\text{ndf}$	95.0/108	85.9/98

**Figure 6:** Fits to (left top) the ratio  $R^+$ , (left middle) the ratio  $R^-$  and (left bottom) the difference between the two ratios. The three  $CP$  hypotheses fits are shown. The red points are from the doubly tagged (DT) dataset, while the black points are from the prompt, singly tagged dataset. The fit results (right) of the three  $CP$  hypotheses.

## 4. Conclusion

The measured values of  $A_\Gamma$ , which correspond to the most precise determination to date, are  $A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}$  and  $A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}$ . The measured difference  $R^+ - R^-$  is consistent with the no CPV hypothesis. Thus no evidence has yet been found for CP violation in the charm system. LHCb continues to produce world leading measurements of CP violation parameters in this system with ever increasing precision.

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