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CP violation and mixing in charm decays at LHCb

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The size of *CP* violation allowed for by the Standard Model is orders of magnitude too small to explain our matter-dominated universe. Processes from physics beyond the Standard Model could enhance this violation and explain the observed asymmetry between matter and antimatter.
The charm sector is a relevant probe to search for New Physics processes and is complementary to other searches in the kaon and *B* systems. *CP* violation has recently been observed for the first time in charm decays by the LHCb collaboration. However, more work needs to be performed in order to understand the full picture.
These proceedings cover six recent analyses from LHCb that explore mixing and *CP* violation in charm decays and contribute to a better understanding of this sector.

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1 Introduction

The allowed amount of charge-parity (*CP*) violation in the Standard Model (SM) is orders of magnitude too small to explain our matter-dominated universe [1,2]. Therefore, new sources of *CP* violation need to be revealed and this forms the basis of a wide range of searches performed by the LHCb experiment at CERN.

CP violation has been observed in the kaon [3], B^0 [4, 5], B^+ [6–8] and B_s^0 [9] systems, where observations agree with SM predictions. In the charm system, *CP* violation is predicted to be very small by the SM [10, 11]. This therefore represents an ideal low SM background environment for New Physics (NP) searches.

The LHCb detector has collected the largest sample of charm decays to date with very good momentum resolution and tracking efficiency, as well as excellent vertex resolution [12]. LHCb is therefore currently the best place to perform precision measurements searching for *CP* violation in charm.

1.1 *CP* violation

CP violation arises in three different forms. First, direct *CP* violation or *CP* violation in the decay arises with a difference of the decay rates between two *CP* conjugate states and is defined as

$$\left|\frac{A_f}{\overline{A}_{\overline{f}}}\right| \neq 1\,, \tag{1}$$

where A_f is the total decay amplitude of a certain $D \to f$ process and $\overline{A}_{\overline{f}}$ is that of its *CP* conjugate process, $\overline{D} \to \overline{f}$.

The second form is *CP* violation in mixing. It manifests itself as a difference of transition rates between two flavour eigenstates, *i.e.* when

$$\left|\frac{q}{p}\right| \neq 1\,, \tag{2}$$

where p and q are the two complex parameters that define the mass eigenstates of the neutral D meson

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle\,, \tag{3}$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle\,, \tag{4}$$

with the normalisation $|p|^2 + |q|^2 = 1$.

Finally, *CP* violation in interference between mixing and decay is caused by the interference between the two previous sources and is defined as

$$\mathrm{Im}\left(\frac{q}{p}\frac{\overline{A}_f}{A_f}\right) \neq 0\,. \tag{5}$$

1.2 Mixing

A D^0 meson can oscillate into a $\overline{D}^0$ meson and vice versa. The mixing parameters are defined as

$$x \equiv \frac{m_1 - m_2}{\Gamma}\,, \quad y \equiv \frac{\Gamma_1 - \Gamma_2}{2\Gamma}\,, \quad \text{with } \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}\,, \tag{6}$$

where the indices refer to the mass eigenstates D_1 and D_2 defined previously.

2 Observation of *CP* violation in charm decays [13]

This analysis is based on the full Run 2 dataset corresponding to an integrated luminosity of $5.9\,\mathrm{fb}^{-1}$. Two Cabibbo-suppressed decay modes are considered, namely $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, where the flavour of the neutral D meson is tagged experimentally either by the slow pion when the D^0 meson comes from a $D^*(2010)^+$ resonance (referred to as the prompt sample), or by the muon when the D^0 meson comes from a B decay (referred to as the semileptonic sample). The four invariant-mass distributions can be seen in Fig. 1.

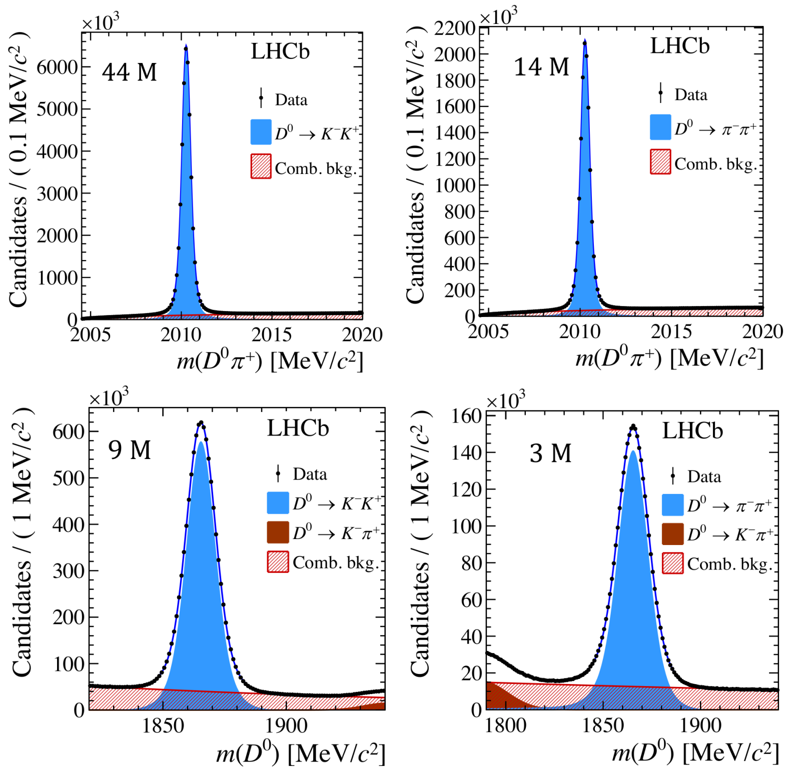

Figure 1: Invariant-mass distributions for the prompt (top) and semileptonic (bottom) analyses for the $D^0 \to K^+K^-$ (left) and the $D^0 \to \pi^+\pi^-$ (right) decay modes.

The raw asymmetry, accessible by counting the number of D^0 and $\bar{D}^0$ mesons, receives contributions from some experimental asymmetries in addition to the physical *CP* asymmetry. It is defined as

$$A_{\mathrm{raw}}(D^0 \to f) \equiv \frac{N_{D^0} - N_{\bar{D}^0}}{N_{D^0} + N_{\bar{D}^0}} \approx A_{CP}(D^0 \to f) + A_P(D^*, B) + A_D(f) + A_D(\pi, \mu), \qquad (7)$$

where $A_P(D^*, B)$ is the production asymmetry between the two *CP*-conjugated mother particles (either the D^* or the B meson). The detection asymmetry between the daughter particles, $A_D(f)$, is due to the different cross-sections of particles of opposite charges when interacting with the detector's material. In this analysis $A_D(f)$ cancels out since the final states, K^+K^- and $\pi^+\pi^-$, are symmetric. $A_D(\pi, \mu)$ is the tagging asymmetry, which is due to a different behaviour in matter of tagging particles of opposite charges. Finally the physical *CP* asymmetry, A_{CP}, is defined as

$$A_{CP} \equiv \frac{\Gamma(i \to f) - \Gamma(\bar{i} \to \bar{f})}{\Gamma(i \to f) + \Gamma(\bar{i} \to \bar{f})} . \tag{8}$$

The experimental asymmetries are difficult to measure. One approach is to analyse two similar decay modes in order to cancel them using a new observable, ΔA_{CP}, which is defined as

$$\begin{aligned} \Delta A_{CP} &\equiv A_{\rm raw}(D^0 \to K^+K^-) - A_{\rm raw}(D^0 \to \pi^+\pi^-) \\ &= A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) . \end{aligned} \tag{9}$$

The results of this analysis are

$$\Delta A_{CP}^{prompt} = [-18.2 \pm 3.2\,(\text{stat}) \pm 0.9\,(\text{syst})] \times 10^{-4} , \tag{10}$$

$$\Delta A_{CP}^{SL} = [-9 \pm 8\,(\text{stat}) \pm 5\,(\text{syst})] \times 10^{-4} , \tag{11}$$

which, combined with the previous Run 1 analyses [14, 15], give

$$\Delta A_{CP} = [-15.4 \pm 2.9] \times 10^{-4} , \tag{12}$$

where the uncertainty includes both statistical and systematic contributions. This is the first observation of *CP* violation in charm decays with a significance of 5.3σ. This result is compatible with the expectation from the SM, albeit somewhat on the upper end of the spectrum of the predictions. More precise theory computations will help understand the nature of this effect.

3 Search for time-dependent *CP* violation in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays [16, 17]

A complementary search to this integrated measurement is to look for time-dependent *CP* violation. The two same decay modes are analysed, $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$, and two analyses are performed in parallel. The prompt analysis [16] uses the data collected in 2015 and 2016 and the semileptonic analysis [17] uses the data collected between 2016 and 2018. The raw asymmetry is defined as

$$A_{\rm raw}(D^0 \to f;t) \approx A_{CP}(D^0 \to f;t) + A_P(D^*, B) + A_D(\pi, \mu) , \tag{13}$$

and it contains a dependence on the decay time in the physical *CP* asymmetry, which can be parametrised as

$$A_{CP} \approx A_{CP}^{\rm dir} - A_\Gamma \frac{t}{\tau} . \tag{14}$$

This means that the time dependence is not affected by experimental asymmetries and A_Γ can directly be extracted from the slope of the graph of the raw asymmetry versus time.

The first goal of both analyses is to verify that the measurement of A_Γ in the control channel $D^0 \to K^-\pi^+$, in which it is expected to be well below the experimental sensitivity, is compatible with zero. This is indeed the case, as shown in Fig. 2, and the obtained values are

$$A_\Gamma = [0.7 \pm 1.1] \times 10^{-4} , \tag{15}$$

$$A_\Gamma = [1.6 \pm 1.2] \times 10^{-4} , \tag{16}$$

for the prompt and the semileptonic analyses, respectively, where the uncertainties are statistical only.

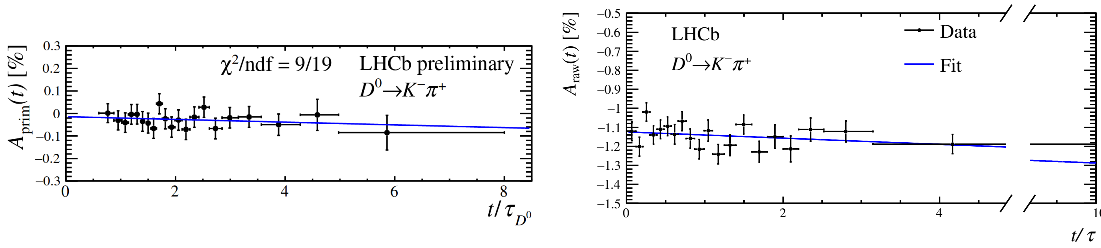

Figure 2: Measurement of A_Γ in the control channel $D^0 \to K^-\pi^+$ from the prompt (left) and the semileptonic (right) analyses.

The measurements of A_Γ for $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ are shown in Fig. 3. The preliminary results of the prompt analysis are

$$A_\Gamma(D^0 \to K^+K^-) = [1.3 \pm 3.5\,(\text{stat}) \pm 0.7\,(\text{syst})] \times 10^{-4}\,, \tag{17}$$

$$A_\Gamma(D^0 \to \pi^+\pi^-) = [11.3 \pm 6.9\,(\text{stat}) \pm 0.8\,(\text{syst})] \times 10^{-4}\,, \tag{18}$$

and of the semileptonic analysis

$$A_\Gamma(D^0 \to K^+K^-) = [-4.3 \pm 3.6\,(\text{stat}) \pm 0.5\,(\text{syst})] \times 10^{-4}\,, \tag{19}$$

$$A_\Gamma(D^0 \to \pi^+\pi^-) = [2.2 \pm 7.0\,(\text{stat}) \pm 0.8\,(\text{syst})] \times 10^{-4}\,. \tag{20}$$

By combining these results with those from Run 1 [18, 19], and assuming that A_Γ is independent of the decay channels, the following preliminary average is obtained

$$A_\Gamma = [-1.1 \pm 1.7\,(\text{stat}) \pm 0.5\,(\text{syst})] \times 10^{-4}\,. \tag{21}$$

No *CP* violation is observed but the sensitivity of these measurements is still one order of magnitude above the SM expectation, which, for A_Γ, is 3×10^{-5} [20]. This analysis will therefore greatly benefit from the addition of more data collected with the upgraded LHCb detector in Run 3.

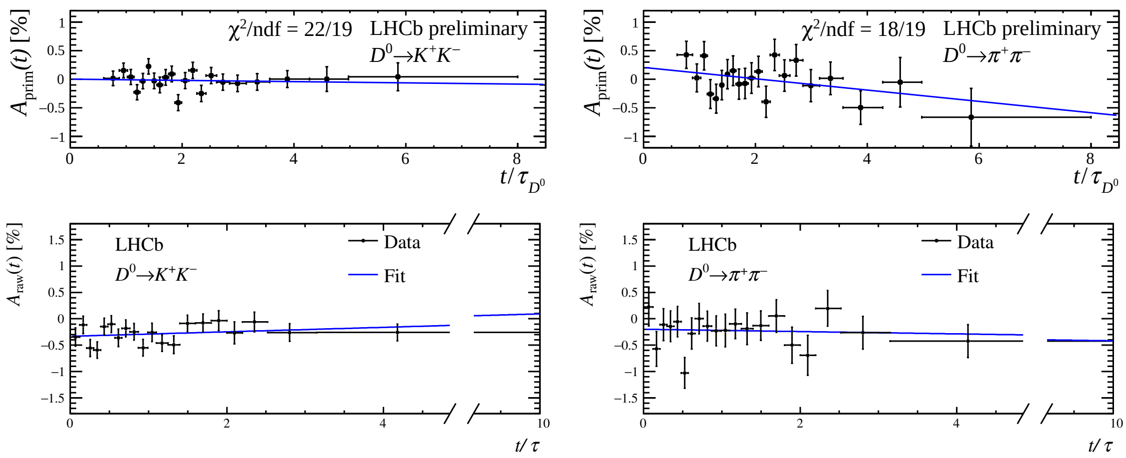

Figure 3: Measurements of A_Γ for the prompt (top) and semileptonic (bottom) analyses of the $D^0 \to K^+K^-$ (left) and $D^0 \to \pi^+\pi^-$ (right) decay modes.

4 Search for *CP* violation in $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$ and $D^+ \to \phi\pi^+$ decays [21]

CP violation is also searched for in other decay modes, such as, $D_s^+ \to K_S^0\pi^+$, $D^+ \to K_S^0K^+$ and $D^+ \to \phi\pi^+$. This analysis uses the data collected between 2015 and 2017. The raw asymmetry is again defined as

$$A_{\mathrm{raw}}(D_{(s)}^+ \to f^+) \approx A_{CP}(D_{(s)}^+ \to f^+) + A_P(D_{(s)}^+) + A_D(f^+)\,. \tag{22}$$

The experimental asymmetries are subtracted by using three Cabibbo-favoured decay modes, in which it is assumed that there is no *CP* violation: $D^+ \to K_S^0\pi^+$, $D_s^+ \to K_S^0K^+$ and $D_s^+ \to \phi\pi^+$. The *CP* asymmetry of the Cabibbo-suppressed modes can then directly be determined as

$$A_{CP}(D_s^+ \to K_S^0\pi^+) \approx A_{\mathrm{raw}}(D_s^+ \to K_S^0\pi^+) - A_{\mathrm{raw}}(D_s^+ \to \phi\pi^+) - A_D(\overline{K}^0), \tag{23}$$

$$\begin{aligned} A_{CP}(D^+ \to K_S^0K^+) \approx{}& A_{\mathrm{raw}}(D^+ \to K_S^0K^+) - A_{\mathrm{raw}}(D^+ \to K_S^0\pi^+) \\ &- A_{\mathrm{raw}}(D_s^+ \to K_S^0K^+) + A_{\mathrm{raw}}(D_s^+ \to \phi\pi^+) + A_D(\overline{K}^0), \end{aligned} \tag{24}$$

$$A_{CP}(D^+ \to \phi\pi^+) \approx A_{\mathrm{raw}}(D^+ \to \phi\pi^+) - A_{\mathrm{raw}}(D^+ \to K_S^0\pi^+) + A_D(\overline{K}^0), \tag{25}$$

where $A_D(\overline{K}^0)$ is the kaon asymmetry that needs to be taken care of separately as it is not present in all decay modes. The invariant-mass distributions of the Cabibbo-favoured and suppressed decay modes can be seen on Fig. 4, and the resulting values for the *CP* asymmetries are

$$A_{CP}(D_s^+ \to K_S^0\pi^+) = [1.6 \pm 1.7\ (\mathrm{stat}) \pm 0.5\ (\mathrm{syst})] \times 10^{-3}\,, \tag{26}$$

$$A_{CP}(D^+ \to K_S^0K^+) = [-0.04 \pm 0.61\ (\mathrm{stat}) \pm 0.45\ (\mathrm{syst})] \times 10^{-3}\,, \tag{27}$$

$$A_{CP}(D^+ \to \phi\pi^+) = [0.03 \pm 0.40\ (\mathrm{stat}) \pm 0.29\ (\mathrm{syst})] \times 10^{-3}\,, \tag{28}$$

which are all compatible with *CP* conservation.

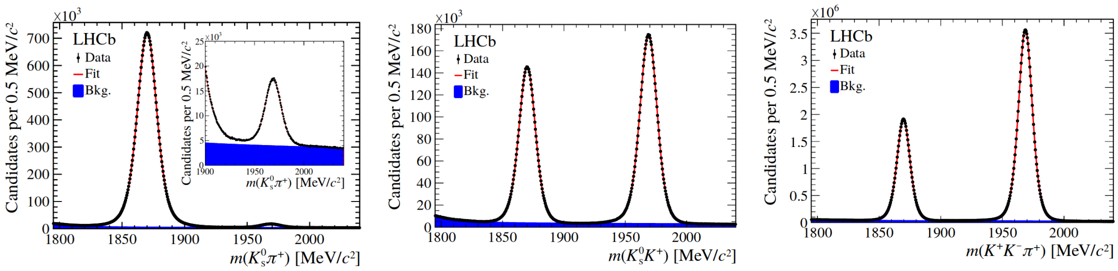

Figure 4: Distributions of the $K_S^0\pi^+$, $K_S^0K^+$ and $K^+K^-\pi^+$ invariant-mass combinations.

5 Search for *CP* violation through an amplitude analysis of $D^0 \to K^+K^-\pi^+\pi^-$ decays [22]

New Physics processes can enhance local *CP* violation effects that could be missed in integrated searches. Multi-body decay modes are a very good probe to look for such local effects due to their large number of interfering amplitudes. The decay mode $D^0 \to K^+K^-\pi^+\pi^-$ has been analysed with the Run 1 dataset, corresponding to an integrated luminosity of $3\,\text{fb}^{-1}$, where the D meson comes from the semileptonic B decay mode.

An amplitude analysis is performed by describing the signal using a coherent sum of amplitudes following the isobar model and the background is described using the lower and upper D^0 mass sidebands. In order to create the signal model, an exhaustive list of potentially contributing amplitudes is created along with a basic model containing the obvious $\phi(1020)$, $\rho(770)$, $K^*(892)^0$ and $\bar{K}^*(892)^0$ resonances. All the amplitudes from the list are iteratively tested and the best amplitude (*i.e.* the one that produces the largest decrease in $-2\ln L$) is permanently added to the model. Amplitudes are added to the model until a stopping criterion, based on the goodness of the fit and the level of interference, is met. A total of 26 amplitudes have been found to be significantly contributing to the $D^0 \to K^+K^-\pi^+\pi^-$ decay channel and the result of the fit is shown in Fig. 5. The five-dimensional phase space of this decay mode is visualised using five variables: the invariant masses of the two kaons, $m(K^+K^-)$, and of the two pions, $m(\pi^+\pi^-)$, the helicity angles of the kaon, θ_K, and of the pion, θ_π, and the angle between the decay planes of the two kaons and the two pions, ϕ.

With this novel D^0 model, a simultaneous fit is performed to the D^0 and $\bar{D}^0$ candidates in order to look for *CP* violation. The result is consistent with *CP* symmetry with a sensitivity ranging from 1% to 15%, depending on the amplitude.

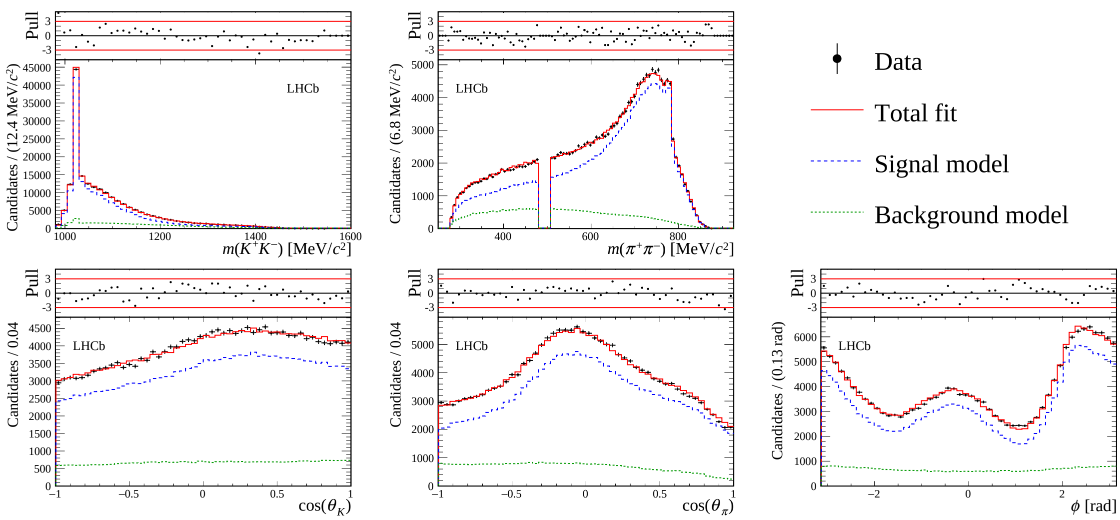

Figure 5: Distributions of the five variables describing the phase space of the selected D^0 and $\bar{D}^0$ candidates. The signal model (dashed blue), background model (dotted green) and total fit function (plain red) are superimposed to the data points (black points with error bars).

6 Measurement of the mass difference between neutral charm-meson eigenstates in $D^0 \to K^0_S\pi^+\pi^-$ decays [23]

Another method to probe local *CP* violation effects is to split the phase space in a model independent manner. Such a technique is used in the analysis of $D^0 \to K^0_S\pi^+\pi^-$ decays, using the

Run 1 dataset and the semileptonic and prompt tagging channels. The phase space is split according to the bin-flip method [24]. The bins are chosen such as to keep a nearly constant strong-phase difference between the D^0 and $\bar{D}^0$ candidates. The separation of the phase space is shown in Fig. 6.

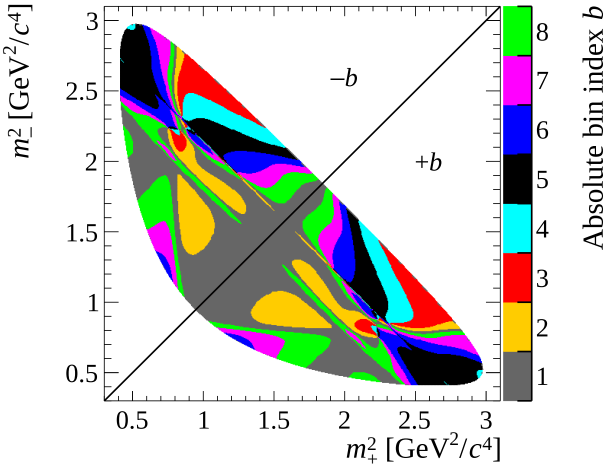

Figure 6: Visualisation of the bins splitting the phase space, where $m_\pm^2$ is defined as $m^2(K_S^0\pi^\pm)$ for $D^0 \to K_S^0\pi^+\pi^-$ decays and as $m^2(K_S^0\pi^\mp)$ for $\bar{D}^0 \to K_S^0\pi^+\pi^-$ decays.

CP violation is parametrised by the quantities

$$x_{CP} \equiv -\mathrm{Im}(z_{CP}), \qquad y_{CP} \equiv -\mathrm{Re}(z_{CP}), \tag{29}$$

$$\Delta x \equiv -\mathrm{Im}(\Delta z), \qquad \Delta y \equiv -\mathrm{Re}(\Delta z), \tag{30}$$

where

$$z_{CP} \pm \Delta z \equiv -(q/p)^{\pm 1}(y + ix)\,. \tag{31}$$

A simultaneous least-square fit of yields in all phase space and decay-time bins is performed and the resulting *CP* parameters are

$$x_{CP} = [2.7 \pm 1.6\ (\mathrm{stat}) \pm 0.4\ (\mathrm{syst})] \times 10^{-3}\,, \tag{32}$$

$$\Delta x = [-0.53 \pm 0.70\ (\mathrm{stat}) \pm 0.22\ (\mathrm{syst})] \times 10^{-3}\,, \tag{33}$$

$$y_{CP} = [7.4 \pm 3.6\ (\mathrm{stat}) \pm 1.1\ (\mathrm{syst})] \times 10^{-3}\,, \tag{34}$$

$$\Delta y = [0.6 \pm 1.6\ (\mathrm{stat}) \pm 0.3\ (\mathrm{syst})] \times 10^{-3}\,, \tag{35}$$

which can be used to derive the mixing parameters shown in Table 1.

The combination of this result with the current world average gives the first evidence for a mass difference between the neutral charm meson eigenstates, *i.e.*

$$x = [3.9^{+1.1}_{-1.2}] \times 10^{-3}\,. \tag{36}$$

Parameter	Value	95.5% CL interval
x $[10^{-2}]$	$0.27\,^{+0.17}_{-0.15}$	$[-0.05, 0.60]$
y $[10^{-2}]$	0.74 ± 0.37	$[\ \ 0.00, 1.50]$
$\lvert q/p\rvert$	$1.05\,^{+0.22}_{-0.17}$	$[\ \ 0.55, 2.15]$
ϕ	$-0.09\,^{+0.11}_{-0.16}$	$[-0.73, 0.29]$

Table 1: Summary of mixing parameters. The uncertainties include statistical and systematic contributions.

7 Conclusion

These proceedings give an overview of six recent LHCb analyses. *CP* violation has been observed for the first time in the charm sector, paving the way to a new era of precision measurements. Many other analyses are trying to measure *CP* violation in this sector in different ways in order to understand the nature of the asymmetry. Significant work on both experimental and theoretical sides is still required to rule out any contribution from New Physics.

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