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Mixing and CP violation in B and D meson systems

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Summary. — This paper reports several new and recent results from the LHCb Collaboration about mixing and CP violation in B and D meson systems, as presented by the author at Les Rencontres de Physique de la Vallée d'Aoste 2017 in Italy.

1. – Introduction

Flavour oscillations have been observed in both neutral beauty and charm meson systems. Measurements of B-mixing and CP violation allow access to parameters which have improved our understanding of CP violation within the framework of the Standard Model (SM). CP violation has not yet been observed in the charm sector and is expected to be very small in the SM, allowing increased sensitivity to New Physics.

The LHCb detector [1,2] is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ and is designed primarily for the study of particles containing b or c quarks. The detector elements that are particularly relevant to the analyses described in this document are the silicon-strip vertex detector surrounding the pp interaction region that allows b and c hadrons to be identified from their characteristically long flight distances, the tracking system that provides a measurement of momenta of charged particles, and two ring-imaging Cherenkov detectors that are able to discriminate between species of charged hadrons. Muons are identified by a system composed of alternating layers of iron and multiwire proportional chambers.

2. – Measurements of the Cabibbo-Kobayashi-Maskawa (CKM) angle γ

Verifying the unitarity of the CKM triangle, with angles α, β and γ, is of the utmost importance since non-unitarity is a clear sign of New Physics. The CKM angle $\gamma\big(\equiv \arg\big(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\big)\big)$ is the least well measured angle of the CKM unitarity triangle and the only one that can be determined in a theoretically clean way using tree-level decays.

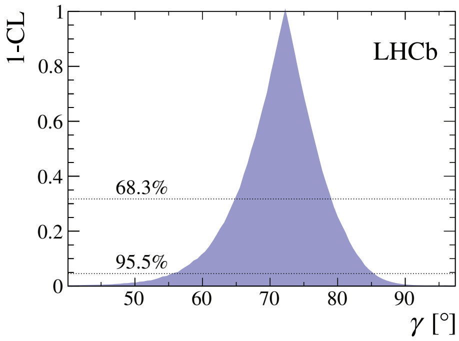


Fig. 1: 1-CL (or p-value) curves for γ from the latest LHCb γ combination measurement [4]. The 1σ and 2σ levels are indicated by the horizontal dotted lines

The LHCb Collaboration has performed CP violation measurements in a wide range of γ sensitive modes with charged and neutral B mesons decaying to a variety of final states. The observables from these various analyses are combined with external inputs [3], resulting in a measurement of $\gamma = (72.2^{+6.8}_{-7.3})^{\circ}$ [4]. This is the world's most precise direct measurement of γ to come from a single experiment. This analysis uses a frequentist approach. The confidence level (CL) is evaluated from the global minimum of the χ^2-function at each value of γ, resulting in the 1-CL distribution given in fig. 1. As a consistency test, a Bayesian procedure is also performed and found to be consistent. All the results that contribute in the combination measurement are extracted from the $3\,\text{fb}^{-1}$ dataset collected in 2011 and 2012.

These direct measurements of γ involve only tree level processes. Global fits to the CKM triangle from CKMfitter [5], shown in fig. 2, use the current best measurements of quantities, such as α, β, Δm_d and Δm_s as inputs, where Δm_d and Δm_s are the mass differences between the mass eigenstates of $B^0_d - \bar{B}^0_d$ and $B^0_s - \bar{B}^0_s$, respectively. Assuming the correctness of SM, *i.e.* the unitarity of the CKM matrix, γ can then be extracted.

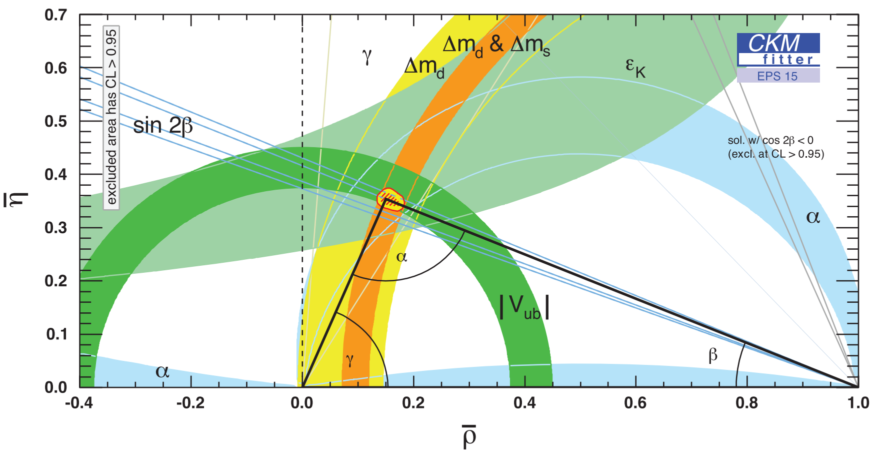
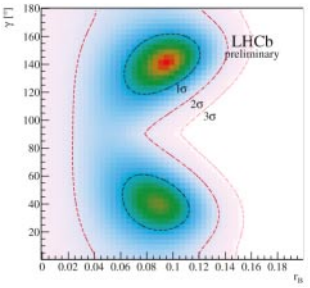
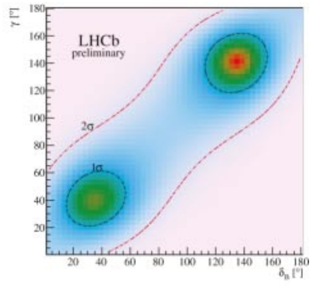


Fig. 2: Diagram on the Argand place showing the current state of measurements of the unitarity triangle [5]. The red hashed region of the global combination corresponds to 68% CL.



(a) γ *vs.* r_B



(b) γ *vs.* δ_B

Fig. 3: 2D scans showing the sensitivity of the results from the $B^{\pm} \to DK^{*\pm}$ analysis [6] to r_B, δ_B and γ.

Note that these inputs include loop processes and therefore in principle are sensitive to New Physics. This indirect method results in a γ measurement of $(66.85^{+0.94}_{-3.44})^{\circ}$. The uncertainties on the indirect measurement are driven by lattice QCD calculations and are expected to decrease with time as lattice calculations become more accurate. The difference between the direct and indirect measurements could become significant with degree-level precision on a direct measurement of γ.

The LHCb Collaboration is now looking to improve on the γ measurement by exploiting the expanding Run 2 dataset and exploring new γ sensitive modes. One such analysis is the γ-sensitive $B^{\pm} \to DK^{*\pm}$, which has now been analysed at LHCb for the first time, and uses both the Run 1 and Run 2 dataset [6]. Sensitivity to γ comes from the interference between $B^- \to D^0K^{*-}$ and $B^- \to \bar{D}^0K^{*-}$, where the D^0 and $\bar{D}^0$ decay to the same final state. This analysis considers two-body D decays, $D^0 \to K^-\pi^+, K^+K^+, \pi^+\pi^-, K^+\pi^-$. A simultaneous fit is performed to all the different D modes to extract the CP observables, which are then interpreted in terms of r_B, δ_B and γ, as shown in fig. 3, where r_B and δ_B are the hadronic parameters of the B decay. The parameter r_B is the magnitude of the ratio between the suppressed and favoured amplitudes of the B decay and δ_B is the strong phase difference between these amplitudes. The sensitivity of this decay, as well as the increase in statistics obtained from Run 2 data, are very promising for constraining γ in the future.

3. – Charm mixing and CPV in $D^0 \to K^{\pm}\pi^{\mp}$

$D^0 - \bar{D}^0$ mixing is characterised by two dimensionless parameters, $x = \Delta M/\Gamma$ and $y = \Delta\Gamma/2\Gamma$, where ΔM and $\Delta\Gamma$ are the mass and decay width differences of the two mass eigenstates, and Γ is the average decay width.

The decay $D^0 \to K^+\pi^-$ is a doubly Cabibbo-suppressed (DCS) decay, while $D^0 \to K^-\pi^+$ is Cabibbo-favoured (CF). When a D meson initially identified as a D^0 is reconstructed in the $K^+\pi^-$ final state, it is denoted "Wrong Sign" (WS), and when it is reconstructed in the $K^-\pi^+$ final state, it is denoted "Right Sign" (RS). The WS decay can proceed via two paths of comparable strength: the direct DCS decay, or via $D^0 - \bar{D}^0$ mixing followed by the CF decay, *i.e.* $D^0 \to \bar{D}^0 \to K^-\pi^+$. The oscillatory behaviour introduces a time dependence into the WS decay rate. Experimentally measuring the time dependence of the ratio $R(t)$ of WS to RS rates gives access to parameters quantifying charm mixing and CP violation. Assuming the mixing parameters x and y are small we can write the time-dependent ratio as

$$R(t)^{\pm} = R_D^{\pm} + \sqrt{R_D^{\pm}}\, y'^{\pm} \left(\frac{t}{\tau}\right) + \frac{(x'^{\pm})^2 + (y'^{\pm})^2}{4} \left(\frac{t}{\tau}\right)^2. \tag{1}$$

Here the first term on the RHS is due to the DCS decay, the third term is due to the mixing and the second term corresponds to the interference between these two paths. The parameters x' and y' are related to the mixing parameters x and y via a rotation by the strong phase $\delta_{K\pi}$, R_D is the ratio of DCS to CF amplitudes, and τ is the average lifetime of the two mass eigenstates. The $\pm$ superscripts correspond to the D^0 and $\bar{D}^0$. Therefore, if $R_D^+ \neq R_D^-$, this implies direct CP violation, whereas if $x'^+ \neq x'^-$ or $y'^+ \neq y'^-$, this points to CP violation in the mixing.

The LHCb Collaboration has previously used the $D^0 \to K^{\pm}\pi^{\mp}$ channel to make the first single-measurement observation of charm mixing using D^* candidates produced directly in the pp collisions, known as the prompt charm sample [7]. This latest measurement uses doubly-tagged candidates from $B \to D^{*\pm}\mu^{\mp}X$, $D^{*\pm} \to D^0\pi^{\pm}$ [8]. Although this sample has about 40 times lower statistics that the prompt sample, it has a much higher purity and improved coverage at low decay times.

The doubly-tagged $D^0 \to K^{\pm}\pi^{\mp}$ analysis uses the full $3\,\mathrm{fb}^{-1}$ sample collected in 2011 and 2012, and after a standard selection process, 1.73×10^6 RS candidates and 6.68×10^3 WS candidates are obtained. Fits are performed to the data in order to extract $R^{\pm}$ in five bins of decay time. The data are analysed under three hypotheses: no CPV included, no direct CP violation included (but CPV in mixing is allowed), and all CPV allowed. The results for each hypothesis are shown in fig. 4(a). No evidence for any CPV is found. The results for the no CPV hypothesis are

$$R_D = (3.48 \pm 0.10 \pm 0.01) \times 10^{-3}, \tag{2a}$$
$$x'^2 = (0.28 \pm 3.10 \pm 0.11) \times 10^{-4}, \tag{2b}$$
$$y'^2 = (4.60 \pm 3.70 \pm 0.18) \times 10^{-3}. \tag{2c}$$

The data are then also combined with the previous sample of D^* candidates produced directly in the pp collision. The fits using the combined data are given in fig. 4(b). These results improve the precision on the measured parameters by 10–20%, even though the doubly-tagged analysis is based on almost 40 times fewer candidates than the previous analysis of the prompt charm sample.

4. – Measurement of A_Γ in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

For decays of D^0 mesons into CP eigenstates f, the time-dependent CP asymmetry can be approximated as

$$A_{CP}(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)} \approx a_{dir}^f - A_\Gamma \frac{t}{\tau_D}, \tag{3}$$

where a_{dir}^f is the asymmetry related to direct CP violation, τ_D is the average lifetime of the D^0 meson and A_Γ is the asymmetry between the effective widths,

$$A_\Gamma \equiv \frac{\hat{\Gamma}_{D^0 \to f} - \hat{\Gamma}_{\bar{D}^0 \to f}}{\hat{\Gamma}_{D^0 \to f} + \hat{\Gamma}_{\bar{D}^0 \to f}}. \tag{4}$$

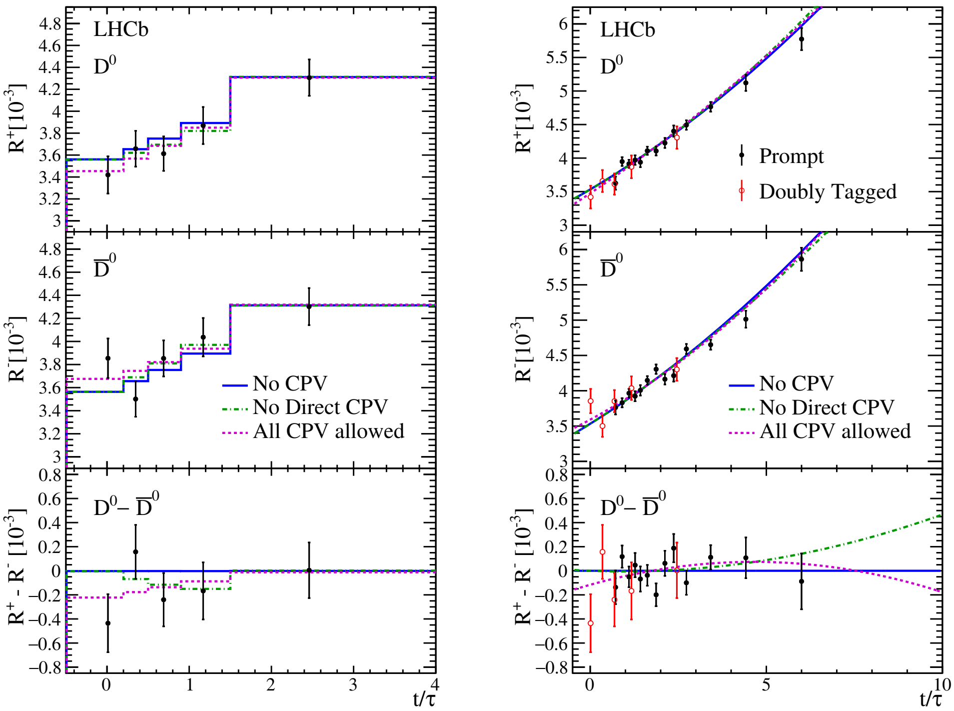


Fig. 4: $R(t)$ fit projections from the wrong-sign $D^0 \to K^+\pi^-$ analysis, using (a) doubly-tagged candidates [8], and (b) combining with the existing data from the $D^{*\pm}$-tagged analysis [7]. In (b) the black points are from the prompt analysis and the red points are from the double-tagged analysis. In each case, the upper panel shows results for D^0, the middle for $\bar{D}^0$, and the lower for the difference between the two samples. The lines show the results of three fits under different CPV hypotheses.

Therefore, there are two ways to extract A_Γ: by fitting the time-dependent ratio to extract the linear coefficient (eq. (3)), or by measuring the lifetimes of D^0 and $\bar{D}^0$ and calculating the asymmetry (eq. (4)). The analysis uses both of these methods to extract a value of A_Γ using K^+K^- and $\pi^+\pi^-$ final states [9]. The main experimental difficulty for the two approaches is to account for residual time-dependent asymmetries. The $D^0 \to K^-\pi^+$ mode, where the time-dependent asymmetry is expected to be negligible, is used as a control sample.

The first analysis computes the ratio $A_{CP}(t)$ and performs a linear fit to extract A_Γ using the full 3 fb^{-1} sample collected in 2011 and 2012. The linear fits to the time-dependent asymmetry are given in fig. 5. The results for A_Γ are

$$A_\Gamma(K^+K^-) = (-0.30 \pm 0.32 \pm 0.10) \times 10^{-3}, \tag{5a}$$

$$A_\Gamma(\pi^+\pi^-) = (0.46 \pm 0.58 \pm 0.12) \times 10^{-3}. \tag{5b}$$

The second analysis uses an unbinned decay-time fit to extract the effective lifetimes of D^0 and $\bar{D}^0$. This analysis is performed on the $2\,\text{fb}^{-1}$ sample collected in 2012, having

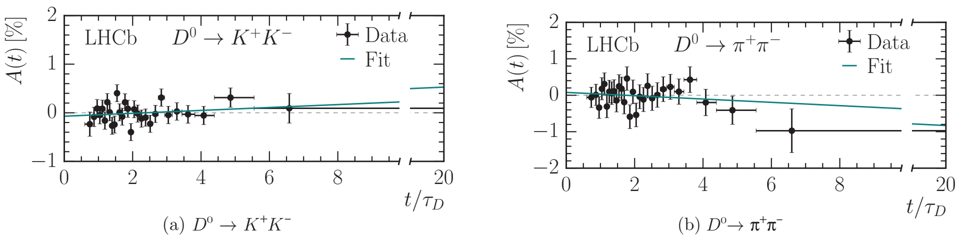


Fig. 5: Linear fits to the asymmetry as a function of decay time for (a) $D^0 \to K^+K^-$, and (b) $D^0 \to \pi^+\pi^-$, for the extraction of A_Γ reported in eqs. (5a) and (5b).

already been performed on $1\,\text{fb}^{-1}$ of 2011 data [10]. Results from the 2012 analysis are

$$A_\Gamma(K^+K^-) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3}, \tag{6a}$$
$$A_\Gamma(\pi^+\pi^-) = (0.03 \pm 0.79 \pm 0.16) \times 10^{-3}. \tag{6b}$$

These are then combined with the 2011 dataset to give a full Run 1 measurement of

$$A_\Gamma(K^+K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3}, \tag{7a}$$
$$A_\Gamma(\pi^+\pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3}. \tag{7b}$$

These two methods give consistent results which are compatible with CP conservation. The two values from eqs. (5a) and (5b) can be averaged to yield a single value of $A_\Gamma = (-0.13 \pm 0.28 \pm 0.10) \times 10^{-3}$, which is the most precise measurement of A_Γ to date.

5. – Search for phase-space dependent CPV in $D^0 \to \pi^+\pi^-\pi^+\pi^-$

CP violation requires that a process has interfering components from at least two amplitudes, in which both the strong and weak phases differ. The rich resonant structure of multibody charm decays leads to a significant variation in strong phase over the final state kinematic space. This allows a search for local CP violation in specific kinematic regions, even if no global asymmetries are observed.

A recent measurement from LHCb uses an unbinned, model-independent method to search for local CP violation in the final state kinematic space of $D^0 \to \pi^+\pi^-\pi^+\pi^-$ decays [11]. This analysis uses the full $3\,\text{fb}^{-1}$ sample collected in 2011 and 2012. For a four-body decay, the final state kinematics can be completely defined by five variables, which are chosen to be the two- and three-pion invariant masses. The method used searches for local CP asymmetries (the energy method) and involves constructing a test metric T which compares the average phase-space separations of candidates for the two samples (D^0 and $\bar{D}^0$). The test metric averages to zero in the case of CP conservation. In order to interpret the result, the test statistic is computed for an ensemble of pseudo-experiments with randomly assiged flavour-tags for all candidates. This results in a distribution, which allows a p-value to be determined for the consistency of the data with CP conservation. The p-value is defined as the fraction of pseudo-experiments with a test metric value greater than that computed from the data.

Two separate measurements are made, one in which the two samples to be compared are defined purely by the initial D^0 flavour (sensitive to P-even asymmetries), and a second in which the samples are defined by both the D^0 flavour and the sign of a triple product computed from the pion momenta (sensitive to P-odd asymmetries). For the P-even test, the p-value is found to be $(4.6 \pm 0.5)\%$, which is consistent with CP symmetry. For the P-odd test, the p-value is found to be $(0.6 \pm 0.2)\%$, which is marginally consistent with CP symmetry (a significance of 2.6σ for CP non-conservation). This is the first application of the energy test in four-body decays.

6. – Measurement of the branching ratio of $B_s^0 \to \eta_c \phi$ and $B_s^0 \to \eta_c \pi^+ \pi^-$

The CP violating phase, ϕ_s, arises from the interference between the direct decay amplitude into a specific final states and the amplitude after $B_s^0 - \bar{B}_s^0$ mixing. This phase is small and well predicted in the SM, $\phi_s = 0.03704^{+0.00064}_{-0.00064}$ [5], and is sensitive to possible New Physics. The latest ϕ_s combination value from LHCb gives $\phi_s = 0.001 \pm 0.037$ [12]. The golden channel for ϕ_s measurements at LHCb is $B_s^0 \to J/\psi \phi$. This final state is a superposition of CP-even and CP-odd final states, therefore analysing the angular distribution of the final state particles is required in order to disentangle the CP-odd and CP-even contributions. The decays $B_s^0 \to \eta_c \phi$ and $B_s^0 \to \eta_c \pi^+ \pi^-$ are also sensitive to ϕ_s, and have a purely CP-even final state. This makes the analysis significantly simpler as no angular analysis is required. As there is not yet enough statistics to perform a time-dependent analysis of these modes, the measurement of branching fractions has been performed [13].

The analysis uses the full $3\,\mathrm{fb}^{-1}$ sample collected in 2011 and 2012. The $B_s^0 \to \eta_c \phi$ channel uses the η_c meson reconstructed in the $p\bar{p}$, $K^+K^-\pi^+\pi^-$, $\pi^+\pi^-\pi^+\pi^-$ and $K^+K^-K^+K^-$ final states. The normalisation channel used when determining the branching fraction is $B_s^0 \to J/\psi \phi$. For the $B_s^0 \to \eta_c \pi^+ \pi^-$ channel a higher level of combinatoric background is expected so the η_c is only reconstructed in the $p\bar{p}$ final state, with $B_s^0 \to J/\psi \pi^+ \pi^-$ as the normalisation mode. This analysis uses a BDT-based selection with particle identification requirements. The branching fractions are measured to be

$$\mathcal{B}(B_s^0 \to \eta_c \phi) = (5.01 \pm 0.53 \pm 0.27 \pm 0.63) \times 10^{-4}, \tag{8a}$$

$$\mathcal{B}(B_s^0 \to \eta_c \pi \pi) = (1.76 \pm 0.59 \pm 0.12 \pm 0.29) \times 10^{-4}, \tag{8b}$$

yielding an observation of $B_s^0 \to \eta_c \phi$ and evidence of $B_s^0 \to \eta_c \pi^+ \pi^-$. Here the first two uncertainties are statistical and systematic respectively, and the third is due to the limited knowledge of external branching fractions.

7. – Search for CPV in $\Lambda_b^0 \to pK^-\mu^+\mu^-$

Recently LHCb showed the first evidence for CPV in baryon decays using $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ [14]. This has initiated enhanced interest in CPV in beauty baryons, and a search for CPV in the rare decay $\Lambda_b^0 \to pK^-\mu^+\mu^-$ [15] has recently been performed. This decay is a flavour changing neutral current process, which is of particular interest due to its sensitivity to New Physics.

The analysis uses the full $3\,\mathrm{fb}^{-1}$ sample collected in 2011 and 2012. Three observables sensitive to CP violation are measured: $\Delta\mathcal{A}_{CP}$, $a_{CP}^{\hat{T}-odd}$ and $a_{P}^{\hat{T}-odd}$. These are sensitive to different manifestations of CP violation; the $\mathcal{A}_{CP}$ is enhanced when the strong phase difference between the two amplitudes is large and the $a_{CP}^{\hat{T}-odd}$ is enhanced when the strong phase difference vanishes. $\Delta\mathcal{A}_{CP}$ is defined as the CP asymmetry difference between $\Lambda_b^0 \to pK^-\mu^+\mu^-$ and the $\Lambda_b^0 \to pK^- J/\psi$ control mode, resulting in cancellation of production and reconstruction asymmetries. The observables $a_{CP}^{\hat{T}-odd}$ and $a_{P}^{\hat{T}-odd}$ are constructed using triple products of final state momenta in the Λ_b^0 rest frame. A non-zero value of $a_{CP}^{\hat{T}-odd}$ or $a_{P}^{\hat{T}-odd}$ would signal CP or parity violation respectively.

The values obtained for the CP violation observables are

$$\Delta\mathcal{A}_{CP} = (-3.5 \pm 5.0 \pm 0.2) \times 10^{-2}, \tag{9a}$$

$$a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0 \pm 0.7) \times 10^{-2}, \tag{9b}$$

$$a_{P}^{\hat{T}-odd} = (-4.8 \pm 5.0 \pm 0.7) \times 10^{-2}. \tag{9c}$$

These results are compatible with CP and parity conservation.

8. – Summary

The LHCb Collaboration has produced many new investigations into CP violation in the beauty and charm sector in both mixing and decay. The understanding of the CP violation in the quark sector continues to be improved, expanding to new analysis methods and decay modes. Measurements are becoming ever more precise with the increasing dataset available. As yet, all measurements in the charm sector continue to be consistent with CP conservation.

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