$D\bar{D}$ mixing and CP-symmetry violation in the charm sector, and rare D -meson decays

Sergey Barsuk
 (For the LHCb Collaboration)

*Laboratoire de l'Accelérateur Lineaire
 Centre Scientifique d'Orsay, Bat. 200, 91898 Orsay, France
 sergey.barsuk@lal.in2p3.fr*

Published 15 May 2014

An overview of selected recent results on $D\bar{D}$ mixing and CP-symmetry violation in the charm sector, and D meson rare decays, was presented at the Physics In Collision conference 2013 in Beijing.

Keywords: Charm mixing; CP-violation; rare decays.

PACS Numbers: 14.40.Lb, 11.30.Er

Flavour mixing and CP-symmetry violation are well established effects in the K and B systems, while charm is the unique up-type system where these effects can occur. In the Standard Model (SM) the neutral charm meson mass eigenstates are related to flavour eigenstates: $|D_{1,2}^0\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$. In the limit of CP-symmetry conservation, $p = q$ (which holds to $O(10^{-4})$ in SM), decays become modulated by mixing, occurring via box-diagrams, and the decay time distribution follows $\frac{e^{-\Gamma t}}{4}(\cosh(\Delta\Gamma t/2) \pm 2\cos\Delta m t)$, where Γ is the average decay width, and Δm and $\Delta\Gamma$ are the mass and decay width splitting between the two mass eigenstates. Denoting by *mixed* transitions $\bar{D}^0 \rightarrow D^0$ and $D^0 \rightarrow \bar{D}^0$ between initial and final D flavours, and by *unmixed* the $\bar{D}^0 \rightarrow \bar{D}^0$ and $D^0 \rightarrow D^0$ transitions, the time-dependent mixing amplitude $A_{mix}(t)$ is written as

$$A_{mix}(t) \equiv \frac{N_{unmixed} - N_{mixed}}{N_{unmixed} + N_{mixed}}(t) = \frac{\cos(\Delta m t)}{\cosh(\Delta\Gamma t/2)}.$$

Mixing parameters $x = \Delta m/\Gamma$ and $y = \Delta\Gamma/\Gamma$ can be evaluated by considering the box diagram for mass and decay width splitting, and generic tree diagram to

This is an Open Access article published by World Scientific Publishing Company. It is distributed under the terms of the Creative Commons Attribution 3.0 (CC-BY) License. Further distribution of this work is permitted, provided the original work is properly cited.

estimate the decay width. Fast or slow oscillations occur for $x \gg 1$ and $x \ll 1$ respectively. According to the above naive considerations, mixing probability is high, about 50% for the $K^0 \bar{K}^0$ and $B_s^0 \bar{B}_s^0$ systems, well established at the level of 18% for the $B^0 \bar{B}^0$ system, and small at the level of 10^{-6} for the $D^0 \bar{D}^0$ system. The corresponding mixing parameters are $x, y \sim O(1)$ for the $K^0 \bar{K}^0$ system, $x \sim 1$, $y \ll 1$ for the $B^0 \bar{B}^0$ system, $x \gg 1$, $y \sim O(1)$ for the $B_s^0 \bar{B}_s^0$ system and $x, y \ll 1$ for the $D^0 \bar{D}^0$ system. Experimentally, most challenging are the opposite cases of rapid $B_s^0 \bar{B}_s^0$ oscillations, requiring high decay time resolution to resolve them, and of small $D^0 \bar{D}^0$ oscillations.

The small $D^0 \bar{D}^0$ flavour mixing can be explained by the fact, that unlike $B_{(s)}^0 \bar{B}_{(s)}^0$ systems, there is no contribution from the heavy t quark to the box diagram, and the b quark contribution is suppressed by λ^{10} due to the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements. Non-perturbative long-range effects are more difficult to calculate with typically 10^{-3} value with large uncertainty, see e.g. Ref. 1. The $D^0 \bar{D}^0$ flavour mixing is well-established, however until 2013 no single 5σ measured was available.²

Three types of CP -symmetry violation (CPV) are distinguished in SM. *Direct CPV* can occur when the final state is reached via tree and penguin diagrams, and thus Cabibbo-suppressed decays (CSD) of both charged and neutral D mesons are involved. If $A_f = \langle f | H | D \rangle$ and $\bar{A}_{\bar{f}} = \langle \bar{f} | H | \bar{D} \rangle$, then $|\bar{A}_{\bar{f}}/A_f| \neq 1$ quantifies the CPV effect. Direct CPV effect is expected to be up to few $\times 10^{-3}$ in SM, and is searched for by studying asymmetries in two-body CSD and the asymmetries across the phase space in multi-body decays. The *CPV in meson mixing* arises when $|p| \neq |q|$, and is expected at the level $O(10^{-4})$ in SM. The condition for *CPV in the interference between the decay with and without mixing* to the common final state is $\arg(q/p \times \bar{A}_{\bar{f}}/A_f) \neq 0$.

Charm sector CSD and flavour mixing involve primarily the 2×2 Cabibbo matrix, where CP-violating phase enters the V_{cd} CKM element with a factor λ^5 . The V_{ub} element, where CPV phase enters with a factor λ^3 , contributes via loops. In the framework of SM, all CPV effects are described by a single phase, providing a strong predictive power for CP asymmetries. Direct CPV of $O(1\%)$ in charm decays could signal physics beyond SM.

A set of decisive SM tests has been proposed in theory papers. Taking into account the fact, that if CPV is small, $\sin \phi \ll 1$, which is valid for D system, the authors of Ref. 3 obtain $y/x = \frac{1-|q/p|}{\tan \phi}$. If the above relation is violated, physics beyond the SM contributes to direct CPV.³ Other examples are proposed in Ref. 4. In the limit of SM direct CPV, the CP-asymmetries in CSD into final CP eigenstates are universal, and $(a_{KK} - a_{\pi\pi})/(a_{KK} + a_{\pi\pi}) \sim 10^{-3}$, which provides another important test. The authors also suggest to separate direct against indirect CPV in CSD using time-integrated CP asymmetry measurements. Assuming negligible new CPV in Cabibbo-allowed decays (CAD) and doubly Cabibbo-suppressed decays (DCSD), time-integrated CP asymmetry in CAD to CP eigenstate arises from a universal indirect asymmetry. It can be subtracted from the time-integrated CP asymmetry

in CSD to CP eigenstate, to obtain the non-universal direct CP asymmetry. Finally, the authors reiterate that any observed non-vanishing CP asymmetry in charged D decays is necessarily direct CPV.

Experimental results in the charm sector come from both e^+e^- and hadron machines. The B -factories, BaBar and Belle operated at the center-of-mass energy corresponding to the $\Upsilon(4S)$ resonance. They accumulated large samples of D mesons from B meson decays, with more than 10^9 $B\bar{B}$ pairs produced, and large D samples from continuum production, with more than 10^9 charm hadron pairs.

The $D\bar{D}$ -factories, CLEO-c and now BES, use quantum correlations at $D\bar{D}$ threshold. They collect data at energies around the charmonium production region, and use beam energy constraint to search for a simple signature for CPV, $\psi(3770) \rightarrow D^0\bar{D}^0 \rightarrow CP(\pm)CP(\pm)$. Clean data samples are available, corresponding to few $\times 10^7$ $\psi(3770)$ at CLEO-c, and more than 2×10^6 D -mesons in the 2010-2011 data sample of BES III.⁵

The pp or $p\bar{p}$ colliders operate in a more challenging environment. The results are delivered by the CDF and D0 experiments at TEVATRON, and the LHCb experiment at LHC. High production cross-section at small rapidities at CDF, and at forward LHCb rapidities, $\sigma(c\bar{c})_{LHCb, 7TeV} \sim 1400 \mu b$,⁶ provide large samples of even rare charm decays. The LHCb reconstructed about 3.5×10^8 charm decays per $1 fb^{-1}$ of integrated luminosity, the number being limited by the trigger bandwidth. The D mesons have a large boost and fly about 3 mm before decaying. Precision track and vertex reconstruction, as well as powerful particle identification at LHCb, favour precision studies in the charm sector by these experiments.

In the following, selected recent results on flavour mixing and CPV in the charm sector, as well as charm rare decays will be discussed.

Among new results on the $D^0\bar{D}^0$ **mixing**, the BaBar experiment measured⁷ $y_{CP} = (\Gamma^{CP=+} + \bar{\Gamma}^{CP=+})/2\Gamma - 1$ via D^0 lifetime difference measurement, where $\Gamma^{CP=+}$ ($\bar{\Gamma}^{CP=+}$) is the partial decay rate of D^0 ($\bar{D}^0$) to the CP -even final state. Assuming no CPV, y_{CP} measures directly y mixing parameter, and not the combination of x and y parameters, as accessible in other methods. BaBar measured the effective D^0 lifetime in three different two-body final states: CSD to CP -even K^-K^+ and $\pi^-\pi^+$ final states, and the $K^\mp\pi^\pm$ final state without a defined CP -parity, or in other words a mixture of $CP = +$ and $CP = -$. The BaBar result, $y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%$, is the most precise single measurement to date, with no-mixing hypothesis excluded at 3.3σ level.

Using the D meson sample from the $D^{*+} \rightarrow D^0\pi^+$ ^a decay mode, the initial D flavour can be tagged by the sign of bachelor pion. Final D flavour is tagged using the final state of the D decay. For the $D^0 \rightarrow K\pi$ transition, the “right-sign” (RS) $K^-\pi^+$ final state can be reached dominantly via CAD, or alternatively via $D^0 \rightarrow \bar{D}^0$ transition, followed by DCSD $D^0 \rightarrow K^+\pi^-$. The D^0 “wrong-sign” (WS) $K^+\pi^-$ final state is reached by competing DCSD, and $D^0 \rightarrow \bar{D}^0$ transition, followed

^aThroughout the paper charge-conjugated states are equally assumed unless stated otherwise.

by CAD $D^0 \rightarrow K^- \pi^+$. Assuming $|x|, |y| \ll 1$ and CP symmetry conservation, the time-dependent WS rate can be written as the sum of the “mixing” term, DCSD term and the interference term,

$$dN_{WS}/dt \approx e^{-\Gamma t} \times ((x'^2 + y'^2)/2 \cdot \Gamma^2 t^2/2 + D^2 + D \cdot y' \cdot \Gamma t),$$

where x' and y' are the x and y mixing parameters rotated by the strong phase δ :

$$y' = y \cos \delta - x \sin \delta, x' = x \cos \delta + y \sin \delta.$$

And the time-dependent ratio is written as:

$$N_{WS}/N_{RS}(t) \approx (x'^2 + y'^2)/2 \cdot \Gamma^2 t^2/2 + R_D + \sqrt{R_D} \cdot y' \cdot \Gamma t,$$

where $\bar{A}(K^- \pi^+)/A(K^- \pi^+) = \sqrt{R_D} e^{-i\delta}$. The effect of mixing is distinguished from the DCSD by measuring time dependence, and x'^2 and y' are determined. For semileptonic decays only the first term in the above expressions is non-zero, and the value $x'^2 + y'^2 = x^2 + y^2$ is accessed.

The LHCb experiment studied⁸ WS and RS decays in D^0 decay time bins, with 3.6×10^4 and 8.4×10^6 candidates in the D^{*+} peak for WS and RS respectively. Background of WS in the analysis was dominated by combinations of real D^0 and a random pion. Contamination from the D^0 from inclusive b -hadron decays was reduced by the impact parameter cuts on D^0 and bachelor pion, with residual contamination of $(2.7 \pm 0.2)\%$. Doubly misidentified RS events contributed to the WS signal at the level of $(0.4 \pm 0.2)\%$. Finally, the mixing parameters were found to be $x'^2 = (-0.09 \pm 0.13) \times 10^{-3}$ and $y' = (7.2 \pm 2.4) \times 10^{-3}$. Note that there is a strong correlation between x'^2 and y' . The R_D parameter was measured to be $R_D = (3.52 \pm 0.15) \times 10^{-3}$ and $(4.25 \pm 0.04) \times 10^{-3}$ for mixing and no-mixing hypothesis respectively. The no-mixing hypothesis was excluded at more than 9σ level.

The same technique was used⁹ by the CDF experiment. The mixing parameters were found to be $x'^2 = (0.08 \pm 0.18) \times 10^{-3}$ and $y' = (4.3 \pm 4.3) \times 10^{-3}$, and the R_D parameter $R_D = (3.51 \pm 0.35) \times 10^{-3}$. The no-mixing hypothesis was excluded at more than 6σ level.

The HFAG¹⁰ averages of mixing parameters, $\bar{x} = (0.53^{+0.16}_{-0.17})\%$ and $\bar{y} = (0.67 \pm 0.09)\%$ for no-CPV hypothesis, and $\bar{x} = (0.39^{+0.16}_{-0.17})\%$ and $\bar{y} = (0.67^{+0.07}_{-0.08})\%$ with CPV allowed, exclude no-mixing hypothesis at more than 12σ level.

Among new results on **CPV in charm sector**, the BaBar experiment searched¹¹ for direct CPV in $D^+ \rightarrow K^- K^+ \pi^+$ decay, using 2.2×10^{-5} candidates in the D^+ signal. The asymmetry in the total rate

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

was studied. A model independent search over the Dalitz plot yielded the p -value of 72% for no CPV, and a model-dependent search using simultaneous fit to D^+ and D^- Dalitz plots showed no indication of CPV in relative phases and magnitudes. Finally, the integrated asymmetry of $A_{CP} = (0.37 \pm 0.30 \pm 0.15)\%$ was obtained.

Several new results on the search for CPV in the $D_{(s)}^+ \rightarrow K_S^0 h^+$ decays have emerged. The $D^+ \rightarrow K_S^0 K^+$ decay proceeds via Feynman diagrams similar to those of the $D^0 \rightarrow K^- K^+$ mode, where the penguin contribution may be enhanced by physics beyond the SM. For the $D^+ \rightarrow K_S^0 \pi^+$ decay, direct CPV from the interference between the CAD and DCSD amplitudes is negligible in SM, but CPV from the kaon mixing may be detectable. Finally, $D_s^+ \rightarrow K_S^0 \pi^+$ decay proceeds via Feynman diagrams similar to those of the $D^+ \rightarrow K_S^0 K^+$ mode.

The CP asymmetry in the $D_{(s)}^+ \rightarrow K_S^0 h^+$ modes accounts also for the $K^0 \bar{K}^0$ mixing:

$$\begin{aligned} A_{CP}^{D_{(s)}^+ \rightarrow K_S^0 h^+} &= \frac{\Gamma(D_{(s)}^+ \rightarrow \bar{K}^0 h^+) \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-) - \Gamma(D_{(s)}^- \rightarrow K^0 h^-) \Gamma(K^0 \rightarrow \pi^+ \pi^-)}{\Gamma(D_{(s)}^+ \rightarrow \bar{K}^0 h^+) \Gamma(\bar{K}^0 \rightarrow \pi^+ \pi^-) + \Gamma(D_{(s)}^- \rightarrow K^0 h^-) \Gamma(K^0 \rightarrow \pi^+ \pi^-)} \\ &= \frac{A_{CP}^{D_{(s)}^+ \rightarrow \bar{K}^0 h^+} + A_{CP}^{\bar{K}^0}}{1 + A_{CP}^{D_{(s)}^+ \rightarrow \bar{K}^0 h^+} \times A_{CP}^{\bar{K}^0}} \approx A_{CP}^{D_{(s)}^+ \rightarrow \bar{K}^0 h^+} + A_{CP}^{\bar{K}^0}. \end{aligned}$$

The A_{CP} value determined at e^+e^- colliders is obtained from the asymmetry in the signal yields:

$$A_{raw}^{D_{(s)}^+ \rightarrow K_S^0 h^+} = \frac{N(D_{(s)}^+) - N(D_{(s)}^-)}{N(D_{(s)}^+) + N(D_{(s)}^-)} = A_{CP}^{D_{(s)}^+ \rightarrow K_S^0 h^+} + A_{FB}^{D_{(s)}^+} + A_{Det}^{h^+} + A_{Det}^{K^0},$$

where the forward-backward asymmetry A_{FB} is an odd function of $\cos \theta_D^*$

$$A_{FB}^{D_{(s)}^+} = \frac{1}{2} \left(A_{raw}^{K_S^0 h^+} (+\cos \theta_D^*) - A_{raw}^{K_S^0 h^+} (-\cos \theta_D^*) \right),$$

the detector asymmetry $A_{Det}^{h^+}$ is determined from the CAD $D^0 \rightarrow K^- \pi^+$ and $D_s^+ \rightarrow \phi \pi^+$, where no CPV is expected, assuming $A_{FB}^{D^0} = A_{FB}^{D_s^+}$, and the detector asymmetry $A_{Det}^{K^0}$ is due to different interaction with matter for K^0 and $\bar{K}^0$ and is estimated numerically to be e.g. about 0.1% in Belle.¹²

The Belle experiment searched for^{13,14} CP asymmetry in the $D^+ \rightarrow \bar{K}^0 K^+$ and $D^+ \rightarrow \bar{K}^0 \pi^+$ decay modes, in bins of $\cos \theta_D^*$. Having 2.8×10^5 and 17.4×10^5 candidates, the CP asymmetry was found to be $A_{CP}(D^+ \rightarrow \bar{K}^0 K^+) = (0.08 \pm 0.28 \pm 0.14)\%$ and $A_{CP}(D^+ \rightarrow \bar{K}^0 \pi^+) = (-0.024 \pm 0.094 \pm 0.067)\%$ in the $D^+ \rightarrow \bar{K}^0 K^+$ and $D^+ \rightarrow \bar{K}^0 \pi^+$ decay modes respectively. The BaBar experiment searched for¹⁵ CP asymmetry in the $D^+ \rightarrow \bar{K}^0 K^+$ and $D_s^+ \rightarrow \bar{K}^0 \pi^+$ decay modes, also in bins of $\cos \theta_D^*$. With 1.6×10^5 and 0.14×10^5 candidates, the CP asymmetry was found to be $A_{CP}(D^+ \rightarrow \bar{K}^0 K^+) = (0.46 \pm 0.36 \pm 0.25)\%$ and $A_{CP}(D_s^+ \rightarrow \bar{K}^0 \pi^+) = (0.3 \pm 2.0 \pm 0.3)\%$ in the $D^+ \rightarrow \bar{K}^0 K^+$ and $D_s^+ \rightarrow \bar{K}^0 \pi^+$ decay modes respectively. In all the three decay modes, the results were found to be compatible with no charm sector driven CPV.

The LHCb experiment searched for¹⁶ direct CPV in the $D^+ \rightarrow \phi\pi^+$ and $D_s^+ \rightarrow K_S^0\pi^+$ decay modes. The CPV asymmetry in the ϕ region of the $D^+ \rightarrow K^-K^+\pi^+$ Dalitz plot was found as:

$$A_{CP}^{D^+ \rightarrow \phi\pi^+} = A_{raw}^{D^+ \rightarrow \phi\pi^+} - A_{raw}^{D^+ \rightarrow K_S\pi^+} + A_{CP}^{K^0-\bar{K}^0}.$$

In addition, a complementary observable $A_{CP|S}$, sensitive to asymmetries that change sign, according to the strong phase variation along the ϕ band, $1.00 \text{ GeV}/c^2 < M(K^+K^-) < 1.04 \text{ GeV}/c^2$, was constructed. A concurrent measurement

$$A_{CP}^{D_s^+ \rightarrow K_S^0\pi^+} = A_{raw}^{D_s^+ \rightarrow K_S^0\pi^+} - A_{raw}^{D_s^+ \rightarrow \phi\pi^+} + A_{CP}^{K^0-\bar{K}^0}$$

was performed. The $A_{CP}^{K^0-\bar{K}^0}$, correction for CPV in neutral kaon system, was found to be¹⁷ $(-0.028 \pm 0.028)\%$. The analysis was performed in 12 bins of transverse momentum p_T and rapidity η . Totals of 1.6×10^6 (3.0×10^6) and 1.1×10^6 (2.4×10^4) candidates were found in the D^+ and D_s^+ signal peaks in the $D_{(s)}^+ \rightarrow \phi\pi^+$ and $D_{(s)}^+ \rightarrow K_S^0\pi^+$ decay modes respectively. The corresponding CP asymmetries were found to be $A_{CP}(D^+ \rightarrow \phi\pi^+) = (-0.04 \pm 0.14 \pm 0.13)\%$, $A_{CP|S}(D^+ \rightarrow \phi\pi^+) = (-0.18 \pm 0.17 \pm 0.18)\%$ and $A_{CP}(D_s^+ \rightarrow K_S^0\pi^+) = (0.61 \pm 0.83 \pm 0.13)\%$, providing no evidence of CPV.

The time-dependent CP asymmetry in D^0 decays to a CP eigenstate f is written as:

$$A_{CP}(f, t) = \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\bar{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\bar{D}^0 \rightarrow f)} \approx a_{CP}^{dir}(f) + (t/\tau)a_{CP}^{ind},$$

where the indirect asymmetry a_{CP}^{ind} is universal to a good approximation. Assuming the a_{CP}^{ind} universality, the difference of the CP asymmetries for the K^-K^+ and $\pi^-\pi^+$ final states, depends on the difference of the corresponding direct CP asymmetries, and suppressed a_{CP}^{ind} term present due to the difference in the average decay time:

$$\Delta A_{CP} = A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+) = a_{CP}^{dir}(K^-K^+) - a_{CP}^{dir}(\pi^-\pi^+) + \Delta\bar{t}/\tau a_{CP}^{ind}.$$

Tagging the D^0 flavour using the sign of the pion from $D^{*+} \rightarrow D^0\pi^+$, the time-integrated raw asymmetry is written as:

$$A_{raw}(f) = \frac{N(D^{*+} \rightarrow D^0\pi^+) - N(D^{*-} \rightarrow \bar{D}^0\pi^-)}{N(D^{*+} \rightarrow D^0\pi^+) + N(D^{*-} \rightarrow \bar{D}^0\pi^-)},$$

and, to the first order,

$$A_{raw}(f) = A_{CP}(f) + A_D(f) + A_D(\pi^+) + A_P(D^{*+}),$$

where $A_D(K^-K^+) = A_D(\pi^-\pi^+) = 0$, and $A_D(\pi^+)$ and $A_P(D^{*+})$ are independent of the final state. Thus, we conclude, that $\Delta A_{CP} = A_{raw}(K^-K^+) - A_{raw}(\pi^-\pi^+)$.

By the end of 2012, the measurements¹⁸⁻²¹ of ΔA_{CP} by the LHCb, CDF, Belle and BaBar experiments suggested a negative value of ΔA_{CP} , and poor agreement with the no-CPV hypothesis, with confidence level 2.0×10^{-5} . The BaBar, Belle

and CDF experiments also quoted individual asymmetries for the the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ channels with partially cancelled systematic uncertainty in the difference.

The LHCb experiment published an update²² of the analysis using the integrated luminosity of 1 fb^{-1} , and 2.2×10^6 and 0.7×10^6 candidates in the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ signal peaks respectively. The difference in the decay time was measured to be $\Delta\bar{t}/\tau = (11.19 \pm 0.13 \pm 0.17)\%$. In the analysis, fiducial cuts were used to exclude a kinematic region with large π^+ detection asymmetry. Impact parameter cuts were used to reduce contamination from D^0 originating from b hadron decays. The resolution on $\Delta M = M(h^- h^+ \pi^+) - M(h^- h^+) - M(\pi^+)$ was improved by constraining the D^{*+} vertex to match the primary vertex. In addition, weighting was applied to account for differences in kinematics of the two final states, in order to properly cancel the production and detection asymmetries. Finally, ΔA_{CP} was measured to be $\Delta A_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$. This result superseded the previous LHCb measurement,¹⁸ and better agrees with the no-CPV hypothesis.

Additionally, LHCb measured²³ ΔA_{CP} by tagging the D^0 flavour using the muon charge in semileptonic $b \rightarrow D^0 \mu X$ decays. This analysis employs a sample which is statistically independent from the analysis discussed above, that was using D^{*+} to tag the D^0 flavour, and has different trigger composition and systematic uncertainty. The raw asymmetry is written as

$$A_{raw} = \frac{\Gamma(D^0 \rightarrow f)\varepsilon(\mu^-)P(D^0) - \Gamma(\bar{D}^0 \rightarrow f)\varepsilon(\mu^+)P(\bar{D}^0)}{\Gamma(D^0 \rightarrow f)\varepsilon(\mu^-)P(D^0) + \Gamma(\bar{D}^0 \rightarrow f)\varepsilon(\mu^+)P(\bar{D}^0)} \approx A_{CP}^f + A_D^\mu + A_P^B,$$

and ΔA_{CP} as

$$\Delta A_{CP} = A_{raw}(K^- K^+) - A_{raw}(\pi^- \pi^+) \approx A_{CP}(K^- K^+) - A_{CP}(\pi^- \pi^+).$$

The difference in the decay time was measured to be $\Delta\bar{t}/\tau = (1.8 \pm 0.7)\%$, so that $\Delta A_{CP} \approx \Delta a_{CP}^{dir}$. The raw asymmetries are determined from samples with 5.6×10^5 and 2.2×10^5 candidates in the signal peaks for the $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decay modes respectively. Weighting was also applied to account for differences in kinematics of the two final states. The value of ΔA_{CP} was measured to be $\Delta A_{CP} = (0.49 \pm 0.30 \pm 0.14)\%$. The two measurements^{22, 23} can be averaged, $\langle \Delta A_{CP} \rangle_{LHCb} = (-0.15 \pm 0.16)\%$. This result shows no evidence of CPV.

Multi-body D^0 decays provide another promising tool to search for CPV, such decays proceed via resonances, and Dalitz-plot like techniques allow to sum up several resonances, providing increased statistics and information about the strong phase. The decays, leading to the $K^- K^+ \pi^- \pi^+$ and $\pi^- \pi^+ \pi^- \pi^+$ final states, comprise contributions from ρ , ϕ , $a_1(1260)^+$, $K_1(1270)^\pm$, $K^*(1410)^\pm$ and other resonances, with Cabibbo-suppressed tree and penguin amplitudes. Direct CPV can be searched for in regions of four-body phase space, providing five combinations of two- and three-body invariant mass squared. No direct CPV is expected in the $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ decay mode, which can be used as a control channel. The LHCb experiment used²⁴ the charge of π^+ from the $D^{*+} \rightarrow D^0 \pi^+$ mode, to tag the D^0

flavour. The signal was extracted via *sPlot* technique, with 57k, 330k and 2900k candidates in the $D^0 \rightarrow K^- K^+ \pi^- \pi^+$, $D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ and $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ signal peaks. Significance was determined in equally populated bins of the 5D phase space. The $D^0 \rightarrow K^- \pi^+ \pi^- \pi^+$ significance distribution showed no evidence for local asymmetries, and the $D^0 \rightarrow K^- K^+ \pi^- \pi^+$ and $D^0 \rightarrow \pi^- \pi^+ \pi^- \pi^+$ distributions were found to be consistent with no CPV.

The HFAG¹⁰ average shows present data to be consistent with no CPV at $CL = 2.1\%$, with $\Delta a_{CP}^{dir} = (-0.329 \pm 0.121)\%$ and $\Delta a_{CP}^{ind} = (-0.010 \pm 0.162)\%$.

New important results on **rare charm decays** have been reported. The Belle experiment performed²⁵ precision study of the D_s^+ leptonic decays. The D_s^+ mesons were produced in the reaction $e^+ e^- \rightarrow c\bar{c} \rightarrow D_{tag} K_{frag} X_{frag} D_s^{*-}$, $D_s^{*-} \rightarrow D_s^- \gamma$, where a tagging charm hadron D_{tag} can be $D^{(*)}$ or Λ_c^+ , K_{frag} is the additional kaon that conserves the strangeness in the event, and X_{frag} denotes additional pions produced in the course of hadronization. The signal was searched by reconstructing the missing mass in the event, and looking at the energy deposit in the electromagnetic calorimeter. Most stringent to date upper limit was obtained on the suppressed $D_s^+ \rightarrow e^+ \nu_e$ channel, $BR(D_s^+ \rightarrow e^+ \nu_e) < 0.83 \times 10^{-4} @ 90\% CL$. This limit still exceeds the SM expectation of 10^{-7} by three orders of magnitude. Measurement of the branching fractions for the $D_s^+ \rightarrow \mu^+ \nu_\mu$ and $D_s^+ \rightarrow \tau^+ \nu_\tau$ decay modes, provides lepton flavour universality check, and allows determination of the D_s^+ decay constant. In the analysis τ^+ leptons were reconstructed using the $\tau^+ \rightarrow e^+ \nu_e \bar{\nu}_\tau$, $\tau^+ \rightarrow \mu^+ \nu_\mu \bar{\nu}_\tau$ and $\tau^+ \rightarrow \pi^+ \bar{\nu}_\tau$ decay modes. The Belle experiment obtained:

$$\begin{aligned} BR(D_s^+ \rightarrow \mu^+ \nu_\mu) &= (5.31 \pm 0.28 \pm 0.20) \times 10^{-3}, \\ BR(D_s^+ \rightarrow \tau^+ \nu_\tau) &= (5.70 \pm 0.21_{-0.30}^{+0.31}) \times 10^{-2}, \end{aligned}$$

and their ratio,

$$R_{\tau/\mu}^{D_s} = (10.73 \pm 0.69_{-0.53}^{+0.56})$$

in agreement with the SM expectations,²

$$R_{\tau/\mu}^{D_s} = m_\tau^2/m_\mu^2 \cdot (1 - m_\tau^2/m_{D_s}^2)^2 / (1 - m_\mu^2/m_{D_s}^2)^2 = (9.762 \pm 0.031).$$

The results are thus consistent with lepton flavour universality, though the precision of the measurement is still significantly larger than that of the expectation. The Belle result provides also most precise single measurement of the D_s^+ decay constant,

$$f_{D_s^+} = (255.5 \pm 4.2 \pm 4.8 \pm 1.8) \text{ MeV},$$

where the first error is statistical, the second error is the systematic uncertainty and the third one is due to the D_s^+ lifetime precision. This result removes the tension between the experimental data and unquenched Lattice QCD expectation,²⁶ $f_{D_s^+} = (248 \pm 2.5) \text{ MeV}$.

The Belle experiment also measured²⁷ the branching fraction of the wrong sign $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ decay, important for $D^0 \bar{D}^0$ mixing studies. The result

$$R_{WS} = (0.324 \pm 0.008 \pm 0.007)\%$$

is the most precise measurement to date. By combining this result with x and y mixing parameters from Ref. 10 and α and δ values from Ref. 28, the R_D parameter is obtained as $R_D = (0.327^{+0.019}_{-0.016})\%$. Using in addition the CAD branching fraction from Ref. 2, the absolute branching fraction for the wrong sign $D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$ decay,

$$BR(D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-) = (2.61 \pm 0.06^{+0.09}_{-0.08}) \times 10^{-4},$$

significantly improves the PDG value precision,² $BR(D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-) = (2.61^{+0.21}_{-0.19}) \times 10^{-4}$.

The $D^0 \rightarrow \mu^+ \mu^-$ rare decay proceeds via loop diagrams and is strongly suppressed in the SM. Using a sample of D^0 mesons from the $D^{*+} \rightarrow D^0 \pi^+$ decay, the LHCb experiment obtained²⁹ the most stringent upper limit to date on the branching fraction of the $D^0 \rightarrow \mu^+ \mu^-$ decay, $BR(D^0 \rightarrow \mu^+ \mu^-) < 7.6 \times 10^{-9} @ 95\% CL$. This result improves the previously available sensitivity² by a factor of 20, however the upper limit value is still three orders of magnitude higher than the SM expectations between 10^{-13} and 10^{-11} .

The $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ rare decay proceeds via box, penguin or annihilation diagram, with a branching fraction as large as 10^{-9} in SM, while physics beyond the SM may increase³⁰ its branching fraction to 10^{-8} . Physics beyond the SM can be searched for in the low and high di-muon invariant mass regions not clouded by resonances, while positive signals in the η , ρ/ω and ϕ regions can be used for normalization. The LHCb experiment set³¹ upper limits on the $D_{(s)}^+ \rightarrow \pi^+ \mu^+ \mu^-$ branching fractions,

$$BR(D^+ \rightarrow \pi^+ \mu^+ \mu^-) < 7.3(8.3) \times 10^{-8} @ 90(95)\% CL,$$

$$BR(D_s^+ \rightarrow \pi^+ \mu^+ \mu^-) < 41(48) \times 10^{-8} @ 90(95)\% CL.$$

The LHCb experiment also searched for the $D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$ decay with two same sign muons, that measures lepton number violation via non-SM particles, e.g. Majorano neutrino. The upper limits on the $D_{(s)}^+ \rightarrow \pi^- \mu^+ \mu^+$ branching fractions,

$$BR(D^+ \rightarrow \pi^- \mu^+ \mu^+) < 2.2(2.5) \times 10^{-8} @ 90(95)\% CL,$$

$$BR(D_s^+ \rightarrow \pi^- \mu^+ \mu^+) < 12(14) \times 10^{-8} @ 90(95)\% CL,$$

are the new world best limits, presenting a factor 50 improvement with respect to previous results.

LHCb searched³² also for another flavour changing neutral current decay, $D^0 \rightarrow \pi^+ \pi^- \mu^+ \mu^-$, that can proceed via box and penguin diagrams. A sample of D^0 mesons from $D^{*+} \rightarrow D^0 \pi^+$ decays was used. In each di-muon $m(\mu^+ \mu^-)$ invariant mass bin, the 2D fit, $m(\pi^+ \pi^- \mu^+ \mu^-)$ and $\Delta m = m(\pi^+ \pi^- \mu^+ \mu^- \pi^+) -$

$m(\pi^+\pi^-\mu^+\mu^-)$, was performed. The ϕ resonance region, i.e. the decay $D^0 \rightarrow \pi^+\pi^-\phi \rightarrow \pi^+\pi^-\mu^+\mu^-$, was used for normalization. Both low and high di-muon invariant mass $m(\mu^+\mu^-)$ regions showed no significant $D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-$ signal, and the upper limit on the branching fraction was set, $BR(D^0 \rightarrow \pi^+\pi^-\mu^+\mu^-) < 7.4 \times 10^{-7} @ 90\%CL$. This result presents a factor 70 improvement in sensitivity compared to previous results.

In **summary**, important progress has been achieved over the last years in understanding and improving precision on the mixing and CP-violation phenomena in the charm quark sector. Large samples of high quality data from both e^+e^- and hadronic machines are available. Charm mixing is well established with the x and y mixing parameters at the level of few $\times 10^{-3}$, with now precise single measurements available. Sensitivity of the CP-symmetry tests in the charm sector will soon approach Standard Model tolerated values. Many charm rare decay searches show low combinatorial background level, even at hadronic machines, suggesting further sensitivity improvement with increased statistics.

Acknowledgments

It is my pleasure to thank F. Anulli, I. Belyaev, M. Calvi, L. Dong, T. Gershon, R. Harr, H. Muramatsu, M. Williams and A. Zupanc for their help in preparing the talk.

References

1. A. F. Falk, Y. Grossman, Z. Ligeti, Y. Nir, A. A. Petrov, *Phys. Rev.* **D69**, 114021 (2004).
2. J. Beringer *et al.*, *Phys. Rev.* **D86**, 010001 (2012).
3. Y. Grossman, Y. Nir, G. Perez, *Phys. Rev. Lett.* **103**, 071602 (2009).
4. Y. Grossman, A. L. Kagan, Y. Nir, *Phys. Rev.* **D75**, 036008 (2007).
5. BES III Collab. (M. Ablikim *et al.*), *arXiv* 1307.2022 (2013).
6. LHCb Collab. (R. Aaij *et al.*), *Nucl. Phys.* **B871**, 1 (2013).
7. BABAR Collab. (J. P. Lees *et al.*), *Phys. Rev.* **D87**, 012004 (2013).
8. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **110**, 101802 (2013).
9. CDF Collab., *CDF NOTE* **10990** (2013).
10. HFAG group, <http://www.slac.stanford.edu/xorg/hfag/charm/index.html>
11. BABAR Collab. (J. P. Lees *et al.*), *Phys. Rev.* **D87**, 052010 (2013).
12. B. R. Ko, E. Won, B. Golob and P. Pakhlov, *Phys. Rev.* **D84**, 111501 (2011).
13. Belle Collab. (B. R. Ko *et al.*), *JHEP* **1302**, 098 (2013).
14. Belle Collab. (B. R. Ko *et al.*), *Phys. Rev. Lett.* **109**, 021601 (2012).
15. BABAR Collab. (J. P. Lees *et al.*), *Phys. Rev.* **D87**, 052012 (2013).
16. LHCb Collab. (R. Aaij *et al.*), *JHEP* **1306**, 112 (2013).
17. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **B718**, 902 (2013).
18. LHCb Collab. (R. Aaij *et al.*), *Phys. Rev. Lett.* **108**, 111602 (2012).
19. CDF Collab. (T. Aaltonen *et al.*), *Phys. Rev. Lett.* **109**, 111801 (2012).
20. Belle Collab. (B. R. Ko *et al.*), *arXiv* 1212.1975 (2012).
21. BABAR Collab. (B. Aubert *et al.*), *Phys. Rev. Lett.* **100**, 061803 (2008).
22. LHCb Collab. (R. Aaij *et al.*), *LHCb-CONF-2013-003* (2013).

23. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **B723**, 33 (2013).
24. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **B726**, 623 (2013).
25. Belle Collab. (A. Zupanc *et al.*), *JHEP* **1309** 139 (2013).
26. C. T. H. Davies, C. McNeile, E. Follana, G. P. Lepage, H. Na and J. Shigemitsu, *Phys. Rev.* **D82**, 114504 (2010).
27. Belle Collab. (E. White *et al.*), *Phys. Rev.* **D88**, 051101 (2013).
28. CLEO Collab. (N. Lowrey *et al.*), *Phys. Rev.* **D80**, 031105 (2009).
29. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **B725**, 16 (2013).
30. A. Paul, I. I. Bigi and S. Recksiegel, *Phys. Rev.* **D83**, 114006 (2011).
31. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **B724**, 203 (2013).
32. LHCb Collab. (R. Aaij *et al.*), *Phys. Lett.* **xB728**, 234 (2014).