

# Mixing and CP violation

Olivier Leroy<sup>1</sup>

CPPM

163 avenue de Luminy Case 902

13288 Marseille cedex 9, FRANCE

## 1 Introduction

In the Standard Model (SM), neutral mesons ( $M^0$ ) mix with their antiparticles ( $\bar{M}^0$ ) via box diagrams. The mass eigenstates ( $M_{L,H}$ ) are linear combinations of the flavour eigenstates:  $M_{L,H} = p|M^0\rangle \pm q|\bar{M}^0\rangle$ . This phenomenon can be characterized by the mass and decay width differences between the mass eigenstates,  $\Delta m$  and  $\Delta\Gamma$ , and by the relative phase between off-diagonal terms of the mass and decay matrices:  $\phi_{12} = \arg(-M_{12}/\Gamma_{12})$ . Three types of CP violation are usually distinguished: in the decay, in the mixing, and in the interference between decay and mixing. In these proceedings, we give an overview of recent experimental results in quark mixing and CP violation. The main actors in this area are recalled in Table 1, together with their main characteristics. In Section 2, we summarize the mixing and CP violation results related to charm mesons. In Section 3, we report on the  $B_s^0$  mixing related parameters:  $\Delta m_s$ ,  $\Delta\Gamma_s$ ,  $\phi_s$  and  $A_{SL}$ . In Section 4, we describe recent progresses towards the measurement of the  $\gamma$  angle of the unitarity triangle.

Experiment	Accelerator	Beam energies	$\sigma(b\bar{b})$	Int. lumi (end 2011)
BaBar	PEP2, $e^+e^-$	3.1 + 9 GeV	1 nb	550 fb <sup>-1</sup>
Belle	KEKB, $e^+e^-$	3.5 + 8 GeV	1 nb	1ab <sup>-1</sup>
CDF, DO	Tevatron, $p\bar{p}$	2 × 0.98 TeV	100 μb	10 fb <sup>-1</sup> each
LHCb	LHC, $pp$	2 × 3.5 TeV	300 μb	1 fb <sup>-1</sup>
ATLAS, CMS	LHC, $pp$	2 × 3.5 TeV	300 μb	5 fb <sup>-1</sup> each

Table 1: Main actors in  $B$  &  $D$  mixing and CP violation. From left to right: experiment, accelerator, beam energies,  $b\bar{b}$  cross-section and integrated luminosity registered by the end of 2011.

---

<sup>1</sup>on behalf of the LHCb Collaboration

	$D^0$	$B^0$	$B_s^0$
$x = \Delta m/\Gamma$	$0.0063^{+0.0019}_{-0.0020}$	$0.770 \pm 0.008$	$26.74 \pm 0.22$
$y = \Delta\Gamma/2\Gamma$	$-0.0075 \pm 0.0012$	$\pm 0.007 \pm 0.009$	$0.072 \pm 0.011$
CPV in decay	<i>e.g.</i> $\Delta A_{CP}(KK, \pi\pi)$	<i>e.g.</i> $A_{CP}(B^0 \rightarrow K\pi)$	<i>e.g.</i> $A_{CP}(B_s^0 \rightarrow K\pi)$
CPV in mixing $ q/p $	$0.88^{+0.18}_{-0.16}$	$1.0017 \pm 0.0017$	$1.0052 \pm 0.0032$
CPV in interf. “arg( $q/p$ )”	$-0.18^{+0.17}_{-0.15}$	$2\beta = 0.746^{+0.028}_{-0.027}$	$\phi_s = -0.044^{+0.090}_{-0.085}$

Table 2: Summary of experimental measurements of mixing and CP violation in neutral  $D$  and  $B$  mesons [1]. Red italic means “ $5\sigma$ ” has not yet been established. The  $B$   $\Delta\Gamma$  convention is adopted for the charm, i.e.  $\Delta\Gamma = \Gamma_L - \Gamma_H$ .  $\Gamma$  is the decay width of meson shown in each column. CP violation is not quantified by a unique number: values or examples are given to illustrate the status in June 2012.

## 2 Charm mixing and CPV

Charm mixing is established at  $10.2\sigma$ , though no single experiment reaches  $5\sigma$  yet. The world average for the mixing parameters  $x = \Delta m/\Gamma$  and  $y = \Delta\Gamma/2\Gamma$  are given in Table 2. In April 2012, BaBar and Belle presented new results concerning the CP violating parameters:  $y_{CP} = \frac{\tau(D^0 \rightarrow K^-\pi^+)}{\tau(D^0 \rightarrow hh)} - 1 = \frac{1}{2}(|q/p| + |p/q|)y \cos \phi - \frac{1}{2}(|q/p| - |p/q|)x \sin \phi$ , where  $hh = K^+K^-$  or  $\pi^+\pi^-$ , and  $A_\Gamma = \frac{\tau(\bar{D}^0 \rightarrow hh) - \tau(D^0 \rightarrow hh)}{\tau(\bar{D}^0 \rightarrow hh) + \tau(D^0 \rightarrow hh)} = \frac{1}{2}(|q/p| - |p/q|)y \cos \phi - \frac{1}{2}(|q/p| + |p/q|)x \sin \phi$ . The world average gives [1]  $y_{CP} = (0.866 \pm 0.155)\%$ , compatible with  $y$  and  $A_\Gamma = (-0.022 \pm 0.161)\%$ , compatible with zero. Hence these results are compatible with CP conservation.

The charm result which created the most excitement is the one on  $\Delta A_{CP}(D^0 \rightarrow K^+K^-, \pi^+\pi^-)$ . This parameter is the difference of CP violating asymmetry measured in  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$ . In November 2011, LHCb reported a value of  $\Delta A_{CP}$   $3.4\sigma$  away from zero [2]. In 2012, CDF found a similar result, bringing the significance of the deviation to  $3.8\sigma$  [3]. The parameter  $\Delta A_{CP}$  measures essentially the direct CP violation, which is expected to be very small within the SM. Figure 1 shows the indirect versus direct CP violating parameters measured in  $D^0 \rightarrow K^+K^-$  and  $D^0 \rightarrow \pi^+\pi^-$  [1]. The world average is  $\Delta a_{CP}^{\text{dir}} = (-0.656 \pm 0.154)\%$  [1]. Theoretical work is ongoing to disentangle SM hadronic effects from possible New Physics. Experimental improvements are expected soon, since LHCb data sample will be 4 times larger by the end of 2012.

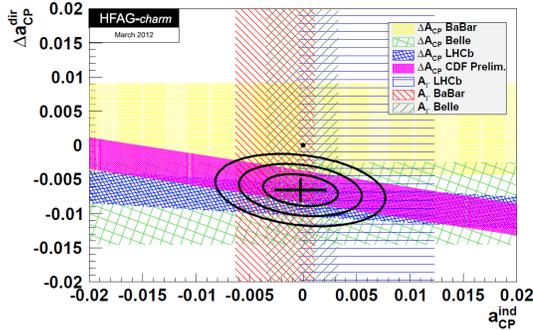


Figure 1: Direct versus indirect CP violating charm parameters [1]. Individual measurements are plotted as bands showing their  $\pm 1\sigma$  range. The no-CPV point (0,0) is shown as a filled circle, and the best fit value is indicated by a cross showing the one-dimensional errors. Two-dimensional 68% CL, 95% CL, and 99.7% CL regions are plotted as ellipses [1].

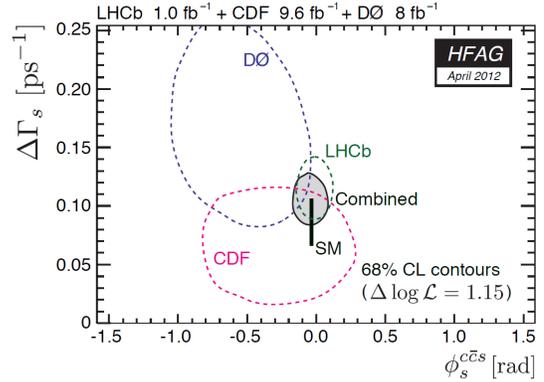


Figure 2: 68% CL regions in  $B_s^0$  width difference  $\Delta\Gamma_s$  and weak phase  $\phi_s^{c\bar{c}s}$  obtained from individual and combined CDF [5], DO [6] and LHCb [4, 7] likelihoods of  $B_s^0 \rightarrow J/\psi\phi$  and  $B_s^0 \rightarrow J/\psi\pi^+\pi^-$  [7] samples. The expectation within the SM [8, 9] is shown as the black rectangle.

### 3 $B_s^0$ mixing parameters ( $\Delta m_s$ , $\Delta\Gamma_s$ , $\phi_s$ ) and $A_{SL}$

We define  $\phi_s^{c\bar{c}s}$  as the weak phase difference between the  $B_s^0\text{-}\bar{B}_s^0$  mixing amplitude and the  $b \rightarrow c\bar{c}s$  decay amplitude. The golden mode to measure this phase is  $B_s^0 \rightarrow J/\psi\phi$ , though it has also been measured in  $B_s^0 \rightarrow J/\psi\pi^+\pi^-$ . A summary of the results on  $\phi_s^{c\bar{c}s}$  is given in Figure 2 and Table 3, together with the decay width difference between the  $B_s^0$  mass eigenstate,  $\Delta\Gamma_s$ . It should be emphasized that this latter parameter has been measured for the first time with greater than  $5\sigma$  significance from zero in 2012 [4]. When combined with other lifetime measurements, including  $B_s^0$  decays to  $K^+K^-$ ,  $J/\psi f_0(980)$ ,  $D_s^-\ell^+\nu_\ell$  and  $D_s^-\pi^+$ , the world average value is  $\Delta\Gamma_s = +0.095 \pm 0.014 \text{ ps}^{-1}$  [1]. The average value of  $\Delta m_s$  is  $17.719 \pm 0.043 \text{ ps}^{-1}$  [1]. It is dominated by [10].

In 2011, DO reported a value of the dimuon asymmetry,  $A_{SL}^b$ ,  $3.9\sigma$  away from the SM expectation [11] (see Figure 3). This asymmetry is linked to the fundamental phase  $\phi_{12}^s$ . Theoretical work is ongoing to determine whether the observed value can be accounted by New Physics effects in the mixing and/or decay matrices of  $B_s^0$  and/or  $B^0$  [12].

Ref.	Mode	$\phi_s = \phi_s^{c\bar{c}s}$	$\Delta\Gamma_s$ (ps <sup>-1</sup> )
CDF [5]	$J/\psi\phi$	$[-0.60, 0.12]$ , 68% CL	$0.068 \pm 0.026 \pm 0.007$
DO [6]	$J/\psi\phi$	$-0.55^{+0.38}_{-0.36}$	$0.163^{+0.065}_{-0.064}$
LHCb [4]	$J/\psi\phi$	$-0.001 \pm 0.101 \pm 0.027$	$0.116 \pm 0.018 \pm 0.006$
LHCb [7]	$J/\psi\pi^+\pi^-$	$-0.019^{+0.173+0.004}_{-0.174-0.003}$	—
Combined [HFAG'2012]		$-0.044^{+0.090}_{-0.085}$	$+0.105 \pm 0.015$

Table 3: Individual and average values of  $\phi_s^{c\bar{c}s}$  and  $\Delta\Gamma_s$  compiled by HFAG [1].

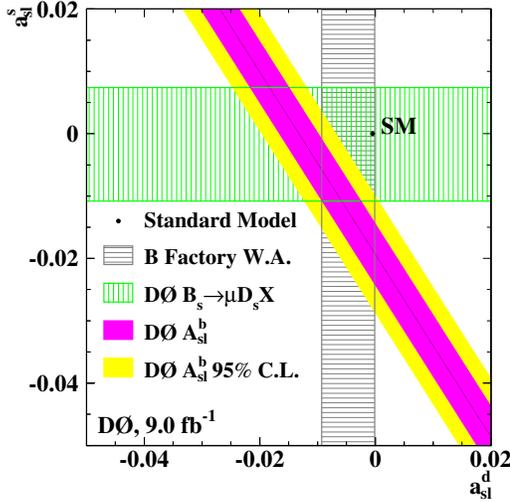


Figure 3:  $A_{SL}^b$  measured by DO (plain magenta and yellow),  $a_{sl}^s$  measured by DO (vertical green hatched) and  $a_{sl}^d$  measured by the  $B$ -factories (horizontal black hatched). The SM model prediction is indicated as a black circle.

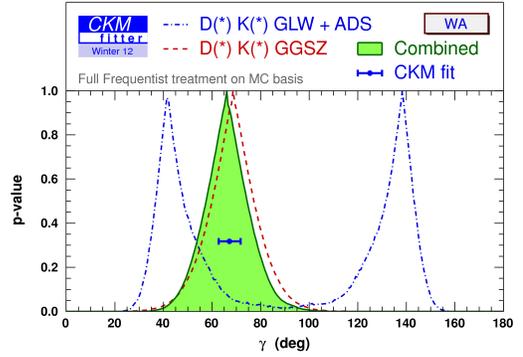


Figure 4: Constraints on  $\gamma$  from world average  $D^{(*)}K^{(*)}$  decays (GLW+ADS) and Dalitz analyzes (GGSZ), compared to the prediction from the global CKM fit (not including these measurements) [8].

## 4 Angle $\gamma$

$\gamma = \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right)$  is the least well measured angle in the unitarity triangle. The indirect determination via a global fit to experimental other directly measured data gives  $\gamma = (67.1 \pm 4.3)^\circ$  [8]. Its determination can be split in methods involving loop-mediated processes and methods dominated by tree-level diagrams.

The main news concerning the determination of  $\gamma$  via loop-mediated processes comes from LHCb results on  $B \rightarrow hh$  [13]. Some steps towards  $\gamma$  have been reached: the world best measurement of direct CP violation in  $B^0 \rightarrow K\pi$ ,  $A_{CP}(B^0 \rightarrow K\pi) = -0.088 \pm 0.011(\text{stat}) \pm 0.008(\text{syst})$  and the first evidence of CP violation in  $B_s^0$  decay,  $A_{CP}(B_s^0 \rightarrow K\pi) = 0.27 \pm 0.08(\text{stat}) \pm 0.02(\text{syst})$ . A first time-dependent CP asymmetry in  $B_s^0 \rightarrow K^+K^-$  is also achieved [14].

The world average direct measurement of  $\gamma$  is dominated by  $B$ -factories results. Two groups obtain slightly different values:  $\gamma = (67.1 \pm 12)^\circ$  [8] and  $\gamma = (75.5 \pm 10.5)^\circ$  [15]. In LHCb, important milestones towards the  $\gamma$  measurement have been reached recently, with the studies of  $B \rightarrow D(hh, hhhh)K$  [16, 17],  $B \rightarrow DK^*$  [18],  $B \rightarrow DK\pi\pi$  [19] and  $B_s^0 \rightarrow D_s K^\pm$  [20]. In [21], LHCb reported the first observation of  $B^\pm \rightarrow [\pi K]_D K^\pm$  and overtook the  $B$ -factories in some “ADS” observables. Figure 4 gives the constraints on  $\gamma$  from world average  $D^{(*)}K^{(*)}$  decays (GLW+ADS) and Dalitz analyzes (GGSZ) [8]. The latest GGSZ result from Belle [22] was not included yet.

## 5 Epilogue

While completing these proceedings, several important new results have been obtained. LHCb has released a preliminary result on  $a_{sl}^s$  [23]. Both BaBar [24] and Belle [25] have updated their  $\text{BR}(B \rightarrow \tau\nu)$  measurements, decreasing the tension with  $\sin 2\beta$ . Atlas presented an untagged analysis of  $B_s^0 \rightarrow J/\psi\phi$  decays [26], bringing new constraints on  $\phi_s$  and  $\Delta\Gamma_s$ , though less precise than the LHCb ones. Belle presented an updated  $\Delta A_{CP}(KK, \pi\pi)$  measurement [27], bringing the new world average value for this CP violating observable in charm  $4.9\sigma$  away from zero.

## 6 Conclusions and prospects

A simplified summary of mixing and CP violation in  $B$  and  $D$  is given in Table 2. Charm mixing is well established ( $10.2\sigma$ ), though no single experiment has reached  $5\sigma$  yet. A hint for CP violation in charm has been reported by LHCb and re-enforced recently by CDF and Belle, bringing the  $\Delta A_{CP}(D^0 \rightarrow K^+K^-, \pi^+\pi^-)$  observable  $4.9\sigma$  away from zero. Theoretical work is ongoing to disentangle SM hadronic effect from

possible New Physics contributions. Experimental improvements are also expected, in particular in LHCb which will have 4 times more data by the end of 2012. All other charm CP measurements are compatible with CP conservation.

Concerning CP violation in the  $B$ -hadron sector, many outstanding new results have been obtained in 2012 by LHCb, the  $B$ -factories and the TeVatron. Uncertainties are much reduced or first measurement ever are reported. Everything is compatible with the Standard Model so far, bringing strong constraints on New Physics. The uncertainty on the CP violating phase  $\phi_s^{ccs}$  is below 0.09 rad. The parameter  $\Delta\Gamma_s$  has been measured for the first time by LHCb, with a significance above  $5\sigma$  from zero. The first evidence for CP violation in  $B_s^0$  has been reported by LHCb. Important milestones towards a first measurement of the  $\gamma$  angle at LHCb has been achieved. The long-standing tension between  $\sin 2\beta$  and the branching ratio of  $B^+ \rightarrow \tau^+ \nu_\tau$  has decreased following the updated measurement of the latter one by the  $B$ -factories. The tension in the dimuon asymmetry reported by DO in 2010 has also decreased, following the updated analysis by DO itself and also a new measurement of  $a_{sl}^s$  by LHCb. Mixing and CP violating in the quark sectors bring stronger constraints than ever on possible extensions of the Standard Model.

## Acknowledgments

I would like to thanks the organizers of the PLHC'2012 for the nice atmosphere during the conference in Vancouver and my LHCb colleagues who helped in the preparation of this talk.

## References

- [1] HFAG, Y. Amhis et al., arXiv:1207.1158 (2012).
- [2] LHCb Collaboration, PRL 108, 111602 (2012).
- [3] CDF Collaboration, CDF note 10784 (2012).
- [4] LHCb Collaboration, CERN-LHCb-CONF-2012-002 (2012).
- [5] CDF Collaboration, CDF note 10778 (2012).
- [6] DO Collaboration, Phys. Rev. D85 032006 (2012).
- [7] LHCb Collaboration, arXiv:1204.5675 (2012).
- [8] J. Charles et al., CKMfitter, Phys. Rev. D84 033005 (2011), with updated results and plots available at <http://ckmfitter.in2p3.fr>.

- [9] A. Lenz and U. Nierste, arXiv:1102.4274 (2011).
- [10] LHCb Collaboration, LHCb-CONF-2011-050 (2011).
- [11] DO Collaboration, PRD 84, 052007 (2011).
- [12] See for exmaple: C. Bobeth and U. Haisch, arXiv:1109.182 (2011). Lenz et al, arXiv:1203.0238 (2012).
- [13] LHCb Collaboration, PRL 108, 201601 (2012).
- [14] LHCb Collaboration, LHCb-CONF-2012-007 (2012).
- [15] M. Bona et al. [UTfit Collab.], JHEP 507, 28 (2005) [hep-ph/0501199], and updates at <http://www.utfit.org/>.
- [16] LHCb Collaboration, LHCb-CONF-2011-031 (2011).
- [17] LHCb Collaboration, LHCb-CONF-2011-044 (2011).
- [18] LHCb Collaboration, PLB 706 32-39 (2011).
- [19] LHCb Collaboration, PRL 108 161801 (2012).
- [20] LHCb Collaboration, arXiv:1204.1237 (2012).
- [21] LHCb Collaboration, PLB 712 (2012).
- [22] Belle Collaboration, arXiv:1204.6561 (2012).
- [23] LHCb Collaboration, LHCb-CONF-2012-022 (2012).
- [24] BaBar Collaboration, arXiv:1207.0698 (2012).
- [25] Y. Yook, (Belle Collaboration), “Leptonic & semileptonic B decays at Belle”, talk given at ICHEP 2012, Melbourne, Australia, (2012).
- [26] ATLAS Collaboration, arXiv:1208.0572 (2012).
- [27] B. R. Ko, (Belle Collaboration), “Direct CP Violation in charm at Belle”, talk given at ICHEP 2012, Melbourne, Australia, (2012).