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A perspective of High Energy Physics from precision measurements
La physique des Hautes Energies du point de vue des mesures de précision

CP violation in *B* decays

Brisure de la symétrie CP dans les désintégrations de mésons beaux

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Abstract. The experimental study of *CP* violation in *B* decays has led to significant progress in our understanding of nature: (i) It demonstrated that the Kobayashi-Maskawa mechanism is the dominant source of *CP* violation in meson decays. (ii) It improved significantly the precision in the determination of the parameters of the Cabibbo–Kobayashi–Maskawa quark-mixing matrix. (iii) It proved that new physics that has order-one flavour-changing couplings to the b quark should be characterised by a mass scale higher than $\mathcal{O}(10^3$ TeV). Further progress is expected from the Belle II and LHC experiments during the next decade and beyond. Present status and perspectives are here discussed.

Résumé. L'étude expérimentale de la brisure de la symétrie *CP* dans les désintégrations de mésons beaux (B) a apporté des contributions majeures à notre compréhension de la nature : (i) Elle a établi que le mécanisme de Kobayashi-Maskawa est la source dominante de brisure de la symétrie *CP* dans les systèmes des mésons K et B. (ii) Elle a amélioré significativement la précision des paramètres qui décrivent la matrice de mélange des quarks Cabibbo–Kobayashi–Maskawa. (iii) Elle a prouvé que l'échelle d'énergie d'une nouvelle physique avec des couplages de changement de saveurs d'ordre unité, devait être supérieure à $\mathcal{O}(10^3$ TeV). Des progrès sont attendus, dans cette décennie et la suivante, des expériences du LHC et Belle II. L'état de l'art de cette Physique et les perspectives des expériences futures sont discutés dans cet article.

Keywords. Meson, Decay, LHC, Large Hadron Collider, CP symmetry violation.

Mots-clés. Méson, Désintégration, LHC, Grand collisionneur de hadrons, Violation de symétrie CP.

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1. Introduction

The noninvariance of the laws of nature under the combined action of charge conjugation (C) and parity (P) transformations, so-called CP violation, is a well established experimental fact since several decades and is well known to be a necessary condition for the dynamical generation of the observed baryon asymmetry of the universe (BAU) [1]. The Standard Model (SM) of particle physics includes CP violation through an irreducible complex phase in the Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix [2, 3]. However, the size of CP violation in the SM appears to be too small to account for the observed BAU [4–6], suggesting the existence of sources of CP violation beyond the SM.

The last two decades have seen enormous experimental progress in the study of CP violation with beauty hadrons, first at the so-called B factories and then at the Large Hadron Collider (LHC). Yet, no experimental findings leading to a major failure of the SM in the flavour sector (nor anywhere else) have emerged so far. In this paper, a brief review of the present experimental status and of future perspectives with CP violation in B decays, also including a historical reminder and a theoretical overview, is made.

2. Historical perspective

Flavour physics has played a prominent role in laying the foundations of what is known nowadays as the SM of particle physics. As a case in point, the existence of a third generation of quarks was predicted in a 1973 work by Kobayashi and Maskawa (KM) [3] by extending the Cabibbo [2] and the Glashow–Iliopoulos–Maiani [7] mechanisms. In the KM paper it was conjectured for the first time that the phenomenon of CP violation, first revealed in a crucial experiment in 1964 using decays of neutral kaons [8], could be included into the model of weak interactions if six quarks existed in nature. Although at the time only hadrons made of the three lighter quarks were known, a new state made of a $c\bar{c}$ quark pair was discovered almost simultaneously at Brookhaven [9] and SLAC [10] one year later. The observation of the b quark followed a few years later at FNAL [11], whereas the t quark was observed for the first time, again at FNAL, only in 1995 [12], more than 20 years after the initial prediction. The KM model, formalised in the so-called Cabibbo–Kobayashi–Maskawa (CKM) quark-mixing matrix, became soon one of the main building blocks of the emerging SM theory.

The experimental proof of the validity of the KM mechanism became a question of utmost importance, and it was soon realised that an accurate test required CP-violation measurements to be performed with quarks heavier than the s quark. At the beginning of the 1980's the CLEO experiment made first studies with b quarks at CESR [13]. In the same period, the idea that $B^0 \to J/\psi K^0_S$ decays could exhibit large time-dependent CP-violating effects was put forward [14, 15]. However, the measurement of CP violation in $B^0 \to J/\psi K^0_S$ decays presented remarkable experimental challenges. First of all, the production rate of B^0 mesons that was required to achieve a precise measurement was enormous with respect to what was conceivable at the time. Furthermore, it was not possible to perform a measurement of the B^0 decay time with B^0 mesons produced at rest at symmetric e^+e^- colliders operating at the centre-of-mass energy of the $\Upsilon(4S)$. A fundamental physics advancement was made in 1987 owing to the ARGUS experiment at DESY, with the first measurement of the B^0–$\bar{B}^0$ mixing rate [16], as the relatively large mixing rate that was observed enhanced the feasibility of measuring CP violation with $B^0 \to J/\psi K^0_S$ decays. In the same year, a proposal to realise a high-luminosity asymmetric e^+e^- collider was made [17]: different energies of the colliding beams would have allowed B^0 mesons boosted towards the direction of the most energetic beam to be produced, enabling the measurement of the B^0 decay time by means of state-of-the-art silicon vertex detectors. The novel idea was then implemented a few years later with the the construction of two similar machines: PEP-II at SLAC and KEKB at KEK. The two machines were able to produce $\mathscr{O}(10^6)$ $b\bar{b}$ pairs per day, to be compared with a few tens at CESR, largely outscoring any previous record of luminosity at e^+e^- colliders. The corresponding detectors, BaBar [18] at PEP-II and Belle [19] at KEKB, by the end of their programmes measured *CP* violation in $B^0 \to J/\psi K^0_S$ decays with a relative precision of about 3% [20,21], performing in addition a plethora of other very relevant measurements [22]. In the same period, relevant progresses were also made with hadronic collisions at the Tevatron, where, as an example, the first observation of B^0_s–$\overline{B}^0_s$ mixing was achieved [23]. It is also important to mention that, in the the course of the 1990's, some relevant b-physics measurements were made by LEP experiments at CERN [24] and SLD at SLAC [25], exploiting decays of Z^0 bosons to b-quark pairs.

While the BaBar and Belle detectors were under approval for construction, dedicated b-physics experiments at the LHC were also being proposed. The various proposals were eventually merged into a single one: the LHC beauty experiment, LHCb [26]. LHCb was designed as a single-arm forward spectrometer, thought to exploit the large $b\bar{b}$ production cross-section in proton-proton collisions at the LHC. The LHCb experiment was approved in 1998 and started taking data in 2009, performing amongst other things a wide range of high-precision measurements of *CP* violation. Although their detectors were designed for different principal purposes, the ATLAS [27] and CMS [28] experiments have also been making significant contributions to the b-quark sector, mainly using final states containing muon pairs.

Meanwhile, even before the LHC was turned on, proposals for constructing upgraded asymmetric e^+e^- colliders capable of achieving two orders of magnitude larger instantaneous luminosity with respect to PEP-II and KEKB were put forward. Eventually, only one of such machines reached the construction phase: SuperKEKB. The associated detector, Belle II [29], started taking first data in 2018, and it is now expected to run for about another decade.

3. A *CP* violation primer

On the theoretical side, a Lagrangian is *CP*-violating if, when all freedom to redefine the phases of the fields is used, there remain couplings with irremovable phases. On the experimental side, *CP* violation is established if a pair of *CP*-conjugate processes (i.e., the initial and final particles in one process are the *CP*-conjugate of the initial and final particles in the other, respectively) proceed at different rates. A necessary condition for such a *CP* asymmetry to occur is that the process has contributions from two amplitudes which depend on (combinations of) couplings that carry different phases. When discussing *CP* violation in meson decays, one distinguishes three classes of *CP* asymmetries, depending on the nature of the interfering amplitudes.

***CP* violation in mixing.** Consider the transition amplitude from a neutral B meson to $\overline{B}$ and the transition amplitude for the *CP*-conjugate transition, from $\overline{B}$ to B:

$$\langle B|\mathscr{H}|\overline{B}\rangle = M_{B\bar{B}} - \frac{\mathrm{i}}{2}\Gamma_{B\bar{B}}, \quad \langle \overline{B}|\mathscr{H}|B\rangle = M^*_{B\bar{B}} - \frac{\mathrm{i}}{2}\Gamma^*_{B\bar{B}}, \tag{1}$$

where M and Γ are associated with transitions via off-shell (dispersive) and on-shell (absorptive) intermediate states. The ratio between the two is given by

$$\left(\frac{q}{p}\right)^2 = \frac{M^*_{B\bar{B}} - \frac{\mathrm{i}}{2}\Gamma^*_{B\bar{B}}}{M_{B\bar{B}} - \frac{\mathrm{i}}{2}\Gamma_{B\bar{B}}}. \tag{2}$$

CP violation in mixing is the result of interference between $M_{B\bar{B}}$ and $\Gamma_{B\bar{B}}$, and corresponds to $\mathscr{I}m(\Gamma_{B\bar{B}}/M_{B\bar{B}}) \neq 0$ or, equivalently,

$$|q/p| \neq 1, \tag{3}$$

which implies that the two neutral B mass eigenstates are not CP eigenstates. It is the only possible source of CP asymmetries in wrong-sign semi-leptonic neutral B decays,

$$A_{\rm sl}^{d(s)} \equiv \frac{\Gamma(\overline{B}^0_{(s)}(t)\to \ell^+ X) - \Gamma(B^0_{(s)}(t)\to \ell^- X)}{\Gamma(\overline{B}^0_{(s)}(t)\to \ell^+ X) + \Gamma(B^0_{(s)}(t)\to \ell^- X)} = \frac{1-|q/p|^4}{1+|q/p|^4}. \tag{4}$$

Here $B^0_{(s)}(t)$ ($\overline{B}^0_{(s)}(t)$) is the time-evolved state that was purely $B^0_{(s)}$ ($\overline{B}^0_{(s)}$) at time $t=0$. CP violation in $B^0_{(s)}-\overline{B}^0_{(s)}$ mixing has been experimentally shown to be a small effect, since it has not been observed yet.

***CP* violation in decay.** Consider the decay of a charged or neutral B meson into a final state f, and the decay of $\overline{B}$ into the CP-conjugate final state $\overline{f}$. The amplitudes for these two processes are defined as

$$A_f = \langle f|\mathscr{H}|B\rangle, \quad \overline{A}_{\overline{f}} = \langle \overline{f}|\mathscr{H}|\overline{B}\rangle. \tag{5}$$

CP violation in decay is the result of interference between two contributions to A_f (such as tree and penguin operators) and it corresponds to

$$|\overline{A}_{\overline{f}}/A_f| \neq 1. \tag{6}$$

It is the only possible source of CP asymmetries in charged B decays,

$$\mathscr{A}_{f^\pm} \equiv \frac{\Gamma(B^-\to f^-) - \Gamma(B^+\to f^+)}{\Gamma(B^-\to f^-) + \Gamma(B^+\to f^+)} = \frac{|\overline{A}_{f^-}/A_{f^+}|^2 - 1}{|\overline{A}_{f^-}/A_{f^+}|^2 + 1}. \tag{7}$$

CP violation in decay has been established (at a level higher than 5σ) for B decays into $\pi^+\pi^-$, $K^+\pi^-$, various DK^+ states and several three-body final states [30].

***CP* violation in interference of decays with and without mixing.** Consider the direct decay amplitude of a neutral B meson to a final CP eigenstate f_{CP}, $A_{f_{CP}}$. An additional contribution to this decay comes from a B to $\overline{B}$ transition followed by $\overline{B}\to f_{CP}$ decay, $M_{B\bar{B}}\overline{A}_{f_{CP}}$. (We neglect here $\Gamma_{B\bar{B}}$ since it is experimentally established that $|\Gamma_{B\bar{B}}| \ll |M_{B\bar{B}}|$.) Define

$$\lambda_{f_{CP}} = \frac{M^*_{B\bar{B}}}{|M_{B\bar{B}}|}\frac{\overline{A}_{f_{CP}}}{A_{f_{CP}}}. \tag{8}$$

CP violation in the interference of decays with and without mixing corresponds to

$$\mathscr{I}m(\lambda_{f_{CP}}) \neq 0. \tag{9}$$

It can be measured in B^0 decays into final CP eigenstates,

$$\mathscr{A}_{f_{CP}}(t) \equiv \frac{\Gamma(\overline{B}^0(t)\to f_{CP}) - \Gamma(B^0(t)\to f_{CP})}{\Gamma(\overline{B}^0(t)\to f_{CP}) + \Gamma(B^0(t)\to f_{CP})} = \mathscr{I}m(\lambda_{f_{CP}})\sin(\Delta m_d t), \tag{10}$$

where Δm_d is the mass difference between the masses of the two B^0 mass eigenstates. The final equality in (10) corresponds to the case that CP violation in mixing and CP violation in decay are neglected. The case of a B^0_s meson is similar, but the non-negligible width difference between the mass eigenstates must also be taken into account generalising equation (10). CP violation in the interference of decays with and without mixing has been established in neutral B decays into $\psi K_{\rm S,L}$, $D^{(*)}h^0$, $\psi\pi^0$, D^+D^-, $D^{*+}D^{*-}$, $\phi K_{\rm S}$, $\eta' K_{\rm S}$, $f_0 K_{\rm S}$, $K^+K^-K_{\rm S}$ and $\pi^+\pi^-$. The average of the results for all charmonium states is subject to the cleanest theoretical interpretation, and it is

$$\mathscr{I}m(\lambda_{c\bar{c}K_{\rm S,L}}) = +0.699 \pm 0.017. \tag{11}$$

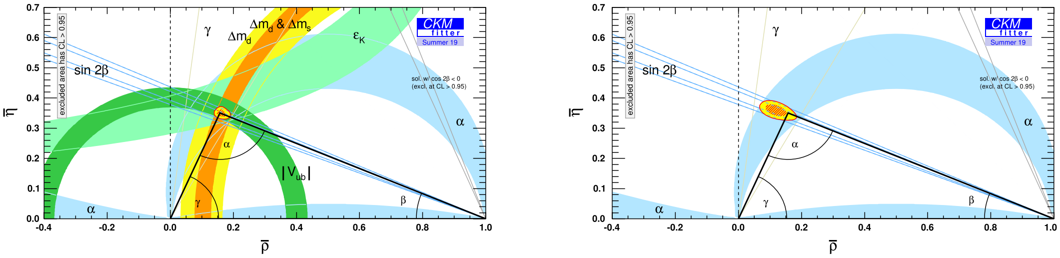

Figure 1. The constraints in the $(\bar{\rho},\bar{\eta})$ plane from (left) all relevant processes, and (right) from *CP*-violating asymmetries in *B* decays only [31].

4. The CKM mechanism and *CP* violation in beauty

The three-generation SM violates *CP*. Among the parameters of the SM Lagrangian, there is a single phase (or, equivalently, a single imaginary parameter), which appears in V, the CKM matrix that parametrises the W^+ interactions with $\overline{u}_{Li} d_{Lj}$ pairs (where $u_{1,2,3} = u, c, t$, and $d_{1,2,3} = d, s, b$)

$$\mathcal{L}_{W,q} = -\frac{g}{\sqrt{2}} \overline{u}_{Li} V_{ij} \not{W}^+ d_{Lj} + \text{h.c.} \tag{12}$$

The CKM matrix depends on three real and one imaginary parameters. The Wolfenstein parametrisation is particularly useful

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - \mathrm{i}\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-\mathrm{i}\eta) & -A\lambda^2 & 1 \end{pmatrix}. \tag{13}$$

The fact that all quark flavour-violating processes and all *CP*-violating processes depend on only three real (λ, A, ρ) and one imaginary $(\mathrm{i}\eta)$ parameters makes the (C)KM mechanism of flavour and *CP* violation subject to stringent tests. Here, *CP*-violating processes play a special role. The fact that *CP* is a good symmetry of the strong interactions implies that *CP* asymmetries dominated by interference of decays with and without mixing are subject to a uniquely clean theoretical interpretation. Thus, for example, within the SM

$$\mathcal{I}m(\lambda_{\psi K_S}) = \frac{2\eta(1-\rho)}{\eta^2 + (1-\rho)^2}, \tag{14}$$

with hadronic uncertainties entering only at the level of a few permil corrections.

In the literature, one often defines $\bar{\rho} + \mathrm{i}\bar{\eta} = -(V_{ud}V_{ub}^*)/(V_{cd}V_{cb})$ which is valid to all orders in λ. The parameters ρ and η approximate $\bar{\rho}$ and $\bar{\eta}$ to order λ^2. The various constraints in the $(\bar{\rho}, \bar{\eta})$ plane are presented in Figure 1. *CP* asymmetries in *B* decays are playing a major role: $\mathcal{A}_{\psi K_S}$, $\mathcal{A}_{\pi\pi}$ and the *CP* asymmetry in $B \to DK$ decays constrain with impressive accuracy the angles

$$\alpha \equiv \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right), \quad \beta \equiv \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right), \quad \gamma \equiv \arg\left(-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right), \tag{15}$$

respectively. As there is a region in the $(\bar{\rho}, \bar{\eta})$ plane that is consistent with all measurements, the CKM mechanism of flavour violation and the KM mechanism of *CP* violation provide a consistent explanation of all data.

5. Probing new physics with *CP* violation in *B* decays

The consistency of the measured *CP* violation in *B* decays with the SM predictions leads to strong constraints on new physics. In the previous section, we assumed that the various flavour-violating and *CP*-violating observables are accounted for by the CKM matrix, and tested the

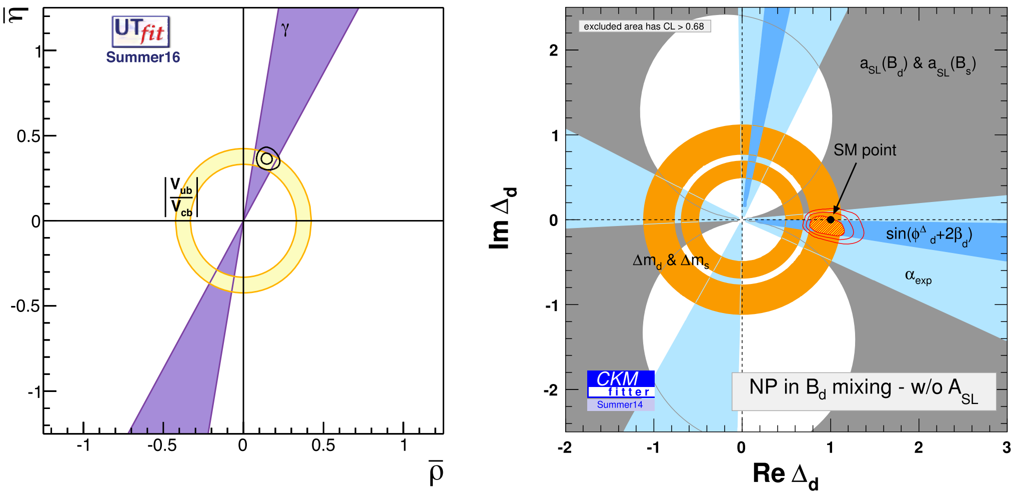

Figure 2. The constraints (left) in the $(\bar{\rho},\bar{\eta})$ plane and (right) in the $(\mathcal{R}e(\Delta_d),\mathcal{I}m(\Delta_d))$ plane from processes involving tree-level decays and $B^0-\overline{B}^0$ mixing only [31,32].

self-consistency of this assumption. To constrain new physics, we here relax this assumption. While we still assume that new physics contributions can be neglected in tree-level flavour-changing processes, we allow new physics contributions to flavour-changing neutral-current processes (FCNC) to be of arbitrary size and phase. This will allow us to ask how much room there is for new physics in these processes.

The most relevant process for our purposes is $B^0-\overline{B}^0$ mixing, and the most general new physics contribution to this process can be represented by a single dimensionless complex parameter Δ_d

$$M_{B\bar{B}} = M_{B\bar{B}}^{\rm SM}\Delta_d. \tag{16}$$

The constraints on z_{bs}/Λ^2 are somewhat weaker. Using only processes that involve no FCNC processes except, possibly, $B^0-\overline{B}^0$ mixing, one can constrain the four parameters $[\bar{\rho},\bar{\eta},\mathcal{R}e(\Delta_d),\mathcal{I}m(\Delta_d)]$, as shown in Figure 2. A similar analysis can be carried out for $B_s^0-\overline{B}_s^0$ mixing.

Thus new physics can contribute no more than $\mathcal{O}(20\%)$ ($\mathcal{O}(10\%)$) of $M_{B\bar{B}}$ if its phase is [mis]aligned with the SM phase. These bounds can be translated into constraints on new physics parameters and, in particular, on new *CP*-violating sources. It can be done for specific models or, assuming that the new degrees of freedom are much heavier than the electroweak-breaking scale, for higher-dimension terms in the SM effective field theory. Take, for example, the dimension-six term

$$\mathcal{L}_{\Delta B=2} = \frac{z_{bd}}{\Lambda^2}(\overline{Q}_{Lb}\gamma_\mu Q_{Ld})(\overline{Q}_{Lb}\gamma^\mu Q_{Ld}), \tag{17}$$

where Q_{Lq} stands for the quark doublet that contains the q quark. Then, for z_{bd} aligned with the SM phase and of $\mathcal{O}(1)$, the lower bound on the scale of new physics is ~660 TeV. If, on the other hand, the relative phase with the SM amplitude is large, the lower bound is raised to close to 10^3 TeV. Conversely, if the scale of new physics is of order TeV, then $\mathcal{R}e(z_{bd}) \lesssim 2.2\times10^{-6}$ and $\mathcal{I}m(z_{bd}) \lesssim 1.2\times10^{-6}$. The constraints on z_{bs}/Λ^2 are somewhat weaker.

The conclusion is that, if there is new physics that has tree-level $\bar{b}d$ coupling of $\mathcal{O}(1)$, then its scale must be at least four orders of magnitude above the weak scale, well above the reach

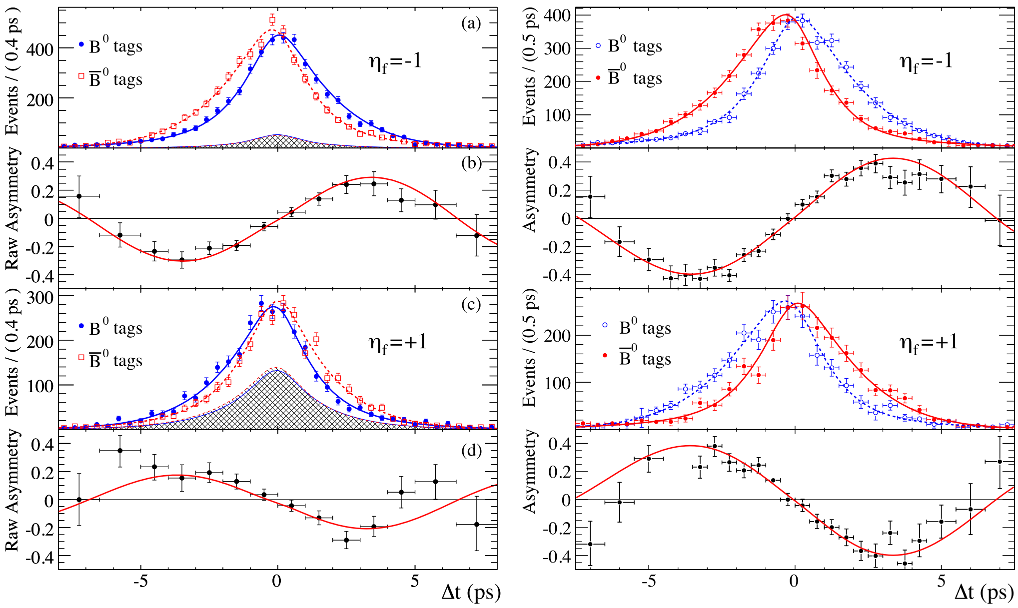

Figure 3. Flavour-tagged Δt distributions (a, c) and raw *CP* asymmetries (b, d) for the BaBar (left) and Belle (right) measurements of $\sin 2\beta$. The two plots at the top show the $B \to c\bar{c}K_S^0$ samples whereas those at the bottom the $B \to J/\psi K_L^0$ sample. The shaded regions for BaBar represent the fitted background, while the Belle distributions are background-subtracted. The plot is taken from Ref. [22].

of direct searches. If, on the other hand, there is new physics at the TeV scale, then its flavour-changing $\bar{b}d$ coupling must be smaller than 10^{-6}, well below a loop suppression. We learn that *CP* violation in *B* decays is a powerful probe of physics at very high scales.

6. The legacy of *B* factories

The measurement of time-dependent *CP*-violation in $B^0 \to J/\psi K_S^0$ decays was the main motivation for the construction of the *B* factories. This is the so-called *golden mode*, belonging to a larger class of decays mediated by $b \to c\bar{c}s$ quark-level transitions, along with other relevant decays, such as $B^0 \to J/\psi K_L^0$. These decay modes have very clean experimental signatures and relatively large branching fractions. They also provide a clean determination of the angle β, as the pollution due to subleading contributions from penguin operators is expected to be at the few permil level.

The two *B* factories have performed their legacy measurements using their entire data samples, with about 465×10^6 [20] and 772×10^6 [21] $B\overline{B}$ pairs. The average of the results from the two experiments gives

$$\sin 2\beta = 0.677 \pm 0.020, \tag{18}$$

corresponding to a 3% precision (which is further improved when considering also LHCb results, as in the world average of (11)). The time-dependent rates and the corresponding *CP*-violating asymmetries are shown in Figure 3.

But the *B* factories were able to go well beyond the measurement of $\sin 2\beta$. In order to check the self-consistency of the KM mechanism of *CP* violation, the measurement of the other two angles α and γ was also of paramount importance. The angle α can be determined by measuring time-dependent *CP* asymmetries in charmless $b \to u\bar{u}d$ transitions. The interference between the tree amplitude and the B^0–$\overline{B}^0$ mixing amplitude provides sensitivity to α. If the tree amplitude were the only one contributing, as in the case of the $B^0 \to J/\psi K^0_{\rm S}$ decay, the measurement of α using the $B \to \pi^+\pi^-$ decay would have been completely analogous to that of β. However, contributions from penguin operators to charmless B decays cannot be neglected. The presence of such contributions is certainly a nuisance for the determination of α, but it also means that new physics might affect the result due to new virtual particles circulating in the loops. As such, the comparison of high-precision measurements of α made with different decays can be exploited to search for possible new physics effects. To overcome the problem of the presence of sizeable penguin amplitudes, techniques which make use of the isospin symmetry of strong interactions have been adopted. One approach is to combine measurements of isospin-related decay modes, as $B^0 \to \pi^+\pi^-$, $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$. Analogously, although the analysis is more complicated due to the presence of vector particles in the final states, $B^0 \to \rho^+\rho^-$, $B^+ \to \rho^+\rho^0$ and $B^0 \to \rho^0\rho^0$ decays can be used. Another approach is to perform a time-dependent Dalitz analysis of $B^0 \to \pi^+\pi^-\pi^0$ decays, using information from the interference between resonances in the corners of the Dalitz plot, also making use of isospin symmetry. All of these methods were pursued at the B factories, and averaging all results the angle α was measured to be [22]

$$\alpha = (88 \pm 5)^\circ. \tag{19}$$

While α and β were determined with precisions at the few percent level, a precise determination of γ turned out to be more difficult, due to the small branching fractions of the relevant decay processes. The most important route to measure γ relies on the interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ quark-level amplitudes using $B \to D^{(*)}K^{(*)}$ decays. The interference is achieved by choosing common final states for D and $\overline{D}$ mesons. As there are no penguin contributions for these decays, all hadronic unknowns are obtainable from data and the interpretation of the measurements in terms of γ turns out to be extremely clean. Different methods have been adopted in B-factory analyses: the GLW method [33, 34], based on Cabibbo-suppressed D^0 decays to *CP* eigenstates, such as K^+K^- or $K^0_{\rm S}\pi^0$; the ADS method [35, 36], where the D^0 meson decays to $K^-\pi^+$ (Cabibbo-favoured) or $K^+\pi^-$ (doubly Cabibbo-suppressed) final states; and the GGSZ method [37], which is based on a Dalitz-plot analysis of multibody D decays, such as $D^0 \to K^0_{\rm S}\pi^+\pi^-$. By combining all available BaBar and Belle measurements, the resulting 1-CL curves for the angle γ are shown in Figure 4. The overall average from the B factories is [22]

$$\gamma = (67 \pm 11)^\circ. \tag{20}$$

As no evidence for inconsistencies in the CKM picture of *CP* violation have emerged from the analyses of the two B factories, their most important legacy is the confirmation that the CKM matrix provides a leading-order description of *CP* violation in the quark sector. For this reason, the focus is now on the search for possible second-order *CP*-violating effects beyond the SM.

7. *CP* violation in beauty at the LHC

The great success of the B factories marked the start of a new era in flavour physics. Experiments of the subsequent generation, owing to the huge $b\bar{b}$ production rate made available by the LHC, made it possible to perform measurements with unprecedented precisions, looking with renovated impetus for new sources of *CP* violation beyond the single phase of the CKM matrix.

Besides a $b\bar{b}$ cross-section much larger than that at the B factories, one further big advantage of the LHC is the possibility to study decays of all b-hadron species, not limiting the search for new physics to B^0- and B^+-meson decays. For example, the large production cross-section of B^0_s mesons and the ultimate capabilities of LHC detectors to resolve B^0_s oscillations have

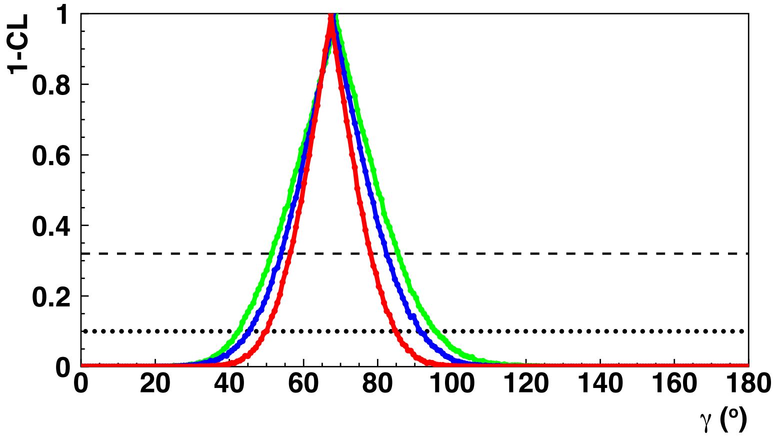

Figure 4. Combined constraint (red curve) on γ obtained using relevant BaBar and Belle data from $B \to D^{(*)}K^{(*)}$ decays. The green (blue) curve represents the results using only the BaBar (Belle) data. The dashed (dotted) line indicates the lower limit of 68% (90%) confidence-level. The plot is taken from Ref. [22].

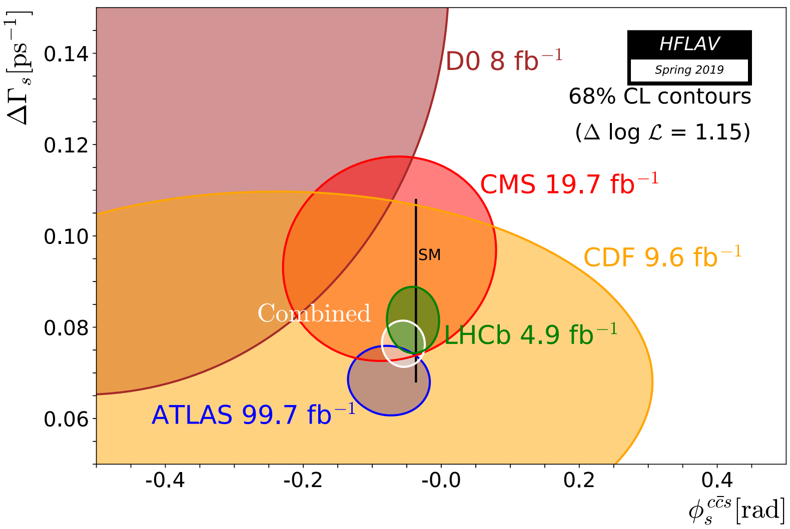

Figure 5. Experimental status for $\Delta\Gamma_s$ and $\phi_s^{c\bar{c}s}$ [42].

enabled precision measurements of the *CP*-violating phase $\phi_s^{c\bar{c}s}$, which in the SM is equal to $-2\beta_s \equiv \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$ neglecting subleading penguin contributions, to be performed. The ATLAS, CMS and LHCb experiments measured $\phi_s^{c\bar{c}s}$, mainly using the decays $B_s^0 \to J/\psi K^+K^-$ [38–40] and $B_s^0 \to J/\psi\pi^+\pi^-$ [41]. Combining all available determinations, LHCb measured $\phi_s^{c\bar{c}s} = -0.041 \pm 0.025$ rad. By averaging ATLAS, CMS and LHCb results, the precision is further increased, obtaining

$$\phi_s^{c\bar{c}s} = -0.055 \pm 0.021 \text{ rad.} \tag{21}$$

The present experimental status, which is well compatible with the SM, is summarised in Figure 5.

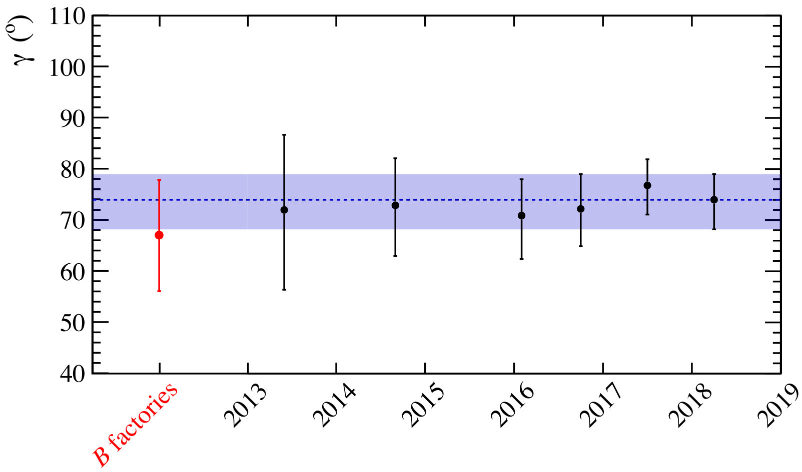

Figure 6. Central value and 1σ uncertainty of the LHCb γ combination (black points with error bars) as a function of time. The blue line (band) shows the central value (68.3% CL). LHCb data points are taken from Ref. [43]. The legacy of B factories is also reported for comparison (red point with error bar).

Concerning the measurement of the angle γ from tree-level decays, the LHCb experiment largely outperforms the B factories, owing to a much larger data sample of $B \to DK$ decays. The LHCb average is achieved by combining several independent measurements, namely from the time-integrated analyses of $B^+ \to DK^+$, $B^+ \to D^*K^+$, $B^+ \to DK^{*+}$, $B^0 \to DK^{*0}$, $B^0 \to DK^+\pi^-$ and $B^+ \to DK^+\pi^+\pi^-$ decays, and from time-dependent analyses of $B_s^0 \to D_s^{\mp}K^{\pm}$ and $B^0 \to D^{\mp}\pi^{\pm}$ decays [43]. The LHCb result is

$$\gamma = (74.0^{+5.0}_{-5.8})^{\circ}. \tag{22}$$

It is worth noting that this result is already twice more precise than the average from the B factories, although obtained only with Run-1 and part of Run-2 data. Hence LHCb has still a vast growth potential to improve our knowledge of γ in the upcoming Run 3 and subsequent LHC runs. The history of the γ sensitivity from LHCb is shown in Figure 6.

An alternative route to γ beyond tree-level decays has been investigated by LHCb. The amplitudes of the charmless decays $B \to hh$ with $h = \pi, K$ receive large contributions from penguin operators and are sensitive to γ. LHCb measured for the first time CP-violation in the $B_s^0 \to K^+K^-$ decay [44], updated later with more statistics in Ref. [45]. Following Refs. [46–48] and assuming U-spin symmetry, a combination of this and other results from $B \to \pi\pi$ modes allows the determination of $\gamma = (63.5^{+7.2}_{-6.7})^{\circ}$ [49]. The dependence on the amount of U-spin breaking is taken into account, allowing for a maximum of 50% breaking of the symmetry, and included in the overall uncertainty.

Large CP-violating asymmetries have been observed by LHCb also in other charmless B decays, namely $B^+ \to h^+h^-h^+$ [50–53]. Particularly striking features of these decays are the very large asymmetries observed in small regions of the phase-space, which could be a sign of long-distance rescattering effects. Furthermore, LHCb performed a first amplitude analysis of the $B_s^0 \to K_S^0K^+\pi^-$ decay, opening the avenue to a new class of amplitude analyses with three-body charmless B_s^0 decays [54].

The same-sign dimuon asymmetry measured some years ago by the D0 collaboration [55] and interpreted as a combination of the semileptonic asymmetries $A_{\rm sl}^d$ and $A_{\rm sl}^s$ in B^0 and B_s^0 decays, respectively, differs from the SM expectation by about 3σ. LHCb has invested significant efforts to

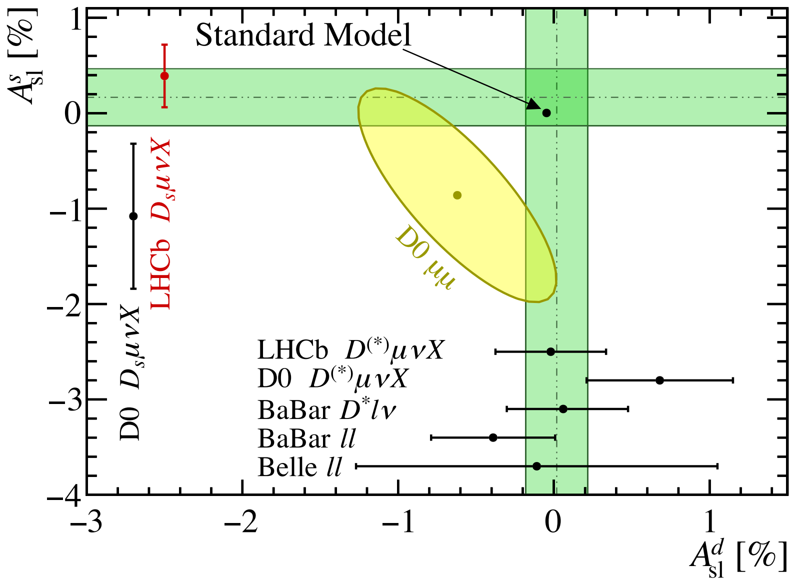

Figure 7. Experimental status on $A^d_{\rm sl}$ and $A^s_{\rm sl}$ from various experiments. The plot is taken from Ref. [57].

understand whether the hint of such a discrepancy was real, but has not been able to confirm the result so far. The measurements from LHCb look for *CP* asymmetries in partially reconstructed $B \to D\mu\nu$ decays, where the flavour of the D meson identifies that of the B. The measured values are [56, 57]

$$A^s_{\rm sl} = [0.39 \pm 0.26\ (\text{stat.}) \pm 0.20\ (\text{syst.})]\%, \tag{23}$$

$$A^d_{\rm sl} = [-0.02 \pm 0.19\ (\text{stat.}) \pm 0.30\ (\text{syst.})]\%, \tag{24}$$

which are both consistent with the SM expectations. The world averages including measurements from the B factories and D0 are shown in Figure 7. The overall results are marginally compatible with the measurement of the dimuon asymmetry by D0.

8. Future perspectives

Physics measurements of *CP* violation performed at the B factories and then, to date, at the LHC have by far exceeded any initial expectation. Yet, in the next 10–15 years we expect huge improvements in statistical sensitivities of all key physics channels, which will bring tests of the (C)KM mechanism of flavour and *CP* violation to a new regime of precision.

In the forthcoming future, the upgraded LHCb and the new Belle II detectors are expected to outperform their previous incarnations. In particular, LHCb Upgrade I will start taking data with the LHCb Run 3 in 2021, whereas Belle II has just started its physics run at SuperKEKB, notably the first major collider to be built since the LHC. Both experiments will operate over the next decade with the LHCb Upgrade I planning to collect 50 fb^{-1} of data in proton-proton collisions at 13–14 TeV, and Belle II 50 ab^{-1} in e^+e^- collisions at the $\Upsilon(4S/5S)$. The two facilities are highly complementary, with LHCb exploiting the availabilty of larger statistics in charged-track decay modes of all b-hadron species, and Belle II having unique capabilities to reconstruct B^0, B^+ and, with lower statistics, B^0_s decays with neutral or missing particles in the final states. Phase-2 upgrades of ATLAS and CMS will follow in the LHC Run 4, with the main intention of fully exploiting the HL-LHC luminosity for high p_{T} physics. The ATLAS and CMS experiments will also continue to contribute to flavour physics, with particular emphasis on b-physics decays to final states containing muons.

In the longer term, a further upgrade of the LHCb experiment to reach an instantaneous luminosity up to $2 \times 10^{34}\ \mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$ and collect more than 300 fb^{-1} of data, to be compared with about 9 fb^{-1} available today, is being planned to exploit the full potential of the HL-LHC in flavour physics [58–60]. The LHCb Upgrade II, along with the enhanced B-physics capabilities of the Phase-2 upgrades of ATLAS and CMS, will enable a host of measurements to be performed with unprecedented precision complementing and extending the reach of LHCb Upgrade I and Belle II. As an example, in the domain of *CP* violation the knowledge of the angle γ will be improved by an order of magnitude at least, reaching the subdegree precision. Furthermore, the precision measurement of the B_s^0 weak mixing phase will be another key part of the programme, with an expected precision on $\phi_s^{c\bar{c}s}$ at the end of the HL-LHC period going below 3 mrad, again an order of magnitude better than today.

More recently, the idea that a Belle III project should be considered has also been put forward. The evident complementarity of the flavour-physics programmes at hadronic and $\mathrm{e}^+\mathrm{e}^-$ colliders makes such a possibility very appealing, extending, along with the LHCb Upgrade II, the horizon of flavour-physics and *CP* violation towards 2035 and beyond, also providing a bridge towards future larger-scale accelerators as FCC-*ee* and FCC-*hh*.

9. Conclusions

The study of *CP* violation in B decays is one of the key subjects of modern research at the intensity frontier. Amongst the various motivations, it is worth mentioning the fact that the Kobayashi-Maskawa mechanism of *CP* violation embedded into the Standard Model appears to fail largely in accounting for the observed baryon asymmetry of the universe. For this reason, new sources of *CP* violation, beyond the Standard Model, must exist in nature. In the context of meson mixing and decays, *CP* is a good symmetry of the strong interactions. Therefore, *CP* asymmetries in meson decays are subject to uniquely clean theoretical interpretation.

The two B-factory experiments, BaBar and Belle, and then the LHC experiments, with LHCb as a front-runner, have measured a large number of *CP* asymmetries in B-meson decays. Although no striking evidence for deviations from Standard Model expectations have emerged so far, the experimental effort allowed some relevant conclusions to be drawn. The three *CP*-violating angles α, β and γ, along with other relevant *CP*-conserving observables, have been measured with great accuracy, and this allowed the Cabibbo–Kobayashi–Maskawa mechanism to be proved as the dominant source of flavour and *CP* violation in meson mixing and decay. New flavour- and *CP*-violating physics must either take place at a scale higher than about 10^3 TeV or, if its scale is significantly lower, have a very strongly suppressed couplings to quarks.

The programme of precision measurements of *CP* violation in B decays will continue to test the Standard Model and search for new physics in the Belle II/III and LHC experiments during the next decade and beyond, waiting for future colliders like FCC-*ee* and FCC-*hh* to grab the flavour-physics torch. Such a programme has the potential to provide crucial clues about the scale of new physics. In the event that no direct evidence for new physics will pop out of the LHC, such measurements can play a leading role in indicating the way for future research developments. Otherwise, they will be a fundamental ingredient to understand the structure of the beyond-the-Standard-Model Lagrangian.

In the current phase of our challenge to understand fundamental physics, it is necessary more than ever to have a programme as diversified as possible. The line of research discussed in this review must be pursued to the uttermost of our capacity, until cracks in the Standard Model will become eventually manifest.

References

[1] A. D. Sakharov, "Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe", *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967), p. 32-35.

[2] N. Cabibbo, "Unitary symmetry and leptonic decays", *Phys. Rev. Lett.* **10** (1963), no. 12, p. 531-533.

[3] M. Kobayashi, T. Maskawa, "CP violation in the renormalizable theory of weak interaction", *Prog. Theor. Phys.* **49** (1973), p. 652-657.

[4] A. G. Cohen, D. B. Kaplan, A. E. Nelson, "Progress in electroweak baryogenesis", *Ann. Rev. Nucl. Part. Sci.* **43** (1993), p. 27-70.

[5] A. Riotto, M. Trodden, "Recent progress in baryogenesis", *Ann. Rev. Nucl. Part. Sci.* **49** (1999), p. 35-75.

[6] W.-S. Hou, "Source of *CP* violation for the baryon asymmetry of the universe", *Chin. J. Phys.* **47** (2009), p. 134-141.

[7] S. L. Glashow, J. Iliopoulos, L. Maiani, "Weak interactions with lepton-hadron symmetry", *Phys. Rev. D* **2** (1970), no. 7, p. 1285-1292.

[8] J. H. Christenson, J. W. Cronin, V. L. Fitch, R. Turlay, "Evidence for the 2π decay of the K_2^0 meson", *Phys. Rev. Lett.* **13** (1964), no. 4, p. 138-140.

[9] J. J. Aubert *et al.*, "Experimental observation of a heavy particle J", *Phys. Rev. Lett.* **33** (1974), no. 23, p. 1404-1406.

[10] J. E. Augustin *et al.*, "Discovery of a narrow resonance in e^+e^- annihilation", *Phys. Rev. Lett.* **33** (1974), no. 23, p. 1406-1408.

[11] S. W. Herb *et al.*, "Observation of a dimuon resonance at 9.5-GeV in 400-GeV proton–nucleus collisions", *Phys. Rev. Lett.* **39** (1977), no. 5, p. 252-255.

[12] CDF collaboration, F. Abe *et al.*, "Observation of top quark production in $\bar{p}p$ collisions", *Phys. Rev. Lett.* **74** (1995), no. 14, p. 2626-2631.

[13] CLEO collaboration, D. Andrews *et al.*, "The CLEO detector", *Nucl. Instrum. Meth.* **211** (1983), no. 1, p. 47-71.

[14] A. B. Carter, A. I. Sanda, "*CP* violation in *B* meson decays", *Phys. Rev. D* **23** (1981), no. 7, p. 1567-1579.

[15] I. I. Y. Bigi, A. I. Sanda, "On B^0–$\overline{B}^0$ mixing and violations of *CP* symmetry", *Phys. Rev. D* **29** (1984), no. 7, p. 1393-1398.

[16] ARGUS collaboration, H. Albrecht *et al.*, "ARGUS: A universal detector at DORIS-II", *Nucl. Instrum. Meth. A* **275** (1989), no. 1, p. 1-48.

[17] P. Oddone, "Detector considerations", *eConf* **C870126** (1987), p. 423-446.

[18] BaBar collaboration, B. Aubert *et al.*, "The BaBar detector", *Nucl. Instrum. Meth. A* **479** (2002), no. 1, p. 1-116.

[19] A. Abashian *et al.*, "The Belle detector", *Nucl. Instrum. Meth. A* **479** (2002), no. 1, p. 117-232.

[20] BaBar collaboration, B. Aubert *et al.*, "Measurement of time-dependent *CP* asymmetry in $B^0 \to c\bar{c}K^{(*)0}$ decays", *Phys. Rev. D* **79** (2009), article ID 072009.

[21] I. Adachi *et al.*, "Precise measurement of the *CP* violation parameter $\sin 2\phi_1$ in $B^0 \to (c\bar{c})K^0$ decays", *Phys. Rev. Lett.* **108** (2012), article ID 171802.

[22] BaBar and Belle Collaborations, A. J. Bevan *et al.*, "The Physics of the *B* Factories", *Eur. Phys. J. X* **74** (2014), article ID 3026.

[23] CDF collaboration, A. Abulencia *et al.*, "Observation of B_s^0–$\overline{B}_s^0$ oscillations", *Phys. Rev. Lett.* **97** (2006), article ID 242003.

[24] G. J. Barker, " *b*-physics at LEP", p. 1-21, Springer Berlin Heidelberg, 2010.

[25] P. C. Rowson, D. Su, S. Willocq, "Highlights of the SLD physics program at the SLAC linear collider", *Ann. Rev. Nucl. Part. Sci.* **51** (2001), p. 345-412.

[26] LHCb collaboration, A. A. Alves Jr. *et al.*, "The LHCb detector at the LHC", *JINST* **3** (2008), article ID S08005.

[27] ATLAS collaboration, G. Aad *et al.*, "The ATLAS experiment at the CERN Large Hadron Collider", *JINST* **3** (2008), article ID S08003.

[28] CMS collaboration, S. Chatrchyan *et al.*, "The CMS experiment at the CERN LHC", *JINST* **3** (2008), article ID S08004.

[29] T. Abe *et al.*, "Belle II Collaboration, Belle II Technical Design Report", KEK Report 2010-1, 2010.

[30] Particle Data Group, M. Tanabashi *et al.*, "Review of particle physics", *Phys. Rev. D* **98** (2018), article ID 030001.

[31] CKMfitter Group, J. Charles *et al.*, " *CP* violation and the CKM matrix: Assessing the impact of the asymmetric *B* factories", *Eur. Phys. J. C* **41** (2005), p. 1-131, updated results and plots available at http://ckmfitter.in2p3.fr.

[32] UTfit Collaboration, M. Bona *et al.*, "Model-independent constraints on $\Delta F = 2$ operators and the scale of new physics", *J. High Energy Phys.* **0803** (2008), article ID 049, updated results and plots available at http://www.utfit.org.

[33] M. Gronau, D. Wyler, "On determining a weak phase from *CP* asymmetries in charged *B* decays", *Phys. Lett. B* **265** (1991), no. 1, p. 172-176.

[34] M. Gronau, D. London, "How to determine all the angles of the unitarity triangle from $B^0 \to DK_S^0$ and $B_s^0 \to D\phi$ ", *Phys. Lett. B* **253** (1991), no. 3-4, p. 483-488.

[35] D. Atwood, I. Dunietz, A. Soni, "Enhanced *CP* violation with $B \to KD^0$ ($\overline{D}^0$) modes and extraction of the CKM angle γ", *Phys. Rev. Lett.* **78** (1997), no. 17, p. 3257-3260.

[36] D. Atwood, I. Dunietz, A. Soni, "Improved methods for observing *CP* violation in $B^\pm \to KD$ and measuring the CKM phase γ", *Phys. Rev. D* **63** (2001), article ID 036005.

[37] A. Giri, Y. Grossman, A. Soffer, J. Zupan, "Determining γ using $B^\pm \to DK^\pm$ with multibody D decays", *Phys. Rev. D* **68** (2003), article ID 054018.

[38] ATLAS Collaboration, Measurement of the *CP* violation phase ϕ_s in $B_s \to J/\psi\phi$ decays in ATLAS at 13 TeV, ATLAS-CONF-2019-009.

[39] CMS Collaboration, V. Khachatryan *et al.*, "Measurement of the *CP*-violating weak phase ϕ_s and the decay width difference $\Delta\Gamma_s$ using the $B_s^0 \to J/\psi\phi(1020)$ decay channel in pp collisions at $\sqrt{s} = 8$ TeV", *Phys. Lett. B* **757** (2016), p. 97-120.

[40] LHCb Collaboration, R. Aaij *et al.*, "Updated measurement of time-dependent *CP*-violating observables in $B_s^0 \to J/\psi K^+K^-$ decays", *Eur. Phys. J. C* **79** (2019), article ID 706.

[41] LHCb Collaboration, R. Aaij *et al.*, "Measurement of the *CP*-violating phase ϕ_s from $B_s^0 \to J/\psi\pi^+\pi^-$ decays in 13 TeV pp collisions", *Phys. Lett. B* **797** (2019), article ID 134789.

[42] HFLAV Collaboration, Y. S. Amhis *et al.*, "Averages of b-hadron, c-hadron, and τ-lepton properties as of 2018", 2019, preprint, updated results and plots available at https://hflav.web.cern.ch, https://arxiv.org/abs/1909.12524.

[43] LHCb Collaboration, Update of the LHCb combination of the CKM angle γ, LHCb-CONF-2018-002.

[44] LHCb Collaboration, R. Aaij *et al.*, "First measurement of time-dependent *CP* violation in $B_s^0 \to K^+K^-$ decays", *J. High Energy Phys.* **2013** (2013), article ID 183.

[45] LHCb Collaboration, R. Aaij *et al.*, "Measurement of *CP* asymmetries in two-body $B^0_{(s)}$-meson decays to charged pions and kaons", *Phys. Rev. D* **98** (2018), article ID 032004.

[46] R. Fleischer, "New strategies to extract β and γ from $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$", *Phys. Lett. B* **459** (1999), p. 306-320.

[47] R. Fleischer, "$B^0_{s,d} \to \pi\pi, \pi K, KK$: Status and Prospects", *Eur. Phys. J. C* **52** (2007), p. 267-281.

[48] M. Ciuchini, E. Franco, S. Mishima, L. Silvestrini, "Testing the Standard Model and Searching for New Physics with $B_d \to \pi\pi$ and $B_s \to KK$ Decays", *J. High Energy Phys.* **1210** (2012), article ID 29.

[49] LHCb Collaboration, R. Aaij *et al.*, "Determination of γ and $-2\beta_s$ from charmless two-body decays of beauty mesons", *Phys. Lett. B* **741** (2015), p. 1-11.

[50] LHCb Collaboration, R. Aaij *et al.*, "Measurements of *CP* violation in the three-body phase space of charmless $B^\pm$ decays", *Phys. Rev. D* **90** (2014), article ID 112004.

[51] LHCb Collaboration, R. Aaij *et al.*, "Amplitude analysis of $B^\pm \to \pi^\pm K^+K^-$ decays", *Phys. Rev. Lett.* **123** (2019), article ID 231802.

[52] LHCb Collaboration, R. Aaij *et al.*, "Observation of several sources of *CP* violation in $B^+ \to \pi^+\pi^+\pi^-$ decays", *Phys. Rev. Lett.* **124** (2020), article ID 031801.

[53] LHCb Collaboration, R. Aaij *et al.*, "Amplitude analysis of the $B^+ \to \pi^+\pi^+\pi^-$ decay", *Phys. Rev. D* **101** (2020), article ID 012006.

[54] LHCb Collaboration, R. Aaij *et al.*, "Amplitude analysis of $B_s^0 \to K_S^0 K^\pm\pi^\mp$ decays", *J. High Energy Phys.* **2019** (2019), article ID 114.

[55] D0 Collaboration, V. M. Abazov *et al.*, "Study of *CP*-violating charge asymmetries of single muons and like-sign dimuons in $p\bar{p}$ collisions", *Phys. Rev. D* **89** (2014), article ID 012002.

[56] LHCb Collaboration, R. Aaij *et al.*, "Measurement of the semileptonic *CP* asymmetry in $B^0-\overline{B}^0$ mixing", *Phys. Rev. Lett.* **114** (2015), article ID 041601.

[57] LHCb Collaboration, R. Aaij *et al.*, "Measurement of the *CP* asymmetry in $B_s^0-\overline{B}_s^0$ mixing", *Phys. Rev. Lett.* **117** (2016), article ID 061803.

[58] LHCb Collaboration, Expression of Interest for a Phase-II LHCb Upgrade: Opportunities in flavour physics, and beyond, in the HL-LHC era, CERN-LHCC-2017-003.

[59] LHCb Collaboration, R. Aaij *et al.*, "Physics case for an LHCb Upgrade II - Opportunities in flavour physics, and beyond, in the HL-LHC era", CERN-LHCC-2018-027, 2018.

[60] A. Cerri *et al.*, "Opportunities in Flavour Physics at the HL-LHC and HE-LHC", *CERN Yellow Rep. Monogr.* **7** (2019), p. 867-1158.