Prospects for B-Decay Studies at the LHC

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Abstract

In this decade, there are huge efforts to explore B-meson decays, which offer interesting probes to test the quark-flavour structure of the Standard Model and to search for signals of new physics. Exciting new perspectives for these studies will soon arise at the LHC, where decays of B_s^0 mesons will be a key target of the B-physics programme. We will discuss theoretical aspects of various benchmark channels and address the question of how much space for new-physics effects in their observables is left by the recent experimental results from the B factories and the Tevatron.

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1 Introduction

In the Standard Model (SM), the phenomenon of CP violation can be accommodated in an efficient way through a complex phase entering the quark-mixing matrix, which governs the strength of the charged-current interactions of the quarks [1]. This Kobayashi–Maskawa (KM) mechanism of CP violation is the subject of detailed investigations in this decade. The main interest in the study of CP violation and flavour physics in general is due to the fact that new physics (NP) typically leads to new patterns in the flavour sector. This is actually the case in several specific extensions of the SM, such as SUSY scenarios, left–right-symmetric models, models with extra Z' bosons, scenarios with extra dimensions, or "little Higgs" models. Moreover, also the observed neutrino masses point towards an origin lying beyond the SM [2], raising the question of having CP violation in the neutrino sector and its connection with the quark-flavour physics. Finally, the baryon asymmetry of the Universe also suggests new sources of CP violation. These could be associated with very high energy scales, where a particularly interesting scenario is provided by "leptogenesis" [3], involving typically new CP-violating sources in the decays of heavy Majorana neutrinos. On the other hand, new CP-violating effects arising in the NP scenarios listed above could in fact be accessible in the laboratory.

Before searching for signals of NP, we have first to understand the SM picture. Here the key problem is due to the impact of strong interactions, leading to "hadronic" uncertainties. The B-meson system is a particularly promising probe for the testing of the quark-flavour sector of the SM, and will be the focus of this presentation. Decays of B mesons are studied at two kinds of experimental facilities. The first are the "B factories" at SLAC and KEK with the BaBar [4] and Belle [5] experiments, respectively. These machines are asymmetric e^+e^- colliders that have by now produced altogether $\mathcal{O}(10^9)$ $B\bar{B}$ pairs, establishing CP violation in the B system and leading to many other interesting results. There are currently discussions of a super-B factory, with an increase of luminosity by two orders of magnitude [6]. Since the B factories are operated at the $\Upsilon(4S)$ resonance, only $B_d^0\bar{B}_d^0$ and $B_u^+B_u^-$ pairs are produced. On the other hand, hadron colliders produce, in addition to B_d and B_u, also B_s mesons,[1] as well as B_c and Λ_b hadrons, and the Tevatron experiments CDF and D0 have reported first $B_{(s)}$-decay results. The physics potential of the B_s system can be fully exploited at the LHC, starting operation in the summer of 2008. Here ATLAS and CMS can also address some B-physics topics, although these studies are the main target of the dedicated LHCb experiment [8]. The central target of these explorations is the well-known unitarity triangle (UT) of the Cabibbo–Kobyashi–Maskawa (CKM) matrix with its three angles α, β and γ, and strongly suppressed "rare" decays of B mesons.

The key processes for the exploration of CP violation are non-leptonic decays of B mesons, where only quarks are present in the final states. In these transitions, CP-violating asymmetries can be generated through interference effects. Depending on the flavour content of their final states, non-leptonic B decays receive contributions from tree and penguin topologies, where we distinguish between QCD and electroweak (EW) penguins in the latter case. The calculation of the decay amplitudes, which can be

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[1]Recently, data were taken by Belle at $\Upsilon(5S)$, allowing also access to B_s decays [7].

written by means of the operator product expansion as follows [9]:

$$A(B \to f) \sim \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle f|Q_k(\mu)|B\rangle}_{\text{"unknown"}}, \qquad (1)$$

remains a theoretical challenge, despite interesting recent progress through QCD factorization [10], PQCD [11], SCET [12], and QCD sum rule applications [13].

For the exploration of CP violation, the calculation of the hadronic matrix elements $\langle f|Q_k(\mu)|B\rangle$ of local four-quark operators can actually be circumvented. This feature is crucial for a stringent testing of the CP-violating flavour sector of the SM. From a practical point of view, two main avenues are offered:

- Amplitude relations allow us in fortunate cases to eliminate the hadronic matrix elements. Here we distinguish between exact relations, using pure "tree" decays of the kind $B^\pm \to K^\pm D$ [14,15] or $B_c^\pm \to D_s^\pm D$ [16], and relations, which follow from the flavour symmetries of strong interactions, i.e. isospin or $SU(3)_{\rm F}$, and typically involve $B_{(s)} \to \pi\pi, \pi K, KK$ modes [17].

- In decays of neutral B_q mesons ($q \in \{d, s\}$), the interference between B_q^0–$\bar{B}_q^0$ mixing and $B_q^0, \bar{B}_q^0 \to f$ decay processes leads to "mixing-induced" CP violation. If one CKM amplitude dominates the decay, the essentially "unknown" hadronic matrix elements cancel. The key application of this important feature is the measurement of $\sin 2\beta$ through the "golden" decay $B_d^0 \to J/\psi K_{\rm S}$ [18].

Following these lines, various processes and strategies emerge for the exploration of CP violation in the B-meson system (for a more detailed discussion, see [19]). In particular, decays with a very different dynamics allow us to probe the same quantities of the UT. These studies are complemented by rare decays of B and K mesons, which originate from loop processes in the SM model and show interesting correlations with the CP violation in the B system. In the presence of NP, discrepancies should show up in the resulting roadmap of quark-flavour physics at some level of accuracy.

2   A Brief Look at the B-Factory Data

Comprehensive and continuously updated analyses of the UT are performed by the "CKM Fitter Group" [20] and the "UTfit collaboration" [21]. The current data show impressive global agreement with the KM mechanism. Nevertheless, there are also potential deviations from the SM description of CP violation, and LHCb will soon allow us to enter a territory of the B-physics landscape that is still largely unexplored.

If a given decay is dominated by SM tree processes, we have typically small effects through NP contributions to its transition amplitude. On the other hand, we may have potentially large NP effects in the penguin sector through new particles in the loops or new contributions at the tree level (this may happen, for instance, in SUSY or models with extra Z' bosons). The search for such signals of NP in the B-factory data has been a hot topic for several years, which is reflected by the great attention that the "$B \to \pi K$ puzzle" has received (see, e.g., [22]). For the CP-averaged branching ratios,

the B-factory data have moved towards the SM prediction, while the mixing-induced CP violation in $B^0 \to \pi^0 K_S$ may still indicate a deviation from the SM, which could be accommodated through a modified EW penguin sector with a large CP-violating phase [23,24]. This effect is complemented by the B-factory measurements of the mixing-induced CP asymmetries of other penguin-dominated $b \to s$ modes [25], which can be converted into $\sin 2\beta$; an outstanding example is the decay $B^0 \to \phi K_S$ [26–28]. The corresponding patterns in the data could be footprints of the same kind of NP.

Unfortunately, it is unlikely that the current B factories will allow us to establish – or rule out – the tantalizing option of having NP in the $b \to s$ penguin processes. However, at LHCb, this exciting topic can be explored with the help of the decay $B_s^0 \to \phi\phi$ [29]. A handful of events have been observed in this mode a few years ago by the CDF collaboration at the Fermilab Tevatron, corresponding to a branching ratio of $(14^{+6}_{-5} \pm 6) \times 10^{-6}$ [30]. A proposal for studying time and angular dependence in this decay mode has been made by the LHCb collaboration [31]. The proposal is based on an estimated sample of about 3100 events collected in one year of running. In order to control hadronic uncertainties, the decay mode $B_s \to \phi\phi$ may be related through the $SU(3)$ flavour symmetry to $B_s \to \phi \bar{K}^{*0}$ and plausible dynamical assumptions, which can be checked through experimental control channels [29]. The current B-factory data on the CP asymmetries of the $b \to s$ penguin modes leave ample space for NP phenomena in the $B_s^0 \to \phi\phi$ decay to be discovered at LHCb.

In the SM, B_q^0–$\bar{B}_q^0$ mixing ($q \in \{d, s\}$) is governed by box diagrams with internal top-quark exchanges and is, therefore, a strongly suppressed loop phenomenon. In the presence of NP, we may get new contributions through NP particles in the box topologies, or new contributions at the tree level. In this case, the off-diagonal element of the mass matrix is modified as follows [32]:

$$M_{12}^{(q)} = M_{12}^{q,\text{SM}} \left(1 + \kappa_q e^{i\sigma_q}\right), \tag{2}$$

where the real parameter κ_q is a measure of the strength of NP with respect to the SM, and σ_q denotes a CP-violating NP phase. The mass difference ΔM_q between the two mass eigenstates and the mixing phase ϕ_q are then modified as

$$\Delta M_q = \Delta M_q^{\text{SM}} + \Delta M_q^{\text{NP}} = \Delta M_q^{\text{SM}} \left|1 + \kappa_q e^{i\sigma_q}\right|, \tag{3}$$

$$\phi_q = \phi_q^{\text{SM}} + \phi_q^{\text{NP}} = \phi_q^{\text{SM}} + \arg(1 + \kappa_q e^{i\sigma_q}). \tag{4}$$

In the case of the B_d^0 mesons, which are accessible at the B factories, we have $\phi_d^{\text{SM}} = 2\beta$. The SM contribution of ΔM_d depends both on the CKM factor $|V_{td}^* V_{tb}|$, which is governed by γ if unitarity is used, and on the hadronic parameter $f_{B_d}^2 \hat{B}_{B_d}$, which is usually taken from non-perturbative lattice QCD calculations [33]. In particular the measurement of the mixing-induced CP violation in $B_d^0 \to J/\psi\phi$, which can be converted into

$$\phi_d^{\text{NP}} = (2\beta)_{\psi K_S} - (2\beta)_{\text{true}}^{\text{tree}}, \tag{5}$$

has a dramatic impact on the allowed region in the σ_d–κ_d plane of NP parameters (for a detailed analysis and discussion, see [32]). On the other hand, in the case of the B_s^0-meson system, we are still left with a large allowed region for the corresponding NP parameter space, as we will discuss in the next section.

3   *B* Physics at the LHC

The *B*-decay studies at the LHC will allow us to enter a new territory of the *B*-physics landscape that is still largely unexplored. This is in particular due to the high statistics which can quickly be accummulated and the access to the B_s-meson system, offering a physics programme that is to a large extent complementary to that of the e^+e^- *B* factories operated at the $\Upsilon(4S)$ resonance.

3.1   General Features of the B_s System

In the SM, we expect a mass difference $\Delta M_s = \mathcal{O}(20\,\mathrm{ps}^{-1})$, which is much larger than the experimental value of $\Delta M_d = 0.5\,\mathrm{ps}^{-1}$. Consequently, the B_s^0–$\bar{B}_s^0$ oscillations are very rapid, thereby making it very challenging to resolve them experimentally.

   Whereas the difference between the decay widths of the mass eigenstates of the B_d^0-meson system is negligible, its counterpart $\Delta\Gamma_s/\Gamma_s$ in the B_s^0-meson system is expected to be of $\mathcal{O}(10\%)$ [34]. Recently, the first results for $\Delta\Gamma_s$ were reported from the Tevatron, using the $B_s^0 \to J/\psi\phi$ channel [35]:

$$\Delta\Gamma_s = \begin{cases} (0.17 \pm 0.09 \pm 0.02)\mathrm{ps}^{-1} & (\text{D0 [36]}) \\ (0.076^{+0.059}_{-0.063} \pm 0.006)\mathrm{ps}^{-1} & (\text{CDF [37]}). \end{cases} \tag{6}$$

It will be interesting to follow the evolution of these data. At LHCb, we expect a precision of $\sigma(\Delta\Gamma_s) = 0.027\mathrm{ps}^{-1}$ already with $0.5\,\mathrm{fb}^{-1}$ data, which is expected to be available by the end of 2009 [38]; ATLAS expects a relative accuracy of 13% with $30\,\mathrm{fb}^{-1}$ of data taken at low luminosity [39]. The width difference $\Delta\Gamma_s$ offers studies of CP violation through "untagged" rates of the following form:

$$\langle\Gamma(B_s(t) \to f)\rangle \equiv \Gamma(B_s^0(t) \to f) + \Gamma(\overline{B_s^0}(t) \to f), \tag{7}$$

which are interesting in terms of efficiency, acceptance and purity. If both B_s^0 and $\bar{B}_s^0$ states may decay into the final state f, the rapidly oscillating $\Delta M_s t$ terms cancel. Various "untagged" strategies exploiting this feature were proposed (see [35] and [40–43]); we will discuss an example in Section 3.3.

   Finally, the CP-violating phase of B_s^0–$\bar{B}_s^0$ mixing is tiny in the SM:

$$\phi_s^{\mathrm{SM}} = -2\lambda^2\eta \approx -2°, \tag{8}$$

where λ and η are the usual Wolfenstein parameters [44]. This feature is very interesting for the search of signals of NP [43, 45, 46] (see Section 3.3).

3.2   Measurement of ΔM_s

For many years, only lower bounds on ΔM_s were available from the LEP (CERN) experiments and SLD (SLAC) [47]. In 2006, the value of ΔM_s could eventually be pinned down at the Tevatron [48]. The most recent results read as follows:

$$\Delta M_s = \begin{cases} (18.56 \pm 0.87)\mathrm{ps}^{-1} & (\text{D0 [49]}) \\ (17.77 \pm 0.10 \pm 0.07)\mathrm{ps}^{-1} & (\text{CDF [50]}). \end{cases} \tag{9}$$
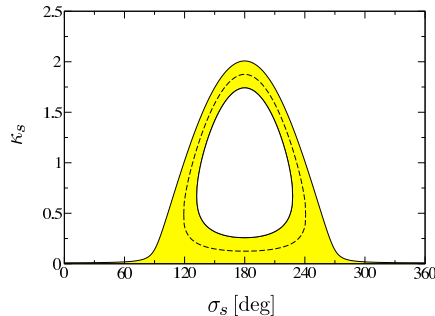
Figure 1: The allowed region in the σ_s–κ_s plane of NP parameters for B_s^0–$\bar{B}_s^0$ mixing.

On the other hand, the HPQCD collaboration has reported the following lattice QCD prediction [51]:

$$\Delta M_s^{\text{SM}} = 20.3(3.0)(0.8)\,\text{ps}^{-1}. \tag{10}$$

In contrast to the case of ΔM_d, the CKM factor entering this SM value does not require information on γ and $|V_{ub}/V_{cb}|$, as

$$|V_{ts}^* V_{tb}| = |V_{cb}| \left[1 + \mathcal{O}(\lambda^2)\right], \tag{11}$$

which is an important advantage. Using (3) and (10), we may convert the experimental value of ΔM_s into the allowed region in the σ_s–κ_s plane shown in Fig. 1, as discussed in detail in [32]. We see that the measurement of ΔM_s leaves ample space for the NP parameters σ_s and κ_s, which can also be accommodated in specific scenarios (e.g. SUSY, extra Z' and little Higgs models). It should be noted that the experimental errors are already significantly smaller than the theoretical lattice QCD uncertainties. The new experimental results on ΔM_s have immediately triggered a lot of theoretical activity (see, e.g., [32, 52, 53]).

As in the case of the B_d-meson system, the allowed region in the σ_s–κ_s plane will be dramatically reduced as soon as measurements of CP violation in the B_s-meson system become available. The "golden" channel in this respect is $B_s^0 \to J/\psi\phi$, our next topic.

3.3 The Decay $B_s^0 \to J/\psi\phi$

This mode is the counterpart of the $B_d^0 \to J/\psi K_{\text{S}}$ transition, where we have just to replace the down quark by a strange quark. The structures of the corresponding decay amplitudes are completely analogous to each other. However, there is also an important difference with respect to $B_d^0 \to J/\psi K_{\text{S}}$, since the final state of $B_s^0 \to J/\psi\phi$ contains two vector mesons and is, hence, an admixture of different CP eigenstates. Using the angular distribution of the $J/\psi[\to \ell^+\ell^-]\phi[\to K^+K^-]$ decay products, the CP eigenstates can be disentangled [54] and the time-dependent decay rates calculated [35, 43]. As in the case of $B_d^0 \to J/\psi K_{\text{S}}$, the hadronic matrix elements cancel then in the mixing-induced observables. For the practical implementation, a set of three linear polarization amplitudes is usually used: $A_0(t)$ and $A_\parallel(t)$ correspond to CP-even final-state configurations, whereas $A_\perp(t)$ describes a CP-odd final-state configuration.

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It is instructive to illustrate how this works by having a closer look at the one-angle distribution, which takes the following form [35, 43]:

$$\frac{d\Gamma(B_s^0(t) \to J/\psi\phi)}{d\cos\Theta} \propto \left(|A_0(t)|^2 + |A_\|(t)|^2\right) \frac{3}{8}\left(1 + \cos^2\Theta\right) + |A_\perp(t)|^2 \frac{3}{4}\sin^2\Theta. \quad (12)$$

Here Θ is defined as the angle between the momentum of the ℓ^+ and the normal to the decay plane of the K^+K^- system in the J/ψ rest frame. The time-dependent measurement of the angular dependence allows us to extract the following observables:

$$P_+(t) \equiv |A_0(t)|^2 + |A_\|(t)|^2, \quad P_-(t) \equiv |A_\perp(t)|^2, \quad (13)$$

where $P_+(t)$ and $P_-(t)$ refer to the CP-even and CP-odd final-state configurations, respectively. If we consider the case of having an initially, i.e. at time $t = 0$, present $\bar{B}_s^0$ meson, the CP-conjugate quantities $\bar{P}_\pm(t)$ can be extracted as well. Using an *untagged* data sample, the untagged rates

$$P_\pm(t) + \overline{P}_\pm(t) \propto \left[(1 \pm \cos\phi_s)e^{-\Gamma_\mathrm{L}t} + (1 \mp \cos\phi_s)e^{-\Gamma_\mathrm{H}t}\right] \quad (14)$$

can be determined, while a *tagged* data sample allows us to measure the CP-violating asymmetries

$$\frac{P_\pm(t) - \overline{P}_\pm(t)}{P_\pm(t) + \overline{P}_\pm(t)} = \pm\left[\frac{2\sin(\Delta M_s t)\sin\phi_s}{(1 \pm \cos\phi_s)e^{+\Delta\Gamma_s t/2} + (1 \mp \cos\phi_s)e^{-\Delta\Gamma_s t/2}}\right]. \quad (15)$$

In the presence of CP-violating NP contributions to B_s^0–$\bar{B}_s^0$ mixing, we obtain

$$\phi_s = -2\lambda^2\eta + \phi_s^{\mathrm{NP}} \approx -2° + \phi_s^{\mathrm{NP}} \approx \phi_s^{\mathrm{NP}}. \quad (16)$$

Consequently, NP of this kind would be indicated by the following features:

- The *untagged* observables depend on *two* exponentials;

- *sizeable* values of the CP-violating asymmetries.

These general features hold also for the full three-angle distribution [35, 43]: it is much more involved than the one-angle case, but provides also additional information through interference terms of the form

$$\mathrm{Re}\{A_0^*(t)A_\|(t)\}, \quad \mathrm{Im}\{A_f^*(t)A_\perp(t)\} \, (f \in \{0, \|\}). \quad (17)$$

From an experimental point of view, there is no experimental draw-back with respect to the one-angle case. Following these lines, $\Delta\Gamma_s$ (see (6)) and ϕ_s can be extracted. Recently, the D0 collaboration has reported first results for the measurement of ϕ_s through the untagged, time-dependent three-angle $B_s^0 \to J/\psi\phi$ distribution [55]:

$$\phi_s = -0.79 \pm 0.56\,(\text{stat.})^{+0.14}_{-0.01}\,(\text{syst.}) = -(45 \pm 32^{+1}_{-8})°, \quad (18)$$

which is complemented by three additional mirror solutions. This phase is therefore not yet stringently constrained. Using (4), we then obtain the curves in the σ_s–κ_s plane
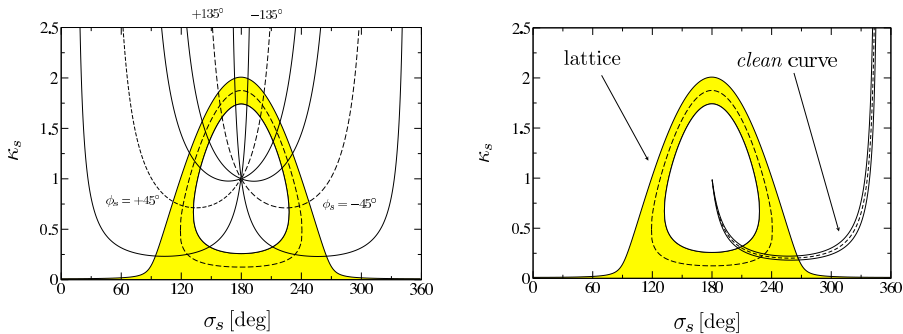
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Figure 2: Impact of the measurement of CP violation in $B_s^0 \to J/\psi\phi$: current D0 data [left panel], and a NP scenario with $(\sin\phi_s)_{\mathrm{exp}} = -0.20 \pm 0.02$ [right panel].

shown in the left panel of Fig. 2. Very recently, the CDF collaboration reported first bounds on ϕ_s from flavour-tagged $B_s^0 \to J/\psi\phi$ decays [56].

Fortunately, ϕ_s will be very accessible at LHCb, where already the initial $0.5\,\mathrm{fb}^{-1}$ of data will give an uncertainty of $\sigma(\phi_s) = 0.046 = 2.6°$ by the end of 2009, which will be significantly improved further thanks to the $2\,\mathrm{fb}^{-1}$ that should be available by the end of 2010 [38]. At some point, also in view of LHCb upgrade plans [57], we have to include hadronic penguin uncertainties. This can be done with the help of the $B_d^0 \to J/\psi\rho^0$ decay [58]. In order to illustrate the impact of the measurement of CP violation in $B_s^0 \to J/\psi\phi$, we show in the right panel of Fig. 2 the case corresponding to $(\sin\phi_s)_{\mathrm{exp}} = -0.20 \pm 0.02$. Such a measurement would give a NP signal at the $10\,\sigma$ level and demonstrates the power of the B_s system to search for NP [32]. It should be emphasized that the contour following from the measurement of ϕ_s would be essentially clean, in contrast to the shaded region representing the constraint from the measured value of ΔM_s, which suffers from lattice QCD uncertainties.

3.4   Further Benchmark Decays for LHCb

This experiment has a very rich physics programme. Besides many other interesting aspects, there are two major lines of research:

1. Precision measurements of γ:
   On the one hand, there are strategies using tree decays: $B_s^0 \to D_s^\mp K^\pm$ $[\sigma_\gamma \sim 5°]$, $B_d^0 \to D^0 K^*$ $[\sigma_\gamma \sim 8°]$, $B^\pm \to D^0 K^\pm$ $[\sigma_\gamma \sim 5°]$, where we have also indicated the expected sensitivities for $10\,\mathrm{fb}^{-1}$; by 2013, a LHCb tree deterimation of γ with $\sigma_\gamma = 2° \sim 3°$ should be available [38]. This very impressive situation should be compared with the current B-factory data, yielding

$$\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (77^{+30}_{-32})° & (\text{CKMfitter [20]}), \\ (88 \pm 16)° & (\text{UTfit [21]}). \end{cases} \tag{19}$$

   These extractions are essentially unaffected by NP effects. On the other hand, γ can also be determined through B decays with penguin contributions: $B_s^0 \to K^+ K^-$ and $B_d^0 \to \pi^+\pi^-$ $[\sigma_\gamma \sim 5°]$, $B_s^0 \to D_s^+ D_s^-$ and $B_d^0 \to D_d^+ D_d^-$. The key question is whether discrepancies will arise in these determinations.

2. Analyses of rare decays, which are absent at the SM tree level: prominent examples are $B_{s,d}^0 \to \mu^+\mu^-$, $B_d^0 \to K^{*0}\mu^+\mu^-$ and $B_s^0 \to \phi\mu^+\mu^-$. In order to complement the studies of CP violation in $b \to s$ penguin modes at the B factories, $B_s^0 \to \phi\phi$ is a very interesting mode for LHCb, as noted in Section 2.

Let us next have a closer look at some of these decays.

3.4.1 CP Violation in $B_s \to D_s^\pm K^\mp$ and $B_d \to D^\pm\pi^\mp$

The pure tree decays $B_s \to D_s^\pm K^\mp$ [59] and $B_d \to D^\pm\pi^\mp$ [60] can be treated on the same theoretical basis, and provide new strategies to determine γ [61]. Following this paper, we write these modes as $B_q \to D_q \bar{u}_q$. Their characteristic feature is that both a B_q^0 and a $\bar{B}_q^0$ meson may decay into the same final state $D_q \bar{u}_q$. Consequently, interference effects between B_q^0–$\bar{B}_q^0$ mixing and decay processes arise, which involve the CP-violating phase combination $\phi_q + \gamma$.

In the case of $q = s$, i.e. $D_s \in \{D_s^+, D_s^{*+}, ...\}$ and $u_s \in \{K^+, K^{*+}, ...\}$, these interference effects are governed by a hadronic parameter $X_s e^{i\delta_s} \propto R_b \approx 0.4$, where $R_b \propto |V_{ub}/V_{cb}|$ is the usual UT side, and hence are large. On the other hand, for $q = d$, i.e. $D_d \in \{D^+, D^{*+}, ...\}$ and $u_d \in \{\pi^+, \rho^+, ...\}$, the interference effects are described by $X_d e^{i\delta_d} \propto -\lambda^2 R_b \approx -0.02$, and hence are tiny.

Measuring the $\cos(\Delta M_q t)$ and $\sin(\Delta M_q t)$ terms of the time-dependent $B_q \to D_q \bar{u}_q$ rates, a theoretically clean determination of $\phi_q + \gamma$ is possible [59,60]. Since the ϕ_q can be determined separately, γ can be extracted. However, in the practical implementation, there are problems: we encounter an eightfold discrete ambiguity for $\phi_q + \gamma$, which is very disturbing for the search of NP, and in the $q = d$ case, an additional input is required to extract X_d since $\mathcal{O}(X_d^2)$ interference effects would otherwise have to be resolved, which is impossible. Performing a combined analysis of the $B_s^0 \to D_s^+ K^-$ and $B_d^0 \to D^+\pi^-$ decays, these problems can be solved [61]. This strategy exploits the fact that these transitions are related to each other through the U-spin symmetry of strong interactions,[2] allowing us to simplify the hadronic sector. Following these lines, an unambiguous value of γ can be extracted from the observables. To this end, X_d has actually not to be fixed, and X_s may only enter through a $1 + X_s^2$ correction, which is determined through untagged B_s rates. The first studies for LHCb are very promising, and are currently further refined [62].

3.4.2 The $B_s \to K^+K^-$, $B_d \to \pi^+\pi^-$ System

The decay $B_s^0 \to K^+K^-$ is a $\bar{b} \to \bar{s}$ transition, and involves tree and penguin amplitudes, as $B_d^0 \to \pi^+\pi^-$ [63,64]. However, because of the different CKM structure, the latter topologies play actually the dominant rôle in $B_s^0 \to K^+K^-$, whereas the major contribution to $B_d^0 \to \pi^+\pi^-$ is due to the tree amplitude. In the SM, we may write

$$A(B_d^0 \to \pi^+\pi^-) \propto \left[e^{i\gamma} - de^{i\theta}\right] \tag{20}$$

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[2]The U spin is an $SU(2)$ subgroup of the $SU(3)_{\mathrm{F}}$ flavour-symmetry group of QCD, connecting d and s quarks in analogy to the isospin symmetry, which relates d and u quarks to each other.
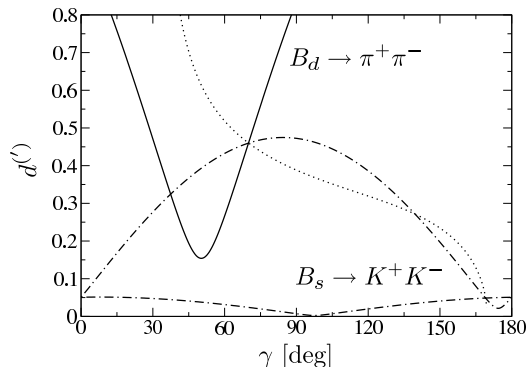
Figure 3: The contours in the γ–$d^{(\prime)}$ plane for an example corresponding to the CP asymmetries $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = -0.24$ and $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) = +0.59$, as well as $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_s \to K^+K^-) = +0.09$ and $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_s \to K^+K^-) = -0.23$.

$$A(B_s^0 \to K^+K^-) \propto \left[e^{i\gamma} + \left(\frac{1-\lambda^2}{\lambda^2} \right) d' e^{i\theta'} \right], \qquad (21)$$

where the CP-conserving hadronic parameters $de^{i\theta}$ and $d'e^{i\theta'}$ describe – sloppily speaking – the ratios of penguin to tree contributions. The direct and mixing-induced CP asymmetries take then the following general form:

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-) = G_1(d,\theta;\gamma), \quad \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-) = G_2(d,\theta;\gamma,\phi_d) \qquad (22)$$

$$\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_s \to K^+K^-) = G_1'(d',\theta';\gamma), \quad \mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_s \to K^+K^-) = G_2'(d',\theta';\gamma,\phi_s). \qquad (23)$$

Since ϕ_d is already known and ϕ_s is negligibly small in the SM – or can be determined through $B_s^0 \to J/\psi\phi$ should CP-violating NP contributions to B_s^0–$\bar{B}_s^0$ mixing make it sizeable – we may convert the measured values of $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_d \to \pi^+\pi^-)$, $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^+\pi^-)$ and $\mathcal{A}_{\mathrm{CP}}^{\mathrm{dir}}(B_s \to K^+K^-)$, $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_s \to K^+K^-)$ into *theoretically clean* contours in the γ–d and γ–d' planes, respectively. In Fig. 3, we show these contours (solid and dot-dashed) for an example, which is inspired by the current B-factory data.

A closer look at the corresponding Feynman diagrams shows that $B_d^0 \to \pi^+\pi^-$ is actually related to $B_s^0 \to K^+K^-$ through the interchange of all down and strange quarks. Consequently, each decay topology contributing to $B_d^0 \to \pi^+\pi^-$ has a counterpart in $B_s^0 \to K^+K^-$ and vice versa, and the corresponding hadronic parameters can be related to each other with the help of the U-spin flavour symmetry of strong interactions, implying the following relations [63]:

$$d' = d, \quad \theta' = \theta. \qquad (24)$$

Applying the former, we may extract γ and d through the intersections of the theoretically clean γ–d and γ–d' contours. In the example of Fig. 3, a twofold ambiguity arises from the solid and dot-dashed curves. However, as discussed in [63], it can be resolved with the help of the dotted contour, thereby leaving us with the "true" solution of $\gamma = 70°$ in this case. Moreover, we may determine θ and θ', which allow an interesting internal consistency check of the second U-spin relation in (24).
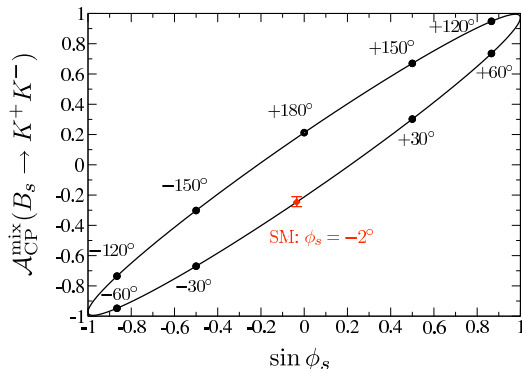
9

Figure 4: The correlation between $\sin\phi_s$, which can be determined through mixing-induced CP violation in $B_s^0 \to J/\psi\phi$, and $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \to K^+K^-)$. Each point on the curve corresponds to a given value of ϕ_s, as indicated by the numerical values [67].

This strategy is very promising from an experimental point of view for LHCb, where an accuracy for γ of a few degrees can be achieved [65]. As far as possible U-spin-breaking corrections to $d' = d$ are concerned, they enter the determination of γ through a relative shift of the γ–d and γ–d' contours; their impact on the extracted value of γ therefore depends on the form of these curves, which is fixed through the measured observables. In the examples discussed in [63] and Fig. 3, the extracted value of γ would be very stable with respect to such effects. It should also be noted that the U-spin relations in (24) are particularly robust since they involve only ratios of hadronic amplitudes, where all $SU(3)$-breaking decay constants and form factors cancel in factorization and also chirally enhanced terms would not lead to U-spin-breaking corrections [63].

A detailed analysis of the status and prospects of the $B_{s,d} \to \pi\pi, \pi K, KK$ system in view of the first results on the B_s modes from the Tevatron [66] was performed in [67]. Interestingly, the data for the $B_d \to \pi^+\pi^-$, $B_s \to K^+K^-$ system favour the BaBar measurement of the direct CP violation in $B_d \to \pi^+\pi^-$, which results in a fortunate situation for the extraction of γ, yielding $\gamma = (66.6^{+4.3+4.0}_{-5.0-3.0})^\circ$, where the latter errors correspond to a an estimate of U-spin-breaking effects. An important further step will be the measurement of mixing-induced CP violation in $B_s \to K^+K^-$, which is predicted in the SM as $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \to K^+K^-) = -0.246^{+0.036+0.052}_{-0.030-0.024}$, where the second errors illustrate the impact of large non-factorizable U-spin-breaking corrections. In the case of CP-violating NP contributions to B_s^0–$\bar{B}_s^0$ mixing also this observable would be sensitively affected, as can be seen in Fig. 4, and allows an unambiguous determination of the B_s^0–$\bar{B}_s^0$ mixing phase with the help of $B_s \to J/\psi\phi$ at LHCb. Finally, the measurement of direct CP violation in $B_s \to K^+K^-$ will make the full exploitation of the physics potential of the $B_{s,d} \to \pi\pi, \pi K, KK$ modes possible.

3.4.3 The Rare Decays $B_{s,d} \to \mu^+\mu^-$

In the SM, these decays originate from Z penguins and box diagrams. A closer look at the corresponding low-energy effective Hamiltonian [9] shows that the hadronic matrix element is simply given by the decay constant f_{B_q}. Consequently, we arrive at a very favourable situation with respect to the hadronic matrix elements. Since, moreover, NLO

QCD corrections were calculated, and long-distance contributions are expected to play a negligible rôle [68], the $B_q^0 \to \mu^+ \mu^-$ modes belong to the cleanest rare B decays.

Using also the data for the mass differences ΔM_q to reduce the hadronic uncertainties,[3] the following SM predictions were obtained in [53]:

$$\mathrm{BR}(B_s \to \mu^+ \mu^-) = (3.35 \pm 0.32) \times 10^{-9} \tag{25}$$

$$\mathrm{BR}(B_d \to \mu^+ \mu^-) = (1.03 \pm 0.09) \times 10^{-10}. \tag{26}$$

Consequently, these branching ratios are extremely tiny. But things could actually be much more exciting, as NP effects may significantly enhance $\mathrm{BR}(B_s \to \mu^+ \mu^-)$. The current upper bounds (95% C.L.) from the CDF collaboration read as follows [69]:

$$\mathrm{BR}(B_s \to \mu^+ \mu^-) < 5.8 \times 10^{-8}, \quad \mathrm{BR}(B_d \to \mu^+ \mu^-) < 1.8 \times 10^{-8}, \tag{27}$$

while the D0 collaboration finds the following 90% C.L. (95% C.L.) upper limit [70]:

$$\mathrm{BR}(B_s \to \mu^+ \mu^-) < 7.5 \ (9.3) \times 10^{-8}. \tag{28}$$

Consequently, there is still a long way to go within the SM. However, by the end of 2009, with $0.5\,\mathrm{fb}^{-1}$ data, LHCb can exclude or discover a NP contribution to $B_s \to \mu^+ \mu^-$ at the level of the SM [38]. This decay is also very interesting for ATLAS and CMS, where detailed signal and background studies are currently in progress [39].

3.4.4 The Rare Decay $B_d^0 \to K^{*0} \mu^+ \mu^-$

The key observable for NP searches through this channel is the following forward–backward asymmetry:

$$A_{\mathrm{FB}}(\hat{s}) = \frac{1}{\mathrm{d}\Gamma/\mathrm{d}\hat{s}} \left[\int_0^{+1} \mathrm{d}(\cos\theta) \frac{\mathrm{d}^2\Gamma}{\mathrm{d}\hat{s}\,\mathrm{d}(\cos\theta)} - \int_{-1}^0 \mathrm{d}(\cos\theta) \frac{\mathrm{d}^2\Gamma}{\mathrm{d}\hat{s}\,\mathrm{d}(\cos\theta)} \right]. \tag{29}$$

Here θ is the angle between the B_d^0 momentum and that of the μ^+ in the dilepton centre-of-mass system, and $\hat{s} \equiv s/M_B^2$ with $s = (p_{\mu^+} + p_{\mu^-})^2$. A particularly interesting kinematical point is characterized by

$$A_{\mathrm{FB}}(\hat{s}_0)|_{\mathrm{SM}} = 0, \tag{30}$$

as $\hat{s}_0$ is quite robust with respect to hadronic uncertainties (see, e.g., [71]). In SUSY extensions of the SM, $A_{\mathrm{FB}}(\hat{s})$ could take opposite sign or take a dependence on $\hat{s}$ without a zero point [72]. The current B-factory data for the inclusive $b \to s\ell^+\ell^-$ branching ratios and the integrated forward–backward asymmetries are in accordance with the SM, but suffer still from large uncertainties. This situation will improve dramatically at the LHC. Here LHCb will measure the zero crossing point by ~ 2013 with $10\,\mathrm{fb}^{-1}$ with $\sigma(s_0) = 0.27(\mathrm{GeV}/c^2)^2$, corresponding to 19k events [38]. For other interesting observables provided by $B_d^0 \to K^{*0} \mu^+ \mu^-$, see [73]. Also alternative $b \to s\mu^+\mu^-$ modes are currently under study, such as $B_s^0 \to \phi\mu^+\mu^-$ and $\Lambda_b \to \Lambda\mu^+\mu^-$ [38, 39].

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[3]This input allows us to replace the decay constants f_{B_q} through the bag parameters $\hat{B}_{B_q}$.

4 Conclusions and Outlook

We have seen tremendous progress in B physics during the recent years, which was made possible through a fruitful interplay between theory and experiment. Altogether, the e^+e^- B factories have already produced $\mathcal{O}(10^9)$ $B\bar{B}$ pairs, and the Tevatron has recently succeeded in observing B_s^0–$\bar{B}_s^0$ mixing. The data agree globally with the KM mechanism of CP violation in an impressive manner, but we have also hints for discrepancies, which could be first signals of NP. Unfortunately, definite conclusions cannot yet be drawn as the uncertainties are still too large.

Exciting new perspectives for B physics and the exploration of CP violation will arise in the summer of 2008 through the start of the LHC, with its dedicated B-decay experiment LHCb. Thanks to the large statistics that can be collected there and the full exploitation of the physics potential of the B_s-meson system, we will be able to enter a new territory in the exploration of CP violation. The golden channel for the search of CP-violating NP contributions to B_s^0–$\bar{B}_s^0$ mixing is $B_s^0 \rightarrow J/\psi\phi$, where the recent measurement of ΔM_s still leaves ample space for such effects both in terms of the general NP parameters and in specific extensions of the SM. In contrast to the theoretical interpretation of ΔM_s, the corresponding CP asymmetries have not to rely on non-perturbative lattice QCD calculations. Moreover, it will be very interesting to search for CP-violating NP effects in $b \rightarrow s$ penguin processes through the $B_s^0 \rightarrow \phi\phi$ channel. These measurements will be complemented by other key ingredients for the search of NP: precision measurements of the UT angle γ by means of various processes with a very different dynamics, and powerful analyses of rare B decays.

In addition to B physics, there are other important flavour probes. An outstanding example is charm physics, where evidence for D^0–$\bar{D}^0$ mixing was found at the B factories in the spring of 2007 [74], and very recently also at CDF [75]. The mixing parameters are measured in the ball park of the SM predictions, which are unfortunately affected by large long-distance effects. A striking NP signal would be given by CP-violating effects (for recent theoretical analyses, see, e.g. [76]). There is also a powerful charm-physics programme at LHCb. As far as kaon physics is concerned, the future is given by the rare decays $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_{\rm L} \rightarrow \pi^0\nu\bar{\nu}$, which are theoretically very clean and would be very desirable to be measured (efforts at CERN and KEK/J-PARC). Moreover, there is of course also exciting flavour violation in the lepton sector (neutrino physics, search for $\mu \rightarrow e\gamma$ at MEG, etc.), and it is crucial to obtain eventually the whole picture.

The main goal of the ATLAS and CMS experiments is to explore electroweak symmetry breaking, in particular the question of whether this is actually caused by the Higgs mechanism, to produce and observe new particles, and then to go back to the deep questions of particle physics, such as the origin of dark matter and the baryon asymmetry of the Universe. It is obvious that there will be a fruitful interplay between these "direct" studies of NP and the "indirect" information provided by flavour physics, including the B-meson system, but also D, K, and top physics as well as the flavour physics in the lepton sector [77]. I have no doubts that the next years will be extremely exciting!

References

[1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).

[2] A. Kusenko, these proceedings.

[3] W. Buchmüller, R. D. Peccei and T. Yanagida, Ann. Rev. Nucl. Part. Sci. **55**, 311 (2005).

[4] C. Hawkes (BaBar Collaboration), these proceedings.

[5] K. Trabelsi (Belle Collaboration), these proceedings.

[6] M. Bona *et al.*, arXiv:0709.0451 [hep-ex]; A. G. Akeroyd *et al.*, arXiv:hep-ex/0406071.

[7] K. Abe *et al.* [Belle Collaboration], hep-ex/0610003; J. Wicht *et al.* [Belle Collaboration], arXiv:0712.2659 [hep-ex].

[8] A. Pellegrino, these proceedings.

[9] G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. **68**, 1125 (1996).

[10] M. Beneke, G. Buchalla, M. Neubert and C. T. Sachrajda, Phys. Rev. Lett. **83** (1999) 1914; Nucl. Phys. B **591** (2000) 313.

[11] H.-n. Li and H. L. Yu, Phys. Rev. D **53**, 2480 (1996); Y. Y. Keum, H.-n. Li and A. I. Sanda, Phys. Lett. B **504**, 6 (2001); Y. Y. Keum and H.-n. Li, Phys. Rev. D **63**, 074006 (2001); A. Ali *et al.*, Phys. Rev. D **76**, 074018 (2007).

[12] C. W. Bauer, D. Pirjol and I. W. Stewart, Phys. Rev. Lett. **87**, 201806 (2001); C. W. Bauer, B. Grinstein, D. Pirjol and I. W. Stewart, Phys. Rev. D **67**, 014010 (2003).

[13] A. Khodjamirian, Nucl. Phys. B **605**, 558 (2001); A. Khodjamirian, T. Mannel and B. Melic, Phys. Lett. B **571**, 75 (2003).

[14] M. Gronau and D. Wyler, Phys. Lett. B **265**, 172 (1991).

[15] D. Atwood, I. Dunietz and A. Soni, Phys. Rev. Lett. **78**, 3257 (1997); Phys. Rev. D **63**, 036005 (2001).

[16] R. Fleischer and D. Wyler, Phys. Rev. D **62**, 057503 (2000).

[17] M. Gronau, J. L. Rosner and D. London, Phys. Rev. Lett. **73**, 21 (1994); M. Gronau, O. F. Hernandez, D. London and J. L. Rosner, Phys. Rev. D **50**, 4529 (1994).

[18] A. B. Carter and A. I. Sanda, Phys. Rev. Lett. **45**, 952 (1980); Phys. Rev. D **23**, 1567 (1981); I. I. Bigi and A. I. Sanda, Nucl. Phys. B **193**, 85 (1981).

[19] R. Fleischer, lectures given at the 2005 European School of High-Energy Physics, Kitzbühel, Austria, 21 August – 3 September 2005 [hep-ph/0608010].

[20] J. Charles *et al.* [CKMfitter Group], Eur. Phys. J. C **41**, 1 (2005); for the most recent updates, see http://ckmfitter.in2p3.fr/.

[21] M. Bona *et al.* [UTfit Collaboration], JHEP **0507**, 028 (2005); for the most recent updates, see http://utfit.roma1.infn.it/.

[22] A. J. Buras and R. Fleischer, Eur. Phys. J. C **16**, 97 (2000); T. Yoshikawa, Phys. Rev. D **68**, 054023 (2003); M. Gronau and J. L. Rosner, Phys. Lett. B **572**, 43 (2003); M. Beneke and M. Neubert, Nucl. Phys. B **675**, 333 (2003); A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, Eur. Phys. J. C **32**, 44 (2003); V. Barger, C. W. Chiang, P. Langacker and H. S. Lee, Phys. Lett. B **598**, 218 (2004); Y. L. Wu and Y. F. Zhou, Phys. Rev. D **72**, 034037 (2005); M. Gronau and J. L. Rosner, Phys. Rev. D **74**, 057503 (2006); M. Gronau and J. L. Rosner, Phys. Lett. B **644**, 237 (2007).

[23] A. J. Buras, R. Fleischer, S. Recksiegel and F. Schwab, Phys. Rev. Lett. **92**, 101804 (2004); Nucl. Phys. B **697**, 133 (2004); Eur. Phys. J. C **45**, 701 (2006).

[24] R. Fleischer, S. Recksiegel and F. Schwab, Eur. Phys. J. C **51**, 55 (2007).

[25] Heavy Flavour Averaging Group [E. Barberio *et al.*], arXiv:0704.3575 [hep-ex]; for online updates, see http://www.slac.stanford.edu/xorg/hfag.

[26] R. Fleischer, Int. J. Mod. Phys. A **12**, 2459 (1997).

[27] Y. Grossman and M. P. Worah, Phys. Lett. B **395**, 241 (1997).

[28] R. Fleischer and T. Mannel, Phys. Lett. B **511**, 240 (2001).

[29] R. Fleischer and M. Gronau, arXiv:0709.4013 [hep-ph], to appear in Phys. Lett. B.

[30] D. Acosta *et al.* [CDF Collaboration], Phys. Rev. Lett. **95**, 031801 (2005).

[31] S. Amato *et al.*, CERN-LHCb-2007-047.

[32] P. Ball and R. Fleischer, Eur. Phys. J. C **48**, 413 (2006).

[33] M. Della Morte, PoS **LAT2007**, 008 (2007).

[34] A. Lenz, arXiv:0710.0940 [hep-ph].

[35] A. S. Dighe, I. Dunietz and R. Fleischer, Eur. Phys. J. C **6**, 647 (1999).

[36] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **98**, 121801 (2007).

[37] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0712.2348 [hep-ex].

[38] T. Nakada, talk at 2nd Workshop on Flavour Dynamics, Albufeira, Portugal, 3–10 November 2007 [http://www.theorie.physik.uni-muenchen.de/lsfritzsch/albufeira/].

[39] A. Krasznahorkay, "Outlook for B physics at the LHC in ATLAS and CMS," in the proceedings of DIS 2007, Munich, Germany, 16–20 April 2007.

[40] I. Dunietz, Phys. Rev. D **52**, 3048 (1995).

[41] R. Fleischer and I. Dunietz, Phys. Rev. D **55**, 259 (1997).

[42] R. Fleischer and I. Dunietz, Phys. Lett. B **387**, 361 (1996).

[43] I. Dunietz, R. Fleischer and U. Nierste, Phys. Rev. D **63**, 114015 (2001).

[44] L. Wolfenstein, Phys. Rev. Lett. **51**, 1945 (1983);

[45] Y. Nir and D. J. Silverman, Nucl. Phys. B **345**, 301 (1990).

[46] G. C. Branco, T. Morozumi, P. A. Parada and M. N. Rebelo, Phys. Rev. D **48**, 1167 (1993).

[47] *B* Oscillations Working Group: http://lepbosc.web.cern.ch/LEPBOSC/.

[48] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **97**, 021802 (2006); A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 062003 (2006).

[49] The D0 Collaboration, D0note 5474-conf (2007) [http://www-d0.fnal.gov].

[50] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 242003 (2006).

[51] E. Dalgic *et al.* [HPQCD Collaboration], Phys. Rev. D **76**, 011501 (2007).

[52] M. Carena *et al.*, Phys. Rev. D **74**, 015009 (2006); M. Ciuchini and L. Silvestrini, Phys. Rev. Lett. **97**, 021803 (2006); M. Endo and S. Mishima, Phys. Lett. B **640**, 205 (2006); Z. Ligeti, M. Papucci and G. Perez, Phys. Rev. Lett. **97**, 101801 (2006); J. Foster, K.I. Okumura and L. Roszkowski, Phys. Lett. B **641**, 452 (2006); Y. Grossman, Y. Nir and G. Raz, Phys. Rev. Lett. **97**, 151801 (2006); S. Baek, J. H. Jeon and C. S. Kim, Phys. Lett. B **641**, 183 (2006); M. Blanke and A. J. Buras, JHEP **0705**, 061 (2007).

[53] M. Blanke, A. J. Buras, D. Guadagnoli and C. Tarantino, JHEP **0610**, 003 (2006).

[54] A. S. Dighe, I. Dunietz, H. J. Lipkin and J. L. Rosner, Phys. Lett. B **369**, 144 (1996).

[55] V. M. Abazov *et al.* [D0 Collaboration], Phys. Rev. Lett. **98**, 121801 (2007).

[56] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0712.2397 [hep-ex].

[57] F. Muheim, Nucl. Phys. Proc. Suppl. **170**, 317 (2007).

[58] R. Fleischer, Phys. Rev. D **60**, 073008 (1999).

[59] R. Aleksan, I. Dunietz and B. Kayser, Z. Phys. C **54**, 653 (1992).

[60] I. Dunietz and R. G. Sachs, Phys. Rev. D **37**, 3186 (1988) [E: D **39**, 3515 (1989)];
    I. Dunietz, Phys. Lett. B **427**, 179 (1998); D. A. Suprun, C. W. Chiang and
    J. L. Rosner, Phys. Rev. D **65**, 054025 (2002).

[61] R. Fleischer, Nucl. Phys. B **671**, 459 (2003).

[62] G. Wilkinson, in G. Cavoto *et al.*, Proceedings of CKM 2005 (WG5), San Diego,
    California, 15–18 March 2005 [hep-ph/0603019]; V. Gligorov and G. Wilkinson,
    work in progress.

[63] R. Fleischer, Phys. Lett. B **459**, 306 (1999).

[64] R. Fleischer and J. Matias, Phys. Rev. D **66**, 054009 (2002).

[65] G. Balbi *et al.*, CERN-LHCb/2003-123 and 124; R. Antunes Nobrega *et al.* [LHCb
    Collaboration], *Reoptimized LHCb Detector, Design and Performance*, Technical
    Design Report 9, CERN/LHCC 2003-030; A. Carbone, J. Nardulli, S. Pennazzi,
    A. Sarti and V. Vagnoni, CERN-LHCb-2007-059.

[66] A. Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **97**, 211802 (2006); CDF
    Note 8579 (2006).

[67] R. Fleischer, Eur. Phys. J. C **52**, 267 (2007).

[68] G. Buchalla and A. J. Buras, Nucl. Phys. B **400**, 225 (1993) and B **548**, 309 (1999);
    M. Misiak and J. Urban, Phys. Lett. B **451**, 161 (1999).

[69] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0712.1708 [hep-ex].

[70] D0 Collaboration, D0 Note 5344-CONF (2007) [http://www-d0.fnal.gov].

[71] G. Burdman, Phys. Rev. D **57**, 4254 (1998); M. Beneke, T. Feldmann and D. Seidel,
    Eur. Phys. J. C **41**, 173 (2005); A. Ali, G. Kramer and G. h. Zhu, Eur. Phys. J. C
    47, 625 (2006).

[72] A. Ali, P. Ball, L. T. Handoko and G. Hiller, Phys. Rev. D **61**, 074024 (2000).

[73] F. Krüger and J. Matias, Phys. Rev. D **71**, 094009 (2005); E. Lunghi and J. Matias,
    JHEP **0704**, 058 (2007).

[74] B. Aubert *et al.* [BABAR Collaboration], Phys. Rev. Lett. **98**, 211802 (2007);
    M. Staric *et al.* [Belle Collaboration], Phys. Rev. Lett. **98**, 211803 (2007);

[75] T. Aaltonen *et al.* [CDF Collaboration], arXiv:0712.1567 [hep-ex].

[76] Y. Nir, JHEP **0705**, 102 (2007); E. Golowich, J. Hewett, S. Pakvasa and
    A. A. Petrov, Phys. Rev. D **76**, 095009 (2007).

[77] These topics were addressed at the CERN Workshop "Flavour in the Era of the
    LHC", November 2005 – March 2007 [http://flavlhc.web.cern.ch/flavlhc/].