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CP Violation and B Physics at the LHC

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Abstract

In this decade, there are huge efforts to explore B -meson decays, which provide an interesting playground for stringent tests of the Standard-Model description of the quark-flavour sector and the CP violation residing there. Thanks to the $e^+e^- B$ factories at KEK and SLAC, CP violation is now a well-established phenomenon in the B -meson system, and recently, also $B_s^0-\bar{B}_s^0$ mixing could be measured at the Tevatron. The decays of B_s^0 mesons are the key target of the B -physics programme at the LHC, and will be the focus of this presentation, discussing the theoretical aspects of various benchmark channels and the question of how much space for new-physics effects in their observables is left by the recent experimental results.

1 Setting the Stage

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” scenarios. Moreover, also the observed neutrino masses point towards an origin lying beyond the SM, raising now also 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” [2], 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. A famous example is the quantity $\text{Re}(\varepsilon'/\varepsilon)_K$, which measures the direct CP violation in neutral K decays (for an overview, see [3]). In the kaon system, where CP violation was discovered in 1964 [4], clean tests of the SM are offered by the decays $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ and $K_L \rightarrow \pi^0 \nu \bar{\nu}$, where the hadronic pieces can be fixed through $K \rightarrow \pi \ell \bar{\nu}$ modes. These rare decays are absent at the tree level of the SM, i.e. originate there exclusively from loop processes, with resulting tiny branching ratios at the 10^{-10} level (for a recent review, see [5]). Experimental studies of these channels are therefore very challenging. Nevertheless, there are plans to measure $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the SPS (CERN) [6], and efforts to explore $K_L \rightarrow \pi^0 \nu \bar{\nu}$ at the E391 (KEK/J-PARC) experiment.

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. It offers various strategies, i.e. simply speaking, there are many B decays that we can exploit, and we may search for clean SM relations that could be spoiled through the impact of NP. There are two kinds of experimental facilities, where B -meson decays can be studied:

- The “ B factories”, which are asymmetric e^+e^- colliders operated at the $\Upsilon(4S)$ resonance, producing only $B_d^0 \bar{B}_d^0$ and $B_u^+ B_u^-$ pairs: PEP-II with the Babar experiment (SLAC) and KEK-B with the Belle experiment (KEK) 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 [7].
- Hadron colliders produce, in addition to B_d and B_u , also B_s mesons,¹ as well as B_c and Λ_b transitions. 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 autumn 2007. Here ATLAS and CMS can also address some B physics topics, although these studies are the main target of the dedicated B -decay experiment LHCb.

The central target of these explorations is the well-known unitarity triangle (UT) of the Cabibbo–Kobayashi–Maskawa (CKM) matrix with its three angles α , β and γ . Its apex is given by the generalized Wolfenstein parameters [9]

$$\bar{\rho} \equiv (1 - \lambda^2/2)\rho, \quad \bar{\eta} \equiv (1 - \lambda^2/2)\eta. \quad (1)$$

The key processes for the exploration of CP violation are given by non-leptonic decays of B mesons, where only quarks are present in the final states. In these

¹Recently, data were taken by Belle at $\Upsilon(5S)$, allowing also access to B_s decays [8].

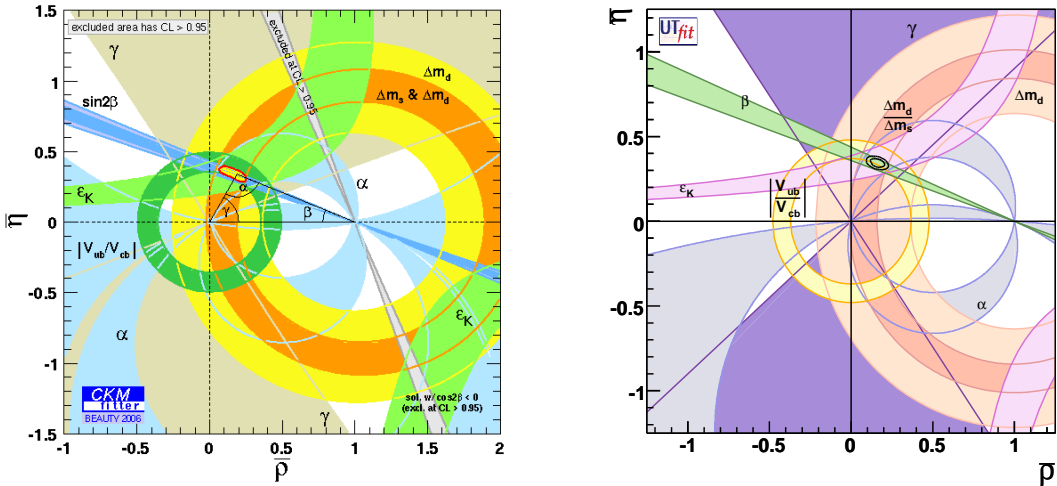


Figure 1: Analyses of the CKMfitter and UTfit collaborations [20, 21].

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 written by means of the operator product expansion as follows [10]:

$$A(B \rightarrow f) \sim \sum_k \underbrace{C_k(\mu)}_{\text{pert. QCD}} \times \underbrace{\langle f|Q_k(\mu)|B\rangle}_{\text{“unknown”}}, \quad (2)$$

remains a theoretical challenge, despite interesting recent progress [11].

However, 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. To this end, we may follow two avenues:

- 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 $B^\pm \rightarrow K^\pm D$ [12, 13] or $B_c^\pm \rightarrow D_s^\pm D$ [14], and relations, which follow from the flavour symmetries of strong interactions, i.e. isospin or $SU(3)_F$, and typically involve $B_{(s)} \rightarrow \pi\pi, \pi K, KK$ modes [15].
- In decays of neutral B_q mesons ($q \in \{d, s\}$), the interference between $B_q^0-\bar{B}_q^0$ mixing and $B_q^0, \bar{B}_q^0 \rightarrow f$ 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 $B_d^0 \rightarrow J/\psi K_S$ [16].

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 [17]). 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 [18], 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.

In Fig. 1, we show the current status of the UT [19] emerging from the comprehensive – and continuously updated – analyses by the “CKM Fitter Group” [20] and the “UTfit collaboration” [21]. We observe that there is impressive global agreement with the KM mechanism. However, there is also some tension present, as the straight line representing the measurement of $(\sin 2\beta)_{\psi K_S}$ is now on the lower side of the UT side R_b measured through $|V_{ub}/V_{cb}|$. We shall return to this topic in Section 2.2. Let us next discuss the interpretation of the B -factory data in more detail.

2 A Brief Look at the Current B -Factory Data

There are two popular avenues for NP to manifest itself in the B -factory data: through effects entering at the decay amplitude level, or through B_q^0 – \bar{B}_q^0 mixing.

2.1 New Physics at the Decay Amplitude Level

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.

CP Violation in $b \rightarrow s$ Penguin Modes

A particularly interesting probe of NP is the decay $B_d^0 \rightarrow \phi K_S$. It is caused by $\bar{b} \rightarrow \bar{s}s\bar{s}$ quark-level processes, i.e. receives only contributions from penguin topologies. The corresponding final state is CP-odd, and the time-dependent CP asymmetry takes

the following form:²

$$\begin{aligned} & \frac{\Gamma(B_d^0(t) \rightarrow \phi K_S) - \Gamma(\overline{B}_d^0(t) \rightarrow \phi K_S)}{\Gamma(B_d^0(t) \rightarrow \phi K_S) + \Gamma(\overline{B}_d^0(t) \rightarrow \phi K_S)} \\ &= \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S) \cos(\Delta M_d t) + \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \phi K_S) \sin(\Delta M_d t), \end{aligned} \quad (3)$$

where $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S)$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \phi K_S)$ denote the direct and mixing-induced CP asymmetries, respectively. Thanks to the weak phase structure of the $B_d^0 \rightarrow \phi K_S$ decay amplitude in the SM, we obtain the following expressions [17]:

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S) = 0 + \mathcal{O}(\lambda^2) \quad (4)$$

$$\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \phi K_S) = -\sin \phi_d + \mathcal{O}(\lambda^2), \quad (5)$$

where ϕ_d is the B_d^0 - \overline{B}_d^0 mixing phase and the doubly Cabibbo-suppressed $\mathcal{O}(\lambda^2)$ terms describe hadronic corrections. Since the mixing-induced CP asymmetry of the $B_d \rightarrow J/\psi K_S$ channel measures also $-\sin \phi_d$, we arrive at the following SM relation [22,23]:

$$-(\sin 2\beta)_{\phi K_S} \equiv \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \phi K_S) = \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow J/\psi K_S) + \mathcal{O}(\lambda^2), \quad (6)$$

which offers an interesting test of the SM. Since $B_d \rightarrow \phi K_S$ is dominated, in the SM, by QCD penguin processes and receives significant contributions from EW penguins as well, the relations in (4) and (6) may well be affected by NP effects. This follows through field-theoretical estimates for generic NP in the TeV regime [24], and is also the case for several specific extensions of the SM (see, e.g., [25]). Concerning the current experimental status [26], it can be summarized through the averages obtained by the ‘‘Heavy Flavour Averaging Group’’ [27]:

$$(\sin 2\beta)_{\phi K_S} = 0.39 \pm 0.18, \quad \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \phi K_S) = 0.01 \pm 0.13. \quad (7)$$

During the recent years, the Belle results for $(\sin 2\beta)_{\phi K_S}$ have moved quite a bit towards the SM reference value of

$$-\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow J/\psi K_S) \equiv (\sin 2\beta)_{\psi K_S} = 0.674 \pm 0.026, \quad (8)$$

and are now, within the errors, in agreement with the BaBar findings. Interestingly, the mixing-induced CP asymmetries of other $b \rightarrow s$ penguin modes show the same trend of having central values that are smaller than 0.674 [27]. This feature may in fact be due to the presence of NP contributions to the corresponding decay amplitudes. However, the large uncertainties do not yet allow us to draw definite conclusions.

²We shall use a similar sign convention also for self-tagging neutral B_d and charged B decays.

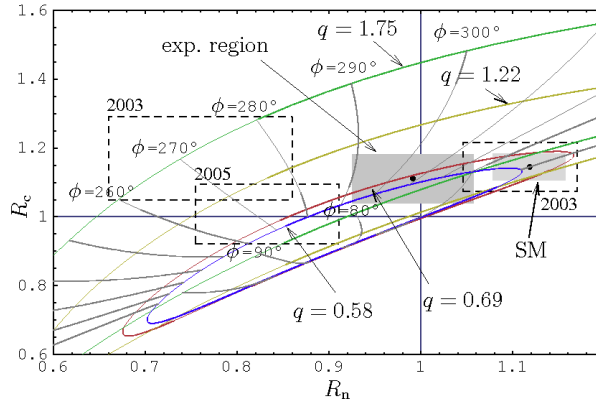


Figure 2: The situation in the R_n - R_c plane, as discussed in the text.

The $B \rightarrow \pi K$ Puzzle

Another hot topic is the exploration of $B \rightarrow \pi K$ decays. Thanks to the B factories, we could obtain valuable insights into these decays, raising the possibility of having a modified EW penguin sector through the impact of NP, which has received a lot of attention in the literature (see, e.g., [28]). Here we shall discuss key results of the very recent analysis performed in [29], following closely the strategy developed in [30]. The starting point is given by $B \rightarrow \pi\pi$ modes. Using the $SU(3)$ flavour symmetry of strong interactions and another plausible dynamical assumption,³ the data for the $B \rightarrow \pi\pi$ system can be converted into the hadronic parameters of the $B \rightarrow \pi K$ modes, thereby allowing us to calculate their observables in the SM. Moreover, also γ can be extracted, with the result

$$\gamma = (70.0^{+3.8}_{-4.3})^\circ, \quad (9)$$

which is in agreement with the SM fits of the UT [20, 21].

As far as the $B \rightarrow \pi K$ observables with tiny EW penguin contributions are concerned, perfect agreement between the SM expectation and the experimental data is found. Concerning the $B \rightarrow \pi K$ observables receiving sizeable contributions from EW penguins, we distinguish between CP-conserving and CP-violating observables. In the former case, the key quantities are given by the following ratios of CP-averaged

³Consistency checks of these working assumptions can be performed, which are all supported by the current data.

$B \rightarrow \pi K$ branching ratios [31]:

$$R_c \equiv 2 \left[\frac{\text{BR}(B^+ \rightarrow \pi^0 K^+) + \text{BR}(B^- \rightarrow \pi^0 K^-)}{\text{BR}(B^+ \rightarrow \pi^+ K^0) + \text{BR}(B^- \rightarrow \pi^- \bar{K}^0)} \right] = 1.11 \pm 0.07 \quad (10)$$

$$R_n \equiv \frac{1}{2} \left[\frac{\text{BR}(B_d^0 \rightarrow \pi^- K^+) + \text{BR}(\bar{B}_d^0 \rightarrow \pi^+ K^-)}{\text{BR}(B_d^0 \rightarrow \pi^0 K^0) + \text{BR}(\bar{B}_d^0 \rightarrow \pi^0 \bar{K}^0)} \right] = 0.99 \pm 0.07, \quad (11)$$

where also the most recent experimental averages are indicated [27]. In these quantities, the EW penguin effects enter in colour-allowed form through the modes involving neutral pions, and are theoretically described by a parameter q , which measures the “strength” of the EW penguin with respect to the tree contributions, and a CP-violating phase ϕ . In the SM, the $SU(3)$ flavour symmetry allows a prediction of $q = 0.60$ [32], and ϕ *vanishes*. As is known for many years (see, for instance, [33]), EW penguin topologies offer an interesting avenue for NP to manifest itself in the B -factory data. In the case of CP-violating NP effects of this kind, ϕ would take a value different from zero. In Fig. 2, we show the situation in the R_n - R_c plane. Here the various contours correspond to different values of q , and the position on the contour is parametrized through the CP-violating phase ϕ . We observe that the SM prediction (on the right-hand side) is very stable in time, having now significantly reduced errors. On the other hand, the B -factory data have moved quite a bit towards the SM, thereby reducing the “ $B \rightarrow \pi K$ puzzle” for the CP-averaged branching ratios, which emerged already in 2000 [34]. In comparison with the situation of the $B \rightarrow \pi K$ observables with tiny EW penguin contributions, the agreement between the new data for the $R_{c,n}$ and their SM predictions is not as perfect. However, a case for a modified EW penguin sector cannot be made through the new measurements of these quantities.

Let us now have a closer look at the CP asymmetries of the $B_d^0 \rightarrow \pi^0 K_S$ and $B^\pm \rightarrow \pi^0 K^\pm$ channels. As can be seen in Fig. 3, SM predictions for the CP-violating observables of $B_d^0 \rightarrow \pi^0 K_S$ are obtained that are much sharper than the current B -factory data. In particular $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^0 K_S)$ offers a very interesting quantity. We also see that the experimental central values can be reached for large *positive* values of ϕ . For the new input data, the non-vanishing difference

$$\Delta A \equiv \mathcal{A}_{\text{CP}}^{\text{dir}}(B^\pm \rightarrow \pi^0 K^\pm) - \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^\mp K^\pm) \stackrel{\text{exp}}{=} -0.140 \pm 0.030 \quad (12)$$

is likely to be generated through hadronic effects, i.e. not through the impact of physics beyond the SM. A similar conclusion was drawn in [35], where it was also noted that the measured values of R_c and R_n are now in accordance with the SM.

Performing, finally, a simultaneous fit to R_n , R_c and the CP-violating $B_d \rightarrow \pi^0 K_S$ asymmetries yields

$$q = 1.7_{-1.3}^{+0.5}, \quad \phi = + (73_{-18}^{+6})^\circ. \quad (13)$$

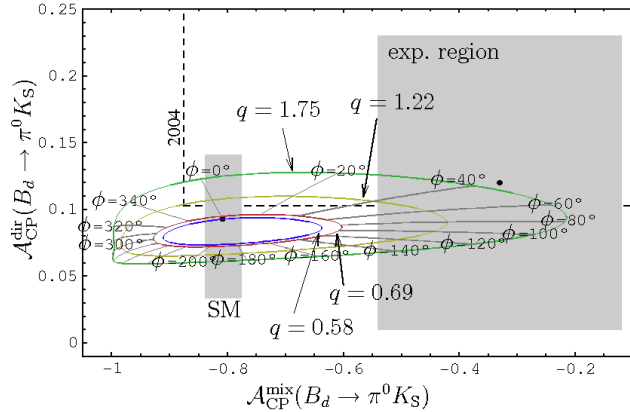


Figure 3: The situation in the $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^0 K_S) - \mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^0 K_S)$ plane.

Interestingly, these parameters – in particular the large *positive* phase – would also allow us to accommodate the experimental values of $(\sin 2\beta)_{\phi_{K_S}}$ and the CP asymmetries of other $b \rightarrow s$ penguin modes with central values smaller than $(\sin 2\beta)_{\psi_{K_S}}$. The large value of q would be excluded by constraints from rare decays in simple scenarios where NP enters only through Z penguins [30], but could still be accommodated in other scenarios, e.g. in models with leptophobic Z' bosons.

2.2 New Physics in $B_d^0 - \bar{B}_d^0$ Mixing

In the SM, $B_d^0 - \bar{B}_d^0$ mixing 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 (e.g. SUSY, Z' models). In this case, the off-diagonal element of the mass matrix is modified as follows [36]:

$$M_{12}^{(d)} = M_{12}^{d,\text{SM}} (1 + \kappa_d e^{i\sigma_d}), \quad (14)$$

where the real parameter κ_d is a measure of the strength of NP with respect to the SM, and σ_d a CP-violating NP phase. The mass difference ΔM_d between the two mass eigenstates and the mixing phase ϕ_d are then modified as

$$\Delta M_d = \Delta M_d^{\text{SM}} + \Delta M_d^{\text{NP}} = \Delta M_d^{\text{SM}} |1 + \kappa_d e^{i\sigma_d}| \quad (15)$$

$$\phi_d = \phi_d^{\text{SM}} + \phi_d^{\text{NP}} = \phi_d^{\text{SM}} + \arg(1 + \kappa_d e^{i\sigma_d}), \quad (16)$$

where $\phi_d^{\text{SM}} = 2\beta$.

Using the B -factory data to measure ΔM_d and to extract the NP phase ϕ_d^{NP} , two sets of contours can be fixed in the $\sigma_d - \kappa_d$ plane. In the former case, the SM

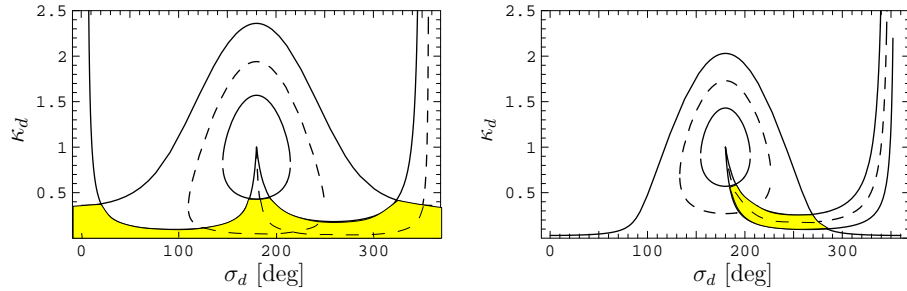


Figure 4: Left panel: allowed region (yellow/grey) in the σ_d - κ_d plane in a scenario with the JLQCD lattice results and $\phi_d^{\text{NP}}|_{\text{excl}}$. Right panel: ditto for the scenario with the (HP+JL)QCD lattice results and $\phi_d^{\text{NP}}|_{\text{incl}}$.

value ΔM_d^{SM} is required. It involves the CKM parameter $|V_{td}^* V_{tb}|$, which is governed by γ in the corresponding numerical analysis if the unitarity of the CKM matrix is used. Moreover, information about the hadronic parameter $f_{B_d}^2 \hat{B}_{B_d}$ is needed, where f_{B_d} is the decay constant of the B_d^0 mesons and B_{B_d} the “bag” parameter of B_d^0 - \bar{B}_d^0 mixing, usually coming from lattice QCD [37]. For the purpose of comparison, we use two benchmark sets of such results for these quantities [36]: the JLQCD results for two flavours of dynamical light Wilson quarks [38], and a combination of f_{B_d} as determined by the HPQCD collaboration [39] for three dynamical flavours with the JLQCD result for \hat{B}_{B_d} [(HP+JL)QCD] [40].

For the determination of the NP phase $\phi_d^{\text{NP}} = \phi_d - \phi_d^{\text{SM}}$, we use

$$\phi_d = (42.4 \pm 2)^\circ, \quad (17)$$

which follows from the CP violation in $B_d \rightarrow J/\psi K^{(*)}$ decays [27], and fix the “true” value of $\phi_d^{\text{SM}} = 2\beta$ with the help of the data for tree processes. This can simply be done through trigonometrical relations between the side $R_b \propto |V_{ub}/V_{cb}|$ of the UT and its angle γ , which are determined through semileptonic $b \rightarrow u\ell\bar{\nu}_\ell$ decays and $B \rightarrow DK$ modes, respectively. A numerical analysis shows, that the value of ϕ_d^{NP} is actually governed by $R_b \propto |V_{ub}/V_{cb}|$, while $(\gamma)_{DK}$, which suffers currently from large uncertainties [41], plays only a minor rôle, in contrast to the SM analysis of ΔM_d . Unfortunately, we are facing a discrepancy between the determinations of $|V_{ub}|$ from exclusive and inclusive decays [42, 43], which has to be resolved in the future. The corresponding NP phases read as follows:

$$\phi_d^{\text{NP}}|_{\text{excl}} = -(3.4 \pm 7.9)^\circ, \quad \phi_d^{\text{NP}}|_{\text{incl}} = -(11.0 \pm 4.3)^\circ, \quad (18)$$

where the latter result corresponds to the “tension” in the fits of the UT discussed in the context with Fig. 1. The resulting situation in the σ_d - κ_d plane is shown in Fig. 4, where the hill-like structures correspond to the constraints from ΔM_d , which are complementary to those of ϕ_d^{NP} . We observe that the measurement of CP

violation in $B_d \rightarrow J/\psi K^{(*)}$ decays has a dramatic impact on the allowed region in NP parameter space; the right panel may indicate the presence of NP, although no definite conclusions can be drawn at the moment. It will be interesting to monitor this effect in the future. In order to detect such CP-violating NP contributions, things are much more promising in the B_s system.

3 Key Targets of B -Physics Studies at the LHC

The exploration of B -meson decays at hadron colliders – and the LHC in particular – is characterized through a high statistics and the access the B_s -meson system, which offers a physics programme that is to a large extent complementary to that of the e^+e^- B factories operating at the $\Upsilon(4S)$ resonance.

3.1 General Features of the B_s System

For B_s^0 -mesons, we expect – within the SM – a mass difference $\Delta M_s = \mathcal{O}(20 \text{ ps}^{-1})$, which is much larger than the experimental value of $\Delta M_d = 0.5 \text{ ps}^{-1}$. 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 $\mathcal{O}(10\%)$ [44]. Recently, the first results for $\Delta\Gamma_s$ were reported from the Tevatron, using the $B_s^0 \rightarrow J/\psi\phi$ channel [45]:

$$\frac{\Delta\Gamma_s}{\Gamma_s} = \begin{cases} 0.65_{-0.33}^{+0.25} \pm 0.01 & \text{(CDF [46])} \\ 0.24_{-0.38}^{+0.28+0.03} & \text{(D0 [47]).} \end{cases} \quad (19)$$

It will be interesting to follow the evolution of the data for this quantity; at the LHC, we expect a precision of about 0.01 after one year of taking data [48, 49]. The width difference $\Delta\Gamma_s$ offers studies of CP violation through “untagged” rates of the following form:

$$\langle \Gamma(B_s(t) \rightarrow f) \rangle \equiv \Gamma(B_s^0(t) \rightarrow f) + \Gamma(\bar{B}_s^0(t) \rightarrow f), \quad (20)$$

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 [45] and [50]–[53]); 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:

$$\phi_s^{\text{SM}} = -2\lambda^2\eta \approx -2^\circ, \quad (21)$$

which is very interesting for the search of signals of NP [53–55] (see Section 3.3).

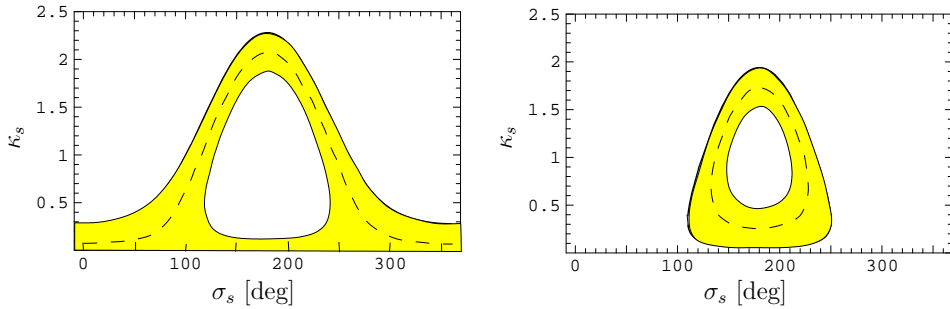


Figure 5: The allowed regions (yellow/grey) in the σ_s - κ_s plane. Left panel: JLQCD lattice results. Right panel: (HP+JL)QCD lattice results.

3.2 Hot News of 2006: Measurement of ΔM_s

For many years, only lower bounds on ΔM_s were available from the LEP (CERN) experiments and SLD (SLAC) [56]. In 2006, the value of ΔM_s could eventually be pinned down at the Tevatron [57]: the D0 collaboration reported a two-sided bound

$$17 \text{ ps}^{-1} < \Delta M_s < 21 \text{ ps}^{-1} \quad (90\% \text{ C.L.}), \quad (22)$$

corresponding to a 2.5σ signal at $\Delta M_s = 19 \text{ ps}^{-1}$ [58], and CDF announced the following result [59]:

$$\Delta M_s = [17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})] \text{ ps}^{-1}, \quad (23)$$

which corresponds to a signal at the 5σ level. These new experimental results have immediately triggered a lot of theoretical activity (see, e.g., [60, 61]).

Let us here follow once again the analysis performed in [36]. In order to explore the allowed region in NP parameter space that follows from the measurements at the Tevatron, we have just to make the substitution $d \rightarrow s$ in (14). Using the unitarity of the CKM matrix and the Wolfenstein expansion, the CKM factor entering the SM expression for ΔM_s takes the simple form

$$|V_{ts}^* V_{tb}| = |V_{cb}| [1 + \mathcal{O}(\lambda^2)]. \quad (24)$$

Consequently, in contrast to the SM analysis of ΔM_d , no information on γ and R_b is needed in this expression, which is an important advantage. The accuracy of the SM prediction of ΔM_s is hence limited by the hadronic parameter $f_{B_s} \hat{B}_{B_s}^{1/2}$. Recently, the HPQCD collaboration has reported the result $\Delta M_s^{\text{SM}} = 20.3(3.0)(0.8) \text{ ps}^{-1}$ [62], which lies between the $\Delta M_s^{\text{SM}}|_{\text{JLQCD}} = (16.1 \pm 2.8) \text{ ps}^{-1}$ and $\Delta M_s^{\text{SM}}|_{(\text{HP+JL})\text{QCD}} = (23.4 \pm 3.8) \text{ ps}^{-1}$ results entering Fig. 5. In this figure, which corresponds to Fig. 4, we show the allowed regions in the σ_s - κ_s plane. We see that the measurement of ΔM_s leaves ample space for the NP parameters σ_s and κ_s . The experimental errors are

already significantly smaller than the theoretical ones. Any more precise statement about the presence or absence of NP in the mass difference ΔM_s requires the reduction of the theoretical lattice QCD uncertainties.

As discussed in [36], the situation is not much better for constraints on NP through $\Delta M_s/\Delta M_d$. In the analysis of this ratio an $SU(3)$ -breaking parameter

$$\xi \equiv \frac{f_{B_s} \hat{B}_{B_s}^{1/2}}{f_{B_d} \hat{B}_{B_d}^{1/2}} \quad (25)$$

enters, which has a reduced theoretical uncertainty in comparison with the individual values of the $f_{B_q} \hat{B}_{B_q}^{1/2}$. Usually, $\Delta M_s/\Delta M_d$ is used for the determination of the side $R_t \propto |V_{td}/V_{cb}| = |V_{td}/V_{ts}| [1 + \mathcal{O}(\lambda^2)]$ of the UT. Alternatively, applying the unitarity of the CKM matrix, the following quantity can be determined:

$$\frac{\rho_s}{\rho_d} = \lambda^2 \underbrace{[1 - 2R_b \cos \gamma + R_b^2]}_{=R_t^2} [1 + \mathcal{O}(\lambda^2)] \frac{1}{\xi^2} \frac{M_{B_d}}{M_{B_s}} \frac{\Delta M_s}{\Delta M_d}, \quad (26)$$

where the ratio on the left-hand side equals 1 in the SM. For the current data, γ is the major source of uncertainty, in addition to the hadronic parameter ξ . Thanks to precision measurements of γ at LHCb, the CKM and lattice uncertainties should be of the same order of magnitude by 2010. However, unless the central values move dramatically, we would still get a result in agreement with 1 [36]. This case could correspond to the SM, but could also have NP contributions that enter in the same manner in ΔM_s and ΔM_d . Consequently, we would still be left with a rather unsatisfactory situation concerning the search for signals of NP through (26), even after a couple of years taking data at LHCb.

As in the case of the B_d -meson system discussed in Section 2.2, the allowed region in the $\sigma_s - \kappa_s$ 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 given by $B_s^0 \rightarrow J/\psi\phi$, which is our next topic.

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

This mode is the counterpart of the $B_d^0 \rightarrow J/\psi K_S$ 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 $B_d^0 \rightarrow J/\psi K_S$, since the final state of $B_s^0 \rightarrow J/\psi\phi$ contains two vector mesons and is, hence, an admixture of different CP eigenstates. Using the angular distribution of the $J/\psi[\rightarrow \ell^+\ell^-]\phi[\rightarrow K^+K^-]$ decay products, the CP eigenstates can be disentangled [63] and the time-dependent decay rates calculated [45, 53]. As in the case of $B_d^0 \rightarrow J/\psi K_S$, 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.

It is instructive to illustrate how this works by having a closer look at the one-angle distribution, which takes the following form [45, 53]:

$$\frac{d\Gamma(B_s^0(t) \rightarrow J/\psi\phi)}{d\cos\Theta} \propto (|A_0(t)|^2 + |A_{\parallel}(t)|^2) \frac{3}{8} (1 + \cos^2\Theta) + |A_{\perp}(t)|^2 \frac{3}{4} \sin^2\Theta. \quad (27)$$

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:

$$P_+(t) \equiv |A_0(t)|^2 + |A_{\parallel}(t)|^2, \quad P_-(t) \equiv |A_{\perp}(t)|^2, \quad (28)$$

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 \overline{B}_s^0 meson, the CP-conjugate quantities $\overline{P}_{\pm}(t)$ can be extracted as well. Using an *untagged* data sample, the untagged rates

$$P_{\pm}(t) + \overline{P}_{\pm}(t) \propto [(1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t}] \quad (29)$$

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

$$\frac{P_{\pm}(t) - \overline{P}_{\pm}(t)}{P_{\pm}(t) + \overline{P}_{\pm}(t)} = \pm \left[\frac{2 \sin(\Delta M_s t) \sin\phi_s}{(1 \pm \cos\phi_s)e^{+\Delta\Gamma_s t/2} + (1 \mp \cos\phi_s)e^{-\Delta\Gamma_s t/2}} \right]. \quad (30)$$

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

$$\phi_s = -2\lambda^2 R_b \sin\gamma + \phi_s^{\text{NP}} \approx -2^\circ + \phi_s^{\text{NP}} \approx \phi_s^{\text{NP}}. \quad (31)$$

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.

It should be emphasized that this avenue to search for NP signals does *not* have to rely on lattice QCD results, in contrast the analyses of ΔM_s discussed above.

These general features hold also for the full three-angle distribution [45, 53]: it is much more involved than the one-angle case, but provides also additional information through interference terms of the form

$$\text{Re}\{A_0^*(t)A_{\parallel}(t)\}, \quad \text{Im}\{A_f^*(t)A_{\perp}(t)\} \quad (f \in \{0, \parallel\}). \quad (32)$$

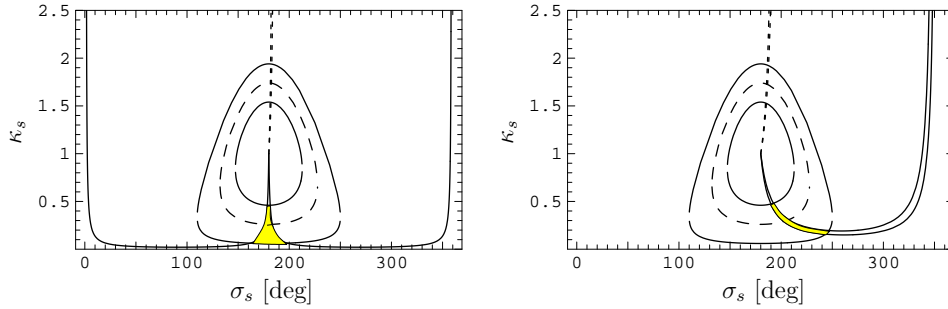


Figure 6: Illustration of the impact of measurements of CP violation in $B_s^0 \rightarrow J/\psi\phi$ for the two 2010 scenarios i) [left panel] and ii) [right panel] discussed in the text.

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 (19)) 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 $B_s^0 \rightarrow J/\psi\phi$ distribution [64]:

$$\phi_s = -0.79 \pm 0.56 \text{ (stat.)}_{-0.01}^{+0.14} \text{ (syst.)} = -(45 \pm 32_{-8}^{+1})^\circ. \quad (33)$$

This phase is therefore not yet stringently constrained. However, it will be very accessible at the LHC, where the following picture is expected with nominal one year data [49]: if ϕ_s takes its SM value, a 2σ measurement will be possible at LHCb (2fb^{-1}), ATLAS and CMS expect uncertainties of $\mathcal{O}(0.1)$ (10fb^{-1}) [65]. At some point, also in view of LHCb upgrade plans [66], we have to include hadronic penguin uncertainties. This can be done with the help of the $B_d^0 \rightarrow J/\psi\rho^0$ decay [67].

In order to illustrate the impact of measurements of CP violation in $B_s^0 \rightarrow J/\psi\phi$, let us discuss two scenarios for the year 2010 [36]:

- i) $(\sin\phi_s)_{\text{exp}} = -0.04 \pm 0.02$: this case corresponds to the SM;
- ii) $(\sin\phi_s)_{\text{exp}} = -0.20 \pm 0.02$: such a measurement would give a NP signal at the 10σ level. This scenario corresponds to a simple translation of the “tension” in the UT fits discussed above for $\kappa_s = \kappa_d$, $\sigma_s = \sigma_d$, and demonstrates the power of the B_s system to search for NP.

We see that it will be very challenging to establish NP effects in $B_s^0\text{-}\overline{B}_s^0$ mixing without new CP-violating contributions to this phenomenon. However, the data still leave a lot of space for such effects in specific scenarios (e.g. SUSY, extra Z' and little Higgs models [36, 60, 68]), which could be detected at the LHC. It will be very exciting to follow the corresponding measurements after the start of this new collider.

3.4 Further Benchmark Decays for LHCb

This experiment has a very rich physics programme (for an experimental overview, see [48]). 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 pure tree decays: $B_s^0 \rightarrow D_s^\mp K^\pm$ [$\sigma_\gamma \sim 14^\circ$], $B_d^0 \rightarrow D^0 K^*$ [$\sigma_\gamma \sim 8^\circ$], $B^\pm \rightarrow D^0 K^\pm$ [$\sigma_\gamma \sim 5^\circ$], where we have also indicated the expected sensitivities after one year of taking data [48]. These numbers should be compared with the current B -factory data, yielding

$$\gamma|_{D^{(*)}K^{(*)}} = \begin{cases} (62^{+38}_{-24})^\circ & \text{(CKMfitter)} \\ (82 \pm 20)^\circ & \text{(UTfit)}. \end{cases} \quad (34)$$

These extractions are very robust with respect to NP effects. On the other hand, γ can also be extracted from B -meson decays with penguin contributions: $B_s^0 \rightarrow K^+ K^-$ and $B_d^0 \rightarrow \pi^+ \pi^-$ [$\sigma_\gamma \sim 5^\circ$], $B_s^0 \rightarrow D_s^+ D_s^-$ and $B_d^0 \rightarrow D_d^+ D_d^-$. 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 $B_{s,d}^0 \rightarrow \mu^+ \mu^-$, $B_d^0 \rightarrow K^{*0} \mu^+ \mu^-$ and $B_s^0 \rightarrow \phi \mu^+ \mu^-$. In order to complement the studies of $B_d^0 \rightarrow \phi K_S$ at the B factories discussed in Section 2.1, $B_s^0 \rightarrow \phi \phi$ is a very interesting mode for LHCb.

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

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

The pure tree decays $B_s \rightarrow D_s^\pm K^\mp$ [69] and $B_d \rightarrow D^\pm \pi^\mp$ [70] can be treated on the same theoretical basis, and provide new strategies to determine γ [71]. Following this paper, we write these modes as $B_q \rightarrow D_q \bar{u}_q$. 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. $D_s \in \{D_s^+, D_s^{*+}, \dots\}$ and $u_s \in \{K^+, K^{*+}, \dots\}$, 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. $D_d \in \{D^+, D^{*+}, \dots\}$ and $u_d \in \{\pi^+, \rho^+, \dots\}$, 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 $B_q \rightarrow D_q \bar{u}_q$ rates, a theoretically clean determination of $\phi_q + \gamma$ is possible [69, 70]. 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 $B_s^0 \rightarrow D_s^+ K^-$ and $B_d^0 \rightarrow D^+ \pi^-$ decays, these problems can be solved [71]. This strategy exploits the fact that these transitions are related to each other through the U -spin symmetry of strong interactions,⁴ 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 [72], and are currently further refined.

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

The decay $B_s^0 \rightarrow K^+ K^-$ is a $\bar{b} \rightarrow \bar{s}$ transition, and involves tree and penguin amplitudes, as $B_d^0 \rightarrow \pi^+ \pi^-$ [73]. However, because of the different CKM structure, the latter topologies play actually the dominant rôle in $B_s^0 \rightarrow K^+ K^-$, whereas the major contribution to $B_d^0 \rightarrow \pi^+ \pi^-$ is due to the tree amplitude. In the SM, we may write

$$A(B_d^0 \rightarrow \pi^+ \pi^-) \propto [e^{i\gamma} - de^{i\theta}] \quad (35)$$

$$A(B_s^0 \rightarrow K^+ K^-) \propto \left[e^{i\gamma} + \left(\frac{1 - \lambda^2}{\lambda^2} \right) d' e^{i\theta'} \right], \quad (36)$$

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:

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^+ \pi^-) = G_1(d, \theta; \gamma), \quad \mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^+ \pi^-) = G_2(d, \theta; \gamma, \phi_d) \quad (37)$$

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \rightarrow K^+ K^-) = G'_1(d', \theta'; \gamma), \quad \mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \rightarrow K^+ K^-) = G'_2(d', \theta'; \gamma, \phi_s). \quad (38)$$

Since ϕ_d is already known (see (17)) and ϕ_s is negligibly small in the SM – or can be determined through $B_s^0 \rightarrow J/\psi \phi$ should CP-violating NP contributions to $B_s^0 - \bar{B}_s^0$ mixing make it sizeable – we may convert the measured values of $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^+ \pi^-)$, $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^+ \pi^-)$ and $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \rightarrow K^+ K^-)$, $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \rightarrow K^+ K^-)$ into *theoretically clean* contours in the γ - d and γ - d' planes, respectively. In Fig. 7, we show these contours (solid and dot-dashed) for an example, which is inspired by the current B -factory data [29].

A closer look at the corresponding Feynman diagrams shows that $B_d^0 \rightarrow \pi^+ \pi^-$ is actually related to $B_s^0 \rightarrow K^+ K^-$ through the interchange of all down and strange

⁴The U spin is an $SU(2)$ subgroup of the $SU(3)_F$ 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.

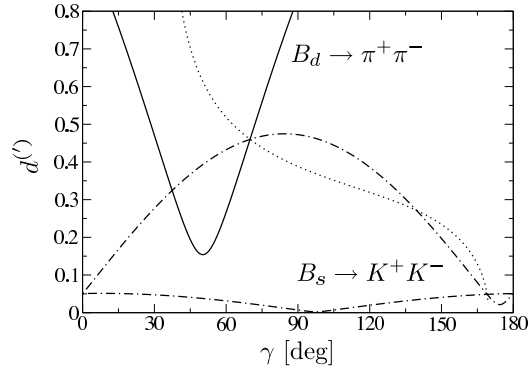


Figure 7: The contours in the γ - $d^{(\prime)}$ plane for an example with $d = d' = 0.46$, $\theta = \theta' = 155^\circ$, $\phi_d = 42.4^\circ$, $\phi_s = -2^\circ$, $\gamma = 70^\circ$, which corresponds to the CP asymmetries $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_d \rightarrow \pi^+\pi^-) = -0.24$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_d \rightarrow \pi^+\pi^-) = +0.59$, as well as $\mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \rightarrow K^+K^-) = +0.09$ and $\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \rightarrow K^+K^-) = -0.23$.

quarks. Consequently, each decay topology contributing to $B_d^0 \rightarrow \pi^+\pi^-$ has a counterpart in $B_s^0 \rightarrow K^+K^-$ 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 [73]:

$$d' = d, \quad \theta' = \theta. \quad (39)$$

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. 7, a twofold ambiguity arises from the solid and dot-dashed curves. However, as discussed in [73], it can be resolved with the help of the dotted contour, thereby leaving us with the “true” solution of $\gamma = 70^\circ$ in this case. Moreover, we may determine θ and θ' , which allow an interesting internal consistency check of the second U -spin relation in (39).

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 [74]. 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 [73] and Fig. 7, 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 (39) 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 [73].

As a by-product of the $B \rightarrow \pi\pi, \pi K$ strategy developed in [30], the observables of the $B_s^0 \rightarrow K^+K^-$ decay can be predicted in the SM. The most recent data yield

the following numbers [29]:

$$\mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \rightarrow K^+ K^-)|_{\text{SM}} = 0.093 \pm 0.015 \quad (40)$$

$$\mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \rightarrow K^+ K^-)|_{\text{SM}} = -0.234_{-0.014}^{+0.017}. \quad (41)$$

In the case of the CP-averaged branching ratio, an $SU(3)$ -breaking form-factor ratio enters the prediction, thereby increasing the uncertainties. Using the result of a QCD sum-rule calculation [75] yields the prediction [29]

$$\text{BR}(B_s \rightarrow K^+ K^-) = (28_{-5}^{+7}) \times 10^{-6}. \quad (42)$$

The $B_s^0 \rightarrow K^+ K^-$ mode was recently observed by CDF [76]; the most recent experimental update for the CP-averaged branching ratio reads as follows [77]:

$$\text{BR}(B_s \rightarrow K^+ K^-) = (24.4 \pm 1.4 \pm 4.6) \times 10^{-6}. \quad (43)$$

Within the uncertainties, (42) is in nice agreement with (43), which is another support of the working hypotheses underlying the $B \rightarrow \pi K$ analysis discussed in Section 2.1.

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

In the SM, these decays originate from Z penguins and box diagrams, and the corresponding low-energy effective Hamiltonian takes the following form [10]:

$$\mathcal{H}_{\text{eff}} = -\frac{G_{\text{F}}}{\sqrt{2}} \left[\frac{\alpha}{2\pi \sin^2 \Theta_{\text{W}}} \right] V_{tb}^* V_{tq} \eta_Y Y_0(x_t) (\bar{b}q)_{\text{V-A}} (\bar{\mu}\mu)_{\text{V-A}} + \text{h.c.}, \quad (44)$$

where α denotes the QED coupling and Θ_{W} is the Weinberg angle. The short-distance physics is described by $Y(x_t) \equiv \eta_Y Y_0(x_t)$, where $\eta_Y = 1.012$ is a perturbative QCD correction [78], and the Inami–Lim function $Y_0(x_t)$ describes the top-quark mass dependence. We observe that only the matrix element $\langle 0 | (\bar{b}q)_{\text{V-A}} | B_q^0 \rangle$ is required. Since here the vector-current piece vanishes, as the B_q^0 is a pseudoscalar meson, this 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 [78], the $B_q^0 \rightarrow \mu^+ \mu^-$ modes belong to the cleanest rare B decays.

Using also the data for the mass differences ΔM_q to reduce the hadronic uncertainties,⁵ the following SM predictions were obtained in [61]:

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) = (3.35 \pm 0.32) \times 10^{-9} \quad (45)$$

$$\text{BR}(B_d \rightarrow \mu^+ \mu^-) = (1.03 \pm 0.09) \times 10^{-10}. \quad (46)$$

⁵This input allows us to replace the decay constants f_{B_q} through the bag parameters \hat{B}_{B_q} .

The upper bounds (95% C.L.) from the CDF collaboration read as follows [79]:

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.0 \times 10^{-7}, \quad \text{BR}(B_d \rightarrow \mu^+ \mu^-) < 3.0 \times 10^{-8}, \quad (47)$$

while the D0 collaboration finds the following 90% C.L. (95% C.L.) upper limit [80]:

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-) < 1.9 \text{ (2.3)} \times 10^{-7}. \quad (48)$$

Consequently, there is still a long way to go within the SM. However, in this case, LHCb expects a 3σ observation for $B_s \rightarrow \mu^+ \mu^-$ with already nominal one year data (2 fb^{-1}) [49]. This decay is also very interesting for ATLAS and CMS, where detailed background studies are currently in progress [65]. Things could actually be much more exciting, as NP effects may significantly enhance $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$. For instance, in SUSY, this enhancement may be dramatic as $\text{BR} \sim (\tan \beta)^6$, where β is here the ratio of the two Higgs vacuum expectation values and not the UT angle β (for recent analyses, see, e.g., [81]), and in scenarios with a modified EW penguin sector a sizeable enhancement is possible (see, e.g., [30]).

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

The key observable for NP searches provided by this decay is the following forward–backward asymmetry:

$$A_{\text{FB}}(\hat{s}) = \frac{1}{d\Gamma/d\hat{s}} \left[\int_0^{+1} d(\cos \theta) \frac{d^2\Gamma}{d\hat{s} d(\cos \theta)} - \int_{-1}^0 d(\cos \theta) \frac{d^2\Gamma}{d\hat{s} d(\cos \theta)} \right]. \quad (49)$$

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

$$A_{\text{FB}}(\hat{s}_0)|_{\text{SM}} = 0, \quad (50)$$

as \hat{s}_0 is quite robust with respect to hadronic uncertainties (see, e.g., [82]). In SUSY extensions of the SM, $A_{\text{FB}}(\hat{s})$ could take opposite sign or take a dependence on \hat{s} without a zero point [83]. The current B -factory data for the inclusive $b \rightarrow s \ell^+ \ell^-$ 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 collect about 4400 decays/year, yielding $\Delta \hat{s}_0 = 0.06$ after one year, and ATLAS expects to collect about 1000 $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ decays per year [48]. Moreover, also other $b \rightarrow s \mu^+ \mu^-$ modes are currently under study, such as $\Lambda_b \rightarrow \Lambda \mu^+ \mu^-$ and $B_s^0 \rightarrow \phi \mu^+ \mu^-$.

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 emerge through the start of the LHC in the autumn of 2007, 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 at the LHC. The golden channel to search for 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. The two major lines of the broad research programme of LHCb are precision measurements of γ , which is a key ingredient for NP searches, and powerful analyses of various rare B decays, offering also sensitive probes for physics beyond the SM. The implementation of this programme will lead to much more stringent consistency checks of the KM mechanism, where also measurements of the rare kaon decays $K^+ \rightarrow \pi^+\nu\bar{\nu}$ and $K_L \rightarrow \pi^0\nu\bar{\nu}$ would be very welcome.

These studies of CP violation and flavour physics play also an outstanding rôle in the context with the major targets of the physics programme of the LHC. Here 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 should be a very fruitful interplay between these “direct” studies of NP and the “indirect” information provided by flavour physics, including the B -meson system, but also K , D and top physics as well as the flavour physics in the lepton sector.⁶ I have no doubts that the next years will be extremely exciting!

I am grateful to the workshop organizers for the invitation to this interesting meeting at such a nice location, and would also like to thank my co-authors for the enjoyable collaborations on topics addressed in this talk.

⁶This synergy is the topic of a CERN Workshop: <http://flavlhq.web.cern.ch/flavlhq/>.

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