In Pursuit of New Physics in the B System

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Abstract

The B-meson system offers interesting probes for the search of physics beyond the Standard Model. After addressing possible signals of new-physics contributions to the $B \to \phi K$ and $B \to \pi K$ decay amplitudes, we focus on the data for B_q^0–$\bar{B}_q^0$ mixing ($q \in \{d, s\}$), giving a critical discussion of their interpretation in terms of model-independent new-physics parameters. We address, in particular, the impact of the uncertainties of the relevant input parameters, discuss benchmarks for future precision measurements at the LHC, and explore the prospects for new CP-violating effects in the B_s-meson system, which could be detected at the LHC.

In Pursuit of New Physics in the B System

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1. SETTING THE STAGE

Thanks to the B factories, remarkable progress in the testing of the Kobayashi–Maskawa [1] mechanism of CP violation could be made over the recent years. The analyses of unitarity triangle of the Cabibbo–Kobayashi–Maskawa (CKM) matrix by the CKMfitter [2] and UTfit [3] collaborations show impressive global agreement with the picture of the Standard Model (SM), although it is no longer perfect, with some tension in the corresponding plots and correlations.

The theoretical tool for the description of weak decays and particle–antiparticle mixing is given by low-energy effective Hamiltonians. In this framework, the heavy degrees of freedom are "integrated out", and are encoded in perturbatively calculable Wilson coefficients $C_k(\mu)$. On the other hand, the long-distance physics resides in the hadronic matrix elements of local operators.

In this formalism, there are two possibilities for new physics (NP) to enter: (i) modification of $C_k(\mu = M_W) \to C_k^{\rm SM} + C_k^{\rm NP}$, where the NP pieces $C_k^{\rm NP}$ may involve new CP-violating phases; (ii) new operators may enter the stage: $\{Q_k\} \to \{Q_k^{\rm SM}, Q_l^{\rm NP}\}$, involving, in general, new sources of flavour and CP violation.

Many specific NP analyses can be found in the literature. In general, they suffer from the problem that the choice of the NP model is governed by personal "biases", and that the predictivity is inversely proportional to the number of NP parameters. However, the central problem for the resolution of NP effects in weak processes is related to hadronic uncertainties. Concerning non-leptonic B decays, interesting progress could recently be made, as discussed in the talks by A. Khodjamirian and Z. Ligeti, although the data show that the theoretical challenge remains.

Fortunately, the B-meson system offers various powerful strategies to circumvent the calculation of the hadronic matrix elements that can be implemented at the B factories and later on at the LHC. In these methods, amplitude relations (exact or derived from QCD flavour symmetries) or interference effects in decays of neutral B_q mesons ($q \in \{d, s\}$), which may lead to mixing-induced CP violation, are used [4]. Following these lines, a rich roadmap for the exploration of quark-flavour physics emerges, where popular avenues for NP to enter are given by effects at the decay amplitude level or in B_q^0–$\bar{B}_q^0$ mixing.

2. NEW PHYSICS IN AMPLITUDES

At the decay-amplitude level, NP effects are small if tree processes of the SM play the dominant role. On the other hand, there are potentially large effects in flavour-changing neutral-current processes through new particles in loop diagrams or new contributions at the tree level. In the following discussion, we address two possible signals for this kind of NP contributions: the $B \to \phi K$ and $B \to \pi K$ systems.

2.1. Challenging the SM through $B \to \phi K$

The $B_d^0 \to \phi K_S$ mode is a $\bar{b} \to \bar{s}$ penguin process, which is dominated by QCD penguins, but receives also significant electroweak (EW) penguin contributions. If we neglect corrections of $\mathcal{O}(\lambda^2)$ in the Wolfenstein parameter $\lambda \equiv |V_{us}| = 0.22$, the CKM structure of the $B_d^0 \to \phi K_S$ channel implies the following relations for the direct and mixing-induced CP asymmetries:

$$\mathcal{A}_{CP}^{dir}(B_d \to \phi K_S) = 0 \qquad (1)$$

$$\underbrace{\mathcal{A}_{CP}^{mix}(B_d \to \phi K_S)}_{\equiv -(\sin 2\beta)_{\phi K_S}} = \underbrace{\mathcal{A}_{CP}^{mix}(B_d \to \psi K_S)}_{\equiv -(\sin 2\beta)_{\psi K_S}}. \qquad (2)$$

The penguin decay $B_d^0 \to \phi K_S$ is a sensitive probe for NP, so that these relations may well be violated through its impact. During the last years, the BaBar and Belle data have converged, yielding now the following averages [5]:

$$\mathcal{A}_{CP}^{dir}(B_d \to \phi K_S) = -0.09 \pm 0.14 \qquad (3)$$

$$(\sin 2\beta)_{\phi K_S} = 0.47 \pm 0.19, \qquad (4)$$

so that $\mathcal{S}_{\phi K} \equiv (\sin 2\beta)_{\phi K_S} - (\sin 2\beta)_{\psi K_S} = -0.22 \pm 0.19$. The central value of this result could generically be accommodated in extensions of the SM, although the current experimental errors are too large to draw definite conclusions. In order to get the whole picture, also $B^\pm \to \phi K^\pm$ observables are required. Such an analysis shows that the $B \to \phi K$ data may indicate a modified EW penguin sector with a large CP-violating phase [4], complementing the "$B \to \pi K$ puzzle".

2.2. Challenging the SM through $B \to \pi K$

There is a long history of studies of the these decays, and since the year 2000, the B-factory data raise the question of a discrepancy with the SM. This "$B \to \pi K$ puzzle" is reflected by the observables of those decays that are significantly affected by EW penguins, and the following ratios are of central interest:

$$R_c \equiv 2 \left[\frac{BR(B^\pm \to \pi^0 K^\pm)}{BR(B^\pm \to \pi^\pm K)} \right] \qquad (5)$$

$$R_n \equiv \frac{1}{2} \left[\frac{BR(B_d \to \pi^\mp K^\pm)}{BR(B_d \to \pi^0 K)} \right]. \qquad (6)$$

Here the EW penguin effects enter through the decays with neutral pions, and are described both
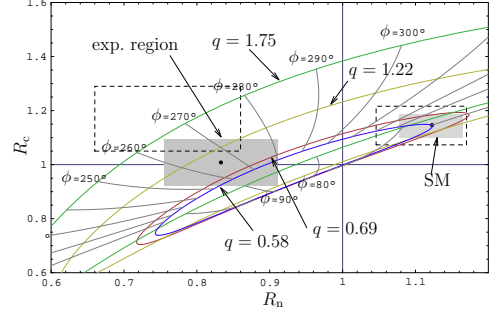

Figure 1. The situation in the R_n–R_c plane.

by a parameter q, which measures the strength of the EW penguins with respect to the tree topologies, and by a CP-violating phase ϕ. In the SM, this phase vanishes, and q can be calculated with the help of the $SU(3)$ flavour symmetry. In Ref. [6], where also a comprehensive guide to the $B \to \pi K$ literature can be found, a systematic strategy for the exploration of the $B \to \pi K$ system was developed. It uses the B-factory data for $B \to \pi\pi$ decays as the starting point, and determines then the hadronic $B \to \pi K$ parameters with the help of the $SU(3)$ flavour symmetry. The resulting situation can transparently be discussed in the R_n–R_c plane, as shown in Fig. 1 for the current data [7]: the shaded areas indicate the SM prediction and the experimental range, the lines show the theory predictions for the central values of the hadronic parameters and various values of q with $\phi \in [0°, 360°]$; the dashed rectangles represent the SM predictions and experimental ranges at the time of the original analysis of Ref. [6]. Although the central values of R_n and R_c have slightly moved towards each other, the puzzle is as prominent as ever. The experimental region can now be reached without an enhancement of q, but a large CP-violating phase ϕ of the order of $-90°$ is still required, although $\phi \sim +90°$ can also bring us rather close to the experimental range of R_n and R_c.

Following Ref. [6], also the CP asymmetries of the $B^\pm \to \pi^0 K^\pm$ and $B_d \to \pi^0 K_S$ modes can be predicted both in the SM and in the scenario of NP effects in the EW penguin sector. The mixing-induced CP asymmetry of the latter decay
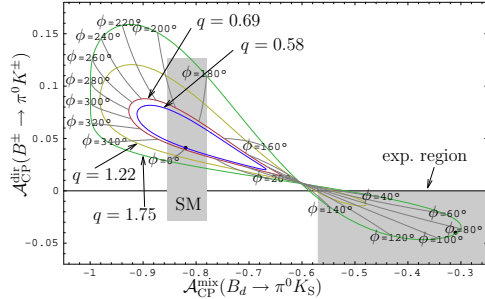
Figure 2. Illustration of the situation in the $\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B_d \to \pi^0 K_{\mathrm{S}})$–$\mathcal{A}_{\mathrm{CP}}^{\mathrm{mix}}(B^\pm \to \pi^0 K^\pm)$ plane.

has recently received a lot of attention, as the current B-factory data give an experimental value of -0.38 ± 0.26 for the quantity

$$\Delta S \equiv (\sin 2\beta)_{\pi^0 K_{\mathrm{S}}} - (\sin 2\beta)_{\psi K_{\mathrm{S}}}. \qquad (7)$$

In the strategy described above, this difference is predicted to be *positive* in the SM, and in the ballpark of 0.10–0.15. Interestingly, the best values for (q, ϕ) that are implied by the measurements of $R_{\mathrm{n,c}}$ make the disagreement of ΔS with the data even larger than in the SM. However, also values of (q, ϕ) can be found for which ΔS could be smaller than in the SM or even reverse the sign. This happens in particular for $\phi \sim +90°$, i.e. if the CP-violating NP phase flips its sign. In this case, also the central value of $(\sin 2\beta)_{\phi K_{\mathrm{S}}}$ in (4) could be straightforwardly accommodated in this scenario of NP [4], and could in fact be another manifestation of a modified EW penguin sector with new sources for CP violation.

Another fruitful testing ground for this scenario is given by the interplay with rare decays such as $K^+ \to \pi^+ \nu\bar{\nu}$, $K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}$ and $B_{s,d} \to \mu^+\mu^-$, which are sensitive probes of Z penguins. As discussed in Ref. [7], the corresponding observables show specific patterns for NP scenarios satisfying the B-factory constraints from $B \to X_s \ell^+\ell^-$ decays, thereby allowing us to pin down a modified EW penguin sector. In these explorations, $K_{\mathrm{L}} \to \pi^0 \nu\bar{\nu}$ turns out to be particularly interesting, as its branching ratio may be dramatically enhanced. Further details of this strategy are discussed in the talk by F. Schwab.

3. NEW PHYSICS IN B MIXING

While B_d^0–$\bar{B}_d^0$ mixing is well established and $\Delta M_d = (0.507 \pm 0.004)\,\mathrm{ps}^{-1}$ known with impressive experimental accuracy, only lower bounds on ΔM_s were available, for many years, from the LEP (CERN) experiments and SLD (SLAC). This spring, ΔM_s could eventually be pinned down at the Tevatron: D0 reported a two-sided bound $17\,\mathrm{ps}^{-1} < \Delta M_s < 21\,\mathrm{ps}^{-1}$ (90% C.L.), corresponding to a $2.5\,\sigma$ signal at $\Delta M_s = 19\,\mathrm{ps}^{-1}$ [8], and CDF announced the following result [9]:

$$\Delta M_s = \left[17.31^{+0.33}_{-0.18}(\mathrm{stat}) \pm 0.07(\mathrm{syst})\right]\,\mathrm{ps}^{-1}. \quad (8)$$

These new measurements have already triggered considerable theoretical activity; in the following discussion, we shall focus on the analysis of Ref. [10], where also a comprehensive guide to the recent literature on ΔM_s can be found.

3.1. A Closer Look at B_q^0–$\bar{B}_q^0$ Mixing

If we use an effective Hamiltonian to write

$$\langle B_q^0 | \mathcal{H}_{\mathrm{eff}}^{\Delta B=2} | \bar{B}_q^0 \rangle = 2 M_{B_q} M_{12}^q, \qquad (9)$$

the mass difference ΔM_q and the CP-violating mixing phase ϕ_q take the forms

$$\Delta M_q = 2|M_{12}^q| \quad \text{and} \quad \phi_q = \arg(M_{12}^q). \qquad (10)$$

In the SM, B_q^0–$\bar{B}_q^0$ mixing arises from box diagrams with top-quark exchanges, yielding

$$M_{12}^{q,\mathrm{SM}} = \frac{G_{\mathrm{F}}^2 M_W^2}{12\pi^2} M_{B_q} (V_{tq}^* V_{tb})^2$$
$$\times S_0(x_t) \hat{\eta}^B \hat{B}_{B_q} f_{B_q}^2. \qquad (11)$$

The phases of the CKM factors imply

$$\phi_d^{\mathrm{SM}} = 2\beta, \quad \phi_s^{\mathrm{SM}} = -2\lambda^2 \eta. \qquad (12)$$

In order to determine $|V_{tq}^* V_{tb}|$, which are required for the SM predictions of ΔM_q, we use the unitarity of the CKM matrix to express them in terms of $|V_{cb}|$, the side $R_b \propto |V_{ub}/V_{cb}|$ of the unitarity triangle, and its angle γ. These quantities can be determined from tree-level processes, which are very robust with respect to NP effects. While $|V_{cb}| = (42.0 \pm 0.7) \times 10^{-3}$, the situation of

$$|V_{ub}|_{\mathrm{incl}} = (4.4 \pm 0.3) \times 10^{-3} \qquad (13)$$
$$|V_{ub}|_{\mathrm{excl}} = (3.8 \pm 0.6) \times 10^{-3} \qquad (14)$$

has to be clarified since inclusive and exclusive $b \to u\ell\bar{\nu}_\ell$ processes show a discrepancy at the 1σ level. For a benchmark scenario of the year 2010, we assume that the inclusive value will be confirmed, with an error of $\pm 0.2 \times 10^{-3}$. Concerning γ, we use a value of $(65 \pm 20)°$, and assume that it will move to $(70 \pm 5)°$ in 2010 thanks to LHCb.

In (11), the short-distance physics is described by the Inami–Lim function $S_0(x_t \equiv m_t^2/M_W^2)$ and the perturbative QCD factor $\hat{\eta}^B$, which are known quantities. On the other hand, the long-distance physics is encoded in $\hat{B}_{B_q} f_{B_q}^2$, which can be determined through lattice QCD studies. Here the front runners are unquenched calculations with 2 or 3 dynamical quarks and Wilson or staggered light quarks, respectively. Despite tremendous progress, the results still suffer from several uncertainties. For the following analysis, we use two sets of parameters from the JLQCD and HPQCD collaborations:

$$\left.\frac{f_{B_d}\hat{B}_{B_d}^{1/2}}{\text{GeV}}\right|_{\text{JLQCD}} = 0.215 \pm 0.019^{+0}_{-0.023} \quad (15)$$

$$\left.\frac{f_{B_s}\hat{B}_{B_s}^{1/2}}{\text{GeV}}\right|_{\text{JLQCD}} = 0.245 \pm 0.021^{+0.003}_{-0.002} \quad (16)$$

$$\xi_{\text{JLQCD}} = 1.14 \pm 0.06^{+0.13}_{-0}, \quad (17)$$

which were obtained for two flavours of dynamical light Wilson quarks, and

$$\left.\frac{f_{B_d}\hat{B}_{B_d}^{1/2}}{\text{GeV}}\right|_{\text{(HP+JL)QCD}} = 0.244 \pm 0.026 \quad (18)$$

$$\left.\frac{f_{B_s}\hat{B}_{B_s}^{1/2}}{\text{GeV}}\right|_{\text{(HP+JL)QCD}} = 0.295 \pm 0.036 \quad (19)$$

$$\xi_{\text{(HP+JL)QCD}} = 1.210^{+0.047}_{-0.035}, \quad (20)$$

where f_{B_q} comes from HPQCD (3 dynamical flavours) and $\hat{B}_{B_q}$ from JLQCD as no value for this parameter is available from the former collaboration; as usual, $\xi \equiv f_{B_s}\hat{B}_{B_s}^{1/2}/(f_{B_d}\hat{B}_{B_d}^{1/2})$. For our 2010 scenario, we assume the set of the numerical values in (18)–(20).

3.2. Space for NP in the B_d System

In the presence of NP, M_{12}^d can be written in the following model-independent way:

$$M_{12}^d = M_{12}^{d,\text{SM}}\left[1 + \kappa_d e^{i\sigma_d}\right]. \quad (21)$$

If we introduce a parameter ρ_d through

$$\rho_d \equiv \left|\frac{\Delta M_d}{\Delta M_d^{\text{SM}}}\right| = \sqrt{1 + 2\kappa_d \cos\sigma_d + \kappa_d^2}, \quad (22)$$

the experimental result for ΔM_d and the theoretical prediction ΔM_d^{SM} allow us to determine κ_d as a function of the CP-violating phase σ_d, i.e. to constrain the space of the NP parameters. Using the input parameters as specified above with $\Delta M_d = (0.507 \pm 0.004)\,\text{ps}^{-1}$, we obtain

$$\rho_d|_{\text{JLQCD}} = 0.97 \pm 0.33^{-0.17}_{+0.26} \quad (23)$$

$$\rho_d|_{\text{(HP+JL)QCD}} = 0.75 \pm 0.25 \pm 0.16, \quad (24)$$

where the first and second errors are due to γ (and a small extent to R_b) and $f_{B_d}\hat{B}_{B_d}^{1/2}$, respectively.

Further constraints are implied by the experimental value of the mixing phase $\phi_d = \phi_d^{\text{SM}} + \phi_d^{\text{NP}}$, which allows us also to determine contours in the σ_d–κ_d plane, as shown in Ref. [10]. Interestingly, it turns out that κ_d is bounded from below for any value of $\phi_d^{\text{NP}} \neq 0$. For example, even a small phase $|\phi_d^{\text{NP}}| = 10°$ implies a clean lower bound of $\kappa_d \geq 0.17$, i.e. NP contributions of at most 17%. For the implementation of these constraints, the NP phase ϕ_d^{NP} has to be determined. To this end, we use the data for the mixing-induced CP violation in $B_d^0 \to J/\psi K_{\text{S}}$ and similar modes, which imply $\phi_d = 2\beta + \phi_d^{\text{NP}} = (43.4 \pm 2.5)°$. Comparing, on the other hand, with the "true" value of 2β following from γ and R_b, we obtain

$$\phi_d^{\text{NP}}|_{\text{incl}} = -(10.1 \pm 4.6)° \quad (25)$$

$$\phi_d^{\text{NP}}|_{\text{excl}} = -(2.5 \pm 8.0)° \quad (26)$$

for the values of $|V_{ub}|$ given in (13) and (14). These values are very stable with respect to γ, i.e. the CKM parameter dependence is complementary to (23) and (24). In Figs. 3 and 4, we show the allowed regions in NP parameter space arising form ΔM_d (hills and closed curves) and ϕ_d. We see that the impact of the information on CP violation is dramatic. On the other hand, values of κ_d as large as 0.5 are still allowed.
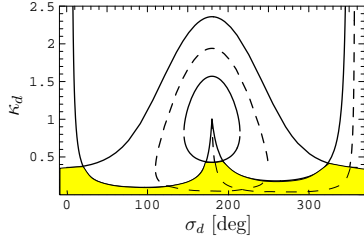
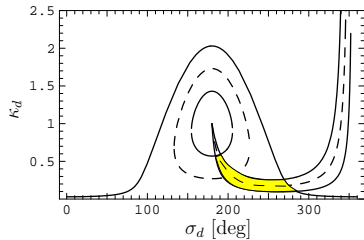Figure 3. Currently allowed region in the σ_d–κ_d plane for the JLQCD results and $\phi_d^{\mathrm{NP}}|_{\mathrm{excl}}$.

Figure 5. Currently allowed region in the σ_s–κ_s plane following from the ΔM_s measurement for the JLQCD results.

Figure 4. Currently allowed region in the σ_d–κ_d plane for the (HP+JL)QCD results and $\phi_d^{\mathrm{NP}}|_{\mathrm{incl}}$.
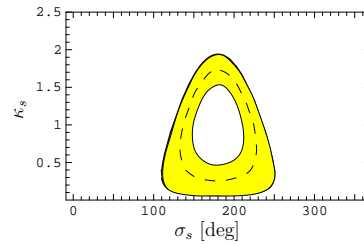
Figure 6. Currently allowed region in the σ_s–κ_s plane following from the ΔM_s measurement for the (HP+JL)QCD results.

3.3. Space for NP in the B_s System

The analysis of the B_s-meson system can be done in analogy to its B_d counterpart, with straightforward replacements of parameters. The relevant CKM factor can be written, with the help of the unitarity of the CKM matrix, as $|V_{ts}^* V_{tb}| = |V_{cb}| \left[1 + \mathcal{O}(\lambda^2)\right]$. We then obtain

$$\rho_s|_{\mathrm{JLQCD}} = 1.08^{+0.03}_{-0.01} \pm 0.19 \qquad (27)$$

$$\rho_s|_{\mathrm{(HP+JL)QCD}} = 0.74^{+0.02}_{-0.01} \pm 0.18, \qquad (28)$$

where the first and second errors have experimental and theoretical origins, respectively. Consequently, the SM prediction using JLQCD is in perfect agreement with the measured value, while the (HP+JL)QCD result is 1.5σ larger. A similar pattern, though at the 1σ level, is interestingly also present in (23) and (24). The resulting situation in the σ_s–κ_s plane is shown in Figs. 5 and 6. We observe that the ΔM_s measurement still leaves a lot of space for the NP parameters.

In the literature, the ratio $\Delta M_s/\Delta M_d$ is often considered. Here the $SU(3)$-breaking parameter ξ enters, which has a reduced theoretical uncer-
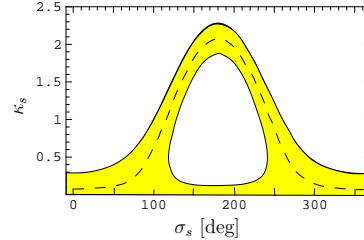
tainty as compared to $f_{B_q} \hat{B}_{B_q}^{1/2}$. Usually, the ratio $|V_{td}/V_{ts}|$ is determined along these lines. If we apply the unitarity of the CKM matrix, we may, alternatively, determine ρ_s/ρ_d through $\Delta M_s/\Delta M_d$. Because of the currently large range for γ, ρ_s/ρ_d is not stringently constrained, although the central values are nicely consistent with 1 for the JLQCD and (HP+JL)QCD parameters. Even in our 2010 scenario, yielding

$$\left.\frac{\rho_s}{\rho_d}\right|_{2010} = 1.07 \pm 0.09(\gamma, R_b)^{+0.06}_{-0.08}(\xi), \qquad (29)$$

a stringent test of whether $\rho_s/\rho_d = 1$ would still not be possible.

The golden decay to search for NP effects in B_s^0–$\bar{B}_s^0$ mixing is $B_s^0 \to J/\psi\phi$, the B_s counterpart of $B_d^0 \to J/\psi K_{\mathrm{S}}$, allowing us to extract

$$\sin\phi_s = \sin(-2\lambda^2 R_b \sin\gamma + \phi_s^{\mathrm{NP}}) \overset{\mathrm{SM}}{\approx} -0.03 \quad (30)$$

through mixing-induced CP violation in the time-dependent angular distribution of its decay products. This decay is very accessible at the LHC.
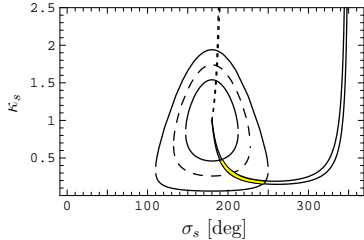
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Figure 7. Impact of a CP violation measurement on the σ_s–κ_s plane in our 2010 scenario.

As was noted in Ref. [10], even a small NP phase $\phi_s^{\mathrm{NP}} \sim -10°$ would yield a CP asymmetry at the -20% level, so that the possible signal of NP in B_d mixing could be greatly magnified. Assuming a measurement of $\sin\phi_s = -0.20 \pm 0.02$ at the LHC for our 2010 scenario, we arrive at the situation shown in Fig. 7. Here the dotted line refers to $\cos\phi_s < 0$, which can also be excluded through further measurements. We see that it will be very challenging to establish NP without new CP-violating effects. On the other hand, Fig. 7 still corresponds to $0.2 \lesssim \kappa_s \lesssim 0.5$; a determination of κ_s with 10% accuracy would require the reduction of the error of $f_{B_s}\hat{B}_{B_s}^{1/2}$ to 10%, i.e. an improvement of the current (HP+JL)QCD lattice results by a factor of 2.

3.4. Impact of ΔM_s on NP Scenarios

Since ϕ_s is still essentially unconstrained, large CP-violating NP effects in B_s^0–$\bar{B}_s^0$ mixing may show up at the LHC. Such effects arise in fact in various extensions of the SM. Let us consider a model with an extra Z' boson as an example, assuming that Z–Z' mixing is negligible and that the Z' has flavour non-diagonal couplings only to left-handed quarks, which means that its effect is described by only one complex parameter:

$$\rho_L e^{i\phi_L} \equiv \frac{g' M_Z}{g M_{Z'}} B_{sb}^L \sim 10^{-3}. \qquad (31)$$

Translating the κ_s–σ_s constraints into the ρ_L–ϕ_L space, $\kappa_s < 2.5$ implies $\rho_L < 2.6 \times 10^{-3}$, yielding $1.5\,\mathrm{TeV}(g'/g)|B_{sb}^L/V_{ts}| < M_{Z'}$, while $\phi_L \leftrightarrow \sigma_s$ leaves ϕ_L still essentially unconstrained. Also in SUSY scenarios, a lot of space for CP-violating NP effects in B_s^0–$\bar{B}_s^0$ mixing is left, as discussed further by V. Lubicz and L. Silvestrini.

4. CONCLUSIONS AND OUTLOOK

The B-decay data agree globally with the Kobayashi–Maskawa picture, but we have also hints for discrepancies. These have to be studied further, and could be first signals of NP requiring *new* sources of CP violation. The recent measurement of ΔM_s at the Tevatron triggered quite some excitement. It still leaves a lot of space for NP, where a smoking-gun signal would be given by new CP violation in $B_s^0 \to J/\psi\phi$ and similar modes, which are very accessible at the LHC.

At this new collider, also exciting perspectives for B-physics studies will emerge, in particular through the full exploitation of the B_s physics potential, various determinations of γ, and explorations of rare decays such as $B_{s,d} \to \mu^+\mu^-$.

Further precision B-decay measurements could be performed in the next decade at an e^+e^- super-B factory. Since also a nice synergy between flavour physics and the direct NP searches at ATLAS and CMS is expected, I have no doubts that exciting years are ahead of us!

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