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## PROBING NEW PHYSICS THROUGH $B_s$ MIXING

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I discuss the interpretation of the recent experimental data on  $B_s$  mixing in terms of model-independent new-physics parameters.

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## 1 Introduction

One of the most promising ways to detect the effects of new physics (NP) on  $B$  decays is to look for deviations of flavour-changing neutral-current (FCNC) processes from their Standard Model (SM) predictions; FCNC processes only occur at the loop-level in the SM and hence are particularly sensitive to NP virtual particles and interactions. A prominent example that has received extensive experimental and theoretical attention is  $B_q^0-\bar{B}_q^0$  mixing ( $q \in \{d, s\}$ ), which, in the SM, is due to box diagrams with  $W$ -boson and up-type quark exchange. In the language of effective field theory, these diagrams induce an effective local Hamiltonian, which causes  $B_q^0$  and  $\bar{B}_q^0$  mesons to mix and generates a  $\Delta B = 2$  transition:

$$\langle B_q^0 | \mathcal{H}_{\text{eff}}^{\Delta B=2} | \bar{B}_q^0 \rangle = 2M_{B_q} M_{12}^q, \quad (1)$$

where  $M_{B_q}$  is the  $B_q$ -meson mass. Thanks to  $B_q^0-\bar{B}_q^0$  mixing, an initially present  $B_q^0$  state evolves into a time-dependent linear combination of  $B_q^0$  and  $\bar{B}_q^0$  flavour states. The oscillation frequency of this phenomenon is characterized by the mass difference of the ‘‘heavy’’ and ‘‘light’’ mass eigenstates,

$$\Delta M_q \equiv M_{\text{H}}^q - M_{\text{L}}^q = 2|M_{12}^q|, \quad (2)$$

and the CP-violating mixing phase

$$\phi_q = \arg M_{12}^q, \quad (3)$$

which enters mixing-induced CP violation. While the mass difference in the  $B_d$  system has been known for a long time,  $\Delta M_s$  has only been measured in 2006, by the CDF collaboration, with the result <sup>1</sup>

$$\Delta M_s = [17.77 \pm 0.10(\text{stat}) \pm 0.07(\text{syst})]\text{ps}^{-1}. \quad (4)$$

In Ref. <sup>2</sup>, we have discussed the impact of this result on a model-independent parametrisation of NP in the  $B_q$  system. In the meantime, experimental information has become available also for the mixing phase in the  $B_s$  system <sup>3,4,5,6</sup>. In these proceedings, we update the constraints obtained on NP in the  $B_s$  system by including this additional information.

In the SM,  $M_{12}^q$  is given by

$$M_{12}^{q,\text{SM}} = \frac{G_{\text{F}}^2 M_W^2}{12\pi^2} M_{B_q} \hat{\eta}^B \hat{B}_{B_q} f_{B_q}^2 (V_{tq}^* V_{tb})^2 S_0(x_t), \quad (5)$$

where  $G_{\text{F}}$  is Fermi’s constant,  $M_W$  the mass of the  $W$  boson,  $\hat{\eta}^B = 0.551$  a short-distance QCD correction (which is the same for the  $B_d^0$  and  $B_s^0$  systems) <sup>7</sup>, whereas the bag parameter  $\hat{B}_{B_q}$  and the decay constant  $f_{B_q}$  are non-perturbative quantities.  $V_{tq}$  and  $V_{tb}$  are elements of the Cabibbo–Kobayashi–Maskawa (CKM) matrix, and  $S_0(x_t \equiv \bar{m}_t^2/M_W^2) = 2.32 \pm 0.04$  with  $\bar{m}_t(m_t) = (163.4 \pm 1.7)$  GeV, Ref. <sup>8</sup>, describes the  $t$ -quark mass dependence of the box diagram with internal  $t$ -quark exchange; the contributions of internal  $c$  and  $u$  quarks are suppressed by  $(m_{u,c}/M_W)^2$ , by virtue of the GIM mechanism. Thanks to the suppression of light-quark loops,  $M_{12}^q$  is dominated by short-distance processes and sensitive to NP.

In the SM, the mixing phase in the  $B_s$  system is given by

$$\phi_s^{\text{SM}} = -2\lambda^2 R_b \sin \gamma \approx -2^\circ, \quad (6)$$

where  $\gamma$  is one of the angles of the unitarity triangle (UT),  $\lambda$  is the Wolfenstein parameter and

$$R_b = \left(1 - \frac{\lambda^2}{2}\right) \frac{1}{\lambda} \left| \frac{V_{ub}}{V_{cb}} \right|. \quad (7)$$

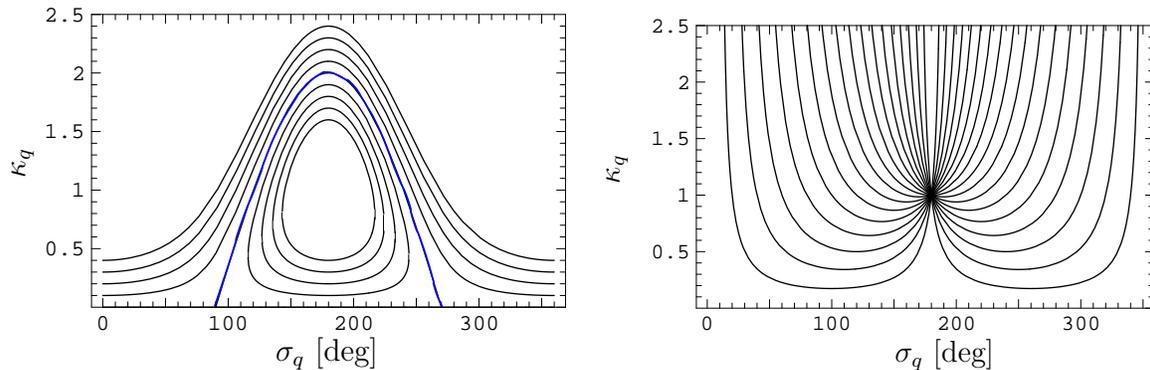


Figure 1: Lines of constant  $\rho_s$  (left) and constant  $\phi_s^{\text{NP}}$  (right) in the  $\sigma_s$ - $\kappa_s$  plane. Blue line:  $\rho_s \equiv 1$ .

Up-to-date values of  $\gamma$  from various sources can be found in Ref. <sup>9</sup>, whereas  $|V_{ub}|$  and  $|V_{cb}|$  can be found in Refs. <sup>10</sup> and <sup>11</sup>, respectively. The corresponding results from global fits can be found in Ref. <sup>12</sup>.

In the presence of NP, the matrix element  $M_{12}^q$  can be written, in a model-independent way, as

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

where the real parameter  $\kappa_q \geq 0$  measures the “strength” of the NP contribution with respect to the SM, whereas  $\sigma_q$  is a new CP-violating phase. Relating  $\kappa_s$  and  $\sigma_s$  to  $\Delta M_s$ , one has

$$\rho_s \equiv \left| \frac{\Delta M_s}{\Delta M_s^{\text{SM}}} \right| = \sqrt{1 + 2\kappa_s \cos \sigma_s + \kappa_s^2}. \quad (8)$$

The lines of  $\rho_s = \text{const.}$  in the  $\sigma_s$ - $\kappa_s$  plane are shown in Fig. 1. The blue line  $\rho_s = 1$  illustrates that even if the experimental value of  $\Delta M_s$  coincides with the SM expectation, it is wrong to conclude that there is no NP in  $B_s$  mixing – in fact, in this case the NP amplitude can be larger than the SM amplitude, i.e.  $\kappa_s > 1$ , if SM and NP contributions differ by a phase  $\sigma_s$  between  $120^\circ$  and  $240^\circ$ .

In order to obtain  $\rho_s$  from the experimental result (4), one has to determine  $\Delta M_s^{\text{SM}}$ . In addition to the input parameters listed after (5), one also needs the CKM matrix elements  $|V_{ts}^* V_{tb}|$  and the hadronic matrix element  $\hat{B}_{B_s} f_{B_s}^2$ . The former is accurately known in terms of  $|V_{cb}|$  and  $\lambda$  and reads <sup>2</sup>

$$|V_{ts}^* V_{tb}| = \left\{ 1 - \frac{1}{2} (1 - 2R_b \cos \gamma) \lambda^2 + \mathcal{O}(\lambda^4) \right\} |V_{cb}^* V_{tb}| = (41.3 \pm 0.7) \times 10^{-3}. \quad (9)$$

The hadronic matrix element  $\hat{B}_{B_s} f_{B_s}^2$  has been the subject of numerous lattice calculations, both quenched and unquenched, using various lattice actions and implementations of both heavy and light quarks. The current front runners are unquenched calculations with 2 and 3 dynamical quarks, respectively, and Wilson or staggered light quarks. Despite tremendous progress in recent years, the results still suffer from a variety of uncertainties which is important to keep in mind when interpreting and using lattice results. The most recent (unquenched) simulation by the JLQCD collaboration <sup>13</sup>, with non-relativistic  $b$  quarks and two flavours of dynamical light (Wilson) quarks, yields

$$f_{B_s} \hat{B}_{B_s}^{1/2} \Big|_{\text{JLQCD}} = (0.245 \pm 0.021_{-0.002}^{+0.003}) \text{ GeV}, \quad (10)$$

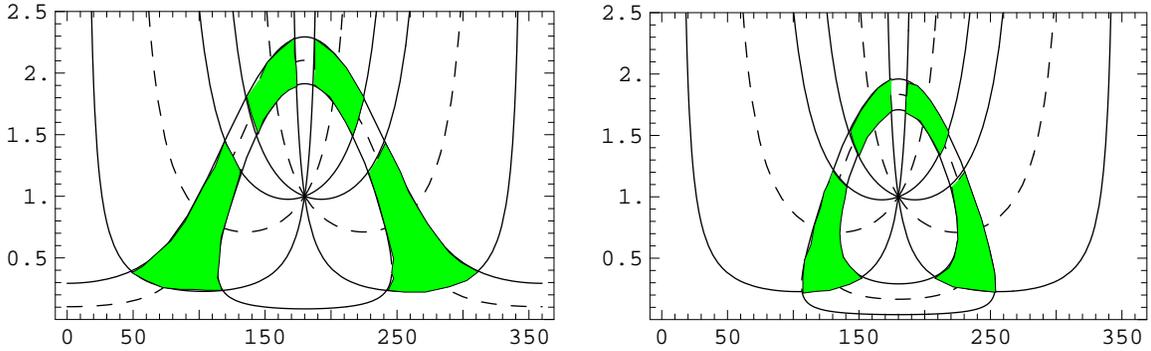


Figure 2: Allowed  $1\sigma$  regions (green/grey) in the  $\sigma_s$ - $\kappa_s$  plane. Left panel: JLQCD lattice results, Eq. (10). Right panel: HPQCD lattice results, Eq. (11). The four allowed regions correspond to the fourfold ambiguity in the determination of  $\phi_s^{\text{NP}}$  from data.

where the first error includes uncertainties from statistics and various systematics, whereas the second, asymmetric error comes from the chiral extrapolation from unphysically large light-quark masses to the  $s$ -quark mass.

More recently, (unquenched) simulations with three dynamical flavours have become possible using staggered quark actions. The HPQCD collaboration obtains<sup>14</sup>

$$f_{B_s} \hat{B}_{B_s}^{1/2} \Big|_{\text{HPQCD}} = (0.281 \pm 0.021) \text{ GeV}. \quad (11)$$

where all errors are added in quadrature.

Although we shall use both (10) and (11) in our analysis, we would like to stress that the errors are likely to be optimistic. There is the question of discretisation effects (JLQCD uses data obtained at only one lattice spacing) and the renormalisation of matrix elements (for lattice actions without chiral symmetry, the axial vector current is not conserved and  $f_{B_q}$  needs to be renormalised), which some argue should be done in a non-perturbative way<sup>15</sup>. Simulations with staggered quarks also face potential problems with unitarity, locality and an odd number of flavours (see, for instance, Ref.<sup>16</sup>). A confirmation of the HPQCD results by simulations using the (theoretically better understood) Wilson action with small quark masses will certainly be highly welcome.

With the above input parameters, one finds

$$\begin{aligned} \Delta M_s |_{\text{JLQCD}} &= (16.1 \pm 2.8) \text{ ps}^{-1}, & \Delta M_s |_{\text{HPQCD}} &= (21.3 \pm 3.2) \text{ ps}^{-1}, \\ \rho_s |_{\text{JLQCD}} &= 1.10 \pm 0.19, & \rho_s |_{\text{HPQCD}} &= 0.83 \pm 0.13. \end{aligned} \quad (12)$$

The corresponding constraints in the  $\sigma_s$ - $\kappa_s$  plane are shown in Fig. 2.

In order to further constrain the NP parameter space, one needs to include information on the NP CP-violating phase  $\phi_s^{\text{NP}}$ . At the time Ref.<sup>2</sup> was written, no such information was available. In the meantime,  $\phi_s^{\text{NP}}$  has been constrained from measurements by the D0 collaboration, of the CP-asymmetry in flavour-specific (semileptonic)  $B_s$  decays<sup>3</sup> and the time-dependent angular analysis of untagged  $B_s \rightarrow J/\psi\phi$  decays<sup>4</sup>. These measurements can be translated, using supplementary information on the semileptonic asymmetry in  $B_d$  decays, in the following results for  $\Delta\Gamma_s$  and  $\phi_s$ :<sup>5,6</sup>

$$\Delta\Gamma_s \equiv \Gamma_L - \Gamma_H = (0.13 \pm 0.09) \text{ ps}^{-1}, \quad \phi_s = -0.70_{-0.39}^{+0.47}. \quad (13)$$

These results actually are determined only up to a 4-fold ambiguity for  $\phi_s$  and the sign of  $\Delta\Gamma_s$ :  $\phi_s \rightarrow \pm\phi_s$  for  $\Delta\Gamma_s > 0$  and  $\phi_s \rightarrow \pm(\pi - \phi_s)$  for  $\Delta\Gamma_s < 0$ . As the SM prediction for  $\phi_s$  is close

to  $0^a$ , we can identify this result with  $\phi_s^{\text{NP}}$ . The combined constraints posed by  $\Delta M_s$  and  $\phi_s^{\text{NP}}$  on the new-physics parameters  $\kappa_s, \sigma_s$  are shown as green areas in Fig. 2, including the 4-fold ambiguity. It is evident that at present the experimental error of  $\phi_s^{\text{NP}}$  is too large to considerably reduce the area constrained by  $\Delta M_s$  alone. The ambiguity can be reduced to a 2-fold one if some theory-input about the signs of  $\cos \delta_{1,2}$  is used, where  $\delta_{1,2}$  are the strong phases involved in the angular analysis of  $B_s \rightarrow J/\psi\phi$ , Ref. <sup>17</sup>. At LHCb, it will be possible to study the time-dependence of flavour-tagged  $B_s$  decays, which gives access to the mixing-induced asymmetry and allows one to reduce the number of discrete ambiguities without input from theory.

The above results can be compared with the following recent theory prediction for  $\Delta\Gamma_s$ , which is based on an improved operator product expansion of  $\Gamma_{12}^s$ , the off-diagonal element of the  $B_s$  decay matrix: <sup>18</sup>

$$\Delta\Gamma_s^{\text{th}} = (0.096 \pm 0.039) \text{ps}^{-1}, \quad (14)$$

which agrees with the experimental result (13) within errors. Ref. <sup>18</sup> also contains a detailed discussion of the theoretical predictions for flavour-specific CP asymmetries both in the  $B_d$  and  $B_s$  system and the constraints on NP in  $B_s$  mixing extracted from all available experimental data.

Let us conclude with a few remarks concerning the prospects for the search for NP through  $B_s^0-\bar{B}_s^0$  mixing at the LHC. This task will be very challenging if essentially no CP-violating effects will be found in  $B_s \rightarrow J/\psi\phi$  (and similar decays). On the other hand, even a small phase  $\phi_s^{\text{NP}} \approx -10^\circ$  would lead to CP asymmetries at the  $-20\%$  level, which could be unambiguously detected after a few years of data taking, and would not be affected by hadronic uncertainties. Ref. <sup>19</sup> quotes a sensitivity to  $\phi_s$  of  $\sigma(\phi_s) = 1.2^\circ$  for an integrated luminosity of  $2\text{fb}^{-1}$  at LHCb and a sensitivity  $\sigma(\Delta\Gamma_s/\Gamma_s) \sim 0.01$  for both LHCb and Atlas/CMS (at  $30\text{fb}^{-1}$ ). Conversely, the measurement of such an asymmetry would allow one to establish a lower bound on the strength of the NP contribution – even if hadronic uncertainties still preclude a direct extraction of this contribution from  $\Delta M_s$  – and to dramatically reduce the allowed region in the NP parameter space. In fact, the situation may be even more promising, as specific scenarios of NP still allow large new phases in  $B_s^0-\bar{B}_s^0$  mixing, also after the measurement of  $\Delta M_s$ , see, for instance, Refs. <sup>20,21</sup>.

In essence, the lesson to be learnt from this discussion is that NP may actually be hiding in  $B_s^0-\bar{B}_s^0$  mixing, but is still obscured by parameter uncertainties, some of which will be reduced by improved statistics at the LHC, whereas others require dedicated work of, in particular, lattice theorists. The smoking gun for the presence of NP in  $B_s^0-\bar{B}_s^0$  mixing will be the detection of a non-vanishing value of  $\phi_s^{\text{NP}}$  through CP violation in  $B_s \rightarrow J/\psi\phi$ . This example is yet another demonstration that flavour physics is not an optional extra, but an indispensable ingredient in the pursuit of NP, also and in particular in the era of the LHC.

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<sup>a</sup>Which also implies that we do not have to distinguish our definition of  $\phi_s$  as  $\arg M_{12}^s$  from the definition used by the D0 collaboration,  $\phi_s = \arg(-M_{12}^s/\Gamma_{12}^s)$ .

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