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B physics: Theory and B-factory results

L. Silvestrini*
INFN, Sez. di Roma, P.le A. Moro, 2, I-00185 Roma, Italy
E-mail: Luca.Silvestrini@roma1.infn.it

We briefly review some of the most New-Physics sensitive $B_{(s)}$ decays.

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1. Introduction

The Standard Model (SM) of electroweak and strong interactions is extremely successful in describing all presently available experimental data. However, its validity can extend at most to energies of the order of the Planck scale, where gravity comes into play. Let us therefore consider the SM as an effective theory valid up to a scale Λ. We can then write the SM Lagrangian as

$$\mathscr{L} = C_2 \Lambda^2 H^\dagger H + \lambda \left(H^\dagger H\right)^2 + \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Yukawa}} + \sum_{d=5}^{\infty} \sum_{i=1}^{n_d} \frac{C_d^i}{\Lambda^{(d-4)}} O_d^i \,, \tag{1.1}$$

where O_d^i is a generic gauge-invariant operator of dimension d. Now, it turns out that the Lagrangian truncated at $d \leq 4$ has some very important "accidental" symmetries that are violated by $O^i_{d>4}$. Most notable examples of such symmetries are given by baryon and lepton number conservation. The agreement of the SM with experimental data would suggest a very high value of Λ, so that the breaking of SM accidental symmetries be strongly suppressed by the inverse powers of Λ in front of the higher-dimensional operators. However, we see from the first term in eq. (1.1) that $C_2\Lambda$ controls the scale of electroweak symmetry breaking. Thus, unless we are willing to accept an extremely small value of C_2 (which means an extremely large amount of fine-tuning, since radiative corrections within the effective theory naturally generate $C_2 \sim \mathscr{O}(1)$), we are forced to consider values of the New Physics (NP) scale Λ not too far above the electroweak scale. But then the SM accidental symmetries require that NP have a peculiar structure, so that the cofficients of symmetry-breaking higher dimensional operators are strongly suppressed and the phenomenological success of the SM remains unscathed. Turning the argument around, the coefficients of those higher dimensional operators that break SM accidental symmetries provide the most stringent constraints on the NP scale and couplings (or better, on a combination thereof).

Let us now concentrate on two accidental symmetries of the SM: i) the absence of tree-level Flavour Changing Neutral Currents (FCNC), and the GIM suppression of loop-mediated FCNC; ii) The absence of tree-level CP violation in weak interactions. These accidental symmetries ensure that flavour physics is extremely sensitive to NP. In particular, there are strong theoretical motivations pointing to large NP effects in B physics. First of all, the flavour symmetry of SM gauge interactions is strongly broken by the $\mathscr{O}(1)$ Yukawa coupling of the top quark. Thus, any NP flavour symmetry cannot avoid this $\mathscr{O}(1)$ breaking, so that NP contributions to flavour violation for the third generation are essentially unprotected. In addition, any NP that stabilizes the electroweak scale must cancel the large top-quark-induced correction to the Higgs mass. This "top-like" contribution cannot decouple, so that large effects in B physics are expected on general grounds. Finally, in models with two Higgs doublets, if the ratio $\tan\beta$ of the two vacuum expectation values is large, the Yukawa coupling of the bottom quark becomes of $\mathscr{O}(1)$, pointing again to large effects in B physics.

2. Looking for NP in B decays

While B physics as a whole represents an excellent window on NP, for reasons of space we will concentrate here on a few processes, chosen among the most sensitive ones: i) $B_{(d,s)}$ mixing and CP violation; ii) $b \to s$ penguin decays, such as $B \to K\pi$ or $b \to s\ell^+\ell^-$; iii) chirally suppressed decays, such as $B \to \tau\nu$ or $B_s \to \mu^+\mu^-$.

Parameter	C_{B_d}	ϕ_{B_d} [°]	C_{B_s}	ϕ_{B_s} [°]
Value	0.90 ± 0.23	-2.7 ± 1.9	0.99 ± 0.23	$(-70 \pm 7) \cup (-18 \pm 7)$

Table 1: Numerical results (at 68% probability) for the NP parameters in B_q mixing.

2.1 New Physics in B_q mixing

B_q mixing is governed by the transition matrix element between B_q and $\bar{B}_q$ mesons, which can be parameterized in terms of two fundamental matrix elements: M_{12}, which is dominated by the exchange of virtual heavy states (top quarks and possibly new heavy particles), and Γ_{12}, which is dominated by the tree-level exchange of on-shell intermediate states. We assume here and in the following that NP is a negligible correction to tree-level processes (except for chirally suppressed decays, where a chirally-enhanced NP could compete with chirally-suppressed tree-level SM amplitudes). We can therefore write the relevant amplitudes in terms of SM ones as follows:

$$\begin{aligned} M_{12,q}^{\text{full}} &= \langle B_q | \mathscr{H}_{\Delta B=2}^{\text{eff}} | \bar{B}_q \rangle = M_{12,q}^{\text{SM}} + M_{12,q}^{\text{NP}} = C_{B_q} e^{i\phi_{B_q}} M_{12,q}^{\text{SM}} \\ \Gamma_{12,q}^{\text{full}} &= \Gamma_{12,q}^{\text{SM}} + \text{penguin effects}\,, \end{aligned} \tag{2.1}$$

with $q = d, s$. Notice that $\text{Im}(\Gamma_{12,q}^{\text{SM}}/M_{12,q}^{\text{SM}}) \sim 0$ due to GIM suppression, since $M_{12,q}^{\text{SM}} \propto (V_{tb}V_{tq}^*)^2$ and $\Gamma_{12,q}^{\text{SM}} \propto (V_{tb}V_{tq}^*)^2 +$ GIM-suppressed terms. On the other hand, in the standard CKM parameterization,

$$\text{Arg}(M_{12,d}^{\text{SM}}) = 2\beta \sim \mathscr{O}(1) \qquad \text{but} \qquad \text{Arg}(M_{12,s}^{\text{SM}}) = -2\beta_s \sim \mathscr{O}(10^{-2})\,. \tag{2.2}$$

From experiments we can extract the following combinations of the above parameters:

$$\begin{aligned} &\Delta m_{B_q} = 2|M_{12,q}^{\text{full}}| = C_{B_q} \Delta m_{B_q}^{\text{SM}}\,, \qquad \frac{\Delta\Gamma_q}{\Delta m_{B_q}} = \text{Re}\frac{\Gamma_{12,q}^{\text{full}}}{M_{12,q}^{\text{full}}} \sim \frac{\Delta\Gamma_q^{\text{SM}}}{\Delta m_{B_q}^{\text{SM}}} \frac{\cos 2\phi_{B_q}}{C_{B_q}}\,, \\ &A_{\text{SL}}^q = \text{Im}\frac{\Gamma_{12,q}^{\text{full}}}{M_{12,q}^{\text{full}}} \sim -\frac{\Delta\Gamma_q^{\text{SM}}}{\Delta m_{B_q}^{\text{SM}}} \frac{\sin 2\phi_{B_q}}{C_{B_q}} \sim -\frac{\Delta\Gamma_q}{\Delta m_{B_q}} \tan 2\phi_{B_q}\,, \\ &S_{J/\Psi K} \sim \sin 2(\beta + \phi_{B_d})\,, \qquad S_{J/\Psi\phi} \sim \sin 2(-\beta_s + \phi_{B_s})\,. \end{aligned} \tag{2.3}$$

To exploit the full constraining power of the measurements in eq. (2.3) we must obtain a NP-free determination of CKM parameters, so that we can compute the SM mixing amplitudes. To this aim, we use tree-level processes: semileptonic B decays determine $|V_{ub}|$ and $|V_{cb}|$, $B \to DK$ decays determine the angle γ of the Unitarity Triangle (UT) and $B \to \pi\pi$, $\pi\rho$ and $\rho\rho$ decays determine the angle α [1]. Using the tree-level UT, we can extract C_{B_q} and ϕ_{B_q} from experimental data [1–3].

Figure 1 shows the result of the NP analysis for the B_d and B_s sectors. Numerical results for NP parameters are summarized in table 1. See ref. [4] for input values and details of the analysis.

Given the experimental measurements, the results for ϕ_{B_s} show a discrepancy of 2.9σ from the SM value, pointing to NP contributions with new sources of flavor violation in the transition within 2^{nd} and 3^{rd} generation. The results for ϕ_{B_d} show a slight discrepancy from the SM value, of the order of 1.5σ. As a consequence, NP contributions in transitions within 1^{st} and 3^{rd} generations are not yet excluded, but are limited to be of $\mathscr{O}(30-40\%)$, while NP contributions in transitions within 2^{nd} and 3^{rd} generations of the order of the SM one are favoured (see Fig. 2).

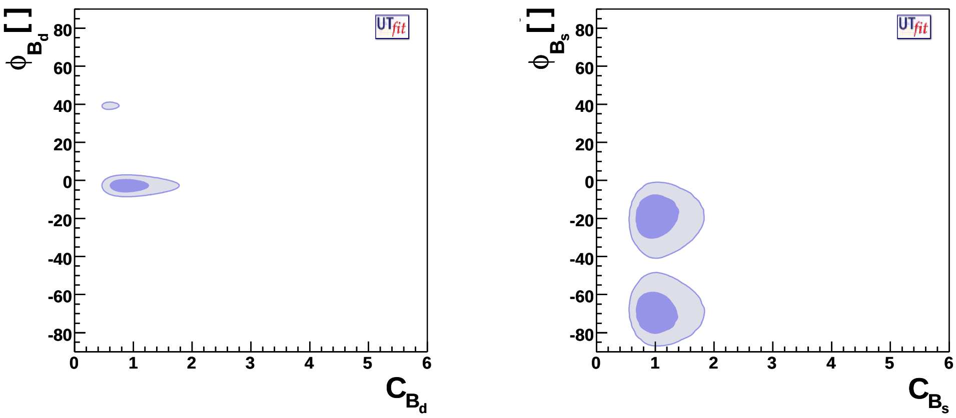

Figure 1: The dark and light colored areas show the 68% and 95% probability regions in the 2-dimensional planes (C_{B_d},ϕ_{B_d}) (left) and (C_{B_s},ϕ_{B_s}) (right).

Large NP contributions to $b \leftrightarrow s$ transitions arise naturally in several NP models. For example, they are expected in nonabelian flavour models, given the large breaking of flavour SU(3) by the top Yukawa coupling. In addition, supersymmetric Grand Unified Theories (SUSY-GUTs) provide a rather general connection between the large mixing angles in neutrino oscillations and large NP contributions to $b \leftrightarrow s$ processes.

2.2 NP in $B \to K\pi$

Let us now turn to NP in $b \to s$ penguins. For reasons of space, we shall concentrate on $B \to K\pi$ decays. The difference $\Delta A_{\rm CP} = A_{\rm CP}(K^+\pi^0) - A_{\rm CP}(K^+\pi^-)$ has recently received considerable attention, following the new measurement $\Delta A_{\rm CP} = 0.164 \pm 0.037$ published by the Belle collaboration [5]. It has been argued that $\Delta A_{\rm CP}$ could be a hint of New Physics (NP), but alternative explanations within the Standard Model (SM) have also been considered.

To understand whether $B \to K\pi$ decays are really puzzling, possibly calling for NP, one has to control the SM expectations for the $B \to K\pi$ amplitudes with a level of accuracy dictated by the size of the potential NP contributions. Thanks to the progress of theory in the last few years, we know that two-body non-leptonic B decay amplitudes are factorizable in the infinite b-quark mass limit, *i.e.* computable in terms of a reduced set of universal non-perturbative parameters [6–8]. However, the accuracy of the predictions obtained with factorization is limited by the uncertainties on the non-perturbative parameters on the one hand and by the uncalculable subleading terms in the $1/m_b$ expansion on the other. The latter problem is particulary severe for $B \to K\pi$ decays where some power-suppressed terms are doubly Cabibbo-enhanced with respect to factorizable

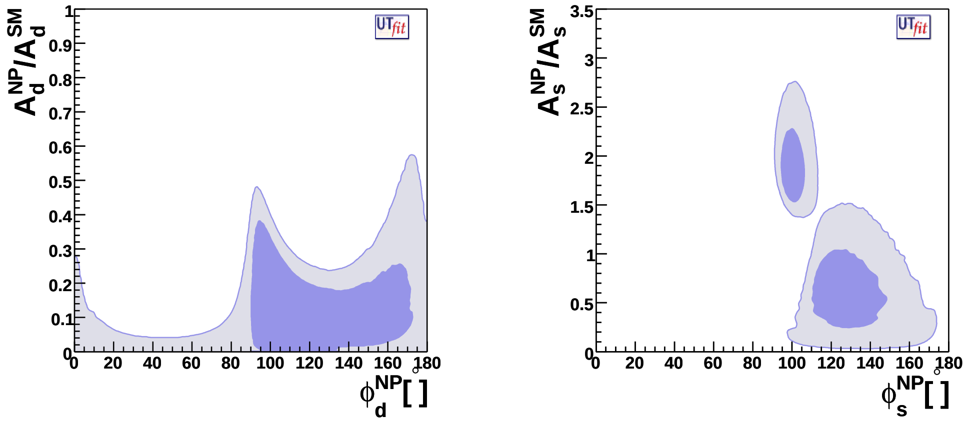

Figure 2: The dark and light colored areas show the 68% and 95% probability regions in the 2-dimensional planes (A_d^{NP}/A_d^{SM},ϕ_d^{NP}) (left) and (A_s^{NP}/A_s^{SM},ϕ_s^{NP}) (right).

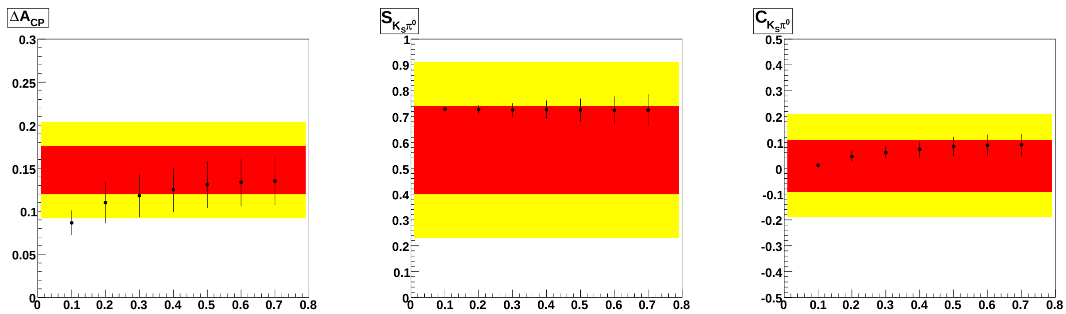

Figure 3: Some fit results as functions of the upper bound on power corrections.

terms [9]. Indeed factorization typically predicts too small $B \to K\pi$ branching ratios, albeit with large uncertainties. The introduction of subleading terms, certainly present at the physical value of the b quark mass, produces large effects in branching ratios and CP asymmetries, leading to a substantial model dependence of the SM predictions. Given this situation, NP contributions to $B \to K\pi$ amplitudes could be easily misidentified.

In Fig. 3 we display the dependence of the SM fit results for some $B \to K\pi$ CP asymmetries. We see that ΔA_{CP} can be reproduced within the SM for power corrections to factorization of the order of 30%, while the coefficients of the time-dependent CP asymmetry in $B \to K_s \pi^0$ are almost insensitive to power corrections and might therefore provide a test of the SM with improved experimental results. Unfortunately, at present the situation is inconclusive: the observed value of $\Delta A_{\rm CP}$ could be given by NP (in particular, by new sources of CP violation in $b \to s$ electroweak penguins), but it can also be explained within the SM due to uncalculable power corrections to factorization.

2.3 $\tan\beta$-enhanced NP in B decays

As a last example of NP-sensitive B decays we discuss the chirally-suppressed $B \to \tau\nu$ and $B_s \to \mu^+\mu^-$ decays. In NP models with two Higgs doublets at large values of $\tan\beta$, the bottom quark Yukawa coupling is large and can strongly enhance Higgs-mediated FCNC transitions. The scalar Lorentz structure of these transitions provides an enhancement over the SM amplitude in chirally-suppressed leptonic decays.

Let us consider the 2HDM-II, which is an extension of the SM with two Higgs doublets with no new source of flavour violation. In this model, for large $\tan\beta$ large effects are generated in $B \to X_s\gamma$, $B \to \tau\nu$ and $B \to D\tau\nu$. Assuming flat priors in $[5,120]$ for $\tan\beta$ [10] and $[100,1000]$ GeV for m_{H^+}, we obtain the plot in Fig. 4. For $\tan\beta \gtrsim 22$ $B \to \tau\nu$ gives a lower bound on m_{H^+} stronger than the one from $B \to X_s\gamma$. The fine-tuned regions for large $\tan\beta/m_{H^+}$ allowed individually by the $B \to \tau\nu$ and the $B \to D\tau\nu$ constraints do not overlap and are therefore excluded. We thus obtain an absolute bound

$$\tan\beta < 7.4 \frac{m_{H^+}}{100\,\text{GeV}} \,. \tag{2.4}$$

In addition, we compute the prediction for $BR(B_s \to \mu^+\mu^-)$ and obtain

$$BR(B_s \to \mu^+\mu^-) = (4.3 \pm 0.9) \times 10^{-9} \qquad ([2.5, 6.2] \times 10^{-9} \text{ @95\% prob.}). \tag{2.5}$$

It has been pointed out that the MSSM with MFV, TeV sparticles and large $\tan\beta$ could give negligible contributions to flavour physics except for $B \to \tau\nu$, Δm_s, $B_s \to \mu^+\mu^-$ and $B \to X_s\gamma$ [11]. In ref. [12] it has been recently shown that, with present data, the combination of the first three constraints leaves little space for large $\tan\beta$. This can be easily understood as this model typically predicts a suppression of $BR(B \to \tau\nu)$ rather than the enhancement required by the present measurements. An enhancement can be obtained only for very large values of $\tan\beta$ which, however, are disfavoured by the other constraints.

We reanalyze the model of Ref. [11] with the following a-priori flat ranges for the relevant low-energy SUSY parameters: $\mu = [-950,-450] \cup [450,950]$ GeV, $A_u = [-3,3]$ TeV, $\tan\beta = [5,65]$, $m_{H^+} = [100,1000]$ GeV, $m_{\tilde{q}} = [400,1000]$ GeV, $m_{\tilde{g}} = [400,1000]$ GeV. The expressions of $B \to \tau\nu$, $B_s \to \mu^+\mu^-$ and Δm_s can be found in Eqs. (3), (11) and (14) of Ref. [11] respectively. The experimental constraints are $\Delta m_s = 17.77 \pm 0.12$ ps^{-1} [13] and the upper bound $BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-8}$ at 95% C.L. [14].

In Figs. 4 we show the p.d.f. in the plane $(\tan\beta, m_{H^+})$ for $\mu > 0$. The combined exclusion region is roughly bounded by a straight line, giving $\tan\beta < 7.3\, m_{H^+}/(100\,\text{GeV})$ at 95% probability, with a remarkable similarity to the 2HDM-II case. From our analysis we also derive the following range for $BR(B_s \to \mu^+\mu^-)$:

$$[3,8] \times 10^{-9} \text{ @68\% prob.} \qquad [2,26] \times 10^{-9} \text{ @95\% prob.} \tag{2.6}$$

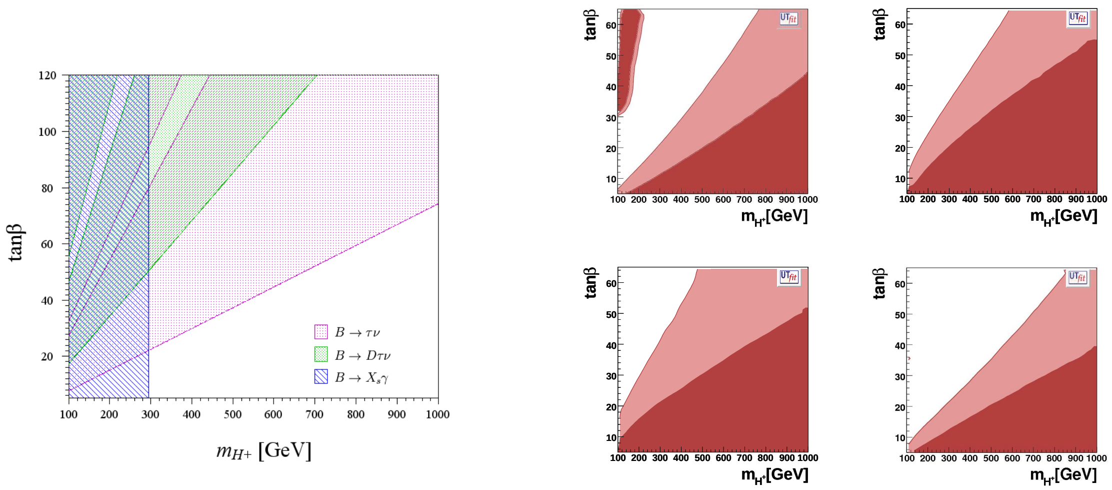

Figure 4: Left: regions in the $(m_{H^+}, \tan\beta)$ parameter space of the 2HDM-II excluded at 95% probability by $BR(B \to \tau\nu)$, $BR(B \to D\tau\nu)/BR(B \to D\ell\nu)$ and $BR(B \to X_s\gamma)$. Right: 68% (dark) and 95% (light) probability regions in the $(m_{H^+}, \tan\beta)$ plane obtained using $BR(B \to \tau\nu)$ (top left), $BR(B_s \to \mu^+\mu^-)$ (top right), Δm_s (bottom left), all constraints (bottom right) for $\mu > 0$ in the considered MFV-MSSM for the parameter ranges specified in the text.

for $\mu > 0$. More details can be found in ref. [12].

3. Conclusions

We have argued that B physics is naturally sensitive to any NP relevant for the stabilization of the electroweak scale. We have remarked that $2-3\sigma$ deviations from the SM expectations have been seen in several processes. First of all, CP violation in B_s mixing deviates almost 3σ from the SM expectation, with negligible theoretical uncertainty. If future results from TeVatron and LHCb will confirm this deviation, this will become a solid evidence of nonstandard CP violation. $B \to \tau\nu$ seems to exceed SM expectations by $\sim 2\sigma$, disfavouring also Minimal Flavour Violation models such as the 2HDM-II or the MFV-MSSM. Finally, CP violation in $b \to s$ penguins displays some deviation from SM expectations, albeit with large theoretical uncertainties. We certainly need more data to check if all these indication consistently point to the theoretically well-motivated scenario of large NP effects in $b \leftrightarrow s$ transitions. In any case, the pessimistic MFV paradigm is presently disfavoured, implying on one hand that there are bright prospects for detecting indirect NP signals in B decays, and on the other hand that we should not expect an msugra-like NP to show up at the LHC. Thus, a global approach to NP searches, combining direct and indirect evidence, is mandatory in order to determine the NP Lagrangian.

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