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New physics in B meson mixing: future sensitivity and limitations

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Luiz Vale Silva[a,*]

[a] *Instituto de Física Corpuscular, Universitat de València - Consejo Superior de Investigaciones Científicas, Parc Científic, E-46980 Paterna, Valencia, Spain*

E-mail: `luizva@ific.uv.es`

The mixing of neutral mesons has been playing a key role in the formulation and testing of the Standard Model. It is also sensitive to some of the highest Beyond the Standard Model scales probed in laboratory experiments. In light of the planned LHCb Upgrades, Belle II and its possible upgrade, and the broad interest in flavour physics in the tera-Z phase of the proposed FCC-ee program, I discuss constraints on New Physics contributions to B_d and B_s mixing which can be obtained in these benchmark scenarios.

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1. Introduction

Flavour physics plays a central role in particle physics: e.g., it provided hints of new heavy particles before their direct discovery, and led to the discovery of Charge-Parity (**CP**) violation. Many flavour observables enjoy the status of precision physics, i.e., they are precisely measured or tightly constrained, and accurately predicted by the Standard Model (SM), which make them sensitive to very high New Physics (NP) energy scales, much beyond the production reach of present colliders. Due to its sensitivity to NP effects, it is expected that flavour physics will be crucial in addressing the questions left open within the SM, such as the huge hierarchies observed in the spectrum of SM particles, and lead to new insights into the structure of NP.

As of now, measurements of low-energy flavour observables are broadly in agreement with SM predictions. This is illustrated in the quark sector by the consensus among different observables in the extraction of the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1]. There are, however, some interesting hints to NP, e.g., in B-meson decays [2].

Looking towards the future, we are on the verge of a new era in flavour physics: LHCb and Belle II will collect large data sets over this decade, and there are proposals for extending their operations [3, 4]; see [5] for BESIII future physics program. Flavour is an important physics case for such future collider, and non-collider, experimental proposals [6]. Conversely, future data will shape the field, further testing the SM and present anomalies, while possibly revealing new tensions.

I discuss a specific kind of manifestation of NP, consisting in changes of bottom number by two units. Processes sensitive to changes of flavour by two units are generally interesting because the SM is loop and CKM suppressed, and there are precision observables available. I show present and expected future bounds, and discuss future limitations of the sensitivity to NP.

2. Present and future bounds on NP contributions to B meson mixing

NP effects in B meson mixing are encoded in the following way, see [7] and references therein:

$$M_{12} = (M_{12})_{\rm SM} \times \left(1 + h_q \, e^{2i\sigma_q}\right) , \quad q = d, s \, , \tag{1}$$

where h_q sets the size of NP relative to the SM, and σ_q allows for new **CP**-violating effects. The SM term is precisely predicted thanks in part to accurate lattice QCD extractions of non-perturbative quantities. A certain number of assumptions is being made; we consider that [8]: NP in changes of flavour by one unit is absent or highly suppressed, and therefore tree level quantities in the SM are essentially free of NP contamination; NP is short distance at the scales relevant to the observables analysed; the CKM matrix remains a unitary 3×3 matrix, described by three mixing angles and a single **CP**-violating phase; and NP effects in B_d and B_s systems are unrelated. For instance, $|\Delta B| = 2$ four-fermion dimension-6 operators of different chiralities of the SM Effective Field Theory (SMEFT) contribute to the NP parameters h_q and σ_q.

Fig. 1 shows the present status of the allowed size of NP, after the combination of a diverse set of observables, that for instance: in the SM come first at the tree or at the one-loop level, directly probe **CP** violation or not, and are dominated by different types of uncertainties (experimental or systematic), see [9] for their full list. We observe that the SM point is favored at about 1σ, but that NP can be as large as $20 - 30\%$ of the SM. In presence of NP, the accuracy in the extraction of the

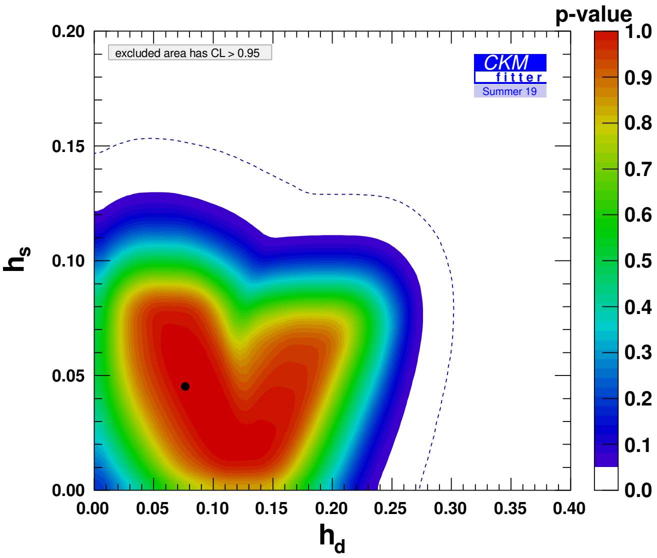

Figure 1: Current sensitivities to $h_d - h_s$ in B_d and B_s mixings as of Summer 2019 [10]. The SM point corresponds to the origin. The black dot indicates the best-fit point, and the dotted curve shows the 99.7% CL (3σ) contour.

Wolfenstein parameters $\bar{\rho}$ and $\bar{\eta}$ of the CKM matrix degrade by a factor 3, illustrating the role of the observables affected by NP of the kind $|\Delta B| = 2$ in extracting these parameters.

To discuss future projections, we define three benchmark phases:

- Phase I (late 2020s) consists of LHCb Upgrade I with a luminosity of 50/fb, together with Belle II with a luminosity of 50/ab;
- in Phase II (late 2030s) these luminosities are multiplied respectively by 6 and 5, thanks to future upgrade proposals;
- and a more speculative Phase III, which consists of Phase II together with a promising candidate for the next generation of colliders, namely, the Future Circular Collider (FCC) [11], more specifically its electron-positron phase. FCC-*ee* can contribute substantially to flavour physics due to the large number of Z and W-pairs produced, which decay into all possible heavy flavours, in a clean experimental environment [12, 13].

Projections for the uncertainties of the specific observables included in our analysis are found in Ref. [9] and the references quoted therein. Some of these projections are still simplistic, being first attempts to estimate future uncertainties. We highlight the following:

- Two key quantities in probing NP in B meson mixing are $|V_{ub}|$ and $|V_{cb}|$, which are going to be precisely extracted in exclusive semi-leptonic decays at Belle II (their extractions being dominated by statistical uncertainties) [4]. FCC-*ee* can produce a qualitatively new measurement of $|V_{cb}|$, based on $W^+ \to c\bar{b}$ thanks to the tagging of heavy flavours [11, 14, 15]. The total uncertainty in the latter quantity is estimated to be better than the one extracted from the future upgrade of Belle II.

Couplings	NP order	Summer 2019 [TeV]		Phase I [TeV]		Phase II [TeV]	
		B_d mixing	B_s mixing	B_d mixing	B_s mixing	B_d mixing	B_s mixing
$\lvert C_{ij}\rvert = \lvert V_{ti}V^*_{tj}\rvert$ (CKM-like)	tree level	9	13	17	18	20	21
	one loop	0.7	1.0	1.3	1.4	1.6	1.7
$\lvert C_{ij}\rvert = 1$ (no hierarchy)	tree level	1×10^3	3×10^2	2×10^3	4×10^2	2×10^3	5×10^2
	one loop	80	20	2×10^2	30	2×10^2	40

Table 1: The scale of the operator in Eq. (1) probed (in TeV, @ 95% CL) by B_d and B_s mixings at present, at Phase I, and Phase II, if the NP contributions in the two meson mixings are unrelated. The impact of SM-like hierarchy of couplings and/or loop suppression is shown.

- Starting from Phase I in this decade, uncertainties on the determinations of the angles $\alpha, \beta, \beta_s, \gamma$ will be better than 1^o [3, 4, 11].
- Key theoretical QCD inputs from lattice QCD extractions will be known at a level better than 1% [3, 4]. (For these, projections in the literature go as far as Phase II, and in the case of Phase III we take the same inputs as in Phase II, which is expected to be conservative.)

The expected bounds on NP are shown in Tab. 1. For Phases I and II, the SM is assumed to remain consistent with the data, meaning that central values of the different observables are shifted in such a way that the best-fit point is located at $h_d = h_s = 0$, which represents the SM. We observe that when moving from the current status (shown in Fig. 1) to Phase I, bounds improve by a factor larger than 3, which is a substantial progress; the improvement then increases by a smaller factor when going to Phase II. One can reduce projections of future uncertainties in order to identify the key quantities whose projected uncertainties prevent better constraints on NP. **(i)** As expected, theoretical QCD inputs will continue playing a key role: by improving decay constants, bag parameters, and perturbative QCD corrections by a substantial factor, bounds on NP become more powerful by (at most) $20-30\%$. **(ii)** Also, $|V_{cb}|$ plays a crucial role, as it sets the overall normalization in the predictions of mass differences in the B systems; improving the uncertainty of $|V_{cb}|$ by an order-of-magnitude factor leads to more powerful bounds on NP by $20-30\%$. Combining both **(i)** and **(ii)** leads to bounds on NP stronger by $\sim 70\%$.

In Tab. 1 we considered that NP shows up with the same chiral structure of the SM, while other chiral structures would involve $\mathcal{O}(1)$ modulations in the case of B physics. Obviously, if NP also suffers from suppression mechanisms as in the case of the SM the bounds on the scale of NP are alleviated, but one still probes energy scales of the order of the TeV. Let us also mention that these bounds are powerful enough to probe effects encoded in SMEFT operators of dimension-8, which could result from double insertions of $|\Delta B| = 1$ dimension-6 operators, see [16] for details. In the latter case, one can still get a sensitivity to NP of many TeVs.

Other than setting bounds, one can discover NP from future data: as seen from Fig. 2, there are good prospects in the future for the discovery of NP manifesting as changes of flavour by two units. (For the sake of determining the potential of future discovery, we keep the central values of the different observables analysed as of now while shrinking their uncertainties according to the available projections, reason why the best-fit point remains the one shown in Fig. 1.)

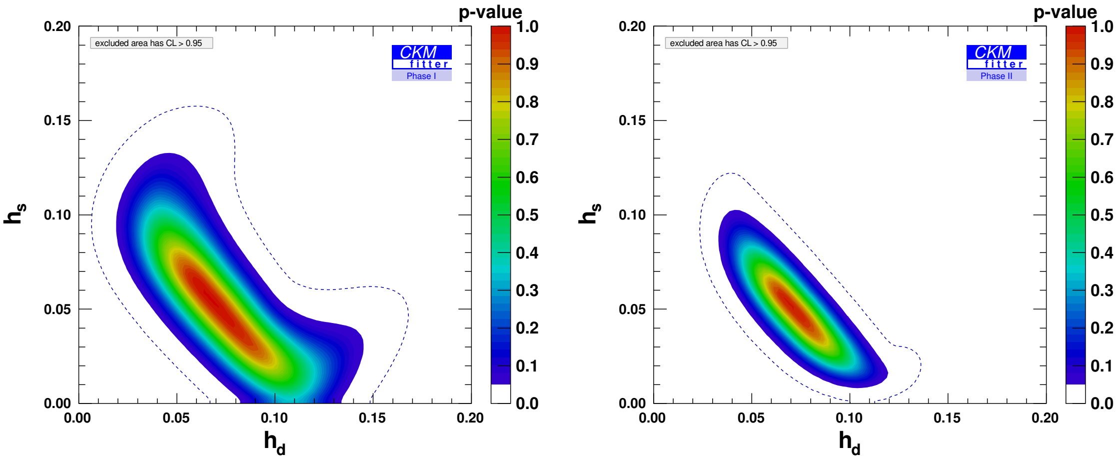

Figure 2: Discovery prospects at Phase I (left) and Phase II (right), if the central values are as in the Summer 2019 fit of Fig. 1.

3. Conclusions

I have discussed flavour physics observables, which play a crucial role in testing the SM while shaping the structure of possible NP candidates. I have discussed more specifically NP in changes of flavour by two units, which is just one flavour aspect of future experimental programs. I discussed present and projections of future data in order to extract the parameters of the SM in presence of NP, and the parameters encoding NP effects in B meson mixing. The allowed size of NP is still sizable, and bounds will be largely improved by (near) future data. I have identified two key categories of inputs that have to be improved in order to fully enjoy of future data when constraining $|\Delta B| = 2$ NP, which are perturbative and non-perturbative QCD inputs, and $|V_{cb}|$. More optimistically, rather than setting bounds, the analysis of future data may lead to the clear observation of NP, which would certainly be a major breakthrough in particle physics.

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