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How large could CP violation in B meson mixing be? Implications for baryogenesis and future searches

Carlos Miró[a,*] **Miguel Escudero**[b] **and Miguel Nebot**[a]

[a]*Departament de Física Teòrica and Instituto de Física Corpuscular (IFIC), Universitat de València – CSIC, E-46100 Valencia, Spain*

[b]*Theoretical Physics Department, CERN, 1211 Geneva 23, Switzerland*

E-mail: carlos.miro@uv.es, miguel.escudero@cern.ch, miguel.nebot@uv.es

It is well-known that CP violation is one of the necessary ingredients to generate the observed matter-antimatter asymmetry of the Universe. Neutral B mesons naturally exhibit CP violating oscillations, such that the amount of CP violation in their mixing can be directly related to the baryon asymmetry through the B-mesogenesis mechanism. With this in mind, it is interesting to analyze the extent to which CP is violated in B meson mixing within different scenarios beyond the Standard Model. In particular, we consider: (i) the effects of heavy new physics in the mass mixing following a model-independent approach, (ii) the implications of CKM unitarity deviations with the inclusion of vector-like quarks, and (iii) the role of new contributions to the decay width mixing. The available parameter space for the relevant CP asymmetries is presented, studying their compatibility with the B-mesogenesis framework and comparing it with the expected experimental sensitivity for these quantities at LHCb and Belle II.

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1. Neutral B meson mixing: general framework and current status

Neutral B mesons, with quark flavor content $|B_q\rangle = |\bar{b}q\rangle$ and $|\bar{B}_q\rangle = |b\bar{q}\rangle$ ($q = d, s$), are eigenstates of the strong and electromagnetic interactions. However, once the weak interaction comes into play, they can mix and decay to other states. In particular, their time evolution is controlled by the 2×2 Hamiltonian

$$\mathcal{H}^q = M^q - i\frac{\Gamma^q}{2} = \begin{pmatrix} M_{11}^q - i\Gamma_{11}^q/2 & M_{12}^q - i\Gamma_{12}^q/2 \\ M_{21}^q - i\Gamma_{21}^q/2 & M_{22}^q - i\Gamma_{22}^q/2 \end{pmatrix}, \tag{1}$$

with $M^q = M^{q\dagger}$ and $\Gamma^q = \Gamma^{q\dagger}$. If CPT is assumed, then $M_{11}^q = M_{22}^q$ and $\Gamma_{11}^q = \Gamma_{22}^q$. On the other hand, the off-diagonal elements are responsible for the $B_q \leftrightarrow \bar{B}_q$ oscillations in two possible ways: (i) through *mass mixing* M_{12}^q if intermediate states are considered to be off-shell, or (ii) through *decay width mixing* Γ_{12}^q when the intermediate states are on-shell. Remarkably, neutral B meson oscillations violate CP if $\mathrm{Im}(\Gamma_{12}^q/M_{12}^q) \neq 0$, that is, if Γ_{12}^q and M_{12}^q have a non-vanishing relative phase. In those cases, we say that there is CP violation *in mixing*.

Experimentally, this phenomenon is measured in the so-called flavor-specific semileptonic decays of B mesons, which are defined by a final state $f = X\ell\nu_\ell$ such that $B_q \nrightarrow \bar{f}$ and $\bar{B}_q \nrightarrow f$. In this context, one can define the semileptonic CP asymmetries as

$$A_{\mathrm{SL}}^q \equiv \frac{\Gamma(\bar{B}_q(t) \to f) - \Gamma(B_q(t) \to \bar{f})}{\Gamma(\bar{B}_q(t) \to f) + \Gamma(B_q(t) \to \bar{f})} = \mathrm{Im}\left(\frac{\Gamma_{12}^q}{M_{12}^q}\right), \tag{2}$$

thus signaling if CP is violated in B mixing. The current experimental world averages are [1]

$$A_{\mathrm{SL}}^{d,\mathrm{Exp}} = (-21 \pm 17) \times 10^{-4}, \qquad A_{\mathrm{SL}}^{s,\mathrm{Exp}} = (-6 \pm 28) \times 10^{-4}, \tag{3}$$

to be compared with their Standard Model (SM) prediction [2]

$$A_{\mathrm{SL}}^{d,\mathrm{SM}} = (-5.1 \pm 0.5) \times 10^{-4}, \qquad A_{\mathrm{SL}}^{s,\mathrm{SM}} = (0.22 \pm 0.02) \times 10^{-4}. \tag{4}$$

Given that large experimental uncertainties are still present, *a priori* there is still ample room to accommodate NP affecting A_{SL}^q. In the following, we address different scenarios that might introduce substantial enhancements of these observables.

2. A_{SL}^q with heavy new physics in M_{12}^q

In this section, we consider the effects of *heavy* new physics (NP) in $B_q - \bar{B}_q$ oscillations. On that regard, it is important to remind that M_{12}^q is defined by a $\Delta B = 2$ transition through intermediate virtual states. These are generated at the one-loop level in the SM through box diagrams that are CKM-suppressed. Therefore, heavy NP affecting M_{12}^q could generate an effect that might compete with the corresponding SM contribution. On the other hand, Γ_{12}^q corresponds to two $\Delta B = 1$ transitions through a real state that is common to B_q and $\bar{B}_q$. In the SM, they arise at the tree-level, so that potential NP effects entering also at tree-level would be suppressed by powers $(M_W/\Lambda_{\mathrm{NP}})^2$.

All in all, a good starting point for our analyses is to solely consider modifications of M_{12}^q. These could be parametrize in a model-independent way as

$$M_{12}^q = M_{12}^{q,\mathrm{SM}} \Delta_q = M_{12}^{q,\mathrm{SM}} |\Delta_q| e^{i\phi_q^\Delta} \,, \qquad \Gamma_{12}^q = \Gamma_{12}^{q,\mathrm{SM}} \,, \qquad \phi_{12}^q = \phi_{12}^{q,\mathrm{SM}} + \phi_q^\Delta \,, \tag{5}$$

being Δ_q a complex parameter. The relative phase ϕ_{12}^q is defined as $\phi_{12}^q \equiv \arg(-M_{12}^q/\Gamma_{12}^q)$.

We perform a global fit to constrain the different parameters of the model, including 3 mixing angles and 1 complex phase describing the CKM mixing matrix in the PDG parametrization. Among the set of observables considered for this purpose, the meson mass differences [1] constraining the modulus of M_{12}^q, together with the phases controlling mixing-induced CP violation that constrain the argument of M_{12}^q [1, 3], place the most stringent bounds. Regarding the latter, we should stress that gluon penguin diagrams are estimated to give a contribution of $\sim 1^\circ$ [4], which has reached the current level of experimental uncertainties. We have appropriately included this effect in our fit, distinguishing between the analyses "w/ penguins" and "w/o penguins". Other constraints include: CKM tree-level data [3],[1] lattice inputs for B_q meson decay constants and bag parameters [5], B meson decay width differences [1], and the semileptonic asymmetries [1]—see [6] for details.

Our results are illustrated in Fig. 1. One can check that the general modification of M_{12}^q in Eq. (5) can lead to enhancements of A_{SL}^q at the level of 10^{-3} for the B_d system and 10^{-4} for the B_s system, still below the expected sensitivity at LHCb and Belle II with 23 fb^{-1} and 50 ab^{-1} of collected data, respectively. Interestingly, there might be a significant cut of the parameter space at the end of the HL-LHC era with 300 fb^{-1}.

3. A_{SL}^q with non-unitary CKM

An alternative approach to enhancing the values of the semileptonic asymmetries is to explore violations of CKM unitarity. This scenario is interesting because one of the ingredients that aligns the phases of Γ_{12}^q and M_{12}^q in the SM, thus leading to small CP asymmetries, is precisely 3×3 CKM unitarity. The latter can be easily evaded by adding, in the simplest cases, either one up-type or one down-type vector-like $SU(2)_L$ singlet to the SM matter content, to be referred as UVLQ and DVLQ models, respectively. The resulting CKM matrix, 4×3 in the UVLQ case and 3×4 in the DVLQ scenario, is part of a larger 4×4 unitary matrix. Consequently, the usual orthogonality relations are modified as

$$\text{UVLQ}: \qquad V_{ub}V_{uq}^* + V_{cb}V_{cq}^* + V_{tb}V_{tq}^* + V_{Tb}V_{Tq}^* = 0 \,, \tag{6}$$

$$\text{DVLQ}: \qquad V_{ub}V_{uq}^* + V_{cb}V_{cq}^* + V_{tb}V_{tq}^* = (D_L)_{qb} \,, \tag{7}$$

with $V_{Tb}V_{Tq}^*$ and $(D_L)_{qb}$ parametrizing the deviation with respect to 3×3 unitarity.

Besides the desired unitarity violations, vector-like quarks generate new contributions to the mass mixing M_{12}^q. In UVLQ models, they arise from SM-like box diagrams with the additional

[1] We have included tree-level data from the moduli $|V_{ud}|$, $|V_{us}|$, $|V_{ub}|$, $|V_{cb}|$, and the angle γ. In all cases, the average result recommended by the PDG is considered [3]. One could have used instead the exclusive or inclusive determinations of $|V_{cb}|$ and $|V_{ub}|$ in order to maximize the semileptonic asymmetries, in particular when considering $|V_{cb}|_{\mathrm{excl}}$ and $|V_{ub}|_{\mathrm{incl}}$. Ignoring the fact that this choice might be in some sense inconsistent, we should remark that it has no relevant impact on the conclusions of our study: there is actually a small shift on the central values of the asymmetries, but no change in the range of variation driven by their uncertainties.

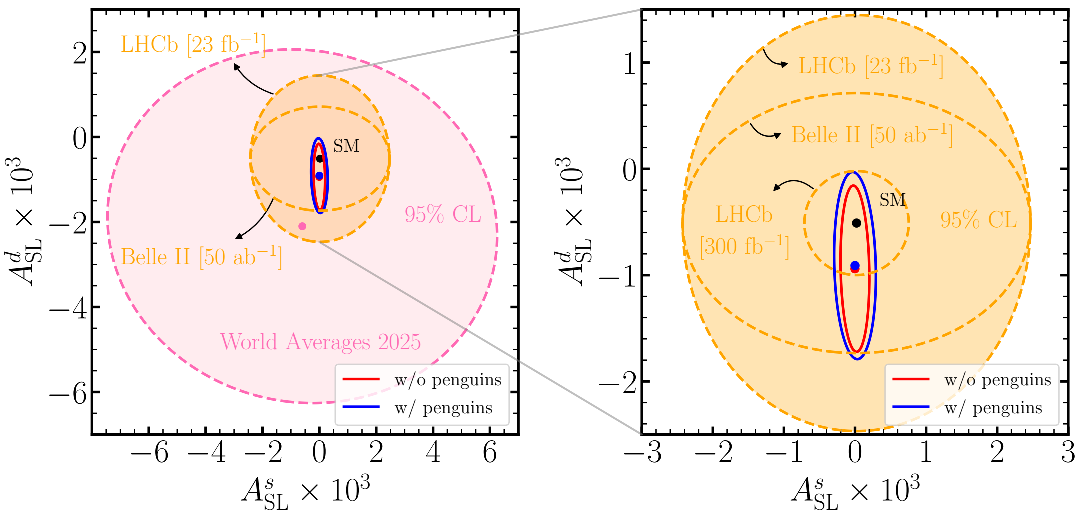

Figure 1: Allowed regions for A_{SL}^d and A_{SL}^s with heavy new physics solely affecting M_{12}^q. All contours are shown at 95% CL (2D-$\Delta\chi^2 = 5.99$), together with the corresponding best fit point. In the left panel, the pink ellipse represents the current experimental world averages as of 2025, while the ellipses in orange project the future expected sensitivity at LHCb with 23 fb^{-1} and Belle II with 50 ab^{-1} of collected data. The blue and red contours show the results of our analysis in Sec. 2, corresponding to the case where SM penguin contributions have been included or neglected, respectively. The point in black is the SM prediction, whose uncertainties are not visible in these axes. In the right panel, we provide the detail of our results along with the projected sensitivities at LHCb (23 fb^{-1}) and Belle II (50 ab^{-1}), and, in addition, at LHCb with 300 fb^{-1}.

heavy T quark running in the loop, and depend on its mass m_T and $V_{Tb}V_{Tq}^*$. In DVLQ models, the new contributions correspond to tree-level and penguin topologies involving the flavor-changing coupling Zd_id_j. They depend on $(D_L)_{qb}$, but not on the new down-type quark mass.

Following our previous approach, we perform a global fit considering the same set of constraints[2] of Sec. 2. Indeed, one could have extended this set by incorporating B_q rare decays, electroweak precision data, kaon mixing observables, *etc*., among other relevant constraints, if our aim was to perform a detailed phenomenological study within these scenarios. However, this is not our goal, namely, to quantify how large the semileptonic asymmetries could be. Consequently, the full range of variation obtained for these observables is not necessarily allowed, but values outside these regions cannot be generated in any case within these models. Finally, two additional comments are in order. First, since CKM is part of a larger 4×4 unitary matrix, 3 additional mixing angles and 2 new phases are required in its parametrization. Second, the mass of the heavy T quark is set to $m_T = 1.6$ TeV in order to avoid lower bounds from direct searches [7], although we have checked that for values of m_T in the range $m_T \in [1.6, 5]$ TeV our results remain unchanged.

The resulting allowed regions for A_{SL}^d and A_{SL}^s within vector-like quark singlet extensions are essentially the same as those shown in Fig. 1. In this sense, deviations from 3×3 unitarity do not provide any advantage over the scenario presented in Sec. 2 with generic heavy NP modifying M_{12}^q.

[2] As 3×3 CKM unitarity does not hold, it is important to further include the experimental determination of $|V_{tb}|$.

4. $A^q_{\rm SL}$ with modifications to Γ^q_{12}

Finally, we explore NP extensions where Γ^q_{12} is also modified. On that regard, we should stress that any time a diagram is found to contribute to Γ^q_{12}, this will also generate a contribution to M^q_{12}, *i.e.*, it is not possible to modify Γ^q_{12} without affecting M^q_{12} at all. Then, we must ensure that the corresponding modification of M^q_{12} satisfies the stringent constraint placed by the meson mass differences, which, in turn, could limit the potential enhancement of Γ^q_{12}, and thus of $A^q_{\rm SL}$. On the other hand, one should keep in mind that Γ^q_{12} arises from tree-level decays, and mediators of these transitions face LHC bounds that generally require their mass to be $M \gtrsim 1$ TeV. Taking into account that the ratio Γ^q_{12}/M^q_{12} typically scales as $\Gamma^q_{12}/M^q_{12} \sim m_b^2/M^2$, it is clear that trying to enhance the values of the semileptonic asymmetries through modifications of Γ^q_{12} is very challenging from the theoretical point of view. In any case, it is to be mentioned that this general argument might be surpassed in other fine-tuned NP scenarios.

Different existing analyses in the literature addressed this question in terms of effective $\Delta B = 1$ operators built out of light degrees of freedom (below the m_b scale) that can induce modifications into decay modes that are common to both B_q and $\bar{B}_q$ mesons, hence capable of modifying Γ^q_{12}. The only viable options include (i) $b \to u_i \bar{u}_j q$ decays, (ii) $b \to \tau\bar{\tau}s$ decays, and (iii) decays into invisible particles. Overall, they can still accommodate substantial NP effects due to the presence of large hadronic uncertainties in case (i), and the difficulty to detect the final state particles allowing for large branching ratios in cases (ii) and (iii). Refs. [8] and [9] have recently addressed options (i) and (ii), respectively, finding values of $|A^q_{\rm SL}| \sim O(10^{-3})$. Nevertheless, in realistic UV completions triggering scenarios (i) [10] and (ii) [11], the enhancements of the asymmetries are actually smaller, $|A^q_{\rm SL}| \sim O(10^{-5})$ at most, in accordance with our previous argument.

On another avenue, the minimal realization of the B-mesogenesis mechanism [12, 13] introduces the modifications of interest in cases (i) and (iii). Within this mechanism the baryon asymmetry of the Universe is directly related to collider observables, namely, the semileptonic asymmetries as well as the branching ratio of a new decay mode of B mesons into a baryon, a dark sector antibaryon ψ and any number of light mesons. Its minimal realization requires the presence of a color-triplet scalar boson Y that mediates this novel decay. In order to have a successful baryogenesis, and given the current bounds on the previous branching ratio—a conservative estimate should be Br $\lesssim$ 1% for $m_\psi \sim 1$ GeV—, one needs

$$A^q_{\rm SL} > +10^{-4}\,, \tag{8}$$

that is, at least one of the asymmetries must be positive, and roughly an order of magnitude larger than the SM prediction. One can check that the $Y\psi d_k$ and $Yu_i d_j$ couplings within this framework yield enhancements of the CP asymmetries that are at most

$$|A^{q,{\rm NP}}_{\rm SL}(\psi)| \lesssim 4\times 10^{-5}\left(\frac{500\ {\rm GeV}}{M_Y}\right)^2\,, \qquad |A^{q,{\rm NP}}_{\rm SL}(\not{\psi})| \lesssim 10^{-4}\,, \tag{9}$$

where we have taken into account that $M_Y > 500$ GeV is the most conservative limit from direct LHC searches on pair produced Y resonances—see [13] for further details on these bounds. Therefore, we obtain smaller enhancements than in the generic heavy NP scenario presented in Sec. 2.

5. Summary and final results

We highlight two important results, that are summarized in Fig. 2.

(i) Upcoming measurements of the semileptonic asymmetries at LHCb and Belle II will not be able to test the most generic NP scenarios, including: general modifications of M_{12}^q, deviations of 3×3 unitarity within vector-like quark extensions, and non-tuned UV complete models modifying Γ_{12}^q.

(ii) The small CP asymmetries that can be obtained beyond the SM place the B-mesogenesis mechanism in tension. Only the region with $A_{\rm SL}^s \simeq (1-5) \times 10^{-4}$ and $A_{\rm SL}^d \simeq A_{\rm SL}^{d,\rm SM}$ can successfully trigger baryogenesis, although this picture might change if stronger bounds on $\text{Br}(B \to \text{baryon} + \psi + \text{mesons})$ are considered.

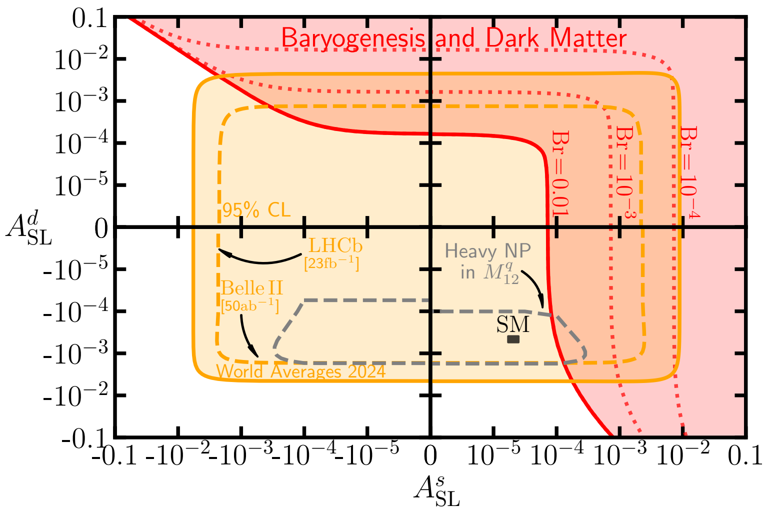

Figure 2: Semileptonic asymmetries $A_{\rm SL}^d$ and $A_{\rm SL}^s$ in logarithmic scale. In orange we show the experimentally allowed regions at 95% CL (2D-$\Delta\chi^2 = 5.99$) as of 2025, and in dashed orange the expected sensitivity from LHCb (23 fb^{-1}) and Belle II (50 ab^{-1}). In red we highlight the region of the parameter space identified in [13] in which the baryon asymmetry of the Universe can be explained through the B-mesogenesis mechanism [12, 13]. The dashed red lines correspond to isocontours of $\text{Br}(B \to \text{baryon} + \psi + \text{mesons})$. Only the region of parameter space with $\text{Br} < 0.01$ is shown since larger branching ratios are conservatively excluded. The dashed gray line is one of the main results of our study and highlights the values of the semileptonic asymmetries that heavy new physics models contributing to M_{12}^q can generate. The small overlap between the red and the gray dashed regions implies that the B-mesogenesis mechanism is in theoretical tension.

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