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Probing CP violation in semi-leptonic b-decays through time-evolution

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We discuss the role of time-dependent observables in probing CP-violation in $b \to s\ell^+\ell^-$ and $b \to s\nu\bar{\nu}$ decays. We identify a set of new observables by looking at the time evolution of the differential decay rate of $B_d \to K_S\ell^+\ell^-$ and $B_d \to K_S\nu\bar{\nu}$ where the interference of $B_d - \bar{B}_d$ meson mixing and decay is probed. We show that these observables do not require a time-dependent analysis but could be obtained by time-integrated or time-asymmetries if flavour tagging is available. These observables are precisely predicted in the SM, are unaffected by NP in models with real contributions to SM and chirally flipped operators, are independent of form factors, and are unaffected by hadronic uncertainties. They are however sensitive probes of NP scenarios involving new CP-odd phases.

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1. Introduction

This talk is based on Refs. [1, 2]. Recently, several deviations from SM predictions, hinting towards Lepton Flavour Universality Violating (LFUV) New Physics (NP), have been observed in semi-leptonic b decays [3]. The potential NP behind these anomalies can be a new source of CP-violation and currently, CP-odd phases entering in the NP Wilson coefficients are only loosely constrained [4]. These phases in semileptonic decays are hard to measure as they often only appear mixed with strong phases that are not well understood.

In the case of the simple case of the $B \to K\ell\ell$ decay, the direct CP-asymmetries are only sensitive to interference between weak and strong phases and no "standard"[1] observable has a sensitivity to the pure weak phases. In the case of vector mesons in the final state like $B \to K^*\ell\ell$ the direct CP-asymmetries suffer from the same issue, and only a small sensitivity to the weak phases is achieved. The sensitivity to these phases from CP-averaged observables is very low as they appear in the interference terms and they are not exempt from hadronic uncertainties. In Ref. [4] the freedom of the weak phases of the Wilson coefficients in global fits is shown explicitly, showing that more efforts to constrain these phases are necessary. In Ref. [1] we discuss that these phases can be probed cleanly through the interference of mixing and decay for $B \to P(S)\ell\ell$ decays, and a similar analysis can be made for $B \to V\ell\ell$ decays based on the expressions in [5].

In the case of $b \to s\nu\bar{\nu}$, CP-phases can be probed in "standard" observables only through the η_ν parameter [6] which corresponds to the interference between left and right handed amplitudes. In Ref. [2] we discuss that these CP-phases can be probed in the absence of right-handed currents through the interference of mixing and decay.

In the following sections, we briefly describe the observables and the framework introduced in Refs. [1, 2] and we discuss the importance of the time-dependent observables in both kinds of decays as they are fundamental to constrain NP phases. For simplicity, we will focus on the $B_d \to K_S\ell\ell$ decay with $\ell\ell = \ell^+\ell^-, \nu\bar{\nu}$, however, with few changes discussed in Refs. [2, 5] this discussion can also be applied to $B \to V\ell\ell$ decays.

2. Effective Hamiltonian

The $b \to s\ell\ell$ transitions can be described through the weak effective theory (WET). The effective Hamiltonian is written as:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}\left[\lambda_t \sum_{i\in I} C_i O_i + \text{h.c.}\right] + \dots \,, \tag{1}$$

where O_i and C_i correspond to the local operators of the effective theory and the their respective Wilson coefficients, $\lambda_t = V_{tb}V_{ts}^*$ and $I = \{7, 7', 9\ell, 9'\ell, 10\ell, 10'\ell\}$. Aditionally , "$\dots$" represent the 4-quark operators[2] and potential NP operators not necessary for this discussion. The main operators of interest for this discussion $O_{9^{(\prime)},10^{(\prime)}}$ are given by:

$$O_{9^{(\prime)}\ell} = \frac{e^2}{(4\pi)^2}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\ell}\gamma_\mu \ell] \,, \qquad O_{10^{(\prime)}\ell} = \frac{e^2}{(4\pi)^2}[\bar{s}\gamma^\mu P_{L(R)} b][\bar{\ell}\gamma_\mu\gamma_5 \ell] \,. \tag{2}$$

[1] With "standard" observables we refer to the observables accessible in the absence of meson mixing.

[2] These operators are not likely to receive very large contributions from NP, as these would show up in non-leptonic B decay amplitudes [7, 8].

Current global fits to experimental data suggest non-standard contributions to $C_{9(\prime)\ell}$ and $C_{10\ell}$[4, 9].

The operators involved in the effective Hamiltonian [3] describing $b \to s\nu\bar{\nu}$ can be recovered formally from the $b \to s\ell^+\ell^-$ Hamiltonian used in Refs. [1, 5] through the identification

$$C_9 \to C_L^\nu\,, \qquad C_{10} \to -C_L^\nu\,, \qquad C_{9'} \to C_R^\nu\,, \qquad C_{10'} \to -C_R^\nu\,, \tag{3}$$

where all the other (NP) Wilson coefficients vanish and a summation over neutrino flavours is required. We have $C_{L,R}^\nu = C_{L,R}^{\nu,\mathrm{SM}} + C_{L,R}^{\nu,\mathrm{NP}}$ where $C_L^{\nu,\mathrm{SM}}$ is non-vanishing and $C_R^{\nu,\mathrm{SM}} = 0$, with the same value for all three neutrino flavours.

3. Amplitudes in absence of mixing

The charged decay $B^+ \to K^+\ell\ell$ angular distribution is given by

$$\frac{d^2\Gamma(B^+ \to K^+\ell\ell)}{dq^2\, d\cos\theta_\ell} = G_0(q^2) + G_1(q^2)\cos\theta_\ell + G_2(q^2)\frac{1}{2}(3\cos^2\theta_\ell - 1) \tag{4}$$

where the angle θ_ℓ and the momentum transfer q^2 describe the emission of the charged leptons (the precise definitions can be found in Ref. [1]). We can describe the angular coefficients G_i as bilinears in the transversity amplitudes A_X which are themselves linear combinations of the relevant Wilson coefficients and the form factors that describe the hadronic transition. For instance, the G_2 angular coefficient is defined as

$$G_2 = -\frac{4\beta_\ell^2}{3}\left(|h_V|^2 + |h_A|^2 - 2\,|h_T|^2 - 4\left|h_{T_t}\right|^2\right) \qquad h_A \propto (C_{10} + C_{10'})^* f_+(q^2) \tag{5}$$

The neutral mode $B^0 \to K_S\ell\ell$ can be described through the same amplitudes due to isospin symmetry. Since the final state is a CP-eigenstate, both B and $\bar{B}$ can decay to the same states, allowing for interference between B meson mixing and decay. In the case of decays into CP eigenstates: $B \to f_{CP}$[4] it is useful to define two different angular coefficients $\bar{G}_i$, $\widetilde{G}_i$ which are CP conjugates of G_i:

- the angular coefficients $\bar{G}_i$, obtained by considering $\bar{A}_X \equiv A_X(\bar{B}_d \to \overline{f}_{CP})$ (with CP-conjugation applied to f_{CP}).
- the angular coefficients $\widetilde{G}_i$ formed by replacing A_X by $\widetilde{A}_X \equiv A_X(\bar{B}_d \to f_{CP})$ (without CP-conjugation applied on f_{CP}).

The first set of amplitudes, $\bar{A}_X$, are simply obtained from A_X by changing the sign of all weak phases. Both sets are related by $\widetilde{A}_X = \eta_X \bar{A}_X$ where η_X are the CP-parities associated to the different transversity amplitudes [2, 5, 10]. A summary of the relevant amplitudes for each decay is given in Fig. 1.

[3]We assume that NP contributes significantly to $b \to s\nu\bar{\nu}$ only through vector/axial operators (such as in NP scenarios currently favoured by global fits to $b \to s\ell^+\ell^-$ data), and that (anti)neutrinos produced in these decays are purely (right) left-handed

[4]In our example $f_{CP} = K_S\ell^+\ell^-$

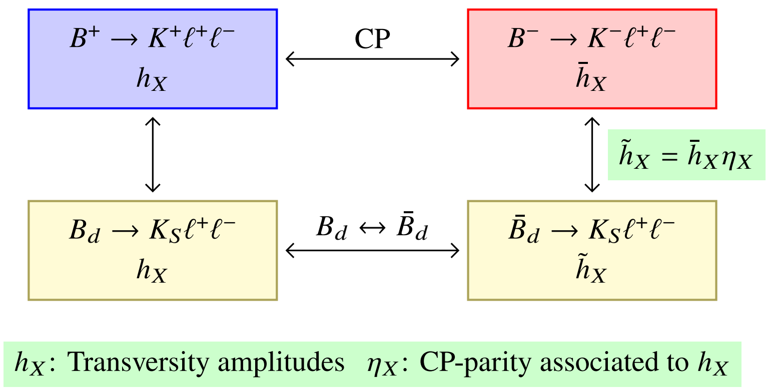

Figure 1: Diagram showing the amplitudes associated to each of the different $B \to K\ell\ell$ decays.

4. Effects of meson mixing in semileptonic decays

The effect of meson mixing in the decay into CP-eigenstates introduces a time dependence in the amplitudes that describe the decay. The time-dependent amplitudes are given by

$$A_X(t) = A_X(B(t) \to f_{CP}\ell\ell) = g_+(t)A_X + \frac{q}{p} g_-(t)\widetilde{A}_X \,, \tag{6}$$

$$\widetilde{A}_X(t) = A_X(\bar{B}(t) \to f_{CP}\ell\ell) = \frac{p}{q} g_-(t)A_X + g_+(t)\widetilde{A}_X \,, \tag{7}$$

where the absence of the t argument denotes the amplitudes in the absence of mixing. The $g_\pm(t)$ functions and the p and q parameters correspond to the usual time-evolution parameters (detailed definitions can be found in Refs. [10, 11]). For all practical purposes one can neglect CP violation in B-$\bar{B}$ mixing and assume $|q/p| = 1$ leaving the mixing angle ϕ (defined as $q/p = e^{i\phi}$) to be the relevant parameter.

The angular coefficients are obtained by replacing time-independent amplitudes with time-dependent ones, leading to the combinations $G_i(t) \pm \widetilde{G}_i(t)$ given by

$$G_i(t) + \widetilde{G}_i(t) = e^{-\Gamma t}\Big[(G_i + \widetilde{G}_i)\cosh(y\Gamma t) - h_i \sinh(y\Gamma t)\Big] \,, \tag{8}$$

$$G_i(t) - \widetilde{G}_i(t) = e^{-\Gamma t}\Big[(G_i - \widetilde{G}_i)\cos(x\Gamma t) - s_i \sin(x\Gamma t)\Big] \,, \tag{9}$$

which appear in the sum and difference of time-dependent decay rates. Above we have defined $x \equiv \Delta m/\Gamma$, $y \equiv \Delta\Gamma/(2\Gamma)$, and we have introduced a new set of angular coefficients s_i, h_i related to the time-dependent angular distribution. These new observables show a sensitivity to weak phases that is not present when mixing is neglected as it can be seen for instance by comparing G_2 (see Eq. (5)) with

$$s_2 = \mathrm{Im}\left[e^{i\phi}\left[\tilde{h}_V h_V^* + \tilde{h}_A h_A^* - 2\tilde{h}_T h_T^* - 4\tilde{h}_{T_t} h_{T_t}^*\right]\right] \,. \tag{10}$$

In order to measure these new angular observables several methods are available. A dedicated time-dependent analysis can be performed to extract these coefficients, however, the measurement of the time-integrated observables (in the case of incoherent production) and the time-asymmetries

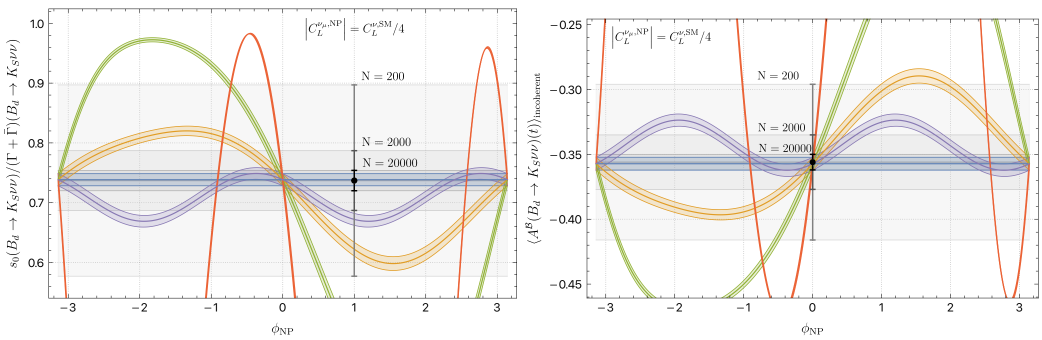

Figure 2: $\langle A^{\mathrm{CP}}\rangle_{\mathrm{incoherent}}$ (bottom) and $s_0/(\Gamma+\bar{\Gamma})$ (top) for the $B \to K_S\nu\bar{\nu}$ decay as a function of the complex phase ϕ_{NP} of the NP Wilson coefficient $C_L^{\nu_\mu,\mathrm{NP}} = e^{-i\phi_{\mathrm{NP}}}\left|C_L^{\nu_\mu,\mathrm{NP}}\right|$ for $\left|C_L^{\nu_\mu,\mathrm{NP}}\right| = \left|C_L^{\nu,\mathrm{SM}}\right|/4$ ($C_R^{\nu,\mathrm{NP}} = 0$ is assumed). The NP Wilson coefficients for the other lepton flavours carry the same phase but follow different lepton flavour structures described in Ref. [2], leading to the variations shown in yellow, green, purple and orange respectively. The SM prediction is shown in blue. The 3 grey bands correspond, from the widest to the narrowest, to the expected experimental uncertainties for N=200, N=2000, and N=20000 events [2].

(in the case of coherent production) allows them to be extracted without performing a dedicated analysis.

5. NP sensitivity and prospects

In the case of the $b \to s\ell^+\ell^-$ transition, model-independent NP effects can be included by considering shifts of the Wilson coefficient values. The observables defined above when normalised to the branching fraction (or the proper angular coefficient) are insensitive to real shifts of the Wilson coefficients[5] and only shifts on the CP-odd phase of the Wilson coefficient changes its value. This can be seen in Table 1.

In the case of $b \to s\nu\bar{\nu}$ because the different neutrino flavours cannot be separated, a flavour structure must be assumed to consider NP effects. We consider several scenarios for these NP effects already described in Ref. [2] and include naive sensitivity projections for the Belle-II and FCC-ee experiments. The effects of a non-zero NP CP-odd phase can be seen in Fig. 2. We see that the observables vary significantly when introducing a CP-violating phase ϕ_{NP} to the NP Wilson coefficient, whereas they reduce back to the SM values when ϕ_{NP} vanishes. These observables should be combined with the branching ratios (and K^* polarisations) in order to constrain both the modulus and the phase of the Wilson coefficients.

6. Conclusion

Employing the time evolution of neutral b mesons, a set of new observables can be extracted from semileptonic decays which probe the interference between mixing and decay. These observables provide a unique method to measure the CP-odd phases entering potential NP contributions. These observables are of interest both for $b \to s\ell^+\ell^-$ decays where they allow these phases to be

[5]This is only true for the SM-like Wilson coefficients and their chirally flipped counterparts. In the case of Scalar and Tensor contribution, the situation is more delicate and a full discussion can be found in Ref. [1]

Observable	SM	$C_{9\mu}^{\rm NP} = -1.12$	$C_{9\mu}^{\rm NP} = -1.12 + i1.00$
$s_0/(\Gamma + \bar{\Gamma})$	0.74(1)	0.74(1)	0.55(1)
$s_2/(\Gamma + \bar{\Gamma})$	−0.72(1)	−0.72(1)	−0.53(1)

Table 1: SM and NP predictions for the s_0 and s_2 observables normalised to the total decay width [1].

probed independently of strong phases, and for $b \to s\nu\nu$ decays where they are the only available method to extract the weak phase of left-handed NP contributions in the absence of right-handed currents.

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