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Hints for the scale of new CP-violating physics from B-CP anomalies

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Abstract: We consider several hints for new physics involving CP-asymmetries in B-decays and interpret them in terms of generic contributions to effective Wilson coefficients. The effects we focus on are: the differences in the fitted value of $\sin 2\beta$ versus the ones directly measured via the time dependent CP asymmetries in $B \to J/\psi K$ or via $B \to (\phi, \eta')K$; the difference between the direct CP asymmetries in $B^- \to K^-\pi^0$ and $\bar{B}^0 \to K^-\pi^+$ and the $\approx 2.2\sigma$ indications for the CP-asymmetry in $B_s \to J/\psi\phi$. To alleviate concerns regarding the disagreement between inclusive and exclusive V_{ub}, we show that our results hold even without the inclusion of V_{ub} in the analysis. We find that no matter what kind of new physics (NP) is invoked to explain these effects, its effective scale is bounded from above from a few hundred GeV to a few TeV depending on specific assumptions regarding the type of new physics. The only exception to this is when the NP contribution is assumed to reside entirely in LR operators in K mixing, then the scale of NP can be as high as around 24 TeV; however, this case cannot account for CP asymmetry in $B_s \to J/\psi\phi$ or a difference in $\sin 2\beta$ from penguin modes compared to that from $J/\psi K$ or for that matter the large difference seen between direct CP asymmetries in $K^-\pi^+$ and in $K^-\pi^0$.

Keywords: Beyond Standard Model, B-Physics, CP violation, Kaon Physics

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1 Introduction

The only source of flavor changing interactions in the Standard Model (SM) is provided by the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix. Unitarity imposes testable constraints on the magnitude and phases of its elements; in particular, the relation

$$V_{td}V_{tb}^* + V_{cd}V_{cb}^* + V_{ud}V_{ub}^* = 0 \tag{1.1}$$

has received considerable attention because of its strong sensitivity to the single CP violating phase that appears in the CKM. The extraction of magnitudes and phases of the various terms in eq. (1.1) from a large number of observables is complicated by the presence of hadronic uncertainties. Due to the superb performance of the two asymmetric B-factories, it has been established that the Standard Model's CKM-paradigm [1] works to an accuracy of around 15-20% [2]; therefore the effects of New Physics (NP) are expected to be a perturbation and sub-dominant. The search for NP therefore requires very good control over theory errors and high statistics data from experiments. The combination of very precise experimental results from the B-factories BaBar and Belle and from the Tevatron experiments CDF and D0, with recent progresses in lattice QCD, namely the improved determination of B_K [3] and of the $B \to \pi$ form factor [4], leads to the emergence of several indications of possible deviations from the SM. We focus on the following issues:

(a) The deduced value of $\sin 2\beta$[1] differs from the directly measured value at the 2σ level. The observables that are used to deduce the value of $\sin 2\beta$ are: the determinations of $|V_{ub}|$ and $|V_{cb}|$ from inclusive and exclusive $b \to (u,c)\ell\nu$ decays, the (indirect) CP violating parameter ε_K, and the ratio of the meson-antimeson mass differences in the B_s and B_d systems. In this deduction of $\sin 2\beta$ the only CP-violating quantity is that in the neutral kaon system. If the SM description of CP-violation through the CKM-paradigm with a single CP-odd phase is correct, then the value of $\sin 2\beta$ thus obtained should agree with the directly measured value of $\sin 2\beta$ in B-factory experiments. Following this logic, we will term this deduced value of $\sin 2\beta$ as $\sin 2\beta_{\rm SM}$. Actually, since there is some $\sim 2\sigma$ discrepancy between the values of $|V_{ub}|$ extracted from inclusive and inclusive decays [5], there is considerable motivation for obtaining $\sin 2\beta_{\rm SM}$ without using $|V_{ub}|$ which we call $\sin 2\beta_{\rm SM}^{\rm noV_{ub}}$. Of course $\sin 2\beta_{\rm SM}^{\rm noV_{ub}}$ will only be of use if it has reasonably small errors. That this has become possible, due to the improved determination of $\hat{B}_K$ from the lattice, was recently empahsized in [6].

There are two important ways for extracting directly $\sin 2\beta$ via measurements of time dependent CP asymmetries. First there is the gold-plated (i.e. free from hadronic uncertainties to a very high degree of accuracy) measurement of $\sin 2\beta$ via the time dependent CP asymmetry in $B \to (J/\psi K)$ [7]; for clarity we will denote this as $\sin 2\beta_{\psi K}$. A second way to measure $\sin 2\beta$ is via $b \to s$ penguin transitions such as B decays to ϕK_S, $\eta' K_S$, $K_S K_S K_S$, $\pi^0 K_S$, $\rho^0 K_S$, ωK_S, $f_0 K_S$, $\pi^0\pi^0 K_S$, $\phi\pi^0 K_S$, $K^+K^-K^0$ [8, 9], etc. Unfortunately, this method has some hadronic uncertainties. In the original papers this was crudely estimated at $\approx \lambda^2 \approx 5\%$ [9, 10]. In the past few years these modes received considerable theoretical attention [11–16] and as a result of that it now seems that amongst the two body modes, the $\eta' K_s$ and ϕK_s final states receive hadronic corrections at the few percent level and are therefore very clean. For this reason, in the present work we will only include these two penguin modes and we will term $\sin 2\beta$ extracted from their weighted average as $\sin 2\beta_{(\phi,\eta')K}$

If the CKM description of CP violation is correct then all three determinations of $\sin 2\beta$ should agree with each other. In fact, both the "predicted" values of $\sin 2\beta$, whether one uses $|V_{ub}|$ or not, differ from the directly measured values by $\sim 2\sigma$.

(b) New physics in $b \to s$ penguin amplitudes is also hinted at by the fact that $\sin 2\beta_{\psi K}$ differs from $\sin 2\beta_{(\phi,\eta')K}$ mentioned above by around 1.5σ.

In passing, we want to briefly mention that there is another feature of the time dependent CP-asymmetry measurements in various penguin modes[2] that deserves discussion. While the difference between $S_{J/\psi K_S}$ and $S_{\rm penguin}$, for each of the penguin modes is not that significant, a specially intriguing feature is that for many modes the central values of the asymmetry tends to be smaller than $S_{J/\psi K_S}$. Since $\sin 2\beta_{\psi K}$ is less than $\sin 2\beta_{SM}$, this obviously implies that the central value of $\sin 2\beta_{\rm penguin}$ for almost all modes is also smaller than $\sin 2\beta_{SM}$.

[1] We recall the usuage of two equivalent notations: $(\phi_1, \phi_2, \phi_3) \equiv (\beta, \alpha, \gamma)$.

[2] Time dependent CP asymmetries in a generic $B \to f$ mode are denoted with the symbol S_f.

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It is also useful to recall that comparison of $S_{J/\psi K_S}$ with $S_{(\phi,\eta')K}$ indicates whether or not $b \to s$ penguin transitions are affected by NP. Since the time dependent CP in *both* tree and penguin modes necessarily involves $B_d\bar{B}_d$ oscillations, comparison between $\sin 2\beta_{\psi K}$ and $\sin 2\beta(\phi,\eta')K$ does not tell us anything about whether there is new physics in B_d mixing.

To the extent that $\sin 2\beta_{\psi K}$ differs from $\sin 2\beta_{SM}$, the possibilty of NP contributions to B_d and/or K mixing (emphasized in particular in ref. [17]) cannot be ruled out. Furthermore, once NP is invoked, we need to be careful in identifying which observables are sensitive to the type of NP that may be out there.

(c) Another hint that $b \to s$ penguin transitions may be exhibiting a non-standard CP-odd phase comes from the comparison of the partial rate asymmetry in $B^0 \to K^+\pi^-$ and $B^+ \to K^+\pi^0$. Experimentally this difference has been determined to be $14.4 \pm 2.9\%$ [5]. These two decays are closely related as they simply require switching the spectator (u,d) quarks. Therefore, the difference between these asymmetries vanishes in the limit of exact isospin and should be small. In sharp contrast, experimentally the two asymmetries are found to have an opposite sign and the result 14.4% is non-vanishing by over 4 σ. It is difficult to rigorously assess the full significance of this unexpectedly large difference since we cannot reliably calculate, in a model independent fashion, the expectation from the SM taking QCD fully into account. In the QCD factorization approach [18, 19], the predictions for BR and CP asymmetries in hadronic two-body B decays suffer from very large hadronic uncertainties, rendering problematic their use in NP searches. However, see for instance refs. [20], a case can be made for NP in the difference $\Delta A_{CP} = A_{CP}(B^- \to K^-\pi^0) - A_{CP}(\bar{B}^0 \to K^-\pi^+)$. Ref. [20, 21] show that in the QCDF analysis of this quantity, most parametric uncertainties that occur for individual asymmetries cancel out and the theoretical prediction becomes under reasonable control (see ref. [22] for an alternate point of view) yielding $(2.2 \pm 2.4)\%$ which is still about 3.5σ away from the measured value.

(d) The time dependent CP asymmetry in $B_s \to J/\psi\phi$ is free from hadronic uncertainties, has been recently measured at CDF [23] and D0 [24, 25] and deviates from the SM at the 2σ level [26, 27]. Beyond the SM, a CP-odd phase in B_s mixing is required in order to explain this discrepancy.

(e) As is well known, over the past decade or so methods have been developed that allow direct measurement of all three angles of the unitarity triangle, (α, β, γ) [2]. What makes these methods so atractive and useful is that attempts are made either not to use any theoretical input or assumptions or make the minimal use if necessary. For the angle β (via time dependent CP studies of e.g. $B \to \psi K_s$ [7]) and the angle γ (via direct CP studies in $B^\pm \to (DK, D^*K, DK^*)$ and/or time dependent CP measurements in $B^0, \bar{B}^0 \to (DK, D^*K, DK^*)$ [28–33]) no theoretical assumptions are needed. The resulting precision is largely data driven with an irreducible theory error of $O(0.1\%)$ for β and $< 0.1\%$ for gamma [2]. For extracting the angle α a simple time dependent study of $B^0, \bar{B}^0 \to \pi^+\pi^-$ does not suffice and an isospin

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analysis [34–36] becomes necessary entailing a somewhat larger irreducible theory error, O(few %). Currently, the angle α is being extracted by using branching ratios and CP asymmetries in $B \to (\pi\pi, \rho\rho, \rho\pi)$.

Thus another useful avenue to exploit in order to test the CKM-paradigm and to constrain NP is to fit the Unitarity Triangle utilizing only the three angles (α, β, γ) which are directly measured without theoretical assumptions or input. We will use this approach to extract the resulting values of the Wolfenstein parameters ρ and η and compare them with the values deduced from the use of other methods and inputs. In particular, we show that once again the use of appropriate lattice matrix elements for ϵ_K, $\Delta M_{s,d}$, V_{cb} and with or without V_{ub} leads to $\sim 2\sigma$ deviations in one or both of the Wolfenstein parameters.

(f) Finally, we mention another approach to determine the fitted value of $\sin 2\beta$ that does not use V_{ub} determined from exclusive or inclusive semi-leptonic decays, rather this makes use of the directly measured values of α and γ (see point *(e)* above) along with ϵ_K and the ratio of mass differences in B_s and B_d mesons (see point *(a)* above). In the tables in figure 2 we list different ways of arriving at the fitted values of $\sin 2\beta$ and indicate the resulting tensions.

These anomalies in CP asymmetries involving B and B_s mesons that we mention above are all at the $(2 \div 3)\sigma$ level and may be indicative of new physics in B_d, B_s and/or in K mixing and also in $b \to s$ penguin transitions. Note that this new physics necessarily has to carry with it a beyond the SM CP-odd phase as all the observables being discussed here involve CP violation.

In this paper we analyze these hints for new physics from an effective theory point of view: we parametrize NP contributions to various operators in terms of effective scales that, with the aid of these measurements, turn out to be constrained from above and from below. The interpretation of the two sigma discrepancies described above in terms of upper bounds on the scale of new physics requires a caveat. In our approach NP contributions are essentially proportional to $1/\Lambda^2$ where Λ is a generic NP scale. The tensions that we discuss translate into $1/\Lambda^2 > 0$ (and hence $\Lambda < \infty$) at the 2σ level; therefore, we are able to set an upper limit on Λ only at the 68% (and maybe 95%) C.L.. Beyond this confidence the measurements we are considering are compatible with the SM and no upper bound on NP is implied.

The paper is organized as follows. In section 2 we summarize the present state of the various fits that we use. In section 3 we perfom a model independent analysis of new physics in B_d/K mixing and in $b \to s$ penguin amplitudes. In sections 4 and 5 we interpret the discrepancies in the fit to the unitarity triangle (UT) and in penguin amplitudes in terms of NP contributions to various operators. In section 6 we summarize and discuss our findings.

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$\lvert V_{cb}\rvert = \begin{cases} (41.67 \pm 0.68) \times 10^{-3} & \text{incl [27]} \\ (38.7 \pm 1.35) \times 10^{-3} & \text{excl [39]} \\ (41.0 \pm 0.63) \times 10^{-3} & \text{comb} \end{cases}$	$\lvert V_{ub}\rvert = \begin{cases} (39.6^{+2.5}_{-2.7}) \times 10^{-4} & \text{incl [27]} \\ (33.8 \pm 3.5) \times 10^{-4} & \text{excl [4]} \\ (37.4 \pm 2.1) \times 10^{-3} & \text{comb} \end{cases}$
$\Delta m_{B_d} = (0.507 \pm 0.005)\ \text{ps}^{-1}$ [27]	$\Delta m_{B_s} = (17.77 \pm 0.10 \pm 0.07)\ \text{ps}^{-1}$ [40]
$\Delta A_{CP} = (14.8 \pm 2.8)\%$ [27]	$\gamma = (78 \pm 12)^\circ$ [37, 38]
$\alpha_{\pi\pi,\rho\rho,\rho\pi} = (88.7 \pm 4.7)^\circ$	$\alpha_{\rho\rho} = (87.8 \pm 5.6)^\circ$
$\eta_1 = 1.51 \pm 0.24$ [41]	$m_{t,pole} = (172.4 \pm 1.2)$ GeV [42]
$\eta_2 = 0.5765 \pm 0.0065$ [43]	$m_c(m_c) = (1.224 \pm 0.057)$ GeV [44]
$\eta_3 = 0.47 \pm 0.04$ [45]	$\varepsilon_K = (2.232 \pm 0.007) \times 10^{-3}$
$\eta_B = 0.551 \pm 0.007$ [46]	$S_{J/\psi\phi} = \left(-0.76^{+0.37}_{-0.33} \ \vee\ -2.37^{+0.33}_{-0.37}\right)$ [25]
$S_{\psi K_S} = 0.672 \pm 0.024$ [27]	$S_{\phi K_S} = 0.44^{+0.17}_{-0.18}$ [27]
$S_{\eta' K_S} = 0.59 \pm 0.07$ [27]	$f_{B_s}\sqrt{\hat{B}_{B_s}} = (0.304 \pm 0.032)$ GeV [47]
$\xi = 1.211 \pm 0.045$ [48]	$\kappa_\varepsilon = 0.92 \pm 0.02$ [17]
$\hat{B}_K = 0.720 \pm 0.013 \pm 0.037$ [3]	$f_K = (155.5 \pm 0.2 \pm 0.8 \pm 0.2)$ MeV [27]
$\lambda = 0.2255 \pm 0.0007$ [49]	

Table 1. Inputs used in the unitarity triangle fit. Quantities not explicitly given are taken from ref. [5].

2 Present status of the SM fits

The set of inputs that we use in the fit is summarized in table 1. $\alpha_{\pi\pi,\rho\rho,\rho\pi}$ and $\alpha_{\rho\rho}$ are the direct determinations of α that we obtain from the isospin analysis of $B \to (\pi\pi, \rho\rho, \rho\pi)$ and $B \to \rho\rho$ decays, respectively (we use the latter when discussing for NP effects in mixing so as to avoid pollution from possible NP contributions from $b \to d$ penguins). The direct determination of γ is taken from the model independent UTfit analysis of $B \to D^{(*)}K^{(*)}$ decays [37, 38]. The explicit expressions for ΔM_{B_q}, $\Delta M_{B_s}/\Delta M_{B_d}$ and ε_K in the SM are:

$$\Delta M_{B_q} = 2\,|M_{12}^q| = \frac{\left|\langle \bar{B}_q^0 | \mathcal{H}_{\text{eff}} | B_q^0 \rangle\right|}{m_{B_q}} = \frac{G_F^2}{12\pi^2} m_W^2 m_{B_q} f_{B_q}^2 \hat{B}_{B_q} \eta_B S_0(x_t) \left|V_{tb}V_{tq}^*\right|^2 , \quad (2.1)$$

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \xi^2 \frac{m_{B_s}}{m_{B_d}} \left|\frac{V_{ts}}{V_{td}}\right|^2 , \quad (2.2)$$

$$|\varepsilon_K| = \frac{G_F^2 m_W^2 f_K^2 m_K}{12\sqrt{2}\pi^2 \Delta m_K^{\text{exp}}} \hat{B}_K \kappa_\varepsilon \,\text{Im}\Big(\eta_1 S_0(x_c)\,(V_{cs}V_{cd}^*)^2 + 2\eta_3 S_0(x_c, x_t) V_{cs}V_{cd}^* V_{ts}V_{td}^* + \eta_2 S_0(x_t)\,(V_{ts}V_{td}^*)^2\Big) . \quad (2.3)$$

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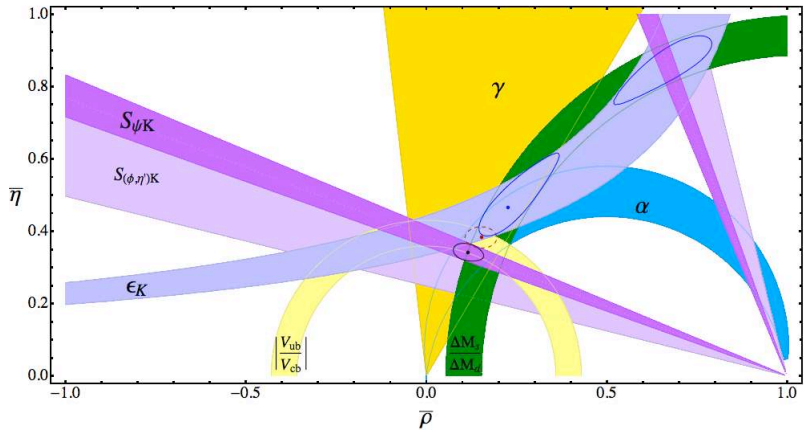

Figure 1. Unitarity triangle fit in the SM (68% C.L.). The solid black, solid blue and dashed red contours are obtained using (α, β, γ), (ε_K, ΔM_{B_s}, ΔM_{B_d}, V_{cb}) and (ε_K, ΔM_{B_s}, ΔM_{B_d}, V_{cb}, V_{ub}), respectively.

The B parameters (for $M = K,\ B_d,\ B_s$) parametrize the matrix elements

$$\langle \bar{M}|Q_1(\mu)|M\rangle = \frac{2}{3} m_M^2 f_M^2 B_M^{\overline{\rm MS}}(\mu) \tag{2.4}$$

where the operator Q_1 is given in eq. (4.2). The $\hat{B}_M$ parameters are renormalization group invariant quantities and differ from the corresponding $B_M^{\overline{\rm MS}}(\mu)$ by a perturbative factor (see, for instance, refs. [46, 50] for the details of this standard procedure). The quantity κ_ε comes from the inclusion in ε_K of the $I = 0$ component of the $K \to \pi\pi$ amplitude [17, 51–54]. The loop-functions can be found, for instance, in ref. [17, 50]. In this paper we will not concern ourselves with possible NP contributions to EW operators in the Kaon sector, whose effect is to alter the extraction of the factor κ_ε from data on ε'/ε (See ref. [51] for a complete discussion of this issue).

Our fitting procedure consists in writing a chi-squared that includes all experimental measurements and lattice determinations. This procedure implies that all systematic errors are treated as gaussian. While the true nature of systematic uncertainties remains subject of debate (see, for instance, the prescriptions adopted in refs. [55, 56]), we believe that our choice is preferable to flat systematic pdf's for several reasons: gaussian systematics lead to more conservative determinations of confidence level intervals; moreover, systematic errors in both lattice QCD and experiments are usually obtained by combining multiple sources of uncertainties, thus partially justifying our assumption. As usual we adopt the Wolfenstein parametrization of the CKM matrix and truncate the expansion at $O(\lambda^4)$. The $68\% C.L.$ allowed regions in the $(\bar{\rho}, \bar{\eta})$ plane are shown in figure 1. In figure 2 we summarize the numerical results that we obtain for $\bar{\rho}$, $\bar{\eta}$ and $\sin 2\beta$. In order to better illustrate the anatomy of the 2σ tension we decided to present the results corresponding to the inclusion of different sets of observables in the fit (we show also the result of the complete fit for comparison). It is interesting to note that the model independent determinations of α and γ affect the fit only in absence of the $|V_{ub}|$ constraint. In the figure we also include

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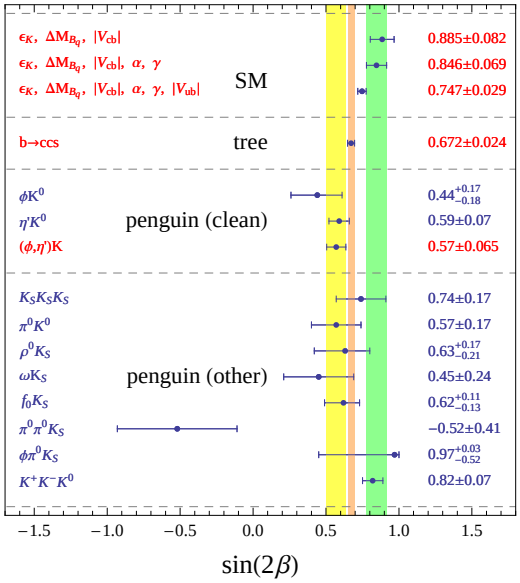
	$\bar{\rho}$	$\bar{\eta}$	$\sin 2\beta$
$\varepsilon_K, \Delta M_{B_{d,s}}, V_{cb}$:	0.236 ± 0.063	0.478 ± 0.066	0.885 ± 0.082
$\varepsilon_K, \Delta M_{B_{d,s}}, V_{cb}, V_{ub}$:	0.152 ± 0.028	0.383 ± 0.019	0.749 ± 0.030
$\varepsilon_K, \Delta M_{B_{d,s}}, V_{cb}, \alpha, \gamma$:	0.209 ± 0.049	0.442 ± 0.046	0.846 ± 0.069
$\varepsilon_K, \Delta M_{B_{d,s}}, V_{cb}, \alpha, \gamma, V_{ub}$:	0.150 ± 0.024	0.382 ± 0.018	0.747 ± 0.029
$\alpha, \gamma, S_{\psi K}$:	0.116 ± 0.027	0.341 ± 0.016	
$\varepsilon_K, \Delta M_{B_{d,s}}, V_{cb}, V_{ub}, \alpha, \gamma, S_{\psi K}$:	0.127 ± 0.020	0.357 ± 0.012	



mode	w/out V_{ub}	with V_{ub}
$S_{\psi K_S}$	$2.4\ \sigma$	$2.0\ \sigma$
$S_{\phi K_S}$	$2.2\ \sigma$	$1.8\ \sigma$
$S_{\eta' K_S}$	$2.6\ \sigma$	$2.1\ \sigma$
$S_{(\phi+\eta')K_S}$	$2.9\ \sigma$	$2.5\ \sigma$

Figure 2. Results of the fit to the unitarity triangle within the SM. In the table on top we collect the results we obtain for different selection of inputs. The plot is a graphical comparison between the SM predictions given above and the direct determinations in $b \to c\bar{c}s$ and $b \to s$ penguin modes. In bottom-right table we show the deviation of the clean $\sin 2\beta$ measurements from the SM predictions obtained using ε_K, ΔM_{B_q}, $|V_{cb}|$, α, γ. The last column shows the impact of $|V_{ub}|$.

a graphical representation of the discrepancy between direct and indirect (SM prediction) determinations of $\sin 2\beta$ as well as a pull table in which we quantify this discrepancy in terms of standard deviations. In the pull table, the w/out (with) V_{ub} column refers to the treatment of V_{ub} on top of a fit that includes ε_K, ΔM_{B_q}, $|V_{cb}|$, α and γ; the reference values of the SM predictions that we use in the pull table are therefore:

$$\sin(2\beta) = \begin{cases} 0.846 \pm 0.069 & \text{without } |V_{ub}| \\ 0.747 \pm 0.029 & \text{with } |V_{ub}| \end{cases} . \tag{2.5}$$

These results summarize nicely the 2σ tensions *(a)* and *(b)* that we discussed in the introduction.

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3 Model independent analysis

The results of the previous analysis can be interpreted in the context of new physics contributions to B_d-mixing ($M_{12}^{B_d}$) , ε_K and to $b \to s$ penguin amplitudes ($A_{b\to s}$). For the sake of simplicity we consider only the two extreme scenarios in which we admit new physics effects to $(M_{12}^{B_d}, A_{b\to s})$ and $(\varepsilon_K, A_{b\to s})$, respectively. In this section we adopt very general parametrizations of possible new physics contributions; the connection to actual mass scales will be discussed in sections 4 and 5.

3.1 Scenario I

We assume all new physics effects to be effectively taken into account via the introductions of two extra phases, ϕ_d and θ_A:

$$M_{12}^d = \left(M_{12}^d\right)_{\rm SM} \, e^{2i\phi_d} \, , \tag{3.1}$$

$$\mathcal{A}_{b\to s} = (\mathcal{A}_{b\to s})_{\rm SM} \, e^{i\theta_A} \, . \tag{3.2}$$

The expressions for the time-dependent CP asymmetries become:

$$S_{\psi K} = \sin\left[2(\beta + \phi_d)\right] \, , \tag{3.3}$$

$$S_{(\phi,\eta')K} = \sin\left[2(\beta + \phi_d + \theta_A)\right] \, . \tag{3.4}$$

Note that we are implicitly assuming that NP effects in $b \to s$ penguin amplitudes are identical in the ϕ and η' modes. This is necessary in order to use a simple parametrization as in (3.2). This assumption will be relaxed in the operator level analysis presented in section 5 where we adopt QCD factorization. Furthermore, the extraction of γ from $B \to D^{(*)}K^{(*)}$ decays is controlled by tree-level decays and is assumed to be insensitive to new physics effects. This assumption does not hold for α. In this case the isospin analysis extracts and effective angle given by $\alpha_{\rm eff} = \alpha - \phi_d + \theta_{\rm penguin}$. Here ϕ_d is the same angle that appears in eq. (3.1), while $\theta_{\rm penguin}$ is a possible new physics phase in $b \to d$ penguin amplitudes. In order to simplify the analysis we will utilize only the $B \to \rho\rho$ channels in the extraction of $\alpha_{\rm eff}$ because, in this case, the penguin contribution turns out to be experimentally very small and we are justified in setting $\theta_{\rm penguin} = 0$. In this scenario, the theory prediction for $\sin(2\beta)$ is obtained by excluding from the chi-squared both $S_{\psi K}$ *and* α; we obtain:

$$\sin(2\beta) = \begin{cases} 0.867 \pm 0.080 & \text{without } |V_{ub}| \\ 0.747 \pm 0.029 & \text{with } |V_{ub}| \end{cases} . \tag{3.5}$$

In the left panel of figure 3 the contours define regions whose projections on the axes yield the one dimensional ranges at 68% (solid) and 95% (dashed) confidence level. Without the inclusion of V_{ub} we obtain:

$$\phi_d = -\left(8.7^{+3.4}_{-2.8}\right)^{\rm o} \tag{3.6}$$

$$\theta_A = -\left(3.8 \pm 2.1\right)^{\rm o} \tag{3.7}$$

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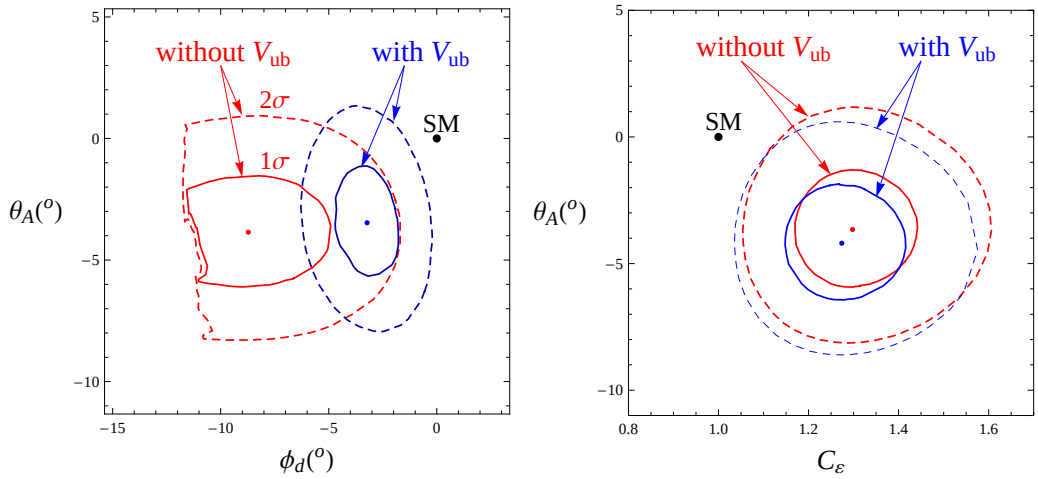

Figure 3. Model independent analysis of new physics effects in B_d (left panel), K (right panel) mixing and $\mathcal{A}_{b\to s}$ (both panels). Solid and dashed lines corresponds to the 1σ and 2σ contours, respectively.

As can be seen from figure 3 the negative error on ϕ_d is highly non-gaussian. The sharp cut-off at $\phi_d \sim -11^o$ is due to the interplay between ϵ_K and $\Delta M_{B_s}/\Delta M_{B_d}$ on one side and $S_{\psi K}$ and $B \to \rho\rho$ on the other (we remind the reader that the former extract $\beta^{\rm eff} = \beta + \phi_d$ and the latter $\alpha^{\rm eff} = \alpha - \phi_d$). The inclusion V_{ub} into the fit lowers considerably the predicted value of $\sin(2\beta)$ (as can be deduced from eq. (2.5) and figure 1, thus impacting strongly the extraction of ϕ_d. On the other hand, θ_A is essentially determined by the difference between the time dependent CP asymmetries in $B \to J/\psi K$ on one side and $B \to (\phi, \eta')K$ on the other; hence the outcome of the fit, eq. (3.7), is largely independent on the inclusion of V_{ub}. Numerically we find that both the ϕ_d central value and error decrease by a factor of two:

$$\phi_d = -\left(3.2^{+1.5}_{-1.3}\right)^{\rm o} \tag{3.8}$$

$$\theta_A = -(3.5^{+2.2}_{-1.9})^{\rm o} \tag{3.9}$$

In this scenario we interpret the tension in the fit to the unitarity triangle in terms of NP contributions to the time dependent CP asymmetries in $b \to c\bar{c}s$ and $b \to s\bar{s}s$ modes. The discrepancy between the predicted and "measured" values of $\sin(2\beta)$ is explained by new physics contributions to B_d mixing; the difference between $S_{\psi K}$ and $S_{(\phi,\eta')K}$ is induced by a new phase in the $b \to s$ penguin amplitude.

3.2 Scenario II

We now assume the absence of new physics contributions to B_d mixing and investigate the possibility that the tension in the fit is induced by new effects in K mixing. The discrepancy between the time dependent CP asymmetries in the $b \to c\bar{c}s$ and $b \to s$ penguin modes

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still requires an independent NP phase. We adopt the following parametrization:

$$\varepsilon_K = C_\varepsilon \ (\varepsilon_K)_{\rm SM} \ , \tag{3.10}$$

$$\mathcal{A}_{s\bar{s}s} = (\mathcal{A}_{s\bar{s}s})_{\rm SM} \ e^{i\theta_A} \ . \tag{3.11}$$

Note that the expressions for the time-dependent CP asymmetries become:

$$S_{c\bar{c}s} = \sin\left[2\beta\right] \ , \tag{3.12}$$

$$S_{s\bar{s}s} = \sin\left[2(\beta + \theta_A)\right] \ . \tag{3.13}$$

In the right panel of figure 3 we show the 68% C.L. (solid) and 95% C.L. (dashed) allowed region in the $(C_\varepsilon, \theta_A)$ plane. The one-sigma ranges for these two parameters without the inclusion of V_{ub} in the fit read:

$$C_\varepsilon = (1.31 \pm 0.14) \ , \tag{3.14}$$

$$\theta_A = -(3.6 \pm 2.3)^{\rm o} \ . \tag{3.15}$$

The impact of V_{ub} shifts only slightly these values:

$$C_\varepsilon = (1.28 \pm 0.13)^{\rm o} \ , \tag{3.16}$$

$$\theta_A = -(4.1 \pm 2.3)^{\rm o} \ . \tag{3.17}$$

In this scenario, the $\sin(2\beta)$ prediction coincides essentially with $S_{\psi K}$ and does not depend much on the inclusion of V_{ub}; hence the amount of new physics required to bring ε_K in agreement with the rest of the fit is quite insensitive to the V_{ub} constraint.

4 Operator analysis of new physics in the fit to the UT

From our previous discussion it is clear that the tension in the fits of the unitarity triangle are related to the presence of new physics either in B_d or K mixing. The effective Hamiltonian that describes meson mixing (B_d, B_s and K) can be written as:

$$\mathcal{H}_{\rm eff} = \frac{G_F^2 m_W^2}{16\pi^2} \left(V_{tq} V_{tq'}^*\right)^2 \left(\sum_{i=1}^{5} C_i O_i + \sum_{i=1}^{3} \tilde{C}_i \tilde{O}_i\right) + \text{h.c.}, \tag{4.1}$$

where we have $(q, q') = (bd), (bs), (sd)$ for B_d, B_s and K mixing. The operators are defined as follows:

$$O_1 = \left(\bar{q}'_L \gamma_\mu q_L\right) \left(\bar{q}'_L \gamma_\mu q_L\right) \tag{4.2}$$

$$O_2 = \left(\bar{q}'_R q_L\right) \left(\bar{q}'_R q_L\right) \tag{4.3}$$

$$O_3 = \left(\bar{q}'^{\alpha}_R q^{\beta}_L\right) \left(\bar{q}'^{\beta}_R q^{\alpha}_L\right) \tag{4.4}$$

$$O_4 = \left(\bar{q}'_R q_L\right) \left(\bar{q}'_L q_R\right) \tag{4.5}$$

$$O_5 = \left(\bar{q}'^{\alpha}_R q^{\beta}_L\right) \left(\bar{q}'^{\beta}_L q^{\alpha}_R\right) \tag{4.6}$$

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and $\tilde{O}_{1,2,3}$ are obtained from $O_{1,2,3}$ via the $L \leftrightarrow R$ substitution. In the following we will consider new physics contributions to the Wilson Coefficients of the operators O_1 and O_4 ($\tilde{O}_4$ has the same anomalous dimension and matrix element as O_4, hence we are really constraining $C_4 + \tilde{C}_4$). O_1 is the only operator that receives a non-negligible contribution in the SM. Contributions to C_4 are especially interesting because they are enhanced by QCD running effects and by chiral factors [57] that appear in the calculation of their matrix elements; in particular, in the K mixing case these effects result in a two order of magnitude enhancement. We parametrize new physics contributions to the various Wilson coefficients as:

$$\delta C_{1,4}^{B_q,K}(\mu^0) = -\frac{1}{G_F^2 m_W^2}\frac{e^{i\varphi}}{\Lambda^2}\,. \tag{4.7}$$

where we retained a factor $1/(16\pi^2)$ to take into account a possible loop-suppression of NP effects[3] and we decided to factor out the CKM couplings. The factor -1 is introduced because we know from the model independent analysis of section 3.1 that the required NP phase has to be negative. Combining eqs. (4.1) and (4.7), the NP contribution to the effective Hamiltonian is

$$\delta\mathcal{H}_{\rm eff} = -\frac{\left(V_{tq}V_{tq'}^*\right)^2}{16\pi^2}\,\frac{e^{i\varphi}}{\Lambda^2}\,O_i + \text{h.c.} \tag{4.8}$$

and the scale Λ absorbs every NP coupling, mass scale and loop function apart from the CKM matrix and the typical $1/(16\pi^2)$. Using eq. (4.7) we obtain $C_{\rm NP}/C_{\rm SM} \simeq -e^{i\varphi}(700\text{ GeV}/\Lambda)^2$; hence for $\Lambda \sim 700$ GeV the new physics and SM contributions to the Wilson coefficients are of similar size. In the remainder of this section we show the bounds on Λ that we obtain in the two scenarios we introduced in section 3. We will also consider the possibility of simultaneous NP contributions to (B_d, B_s) and (B_d, B_s, K) mixing

4.1 New physics in B_d mixing

We begin by assuming that new physics contributes to a single operator relevant to B_d mixing (this corresponds to Scenario I of section 3.1) and take $\delta^{\rm NP}C_1^{B_d} \neq 0$. We do not consider NP contributions to the other $(\bar{b}d)(\bar{b}d)$ operators that appear in eq. (4.1) because their hadronic matrix elements are all very similar (e.g. no large chiral enhancement of LR operators) and the outcome of the analysis does not change appreciably. Note that we introduce new physics to the the B_d mixing amplitude only; as a consequence, the phase ϕ_d is non vanishing and, since we do not allow contributions to B_s mixing, the ratio $\Delta M_{B_s}/\Delta M_{B_d}$ will be affected too. Using the expression eq. (4.7) for the generic NP contribution to $C_1^{B_d}$ we have:

$$M_{12}^d = \left|M_{12}^d\right|_{\rm SM} e^{2i\beta}\left(1 - \frac{e^{i\varphi}}{\kappa\Lambda^2}\right) \tag{4.9}$$

where $\kappa = G_F^2 m_W^2 S_0(x_t)$. From the model independent results we obtained in section 3, we see that the phase $\phi_d = 1/2\arg(1 - e^{i\varphi}/\kappa\Lambda^2)$ is negative, implying $\varphi > 0$. In figure 4

[3] This factor appears in the definition of the effective Hamiltonian (4.1).

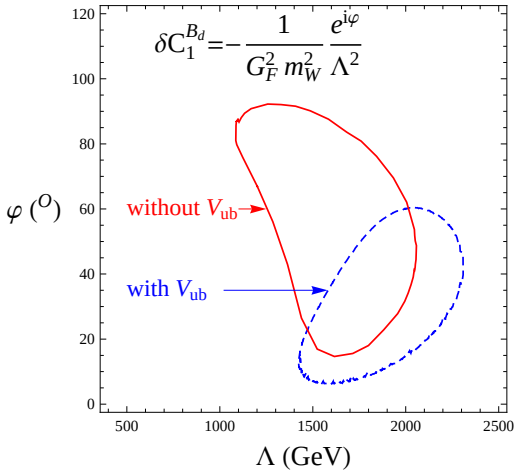

Figure 4. New physics in B_d mixing.

we show the allowed regions in the Λ, φ plane. We write a chi-squared that contain all the observables we discussed in sections 2 and 3 (namely ε_K, $\Delta M_{B_{d,s}}$, V_{cb}, $|V_{ub}|$, γ from $D^{(*)}K^{(*)}$ decays, α from $B \to \rho\rho$, and $S_{\psi K_S}$) and minimize with respect to all variables (including $\bar{\rho}$ and $\bar{\eta}$). The contours are such that their projections on the axis correspond to the one-dimensional 68% C.L. regions for Λ and φ. The green (dashed) and blue (solid) contours are obtained with and without the inclusion of $|V_{ub}|$ in the fit, respectively. The presence of the upper limit $\Lambda \lesssim 2.3$ TeV reflects the two sigma effects eqs. (3.6) and (3.8). The lower bound $\Lambda \gtrsim 1.$ TeV is a direct consequence of NP contributions to X_{sd}:

$$\frac{\Delta M_{B_s}}{\Delta M_{B_d}} = \left(\frac{\Delta M_{B_s}}{\Delta M_{B_d}}\right)_{\rm SM} \left|1 - \frac{e^{i\varphi}}{\kappa \Lambda^2}\right|^{-1} . \tag{4.10}$$

The qualitative impact of the V_{ub} constraint can be inferred from the analysis of section 3.1 and from figure 3. A reduction in the absolute size of ϕ_d translates into smaller values for $\varphi - \pi$. Finally, it is interesting to extract the predicted value for $\sin(2\beta)$:

$$\sin(2\beta) = \begin{cases} 0.82 \pm 0.10 & \text{without } V_{ub} \\ 0.73 \pm 0.03 & \text{with } V_{ub} \end{cases} . \tag{4.11}$$

The comparison of this result with the SM prediction given in eq. (2.5), shows that in this scenario the tension between $\sin(2\beta)$ and the CP asymmetries in the ϕK and $\eta' K$ channels is somewhat eased: $S_{(\phi+\eta')K}$ deviates from $\sin(2\beta)$ at the 2.2/2.1 σ level with/without the inclusion of V_{ub}.

4.2 New physics in both B_d and B_s mixing

In this section we modify the analysis of section 4.1 by allowing simultaneous identical NP contributions to B_d and B_s mixing: $\delta C_1^{B_d} = \delta C_1^{B_s}$. This approach is inspired by a Minimal Flavor Violating (MFV) ansatz[4] in which NP contributions to $M_{12}^{d,s}$ are identical up to

[4]However, we stress that if the B-CP anomalies we discussed in here are confirmed, that would be quite inconsistent with the general notions and expectations of models based on MFV.

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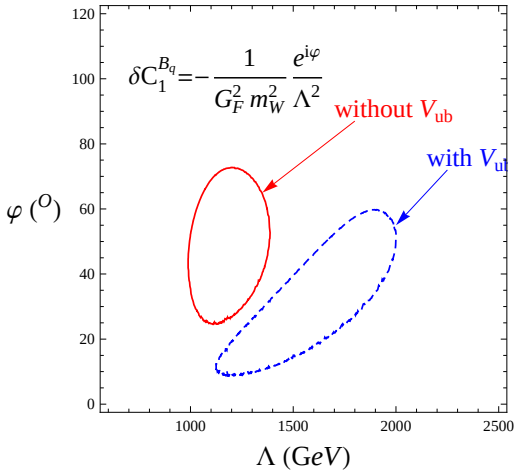

Figure 5. New physics contributions to B_d and B_s mixing.

CKM factors:

$$\delta M_{12}^d \propto -(V_{tb}V_{td}^*)^2 \frac{e^{i\delta}}{\Lambda^2} \qquad \text{and} \qquad \delta M_{12}^s \propto -(V_{tb}V_{ts}^*)^2 \frac{e^{i\delta}}{\Lambda^2}\,. \tag{4.12}$$

It is important to stress that we introduce this complex contribution only in flavor changing operators involving quarks. In explicit NP models that implement this idea, e.g. extra Z' with flavor changing quark couplings, it is important to keep under control phases that appear in interactions that conserve flavor or involve leptons (the latter, in particular, are constrained by CP asymmetries in exclusive $b \to s\ell^+\ell^-$ decays). The inclusion of a complex correction to M_{12}^s is of great interest because it allows to reconcile the constraint coming from the time dependent CP asymmetry in the $B \to J/\psi\phi$ system with the rest of the fit. In the numerics we utilize the HFAG combination of D0 and CDF data: $\phi_s = -0.76^{+0.37}_{-0.33}$ or $\phi_s = -2.37^{+0.33}_{-0.37}$ [27] (information from the flavor specific life time and the semileptonic asymmetry is included).

In this scenario the mass differences ΔM_{B_s}, ΔM_{B_d}, as well as the B_q mixing phases are affected but the ratio $\Delta M_{B_s}/\Delta M_{B_d}$ does not receive contributions. This is because the relative impact of NP on the B_q systems is identical. The measurements that we include into the fit are ε_K, $\Delta M_{B_{d,s}}$, V_{cb}, $|V_{ub}|$, γ from $D^{(*)}K^{(*)}$ decays, α from $B \to \rho\rho$, $S_{\psi K_S}$ and $S_{J/\psi\phi}$. The result of the analysis is summarized in figure 5. A striking feature of these results is the large impact that the inclusion of V_{ub} has on the allowed regions in the (Λ, φ) plane. The impact of V_{ub} is to require a smaller ϕ_d phase because the discrepancy between the direct and indirect determinations of $\sin(2\beta)$ decreases in absolute value. On the other hand the observed discrepancy in the phase measured in the $J/\psi\ \phi$ system still points to large effects. The friction between these two competing effects results is responsible for the large shifts in the contours obtained with and without V_{ub}. The predictions that we obtain

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for $\sin(2\beta)$ are:

$$\sin(2\beta) = \begin{cases} 0.88 \pm 0.07 & \text{without } V_{ub} \\ 0.75 \pm 0.03 & \text{with } V_{ub} \end{cases} . \tag{4.13}$$

In this case, the tension between the global extraction of $\sin(2\beta)$ and the $(\phi, \eta')K$ CP asymmetries is unaffected.

4.3 New physics in K mixing

The scenario described in section 3.2 corresponds to new physics contributions to the K mixing amplitude only. We implement this framework by allowing contributions to either C_1^K or C_4^K: all new physics effects are confined to ε_K. Note that this time we consider separately possible NP effects in the LR operator O_4^K: because of the large QCD running effects on its Wilson coefficient and of the chiral enhancement of its matrix element, the bounds that we extract for this case are about one order of magnitude stronger then the ones we obtain for new physics in O_1. The explicit formula for ε_K that we use to study NP contributions to the Wilson coefficients of the operators O_1^K and O_4^K is obtained from the SM formula (2.3) via the substitution:

$$S_0(x_t) \to S_0(x_t) \left[1 - \frac{e^{i\varphi}}{\kappa \Lambda^2}\right], \quad \text{for NP in } C_1^K \tag{4.14}$$

$$S_0(x_t) \to S_0(x_t) \Big[1 - \underbrace{\frac{e^{i\varphi}}{\kappa \Lambda^2} \frac{B_4 K_{44}}{\hat{B}_K \eta_2} \frac{3\, m_K^2}{4(m_s + m_d)^2}}_{\equiv \chi}\Big], \quad \text{for NP in } C_4^K \tag{4.15}$$

where $\kappa = G_F^2 m_W^2 S_0(x_t)$, $m_s = (100 \pm 10)$ MeV [58, 59], $m_d = (4.6 \pm 3)$ MeV [58], $B_4 = 1.03 \pm 0.06$ [60] and $K_{44} \simeq 3.7$ is calculated below. The factor χ, whose numerical estimate is given below in eq. (4.19), quantifies the different impact that new physics contributions to the Wilson coefficients C_1 and C_4 have on ε_K and is enhanced by chiral and QCD-running effects. The masses of the strange and down quarks are defined in the $\overline{MS}$ scheme at the scale $\mu_L \sim 2$ GeV and are taken from ref. [58, 59] (the actual value of m_s that we adopt reflects the dispersion of several lattice results). $B_4 = B_4^{\overline{MS}}(\mu_L)$ is the bag parameter of the operator O_4 and it has been calculated in quenched lattice QCD; the value we use is taken from ref. [60]. Note that we have:

$$\frac{\langle O_4^K(\mu_L)\rangle}{\langle O_1^K(\mu_L)\rangle} = \frac{3\, m_K^2}{4(m_s + m_d)^2} \frac{B_4}{B_K} , \tag{4.16}$$

Finally, QCD effects in the running of the Wilson coefficients between μ_H and μ_L are summarized in the matrix K_{rs}:

$$K_{rs} = \sum_i \left(b_i^{(r,s)} + \eta\, c_i^{(r,s)}\right) \eta^{a_i} , \tag{4.17}$$

$$C_r(\mu_L) = \sum_s K_{rs}\, C_s(\mu_H) , \tag{4.18}$$

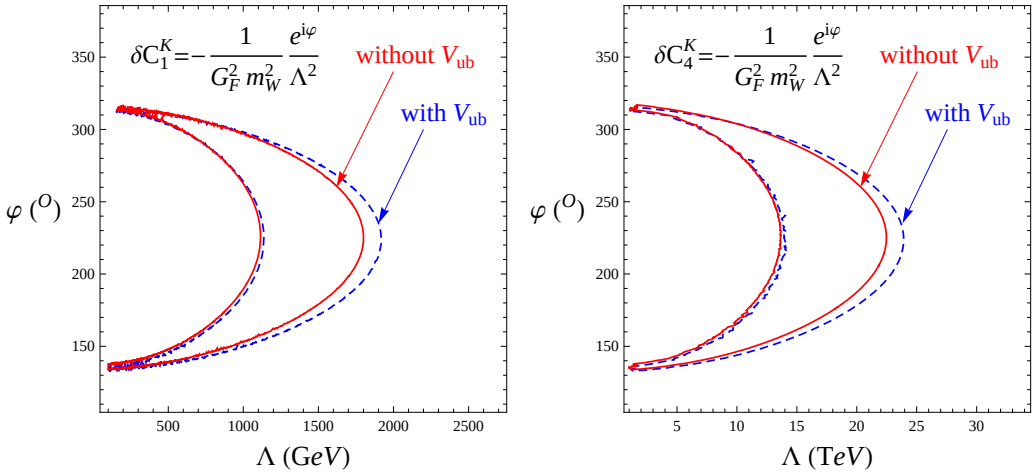

Figure 6. New physics in K mixing.

where $\eta = \alpha_s(M_H)/\alpha_s(m_t)$ and the magic numbers a_i, b_i and c_i have been calculated for $\mu_L = 2$ GeV in ref. [60]. In this analysis we take $\mu_H = m_t$. The MS-bar scheme dependence of the bag parameters B_i can be removed by including part of the QCD running effects into their definition, thus leading to the introduction of the hat parameters $\hat{B}_i$. Eq. (4.15) is justified because we have $B_K K_{11} = \hat{B}_K \eta_2$. Putting everything together we find

$$\chi = (157 \pm 33)\left(\frac{0.720}{\hat{B}_K}\right)\left(\frac{0.5765}{\eta_2}\right). \tag{4.19}$$

The presence of NP in M_{12}^K affects the extraction of $\sin(2\beta)$ from $S_{\psi K}$. In the present case NP contributions to K mixing are proportional to $(V_{td}V_{ts}^*)^2$; hence their effect is $O(1)$ on $\varepsilon_K \sim \mathrm{Im}M_{12}^K$ but only $O(0.1\%)$ on $\mathrm{Re}M_{12}^K$. In the following we will neglect such corrections to $S_{\psi K}$. In figure 6 we show the results of the analysis. The projections of the blue (solid) and green (dashed) contours onto the Λ and φ axes correspond to the one-dimensional 68% C.L. ranges.

Note that the inclusion of V_{ub} in the fit does not impact appreciably the allowed regions in the (Λ, φ) plane. In this scenario the role of NP effects is to reconcile the ε_K constraint with the rest of the fit (V_{cb}, V_{ub}, ΔM_{B_q}, α, γ and, especially, $S_{\psi K}$). In particular, the inclusion of $S_{\psi K}$ in the fit renders the latter quite insensitive to V_{ub}. In general V_{ub} tends to slightly improve the overall consistency of the fit to the UT within the SM, therefore after the inclusion of V_{ub} the bounds on Λ become slightly weaker.

Another interesting feature of figure 6 is the absence of a lower limit on the scale of NP. This happens because ε_K is given by the imaginary part of M_{12}^K; hence a given correction can be obtained for any arbitrarily small Λ by appropriately choosing φ. Note that the NP contribution to M_{12}^K is proportional to $-e^{i(2\beta+\varphi)}/\Lambda^2$ and in the limit $\varphi \to (\pi - 2\beta, 2\pi - 2\beta)$ the correction induced on ε_K vanishes: this feature is evident in figure 6 in which the asymptotic values of φ in the limit $\Lambda \to 0$ are very close to $\pi - 2\beta$ and $2\pi - 2\beta$.

The upper bounds on the NP scale that we extract are about $1.8 \div 1.9$ TeV and $23 \div 24$ TeV for the C_1^K and C_4^K scenarios, respectively.

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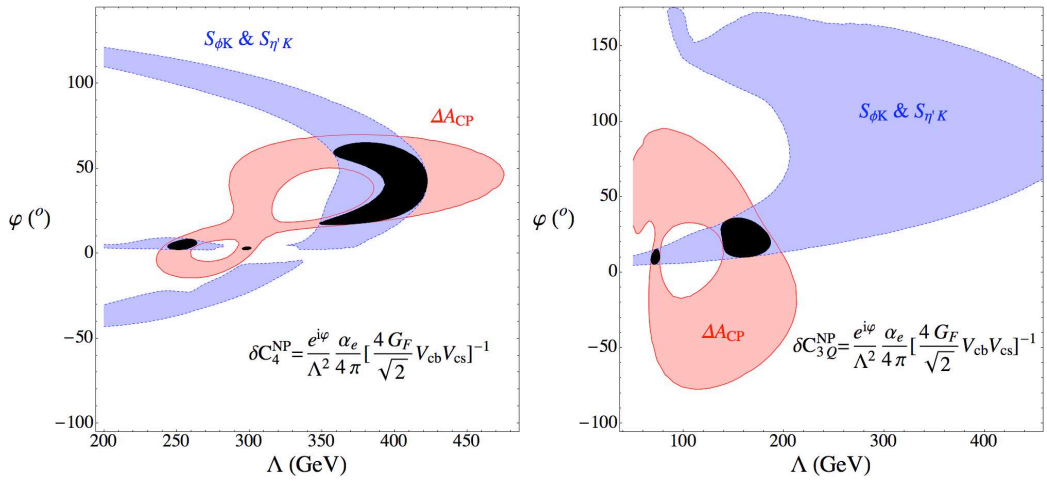

Figure 7. New physics in $b \to s$ penguin amplitudes.

5 Operator analysis of new physics in $b \to s$ amplitudes

In this section we interpret the difference between the time dependent CP asymmetries $S_{\psi K}$ and $S_{\phi,\eta'}$ in terms of new physics contributions to the QCD or EW penguin operators. The effective Hamiltonian responsible for the $B \to (\phi, \eta')K_S$ amplitudes is:

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb}V_{cs}^* \left(\sum_{i=1}^{6} C_i(\mu) O_i(\mu) + \sum_{i=3}^{6} C_{iQ}(\mu) O_i(\mu) \right) + \text{h.c.} \,. \tag{5.1}$$

The definition of the various operators can be found, for instance, in ref. [61]. Here we focus on two operators whose matching conditions are are likely to receive new physics contributions:

$$Q_4 = (\bar{s}_L \gamma^\mu T^a b_L) \sum_q (\bar{q} \gamma_\mu T^a q) \ . \tag{5.2}$$

$$Q_{3Q} = (\bar{s}_L \gamma^\mu b_L) \sum_q Q_q \, (\bar{q} \gamma_\mu q) \ . \tag{5.3}$$

We adopt the following parametrization of new physics effects:

$$\delta C_{4,3Q} = \frac{e^{i\varphi}}{\Lambda^2} \frac{\alpha_{s,e}}{4\pi} \left[\frac{4G_F}{\sqrt{2}} V_{cb}V_{cs}^* \right]^{-1} \ , \tag{5.4}$$

where we kept the coupling and loop suppression typical of QCD and EW penguins (the factor $\alpha_{s,e}/(4\pi) = (e^2, g_s^2)/(16\pi^2)$). Note that we have absorbed all new physics couplings in the effective scale Λ. It is important to notice that once we introduce new physics contributions in these penguin operators we induce important effects in the $B \to K\pi$ system as well; in particular, we will consider the difference of CP asymmetries $\Delta A_{CP} = A_{CP}(B^- \to K^- \pi^0) - A_{CP}(\bar{B}^0 \to K^- \pi^+)$. In order to describe the impact of the new physics coefficients onto the ϕK, $\eta' K$ and $K\pi$ system, we follow the QCD factorization

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analysis of refs. [11, 18, 19]. Within the SM we find:

$$\delta S_{\phi K} = 0.03 \pm 0.01 \,, \tag{5.5}$$

$$\delta S_{\eta' K} = 0.01 \pm 0.025 \,, \tag{5.6}$$

$$\Delta A_{CP}^{\rm SM} = (2.2 \pm 2.4)\% \,. \tag{5.7}$$

The errors in eqs. (5.5), (5.7) are obtained by varying simultaneously all the hadronic inputs that we take from refs. [11, 18, 19]. In the left and right panels of figure 7, we present the allowed regions of the (Λ, φ) plane in presence of new physics contributions to C_4 and C_{3Q}. The blue and red shaded regions are obtained using the constraints from $S_{(\phi,\eta')K}$ and ΔA_{CP}, respectively. The black areas are obtained by requiring both constraints simultaneously. The excluded regions within the ΔA_{CP} contours correspond to a part of the parameter space that yields a too large value of ΔA_{CP}. The irregular behavior of the $S_{(\phi,\eta')K}$ contours is due to the complicated structure of the theoretical errors on these quantities. For each point in the (Λ, φ) plane we determine the theoretical error by varying all the hadronic inputs; the resulting two-dimensional error function is then utilized in the chi-squared fit.

The most important result of this analysis is the existence of an upper limit on the effective scale of about 400 GeV (200 GeV) for new physics contributions to QCD (EW) penguin operators.

6 Summary

We discussed several anomalies involving CP asymmetries in B and B_s decays. The measured CP asymmetry in $B \to J/\psi K_S$ when compared with the SM prediction from the fits of the UT seems to be too small by about 15% and this hints to new physics in either B_d or K mixing. The non-vanishing differences between the time dependent CP asymmetries in $B \to J/\psi K_S$ and $B \to (\phi, \eta')K$ modes monitors the presence of new physics in $b \to s$ transitions. The latter is also hinted at by the direct CP asymmetries in the $K\pi$ system (ΔA_{CP}). The large asymmetry in $B_s \to J/\psi\phi$ also indicates a non-vanishing beyond the SM phase in B_s mixing on the face of a negligible asymmetry in the SM.

The tension in the fit to the UT can, for example, be explained with an extra phase in M_{12}^d whose value is found to be $\phi_d \approx -(3 \pm 1.5)^{\rm o}$ (we obtain $-(9 \pm 3)^{\rm o}$ if no use of V_{ub} is made) or by new physics in ε_K for which we find $C_\varepsilon \approx 1.3 \pm 0.1$, where in the SM, $C_\varepsilon = 1$. The anomaly in the (ϕ, η') system points to a new phase in $b \to s$ amplitudes for which we obtain $\theta_A \approx -(4 \pm 2)^{\rm o}$.

These results can be interpreted in an effective Hamiltonian formalism in terms of NP contributions to Wilson coefficients. In this way we can translate these hints for NP into scales at which we expect to find accelerator signals. Our results for different physics scenarios are summarized in table 2. Our main finding is that, no matter what kind of new physics is invoked to explain these effects, its effective scale is bounded from above at few TeV. The only exception are NP contributions solely confined to the LR operator in K-mixing; however, it should be stressed that if NP affects only K mixing, then it cannot

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Scenario	Operator	Λ (TeV)	φ (^{o})
B_d mixing	$O_1^{(d)}$	$\begin{cases} 1.1 \div 2.1 & \text{no } V_{ub} \\ 1.4 \div 2.3 & \text{with } V_{ub} \end{cases}$	$\begin{cases} 15 \div 92 & \text{no } V_{ub} \\ 6 \div 60 & \text{with } V_{ub} \end{cases}$
$B_d = B_s$ mixing	$O_1^{(d)}$ & $O_1^{(s)}$	$\begin{cases} 1.0 \div 1.4 & \text{no } V_{ub} \\ 1.1 \div 2.0 & \text{with } V_{ub} \end{cases}$	$\begin{cases} 25 \div 73 & \text{no } V_{ub} \\ 9 \div 60 & \text{with } V_{ub} \end{cases}$
K mixing	$O_1^{(K)}$ $O_4^{(K)}$	< 1.9 < 24	$130 \div 320$
$\mathcal{A}_{b\to s}$	$O_4^{b\to s}$ $O_{3Q}^{b\to s}$	$.25 \div .43$ $.09 \div .2$	$0 \div 70$ $0 \div 30$

Table 2. Bounds on the scale and phase of NP contributions to B_d, B_s, K mixing and to $b \to s\bar{s}s$ penguin amplitudes. Λ and φ are defined in eqs. (4.7) and (5.4).

explain the difference in the extraction of $sin2\beta$ from $B \to J/\psi K_S$ and $B \to (\phi, \eta')K$ and, in addition, it cannot account for both $\Delta A_{CP}(k\pi)$ and the asymmetry in $B_s \to J/\psi\phi$.

Let us comment on a similar analysis for the scale of NP presented in ref. [62]. One important difference concerns the treatment of ε_K: we utilize the recent (2+1)-flavors determination of $\hat{B}_K$ from the RBC collaboration and the estimation of the effect of the 0-isospin $K \to \pi\pi$ amplitude on K mixing (the factor κ_ε) [17, 51–54]. The combined effect of the updated values for these parameters is to strengthen the impact of the ε_K constraint on the fit to the UT and to introduce the $\gtrsim 2\sigma$ discrepancy responsible for the upper limits on the NP scales that we find. Another important difference of the present analysis from ref. [62] is in the treatment of NP effects on the CP asymmetries in $b \to s$ penguin and $K\pi$ modes, both of which are included in our analysis and not in ref. [62].

Lastly, we want to briefly comment on the possibility of resolving these anomalies within the SM. In particular the impact of indirect CP violation in the K system, ϵ_K, depends crucially on the hadronic matrix elements $\hat{B}_K$ and on the precise value of $|V_{cb}|$ (we remind the reader that the ρ and η dependent part of ε_K is proportional to $|V_{cb}|^4$). While a rather large shift in a single input parameter (such as $\hat{B}_K$ or V_{cb}) is needed to reduce the discrepancy between the fitted and measured (via $B \to J/\psi K_S$) values of $\sin 2\beta$, a correlated set of smallish shifts in several inputs, while implausible, can certainly not be ruled out. However, for the effects that we discuss to disappear, any such problems in the hadronic matrix elements from the lattice and/or elsewhere will only suffice, *if* simultaneously it is proven that the $B_s \to J/\psi\phi$ asymmetry and the smaller values of $\sin 2\beta$ from penguin modes were all a statistical fluctuation.

Finally, let us summarize the impact of future experimental and theoretical progresses

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on the anomalies we considered in this analysis. The most promising developments will be the high precision measurement of the $B_s \to J/\psi\phi$ asymmetry, additional lattice-QCD calculations of $\hat{B}_K$, the inclusion of $O(\alpha_s^2)$ and $O(\alpha_s/m_b)$ corrections in the global fit to inclusive $b \to c\ell\nu$ decays for the extraction of $|V_{cb}|$, and the calculation of the parameter κ_ε introduced in (2.3) using 2+1 flavors lattice-QCD (κ_ε is controlled by the matrix element of the QCD penguin O_6 - not presently calculable with lattice QCD methods - and can be extracted, within the SM, from the measurement of ε'/ε and the lattice determination of the matrix element of the electro-weak penguin operator O_8.). The errors on $\hat{B}_K$ and κ_ε do not impact too strongly the fit to the unitarity triangle; therefore new determinations of these parameters will serve mainly to build confidence in the central values that we are presently using. On the other hand, the role of $|V_{cb}|$ is of the utmost importance: if the inclusion of higher order QCD corrections to inclusive semileptonic B decays will help closing the 2σ gap between inclusive and exclusive determinations of $|V_{cb}|$, the discrepancies we considered in this work will be strongly reinforced. Improved determinations of CP asymmetries in $B \to K\pi$ and $b \to s$ penguin modes will most probably have to wait for LHC-b; unfortunately the interpretation of these discrepancies relies heavily on QCD-factorization methods and suffers from our the lack of control over power corrections.

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