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CP violation in models with Minimal Flavour Violation

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Summary. — We shortly describe the framework of Minimal Flavour Violation (MFV), emphasizing that it does not necessarily imply that CP violation be minimal as well. We then reconsider the correlation between the amount of CP violation in the K- and B_d-systems within the Standard Model, quantified by ϵ_K *vs.* $\sin 2\beta$. We show that, in view of recent improvements in the ϵ_K theoretical formula, this consistency test is in fact less than perfect. Finally, we briefly outline how a solution to a confirmed discrepancy may be found without going beyond MFV.

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1. – Introduction

Aa is well known, within the Standard Model (SM) all the flavour and CP violation originates from the "misalignment" between the up-quark and down-quark Yukawa couplings Y_u, Y_d when they are diagonalized via chiral unitary transformations on the quark fields. These transformations leave a physical remnant in that the CKM matrix appears in W-quark-quark interactions, but not on those with the Z. As a consequence, neutral-current interactions can change flavour only at the loop level. Hence, within the SM, flavour-changing neutral current effects are generally and naturally small, due to the loop suppression, and to the fact that they must be proportional to quark squared-mass differences. In fact, the misalignment between the transformations on u_L and d_L becomes immaterial if either u- or d-quarks are degenerate. This mechanism of flavour and CP violation leads to highly non-generic patterns of experimental predictions, that have been widely tested, with no established discrepancy to date. One can make this piece of information useful in the construction of SM extensions by addressing the question: Can a SM-like mechanism of near-flavour-conservation be embedded in a generic, Fermi-scale extension of the SM?

The crucial observation [1] is that, in the absence of the Yukawa interactions, the SM is invariant under an $SU(3)^5$ group of global, chiral transformations, called the flavour group. One can then postulate ("Minimal Flavour Violation principle" [2]) that the SM Yukawas are the only source of flavour violation even beyond the SM. This implies that any new, potential source M of flavour violation must *inherit* from the SM Yukawas, *i.e.* effectively be a function $M(Y_u, Y_d, \ldots)$, the functional form being fixed by treating the Yukawas as spurions of the flavour group. If one thinks of the functional form as a polynomial expansion in the Yukawas, the coefficients will in general not be fixed by the MFV principle itself, and may be free complex numbers where applicable. This implies that, within MFV, CP violation is actually not necessarily minimal, *i.e.* is not described by exclusively the CKM phase.

It is clear that MFV is not the easiest scenario where to search for non-SM effects. Recent phenomenological analyses within the MSSM, adopting the MFV definition of [2], can be found in [3] and show that resolving discrepancies with respect to the sheer SM often requires high accuracies. On the other hand, the fact that data seem to point to MFV would induce to take MFV at the very least as a good approximation to reality. A realistic strategy seems then to look for instances where MFV *is* distinguishable from the plain SM. In the next section, I will present one such instance, where new physics may be of MFV type and, nonetheless, could be already manifesting itself. Reaching firmer conclusions depends, as often in MFV, on improvements in the control of the theoretical input. The main point is that the required improvement may well be feasible in this case.

2. – CP violation in the K- *vs.* B_d-systems

Within the K-meson system, indirect CP violation is described by the parameter ϵ_K, which can be calculated with the following theoretical formula [4]:

$$\epsilon_K = e^{i\phi_\epsilon} \sin\phi_\epsilon \left(\frac{\mathrm{Im}(M_{12}^K)}{\Delta M_K} + \xi \right), \tag{1}$$

with $\xi = \mathrm{Im}\, A_0 / \mathrm{Re}\, A_0$, A_0 the 0-isospin amplitude in $K \to \pi\pi$ decays, $M_{12}^K = \langle K | \mathcal{H}_{\Delta F=2}^{\mathrm{full}} | \overline{K} \rangle$ and ΔM_K the $K - \overline{K}$ system mass difference. The phase ϕ_ϵ is measured to be $\phi_\epsilon = (43.5 \pm 0.7)^\circ$ [5]. In contrast with the ϵ_K formula used in basically all phenomenological applications, eq. (1) takes into account $\phi_\epsilon \neq \pi/4$ and $\xi \neq 0$. In order to make the impact of these two corrections transparent, we will parameterize them through an overall factor κ_ϵ in ϵ_K:

$$\kappa_\epsilon = \sqrt{2} \sin\phi_\epsilon \overline{\kappa}_\epsilon, \tag{2}$$

with $\overline{\kappa}_\epsilon$ parameterizing the effect of $\xi \neq 0$ through $\overline{\kappa}_\epsilon = 1 + \frac{\xi}{\sqrt{2}|\epsilon_K|} \equiv 1 + \Delta_\epsilon$, where Δ_ϵ has been introduced for later convenience. It turns out that both $\xi \neq 0$ and $\phi_\epsilon < \pi/4$ imply suppression effects in ϵ_K relative to the approximate formula, with the correction from $\xi \neq 0$ being of O(5%) by itself. For the total correction factor one finds, within the SM [4]

$$\kappa_\epsilon = 0.92 \pm 0.02. \tag{3}$$

Hence the like sign of the two corrections in eq. (2) turns out to build up a -8% total shift with respect to the approximate ϵ_K formula.

Before discussing the phenomenological impact of κ_ϵ, it is worth shortly describing how ξ can actually be estimated. As discussed in detail in [4,6], a *direct* calculation of ξ is

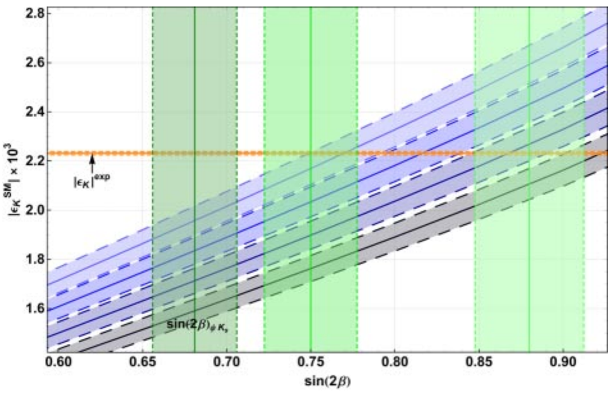

Fig. 1. – (Colour on-line) $|\epsilon_K^{\rm SM}|$ *vs.* $\sin 2\beta$ with only $\hat{B}_K$ errors included. $\hat{B}_K \in \{0.65, 0.70, 0.75, 0.80\} \pm 3\%$ are shown as blue areas (darker to lighter). Vertical green areas display $\sin 2\beta \in \{0.681, 0.75, 0.88\} \pm 3.7\%$ (from [4]).

subject at present to very large hadronic uncertainties, as no consensus exists on the value of the non-perturbative parameter B_6, describing QCD-penguin operators, that dominate ξ. Much more reliable is the indirect strategy [7] of estimating ξ from the *experimental* value of ϵ'/ϵ, through the relation $\epsilon'/\epsilon = -\omega \Delta_\epsilon (1 - \Omega)$. Here $\omega = {\rm Re}\, A_2 / {\rm Re}\, A_0 = 0.045$ the well-known $\Delta I = 1/2$ rule, and Ω the ratio between EW-penguin and QCD-penguin contributions to ϵ'/ϵ. Ω represents the main theoretical input in this procedure, but is in much better theoretical control than ξ. The analysis by [8] finds $\Omega = 0.4 \pm 0.1$ within the SM and this 25% error translates into $\Delta_\epsilon = -0.061 \pm 0.014$, whence one arrives at the estimate (3).

It should be noted that Ω is in general sensitive to non-SM contributions, because EW penguins are. However, a shift in Ω due to non-SM EW-penguin contributions can be parameterized most generally [6], and Δ_ϵ be accordingly estimated through a generalization of the above-mentioned strategy. It turns out that realistic EW-penguin shifts below 50% of the SM contribution typically lead to $\Delta_\epsilon \lesssim -0.04$ (see [6] for the details). This speaks for the robustness of the estimate (3) beyond the SM.

Let us now turn to the consequences of a -8% suppression effect on $\epsilon_K^{\rm SM}$. Once the rest of the input is fixed, the formula for $\epsilon_K^{\rm SM}$ allows to predict $\sin 2\beta$, that measures CP violation in the B_d system. In fact, it is easy to see that the top-top contribution to $\epsilon_K^{\rm SM}$, amounting to roughly 75% of the SM prediction, is directly proportional to $\sin 2\beta$. It obviously follows that, being the ϵ_K experimental result fixed, a suppression from κ_ϵ implies a larger predicted value for $\sin 2\beta$. The situation is quantitatively illustrated in fig. 1, reporting the $|\epsilon_K^{\rm SM}|$ prediction as a function of $\sin 2\beta$ for various values of the $\hat{B}_K$ parameter (see figure caption for more details). Since a realistic range for $\hat{B}_K$ is $\hat{B}_K = 0.72 \pm 5\%$ (see, *e.g.*, the unquenched result of [9], and the caption of their fig. 4 for more details on the error components), fig. 1 points, for $\sin 2\beta = \sin 2\beta_{J/\psi K_s}$, to a central value for $|\epsilon_K^{\rm SM}|$ about 20% below experiment. Even if fig. 1 *does not* include all components of the ϵ_K error, we believe the above issue warrants further attention. In particular, one can investigate whether the value of $\sin 2\beta$ required to accommodate $|\epsilon_K|$ within the SM may be too high with respect to the $\sin 2\beta$ determination from B_d physics, as pointed out in [10] for $\kappa_\epsilon = 1$. As emphasized in [4], the above could more generally entail the presence of a new phase either dominantly in the B_d system, or respectively in the K system, or, alternatively, of two smaller phases in both systems, defining in turn three new-physics scenarios. The vertical $\sin 2\beta$ ranges in fig. 1, with a relative error chosen at 3.7% as in the $\sin 2\beta_{\psi K_s}$ case, define the scenarios in question. Addressing the significance of either scenario crucially depends on the errors associated with the theoretical input entering the $\epsilon_K^{\rm SM}$ formula.

Indeed, let us now focus on the first scenario, where no new phase is assumed in the B_d system, so that $\sin 2\beta = \sin 2\beta_{\psi K_s}$. In this case, varying all the ϵ_K input with Gaussian distributions around their respective determinations (see input table in [6]), one obtains $|\epsilon_K^{\rm SM}| = (1.78 \pm 0.25) \times 10^{-3}$ [6], to be compared with $|\epsilon_K^{\rm SM}| = (2.229 \pm 0.012) \times 10^{-3}$ [5]. In this case, the most straightforward kind of new physics that may fix ϵ_K is a shift in the $\Delta F = 2$ loop function, which is of MFV type [11]. In particular, barring non-SM operators mediating meson mixings, this shift would be universal, *i.e.* proportionally affect also B_d and B_s mass differences $\Delta m_{d,s}$. In particular, it would cancel in their ratio $\Delta m_d/\Delta m_s$, the combination actually relevant in Unitarity Triangle fits.

Conversely, in the third scenario [10], one assumes new physics to mostly affect the $\sin 2\beta$ determination, with ϵ_K being essentially SM-like. Since in this case one has $\sin 2\beta_{J/\psi K_s} = \sin 2(\beta + \phi_{\rm NP})$, with $\phi_{\rm NP}$ a non-SM phase, it is clear that β cannot be accessed from the $J/\psi K_s$ mode alone. One possible strategy is to determine β from the ϵ_K, Δm_d and ΔM_s constraints. With this procedure, we get $\sin 2\beta = 0.88^{+0.11}_{-0.12}$ [4], to be compared with the (2007) HFAG average $\sin 2\beta = 0.681 \pm 0.025$ [12]. One gathers that the $\phi_{\rm NP}$ phase, *negative*, may be correlated, even in size, with the (again negative) new phase in B_s hinted at by Fermilab [13]. In spite of the presence of a new phase, the non-SM physics resposible for it does not need to be beyond MFV. However, the answer is highly model-dependent in this case.

3. – Conclusions

The ϵ_K *vs.* $\sin 2\beta$ correlation is a fundamental consistency test of SM CP violation, in fact the only one available at present. Our analysis shows that an accurate SM formula for ϵ_K implies a -8% shift in its central value. Looking at the entailed prediction for $\sin 2\beta$, the above shift hints at a tension with respect to $\sin 2\beta_{J/\psi K_s}$. Reaching firmer conclusions about this tension requires improvement in the $\epsilon_K^{\rm SM}$ theoretical input. To give an idea, the dominant (75%) top-top contribution to ϵ_K leads to the following error budget (see [6]):

$$\frac{\delta|\epsilon_K^{\rm SM}|}{|\epsilon_K^{\rm SM}|} \approx 5\%_{\hat{B}_K} \oplus 11\%_{|V_{cb}|^4} \oplus 8\%_{R_t^2} \approx 15\%. \tag{4}$$

The R_t error should drastically improve after a precise γ determination at LHCb and some room for improvement can be expected also on $\hat{B}_K$ from lattice QCD. Therefore the fate of the bulk of the error in eq. (4) is arguably in the hands of $|V_{cb}|$.

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