

NEW PHYSICS BOUNDS FROM CKM-UNITARITY

M. GONZÁLEZ-ALONSO

*Departament de Física Teòrica and IFIC, Universitat de València-CSIC,
Apt. Correus 22085, E-46071 València, Spain*

Using an effective field theory approach, we study the new physics (NP) corrections to muon and beta decays and their effects on the extractions of V_{ud} and V_{us} . Assuming nearly flavor blind NP interactions we find that the CKM-unitarity test is the only way to expose NP. The four short-distance operators that can generate a deviation are strongly constrained by the phenomenological bound $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (-1 \pm 6) \times 10^{-4}$, corresponding to an effective scale $\Lambda > 11$ TeV (90% CL). Depending on the operator, this constraint is at the same level or better than that generated by the Z pole observables.

1 Introduction

In the last years there have been a continuous advance in the theoretical description of semileptonic kaon decays, both in the lattice sector¹ and using analytical approaches². These improvements, in combination with new experimental measurements³, make these decays a deep probe of the nature of weak interactions^{4,5}. In particular, the elements V_{ud} and V_{us} of the Cabibbo-Kobayashi-Maskawa (CKM)⁶ quark mixing matrix are known with an accuracy below the percent level: $V_{ud} = 0.97425(22)$ ⁷ and $V_{us} = 0.2253(9)$ ⁵. These precise determinations can be used to test the CKM unitarity condition^a

$$\Delta_{\text{CKM}} \equiv |V_{ud}^{(\text{pheno})}|^2 + |V_{us}^{(\text{pheno})}|^2 + |V_{ub}^{(\text{pheno})}|^2 - 1 = (-1 \pm 6) \times 10^{-4}, \quad (1)$$

or equivalently, the quark-lepton universality. Assuming that new physics contributions scale as $\alpha/\pi(M_W^2/\Lambda^2)$, the unitarity test probes energy scales Λ on the order of the TeV, which will be directly probed at the LHC.

While the consequences of these unitarity tests on Standard Model (SM) extensions have been considered in some explicit scenarios⁸, a model-independent analysis was missing until recently⁹. In order to perform such an analysis, the main idea is to study in a model-independent effective theory setup new physics contributions to low energy charged-current (CC) processes, in such a way that we can assess in a fairly general way the impact of semileptonic processes in constraining and discriminating SM extensions. We shall pay special attention to purely leptonic and semileptonic decays of light hadrons used to extract the CKM elements V_{ud} and V_{us} .

2 Weak scale effective lagrangian

In order to analyze in a model-independent framework NP contributions to both beta decays and electroweak precision observables (EWPO) we take the SM (including the Higgs) as the

^a $V_{ub} \sim 10^{-3}$ contributes negligibly to this relation.

low-energy limit of a more fundamental theory, and more specifically we assume that: (i) there is a gap between the weak scale v and the NP scale Λ where new degrees of freedom appear; (ii) the NP at the weak scale is weakly coupled, so the electroweak (EW) gauge symmetry is linearly realized; (iii) the violation of total lepton and baryon number is suppressed by a scale much higher than Λ . These assumptions lead us to an effective non-renormalizable lagrangian¹⁰:

$$\mathcal{L}^{(\text{eff})} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \frac{1}{\Lambda^3}\mathcal{L}_7 + \dots \quad (2)$$

where $\mathcal{L}_n = \sum_i \alpha_i^{(n)} O_i^{(n)}$, being $O_i^{(n)}$ local gauge-invariant operators of dimension n built out of SM fields. It can be shown that under the above assumptions, there are no corrections at dimension five, whereas seventy-seven operators appear at dimension six^{9,10}, where we truncate the expansion. For the sake of consistency we will work at linear order in the NP corrections.

For the EWPO *and* beta decays it can be shown that we only need a twenty-five operator basis, with twenty-one $U(3)^5$ invariant and four non-invariant^b (we will see the usefulness of this separation later). Nine of those operators contribute to the beta and muon decays, being the following five the only $U(3)^5$ -invariant:

$$O_{ll}^{(1)} = \frac{1}{2}(\bar{l}\gamma^\mu l)(\bar{l}\gamma_\mu l) \quad O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^\mu \sigma^a l)(\bar{l}\gamma_\mu \sigma^a l), \quad (3)$$

$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q), \quad (4)$$

$$O_{\varphi l}^{(3)} = i(h^\dagger D^\mu \sigma^a \varphi)(\bar{l}\gamma_\mu \sigma^a l) + \text{h.c.}, \quad O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q) + \text{h.c.}, \quad (5)$$

3 Effective lagrangian for μ and quark β decays

Deriving the low-energy effective lagrangian that describes the muon and beta decays we find⁹

$$\mathcal{L}_\mu = \frac{-g^2}{2m_W^2} \left[(1 + \tilde{v}_L) \cdot \bar{e}_L \gamma_\mu \nu_{eL} \bar{\nu}_{\mu L} \gamma^\mu \mu_L + \tilde{s}_R \cdot \bar{e}_R \nu_{eL} \bar{\nu}_{\mu L} \mu_R \right] + \text{h.c.}, \quad (6)$$

$$\begin{aligned} \mathcal{L}_{d_j} = \frac{-g^2}{2m_W^2} V_{ij} \left[(1 + [v_L]_{\ell ij}) \bar{\ell}_L \gamma_\mu \nu_{\ell L} \bar{u}_L^i \gamma^\mu d_L^j + [v_R]_{\ell ij} \bar{\ell}_L \gamma_\mu \nu_{\ell L} \bar{u}_R^i \gamma^\mu d_R^j \right. \\ \left. + [s_L]_{\ell ij} \bar{\ell}_R \nu_{\ell L} \bar{u}_R^i d_L^j + [s_R]_{\ell ij} \bar{\ell}_R \nu_{\ell L} \bar{u}_L^i d_R^j \right. \\ \left. + [t_L]_{\ell ij} \bar{\ell}_R \sigma_{\mu\nu} \nu_{\ell L} \bar{u}_R^i \sigma^{\mu\nu} d_L^j \right] + \text{h.c.} \quad (7) \end{aligned}$$

The effective couplings $\tilde{v}_L, \tilde{s}_R, v_{L,R}, s_{L,R}$, and t_L encode information on interactions beyond the SM⁹ and are of order v^2/Λ^2 , where v is the SM Higgs expectation value.

4 Flavor structure of the effective couplings

So far we have not made any assumption about the flavor structure of the new physics, but given that flavor changing neutral current (FCNC) processes forbid generic structures if $\Lambda \sim \text{TeV}$, it is convenient to organize the discussion in terms of perturbations around the $U(3)^5$ flavor symmetry limit, where no problem arises with FCNC. In this $U(3)^5$ -limit the expressions greatly simplify: the effective couplings $\tilde{s}_R, v_R, s_{L,R}$, and t_L vanish and all the NP effects can be encoded into the following redefinitions

$$G_F^\mu = (G_F)^{(0)} (1 + \tilde{v}_L) = (G_F)^{(0)} \left(1 + 4\hat{\alpha}_{\varphi l}^{(3)} - 2\hat{\alpha}_{ll}^{(3)} \right), \quad (8)$$

$$G_F^{\text{SL}} = (G_F)^{(0)} (1 + v_L) = (G_F)^{(0)} \left(1 + 2 \left(\hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} - \hat{\alpha}_{lq}^{(3)} \right) \right), \quad (9)$$

^bWe refer to the $U(3)^5$ flavor symmetry of the SM gauge lagrangian (the freedom to make $U(3)$ rotations in family space for each of the five fermionic gauge multiplets).

where $G_F^{(0)} = g^2/(4\sqrt{2}m_W^2)$. Consequently we will have

$$V_{ij}^{(\text{pheno})} = \frac{V_{ij} G_F^{\text{SL}}}{G_F^\mu} = V_{ij} \left[1 + 2 \left(\hat{\alpha}_{ll}^{(3)} - \hat{\alpha}_{lq}^{(3)} - \hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} \right) \right], \quad (10)$$

as phenomenological values of $V_{ud,us}$, independently of the channel used to extract them. Therefore the only way to expose NP contributions is to construct universality tests ($\Delta_{\text{CKM}} \neq 0$), in which the absolute normalization of V_{ij} matters. In our framework we have

$$\Delta_{\text{CKM}} = 4 \left(\hat{\alpha}_{ll}^{(3)} - \hat{\alpha}_{lq}^{(3)} - \hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} \right). \quad (11)$$

In specific SM extensions, the $\hat{\alpha}_i$ are functions of the underlying parameters. Therefore, through the above relation one can work out the constraints of quark-lepton universality tests on any weakly coupled SM extension.

The Minimal Flavor Violation hypothesis requires that $U(3)^5$ symmetry is broken in the underlying model only by structures proportional to the SM Yukawa couplings¹¹, and structures generating neutrino masses¹², and therefore the coefficients parameterizing deviations from the $U(3)^5$ -limit are highly suppressed⁹. Consequently we expect the conclusions of the previous subsection to hold, with the elements V_{ij} receiving a common dominant shift plus suppressed channel-dependent corrections.

In a more general framework the situation can be different because the channel-dependent shifts to V_{ij} could be appreciable and Δ_{CKM} would depend on the channels used. Work in this direction is in progress.

5 Δ_{CKM} versus precision EW measurements

The four operators that contribute to Δ_{CKM} in the limit of approximate $U(3)^5$ invariance also contribute to the different EWPO¹³, together with the remaining seventeen operators that make up the $U(3)^5$ invariant sector of our TeV scale effective lagrangian. Han and Skiba¹³ studied the constraints on the same set of twenty-one $U(3)^5$ invariant operators from the EWPO, performing a global fit, and from this work we have the following indirect bound on Δ_{CKM}

$$-9.5 \times 10^{-3} \leq \Delta_{\text{CKM}} \leq 0.1 \times 10^{-3} \quad (90\% \text{ C.L.}). \quad (12)$$

Comparing with the direct experimental limit, $|\Delta_{\text{CKM}}| \leq 1. \times 10^{-3}$ (90% C.L.), we see that EWPO leave room for a sizable violation of unitarity and consequently we have to include the direct Δ_{CKM} constraint in the global fit to improve the bounds on NP-couplings. It has been shown⁹ that the main effect of this addition is to strengthen the constraints on $O_{lq}^{(3)}$.

In Fig. 1 we show the bounds if we assume a single operator dominance. For all the CKM-operators the direct Δ_{CKM} measurement provides competitive constraints and in the case of $O_{lq}^{(3)}$ the improvement is remarkable.

6 Conclusions

In an effective field theory framework and assuming nearly $U(3)^5$ -invariant NP interactions, it has been shown that the extraction of $V_{ud,us}$ is channel independent and the only NP probe is Δ_{CKM} , that receives contributions from four short distance operators: $O_{ll,lq,\varphi l,\varphi q}^{(3)}$.

We have shown that the CKM-unitarity (first row) test provide constraints on NP that currently cannot be obtained from other EW precision tests and collider measurements. The Δ_{CKM} constraint bounds the effective NP scale of all four CKM-operators to be $\Lambda > 11$ TeV (90 % C.L.), what for $O_{lq}^{(3)}$ is five times stronger than EWPO-bound. Equivalently, if V_{ud} and V_{us} move from their current central values, EWPO data would leave room for sizable deviations from CKM-unitarity.

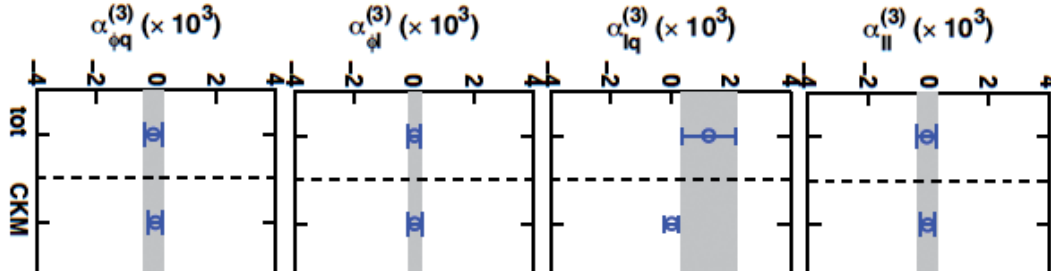


Figure 1: 90 % C.L. regions in the single operator analysis. The first row displays the constraint from EWPO and the second row those coming only from Δ_{CKM} .

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