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New Physics in $d(s) \to u\ell\nu$

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This talk is based on the results of Ref. [1] and it discusses the constraints on Beyond Standard Model (BSM) physics obtained from the combination of $d \to u\ell\nu$, $s \to u\ell\mu$ and $\tau \to ud\nu$ decays using an Effective Field Theory (EFT) approach. We discuss the implications for BSM couplings of the tensions between the determination of the Cabibbo angle (V_{us}) from these different observables, the so-called Cabibbo anomaly.

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1. Introduction

It is well known that the extractions of the Cabibbo angle, V_{us}, from different low-energy processes are not in good internal agreement (see e.g. Refs. [2–4]), as shown in the left panel of Fig. 1. Within the SM, this so-called Cabibbo anomaly can only be explained by some underestimated theoretical or experimental uncertainties, or highly unlikely statistical fluctuations.

If we assume the existence of BSM physics, the observables do not measure the Cabibbo angle but rather a combination of the Cabibbo angle and BSM parameters. Furthermore, different observables probe different combinations of them. Thus, the Cabibbo anomaly could be a manifestation of new physics in such a way that, once BSM contributions are taken into account, the different measurements of the Cabibbo angle become consistent with each other.

In the following we summarize some of the findings of Ref. [1], where these various processes where analyzed and combined using an EFT approach. We will discuss some simplified scenarios where just one or a combination of a few parameters are present, with the capability of addressing the Cabibbo anomaly.

2. Theory framework

In order to carry out a phenomenological analysis in which BSM effects are taken into account, we use an EFT below the Electro-Weak scale [5]:

$$\begin{aligned}\mathcal{L}_{\rm eff} \;=\; & -\frac{G_\mu V_{uD}}{\sqrt{2}}\Bigg[\left(1+\epsilon_L^{D\ell}\right)\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}\gamma^\mu(1-\gamma_5)D+\epsilon_R^{D\ell}\,\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell\cdot\bar{u}\gamma^\mu(1+\gamma_5)D \\ & +\bar{\ell}(1-\gamma_5)\nu_\ell\cdot\bar{u}\left[\epsilon_S^{D\ell}-\epsilon_P^{D\ell}\gamma_5\right]D+\frac{1}{4}\hat{\epsilon}_T^{D\ell}\,\bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell\cdot\bar{u}\sigma^{\mu\nu}(1-\gamma_5)D\Bigg]+\text{h.c.} \qquad (1)\end{aligned}$$

where $D = d, s$ stands for the down-type flavor, $\ell = e, \mu, \tau$ for the lepton flavor and $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$. We have parametrized BSM physics through the Wilson Coefficients (WC) $\epsilon_X^{q\ell}$. The SM parameters appearing in this Lagrangian are the Fermi constant G_μ, extracted form μ decays,

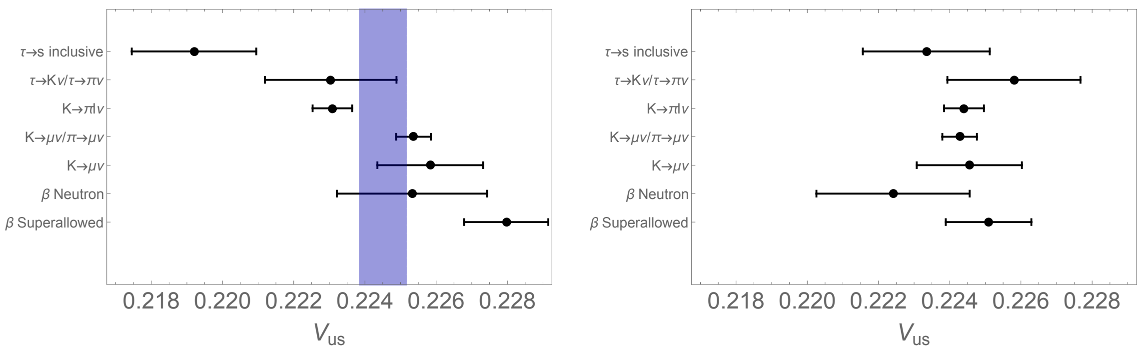

Figure 1: (From Ref. [1]) *Left*: 68% CL constraints on V_{us} from different processes, assuming the SM (i.e., $\epsilon_X^{D\ell} = 0$). The purple band corresponds to a combination of these measurements with the final error inflated by a factor $S = 2.0$ to account for the large tension between the individual inputs. *Right*: Same plot, this time including three non-zero WC: $\epsilon_R^d = 6.8 \times 10^{-4}$, $\epsilon_R^s = 5.9 \times 10^{-3}$ and $\epsilon_L^{s\tau} = -1.8 \times 10^{-2}$.

and the Cabibbo angle V_{us}. Note that V_{ud} is not independent since $V_{ud}^2 \approx \sqrt{1 - V_{us}^2}$. It is convenient to define the so-called polluted CKM elements

$$\hat{V}_{uD} = (1 + \epsilon_L^{De} + \epsilon_R^{De}) V_{uD} \,, \tag{2}$$

which are the combinations of SM and BSM parameters that can be extracted from low-energy semileptonic decays.

We match this EFT to the Standard Model EFT at the scale 100 GeV, assuming the absence of non-SM degrees of freedom lighter than ~ 100 GeV. Then it can be shown that the new physics corrections to the $V + A$ currents are lepton-flavor universal, leading to the relation: $\epsilon_R^{qe} = \epsilon_R^{q\mu} = \epsilon_R^{q\tau} \equiv \epsilon_R^q$ up to negligible corrections from dimension-8 operators [5, 6].

3. Data

3.1 β decays

These are the results of Ref. [7], where numerous nuclear and neutron decay observables were studied. We have, however, updated some of the inputs. Namely: the $\beta-\nu$ correlation of the neutron, the neutron lifetime, the axial coupling of the nucleon and the associated radiative corrections (see Ref. [1] and references therein for details). This analysis leads to the following results

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R^d \\ \epsilon_S^{de} \\ \hat{\epsilon}_T^{de} \end{pmatrix} = \begin{pmatrix} 0.97382(42) \\ -0.012(12) \\ 0.0002(10) \\ -0.0006(12) \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & 0.01 & 0.78 & 0.79 \\ & 1 & 0.01 & 0. \\ & & 1 & 0.64 \\ & & & 1 \end{pmatrix}. \tag{3}$$

As can be seen, β decays probe $\hat{V}_{ud}$ and BSM physics in the de sector, parametrized by the coefficients ϵ_X^{de}. This is due to the fact that the underlying process responsible for these decays is the transition $u \longrightarrow de\nu$. Sub-permille and permille constraints have been obtained on $\hat{V}_{ud}$ and $\epsilon_{S,T}^{de}$ respectively. However, the ϵ_R^d has only been constrained on the percent level since this relies on the lattice determination of g_A.

3.2 π decays

Here, we update the analysis of Ref. [8]. A total of four decays are studied: $\pi \longrightarrow \mu\nu$, $\pi \longrightarrow e\nu$, $\pi \longrightarrow e\nu\gamma$ and $\pi^+ \longrightarrow \pi^0 e^+ \nu$. The first of these decays probes a linear combination of $\epsilon_X^{d\mu}$, whereas the second one gives access to ϵ_P^{de}. On the other hand, the last two decays probe the same parameters as β decay processes, but with less precision. All in all, the combination of the nuclear and pion data gives the following results:

$$\begin{pmatrix} \hat{V}_{ud} \\ \epsilon_R^d \\ \epsilon_S^{de} \\ \hat{\epsilon}_T^{de} \\ \epsilon_P^{de} \\ \epsilon_{LP}^{d\mu} \end{pmatrix} = \begin{pmatrix} 0.97386(40) \\ -0.012(12) \\ 0.00032(99) \\ -0.0004(11) \\ 3.9(4.3) \times 10^{-6} \\ -0.021(24) \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & 0.01 & 0.75 & 0.64 & 0.01 & -0.01 \\ & 1 & 0.01 & 0. & -0.96 & 0.96 \\ & & 1 & 0.6 & 0.01 & -0.01 \\ & & & 1 & 0.01 & -0.01 \\ & & & & 1 & -0.999 \\ & & & & & 1 \end{pmatrix}, \tag{4}$$

where $\epsilon_{LP}^{d\mu} \equiv \epsilon_L^{d\mu} - \epsilon_L^{de} - \epsilon_P^{d\mu} \frac{m_\pi^2}{m_\mu(m_u+m_d)}$. The strong constraints of $\epsilon_P^{d\ell}$ ($\ell = e, \mu$) are due to the chiral enhancement $m_\pi^2/(m_\ell(m_u + m_d))$. This allows some BSM models to probe new particles with masses above the LHC reach through π decays. However, it is currently impossible to probe the $\epsilon_X^{d\mu}$ coefficients separately. In order to do that, more precision observables probing that sector (e.g. low energy μ scattering or μ capture on nuclei) are needed.

3.3 Kaon and hyperon decays

The analysis of these decays is based on the work of Ref. [8], which we update using the experimental input on semileptonic kaon decays of Ref. [9]. The sensitivities of these decays to new physics are the following:

- $K \to \mu\nu$ and $K \to e\nu$. These decays probe a combination of ϵ_R^s, $\epsilon_L^{s\mu} - \epsilon_L^{se}$ and the pseudoscalar coefficients ϵ_P^{se} and $\epsilon_P^{s\mu}$, respectively.

- Semileptonic kaon decays. The widths of the electronic ones probe $\hat{V}_{us}$ while the muonic ones probe a combination of $\hat{V}_{us}$, ϵ_R^s, $\hat{\epsilon}_T^{s\mu}$ and $\epsilon_L^{s\mu} - \epsilon_L^{se}$. Besides, the $K^- \to \pi^0\mu^-\nu$ differential distribution allows one to constrain $\hat{\epsilon}_T^{s\mu}$ and the comparison between its phenomenological and theoretical scalar form factor sets a constraint on $\epsilon_S^{s\mu}$.

- The comparison of measured and lattice axial coupling in hyperon decays gives access to ϵ_R^s.

The combination of these processes yields the following results for $\hat{V}_{us}$ and the BSM couplings:

$$\begin{pmatrix} \hat{V}_{us} \\ \epsilon_L^{s\mu} - \epsilon_L^{se} \\ \epsilon_R^s \\ \epsilon_S^{s\mu} \\ \epsilon_P^{se} \\ \epsilon_P^{s\mu} \\ \hat{\epsilon}_T^{s\mu} \end{pmatrix} = \begin{pmatrix} 0.22306(56) \\ 0.0008(22) \\ 0.001(50) \\ -0.00026(44) \\ -0.3(2.0) \times 10^{-5} \\ -0.0006(41) \\ 0.002(22) \end{pmatrix}, \qquad \rho = \begin{pmatrix} 1 & -0.11 & 0. & -0.12 & 0.03 & 0.02 & 0. \\ & 1 & 0. & 0. & 0. & 0.02 & 0.55 \\ & & 1 & 0. & -0.997 & -0.997 & 0. \\ & & & 1 & -0.01 & -0.01 & 0. \\ & & & & 1 & -0.9996 & 0. \\ & & & & & 1 & 0.01 \\ & & & & & & 1 \end{pmatrix}. \tag{5}$$

All Lorentz structures are resolved in the strange-muon sector, $\epsilon_X^{s\mu}$, thanks to the interplay of width and differential distribution observables. As in π decays, chiral enhancement is responsible for the strong constraints on the pseudoscalar interactions. However, we cannot set constraints (at linear order) on $\widehat{\epsilon}_T^{se}$ and ϵ_S^{se} since their contributions are suppressed by the electron mass, but they can be bounded using their quadratic effects on the K_{e3} differential distributions.

3.4 Hadronic τ decays

The constraints on new physics from these decays are the main result of Ref. [1], where a comprehensive list of channels is considered. Let us mention them and briefly discuss which interactions can be probed in each case:

- $\tau \to \pi\nu$ and $\tau \to K\nu$: The total widths are sensitive to $\epsilon_L^{D\tau} - \epsilon_L^{De}$, ϵ_R^D and $\epsilon_P^{D\tau}$.

- $\tau \to \pi\pi\nu$: This three-body channel is sensitive to $\epsilon_L^{d\tau} - \epsilon_L^{de}$ and $\hat{\epsilon}_T^{d\tau}$. The contribution of the scalar interaction is very suppressed and thus cannot be constrained using this channel. Comparing the spectral function with that obtained from $e^+e^- \to \pi^+\pi^-$ (corrected by isospin-breaking effects) one can access the BSM couplings.

- $\tau \to \pi\eta\nu$: Contrary to the previous channel, in this case the scalar contribution is dominant [10], which allows us to constrain $\epsilon_S^{d\tau}$.

- Non-strange inclusive decays, which are sensitive to $\epsilon_L^{D\tau} - \epsilon_L^{De}$, ϵ_R^D and $\hat{\epsilon}_T^{d\tau}$. Several constraints can be obtained by integrating the vector or axial spectral functions with different weights. The contributions from (pseudo)scalar interactions are suppressed due to isospin symmetry.

- Strange inclusive decays: compared to the non-strange case, isospin symmetry is replaced by $SU(3)$ symmetry and, as a result, (pseudo)scalar interactions cannot be neglected. In this case, since we do not have the spectral functions, we can only obtain a single constraint using the total branching ratio.

The bounds obtained combining the constraints of the previously mentioned channels are:

$$\begin{pmatrix} \epsilon_L^{d\tau} - \epsilon_L^{de} \\ \epsilon_R^d \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_{LRP}^{s\tau} \\ \epsilon_{LSPT}^{s\tau} \end{pmatrix} = \begin{pmatrix} 0.024(26) \\ 0.007(14) \\ 0.004(10) \\ -0.033(60) \\ -0.002(10) \\ -0.013(12) \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & 0.87 & -0.18 & -0.98 & -0.03 & -0.45 \\ & 1 & -0.59 & -0.86 & 0.06 & -0.59 \\ & & 1 & 0.18 & -0.36 & 0.38 \\ & & & 1 & 0.04 & 0.49 \\ & & & & 1 & 0.16 \\ & & & & & 1 \end{pmatrix}, \tag{6}$$

where $\epsilon_{LRP}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} - 2\epsilon_R^s - \frac{m_{K^\pm}^2}{m_\tau(m_u+m_s)}\epsilon_P^{s\tau}$ and $\epsilon_{LSPT}^{s\tau} \equiv \epsilon_L^{s\tau} - \epsilon_L^{se} + 0.08(1)\epsilon_S^{s\tau} - 0.38\epsilon_P^{s\tau} + 0.40(13)\epsilon_T^{s\tau}$. As can be seen in Eq. (6), all Lorentz structures are resolved in the down sector, $\epsilon_X^{d\tau}$, whereas only two combinations of WC are probed in the strange sector. All in all, we obtain percent level marginalized constraints on new physics.

4. Numerical analysis

The various results presented in the previous section were combined in a global likelihood in Ref. [1]. This represents the most comprehensive analysis of the low-energy semileptonic charged-current interactions involving light quarks.

It is worth stressing that the $d \to u\ell\nu$, $s \to u\ell\nu$ and $\tau \to \nu u D$ subsets are not independent because they are sensitive to the same polluted Cabibbo angle $\hat{V}_{us}$, some common hadronic quantities (such as the pion decay constant) and the lepton-universality of the right-handed coupling ϵ_R^D. These interrelations were fully taken into account in Ref. [1].

The χ^2 difference between this global EFT fit and the SM one is $\chi^2_{\rm SM} - \chi^2_{\rm WEFT} = 37.4$, which translates into a 3σ preference for new physics.

4.1 SM limit

As a first application of the combined χ^2, we can consider the SM limit. That is, we set $\epsilon_X^{D\ell} = 0$ and the only free parameter is V_{us}. Naively, the global fit yields $V_{us} = 0.22450(34)$. However, the measurements used to obtain this result are in strong tension with each other, as can be seen in the left panel of Fig. 1. Although it can be interpreted as a hint of BSM physics, in the SM context this is just an inconsistency between the different datasets. A way to fix this is to inflate all errors equally by a factor S until χ^2/d.o.f= 1 à la PDG. This way, we obtain:

$$V_{us} = 0.22450(67)\,, \quad S = 2.0, \tag{7}$$

from which $V_{ud} = 0.97447(15)$ is obtained.

4.2 One-by-one BSM fit and simple scenarios

The combined χ^2 can be used as well to study simple new physics scenarios with just one WC present at a time. The results of such analysis are presented in Table 1, where we highlighted in red the cases with 3σ or larger preference for new physics. The one-by-one constraints are usually an order of magnitude better than those of the global fit since large correlations are present in the latter. The strong preference for ϵ_L^{de}, ϵ_R^{s} and $\epsilon_L^{s\tau}$ is due to the fact that these WC modify the relation between the Cabibbo angle and some observables, partially solving the inconsistency between measurements. In particular, ϵ_L^{de} and ϵ_R^{s} eases the tension between nuclear beta decay and kaon decays. On the other hand, $\epsilon_L^{s\tau}$ ease the tension between the inclusive $\tau \to s$ and kaon decays.

The Cabibbo anomaly can be completely removed through multi-parameter scenarios. For instance, a scenario with ϵ_R^{d}, ϵ_R^{s} and $\epsilon_R^{s\tau}$ makes all data sets compatible, as can be seen in the right panel of Fig. 1, improving the goodness of fit by 4.4σ compared to the SM and yielding $V_{us} = 0.22432(36)$ for the Cabibbo angle.

One can also consider another simple BSM scenario in which a lepton-flavor dependent V-A interaction is present. In this case, the constraints are the following:

$$\begin{pmatrix} \epsilon_L^{se} \\ \epsilon_L^{s\mu} - \epsilon_L^{se} \\ \epsilon_L^{s\tau} - \epsilon_L^{se} \end{pmatrix} = \begin{pmatrix} -0.0145(52) \\ 0.0004(12) \\ -0.0176(62) \end{pmatrix}, \tag{8}$$

which shows a strong hint for lepton flavor universality violation in the strange-tau sector.

5. Conclusions

We have presented a comprehensive Effective-Field-Theory analysis of semileptonic charged-current transitions involving light quarks. Our partial and global likelihoods can be applied to a plethora of specific new physics models.

As we have seen, the different data sets by themselves do not show a particular preference for new physics. However, a global combination of them shows a strong preference for BSM physics reflecting the Cabibbo anomaly. We find that the anomaly can be fully removed in certain multi-parameter scenarios with just a few WC, making all the data sets compatible with each other.

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
L	-0.79(25)	-0.6(1.2)	0.40(87)	0.5(1.2)	5.0(2.5)	-18.2(6.2)
R	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)	-0.62(25)	-5.2(1.7)
S	1.40(65)	-1.6(3.2)	x	-0.51(43)	-6(16)	-270(100)
P	0.00018(17)	-0.00044(36)	-0.015(32)	-0.032(64)	1.7(2.5)	10.4(5.5)
$\hat{T}$	0.29(82)	0.035(70)	x	2(18)	28(10)	-55(27)

Table 1: (From Ref. [1]) Constraints on the WC $\epsilon_X^{D\ell}$, fitting one parameter at a time. The entries where 3σ or larger preference for new physics is displayed are highlighted in red. The cross means that the WC is not constrained by our analysis.

As any hint of BSM physics, the Cabibbo anomaly is most likely a problem with underestimated uncertainties in experiment and/or theory. However, at face value the data points to the presence of nonstandard contributions. The hint of lepton flavor universality violation in the strange quark sector, which can be seen in Eq. (8), intriguingly adds to the hints of lepton flavor universality violation in the bottom quark sector.

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