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Semileptonic τ decays Beyond the Standard Model

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This talk is based on Ref. [1]. Using an Effective Field Theory approach, we obtain model independent new physics bounds from semi-leptonic τ decays. These bounds are then combined with the ones from nuclear β decay, π decays and K and hyperon decays, originally obtained in Ref. [2] and Ref. [3] respectively and updated in Ref. [1]. The interplay of the results with the so-called Cabibbo anomalies is discussed.

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1. Introduction and theoretical framework

There is a great experimental precision and theoretical understanding of hadronic τ decays. Because of this, they have been extensively used to determine various Standard Model (SM) parameters such as the pion decay constant, the strong coupling constant and the CKM matrix elements. Since these parameters can also be determined through other observables, tensions may arise between different determinations. These tensions can be interpreted as a hint for Beyond Standard Model (BSM) physics.

The most prominent example of such tensions arise in the different determinations of the Cabibbo angle, V_{us} (see, e.g. [4–6]). They are known as Cabibbo anomalies. The Cabibbo angle can be obtained through hadronic τ decays, but also through other low energy proceses. Namely: nuclear β decays, π decays and K decays. This motivates the analysis of all these different sorts of decays in a BSM scenario.

The goal of Ref. [1] is to obtain model independent bounds from semi-leptonic processes at low energies, well below the electroweak scale $v \sim 246\,\text{GeV}$. Therefore, we have to use the following Effective Field Theory (EFT) [7]:

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

where G_μ is the Fermi constant extracted from μ decay, V_{uD} are the top-row CKM matrix elements and $\epsilon_X^{D\ell}$ are the Wilson Coefficients. This is just the Fermi Lagrangian plus a set of new interactions. Thus, the Wilson Coefficients parametrize BSM physics. As such, the bounds to be obtained will constrain their values. We will assume that the Standard Model EFT is the UV-completion of this EFT. As a result, the right handed interaction is flavor independent: $\epsilon_R^{D\ell} = \epsilon_R^D$ [7, 8].

2. Hadronic τ decays

The first data set to be analyzed is the one corresponding to hadronic τ decays. We can classify these decays into two categories: exclusive decays and inclusive decays.

In Ref. [1], we have considered the following exclusive decays channels: two two-body decay, channels, $\tau \to \pi\nu_\tau$ and $\tau \to K\nu_\tau$, and two three-body decay channels, $\tau \to \pi\pi\nu_\tau$ and $\tau \to \pi\eta\nu_\tau$. For the inclusive decays, we have classified them into strange and non-strange.

2.1 Observables and Sensitivities

The individual bounds and the sensitivities of each decay channel to the Wilson Coefficients of Eq. 1 are displayed in Table 1, along with its corresponding observable. There is an aditional sensitivity to ϵ_L^{de} because we redefine the CKM matrix elements as $V_{uD} = \widehat{V}_{uD}(1 - \epsilon_L^{de} - \epsilon_R^D)$, where $\widehat{V}_{uD}$ can be extracted directly from data[1]. The choices for them are easily justified: in each decay channel they allow to have the non-perturbative QCD dynamics under control.

[1] $\widehat{V}_{ud}$ can be extracted from nuclear decays, and $\widehat{V}_{us}$ from $K \to \pi e\nu$.

	$\epsilon_L^{d\tau}\times 10^3$	$\epsilon_L^{de}\times 10^3$	$\epsilon_R^{d}\times 10^3$	$\epsilon_P^{d\tau}\times 10^3$	$\epsilon_T^{d\tau}\times 10^3$	$\epsilon_S^{d\tau}\times 10^3$	Observable
$\tau\to\pi\nu$	-0.9(7.3)	0.9(7.3)	0.9(7.3)	0.6(5.0)	x	x	$\Gamma(\tau\to\pi\nu)$
$\tau\to\pi\pi\nu$	10(4.9)	-10(4.9)	x	x	23(12)	x	$a_\mu^{\text{had,LO}}$
$\tau\to\pi\eta\nu$	x	x	x	x	x	$(-21,10)$	$\text{BR}(\tau\to\pi\eta\nu)$
$V+A$	6.9(7.0)	-6.9(7.0)	-8.6(8.4)	x	15(19)	x	$\rho_{\text{V+A}}$
$V-A$	7.0(9.5)	-7.0(9.5)	3.6(4.9)	x	15(17)	x	$\rho_{\text{V−A}}$

	$\epsilon_L^{s\tau}\times 10^3$	$\epsilon_L^{se}\times 10^3$	$\epsilon_R^{s}\times 10^3$	$\epsilon_P^{s\tau}\times 10^3$	$\epsilon_T^{s\tau}\times 10^3$	$\epsilon_S^{s\tau}\times 10^3$	Observable
$\tau\to K\nu$	-2(10)	2(10)	2(10)	1.2(6.1)	x	x	$\Gamma(\tau\to K\nu)$
S Inc.	-17(16)	17(16)	23(22)	340(327)	-34(35)	-170(161)	$\widehat{V}_{us}^{\text{incl}}$

Table 1: Individual bounds for each decay channel along with the observable used to obtain such bounds. The cross means that the decay channel is not sensitive to that Wilson Coefficient.

The different sensitivities can be understood in terms of the symmetries of the final state: a final state with a pseudoscalar meson is sensitive to the pseudoscalar interaction $\epsilon_P^{D\tau}$, whereas a final state with two pseudoscalar mesons is sensitive to the tensor and scalar interactions, $\epsilon_T^{D\tau}$ and $\epsilon_S^{D\tau}$. Note, however, that for the channel $\tau\to\pi\pi\nu$ the scalar interaction is suppressed by isospin symmetry. Since this makes the sensitivity to $\epsilon_S^{d\tau}$ very poor we have taken the isospin limit, removing it altogehter. On the other hand, the channel $\tau\to\pi\eta\nu_\tau$ is only sensitive to $\epsilon_S^{d\tau}$. This is so because this decay is strongly suppressed in the SM as it only occurs through-isospin violation, and the scalar interaction is enhanced by chiral symmetry breaking[2] [9].

The same reasoning can be applied to the inclusive decays. For the non-strange case the isospin limit is likewise taken, removing the poor sensitivity to $\epsilon_S^{d\tau}$[3]. For the strange inclusive decays, the isospin symmetry is replaced by $SU(3)$ flavor symmetry. Therefore, these decays are sensitive to every Wilson Coefficient, although with large errors for $\epsilon_T^{s\tau}$ and $\epsilon_S^{s\tau}$.

2.2 Bounds and fit

The different bounds for each decay channel can be found in Ref. [1]. Combining all of them, the following marginalized constraints are readily obtained:

$$\begin{pmatrix} \epsilon_L^{d\tau}-\epsilon_L^{de} \\ \epsilon_R^{d} \\ \epsilon_P^{d\tau} \\ \hat{\epsilon}_T^{d\tau} \\ \epsilon_{LRP}^{s\tau} \\ \epsilon_{LSPT}^{s\tau} \end{pmatrix} = \begin{pmatrix} 0.024(26) \\ 0.007(14) \\ 0.004(10) \\ -0.033(60) \\ -0.002(10) \\ -0.013(12) \end{pmatrix}, \quad \rho = \begin{pmatrix} 1 & 0.87 & -0.18 & -0.98 & -0.03 & -0.45 \\ & 1 & -0.59 & -0.86 & 0.06 & -0.59 \\ & & 1 & 0.18 & -0.36 & 0.38 \\ & & & 1 & 0.04 & 0.49 \\ & & & & 1 & 0.16 \\ & & & & & 1 \end{pmatrix}, \quad (2)$$

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 $\epsilon_{LSPT}^{s\tau}\equiv\epsilon_L^{s\tau}-\epsilon_L^{se}+0.08(1)\epsilon_S^{s\tau}-0.38\epsilon_P^{s\tau}+0.40(13)\epsilon_T^{s\tau}$. The coefficients are constrained at the percent level. Note, however, that while most

[2] In fact, it is so enhanced that a quadratic term in $\epsilon_S^{d\tau}$ has to be retained.

[3] There is also no sensitivity to $\epsilon_P^{d\tau}$ because the channel $\tau\to\pi\nu$ is not considered as part of the inclusive non-strange decays.

of the individual WC on the $d\tau$ sector are constrained, the individual Wilson Coefficients on the $s\tau$ sector are not. This is because there are not enough bounds to resolve them.

3. Other probes

In the following, we review the bounds that are obtained in nuclear β and π decays, and in K and hyperon decays. These results were first obtained in Refs. [2, 3], and updated in Ref. [1].

3.1 Nuclear β decays and π decays

These decays constrain the de and $d\mu$ sectors since they do not involve strange particles. The data set for nuclear β decays include neutron decay, superallowed $0^+ \to 0^+$ transitions and mirror β decays. For π decays, four decay channels are considered: $\pi \to \mu\nu$, $\pi \to e\nu$, $\pi \to e\nu\gamma$ and $\pi^+ \to \pi^0 e^+ \nu$. The constraints resulting from the combination of the bounds for these decays can be found in Section 6.2 of Ref. [1]. Strong constraints are obtained for the de sector, reaching the permille and sub-permille levels. In particular, ϵ_P^{de} is strongly constrained because it is chiraly enhanced. In contrast, individual constraints in the $d\mu$ sector cannot be set because it is only probed by one decay channel: $\pi \to \mu\nu$.

3.2 K and hyperon decays

These decays are only sensitive to the se and $s\mu$ sectors. For K decays, we have considered the leptonic decays $K \to e\bar{\nu}$ and $K \to \mu\bar{\nu}$ along with the semi-leptonic decays $K \to \pi e(\mu)\bar{\nu}$. For hyperon β decays, only one bound is obtained by comparing the experimentally meassured axial charge, g_1, with its lattice determination. The constraints obtained combining the different bounds are given in Section 6.2 of Ref. [1]. The $s\mu$ sector is individually constrained. However, one cannot set bounds for the scalar and tensor interactions in the se sector at linear level in the WC because they are suppressed by the electron mass. Nonetheless, they can be constrained by keeping their quadratic effects in the K_{e3} differential distribution. As in the de sector, the pseudoscalar coefficients are strongly constrained because of chiral enhancement.

4. Global fit

The result of combining the previous three marginalized set of constraints can be found in Section 6.2 of Ref. [1], where one can find for the first time global bounds on the BSM parameters for the three lepton families in the light quark sector. What is interesting about this result is that we get a $\sim 3\sigma$ preference for BSM physics despite having so many free parameters. The reason for this can be clearly seen in the left pannel of Figure 1: every bound obtained from the different decay channels considered throughout the text can be translated into a determination of V_{us}. The tensions between the different data sets (the Cabibbo anomalies) result in a strong preference for BSM physics since the Wilson Coefficients modify the relation between V_{us} and data.

We have displayed in Table 2 the constraints for each BSM parameter in a one-at-a-time fit, hightlighting the ones with a 3σ or more preference for BSM physics. The particular preference for certain coefficients is easily understood: ϵ_L^{de} and ϵ_R^{s} ease the existing tension between nuclear and kaon decays, whereas $\epsilon_L^{s\tau}$ eases the tension between kaon decays and the strange inclusive decays.

	$\epsilon_X^{de} \times 10^3$	$\epsilon_X^{se} \times 10^3$	$\epsilon_X^{d\mu} \times 10^3$	$\epsilon_X^{s\mu} \times 10^3$	$\epsilon_X^{d\tau} \times 10^3$	$\epsilon_X^{s\tau} \times 10^3$
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 2: (From Ref. [1]) One-at-a-time constraints for the different Wilson Coefficients. We have highlighted in red the ones that show a 3σ or larger preference for BSM physics. The cross indicates that the coefficient is not constrained in our results.

By carefully choosing the BSM coefficients, the tension for all data sets can be completely removed. For instance, in the right pannel of Figure 1 we have plotted the result of a BSM scenario with only three coefficients: ϵ_R^d, ϵ_R^s and $\epsilon_L^{s\tau}$.

5. Summary and outlook

Through the combination of marginalized bounds from different data sets, we have obtained model independent bounds for the three lepton families in the light quark sector. In this result, there is a strong preference for BSM physics. This is nothing more than a consequence of the inconsistency between different determinations of V_{us}, known as the Cabibbo anomalies.

There are different ways in which an improvement of the current analysis can be achieved. First of all, as can be seen in the left pannel of Figure 1, there are several channels dominated by experimental uncertainties. Thus, more precise measurements of relevant quantities in our analysis, such as branching ratios, will significantly improve the constraints.

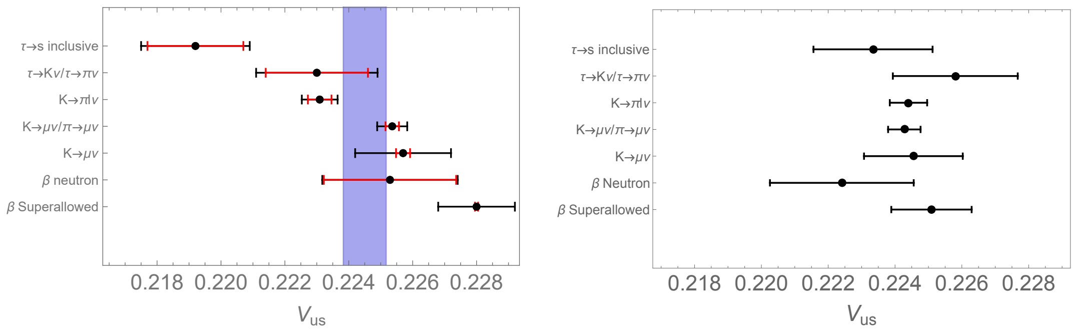

Figure 1: *Left*: 68% CL constraints on V_{us} from different decay processes, in a SM scenario (i.e., $\epsilon_X^{D\ell} = 0$). The black lines are the total uncertainties and the red lines the uncertainties from experiment. The purple band is the average of the individual results, with its uncertainty inflated by a factor of 2 in order to account for the large tension between the inputs. *Right*: (From Ref. [1]) Same plot, but in a BSM scenario with three non-zero Wilson Coefficients: $\epsilon_R^d = 6.8 \times 10^{-4}$, $\epsilon_R^s = 5.9 \times 10^{-3}$ and $\epsilon_L^{s\tau} = -1.8 \times 10^{-2}$.

Our results can also be improved including more observables, since this allows to put constraints in more individual Wilson Coefficients. In particular, this is necessary in the $d\mu$ and $s\tau$ sectors. For the $d\mu$ sector, more precise measurements of observables are needed, such as low energy μ-hadron scattering or μ capture. For the $s\tau$ sector, if the spectral functions for the strange τ inclusive decays eventually become avalaible the same analysis as in the non-strange case can be done. This would allow us to resolve that whole sector. Another possibility would be to try to analyze the $K\pi$ differential distribution using some form factor parametrization, acknowledging the potential uncertainty asociated to choosing a particular parametrization.

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