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Probes of non-standard interactions from exclusive hadronic tau decays

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In this talk we study the sensitivity of exclusive hadronic tau decays to non-standard interactions using the low-energy limit of the Standard Model Effective Field Theory. Employing Lattice input and dispersive form factors, along with experimental data, we analyze both one and two meson decays to set bounds on the new physics effective couplings. Our results complement the traditional low-energy probes, such as nuclear β or $K_{\ell 3}$ decays, and can be improved with new data, e.g. from Belle-II.

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1. Introduction

Exclusive hadronic tau decays offer a good environment to study low-energy effects of the strong interaction, as the hadrons in the final state are isolated and can be used to learn specific hadron properties and their interactions. For the simplest, one-meson decays $\tau^- \to P^-\nu_\tau$ ($P = \pi, K$) the only hadronic input required are the meson decay constants, which are well calculated by the Lattice QCD collaborations [1]. Two-meson decays $\tau^- \to P^-P^0\nu_\tau$, on the other hand, are much harder to describe as the hadronic information is encoded in form factors. Such decays have been extensively studied in the last decades to learn about hadronic physics, and the agreement between theory and the rich experimental data have been possible thanks to the advanced analytical QCD methods for modeling the form factors [2–6]. Decay modes with three or more hadrons in the final state show a more complex dynamical structure that demand a new level of sophistication of the theoretical methods for the data analysis, and will not be covered in this contribution.

The aim of this talk is to highlight that semileptonic tau decays are not only a clean QCD laboratory but also offer a potentially rich environment to search for new-physics effects [7–11], complementing the traditional low-energy precision observables, such nuclear β decays or semileptonic pion and kaon decays [12, 13], and high-energy measurements at the LHC. Indeed, to increase the accuracy of the search for such effects, one needs robust theoretical determinations of the participant form factors within the Standard Model. As a benefit of our controlled determination of such input [2–4, 14], in this talk we perform a global analysis of exclusive tau decays into one and two mesons using the low-energy limit of the Standard Model Effective Field Theory up to dimension six and set bounds on the new physics effective couplings.

2. SMEFT Lagrangian and decay rate

In our case of interest, the corresponding Lagrangian can be written as [12]:

$$\mathcal{L}_{CC} = -\frac{G_F V_{uD}}{\sqrt{2}}\Big[(1+\epsilon_L^\tau)\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau \cdot \bar{u}\gamma^\mu(1-\gamma^5)D + \epsilon_R^\tau\bar{\tau}\gamma_\mu(1-\gamma^5)\nu_\tau \cdot \bar{u}\gamma^\mu(1+\gamma^5)D$$
$$+\bar{\tau}(1-\gamma^5)\nu_\tau \cdot \bar{u}(\epsilon_S^\tau - \epsilon_P^\tau\gamma^5)D + \epsilon_T^\tau\bar{\tau}\sigma_{\mu\nu}(1-\gamma^5)\nu_\tau\, \bar{u}\sigma^{\mu\nu}(1-\gamma^5)D\Big] + h.c., \quad (1)$$

where $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$, G_F is the tree-level definition of the Fermi constant and ϵ_i ($i = L, R, S, P, T$) are effective couplings characterizing new physics.

The simplest application of Eq. (1) in searching for heavy new physics is the $\tau^- \to \pi^-\nu_\tau$ decay rate, which reads:

$$\Gamma(\tau^- \to \pi^-\nu_\tau) = \frac{G_F^2|\tilde{V}_{ud}^e|^2 f_\pi^2 m_\tau^3}{16\pi}\left(1-\frac{m_\pi^2}{m_\tau^2}\right)^2 \times (1+\delta_{\rm em}^{\tau\pi} + 2\Delta^{\tau\pi} + O(\epsilon_i^\tau)^2 + O(\delta_{\rm em}^{\tau\pi}\epsilon_i^\tau)), \quad (2)$$

where f_π is the pion decay constant, the quantity $\delta_{\rm em}^{\tau\pi}$ accounts for the electromagnetic radiative corrections and the term $\Delta^{\tau\pi}$ contains the tree-level NP corrections that arise from the Lagrangian in Eq. (1)[1] that are not absorbed in $\tilde{V}_{ud}^e$. For the mode $\tau^- \to K^-\nu_\tau$, the decay rate is that of Eq. (2) but replacing $\tilde{V}_{ud}^e \to \tilde{V}_{us}^e$, $f_\pi \to f_K$, $m_\pi \to m_K$, and $\delta_{\rm em}^{\tau\pi}$ and $\Delta^{\tau\pi}$ by $\delta_{\rm em}^{\tau K}$ and $\Delta^{\tau K}$, respectively.

[1]In Eq. (2) we have expanded up to linear order on the ϵ_i^τ couplings.

The amplitude for two-meson decays $\tau^- \to (PP')^-\nu_\tau$ from Eq. (1) contains a vector, an scalar and a tensor contribution, and the resulting partial decay width is given by: (s is the two-meson invariant mass):

$$\begin{aligned} \frac{d\Gamma}{ds} &= \frac{G_F^2|\tilde{V}_{uD}^e|^2 m_\tau^3 S_{EW}}{384\pi^3 s}\left(1-\frac{s}{m_\tau^2}\right)^2 \lambda^{1/2}(s,m_P^2,m_{P'}^2) \\ &\times \left[\left(1+2(\epsilon_L^\tau-\epsilon_L^e+\epsilon_R^\tau-\epsilon_R^e)\right) X_{VA}+\epsilon_S^\tau X_S+\epsilon_T^\tau X_T+(\epsilon_S^\tau)^2 X_{S^2}+(\epsilon_T^\tau)^2 X_{T^2}\right], \end{aligned} \tag{3}$$

where

$$\begin{aligned} X_{VA} &= \frac{1}{2s^2}\left\{3\left(C_{PP'}^S\right)^2|F_0^{PP'}(s)|^2\Delta_{PP'}^2 \right.\\ &\left. +\left(C_{PP'}^V\right)^2|F_+^{PP'}(s)|^2\left(1+\frac{2s}{m_\tau^2}\right)\lambda(s,m_P^2,m_{P'}^2)\right\}, \\ X_S &= \frac{3}{s\,m_\tau}\left(C_{PP'}^S\right)^2|F_0^{PP'}(s)|^2\frac{\Delta_{PP'}^2}{m_d-m_u}, \\ X_T &= \frac{6}{s\,m_\tau}C_{PP'}^V\,\mathrm{Re}\left[F_T^{PP'}(s)\left(F_+^{PP'}(s)\right)^*\right]\lambda(s,m_P^2,m_{P'}^2), \\ X_{S^2} &= \frac{3}{2\,m_\tau^2}\left(C_{PP'}^S\right)^2|F_0^{PP'}(s)|^2\frac{\Delta_{PP'}^2}{(m_d-m_u)^2}, \\ X_{T^2} &= \frac{4}{s}|F_T^{PP'}(s)|^2\left(1+\frac{s}{2\,m_\tau^2}\right)\lambda(s,m_P^2,m_{P'}^2), \end{aligned} \tag{4}$$

where $C_{PP'}^{V,S}$ are Clebsch-Gordan coefficients and $\Delta_{PP'}=m_P^2-m_{P'}^2$. In Eq. (3), $S_{EW}=1.0201$ [15] resums the short-distance electroweak corrections and the function $\lambda(x,y,z)=x^2+y^2+z^2-2xy-2xz-2yz$ is the usual Kallen function. The functions $F_0^{PP'}(s)$, $F_+^{PP'}(s)$ and $F_T^{PP'}(s)$ in Eq. (4) are, respectively, the scalar, the vector and the tensor form factors. A detailed description description of these form factors can be found in Ref. [7], and references therein.

3. New physics bounds from:

3.1 Strangeness-conserving $\Delta S=0$ decays

We start discussing the determination from the strangeness-conserving decay $\tau^-\to\pi^-\nu_\tau$. Using Eq. (2), $f_\pi=130.2(8)$ MeV from lattice [1],[2] $\delta_{\rm em}^{\tau\pi}=1.92(24)\%$ from a combination of the values given in [16], and the PDG reported values [17] for $m_\pi, BR(\tau^-\to\pi^-\nu_\tau), m_\tau, \Gamma_\tau, G_F$ and $|\tilde{V}_{ud}^e|=0.97420(21)$ from nuclear β decays, we obtain the constraint:

$$\epsilon_L^\tau-\epsilon_L^e-\epsilon_R^\tau-\epsilon_R^e-\frac{m_\pi^2}{m_\tau(m_u+m_d)}\epsilon_P^\tau=(-0.12\pm0.68)\times10^{-2}, \tag{5}$$

where the error is dominated by f_π, followed by the uncertainties of branching ratio and $\delta_{\rm em}^{\tau\pi}$.

[2] One cannot use f_π determined from data as it can be contaminated with new physics effects.

We next perform a combined fit to one and two meson strangeness-conserving decays, which include: the $\tau^- \to \pi^-\pi^0\nu_\tau$ spectrum and branching ratio from Belle [18], and the branching ratios of the decays $\tau^- \to K^-K^0\nu_\tau$ and $\tau^- \to \pi^-\nu_\tau$ from the PDG [17]. The limits for the non-standard effective couplings resulting from such fit are found to be [7]:

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_\pi^2}{2m_\tau(m_u+m_d)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 0.6^{+2.3}_{-1.8}{}^{+0.2}_{-0.1} \pm 0.4 \\ 0.3 \pm 0.5^{+1.1}_{-0.9}{}^{+0.1}_{-0.0} \pm 0.2 \\ 9.7^{+0.5}_{-0.6} \pm 21.5^{+0.0}_{-0.1} \pm 0.2 \\ -0.1 \pm 0.2^{+1.1}_{-1.4}{}^{+0.0}_{-0.1} \pm 0.2 \end{pmatrix} \times 10^{-2}, \tag{6}$$

where the first error is the statistical fit uncertainty, the second comes from the error of the pion vector form factor, while the third and fourth come from quark masses error and the tensor form factors, respectively. Comparing our limits with those from $K_{\ell 3}$ decays, $\epsilon_S^\mu = (-0.039 \pm 0.049) \times 10^{-2}$ and $\epsilon_T^\mu = (0.05 \pm 0.52) \times 10^{-2}$ [13], our limits cannot compete with the limits on ϵ_S, whereas we obtain a competitive constraint on the ϵ_T coupling. In addition, our results are in general accord with respect to those from [19] obtained through a combination of inclusive and exclusive tau decays.

3.2 Strangeness-changing $|\Delta S = 1|$ decays

The decay $\tau^- \to K^-\nu_\tau$ can be used to constrain the combination of the couplings of Eq. (5), but replacing $m_d \to m_s$ and $m_\pi \to m_K$ and with the ϵ's corresponding to $u \to s$ transitions. Using $f_K = 155.7(7)$ MeV [1], the radiative corrections $\delta_{\rm em}^{\tau K} = 1.98(31)\%$ from [16] and the PDG input for $|\tilde{V}_{us}^e| = 0.2231(7)$, $BR(\tau^- \to K^-\nu_\tau)$ and m_K, we obtain the constraint:

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_K^2}{m_\tau(m_u + m_s)}\epsilon_P^\tau = (-0.41 \pm 0.93) \times 10^{-2}, \tag{7}$$

where the uncertainty is dominated by f_K and $|V_{us}|$ followed by the branching ratio and $\delta_{\rm em}^{\tau K}$.

Similar to the previous section, we next analyze strangeness-changing exclusive transitions with one and two mesons in the final state simultaneously. For the analysis we include the $\tau^- \to K_S\pi^-\nu_\tau$ Belle spectrum and branching ratio [20] and the branching ratios of the decays $\tau^- \to K^-\eta\nu_\tau$ and $\tau^- \to K^-\nu_\tau$ from the PDG. In this case, the limits for the NP effective couplings are found to be [7]:

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_K^2}{2m_\tau(m_u+m_s)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 1.5 \pm 0.3 \\ 0.4 \pm 0.9 \pm 0.2 \\ 0.8^{+0.8}_{-0.9} \pm 0.3 \\ 0.9 \pm 0.7 \pm 0.4 \end{pmatrix} \times 10^{-2}, \tag{8}$$

where the first error is the statistical fit uncertainty while the second one is a systematic uncertainty due to the tensor form factor. Different to Eq. (8), the uncertainty associated to the kaon vector form factor and to the quark masses is negligible. Comparing the results of Eq. (8) with those of Eq. (6) serve as a consistency check. As seen, the results of the first and second rows in Eq. (8) are in accord with those from Eq. (6). As for the central value of the coefficient $\epsilon_S^\tau(\epsilon_T^\tau)$ from the $|\Delta S| = 1$ sector, it has decreased(increased) by about one order of magnitude with respect to the $\Delta S = 0$ one; ϵ_S^τ is now more competitive while the sign of ϵ_T^τ has changed.

3.3 Global analysis to both $\Delta S = 0$ and $|\Delta S = 1|$ sectors

We close our analysis by performing a simultaneous fit to both $\Delta S = 0$ and $|\Delta S = 1|$ sectors. In this case, the participant CKM elements, $|V_{ud}|$ and $|V_{us}|$, are not independent but rather correlated; we use the relation $|V_{us}|/|V_{ud}| = 0.2313(5)$ [1] along with $|V_{us}| = 0.2231(7)$ [17] to extract $|V_{ud}|$. For the global fit, we include all decays that were considered in sections 3.1 and 3.2 for the analysis of the $\Delta S = 0$ and $|\Delta S| = 1$ transitions, respectively. The resulting limits for the new physics effective couplings are found to be [7]:

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau \\ \epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 2.9 & \pm 0.6 & {}^{+1.0}_{-0.9} & \pm 0.6 & \pm 0.0 & \pm 0.4 & {}^{+0.2}_{-0.3} \\ 7.1 & \pm 4.9 & {}^{+0.5}_{-0.4} & {}^{+1.3}_{-1.5} & {}^{+1.2}_{-1.3} & \pm 0.2 & {}^{+40.9}_{-14.1} \\ -7.6 & \pm 6.3 & \pm 0.0 & {}^{+1.9}_{-1.6} & {}^{+1.7}_{-1.6} & \pm 0.0 & {}^{+19.0}_{-53.6} \\ 5.0 & {}^{+0.7}_{-0.8} & {}^{+0.8}_{-1.3} & {}^{+0.2}_{-0.1} & \pm 0.0 & \pm 0.2 & {}^{+1.1}_{-0.6} \\ -0.5 & \pm 0.2 & {}^{+0.8}_{-1.0} & \pm 0.0 & \pm 0.0 & \pm 0.6 & \pm 0.1 \end{pmatrix} \times 10^{-2}, \quad (9)$$

where the first error is statistical from the fit, the second comes from the pion form factor error, the third error corresponds to $|V_{ud}|$ and $|V_{us}|$, the fourth one is due to $\delta_{\rm em}^{\tau\pi}$ and $\delta_{\rm em}^{\tau K}$, the fifth estimates the (uncontrolled) uncertainty of the tensor form factor, while the last is due to the quark masses error. Notice that this fit yields an independent determination of the couplings ϵ_R^τ and ϵ_P^τ which, in turn, carry a large statistical (and systematic) error. Also notice that, different to the results of Eqs. (6) and (8), an independent determination of the couplings ϵ_R^τ and ϵ_P^τ can be obtained from the combined fit; these couplings, however, carry large errors. For the combination of the couplings of the first line in Eq. (9), our limits are competitive and within errors with [19]. As for ϵ_S^τ, our limit is not competitive, and disagrees, with the bounds of Refs. [8, 19], where a constraint for ϵ_S^τ was placed from the isospin-violating decay $\tau^- \to \pi^-\eta\nu_\tau$. In our analysis, we do not consider this channel as it has not been measured yet, only an upper bound exists. Finally, our bound for ϵ_T^τ is competitive and found to be in agreement with [9, 19]. We would like to note that the uncertainty associated to the CKM elements dominates the error of those coefficients in Eq. (9) for what we get competitive bounds. Therefore, improved lattice results can result in tighter constraints in the future.

4. Conclusions

In this contribution we have studied the sensitivity of exclusive one and two-meson hadronic tau decays to new physics effects. This has been possible due to the controlled theoretical determination of the necessary Standard Model hadronic input, i.e. decay constants and form factors, along with experimental data. Our bounds on the new physics effective couplings are summarized in Eqs. (6), (8) and (9). In general, our limits are competitive when compared with other low-energy probes. This is particularly the case of the combination of couplings $\epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e$, and for ϵ_T^τ. Our limits for the latter that can even compete with the constraints from the theoretically cleaner $K_{\ell 3}$ decays (lepton flavor universality is assumed for the comparison).

Our analysis, however, is presently limited by the fact that the Standard Model form factors contain parameters which have been fitted to data previously, and thus they may have absorbed

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some new physics information, if this is in the data. To address this drawback, we have tried fits where both the new physics effective couplings and the Standard Model input parameters entering the corresponding form factors are considered as free parameters to fit. In doing so, we have too many free parameters to fit and found no sensitivity to the new physics couplings. This is indeed interesting to prove in the future, with a higher-quality data, but at present is not feasible. This is another reason to encourage the experimental tau physics groups at Belle-II to measure these decays with higher accuracy as this would render bounds at the level of the currently most stringent ones.

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