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Global analysis of NSI in exclusive semileptonic tau decays

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We perform a global analysis of exclusive hadronic tau decays into one and two mesons using the low-energy limit of the Standard Model Effective Field Theory up to dimension six, assuming left-handed neutrinos. A controlled theoretical input on the Standard Model hadronic form factors, based on chiral symmetry, dispersion relations, data and asymptotic QCD properties, has allowed us to set bounds on the New Physics (NP) effective couplings using the present experimental data. Our results highlight the importance of semileptonic τ decays in complementing the traditional low-energy probes, such nuclear β decays or semileptonic pion and kaon decays, and the high-energy measurements at LHC scales. This makes yet another reason for considering hadronic tau decays as golden modes at Belle-II.

Keywords: Effective field theories; beyond standard model; tau decays.

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1. Introduction

The present work is based on the article [1] that we have published recently. More information can also be found in my PhD thesis [2].

It is well known that tau physics is a clean low energy laboratory for QCD and also a powerful tool for precision electroweak studies. Here, we want to show that in addition, tau physics is a very useful tool to study potential heavy NP effects. We follow an EFT approach with the low energy limit of the Standard Model Effective Field Theory (SMEFT) [3, 4] as the natural framework. Within this frame we construct the most general charged current effective Lagrangian with dimension six operators, which are dominant. With this Lagrangian we calculate several interesting observables for hadronic tau decays into one and two mesons, namely, the decay rates for the one-meson processes $\tau^- \to P^-\nu_\tau$ with $P = \pi, K$, and the partial decay widths for the two-meson decays $\tau^- \to (PP')^-\nu_\tau$. Our work divides naturally in three sections: an analysis for strangeness-conserving decays ($\Delta S = 0$), an analysis for strangeness-changing decays ($|\Delta S| = 1$) and finally a global analysis for both sectors simultaneously (relying on the well-motivated and experimentally supported hypothesis of minimal flavor violation in the last case).

Recently, several works [5–9] have studied non-standard weak charged current interactions in semileptonic tau decays and they have indicated that these kinds of decays offer an interesting scenario to study effects of heavy NP. These studies have opened a new window and have shown the importance of hadronic tau decays in complementing other traditional low-energy semileptonic probes such as nuclear beta decays, purely leptonic lepton, pion and kaon decays, and also hyperon decays [10–20]. The idea in this work is to take advantage from our previous individual analyses of tau decays into two mesons (plus a neutrino) discussed above [5, 6, 8, 9] and perform in this case a global analysis in the same spirit as Ref. [7] but taking into account in this case also strangeness-changing decays and not only strangeness-conserving decays, and also taking into account purely exclusive hadronic tau decays and not a combination of exclusive and inclusive semileptonic tau decays as the authors do in Ref. [7].

We organize this article in the following way: we discuss the theoretical framework in Sec. 2, where we present the effective Lagrangian that we use and calculate the analytical expressions for the important observables in our analysis. Next, in Secs. 3 and 4, we study the bounds on the NP effective couplings for the strangeness-conserving ($\Delta S = 0$) and the strangeness-changing ($|\Delta S| = 1$) transitions, respectively. Then, a simultaneous global fit to the two sectors ($\Delta S = 0$ and $|\Delta S| = 1$), is studied in Sec. 5. We state our conclusions in Sec. 6.

2. Effective Lagrangian and decay rates

The appropriate effective Lagrangian considering dimension six operators for the energy scale of interest ($\mathcal{O}$(1 GeV)) is given by [10, 11]

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

where G_F is the tree-level definition of the Fermi constant, $\sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$, and ϵ_i ($i = L, R, S, P, T$) are effective couplings encoding NP. The CKM element V_{uD} becomes V_{ud} for strangeness-conserving decays and V_{us} for strangeness-changing decays. It is important to note at this point that the combination $G_F V_{uD}$ in Eq. (1) will carry a dependence on ϵ_L^e and ϵ_R^e since it is determined from superallowed nuclear Fermi β decays, this dependence is given by [16]

$$G_F \tilde{V}^e_{uD} = G_F\left(1 + \epsilon^e_L + \epsilon^e_R\right) V_{uD}\,, \tag{2}$$

note that if we set the coefficients $\epsilon_i = 0$ in Eqs. (1) and (2), we recover the SM Lagrangian.

We start our analysis with the one-meson decay modes $\tau^- \to P^-\nu_\tau$ $(P = \pi, K)$ since these are the simplest hadronic tau decays that can be calculated with the effective Lagrangian of Eq. (1). This simplicity arises from the fact that these are two-body decays so that the kinematics is fixed and the form factors become decay constants. The expression for the decay rate for the process $\tau^- \to \pi^-\nu_\tau$ takes the form

$$\begin{aligned}\Gamma(\tau^- \to \pi^-\nu_\tau) &= \frac{G_F^2|\tilde{V}^e_{ud}|^2 f_\pi^2 m_\tau^3}{16\pi}\left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 \\ &\quad\times\left(1 + \delta^{\tau\pi}_{\text{em}} + 2\Delta^{\tau\pi}\right. \\ &\quad\left. + \mathcal{O}(\epsilon_i^\tau)^2 + \mathcal{O}(\delta^{\tau\pi}_{\text{em}}\epsilon_i^\tau)\right)\,, \end{aligned}\tag{3}$$

where f_π is the decay constant of the pion[i], the term $\delta^{\tau\pi}_{\text{em}}$ takes into account the electromagnetic radiative corrections, and the quantity $\Delta^{\tau\pi}$ takes into account the tree-level NP corrections that arise from the effective Lagrangian in Eq. (1)[ii] that are not considered in $\tilde{V}^e_{ud}$. For the process $\tau^- \to K^-\nu_\tau$, the decay rate is again given by Eq. (3) but with the replacements $\tilde{V}^e_{ud} \to \tilde{V}^e_{us}$, $f_\pi \to f_K$, $m_\pi \to m_K$, and $\delta^{\tau\pi}_{\text{em}}$ and $\Delta^{\tau\pi}$ by $\delta^{\tau K}_{\text{em}}$ and $\Delta^{\tau K}$, respectively.

Next, we continue our discussion with the two-meson decay modes $\tau^- \to (PP')^-\nu_\tau$. The partial decay width for these decays is given by

$$\begin{aligned}\frac{d\Gamma}{ds} &= \frac{G_F^2|\tilde{V}^e_{uD}|^2 m_\tau^3 S_{EW}}{384\pi^3 s}\left(1 - \frac{s}{m_\tau^2}\right)^2 \lambda^{1/2}(s, m_P^2, m_{P'}^2) \\ &\quad\times\Bigg[\left(1 + 2(\epsilon^\tau_L - \epsilon^e_L + \epsilon^\tau_R - \epsilon^e_R)\right) X_{VA} \\ &\quad + \epsilon^\tau_S X_S + \epsilon^\tau_T X_T + (\epsilon^\tau_S)^2 X_{S^2} + (\epsilon^\tau_T)^2 X_{T^2}\Bigg]\,, \end{aligned}\tag{4}$$

where the variable s is the invariant mass of the corresponding two-meson system, that is, $s = (p_P + p_{P'})^2$, and where we have made the following definitions:

$$\begin{aligned}X_{VA} &= \frac{1}{2s^2}\Bigg\{3\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \Delta^2_{PP'} \\ &\quad + \left(C^V_{PP'}\right)^2 |F_+^{PP'}(s)|^2 \left(1 + \frac{2s}{m_\tau^2}\right)\lambda(s, m_P^2, m_{P'}^2)\Bigg\}\,, \\ X_S &= \frac{3}{s\, m_\tau}\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \frac{\Delta^2_{PP'}}{m_d - m_u}\,, \\ X_T &= \frac{6}{s\, m_\tau} C^V_{PP'}\,\text{Re}\left[F_T^{PP'}(s)\left(F_+^{PP'}(s)\right)^*\right]\lambda(s, m_P^2, m_{P'}^2)\,, \\ X_{S^2} &= \frac{3}{2\, m_\tau^2}\left(C^S_{PP'}\right)^2 |F_0^{PP'}(s)|^2 \frac{\Delta^2_{PP'}}{(m_d - m_u)^2}\,, \\ X_{T^2} &= \frac{4}{s}|F_T^{PP'}(s)|^2\left(1 + \frac{s}{2\, m_\tau^2}\right)\lambda(s, m_P^2, m_{P'}^2)\,, \end{aligned}\tag{5}$$

where $C^V_{PP'}$ and $C^S_{PP'}$ are the corresponding Clebsch-Gordan coefficients for the different channels, $\lambda(x,y,z) = x^2 + y^2 + z^2 - 2xy - 2xz - 2yz$ is the Kallen function, and $\Delta_{PP'} = m_P^2 - m_{P'}^2$. The form factors $F_0^{PP'}(s), F_+^{PP'}(s)$ and $F_T^{PP'}(s)$ (scalar, vector and tensor, respectively) in Eq. (5) are obtained using chiral perturbation theory (ChPT), dispersion relations, and data. For the vector form factors we benefit from the previous works [29–35] and for the scalar form factors we benefit from [36–40] while for the tensor form factors we use an Omnès dispersive representation [6, 8, 9, 41, 42]:

$$F_T^{PP'}(s) = F_T^{PP'}(0)\exp\left[\frac{s}{\pi}\int_{s_{\text{th}}}^{s_{\text{cut}}}\frac{ds'}{s'}\frac{\delta_T^{PP'}(s')}{(s' - s - i0)}\right]\,, \tag{6}$$

where $s_{\text{th}} = (m_P + m_{P'})^2$ is the two-meson production threshold for the lightest pair of mesons with the same quantum numbers as the given pair PP', and where the normalization $F_T^{PP'}(0)$ is obtained with the help of ChPT with tensor sources [43] and lattice data [44]. We have studied the normalization of the tensor form factors for the different channels in our previous works [6, 8, 9].

3. NP bounds from $\Delta S = 0$ decays

Before discussing the global analysis for $\Delta S = 0$ decays, which is the main goal for this section, we will see first what we can learn from the individual decay mode $\tau^- \to \pi^-\nu_\tau$. From the decay rate in Eq. (3) and using as input: $f_\pi = 130.2(8)$ MeV from the lattice[iii] [45], $\delta^{\tau\pi}_{\text{em}} = 1.92(24)\%$ [46–48], and also the following values taken from the PDG [49]; $|\tilde{V}^e_{ud}| = 0.97420(21)$ from nuclear β decays, the branching ratio $BR(\tau^- \to \pi^-\nu_\tau) = 10.82(5)\%$, $m_\pi = 0.13957061(24)$ GeV, $m_\tau = 1.77686(12)$ GeV, $\Gamma_\tau = 2.265\times 10^{-12}$ GeV, and $G_F = 1.16637(1)\times 10^{-5}$ GeV^{-2}, we obtain the following constraint:

$$\begin{aligned}&\epsilon^\tau_L - \epsilon^e_L - \epsilon^\tau_R - \epsilon^e_R - \frac{m_\pi^2}{m_\tau(m_u + m_d)}\epsilon^\tau_P \\ &\quad= (-0.12 \pm 0.68)\times 10^{-2}\,. \end{aligned}\tag{7}$$

The value shown in Eq. (7) was reported in our paper [1], but recently the radiative corrections have been updated in [50], using the results for the real photon emission in [51]. Employing also the updated V_{ud} value [52] $(|V_{ud}| = 0.97373 \pm 0.00031)$, this results in the limit

$$\begin{aligned}&\epsilon^\tau_L - \epsilon^e_L - \epsilon^\tau_R - \epsilon^e_R - \frac{m_\pi^2}{m_\tau(m_u + m_d)}\epsilon^\tau_P \\ &\quad= (-0.15 \pm 0.72)\times 10^{-2}\,. \end{aligned}\tag{8}$$

Now, we turn to the global analysis for $\Delta S = 0$ decays. For this task we perform a simultaneous fit to one and two meson strangeness-conserving exclusive semileptonic decays of the tau lepton taking into account the following observables:

- the data for $\tau^- \to \pi^-\pi^0\nu_\tau$ reported by the Belle collaboration [53], including the normalized unfolded spectrum and also the branching ratio.
- the branching ratio for the process $\tau^- \to K^-K^0\nu_\tau$.
- the branching ratio for $\tau^- \to \pi^-\nu_\tau$.

The χ^2 function that is minimized in this global fit has the following form

$$\chi^2 = \sum_k \left(\frac{\bar{N}_k^{\rm th} - \bar{N}_k^{\rm exp}}{\sigma_{\bar{N}_k^{\rm exp}}}\right)^2 + \left(\frac{BR_{\pi\pi}^{\rm th} - BR_{\pi\pi}^{\rm exp}}{\sigma_{BR_{\pi\pi}^{\rm exp}}}\right)^2 + \left(\frac{BR_{KK}^{\rm th} - BR_{KK}^{\rm exp}}{\sigma_{BR_{KK}^{\rm exp}}}\right)^2 + \left(\frac{BR_{\tau\pi}^{\rm th} - BR_{\tau\pi}^{\rm exp}}{\sigma_{BR_{\tau\pi}^{\rm exp}}}\right)^2 , \quad (9)$$

where $\bar{N}_k^{\rm th}$ associates the decay rate of Eq. (4) for $\tau^- \to \pi^-\pi^0\nu_\tau$ with the normalized distribution for the measured number of events. This relation is given by

$$\frac{1}{N_{\rm events}}\frac{dN_{\rm events}}{ds} = \frac{1}{\Gamma(\epsilon_i^\tau, \epsilon_j^e)}\frac{d\Gamma(s, \epsilon_i^\tau, \epsilon_j^e)}{ds}\Delta^{\rm bin} , \quad (10)$$

where $N_{\rm events}$ represents the total number of measured events and $\Delta^{\rm bin}$ represents the bin width. Additionally, $\bar{N}_k^{\rm exp}$ and $\sigma_{\bar{N}_k^{\rm exp}}$ in Eq. (9) represent, respectively, the experimental number of events and the corresponding uncertainties in the k-th bin.

The bounds for the effective couplings characterizing the NP that result from our global fit are

$$\begin{pmatrix} \epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e \\ \epsilon_R^\tau + \frac{m_\pi^2}{2m_\tau(m_u+m_d)}\epsilon_P^\tau \\ \epsilon_S^\tau \\ \epsilon_T^\tau \end{pmatrix} = \begin{pmatrix} 0.5 \pm 0.6^{+2.3}_{-1.8}{}^{+0.2}_{-0.1} \pm 0.4 \\ 0.3 \pm 0.5^{+1.1}_{-0.9}{}^{+0.1}_{-0.0} \pm 0.2 \\ 9.7^{+0.5}_{-0.6} \pm 21.5\,{}^{+0.0}_{-0.1} \pm 0.2 \\ -0.1 \pm 0.2^{+1.1}_{-1.4}{}^{+0.0}_{-0.1} \pm 0.2 \end{pmatrix} \times 10^{-2}, \quad (11)$$

where the first error is the statistical uncertainty of the fit, the second one –which is the dominant one– comes from the theoretical uncertainty associated with the vector form factor of the pion, and finally the third and fourth errors are systematic uncertainties obtained, respectively, from the error of the quark masses and from the uncertainty of the corresponding tensor form factors (we have worked in the $\overline{MS}$ scheme at a scale $\mu = 2$GeV in Eq. (11)).

The correlation matrix (ρ_{ij}) associated to the results of Eq. (11) is

$$\rho_{ij} = \begin{pmatrix} 1 & 0.684 & -0.493 & -0.545 \\ & 1 & -0.337 & -0.372 \\ & & 1 & 0.463 \\ & & & 1 \end{pmatrix} , \quad (12)$$

with χ^2/d.o.f.~ 0.6.

4. NP bounds from $|\Delta S| = 1$ decays

In this section we perform a global analysis for $|\Delta S| = 1$ decays, but before we do so, following the ideas of the previous section, we will first discuss what we can learn from the individual decay mode $\tau^- \to K^-\nu_\tau$. As we have pointed out before, this strangeness-changing decay rate has the same form that the one in Eq. (3), thus, using that formula with the appropriate replacements and using the lattice calculation of $f_K = 155.7(7)$ MeV [45], the radiative corrections $\delta_{\rm em}^{\tau K} = 1.98(31)\%$ [46–48], and the PDG numerical inputs [49]: $|\tilde{V}_{us}^e| = 0.2231(7)$, $BR(\tau^- \to K^-\nu_\tau) = 6.96(10) \times 10^{-3}$ and $m_K = 0.493677(16)$ GeV, we get the following constraint:

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_K^2}{m_\tau(m_u+m_s)}\epsilon_P^\tau = (-0.41 \pm 0.93) \times 10^{-2} . \quad (13)$$

The value shown in Eq. (13) was reported in our paper [1]. Taking into account the update in the radiative corrections that we mentioned in the previous section [50], we find

$$\epsilon_L^\tau - \epsilon_L^e - \epsilon_R^\tau - \epsilon_R^e - \frac{m_K^2}{m_\tau(m_u+m_s)}\epsilon_P^\tau = (-0.36 \pm 1.18) \times 10^{-2} . \quad (14)$$

Next, for the global analysis for $|\Delta S| = 1$ decays, we proceed exactly as we did for the $\Delta S = 0$ case, that is, we perform a simultaneous fit to one and two meson strangeness-changing exclusive semileptonic decays of the tau lepton taking into account the following observables:

- the $\tau^- \to K_S\pi^-\nu_\tau$ Belle spectrum [54] together with the measured branching ratio, $BR_{K\pi}^{\rm exp} = 0.404(2)(13)\%$.
- the branching ratio of the process $\tau^- \to K^-\eta\nu_\tau$ ($BR_{K\eta}^{\rm exp} = 1.55(8) \times 10^{-4}$) [49]^{iv,v}.
- the branching ratio of the process $\tau^- \to K^-\nu_\tau$ ($BR_{\tau K}^{\rm exp} = 6.96(10) \times 10^{-3}$) [49].

In this case the χ^2 function that is minimized in our fits is given by

$$\chi^2=\sum_k\left(\frac{\bar N_k^{\rm th}-\bar N_k^{\rm exp}}{\sigma_{\bar N_k^{\rm exp}}}\right)^2+\left(\frac{BR_{K\pi}^{\rm th}-BR_{K\pi}^{\rm exp}}{\sigma_{BR_{K\pi}^{\rm exp}}}\right)^2+\left(\frac{BR_{K\eta}^{\rm th}-BR_{K\eta}^{\rm exp}}{\sigma_{BR_{K\eta}^{\rm exp}}}\right)^2+\left(\frac{BR_{\tau K}^{\rm th}-BR_{\tau K}^{\rm exp}}{\sigma_{BR_{\tau K}^{\rm exp}}}\right)^2, \quad (15)$$

where $\bar N_k^{\rm th}$ refers to the $K_S\pi^-$ decay mode. The explicit expression reads

$$\frac{dN_{\rm events}}{d\sqrt{s}}=\frac{N_{\rm events}}{\Gamma(\epsilon_i^\tau,\epsilon_j^e)}\frac{d\Gamma(\sqrt{s},\epsilon_i^\tau,\epsilon_j^e)}{d\sqrt{s}}\Delta^{\rm bin}. \quad (16)$$

The bounds coming from the global fit to the $|\Delta S|=1$ decays are given by[vi]

$$\begin{pmatrix}\epsilon_L^\tau-\epsilon_L^e+\epsilon_R^\tau-\epsilon_R^e\\ \epsilon_R^\tau+\frac{m_K^2}{2m_\tau(m_u+m_s)}\epsilon_P^\tau\\ \epsilon_S^\tau\\ \epsilon_T^\tau\end{pmatrix}=\begin{pmatrix}0.5\pm1.5\pm0.3\\ 0.4\pm0.9\pm0.2\\ 0.8^{+0.8}_{-0.9}\pm0.3\\ 0.9\pm0.7\pm0.4\end{pmatrix}\times10^{-2}, \quad (17)$$

where the first error is the statistical uncertainty of the fit and the second error is the systematic uncertainty coming from the tensor form factor. In contrast with the $\Delta S=0$ case which is given in Eq. (11), the uncertainty associated with the vector form factor of the kaon and with the quark masses is negligible.

The correlation matrix for to the results of Eq. (17) reads

$$\rho_{ij}=\begin{pmatrix}1&0.854&-0.147&0.437\\ &1&-0.125&0.373\\ &&1&-0.055\\ &&&1\end{pmatrix}, \quad (18)$$

with χ^2/d.o.f.~ 0.9.

There are two important points to note from Eqs. (17) and (18), one is that the element ρ_{12} in Eq. (18) is large (it was also the largest element in Eq. (12)). This is a result of the strong correlation between the couplings ϵ_R^τ and ϵ_P^τ. The other point is that the ϵ_S^τ coupling is more competitive by an order of magnitude than the corresponding one for the $\Delta S=0$ sector shown in Eq. (11). However, the ϵ_T^τ coupling has now increased by about one order of magnitude and has changed sign which makes it a little less restrictive than in the $\Delta S=0$ case. In the next section we will see that if we combine both ($\Delta S=0$ and $|\Delta S|=1$) kinds of decays we take the advantages of each sector.

5. NP bounds from a global fit to both $\Delta S=0$ and $|\Delta S|=1$ sectors

In this section we take advantage of the previous two and perform a global fit to both the strangeness-conserving ($\Delta S=0$) and the strangeness-changing ($|\Delta S|=1$) sectors simultaneously. This can only be done under the assumption of $d\leftrightarrow s$ universality (apart from the CKM mixing), which is quite reasonable as a realization of the celebrated Minimal Flavor Violation hypothesis [57]. The reason to do this is that, on the one hand, we will be able to disentangle the ϵ_R^τ and the ϵ_P^τ couplings, and on the other hand, we will benefit in our bounds for ϵ_T^τ and ϵ_S^τ from the strangeness-conserving sector and the strangeness-changing sector, respectively.

Since the correlation of parameters is important, we will take the $|V_{ud}|$ and $|V_{us}|$ elements of the CKM matrix correlated according to [45]

$$\frac{|V_{us}|}{|V_{ud}|}=0.2313(5). \quad (19)$$

For the analysis, we use $|V_{us}|=0.2231(7)$ [49] and then we extract $|V_{ud}|$ using Eq. (19).

For our global fit the χ^2 function that is minimized includes all the quantities that we used for the separate analyses (see Eqs. (9) and (15)). In this case the NP effective couplings are given by (again in the scheme $\overline{\rm MS}$ at a scale $\mu=2$ GeV)

$$\begin{pmatrix}\epsilon_L^\tau-\epsilon_L^e+\epsilon_R^\tau-\epsilon_R^e\\ \epsilon_R^\tau\\ \epsilon_P^\tau\\ \epsilon_S^\tau\\ \epsilon_T^\tau\end{pmatrix}=10^{-2}\times\begin{pmatrix}2.9&\pm0.6&^{+1.0}_{-0.9}&\pm0.6&\pm0.0&\pm0.4&^{+0.2}_{-0.3}\\ 7.1&\pm4.9&^{+0.5}_{-0.4}&^{+1.3}_{-1.5}&^{+1.2}_{-1.3}&\pm0.2&^{+40.9}_{-14.1}\\ -7.6&\pm6.3&\pm0.0&^{+1.9}_{-1.6}&^{+1.7}_{-1.6}&\pm0.0&^{+19.0}_{-53.6}\\ 5.0&^{+0.7}_{-0.8}&^{+0.8}_{-1.3}&^{+0.2}_{-0.1}&\pm0.0&\pm0.2&^{+1.1}_{-0.6}\\ -0.5&\pm0.2&^{+0.8}_{-1.0}&\pm0.0&\pm0.0&\pm0.6&\pm0.1\end{pmatrix}, \quad (20)$$

where the first error is the statistical error of the fit, the second error is due to the uncertainty of the vector form factor of the pion, the third one comes from the CKM elements $|V_{ud}|$ and $|V_{us}|$, the fourth error comes from the radiative corrections $\delta_{\rm em}^{\tau\pi}$ and $\delta_{\rm em}^{\tau K}$, the fifth comes from the systematic uncertainty of the tensor form factor, and the last error, is due to the errors coming from the quark masses.

The correlation matrix in this case is given by

$$\mathcal{A}=\begin{pmatrix}1&0.055&0.000&-0.279&-0.394\\ &1&-0.997&-0.015&-0.022\\ &&1&0.000&0.000\\ &&&1&0.243\\ &&&&1\end{pmatrix}, \quad (21)$$

where χ^2/d.o.f.~ 1.38.

As we see from Eq. (21) the price that we pay for disentangling the effective couplings ϵ_R^τ and ϵ_P^τ is that they are strongly correlated, but otherwise we gain in our capacity to constrain at the same time ϵ_T^τ and ϵ_S^τ.

The NP effective couplings can be translated into bounds for the corresponding NP scale in the following way

$$\Lambda \sim v \left(V_{uD}\epsilon_i\right)^{-1/2} , \qquad (22)$$

where $v = (\sqrt{2}G_F)^{-1/2} \sim 246$ GeV, thus our bounds can probe scales of $\mathcal{O}(5)$ TeV.

6. Conclusions

In this article we have studied non-standard interactions by analizing a charged current effective Lagrangian for semileptonic tau decays constructed with dimension six operators. We have set bounds on the non-standard effective couplings by using exclusive hadronic tau decays with one and two mesons in the final state. Our main results are found in Eqs. (11), (17) and (20), which represent our bounds for the NP effective couplings, for the strangeness-conserving sector, the strangeness-changing sector, and the global case, respectively. Our bounds for the NP effective couplings, are found competitive, in particular two of them: the combination $\epsilon_L^\tau - \epsilon_L^e + \epsilon_R^\tau - \epsilon_R^e$ and ϵ_T^τ. The first is in accord with the analogue constraint presented in Ref. [7], and the second can compete with $K_{\ell 3}$ decays (assuming of course lepton flavor universality). From the individual fits to the strangeness-conserving and the strangeness-changing decays, we see that we cannot separate the couplings ϵ_P^τ and ϵ_R^τ, however, with the simultaneous global fit (relying on the well-motivated and experimentally supported hypothesis of minimal flavor violation) these can be separated, the price we must pay is of course the strong correlation between both couplings. Finally, for ϵ_S^τ, we see that it is impossible to compete with the bounds coming from $K_{\ell 3}$ decays. To improve this last coupling, special attention must be paid to the decay channel $\tau^- \to \pi^-\eta\nu_\tau$, we have not included this channel in the analysis since higher quality data is needed.

With these analyses we want to show the importance of semileptonic tau decays as low-energy probes of NP. We hope that our works can serve as a motivation for the experimental tau physics groups at Belle-II to measure the different observables we have discussed.

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i. We use here, for convenience, the 'electroweak' decay constant, ~ 130 MeV, which is $\sqrt{2}$ times larger than its chiral counterpart ~ 92 MeV.

ii. In Eq. (3) we expanded up to linear order on the NP effective couplings ϵ_i^τ.

iii. We cannot employ the pion decay constant determined from data since it could be contaminated with NP effects.

iv. The $\tau^- \to K^-\eta\nu_\tau$ decay spectrum has been measured by Belle [55], but unfolding detector effects have not been implemented and for that reason we have decided to include only the branching ratio in this study.

v. The decay $\tau^- \to K^-\eta'\nu_\tau$ has not been detected yet, there is only an upper limit at the 90% confidence level placed by BaBar [56] and we therefore have decided to not include it in our analysis.

vi. The bounds are obtained in the $\overline{MS}$ at a scale $\mu = 2$GeV just as was done for the $\Delta S = 0$ case.

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