Low-energy limit of SMEFT applied to $\tau^- \to \pi^-\pi^0\nu_\tau$ decays

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Abstract

We perform an effective field theory analysis of the $\tau^- \to \pi^-\pi^0\nu_\tau$ decays, that includes the most general interactions between Standard Model fields up to dimension six, assuming left-handed neutrinos. We constrain as much as possible the necessary Standard Model hadronic input using chiral symmetry, dispersion relations, data and asymptotic QCD properties. As a result, we set precise (competitive with low-energy and LHC measurements) bounds on (non-standard) charged current tensor interactions, finding a very small preference for their presence, according to Belle data. Belle-II near future measurements can thus be very useful in either confirming or further restricting new physics tensor current contributions to these decays. For this, the spectrum in the di-pion invariant mass turns out to be particularly promising. Distributions in the angle defined by the τ^- and π^- momenta can also be helpful if measured with less than 10% accuracy, both for non-standard scalar and tensor interactions.

Introduction

Early studies of nuclear beta decays and, particularly, the problem of apparent non-conservation of energy and violation of the spin-statistics theorem lead to Pauli's postulation of the neutrino. Soon after, Fermi proposed a theory [1] describing these decays which was inspired by QED's vector current interaction which, however, was of a local current-current type. This was the first step towards establishing the V-A nature of the weak force and understanding its maximal parity violation. Now the original Fermi theory is regarded as one of the possible contributions of dimension six effective operators to these decays and it constitutes the basis for effective field theories.

Effective theory analysis of $\tau^- \to \nu_\tau \bar{u} d$

For low-energy charged current processes, the effective Lagrangian with $SU(2)\otimes U(1)$ invariant dimension six operators reads [2, 3]

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum_i \alpha_i O_i^{(6)} \quad \to \quad \mathcal{L}_{SM} + \frac{1}{v^2}\sum_i \hat{\alpha}_i O_i^{(6)}, \tag{1}$$

If we particularize it for the $\mathcal{O}(1\text{ GeV})$ semileptonic strangeness and lepton-flavor conserving charged current transitions involving any lepton ($\ell = e, \mu, \tau$) and only left-handed neutrino fields, the following Lagrangian is obtained

$$\begin{aligned}\mathcal{L}_{CC} = -\frac{4G_F}{\sqrt{2}}\big[&(1+[v_L]_{\ell\ell})\bar{\ell}_L\gamma_\mu\nu_{\ell L}\,\bar{u}_L\gamma^\mu d_L + [v_R]_{\ell\ell}\,\bar{\ell}_L\gamma_\mu\nu_{\ell L}\,\bar{u}_R\gamma^\mu d_R \\ &+ [s_L]_{\ell\ell}\,\bar{\ell}_R\nu_{\ell L}\,\bar{u}_R d_L + [s_R]_{\ell\ell}\,\bar{\ell}_R\nu_{\ell L}\,\bar{u}_L d_R \\ &+ [t_L]_{\ell\ell}\,\bar{\ell}_R\sigma_{\mu\nu}\nu_{\ell L}\,\bar{u}_R\sigma^{\mu\nu}d_L\big] + h.c..\end{aligned} \tag{2}$$

It is advantageous to shift our basis for the spin-zero currents so that the new ones have defined parity. This is achieved by means of introducing $\epsilon_S = s_L + s_R$, $\epsilon_P = s_L - s_R$, $\epsilon_{R,L} = v_{L,R}$ and $\epsilon_T = t_L$.

Semileptonic τ decay amplitude

The decay amplitude reads

$$\begin{aligned}\mathcal{M} &= \mathcal{M}_V + \mathcal{M}_S + \mathcal{M}_T \\ &= \frac{G_F V_{ud}\sqrt{S_{EW}}}{\sqrt{2}}(1+\epsilon_L+\epsilon_R)\big[L_\mu H^\mu + \hat{\epsilon}_S L H + 2\hat{\epsilon}_T L_{\mu\nu}H^{\mu\nu}\big]\end{aligned} \tag{3}$$

where the following lepton currents were introduced:

$$L_\mu = \bar{u}(P')\gamma^\mu(1-\gamma^5)u(P), \tag{4a}$$

$$L = \bar{u}(P')(1+\gamma^5)u(P), \tag{4b}$$

$$L_{\mu\nu} = \bar{u}(P')\sigma_{\mu\nu}(1+\gamma^5)u(P), \tag{4c}$$

The scalar (H), vector (H_μ) and tensor ($H_{\mu\nu}$) hadron matrix elements entering eq. (3) can be decomposed using Lorentz invariance and discrete QCD symmetries in terms of a number of allowed Lorentz structures times the corresponding form factors, which are scalar functions encoding the hadronization procedure, these are

$$H^\mu = \langle\pi^0\pi^-|\bar{d}\gamma^\mu u|0\rangle = C_V Q^\mu F_+(s) + C_S\left(\frac{\Delta_{\pi^-\pi^0}}{s}\right)q^\mu F_0(s), \tag{5a}$$

$$H = \langle\pi^0\pi^-|\bar{d}u|0\rangle \equiv F_S(s), \tag{5b}$$

$$H^{\mu\nu} = \langle\pi^0\pi^-|\bar{d}\sigma^{\mu\nu}u|0\rangle = iF_T(s)(P^\mu_{\pi^0}P^\nu_{\pi^-} - P^\mu_{\pi^-}P^\nu_{\pi^0}), \tag{5c}$$

Decay Observables

In order to study possible NP effects in these decays, one should use not only the hadronic spectrum and branching ratio, but also Dalitz plot distributions and the measurable forward-backward asymmetry.

Dalitz Plots

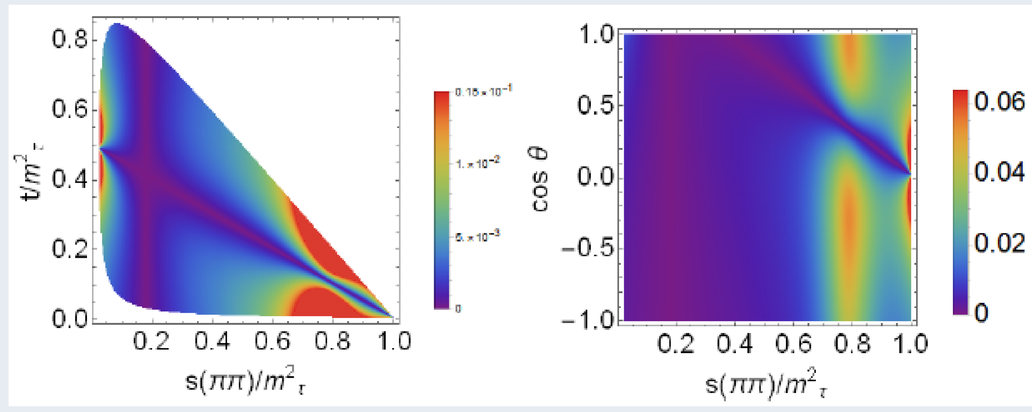

Figure 1: Dalitz plot distribution for $\tilde{\Delta}(\hat{\epsilon}_S = 0.008, \hat{\epsilon}_T = 0)$.

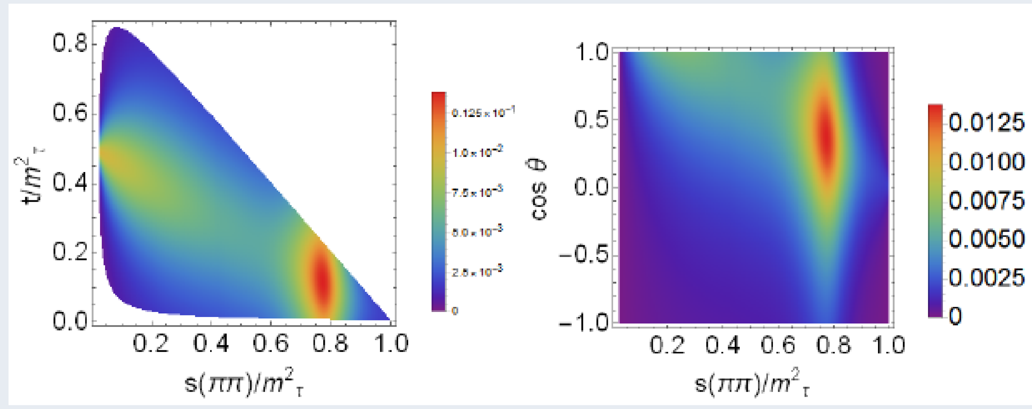

Figure 2: Dalitz plot distribution for $\tilde{\Delta}(\hat{\epsilon}_S = 0, \hat{\epsilon}_T = -0.001)$.

Decay rate

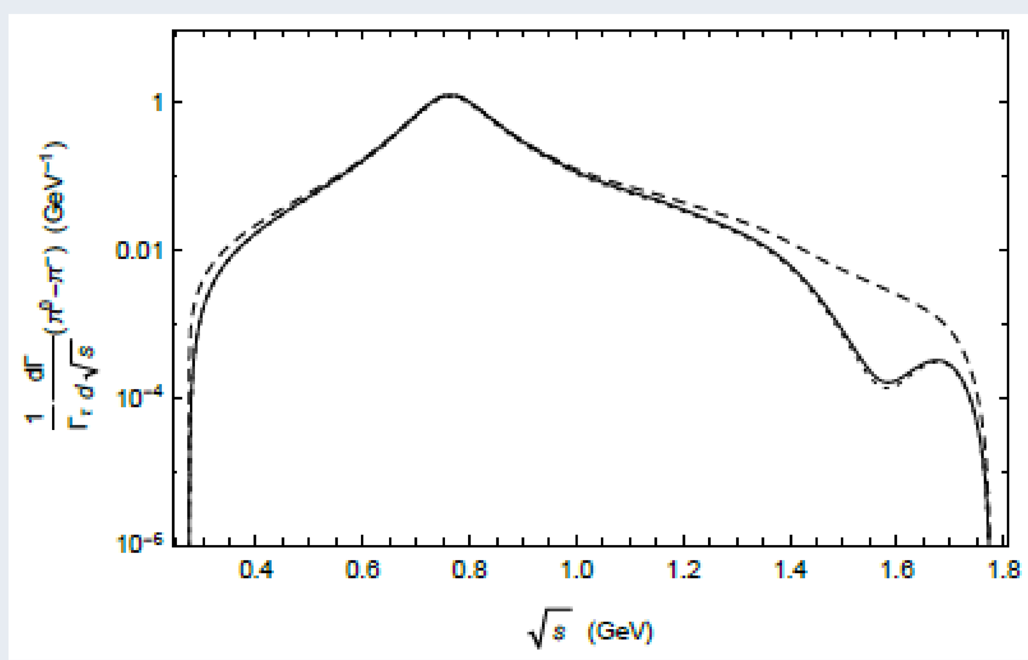

Figure 3: The $\pi^0\pi^-$ hadronic invariant mass distribution for the SM (solid line) and $\hat{\epsilon}_S = 1.31$, $\hat{\epsilon}_T = 0$ (dashed line), $\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = -0.014$ (dotted line).

Forward-backward asymmetry

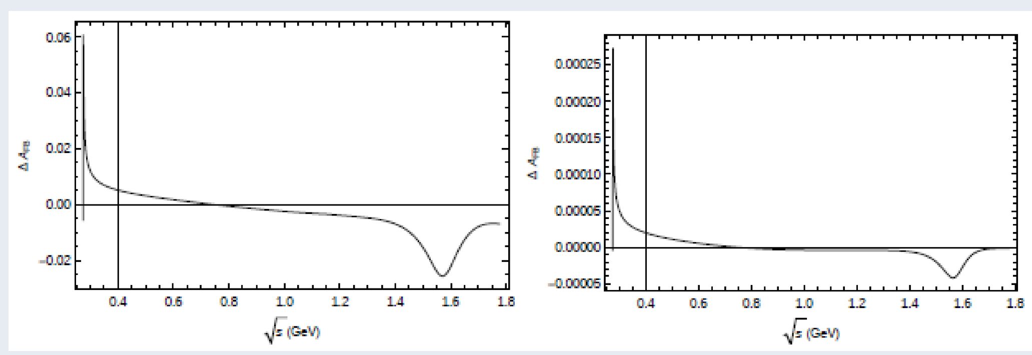

Figure 4: Normalized difference with respect to the SM forward-backward asymmetry (ΔA_{FB}) in the case of scalar interactions (left, $\hat{\epsilon}_S = 0.008$, $\hat{\epsilon}_T = 0$) and tensor interactions (right, $\hat{\epsilon}_S = 0$, $\hat{\epsilon}_T = -0.001$).

Another observables are found in [4].

Limits on $\hat{\epsilon}_S$ and $\hat{\epsilon}_T$

Integrating the decay rate, we get the relative shift produced by NP contributions as follows

$$\Delta \equiv \frac{\Gamma - \Gamma^0}{\Gamma^0} = \alpha\hat{\epsilon}_S + \beta\hat{\epsilon}_T + \gamma\hat{\epsilon}_S^2 + \delta\hat{\epsilon}_T^2 \tag{6}$$

Δ limits	$\hat{\epsilon}_S$ ($\hat{\epsilon}_T = 0$)	$\hat{\epsilon}_T$ ($\hat{\epsilon}_S = 0$)	$\hat{\epsilon}_S$	$\hat{\epsilon}_T$
Belle	$[-1.33, 1.31]$	$[-0.79, -0.57] \cup [-1.4, 1.3] \cdot 10^{-2}$	$[-5.2, 5.2]$	$[-0.79, 0.013]$
3-fold improved measurement	$[-1.20, 1.18]$	$[-0.79, -0.57] \cup [-1.1, 1.1] \cdot 10^{-2}$	$[-5.1, 5.1]$	$[-0.78, 0.011]$

Table 1: Constraints on the scalar and tensor couplings obtained (at three standard deviations) through the limits on the current branching ratio measurements and the hypothetical case where this value be measured by Belle II with a three times smaller error. Theory errors are included.

We made a fit to the current data measured by Belle for the $\tau^- \to \pi^-\pi^0\nu_\tau$ decays and using the limit obtained from the radiative pion decays $\pi \to e\nu\gamma$ for the scalar interactions, we get $\hat{\epsilon}_T = (-1.3^{+1.5}_{-2.2}) \times 10^{-3}$.

	$\lvert\hat{\epsilon}_S\rvert$	$\lvert\hat{\epsilon}_T\rvert$
Low energy	0.8	0.1
LHC ($e\nu$)	1.3	0.3
LHC (e^+e^-)	1.0	0.1

Table 2: Summary of 90% C.L. bounds (in units of 10^{-2}) on the non-standard couplings $\hat{\epsilon}_\alpha$ obtained from low-energy and LHC searches [5].

Conclusion

It turns out that Dalitz plot distributions (both in the Mandelstam variables s and t and also replacing t by the angle between the two charged particles) are not very sensitive to non-zero realistic values of $\hat{\epsilon}_S$ and $\hat{\epsilon}_T$, as it also happens with the forward-backward asymmetry. Apparently, the hadronic invariant mass distribution is not sensitive either to charged-current tensor interactions.
However, a fit to Belle data on this observable hints for a slight preference (0.9σ) for non-zero $\hat{\epsilon}_T$.

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