

CP Violation in Hadronic τ Decays

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We examine CP violation in the $\Delta S = 0$ decays $\tau \rightarrow \omega\pi\nu_\tau$ and $\tau \rightarrow a_1\pi\nu_\tau$ and the $\Delta S = 1$ decay $\tau \rightarrow K\pi\pi\nu_\tau$. We assume that the new physics is a charged Higgs. We show that sizeable CP-violating effects are possible in $\tau \rightarrow a_1\pi\nu_\tau$ (polarization-dependent rate asymmetry) and $\tau \rightarrow \omega\pi\nu_\tau$ (triple-product asymmetry). The $\Delta S = 1$ decay $\tau \rightarrow K\pi\pi\nu_\tau$ can proceed via several resonances. We construct two modified rate asymmetries and a triple product asymmetry for this decay and discuss the potential sensitivities of these asymmetries.

1. Introduction

In the Standard Model (SM) of particle physics, CP violation is due to a complex parameter in the Cabibbo-Kobayashi-Maskawa (CKM) matrix. Extensions of the SM typically include new sources of CP violation. To understand the origin of CP violation it is important to investigate as many systems as possible.

One area that deserves further investigation is the τ system. We consider a few hadronic decay modes of the τ . In the SM, there is virtually no CP violation in these decay modes. Thus, any observation of CP violation for these decays would be a clear indication of New Physics (NP).

CP-odd observables require at least two contributing amplitudes in order to be non-zero. In addition to the usual W-exchange amplitude that is present in the SM, we assume that there is also a contribution that arises due to the exchange of a charged Higgs boson – see Fig. 1.

Many extensions of the SM include extra Higgs bosons. The charged Higgs couplings to light quarks in these models are often proportional to the quark masses, and are thus very small. We investigate τ decays that contain light quarks in the final state [1, 2].¹ If CP violation is to be large in these decays, the charged Higgs couplings must be large. Thus, these decays probe “non-standard” NP CP violation.

2. CP Asymmetries

Suppose two amplitudes contribute to a particular process. Then the total amplitude may be written as

$$\mathcal{A} = A_1 + A_2 e^{i\phi} e^{i\delta}, \quad (1)$$

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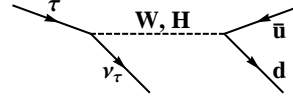


Figure 1: Quark-level Feynman diagram for the $\Delta S = 0$ decays showing the W and H contributions.

where ϕ and δ are the relative weak (CP-odd) and strong (CP-even) phases, respectively.

The full rate for the process is obtained by calculating $|\mathcal{A}|^2$, summing/averaging over spins, and integrating over phase space. The regular rate asymmetry for a particular decay mode is proportional to the difference between the rate for the process and that for its associated anti-process. The result is proportional to

$$\sin \phi \sin \delta \quad (2)$$

and thus requires both a weak phase difference (ϕ) and a strong phase difference (δ) between the contributing amplitudes.

The rate asymmetry can be altered in various ways. For example, if some of the spins are measured, one does not sum over them. One can also integrate asymmetrically over phase space (or use a more general weighting function) to isolate certain terms in the differential width. In some cases this leads to asymmetries that are proportional to $\sin \phi \sin \delta$, similar to the regular rate asymmetry. One particular class of asymmetries involves triple products, which have the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where \vec{v}_1 , \vec{v}_2 and \vec{v}_3 are momenta and/or spins. CP asymmetries constructed from triple products have the form

$$\sin \phi \cos \delta \quad (3)$$

and thus require a weak phase difference, but not a strong phase difference.

3. Decays with $\Delta S = 0$: $\tau \rightarrow \omega\pi\nu_\tau$ and $\tau \rightarrow a_1\pi\nu_\tau$

3.1. Form Factors

Consider the decay $\tau \rightarrow V\pi\nu_\tau$, where V represents a vector or axial vector meson. The general structure

for the SM hadronic current for this decay is given by [3, 4],

$$\begin{aligned} J^\mu &= \langle V(q_1)\pi(q_2)|\bar{d}\gamma^\mu(1-\gamma^5)u|0\rangle \\ &= F_1(Q^2)(Q^2\epsilon_1^\mu - \epsilon_1 \cdot q_2 Q^\mu) \\ &+ F_2(Q^2)\epsilon_1 \cdot q_2 \left(q_1^\mu - q_2^\mu - Q^\mu \frac{Q \cdot (q_1 - q_2)}{Q^2} \right) \\ &+ iF_3(Q^2)\epsilon^{\mu\alpha\beta\gamma}\epsilon_{1\alpha}q_{1\beta}q_{2\gamma} + F_4(Q^2)\epsilon_1 \cdot q_2 Q^\mu, \end{aligned} \quad (4)$$

where $Q^\mu \equiv (q_1 + q_2)^\mu$ and where ϵ_1 denotes the polarization tensor of the V . Experimentally, the form factor F_3 dominates for $V = \omega$ and F_1 and/or F_2 are expected to dominate for $V = a_1$. The scalar form factor, F_4 , is expected to be very small within the SM.

The NP charged Higgs effect may be parameterized in terms of new scalar and pseudo-scalar quark-level operators. The resulting current is given by,

$$\begin{aligned} J_{\text{Higgs}} &= \langle V(q_1)\pi(q_2)|\bar{d}(a + b\gamma^5)u|0\rangle \\ &= \begin{cases} bf_H\epsilon_1 \cdot q_2, & V = \omega, \\ af_H\epsilon_1 \cdot q_2, & V = a_1, \end{cases} \end{aligned} \quad (5)$$

where f_H is a form factor for the quark-level operators and a and b arise from the coupling of the charged Higgs boson to the quarks and leptons. The charged Higgs effect can be incorporated into the expression for the hadronic current [Eq. (4)] by the replacement $F_4(Q^2) \rightarrow \tilde{F}_4(Q^2)$, where

$$\tilde{F}_4(Q^2) = \begin{cases} F_4(Q^2) + (bf_H/m_\tau), & V = \omega, \\ F_4(Q^2) + (af_H/m_\tau), & V = a_1. \end{cases} \quad (6)$$

The parameters a and b can be complex; that is, they can contain a (CP-odd) weak phase. The various form factors are potential sources of strong phases.

3.2. Results for $\Delta S = 0$

3.2.1. Rate Asymmetry

The regular rate asymmetry is proportional to $|F_4 f_H b| \sin(\delta_4 - \delta_H) \sin(\phi_b)$ for the $V = \omega$ case (integrated over phase space), where the δ 's are the strong phases associated with the form factors and ϕ_b is the (CP-odd) phase of the complex Higgs coupling b . An analogous expression (with b replaced by a) holds for the case $V = a_1$. Since F_4 is expected to be very small, we conclude that the rate asymmetry is unlikely to be measurable, even in the presence of NP.

3.2.2. Polarization-dependent Rate Asymmetry

Weighting the differential width by $\cos\beta$ while performing the integration over phase space (β is a particular kinematical angle – see Ref. [1]) extracts terms containing the combinations $F_1 f_H^*$ and $F_2 f_H^*$. Such terms could be non-vanishing for the decay $\tau \rightarrow a_1 \pi \nu_\tau$

(since F_1 and/or F_2 are expected to be the dominant SM form factors in this case). Constructing a CP asymmetry from this quantity yields an expression that depends on the polarization of the τ and that contains pieces such as $|F_1 f_H a| \sin(\delta_1 - \delta_H) \sin(\phi_a)$. This asymmetry requires a strong phase difference between F_1 (or F_2) and f_H . Numerical estimates (see Ref. [1] for details) indicate that asymmetries of order 15% (7.5%) could be possible, given the uncertainties in the experimental measurement of the branching ratio. The first estimate assumes that only F_2 contributes to the SM amplitude; the second that only F_1 does.

3.2.3. Triple-product Rate Asymmetry

A triple product (TP) can be constructed using the polarization tensor of the vector meson. The TP contains the combination of form factors $F_3 f_H^*$, and could thus be non-zero for the decay $\tau \rightarrow \omega \pi \nu_\tau$ (for which F_3 dominates the SM hadronic current). Constructing a CP asymmetry from the TP yields an expression that contains $|F_3 f_H b| \cos(\delta_3 - \delta_H) \sin(\phi_b)$; thus this CP asymmetry does not require the presence of a relative strong phase between the SM and NP amplitudes. A numerical estimate performed in Ref. [1] indicates that the TP asymmetry could be as large as 30% multiplied by $(\vec{\epsilon}_1 \cdot \vec{n}_1)(\vec{\epsilon}_1 \cdot \vec{n}_2)$, where \vec{n}_1 and \vec{n}_2 are particular direction vectors in the hadronic rest frame and $\vec{\epsilon}_1$ is the polarization vector of the ω .

4. A Decay with $\Delta S = 1$: $\tau \rightarrow K \pi \pi \nu_\tau$

4.1. Overview and Preliminary Results

The previous approach can be generalized to the decay $\tau \rightarrow K \pi \pi \nu_\tau$. The quark-level process is the same as that shown in Fig. 1, but with $d \rightarrow s$. The hadronic current is given by [2, 5, 6],

$$\begin{aligned} J^\mu &\equiv \langle K^-(p_1)\pi^-(p_2)\pi^+(p_3)|\bar{s}\gamma^\mu(1-\gamma^5)u|0\rangle \\ &= [F_1(s_1, s_2, Q^2)(p_1 - p_3)_\nu \\ &+ F_2(s_1, s_2, Q^2)(p_2 - p_3)_\nu] T^{\mu\nu} \\ &+ iF_3(s_1, s_2, Q^2)\epsilon^{\mu\nu\rho\sigma}p_{1\nu}p_{2\rho}p_{3\sigma} \\ &+ F_4(s_1, s_2, Q^2)Q^\mu, \end{aligned} \quad (7)$$

where $Q^\mu = (p_1 + p_2 + p_3)^\mu$, $T^{\mu\nu} = g^{\mu\nu} - Q^\mu Q^\nu / Q^2$, $s_1 = (p_2 + p_3)^2$ and $s_2 = (p_1 + p_3)^2$. Several decay chains contribute to the form factors within the SM. The dominant form factors F_1 and F_2 have been studied experimentally by CLEO [7]. These form factors receive contributions due to $\tau \rightarrow K_1^- \nu_\tau \rightarrow K^* \pi^- \nu_\tau \rightarrow K^- \pi^- \pi^+ \nu_\tau$ and $\tau \rightarrow K_1^- \nu_\tau \rightarrow \rho K^- \nu_\tau \rightarrow K^- \pi^- \pi^+ \nu_\tau$, respectively. The subdominant processes $\tau \rightarrow K^* \nu_\tau \rightarrow K^* \pi^- \nu_\tau \rightarrow K^- \pi^- \pi^+ \nu_\tau$ and $\tau \rightarrow K^* \nu_\tau \rightarrow \rho K^- \nu_\tau \rightarrow K^- \pi^- \pi^+ \nu_\tau$ are also possible, and could contribute to F_3 . The scalar form factor, F_4 , is

expected to be small within the SM. The NP charged Higgs contribution may be taken into account by the replacement,

$$F_4 \rightarrow \tilde{F}_4 = F_4 + \frac{f_H}{m_\tau} (\eta_{RL} - \eta_{LL}), \quad (8)$$

where f_H is the pseudoscalar form factor and η_{RL} and η_{LL} are (possibly complex) NP parameters defined somewhat similarly to a and b in the $\Delta S = 0$ case.

We again consider several possible CP asymmetries. Each asymmetry is proportional to $|f_H| \text{Im}(\eta_{RL} - \eta_{LL})$ (integrated over phase space). The regular rate asymmetry contains the combination $|F_4 f_H| \text{Im}(\eta_{RL} - \eta_{LL})$ and is thus expected to be very small. It is also possible to construct other asymmetries by employing various weighting functions when performing the integration over phase space (see, for example, Refs. [5, 8]). In this manner we have constructed two modified rate asymmetries, as well as one TP asymmetry. The modified rate asymmetries contain the SM hadronic currents F_1 and F_2 and they require a non-zero relative strong phase between the SM and NP amplitudes in order to be non-zero. The TP asymmetry depends on F_3 and does not require a relative strong phase between the interfering amplitudes.

A preliminary numerical analysis of the modified and TP asymmetries indicates that some amount of cancellation tends to occur as one performs the integrations over phase space. These cancellations would tend to make the asymmetries quite small. Larger asymmetries are possible if one includes extra weighting factors to offset the cancellations. Alternatively, experimentalists could perform fits to differential asymmetries (such as da_{CP}/dQ , for example). Our initial study indicates that asymmetries of up to the order of a percent might be possible if the only assumption regarding the NP scalar contribution is that it is “hidden” in the current experimental uncertainty in the branching ratio. Incorporating the CLEO bound on the scalar coupling coming from $\tau \rightarrow K\pi\nu_\tau$ [9] and making a reasonable estimate for the scalar form factor, we find that the CP asymmetries are likely to be smaller than this. Further analysis and refinement of the numerical estimates will be provided in Ref. [2].

[Note added: As noted in Ref. [2] (and contrary to the statement made above), the CLEO bound does not actually place a direct constraint on the NP coupling considered here. In the notation of Ref. [2], the CLEO experiment placed a bound on η_S , while

$\tau \rightarrow K\pi\nu_\tau$ probes η_P . For more details, please see Ref. [2].]

5. Conclusions

We have considered CP violation in certain $\Delta S = 0$ and $\Delta S = 1$ τ decays. In both cases CP violation requires the interference of (at least) two amplitudes that have a differing weak phase. One amplitude is provided by the usual SM W-exchange diagram. The other amplitude is assumed to be due to a NP Higgs-exchange diagram. While the regular rate asymmetries are expected to be very small in these decays, larger asymmetries can be obtained by forming triple products or by considering other modifications to the usual rate asymmetries.

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References

- [1] A. Datta, K. Kiers, D. London, P. J. O’Donnell and A. Szykman, Phys. Rev. D **75**, 074007 (2007) [Erratum-ibid. D **76**, 079902 (2007)].
- [2] K. Kiers, K. Little, A. Datta, D. London, M. Nagashima and A. Szykman, arXiv:0808.1707 [hep-ph].
- [3] R. Decker, Z. Phys. C **36**, 487 (1987).
- [4] R. Decker and E. Mirkes, Z. Phys. C **57**, 495 (1993).
- [5] J. H. Kuhn and E. Mirkes, Z. Phys. C **56**, 661 (1992) [Erratum-ibid. C **67**, 364 (1995)].
- [6] R. Decker, E. Mirkes, R. Sauer and Z. Was, Z. Phys. C **58**, 445 (1993).
- [7] D. M. Asner *et al.* [CLEO Collaboration], Phys. Rev. D **62**, 072006 (2000) [arXiv:hep-ex/0004002].
- [8] U. Kilian, J. G. Korner, K. Schilcher and Y. L. Wu, Z. Phys. C **62**, 413 (1994).
- [9] G. Bonvicini *et al.* [CLEO Collaboration], Phys. Rev. Lett. **88**, 111803 (2002) [arXiv:hep-ex/0111095].