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903: CP Violation from Charged Higgs Exchange in Hadronic Tau Decays with Unpolarized Beams

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Abstract. CP violating signals in semileptonic τ decays induced by an exotic scalar exchange are studied in a completely model-independent way. These can be observed in decays of unpolarized single τ's even if their rest frame cannot be reconstructed. No beam polarization is required. The importance of the two-meson channel, in particular the $K\pi$ final state is emphasized.

1 Introduction

CP violation has been experimentally observed only in the K meson system. The effect can be explained by a nontrivial complex phase in the CKM flavour mixing matrix [1]. However, the fundamental origin of this CP violation is still unknown. In particular the CP properties of the third fermion family are largely unexplored. Production and decay of τ leptons might offer a particularly clean laboratory to study these effects. In this contribution, we investigate the effects of CP violation [2] to be observed in semileptonic τ decays which could arise in a framework outside the mechanism prosposed by Kobayashi and Maskawa. We show that the structure function formalism of Ref. [3] allows for a systematic analysis of possible CP violation effects in the two and three meson channels. Special emphasis is put on the $\Delta S = 1$ transition $\tau \to K\pi\nu_\tau$ where possible CP violating signals from multi Higgs boson models [4] would be signaled by a nonvanishing difference between the structure functions $W_{SF}[\tau^- \to (K\pi)^-\nu_\tau]$ and $W_{SF}[\tau^+ \to (K\pi)^+\nu_\tau]$. Such a measurement is possible for unpolarized single τ's without reconstruction of the τ rest frame and without polarized incident e^+e^- beams. It is shown that this CP violation requires both nonvanishing hadronic phases and CP violating phases in the Hamiltonian, where the hadronic phases arise from the interference of complex Breit-Wigner propagators, whereas the CP violating phases could arise from an exotic charged Higgs boson. An additional independent test of CP violation in the two meson case is possible, but would require the knowledge of the full kinematics and τ polarization.

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2 CP Violating Signals in the $\tau \to K\pi\nu_\tau$ Decay Mode

Transitions from the vacuum to two pseudoscalar mesons h_1 and h_2 are induced through vector and scalar currents only. Expanding these hadronic matrix elements along the set of independent momenta $(q_1 - q_2)_\beta$ and $Q_\beta = (q_1 + q_2)_\beta$ we define $(T_{\alpha\beta} = g_{\alpha\beta} - (Q_\alpha Q_\beta)/Q^2)$

$$\langle h_1(q_1)h_2(q_2)|\bar{u}\gamma_\beta d|0\rangle = (q_1 - q_2)^\alpha \, T_{\alpha\beta} \; F(Q^2) \, + \, Q_\beta \, F_S(Q^2) \tag{1}$$

$$\langle h_1(q_1)h_2(q_2)|\bar{u}d|0\rangle = F_H(Q^2). \tag{2}$$

The representation of the hadronic amplitude $\langle h_1 h_2|\bar{u}\gamma_\beta d|0\rangle$ corresponds to a decomposition into spin one and spin zero contributions, *e.g.* the vector form factor $F(Q^2)$ corresponds to the $J^P = 1^-$ component of the weak charged current, and the scalar form factor $F_S(Q^2)$ to the $J^P = 0^+$ component. A fictitious scalar Higgs exchange contribution is proportional to $\eta_S F_H$. The general amplitude for the $\Delta S = 1$ decay (where $h_1 \equiv K, h_2 \equiv \pi$)

$$\tau^-(l,s) \to \nu(l',s') + h_1(q_1,m_1) + h_2(q_2,m_2)\,, \tag{3}$$

can thus be written as

$$\mathcal{M} = \sin\theta_c \frac{G}{\sqrt{2}} \bar{u}(l',s')\,\gamma_\alpha(1-\gamma_5)\,u(l,s)\,\left[(q_1 - q_2)_\beta \, T^{\alpha\beta} \, F \, + \, Q^\alpha \, \tilde{F}_S\right] \tag{4}$$

$$\text{with} \qquad \tilde{F}_S = F_S \, + \, \frac{\eta_S}{m_\tau} \, F_H \tag{5}$$

In Eq. (4) s denotes the polarization 4-vector of the τ lepton. The complex parameter η_S in Eq. (5) transforms like

$$\eta_S \xrightarrow{\text{CP}} \eta_S^* \tag{6}$$

and thus allows for the parametrization of possible CP violation. Up to the small isospin breaking terms, induced for example by the small quark mass difference, CVC implies the vanishing of F_S for the two pion $(h_1 \equiv \pi^-, h_2 \equiv \pi^0)$ case. For the transition $\tau \to K\pi\nu$ the $J = 1$ form factor F is dominated by the $K^*(892)$ vector resonance contribution. The scalar form factor F_S is expected to receive a sizable resonance contribution ($\sim 5\%$ to the decay rate) from the $K_0^*(1430)$ with $J^P = 0^+$ [5]. The corresponding τ^+ decay is obtained from Eq. (4) through the substitutions

$$(1-\gamma_5) \, \to \, (1+\gamma_5), \qquad \eta_S \, \to \, \eta_S^*. \tag{7}$$

Reaction (3) is most easily analyzed in the hadronic rest frame $\mathbf{q}_1 + \mathbf{q}_2 = 0$ [3]. After integration over the unobserved neutrino direction, the differential decay rate in the rest frame of $h_1 + h_2$ is given by [5, 3]

$$d\Gamma(\tau^- \to 2h\nu_\tau) = \left\{\bar{L}_B W_B + \bar{L}_{SA} W_{SA} + \bar{L}_{SF} W_{SF} + \bar{L}_{SG} W_{SG}\right\}$$

$$\frac{G^2}{2m_\tau}\sin^2\theta_c \frac{1}{(4\pi)^3}\frac{(m_\tau^2 - Q^2)^2}{m_\tau^2}\,|\mathbf{q}_1|\,\frac{dQ^2}{\sqrt{Q^2}}\,\frac{d\cos\theta}{2}\,\frac{d\alpha}{2\pi}\,\frac{d\cos\beta}{2}\,. \quad (8)$$

For the definition and discussion of the angles and leptonic coefficients $\bar{L}_X$ in Eq. (8) we refer the reader to Ref. [2]. The coefficients $\bar{L}_X$ contain all α, β and θ angular and τ-polarization dependence. The hadronic structure functions W_X, $X \in \{B, SA, SF, SG\}$, depend only on Q^2 and the form factors F and $\tilde{F}_S$ of the hadronic current. One has [5, 3, 2]:

$$\begin{aligned} W_B[\tau^-] &= 4(\mathbf{q}_1)^2\,|F|^2 & W_{SF}[\tau^-] &= 4\sqrt{Q^2}|\mathbf{q}_1|\,\mathrm{Re}\left[F\tilde{F}_S^*\right] \\ W_{SA}[\tau^-] &= Q^2\,|\tilde{F}_S|^2 & W_{SG}[\tau^-] &= -4\sqrt{Q^2}|\mathbf{q}_1|\,\mathrm{Im}\left[F\tilde{F}_S^*\right] \end{aligned} \quad (9)$$

The hadronic structure functions $W_X[\tau^+]$ are obtained by the replacement $\eta_S \to \eta_S^*$ in $\tilde{F}_S$ in Eqs. (9,5). CP conservation implies that all four structure functions are identical for τ^+ and τ^-. With the ansatz for the form factors formulated in Eq. (4) CP violation can be present in W_{SF} and W_{SG} only and requires complex η_S.

As demonstrated in Ref. [2] W_{SF} can be measured in e^+e^- annihilation experiments in the study of single unpolarized τ decays even if the τ rest frame cannot be reconstructed. In this respect the result differ from earlier studies of the two meson modes where either polarized beams and reconstruction of the full kinematics [6] or correlated fully reconstructed τ^- and τ^+ decays were required [7]. The determination of W_{SG}, however, requires the knowledge of the full τ kinematics and τ polarization [2] which is possible with the help of vertex detectors. The corresponding distributions in this second case are equivalent to the correlations proposed in Refs. [6, 7].

The crucial observation made in Ref. [2] is that one can measure the following CP-violating differences

$$\Delta W_{SF} = \frac{1}{2}\left(W_{SF}[\tau^-] - W_{SF}[\tau^+]\right) \qquad \Delta W_{SG} = \frac{1}{2}\left(W_{SG}[\tau^-] - W_{SG}[\tau^+]\right) \quad (10)$$

under the above mentioned conditions. The hadronic structure functions $W_X[\tau^-]$ and $W_X[\tau^+]$ differ only in the phase os η_S and one obtains

$$\Delta W_{SF} \;=\; 4\sqrt{Q^2}|\mathbf{q}_1|\,\frac{1}{m_\tau}\,\mathrm{Im}\,(FF_H^*)\;\;\mathrm{Im}\,(\eta_S)\;. \quad (11)$$

In essence the measurement on ΔW_{SF} analyses the difference in the correlated energy distribution of the mesons h_1 and h_2 from τ^+ and τ^- decay in the laboratory. As already mentioned, ΔW_{SF} is observable for single τ^+ and τ^- decays without knowledge of the τ rest frame. Any nonvanishing experimental result for ΔW_{SF} would be a clear signal of CP violation. Note that a nonvanishing ΔW_{SF} requires nontrivial hadronic phases (in addition to the

CP violating phases η_S) in the form factors F and F_H. Such hadronic phases in F (F_H) originate in the $K\pi\nu_\tau$ decay mode from complex Breit Wigner propagators for the K^* (K_0^*) resonance. Sizable effects of these hadronic phases are expected in this decay mode [5].

Once the τ rest frame is known and a preferred direction of polarization exists one may also determine ΔW_{SG} which is theoretically given by

$$\Delta W_{SG} \;=\; 4\sqrt{Q^2}|\mathbf{q}_1| \;\frac{1}{m_\tau}\; \mathrm{Re}\,(FF_H^*)\;\; \mathrm{Im}\,(\eta_S)\;. \qquad (12)$$

Any observed nonzero value of $\Delta W_{SF}, \Delta W_{SG}$ would signal a true CP violation. Eqs.(11) and (12) show that the sensitivity to CP violating effects in ΔW_{SF} and ΔW_{SG} can be fairly different depending on the hadronic phases. Whereas ΔW_{SF} requires nontrivial hadronic phases ΔW_{SG} is maximal for fixed η_S in the absence of hadronic phases.

3 Three Meson Decays

The structure function formalism [3] allow also for a systematic analysis of possible CP violation effects in the three meson case. Some of these effects have already been briefly discussed in Ref. [8]. The $K\pi\pi$ and $KK\pi$ decay modes with nonvanishing vector <u>and</u> axial vector current are of particular importance for the detection of possible CP violation originating from exotic intermediate vector bosons. This would be signalled by a nonvanishing difference between the structure functions $W_X(\tau^-)$ and $W_X(\tau^+)$ with $X \in \{F,G,H,I\}$. A difference in the structure functions with $X \in \{SB,SC,SD,SE,SF,SG\}$ can again be induced through a CP violating scalar exchange. CP violation in the three pion channel has been also discussed in Ref. [9] and in the $K\pi\pi$ and $KK\pi$ channels in Ref. [10], where the latter analysis is based on the "$T-$odd" correlations in Ref. [3] and the vector meson dominance parametrizations in Ref. [11].

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