EFFECTS OF CHARGED HIGGS IN τ DECAY*

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ABSTRACT

An experiment to test the effect of charged Higgs exchange in τ decay is proposed. It is pointed out that in the decay $\tau^- \to \nu_\tau + \pi^- + \pi^0$ the effect due to Higgs exchange can be obtained by observing the angular distribution of the π^- in the rest frame of the $\pi^- + \pi^0$. For each value of invariant mass of the $\pi^- + \pi^0$ system, the π^- must have a unique p-wave angular distribution independent of the strong interaction if it is due to W^- exchange alone. Any s-wave interference with this p-wave angular distribution can be attributed to the scalar exchange.

1. INTRODUCTION

In the Standard Model[1] there is one neutral Higgs particle and no charged ones. In most other models[2–4] charged Higgs-particles are required. Thus the discovery of effects due to a charged Higgs will demonstrate that the Standard Model needs to be revised. In this paper we propose an experiment to test the effects of charged Higgs exchange through two π–decay modes of τ. In the Standard Model the decay $\tau^- \to \nu_\tau + \pi^- + \pi^0$ proceeds via W^- exchange as shown in Fig. 1(a). If a charged Higgs exists, it can also proceed via H^- exchange as shown in Fig. 1(b).

This channel was chosen for the following reasons:

1. It has a relatively simple structure to be analyzed experimentally; both π^- and π^0 ($\to 2\gamma$) can be identified and momentum analyzed.

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2. $\pi^- + \pi^0$ state via W^- exchange can be either $J^P = 1^-$ or 0^+. But the state $J^P = 0^-$ is forbidden because the vector current is conserved.[5] Thus the existence of a 0^+ state for $\pi^- + \pi^0$ from τ^- decay must go through something other than W^-. The $\pi^-\pi^0\, W^-$ and $\pi^-\pi^0\, H^-$ vertex form factors are functions of $q^2 \;=\; (q_1 + q_2)^2$ only. Thus in the rest frame of $q_1 + q_2$ for a given value of q^2, the p-wave due to W^- exchange has a unique angular distribution:

$$\cos^2\theta + \frac{q^2}{m_\tau^2 - q^2} \quad , \tag{1.1}$$

where θ is the angle between π^- and τ^- in the rest frame of $q_1 + q_2$. This distribution is independent of form factors coming from the strong interaction. The effects of adding the Higgs exchange is to add an s-wave term $a(q^2)$ and the interference term $b(q^2)\cos\theta$ to Eq. (1.1); thus Eq. (1.1) is changed into:

$$\cos^2\theta + \frac{q^2}{m_\tau^2 - q^2} + a(q^2) + b(q^2)\cos\theta \quad . \tag{1.2}$$

The functions $a(q^2)$ and $b(q^2)$ depend upon the details of the strong interaction, as well as the Higgs mass m_H and the coupling constants of Higgs to $\tau\nu_\tau$ and to the quarks. The $a(q^2)$ is probably too small to be observable because it comes from the square of the Higgs exchange term [see Fig. 1(b)]. With the proposed Tau–Charm Factory,[9] one is supposed to get more than 10^7 τ events, and thus one should be able to observe $b(q^2)$ even if it is as small as 10^{-2}.

CALCULATIONS

Let us denote the matrix element for the W exchange diagram, Fig. 1(a), by:

$$M_W \;=\; \bar{u}(p_2)\, \not{p}(1 - \gamma_5)\, u(p_1)\; F_W(q^2) \quad , \tag{2.1}$$

where $p = q_1 - q_2$, $q = q_1 + q_2$ and $F_W(q^2)$ is a function of q^2 representing the effect due to the W propagator and the p-wave $\pi\pi$ form factor. The matrix element for the Higgs exchange, Fig. 1(b), can be written as:

$$M_H = \bar{u}(p_2)\, u(p_1)\, F_H(q^2) \quad , \tag{2.2}$$

where $F_H(q^2)$ is a function of q^2 representing the effect due to the Higgs propagator and the s-wave $\pi\pi$ form factor. The decay rate can then be written as:

$$\begin{aligned} \Gamma\left(\tau^- \rightarrow \nu_\tau + \pi^- + \pi^0\right) &= \frac{1}{2m_\tau}\, \frac{1}{(2\pi)^5} \int \frac{d^3p_2}{2E_2} \int \frac{d^3q_1}{2\omega_1} \int \frac{d^3q_2}{2\omega_2} \\ &\quad \times\, \delta^4\left(p_1 - p_2 - q_1 - q_2\right)\, \left|M_W + M_H\right|^2 \quad , \end{aligned} \tag{2.3}$$

where

$$\left|M_W + M_H\right|^2 = \left|F_W\right|^2 F_{11} + \left|F_H\right|^2 F_{00} + 2Re\left(F_W^* F_H\right) F_{10} \quad , \tag{2.4}$$

$$\begin{aligned} F_{11} &= \frac{1}{2}\, Tr(\not{p}_1 + m_\tau)\, (1+\gamma_5)\, \not{q}\, \not{p}_2\, \not{q}(1-\gamma_5) \\ &= 2\left(q^2 - 4m_\pi^2\right)\, \frac{(m_\tau^2 - q^2)^2}{q^2}\, \left[\cos^2\theta + \frac{q^2}{m_\tau^2 - q^2}\right] \quad , \end{aligned} \tag{2.5}$$

$$\begin{aligned} F_{00} &= \frac{1}{2}\, Tr(\not{p}_1 + m_\tau)\, \not{p}_2 \\ &= m_\tau^2 - q^2 \quad , \end{aligned} \tag{2.6}$$

$$\begin{aligned} F_{10} &= \frac{1}{2}\, Tr\left(\not{p}_1 + m_\tau\right)\, (1+\gamma_5)\, \not{q}\, \not{p}_2 \\ &= -m_\tau \sqrt{q^2 - 4m_\pi^2}\, \frac{(m_\tau^2 - q^2)}{\sqrt{q^2}}\, \cos\theta \quad , \end{aligned} \tag{2.7}$$

where θ is the angle between $\mathbf{p_1}$ and $\mathbf{q_1}$ in the rest frame of $q = q_1 + q_2$. F_{11}, F_{00} and F_{10} are independent of the detail of strong interaction; they come only from properties of angular momenta of the $\pi^-\pi^0$ system.

From Eqs. (2.4) through (2.7) we see that $a(q^2)$ and $b(q^2)$ of Eq. (1.2) are given by:

$$a(q^2) = \frac{q^2\, \left|F_H\right|^2}{2\left(q^2 - 4m_\pi^2\right)\, \left(m_\tau^2 - q^2\right)\, \left|F_W\right|^2} \quad , \tag{2.8}$$

and

$$b(q^2) = \frac{-2Re\,(F_W^* F_H)\; m_\tau \sqrt{q^2}}{\sqrt{q^2 - 4m_\pi^2}\;(m_\tau^2 - q^2)\,|F_W|^2} \quad . \tag{2.9}$$

Now the functions F_H and F_W are dependent on the strong interactions and the detail of the Higgs mechanism. The $a(q^2)$ is probably too small to be observable because it is proportional to $|F_H|^2 / |F_W|^2$. The $b(q^2)$ is proportional to F_H/F_W, so let us concentrate on this term. Equation (2.9) shows that $b(q^2)$ is large when $q^2 \to m_\tau^2$. Since the $\pi^+\pi^0$ system is charged, it cannot be in $I = 0$ state. Also, the s-wave $\pi^+\pi^0$ system cannot be in $I = 1$ state because it must obey Bose statistics; thus it must have $I = 2$. We do not see any resonance having these quantum numbers, so we may assume that F_H is mostly real. F_W is dominated by ρ. At the peak of the resonance, F_W is purely imaginary; hence, $b(q^2)$ is small at the ρ peak.

In order to see how $b(q^2)$ may behave, let us assume that F_W is dominated[6] by ρ, and F_H is a simple H exchange with a reasonable form factor assumed for the $\pi\pi$ system:

$$F_W = g_{\tau\nu\rho}\, g_{\rho\pi\pi} \frac{1}{(q_1 + q_2)^2 - m_\rho^2 + i\Gamma_\rho m_\rho} \quad , \tag{2.10}$$

where $g_{\rho\pi\pi}$ is related[6] to the ρ width by:

$$\Gamma_\rho(q^2) = \frac{g_{\rho\pi\pi}^2}{48\pi} \frac{q^3}{m_\rho^2} \left(1 - \frac{4m_\pi^2}{q^2}\right)^{3/2} \quad . \tag{2.11}$$

From

$$\Gamma_\rho\left[m_\rho^2 = (0.77\text{ GeV})^2\right] = 0.153\text{ GeV} \quad ,$$

we have

$$g_{\rho\pi\pi} = 6.088 \quad . \tag{2.12}$$

The $g_{\tau\nu\rho}$ can be obtained either from $e^+e^- \to \rho$ using CVC, or from the partial width of $\tau \to \nu_\tau + \rho$.

The partial decay width of $\tau \rightarrow \nu_\tau + \rho$ is given by[7]:

$$\Gamma(\tau \rightarrow \rho^- + \nu) = \frac{g^2_{\tau\nu\rho}}{8\pi}\frac{m^3_\tau}{m^2_\rho}\left(1 - \frac{m^2_\rho}{m^2_\tau}\right)^2\left(1 + \frac{2m^2_\rho}{m^2_\tau}\right)^2 \quad , \tag{2.13}$$

$$= \Gamma(\tau \rightarrow \text{all})\ B(\tau \rightarrow \rho^- + \nu)$$

$$= \frac{6.582 \times 10^{-25}\ \text{GeV}}{3.04 \times 10^{-13}} \times 0.223$$

$$= 0.4828 \times 10^{-12}\ \text{GeV} \quad .$$

From which we obtain:

$$g_{\tau\nu\rho} = 1.13 \times 10^{-6} \quad . \tag{2.14}$$

Combining Eqs. (2.12) and (2.14) we obtain:

$$/g_{\tau\nu\rho}\ g_{\rho\pi\pi} = 6.88 \times 10^{-6} \quad , (1) no (2.15)$$

which is very close to the value given by CVC and the vector dominance,[8]

$$g_{\tau\nu\rho}\ g_{\rho\pi\pi} = m^2_\rho G_F\ \cos\theta_c = 6.73 \times 10^{-6} \quad . \tag{2.16}$$

The form factor for the Higgs, F_H, is highly model-dependent and almost nothing about it is known. In the Standard Model,[1] the Higgs-particle is coupled to the lepton or quark with coupling constant proportional to the mass of the lepton or quark:

$$m_i\ 2^{3/4}\ \sqrt{G_f} \quad , \tag{2.17}$$

where m_i is the mass of the lepton or quark to which the Higgs is coupled, and $G_F = 1.166 \times 10^{-5}\ \text{GeV}^{-2}$ is the Fermi coupling constant. In some non-standard theory,[2,3,4] the Higgs coupling can be proportional to the mass of the heaviest lepton, m_τ, or the heaviest quark,

m_t, depending upon whether it is coupled to leptons or quarks. In this case, the Higgs-particle does not necessarily couple more favorably to heavier particles, and $F_H(q^2)$ can be written as:

$$F_H(q^2) \;=\; \mathcal{O}\left(\frac{G_F\, m_\tau\, m_t\, m_s}{m_H^2}\right) \quad , \tag{2.18}$$

where the Higgs mass comes from the propagator of the Higgs-particle, m_s represents some strong interaction mass in order to make $a(q^2)$ and $b(q^2)$ in Eqs. (2.8) and (2.9) dimensionless. From Eqs. (2.10), (2.16) and (2.18), we see that $b(q^2) = \mathcal{O}(m_\tau m_t/m_H^2)$ and $a(q^2) = \mathcal{O}(m_\tau^2 m_t^2/m_H^4)$. Since $\cos\theta$ in Eq. (1.2) integrates to zero, $b(q^2)$ does not contribute to the total rate of $\tau^- \to \nu_\tau + \pi^- + \pi^0$. A limit on the magnitude of $a(q^2)$ can be obtained by comparing the experimental rate of $\tau^- \to \nu_\tau + \pi^- + \pi^0$ and the prediction[8] of CVC. The difference could be as large as 4%. However, the rate of $\tau^- \to \nu_\tau + \pi^- + \pi^0$ is dominated by the ρ resonance peak where $a(q^2)$ is small. Thus, in the nonresonance region, $a(q^2)$ could be as large as 10% and $b(q^2)$ could be as large as 30%.

In conclusion, the proposed Tau–Charm Factory[9] can be used to investigate the detailed structure of the charged Higgs effect using the decay mode $\tau^- \to \nu_\tau + \pi^- + \pi^0$ described above.

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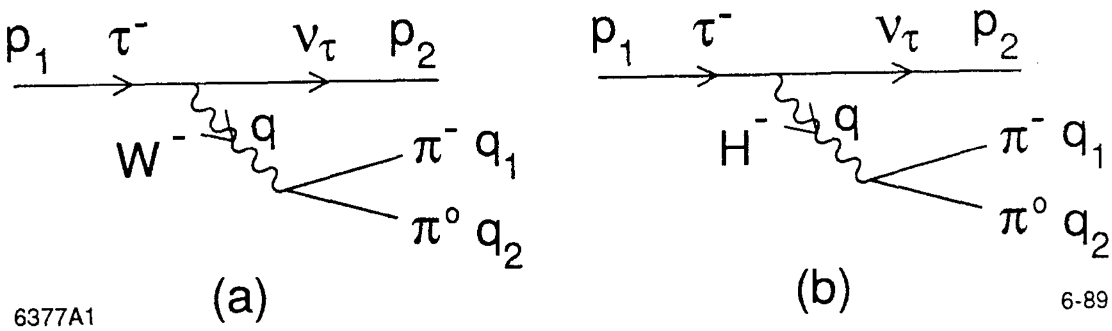

Fig. 1. Feynman diagrams for $\tau^- \to \nu_\tau + \pi^- + \pi^0$ via W^- and H^- exchanges.