τ Polarization as a Signal of Charged Higgs Bosons

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A measurement of the τ polarization at hadron colliders offers an excellent signal for the detection of charged Higgs bosons, via the decay $H^\pm \to \tau^\pm \nu$. We show how such a determination can distinguish these events from the $W^\pm \to \tau^\pm \nu$ background, for each of the $\tau \to \pi\nu$, $\rho\nu$, $a_1\nu$, and $l\nu\bar{\nu}$ decay channels.

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The existence of charged Higgs bosons, $H^\pm$, is a necessary ingredient of most extensions of the minimal Higgs sector of the standard model. The supersymmetric extension is a notable example. Surprisingly, few viable signals exist for the detection [1,2] of the charged Higgs boson; however, we shall show that the unexpected massiveness of the top quark offers an excellent chance of discovering $H^\pm$ at hadron colliders. Provided the mass, m_H, of the charged Higgs boson is in the range $m_H < m_t$, it can be produced via $t \to H^+ b$ (or $\bar{t} \to H^- \bar{b}$) and can be detected via the subsequent decays $H^\pm \to \tau^\pm \nu_\tau$. The event rate [1,3] depends on the branching fractions of these decays, which in turn depend on the magnitudes of the Yukawa couplings. The main background to the τ signal for the $H^\pm$ is $W^\pm \to \tau^\pm \nu$, where, in addition to $t \to W^+ b$ (and $\bar{t} \to W^- \bar{b}$), the W boson can also be produced by the Drell-Yan mechanism.

At first sight it appears that it will be difficult to identify the presence of $H \to \tau\nu$ decays from among the $W \to \tau\nu$ events; the signal relying simply on an excess of $\tau\nu$ events over the known rate for $W \to \tau\nu$ events would require high statistics and a good control of systematic errors to be convincing. However, here, we emphasize that the decay products of the τ have strikingly different topologies according to whether they originate from a parent $W^\pm$ or $H^\pm$. To be specific let us discuss the τ^- channel. The crucial observation is that τ^- leptons arising from $H^- \to \tau^- \bar{\nu}$ decays are almost purely right handed, in contrast to the left-handed τ^-'s which arise from W^- decays. This is a consequence of the helicity flip nature of the Yukawa couplings of the Higgs fields, and, indeed, the $H^- \to \tau_R^- \bar{\nu}_R$ character of the decay is true in all models containing only left-handed neutrinos (and right-handed antineutrinos). Now it has been known for a long time [4] that the decay distributions of τ leptons depend on the polarization of the parent τ; in particular, the distributions of a τ_R^- can be significantly different from those of a left-handed tau, τ_L^-. That is, for each decay channel ($\tau^- \to \pi^-\nu, \rho^-\nu, \ldots$) the momentum distribution of the decay products (π^-, $\rho^- \to \pi^-\pi^0, \ldots$) differs according to whether the parent is a τ_R^- or a τ_L^-. We shall see that these differences are sufficiently striking to establish, from a relatively low number of events, whether or not a τ_R^- occurs, and hence the existence of the charged Higgs boson, H^-.

In Fig. 1 we show in the collinear limit ($E_\tau/m_\tau \gg 1$) the energy distributions of the charged particles arising from the various (primary) decay modes of the τ^-. That is,

$$\frac{1}{\Gamma_\tau}\frac{d\Gamma}{dz}(\tau^- \to A^- \nu\text{'s}) = B(\tau^- \to A^- \nu\text{'s}) H_A(z)\,, \quad (1)$$

where $z = E_A/E_\tau$ with $A = e, \pi, \rho, a_1$ arising respectively from the $\tau^- \to e^-\bar{\nu}_e\nu_\tau$, $\pi^-\nu_\tau$, $\rho^-\nu_\tau$, $a_1^-\nu_\tau$ decay modes. $B(\tau^- \to A^- \nu\text{'s})$ are the branching fractions for these decays modes (which we take to be 0.177, 0.11, 0.227, and 0.146 for $A = e$, π, ρ, and a_1, respectively), while the

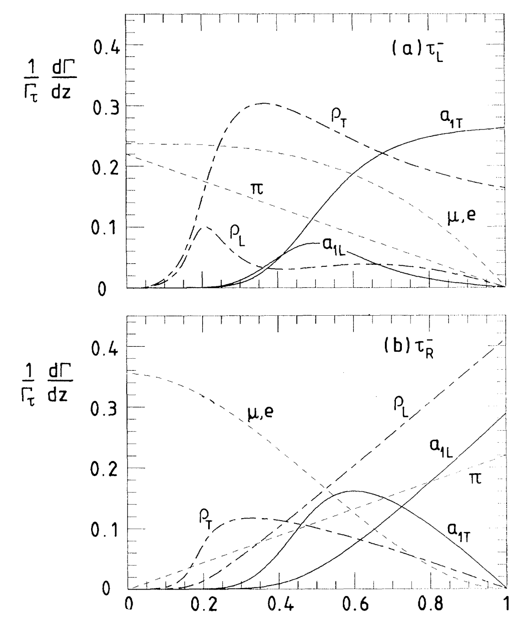

FIG. 1. The fractional energy distributions of particle A^- arising from (a) left-handed and (b) right-handed τ^- decays, i.e., $\tau^- \to A^- +$missing energy where $z = E_A/E_\tau$, and where it is assumed that $E_\tau \gg m_\tau$. The T,L subscripts refer to transversely, longitudinally polarized vector mesons. The effects of the finite widths of the ρ and a_1 are included. Distributions (a) and (b) characterize W^- and H^- decays, respectively.

explicit expressions for H_e, H_π, and H_{ρ,a_1} can be found in Ref. [5]. Below we shall study how the subsequent $\rho \rightarrow 2\pi$ and $a_1 \rightarrow 3\pi$ decays can be used to give further information on the polarization of the τ [5–7], and, in preparation for this discussion, we show separately the distributions of both transversely and longitudinally polarized vector mesons produced in τ decay (which we have denoted as ρ_T,ρ_L and a_{1T},a_{1L} in Fig. 1). In contrast to Ref. [5], the distributions shown in Fig. 1 take account of the effects of the finite width of the ρ and a_1 mesons. That is, the distributions H_{ρ,a_1} of (1) are computed by integrating over a realistic $n\pi$ invariant-mass distribution in the $\tau \rightarrow n\pi + \nu$ decay modes

$$H_v(z) = \int_{(nm_\pi)^2}^{zm_\tau^2} F_v(m^2) H_v^0(z,m^2)\,dm^2\,, \tag{2}$$

where $n=2,3$ for $v=\rho,a_1$, respectively. The distributions $H_v^0(z,m^2)$ are given by Eqs. (18) and (19) of Ref. [5] with $m_v^2=m^2$. The function F_v embodies both the phase-space factor and the $\tau \rightarrow n\pi + \nu$ decay matrix element which involves the usual Breit-Wigner form, $[m^2 - m_v^2 + im\Gamma_v(m)]^{-1}$. Here we adopt a simple parametrization [8] of the $W^* \rightarrow n\pi$ matrix elements and take the resonance parameters to be $(m_\rho,\Gamma_\rho)=(0.77,0.15)$ GeV and $(m_{a_1},\Gamma_{a_1})=(1.22,0.42)$ GeV [9]. The plots shown in this paper are, however, insensitive to the detailed form assumed for the matrix elements. The smearing effects arising from the finite widths of the ρ and a_1 are only found to be significant for $z \lesssim m_v^2/m_\tau^2$; note that the zero-width approximation would give no events for $z < m_v^2/m_\tau^2$.

We see that the energy distributions arising from the $W^- \rightarrow \tau_L^- \rightarrow A^-$ events [Fig. 1(a)] are significantly different from those of $H^- \rightarrow \tau_R^- \rightarrow A^-$ decays [Fig. 1(b)]. In particular, the most energetic particles from τ_L^- decays are *transversely* polarized ρ^- and a_1^- mesons, whereas the energetic particles arising from τ_R^- decay are π^-, and *longitudinally* polarized ρ^- and a_1^- mesons. Therefore the H^- signal can be considerably enhanced if we can use the subsequent $\rho \rightarrow 2\pi$ and $a_1 \rightarrow 3\pi$ decay distributions to distinguish between transversely and longitudinally polarized ρ, and a_1, mesons.

Now the final-state pions arising from a massive W or H boson, via τ decay, will be observed to be approximately collinear. Based on the classical work of Berman and Jacob [10], Rougé [7] has proposed decay angular distributions which, in principle, can act as the polarization analyzer of the τ. However, in the essentially collinear experimental configuration, it will be difficult to measure the proposed angles (for example, the angle ψ between the laboratory line of flight of the a_1 meson and the normal to the plane defined by three pions in the a_1 rest frame). Rather, here, we seek experimental distributions which rely only on the measurement of the pion energies, rather than their angular configuration, but which differ between events of $W \rightarrow \tau_L^-$ and $H \rightarrow \tau_R^-$ origin.

For the decay $\rho^- \rightarrow \pi^-\pi^0$ the π^- energy distribution, in the collinear limit, is of the form [5]

$$\frac{d\Gamma}{dx}(\rho_T \rightarrow \pi^-\pi^0) \sim 2x(1-x) - \frac{2m_\pi^2}{m_\rho^2}\,, \tag{3}$$

$$\frac{d\Gamma}{dx}(\rho_L \rightarrow \pi^-\pi^0) \sim (2x-1)^2\,, \tag{4}$$

according to whether the ρ is transversely or longitudinally polarized, where $x=E_{\pi^-}/E_\rho$. That is, transversely polarized ρ's favor equal splitting of the ρ energy between the two decay pions, whereas longitudinally polarized ρ's lead to large differences of the π^- and π^0 energies. Combined with the preference of energetic ρ_L (ρ_T) mesons from $H^- \rightarrow \tau_R^- \rightarrow \rho^-$ ($W^- \rightarrow \tau_L^- \rightarrow \rho^-$) decays, we therefore expect that the energetic ρ mesons from H^- decays will tend to give pions which are much more asymmetric in energy than those from W^- decays.

Similarly for the measurement of the a_1 polarization we assume only that the energy fractions,

$$x_i = E_i/(E_1+E_2+E_3)\,, \tag{5}$$

of the three outgoing pions are known. For both the $a_1^- \rightarrow \pi^-\pi^-\pi^+$ and $a_1^- \rightarrow \pi^0\pi^0\pi^-$ decay modes there are two identical pions in the final state, which we take as $\pi_1=\pi_2$ and so the distinct pion is labeled π_3. In Fig. 2 we show the scatter plot $d\Gamma/dx\,dy$ arising from the decays of both longitudinally and transversely polarized a_1 mesons, where

$$x=x_3 \text{ and } y=\min(x_1,x_2)\,. \tag{6}$$

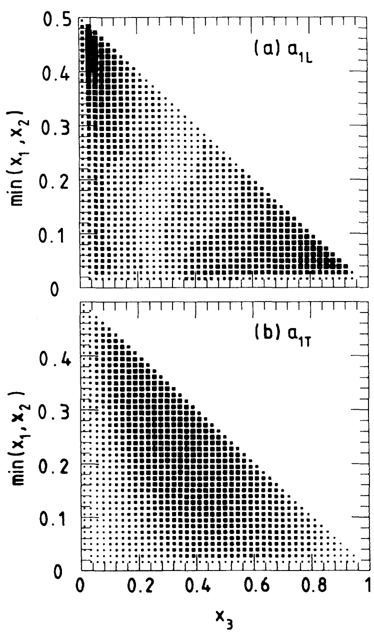

FIG. 2. The scatter plots for (a) longitudinally and (b) transversely polarized $a_1 \rightarrow 3\pi$ decays, where x_i are the energy functions carried by three pions (with pions 1,2 having identical charges). It is assumed that $m_{3\pi}=m_{a_1}=1.22$ GeV.

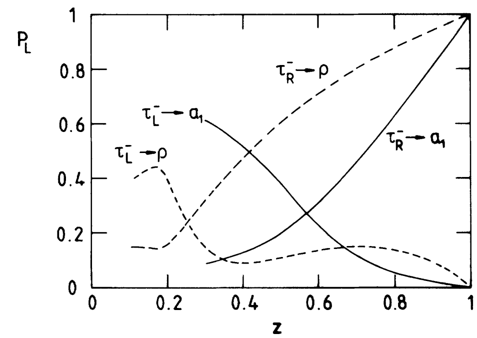

FIG. 3. The probability that the ρ and a_1 are longitudinally polarized, depending on whether they originate from τ_L^- or τ_R^- decays, as a function of $z = E_{n\pi}/E_\tau$.

Again the difference between a_{1L} and a_{1T} decays is striking. For a_{1T} decays, Fig. 2(b), all three pions have a tendency to share equally the energy. On the contrary for a_{1L} decays, Fig. 2(a), the favored configurations are those in which one or two of the three pions are soft; the upper densely populated corner of the plot corresponds to π_3 being soft and π_1,π_2 sharing all the energy, whereas the right-hand populated corner corresponds to both π_1,π_2 being soft and π_3 energetic.

It is remarkable, and fortunate, that the energetic $n\pi$ systems from $W^- \to \tau_L^- \bar{\nu}_R$ and $H^- \to \tau_R^- \bar{\nu}_R$ decays are predicted to be so very different. For the $W \to \tau$ decays the leading particle is either ρ_T or a_{1T} [see Fig. 1(a)], both of which prefer their energy to be equally shared between the outgoing pions; whereas the leading particle resulting from $H \to \tau$ decays is either π, ρ_L, or a_{1L}, where the subsequent ρ_L decay gives rise to one energetic pion and the a_{1L} decay to either a single energetic pion or two energetic identical pions. This difference should allow a clear separation of a possible $H \to \tau\nu$ signal from the $W \to \tau\nu$ background. We notice in passing that these characteristic differences in the multiparticle distributions of polarized τ decays will affect the efficiency of detectors to isolate the τ decay signal from the low multiplicity hadronic background in hadronic collisions.

We cannot, of course, distinguish ρ_T from ρ_L (or a_{1T} from a_{1L}) on an event-by-event basis. Rather, in a quantitative study we can measure the probability P_L of a 2π (or 3π) event arising from the decay of a longitudinally polarized meson as a function of the kinematic variables of the decay. For example, the "polarimeter," P_L, of a $\pi^-\pi^0$ system of momentum fraction z $(=E_{2\pi}/E_\tau)$ may be readily determined by comparing the observed x $(=E_{\pi^-}/E_{2\pi})$ distribution with the form

$$[1-P_L(z)]d\Gamma(\rho_T)/dx + P_L(z)d\Gamma(\rho_L)/dx\,. \qquad (7)$$

Similarly the polarization of a 3π system may be extracted by comparing the observed scatter plot distribution with

$$[1-P_L(z)]d\Gamma(a_{1T})/dx\,dy + P_L(z)d\Gamma(a_{1L})/dx\,dy\,. \qquad (8)$$

In fact, it is a good approximation to simply take $d\Gamma/dx$ in (7) to be (4) evaluated at $m_{2\pi}=m_\rho$, and $d\Gamma/dx\,dy$ in (8) to be those of Fig. 2 (which were obtained using $m_{3\pi}=m_{a_1}=1.22$ GeV), for all values of z, except those at low z $(z \lesssim m_v^2/m_\tau^2)$ where the $n\pi$ system is forced off the vector-meson mass shell.

In Fig. 3 we show the theoretical expectations for the polarimeter P_L as a function of $z=E_v/E_\tau$ for both τ_L^- and τ_R^-. Here the effects of the finite ρ and a_1 widths have been included. As expected, we see that the energetic $n\pi$ systems which arise from $W^- \to \tau_L^-$ decays will have a low P_L (i.e., will be predominantly transversely polarized), whereas $H^- \to \tau_R^-$ will lead to predominantly longitudinally polarized energetic $n\pi$ systems. Of course, in a realistic confrontation with data it will also be necessary to fold in the parent τ energy distribution, which is dependent on the production mechanism and on m_t, m_H, etc.

In summary, we have shown that a charged Higgs boson has a very distinctive $H^\pm \to \tau^\pm \nu$ decay signature, which is significantly different from the $W^\pm \to \tau^\pm \nu$ decays. It is characterized by $\tau \to \pi$, ρ, a_1 decays with a *single, energetic,* pion (or two energetic identical pions in a fraction of the a_1 decays) with the overall event having large missing transverse momentum. These features will also be useful to identify the $H^\pm$ signal in $e^+e^- \to H^+H^-$, particularly if $m_H \simeq m_W$.

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