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Distinguishing a charged Higgs signal from a heavy W_R signal

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It is shown that non-Standard Model bosons should obey an observable asymmetry in their decays to taus. This asymmetry enables a distinction to be made between charged Higgs boson signals and heavy right-handed W boson signals, by reconstructing the orientation of the τ with respect to the beam axis.

The generation of accelerators currently under construction promises to enable physicists to probe various extensions of the Standard Model (SM), including Supersymmetric and Left–Right Symmetric models. Each of these models introduces new groups of presently-undetected particles, whose experimental signals must be distinguished from known SM processes. In the cases of charged Higgs bosons ($H^{\pm}$) and heavy right-handed W bosons ($W_R^{\pm}$), two groups have independently demonstrated that the new bosons may be differentiated from SM $W(80)$ backgrounds by examining polarization effects in tau-lepton decays: both the $H^{\pm}$ [1] and the $W_R^{\pm}$ [2] are predicted to couple preferentially to right-handed τ's, as opposed to the SM (V−A) coupling $W^-(80)\to\tau_L^- + \bar{\nu}_\tau$. Refs. [1,2] trace the effects of the τ helicity on its $(n\pi)^-$ decays. For example, in an $n=1$ decay, $\tau_\alpha^-\to\pi^-\nu_\tau$, where α is the τ helicity, the single pion should be backward-scattered and soft ($x\to0$, where $x\equiv E_\pi/E_\tau$) for $\alpha=\mathrm{L}$, but should be forward-scattered and hard ($x\to1$) for $\alpha=\mathrm{R}$. In this way, a measure of the τ helicity, based on the energy spectrum of the final-state pion, may be used to isolate non-SM boson signals from τ's parented by $W(80)$'s. Further correlations can be constructed for $n=2$, 3 decays via intermediate polarized vector mesons [1]. However, a problem which both refs. [1,2] fail to address is how to distinguish between $H^{\pm}$ and $W_R^{\pm}$: the final-state pion correlations would remain powerless to reveal the actual identity of the new boson.

Other proposed means of separating non-SM bosons from $W(80)$ signals would similarly fail to distinguish between $H^{\pm}$ and $W_R^{\pm}$. It has been shown that the most important sub-process for $H^{\pm}$ production is gluon + b-quark fusion: $gb\to H^{\pm}t$. Gunion et al. have argued that the signal-to-background ratio (S/B) for detection of a charged Higgs boson in the ($\tau\nu$)-channel could be increased as much as 30 times against the $W(80)$ background by correlating the τ-decays with a trigger on the "spectator" t-quark semileptonic decays [3]. Such a "stiff lepton trigger" would weed out all SM events except for $gb\to W(80)t$, which could be distinguished from the $H^{\pm}$ case by the (assumed) large mass difference between the $H^{\pm}$ and the $W(80)$. Yet such a mass-related cut could not separate $H^{\pm}$ from $W_R^{\pm}$ signals: Gunion and company estimate that $m_{W_R}\geqslant2.5$ TeV would be required to differentiate a $W_R^{\pm}$ signal from a $m_{H^{\pm}}\leqslant1$ TeV signal [3]. Current limits on m_{W_R} are as low as 316 GeV [4], however, which places the $W_R^{\pm}$ in precisely the same mass range as the $H^{\pm}$. Thus, although a stiff lepton trigger on spectator-t quark decays could highlight new non-SM bosons, it would be ineffective in distinguishing a charged Higgs signal from a heavy W signal.

Clearly some further information is required to identify the parent boson in τ decays. One difference between the $H^{\pm}$ and $W_R^{\pm}$ concerns lepton-universality: the $H^{\pm}$ should *violate* universality, coupling preferentially to the heavy τ, whereas the $W_R^{\pm}$ should obey universality. Measurement of the W_R mass in decays to electrons and muons might allow a distinction to be made between the $W_R^\pm$ and $H^\pm$ in decays to taus. However, the electron and muon channels would be unable to determine the handedness of the heavy W_R [2]; furthermore, the close proximity of the mass ranges for the $H^\pm$ and $W_R^\pm$ encourages a non-mass-related approach.

Another obvious difference between the $H^\pm$ and $W_R^\pm$, which does not depend on mass, concerns spin: whereas the charged Higgs boson is postulated to be scalar, the heavy W is assumed to be spin 1 [#1]. This difference in spin means that the angular distributions of decay products should differ between the two bosons. The angular distributions therefore offer a means of measuring the spin of the parent boson, and hence of separating a $H^\pm$ signal from a $W_R^\pm$ signal, as will be shown here.

First consider the production of heavy W_R bosons by q–$\bar{q}$ annihilation at hadron colliders [#2]. The left-right symmetric models which motivate our search for the heavy right-handed W's generally replace the SM electroweak group $\mathrm{SU(2)_L \otimes U(1)}$ with $\mathrm{SU(2)_L \otimes SU(2)_R \otimes U(1)}$. The $\mathrm{SU(2)_R}$ interaction is believed to be mediated by the $W_R^\pm$ via pure (V+A) currents. Thus, the q–$\bar{q}$–W_R^- vertex has the factor

$$\mathcal{M}_{W_R} = \mathrm{i}\frac{g}{2\sqrt{2}} V_{ab} \epsilon_\mu^\lambda \bar{v}_a \gamma^\mu (1+\gamma^5) u_b , \qquad (1)$$

where ϵ_μ^λ is the W_R polarization vector, V_{ab} is the appropriate Kobayashi–Maskawa matrix element, and $\bar{v}_a$ and u_b are Dirac spinors for the $\bar{q}_a$ and q_b. Neglecting the quark masses, eq. (1) has the following dependencies upon the W_R polarization (as measured along the beam axis, $\hat{z}$):

$$|\mathcal{M}_R|^2 \propto \tfrac{1}{4} g m_{W_R}^2 (1+\cos\phi)^2, \qquad (2)$$

$$|\mathcal{M}_L|^2 \propto \tfrac{1}{4} g m_{W_R}^2 (1-\cos\phi)^2,$$

$$|\mathcal{M}_S|^2 \propto \tfrac{1}{2} g m_{W_R}^2 \sin^2\phi, \qquad (2\text{ cont'd})$$

where R, L, and S correspond to the production of right-handed, left-handed, and scalar (longitudinal) polarization states of the W_R^-, respectively; that is, for $\epsilon_\mu^R = 2^{-1/2}(0, 1, +\mathrm{i}, 0)$, $\epsilon_\mu^L = 2^{-1/2}(0, 1, -\mathrm{i}, 0)$, and $\epsilon_\mu^S = m_W^{-1}(|\boldsymbol{p}|, 0, 0, E)$. In eq. (2), ϕ is the angle that one of the quarks makes with respect to the beam axis, $\hat{z}$, in the W_R rest frame. Thus, for small p_T, $\phi \to 0$ (π), and the W_R^- is produced predominantly in a right-handed (left-handed) polarization state along the beam axis.

Now consider the W_R decay: $W_R^- \to \tau_a^- \bar{N}$, where N is some unobserved right-handed neutrino. Eq. (1) also gives the matrix element for this vertex, with $V=1$, and $\bar{u}_a$ and v_b spinors for the τ and the $\bar{N}$, respectively. Keeping terms in the tau mass and spin, eq. (1) yields

$$|\mathcal{M}_{W_R}|^2 = \tfrac{1}{2} g^2 [A^\mu B^\nu + A^\nu B^\mu - g^{\mu\nu}(A\cdot B) + \mathrm{i} A_\alpha B_\beta \epsilon^{\alpha\mu\beta\nu}] \epsilon_\mu^\lambda \epsilon_\nu^{\lambda *} . \qquad (3)$$

In eq. (3), $A^\mu \equiv (p_a + m_\tau s_\tau)^\mu$, where p_a is the τ four-momentum, m_τ is the τ mass, and s_τ is the τ spin four-vector; $B^\mu \equiv (p_b)^\mu$ is the antineutrino's four-momentum; and $\epsilon^{\alpha\mu\beta\nu}$ is the totally-antisymmetric tensor ($\epsilon_{0123} = -\epsilon^{0123} = 1$). The only differences between eq. (3) and a $W(80)$ decay are the sign of the $\epsilon^{\alpha\mu\beta\nu}$-term and the sign of the spin term in A^μ, both of which flip sign when changing from a (V−A) to a (V+A) current.

Eq. (3) may be evaluated in the W_R rest frame, giving

$$\begin{aligned} \frac{2}{g^2} |\mathcal{M}_{W_R}|^2 = {} & |\boldsymbol{p}| [(E_\tau + |\boldsymbol{p}|)(1+\cos\theta) \\ & - |\boldsymbol{p}| \sin^2\theta - m_\tau \sin\theta\, \hat{s}_x + m_\tau \hat{s}_z] \\ & + 2\alpha |\boldsymbol{p}| [(E_\tau - m_\tau)(\cos^2\theta + \cos\theta) \\ & + |\boldsymbol{p}| (1+\cos\theta) + m_\tau], \end{aligned} \qquad (4)$$

where $|\boldsymbol{p}|$ is the magnitude of the momentum for both the τ and the $\bar{N}$ in this frame, θ is the angle of the τ with respect to the beam axis, $\hat{s}$ is a unit vector in the direction of the τ spin in the τ rest frame, and $\alpha \equiv \hat{s}\cdot \boldsymbol{p}/2|\boldsymbol{p}|$ gives a measure of the τ helicity ($\alpha = +\frac{1}{2}$ for R, $-\frac{1}{2}$ for L). It has been assumed that the decaying W_R was in a pure right-handed state of polarization.

[#1] The second paper of ref. [1] does treat the spin of the parent boson, but only for the case of separating a *neutral* Higgs from SM Z^0's in decays to $\tau^+\tau^-$ pairs.

[#2] This is the production mechanism treated in ref. [2]. Ref. [2] makes the further assumption that $\phi = 0$, i.e. that W is emitted along the beam axis. Yet other contributing production mechanisms, such as $g + b \to W_R + t$, will have non-vanishing p_T. The angular asymmetry examined in this paper may still hold, however, in the case that $m_{W_R} \gg m_{\text{top}}$, such that the mass and p_T of the "spectator" t-quark is negligible as compared to m_{W_R}. Further study of such production mechanisms is required.

Exactly the same follows when the decaying W_R is in a pure left-handed state.

In the limit $m_\tau \ll m_W$, eq. (4) reduces to

$$|\mathcal{M}_{W_R}|^2 \propto (1+\cos\theta)^2 (\tfrac{1}{2}+\alpha) . \tag{5}$$

Thus, in this limit, the τ will be almost purely right-handed, $\alpha = +\frac{1}{2}$ [2], and will be emitted at some average angle of flight:

$$\langle\cos\theta\rangle = \tfrac{3}{8}\int_{-1}^{1} u(1+u)^2\,\mathrm{d}u = \tfrac{1}{2} , \tag{6}$$

where $u \equiv \cos\theta$. In other words, a right-handed τ^- originating from the decay of a W_R^- should make an angle of about 60° with respect to the beam direction, in the W_R rest frame[3].

The preferred angle of decay in the W_R case may be contrasted with $H^\pm$ decays, which have no θ-dependence; there is no preferred angle of flight for the τ in the decay of the scalar $H^\pm$. Thus there exists an observable asymmetry between the decays of $W_R^\pm$ and $H^\pm$ to taus. Whereas the W_R^- should emit its τ_R^- most frequently along $\theta_0 = 60°$, the H^- should emit its τ_R^- equally frequently at all θ. Note that this result agrees with strange-interaction studies from 1958, which showed that

$$\langle\cos\theta\rangle = \frac{\langle\mu\rangle\langle J_z\rangle}{J(J+1)} , \tag{7}$$

where θ is the angle of flight made by a daughter in the parent particle's rest frame, $\langle\mu\rangle$ is the total helicity of the daughters, and J, J_z refer to the parent particle [5]. For the W_R^- decay, $\langle\mu\rangle = (\frac{1}{2}+\frac{1}{2})$ and $(J, J_z) = (1, +1)$, whereas for the H^- decay, $\langle\mu\rangle = 0$ and $(J, J_z) = (0, 0)$.

Thus, by reconstructing θ_0 from $n=1$, 2 and 3 pionic decays [6–9], the τ orientation with respect to the beam axis would provide a measure of the spin of the parent, non-SM boson. With moderate statistics, spin-1 W_R events (with $\langle\theta_0\rangle = 60°$) could therefore be separated from scalar $H^\pm$ events (with $\langle\theta_0\rangle = 0$).

Tsai has treated a related problem of how to separate virtual W_R's from virtual $H^\pm$'s in τ decays to muons. His method involves large statistics, correlating the angular distribution with the polarization of the final-state muons [10].

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