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TAUS – A PROBE OF NEW W AND Z COUPLINGS*

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Summary

If new heavier W's and/or Z's are discovered at the SSC, only partial information on their couplings to quarks and leptons can be obtained by studying their decays into electrons and muons. In particular, without polarized beams, one cannot distinguish between heavy W's which have left-handed (W_L) or right-handed (W_R) couplings to all fermions. Here, we study the τ decays of W_L and W_R and compute the distributions of the τ decay products. The most striking effect is $W \to \tau + N$ followed by $\tau \to \pi\nu_\tau$; the p_T distribution of the pion can distinguish W_L from W_R (without a measurement of the pion electric charge).

1. Introduction

If new heavier W's and/or Z's are discovered at the SSC, it will be important to investigate their couplings to quarks and leptons.[1] We presume that a new vector boson will first be discovered by its purely leptonic decay mode: $W \to eN$, μN and $Z \to e^+e^-, \mu^+\mu^-$. Based on the experience obtained at the CERN $Sp\bar{p}S$ with the discovery of the $W(83)$ and the $Z(94)$,[2] we expect that only of order 10 leptonic events are needed in order to discover a new W or Z. (A possible complication arises if N is a new heavy neutrino which decays inside the detector. However, the presence of the Jacobian peak in the p_T distribution of the electron (or muon) should be sufficient to identify the new W signal.)

The dominant production mechanism responsible for new W and Z production is $q\bar{q}$ annihilation. Thus, some information about the couplings of the vector boson to quarks and leptons can be obtained by measuring distributions of the final state leptons. In this article, we shall focus on what one can learn about the couplings of a new charged $W^\pm$. For simplicity, we shall assume that the couplings of the $W^\pm$ to quarks and leptons are universal – either pure $V - A$ or $V + A$. The vector boson will be denoted by either W_L or W_R respectively. Suppose such a vector boson is found in $p\bar{p}$ collisions and is seen to decay into e^-N (where the N is not observed or ignored). The electron angular distribution is shown in figure 1, reflecting the $(1 + \cos\theta)^2$ distribution of the subprocess $\bar{u}d \to W^-_{L,R} \to e^-N$. Note that both W^-_L and W^-_R lead to the same distributions. To obtain a distribution of electrons peaking at $\theta = 180°$ would require a $V - A$ coupling at the $\bar{u}dW$ vertex and a $V + A$ coupling at the e^-NW vertex or vice versa. For $p\bar{p} \to W^+ \to e^+N$, the above statements are modified by replacing $\cos\theta \to -\cos\theta$. (In pp scattering, the $\cos\theta$ distribution is symmetric about 90°.) Other distributions can be studied;[3] nevertheless, one always finds that W^-_L and W^-_R are indistinguishable unless polarized beams are employed.

In this article, we will examine another way to untangle the coupling of new vector bosons to quarks and leptons. The method involves observing the decay $W \to \tau N$ and measuring the distributions of the final state decay products of the τ. The decay of the τ proceeds via the emission of a virtual $W(83)$ which has $V - A$ couplings to quarks and leptons. However, the τ produced from a new W decay is either purely left-handed or right-handed depending on the nature of the τ^-NW vertex. Therefore, the decay distributions of the τ decay products can differentiate between W_L and W_R.

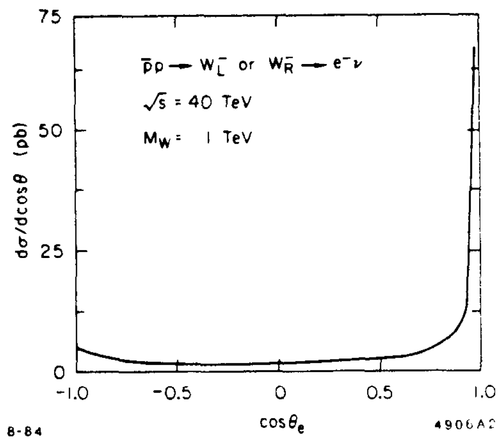

Fig. 1. Angular distribution of electrons from a 1 TeV heavy W_L or W_R, integrated over p_T. The angle θ_e is defined relative to the proton beam.

2. Taus–Distinguishing between W_L and W_R

We shall summarize the needed formulas for determining the spectrum of some final state particle arising from the sequential decay process $W \to \tau N$ followed by τ decay. Let us denote the observed final state particle by a (i.e. $\tau \to a + X'$, where X' is unobserved). The appropriate parton model formula for $p\bar{p} \to a + X$ is:

$$E_a \frac{d^3\sigma}{dp_a^3} = \frac{1}{2\pi} \sum_{ij} \int dx_1 dx_2 \; f_i(x_1) f_j(x_2) \; \frac{1}{\hat{p}_a} \; \frac{d\hat{\sigma}}{d\hat{E}_a \; d\cos\hat{\theta}_a} \quad (1)$$

where $\hat{p}_a = (\hat{E}_a^2 - m_a^2)^{1/2}$, and variables $\hat{E}_a$, $\hat{\theta}_a$ are defined in the parton center-of-mass frame. In the limit where all final state particle masses are neglected, $\hat{E}_a$ and $\hat{\theta}_a$ are related to the variables E_a, θ_a measured in the laboratory frame ($p\bar{p}$ center-of-mass frame) via:

$$\hat{E}_a = \frac{E_a}{(x_1 x_2)^{1/2}} \left[x_1 \sin^2 \frac{\theta_a}{2} + x_2 \cos^2 \frac{\theta_a}{2} \right] \quad (2a)$$

$$\cos\hat{\theta}_a = \frac{x_2 - x_1 \tan^2 \theta_a/2}{x_2 + x_1 \tan^2 \theta_a/2} \quad (2b)$$

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The sum in equation (1) is taken over the appropriate quark distribution functions $f_i(x, M_W^2)$ evaluated at a Q^2 equal to the squared vector boson mass. The partonic cross section $\hat{\sigma}$ of interest is $\bar{u}d \to a + X$ via the sequential process $\bar{u}d \to W^- \to \tau^- N$, $\tau^- \to a + X'$. We now turn to the computation of $\hat{\sigma}$ for the cases of interest:

(a) $\bar{u}d \to e^- + X$ (via $W^-_{L,R} \to \tau^- N$, $\tau^- \to e^- \bar{\nu}_e \nu_\tau$)

The calculation is simplified by observing that τ's originating from $W^-_{L,R}$ decay are completely polarized (where, we are neglecting effects of order m_τ^2/M_W^2). Thus, we may use the method of calculation described by Barnett, et al.[4] The result for W_L^- was obtained there and the result for W_R^- is new. We define

$$C(\hat{\theta}_e) = \frac{\pi\alpha^2\sqrt{\hat{s}}(1+\cos\hat{\theta}_e)^2}{24\sin^4\theta_W[(M_W^2-\hat{s})^2+\Gamma_W^2 M_W^2]} \tag{3}$$

where $\hat{s} = sx_1x_2$ is the partonic squared center-of-mass energy and $\hat{\theta}_e$ is the angle of the e^- measured with respect to the incoming d-quark. Then,

$$\frac{d\hat{\sigma}}{d\hat{E}_e d\cos\hat{\theta}_e} = B_e C(\hat{\theta}_e) \times \begin{cases} \frac{2}{3}(1-x^3) & , \quad W_L \\ (1+2x)(1-x)^2 & , \quad W_R \end{cases} \tag{4}$$

where $x = 2\hat{E}_e/\sqrt{\hat{s}}$, $0 \le x \le 1$. B_e is the branching ratio for $\tau^- \to e^- \nu\nu$ which we take to be about 17%.[5]

(b) $\bar{u}d \to \pi^- + X$ (via $W^-_{L,R} \to \tau^- N$, $\tau^- \to \pi^- \nu_\tau$)

Using the same method of calculation as above, we find:

$$\frac{d\hat{\sigma}}{d\hat{E}_\pi d\cos\hat{\theta}_\pi} = B_\pi C(\hat{\theta}_\pi) \times \begin{cases} 1-x & , \quad W_L \\ x & , \quad W_R \end{cases} \tag{5}$$

where $C(\hat{\theta})$ is given by equation (3), $x = 2\hat{E}_\pi/\sqrt{\hat{s}}$ and $B_\pi \approx$ 11%.[5] The pion mass has been neglected.

This result has a simple physical interpretation. The τ^- is either left or right-handed depending on whether it came from W_L or W_R. But the ν_τ is always left-handed. Thus, because the π is spinless, conservation of angular momentum implies that π is emitted preferentially "forward" in the case of W_R decay and "backward" in the case of W_L decay. This is illustrated in figure 2. In the $\bar{u}d$ center-of-mass frame, this corresponds to an energy spectrum of the π which is harder (peaked at $x = 1$) in W_R decay and softer (peaked at $x = 0$) in W_L decay.

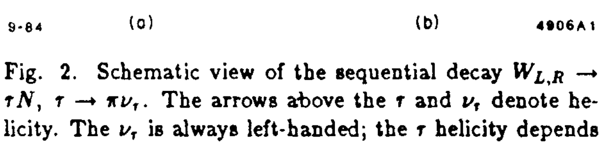

Fig. 2. Schematic view of the sequential decay $W_{L,R} \to \tau N$, $\tau \to \pi\nu_\tau$. The arrows above the τ and ν_τ denote helicity. The ν_τ is always left-handed; the τ helicity depends on the nature of the W as shown. Angular momentum conservation demands that the configurations shown above are the ones favored.

This result can be obtained in another way. Let k be the four-momentum of the π. In the rest frame of the τ, we define the z-axis to be the axis of quantization for the τ spin. In this frame, $k = \frac{m_\tau}{2}(1;\ \sin\theta,\ 0,\ \cos\theta)$. If we boost to a frame where the τ is moving along the z-axis with velocity v, then in this frame $E_\pi = \frac{1}{2}\gamma m_\tau(1+v\cos\theta)$ and $E_\tau = \gamma m_\tau$ where $\gamma = \sqrt{1-v^2}$. In the limit where $v \to 1$, the pion energy fraction $x = E_\pi/E_\tau \to \cos^2\frac{\theta}{2}$. The decay rate of a τ^- with helicity $\pm\frac{1}{2}$ into $\pi^-\nu_\tau$ is given by

$$\Gamma\left(\tau^-(\pm 1/2) \to \pi^-\nu_\tau\right) \propto \left|d^{1/2}_{\pm 1/2,\,1/2}(\theta)\right|^2 \tag{6}$$

which leads to a $\cos^2\frac{\theta}{2}$ ($\sin^2\frac{\theta}{2}$) distribution for a τ helicity of $+\frac{1}{2}$ $(-\frac{1}{2})$. In the partonic center-of-mass frame where the τ^- is moving, this translates into a pion energy distribution of x $(1-x)$ which agrees with equation (4).

(c) $\bar{u}d \to \rho^- + X$ (via $W^-_{L,R} \to \tau^- N$, $\tau^- \to \rho^- \nu_\tau$)

We find:

$$\frac{d\hat{\sigma}}{d\hat{E}_\rho d\cos\hat{\theta}_\rho} = \frac{B_\rho C(\hat{\theta}_\rho) m_\tau^2}{(m_\tau^2-m_\rho^2)^2(m_\tau^2+2m_\rho^2)} \times \begin{cases} 2m_\rho^2(m_\tau^2-m_\rho^2)+m_\tau^2(m_\tau^2-2m_\rho^2)(1-x) & , \ W_L \\ m_\tau^2[m_\rho^2+(m_\tau^2-2m_\rho^2)x] & , \ W_R \end{cases} \tag{7}$$

where $C(\hat{\theta})$ is given by equation (3), $x = 2\hat{E}_\rho/\sqrt{\hat{s}}$, $(m_\rho^2/m_\tau^2 \le x \le 1)$ and $B_\rho \approx 22\%$.[5]

Note that for $m_\rho = 0$, we obtain a result identical to the pion case. Using the helicity arguments previously made (see figure 2), this observation implies that in the limit of $m_\rho \to 0$, helicity-zero ρ's are dominant. This is correct as can be verified by explicit calculation of $\Gamma(\tau^- \to \rho^-\nu_\tau)$. To understand why this is true, recall that as $m_\rho \to 0$, the longitudinal polarization vector for the ρ is approximately $\epsilon_\mu \approx k_\mu/m_\rho$ (where k is the ρ momentum), which blows up as $m_\rho \to 0$. In addition, the leptonic current $j^\mu \equiv \bar{u}_\nu\gamma^\mu[(1-\gamma_5)/2]u_\tau$ is not conserved (i.e. $k_\mu j^\mu \neq 0$). Thus, the matrix element for $\tau^- \to \rho^-\nu_\tau$ (which is proportional to $j^\mu\epsilon_\mu$) favors the longitudinal ρ's as we have observed above.

(d) $\bar{u}d \to A_1^- + X$ (via $W^-_{L,R} \to \tau^- N$, $\tau^- \to A_1^- \nu_\tau$)

This is a convenient way to parameterize the decay $\tau^- \to \pi^+\pi^-\pi^-\nu_\tau$. The formulas are identical to equation (7).

All cases described above assumed $W^-_{L,R}$ production. For $W^+_{L,R}$ production, the above formulas (equations (4), (5), (7)) are modified by replacing $C(\theta)$ by $C(\pi-\theta)$. *The energy distributions are independent of the charge of the vector boson.* This implies that we may differentiate W_L from W_R without measuring the charge of the final state particle.

3. Pion-Spectrum From Sequential $W^\pm_{L,R} \to \tau^\pm \to \pi^\pm$ Decay

We shall illustrate the results of section 2 by calculating the p_T spectrum of the outgoing pions resulting from $pp \to W_{L,R} \to \tau N$, $\tau \to \pi\nu_\tau$ at $\sqrt{s} = 40$ TeV, where we have chosen $M_W = 1$ TeV. Inserting equation (5) into equations (1) and (2) and using

EHLQ structure functions,[6] we have computed the p_T distribution of outgoing pions as shown in figure 3. Note that the distinguishing feature of equation (5) is preserved, namely that $W_R^\pm$ leads to a harder pion spectrum as compared to $W_L^\pm$. The feasibility of such a proposal depends on how efficiently one can measure isolated energetic pions in an otherwise quiet event. It would be of great interest to attempt such a measurement at the CERN $Sp\bar{p}S$, since at present we have no direct evidence that the $W(83)$ is a W_L^--boson.

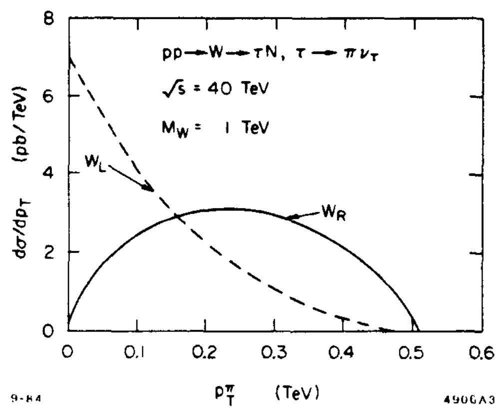

Fig. 3. The p_T spectrum of the pion resulting from the sequential decay $W_{L,R} \to \tau N$, $\tau \to \pi\nu_\tau$.

4. Discussion and Conclusions

We have argued that observing τ's from new heavy vector bosons could provide an important method to help unravel the couplings of the vector boson to quarks and leptons. We have illustrated the possibility of distinguishing W_L from W_R by observing isolated energetic pions coming from τ decay. Other τ decay modes would also be useful. In particular, multi-prong τ decays would allow the possibility of using vertex detectors to increase the efficiency of τ detection. On the other hand, the detection of e^- and μ^- from τ^- decay is probably very difficult. Such a signal would be buried under the spectrum of direct e^- and μ^- from the new W as well as from the $W(83)$.[7] One can also learn about the couplings of a new heavy Z^0 by examining $Z^0 \to \tau^+\tau^-$ and studying the distributions of the τ decay products. More formalism will be needed and the formulas analogous to equations (3), (4), (5), and (7) must be obtained. This is presently under investigation.

The efficient detection of τ's is an important goal at the SSC. Learning how to detect isolated τ's at the CERN $Sp\bar{p}S$ and the FERMILAB TEVATRON would be a significant first step; the ability to study $W(83) \to \tau\nu$ and $Z(94) \to \tau^+\tau^-$ will provide important groundwork for future applications at the SSC.

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