# Some signatures of right-handed $W$ bosons in hadron colliders

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Several signatures for right-handed $W$ ($W_R$) production in collider experiments are noted. If the right-handed neutrino $N$ is too heavy to permit the decay $W_R \rightarrow eN$, the decay $W_R \rightarrow t+(d,\ s, \text{ or } b)$ may still be allowed. Given present limits on the top-quark mass, it is then likely that $t$ will decay 100% of the time to $W+b$. We thus urge that the signature $W+2$ jets be examined for clusters of events consistent with $M(W+\text{jet}_1+\text{jet}_2)=M_{W_R}$, $M(W+\text{jet}_2)=m_t$. Some decay modes involving the right-handed neutrino are also mentioned briefly.

The weak charge-changing interactions favor left-handed particles. This asymmetry could either be a relic of physics at a fundamental (e.g., Planck-length) level, or it could arise from the way in which the symmetry of an initially left-right-symmetric theory is broken.

If the theory before symmetry breaking is left-right symmetric, it will contain right-handed charged weak bosons $W_R$ in addition to the usual $W_L$ bosons.[1] Direct searches are the best way to see or exclude such bosons, though there are indirect limits on right-handed $W$'s set by the absence of unusual contributions to such processes as $K$-$\bar{K}$ mixing.[2] With reasonable assumptions, these limits imply $M_{W_R} > 300\ \text{GeV}/c^2$.

One would normally expect to be able to see $W_R$ in its decay to a charged lepton and a right-handed neutrino. However, we have no assurance that neutrinos are Dirac particles. If they are not, the properties of the (ordinary) left-handed and the (hypothetical) right-handed neutrinos could be very different. For example, (1) the right-handed neutrinos could decay promptly within the detector, leading to the absence of a signal involving missing transverse energy, (2) the right-handed neutrinos could decay after a finite flight path within the detector, leading to secondary vertices but possibly not to missing transverse energy, or (3) the right-handed neutrinos could be so heavy as to prevent their production altogether in the decays of $W_R$. Leptonic decays of $W_R$ to Majorana neutrinos are likely to produce some events with same-sign charged-lepton pairs, as pointed out in Ref. 3.

In this Brief Report we wish to draw attention to another decay mode of $W_R$ that does not depend on the mass of right-handed neutrinos: the process

$$W_R \rightarrow t+(\bar{d},\ \bar{s}, \text{ or } \bar{b}) , \tag{1}$$

followed by the subsequent decay

$$t \rightarrow W^+ + b . \tag{2}$$

The down-type quark in Eq. (1) is assumed to fragment to a jet which we shall call $\text{jet}_1$, while the products of the $b$ quark in Eq. (2) will be denoted $\text{jet}_2$. We have not specified which type of down quark is favored in Eq. (1), since it is often necessary to assume a coupling pattern other than that for left-handed quarks in order to evade some very stringent limits[2] on right-handed $W$'s. We have assumed for present purposes that the $t$ quark is heavy enough that the process (2) is kinematically allowed, though present lower bounds on the top quark mass[4] are only in the range of 72–77 $\text{GeV}/c^2$.

The chain of decays [(1) and (2)] is illustrated for one example of final states in Fig. 1. Its signature is then the final state $\text{jet}_1+\text{jet}_2+W$, with

$$\begin{aligned} &M(W+\text{jet}_1+\text{jet}_2)=M, \quad M \equiv M_{W_R} , \\ &M(W+\text{jet}_2)=m, \quad m \equiv m_t . \end{aligned} \tag{3}$$

We have estimated that with present data, the Collider Detector at Fermilab (CDF) experiment should have been able to detect a right-handed $W$ with $M=250\ \text{GeV}/c^2$, decaying to a top quark with $m=100\ \text{GeV}/c^2$. Detailed simulations, beyond the scope of this Brief Report, are needed to determine the two-dimensional region

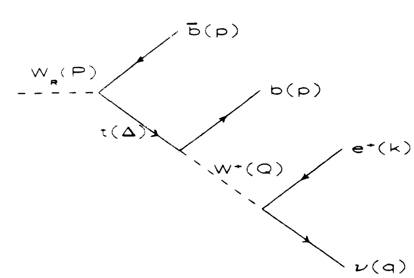


FIG. 1. Diagram illustrating the decay of a right-handed $W$ to a top quark, which decays subsequently to a left-handed $W$ and a $b$ quark [Eqs. (1) and (2)].

 

of $M$ and $m$ in which present and future collider experiments would be sensitive. Our purpose is to present some of the theoretical aspects of such searches.

The decay (1) should lead to a sharp Jacobian peak in the distribution of transverse momentum $p_T$ of the jet associated with the down-type quark. Let us define $\xi \equiv m^2/M^2$ and $x \equiv (p_T/p_{\max})^2$, where $p_{\max} \equiv (M^2 - m^2)/2M$. Then for an initial $W_R$ with no transverse momentum and polarized initially with $J_z = \pm 1$ with respect to the beam (a reasonable approximation to the way it is produced), the normalized distribution of events with respect to $x$ is

$$dN/dx = \frac{3}{2(2+\xi)} \frac{1+(\xi-1)x/2}{\sqrt{1-x}} . \quad (4)$$

Examples are shown in Fig. 2 for two extreme values of $\xi$. The peaking is even more pronounced in the variable $y \equiv p_T/p_{\max} = \sqrt{x}$. Also shown is the Jacobian peak smoothed by the expected $W_R$ width[5] of 6 GeV for a $W_R$ of mass 250 GeV/$c^2$, with $m_t = 100$ GeV/$c^2$.

To see if the jet in reaction (1) can be distinguished from background, we compared its $p_T$ distribution with that of jets in $W+2$ jet events arising from QCD. The theoretical cross section for such background events[6] is satisfactorily reproduced[7] by the simulation program PAPAGENO,[8] which we employ. The transverse-momentum distribution of jets from the background process is shown as the unshaded histogram in Fig. 3, for $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. We have assumed $p_T(e)$ and $p_T(\nu)$ both to be greater than 20 GeV/$c$, the electron to be in the central region $|\eta(e)| \leq 1$, and isolation cuts[9] on the electron and jets similar to those adopted in the top-quark searches of Ref. 4. Without these cuts, the unshaded entries in the histogram would be about a factor of 3.3 as large. The branching ratio $B_{e\nu} = \frac{1}{9}$ of $W$ is included in the result shown.

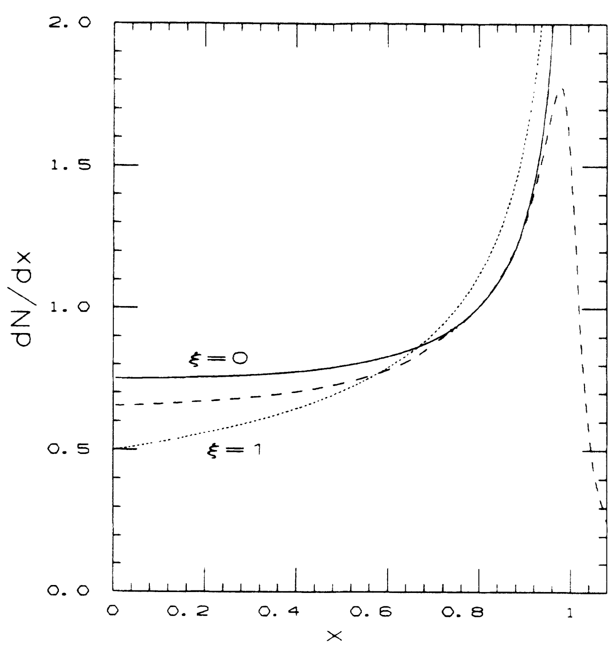


FIG. 2. Normalized spectrum for decay of a heavy $W$ with mass $M$ (right or left handed), with $J_z = \pm 1$, into a top quark with mass $m$. Here $\xi \equiv (m/M)^2$ and $x \equiv (p_T/p_{\max})^2$. The dashed line corresponds to a spectrum smeared by the $W_R$ total width, for the case $M = 250$ GeV/$c^2$, $\Gamma_W = 6$ GeV, $m = 100$ GeV/$c^2$ (i.e., $\xi = 0.16$).

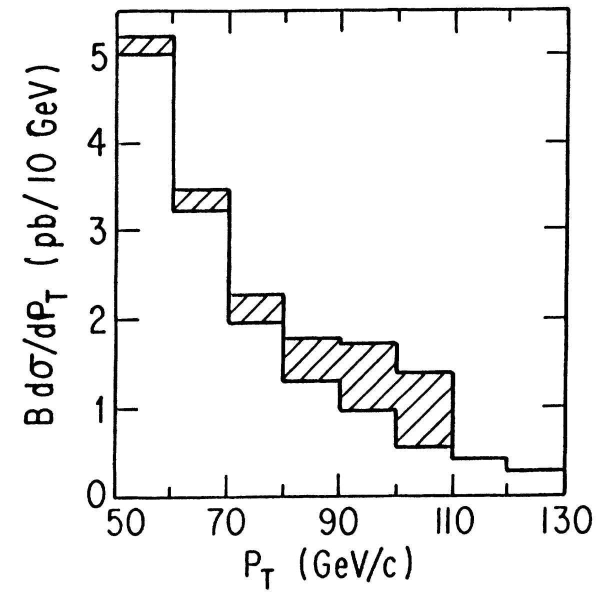


FIG. 3. Transverse-momentum spectra of jets in background (unshaded) and signal (shaded) processes. The background process is the production of $W+2$ jets, while the signal process corresponds to the chain of Eqs. (1) and (2) illustrated in Fig. 1. For the signal process, only the contribution of the light antiquark jet is shown.

The cross section for $W_R$ production is estimated using Eichten-Hinchliffe-Lane-Quigg[10] (EHLQ) structure functions to be about 330 pb for $M = 250$ GeV/$c^2$, summing over charge states. We have assumed that the right-handed neutrinos are sufficiently heavy that the only decay modes available to the $W_R$ are those involving quark pairs. We shall take the top quark to have a mass of 100 GeV. The branching ratio for $W_R \to t\bar{b}$ is then sufficiently close to its light-$t$ value of $\frac{1}{3}$ that we shall adopt this value in what follows. (We assume that *all* the right-handed neutrinos are heavy enough so that the leptonic modes are shut off.) Including the branching ratio of the $W$ produced in top-quark decay [Eq. (2)] to decay to $e\nu$, we have a total cross section of 12 pb for production of an electron, two jets, and missing transverse energy from the chain [(1) and (2)]. Convoluting this cross section with the $p_T$ distribution of the light-quark jet in Eq. (1), shown in Eq. (4) and Fig. 2, and dividing by the same factor of 3.3 mentioned above for $W+2$ jet events associated with jet and $p_T$ cuts, we obtain the shaded contributions to the histogram in Fig. 3 (Ref. 11). Clearly a more precise calculation is needed to estimate the effects of jet and $p_T$ cuts, but we doubt that the chain [(1) and (2)] suffers more under such cuts than does the background process.

The signal in the bins from 90 to 110 GeV/$c$ in Fig. 3 corresponds to about 1.9 pb above a background of 1.5 pb. For the present CDF sample[4] of 4.4 pb$^{-1}$ one would then expect a signal of about eight events above a background of 6.8 events, corresponding to a $3\sigma$ excess.

If the top quark has a mass of 100 GeV as assumed above, the hadronic production of $t\bar{t}$ and the subsequent decays of each of these quarks to $W+b$ will also lead to $e\nu jj$ events, where the leptons come from one $W$ and the jets come from the other. However, one expects that these jets are unlikely to have sufficiently high transverse momenta to populate the Jacobian peak region in Fig. 3.

The above example is meant only to illustrate the ability of present experiments to search for the right-handed $W$ even if its leptonic decay channel is closed. Obviously with present statistics such searches will be limited in scope. In particular, for $M=300$ GeV/$c^2$ the cross section for $W_R$ production is expected to be less than half of that for 250 GeV/$c^2$, so that statistics will be a limiting factor. For $M=250$ GeV/$c^2$ and a top quark much heavier than 100 GeV/$c^2$, the maximum transverse momentum of the light-quark jet in Eq. (1) will be small enough that the Jacobian peak will be smothered by the background of the $W+2$ jet process.

With a sample of sufficient statistics, one can search for a clustering of events with respect to effective masses of the top quark and the right-handed $W$. Refer to the definitions of momenta in Fig. 1. The momentum $k$ of the electron is known, as is the transverse momentum $q_T$ of the neutrino (assuming that it is the source of the missing transverse momentum in the event). One can then assume that the electron and neutrino form a $W$, so that

$$M_W^2 = 2k_T q_T[\cosh(\eta_e - \eta_\nu) - \cos(\phi_e - \phi_\nu)] \ . \quad (5)$$

Here $\eta$ and $\phi$ refer to pseudorapidity and azimuthal angle, respectively. The only unknown quantity in Eq. (6) is $\eta_\nu$. If a solution exists for it, that solution will have a twofold ambiguity, and hence so will the longitudinal component (and energy) of the $W$ four-momentum $Q$.

One then chooses one of the two jets to be a candidate for $b(p)$ in Fig. 1. Again, there is a twofold ambiguity in this choice, so that the overall ambiguity is fourfold. With such a choice, one now can reconstruct candidate values for the four-vectors $\Delta$ and $P$ of the top quark and right-handed $W$, and corresponding values $m$ and $M$ for their masses. One would form a scatter plot of $m$ versus $M$, with each candidate for the chain [(1) and (2)] plotted four times. A detailed simulation would be useful to see whether this method helps to distinguish $W_R$ events from $W+2$ jet background.

We close with a few remarks regarding the possible decays of $W_R$ to a lepton and a heavy neutrino $N$. This process is illustrated in Fig. 4. Here the $W$ can be real or virtual, depending on the mass of $N$, and can decay to any of the final states to which a $W$ usually decays. The decay $N \rightarrow$(lepton)+(gauge boson) must proceed by mixing of $N$ with an ordinary neutrino, presumably of the same flavor as $N$. It can either involve a charged lepton and a (real or virtual) $W$, as shown in Fig. 4, or a neutrino and a (real or virtual) $Z$. A list of possibilities for the decay of $N$ has been given, for example, in Ref. 12.

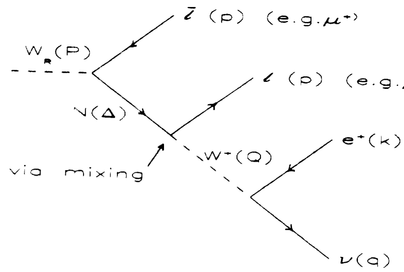


FIG. 4. Diagram illustrating the decay of a right-handed $W$ to a charged antilepton $\bar{l}$ and a right-handed neutrino $N$, which subsequently decays to a charged lepton $l$ and a (real or virtual) $W$. The leptonic decay of the $W$ is shown for illustration.

One would probably begin looking for decays of the form shown in Fig. 4 by examining events with a lepton at larger transverse momentum than expected for $W$ or $Z$ decays (say, at least 60 GeV/$c^2$). Under some circumstances one might be able to fully reconstruct the decays of the right-handed neutrino (if it decayed via the charged current to a lepton and jets, for example). One could also examine events with high-$p_T$ leptons for displaced vertices, signifying the decay of a relatively long-lived right-handed neutrino. The amount of the displacement depends on the mixing between the right-handed neutrino and an ordinary neutrino, for which only guesses[12,13] exist. As mentioned earlier,[3] a Majorana right-handed neutrino can decay to "wrong"-sign leptons, leading to the signature of two same-sign charged leptons at high transverse momenta.

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[1]Jogesh C. Pati and Abdus Salam, Phys. Rev. D **8**, 1240 (1973); **10**, 275 (1974); Rabindra N. Mohapatra and Jogesh C. Pati, *ibid.* **11**, 566 (1975).

[2]Paul Langacker and S. Uma Sankar, Phys. Rev. D **40**, 1569 (1989).

[3]Wai-Yee Keung and Goran Senjanović, Phys. Rev. Lett. **50**, 1427 (1983).

[4]CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **64**, 142 (1990); **64**, 147 (1990).

[5]In arriving at this estimate of the $W_R$ width we have assumed the $SU(2)_L$ and $SU(2)_R$ couplings to be equal, and have assumed that the $W_R$ decays only to $u\bar{d}$, $c\bar{s}$, and $t\bar{b}$.

[6]V. Barger, T. Han, J. Ohnemus, and D. Zeppenfeld, Phys. Rev. Lett. **62**, 1971 (1989); Phys. Rev. D **40**, 2888 (1989); F. A.

Berends *et al.*, Phys. Lett. B **224**, 237 (1989); Michaelangelo Mangano and Stephen Parke, Phys. Rev. D **41**, 59 (1990).

[7]Jonathan L. Rosner, Phys. Rev. D **39**, 3297 (1989); **40**, 1701(E) (1989).

[8]I. Hinchliffe (private communication).

[9]Specifically, we take $\Delta R$ to be at least 0.7 for jet-jet pairs and at least 0.4 for jet-lepton pairs, where $\Delta R^2 \equiv \Delta\eta^2 + \Delta\phi^2$.

[10]E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984); **58**, 1065(E) (1986).

[11]No correction is made for the finite width of the $W_R$; as one sees from Fig. 3, the Jacobian peak is smeared out by considerably more than the expected $W_R$ width of 6 GeV.

[12]Michael Gronau, C. N. Leung, and Jonathan L. Rosner, Phys. Rev. D **29**, 2539 (1984).

[13]Emmanuel A. Paschos and Christopher T. Hill, Fermilab report, 1989 (unpublished).