Model Dependence of $W_R$ Searches at the Tevatron

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Abstract

We explore the sensitivity of the on-going Tevatron search for charged, right-handed
gauge bosons, $W_R^\pm$, to various model dependent assumptions such as the magnitude of
the $SU(2)_R$ gauge coupling, the values of the right-handed Kobayashi-Maskawa mixing
matrix elements, $(V_R)_{ij}$, and the nature of the right-handed neutrino. These results
also have important implications for HERA searches for right-handed currents.
Despite the many successes of the Standard Model (SM), there are many reasons to believe that new physics must exist at a scale not far above that being probed by current accelerator experiments. These beliefs originate from the fact that too many of the pieces of the SM are put in by hand in order to conform to experimental observation. Perhaps one of the oldest of these pieces is the $V - A$ nature of the charged current interaction which forces the SM gauge group to be its canonical $SU(2)_L \times U(1)_Y$ structure. One of the earliest extensions of the SM, the Left-Right Symmetric Model (LRM) \cite{1}, which is based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)$, ‘explains’ the apparent absence of right-handed currents (RHC) by associating them with a much more massive gauge boson, $W^\pm_R$. This model, in its more modern, supersymmetric version can be nicely embedded into an $SO(10)$ GUT structure which yields correct predictions for $\sin^2 \theta(M_Z)$ and $\alpha_s(M_Z)$, interesting relationships among neutrino masses, and allows for the possibility that $W_R$ can be lighter than a few TeV\cite{2} and hence potentially visible at existing or planned colliders. In this paper we would like to focus upon several specific aspects of this model related to the direct searches for $W_R$ at the Tevatron. As we will see, these considerations will have important implications for the RHC searches at HERA as well.

In order to establish limits on the mass of $W_R$'s, either from low energy data or from collider searches, there are five important aspects of the LRM which come into play which can be phrased as a series of questions:

(i) How large is the ratio of the $SU(2)_R$ and $SU(2)_L$ coupling constants, $\kappa = g_R/g_L$? Ordinarily one might expect such a ratio to be of order unity and it can be shown\cite{3} that internal consistency within the LRM requires that $\kappa^2 \geq x_w/(1 - x_w)$, where $x_w = \sin^2 \theta_w$. Numerically, this implies $\kappa \geq 0.55$. With the GUT context, however, $\kappa$ is either very close to unity or lies in the range $0.55 \leq \kappa \leq 1$. The implication of the size of $\kappa$ for $W_R$ Tevatron collider searches is quite obvious as the production cross section is quadratic in $\kappa$. Thus as
κ decreases(increases) in magnitude the resulting $W_R$ search reach is reduced(enhanced).

(ii) What is the magnitude of the mass of the right-handed neutrino, $\nu_R$? Clearly, if neutrinos are Dirac fields then $\nu_R$ is simply a part of the four component $\nu$ spinor and is thus essentially massless. However, if the rather attractive see-saw mechanism is invoked, $\nu_R$ is a heavy Majorana neutrino. If the Dirac path is realized, the lightness of the neutrinos imply that they appear as missing $E$ or $p_t$ in collider detectors and that polarized $\mu$ decay experiments can place stringent limits on the $W_R$ mass, of order 480 GeV, as well as its possible mixing with the SM $W$. If, however, $\nu_R$’s are heavy this situation changes drastically. For example, if $\nu_R$’s are more massive than a few hundred MeV then they cannot be produced as final states in $K$, $\pi$, or $\mu$ decay thus avoiding the low energy bounds. If $\nu_R$’s are even heavier, they can easily decay inside the collider detector and the missing $E$ or $p_t$ signature is lost. The resulting final state would then consist of two leptons plus two jets with only one of the leptons being isolated and at very high $p_t$. Depending on the $\nu_R$ mass, the second lepton and both jets may be quite close in $\Delta R$. Such a scenario would require a completely different search technique than what is conventionally employed and is outside of the scope of the present paper.

(iii) What is the branching fraction($B$) for leptonic $W_R$ decays? Since conventional Tevatron searches require the presence of a hi-$p_t$ lepton, a reduction in the value of $B$ due to the existence of $W_R$ decays into non-SM final states, such as SUSY particles, will result in a loss of mass reach.

(iv) Perhaps the most important and least easily addressed question is ‘what are the values of the elements of the ‘right-handed’ Kobayashi-Maskawa(KM) mixing matrix, $V_R$?’ Most analyses of the LRM assume that the elements of $V_R$ and the conventional KM matrix, $V_L$, differ at most by phase factors. If $V_R = V_L$, then it has been known for some time that considerations of the $K_L - K_S$ mass difference result in a strong lower bound
on the mass of $W_R$ of 1.6 TeV thus placing it outside the search capabilities of existing colliders. If, however, we remove the constraint of $V_R = V_L$ and allow $V_R$ to be arbitrary, even in the absence of fine-tuning we find that $W_R$ can be as light as 280 GeV for a top quark mass of 160 GeV. Also if $V_R$ differs from $V_L$ significantly, the $W_R$ production cross section at the Tevatron can be drastically reduced since the initial valence $u\bar{d}$ parton flux has the greatest luminosity. It is important to note that HERA searches for RHC are not susceptible to this $V_R$ uncertainty. Consider the scattering of $e^-_R$ off of valence u-quarks via $W^-_R$ exchange. At the parton level, depending on the form of $V_R$, the initial u-quark is transformed mostly into d-, s-, or b-quarks. However, if we sum over all three final states and neglect the b-quark mass as a first approximation, we find the resulting cross section to be independent of $V_R$ due to the fact that $V_R$ is unitary. This implies that the usually quoted search reach for $W_R$ at HERA\[7\], using right-handed polarized $e^-$ beams, of approximately 400 GeV (assuming $\kappa = 1$ and light $\nu_{R}$’s) is quite insensitive to the form of $V_R$. We note, however, that the corresponding result for $e^+_R$ may be reasonably $V_R$ sensitive since in this case the initial valence d-quark can be transformed into u-, c-, or t-quarks. Since top quarks are quite massive, their production is highly suppressed so that we can no longer make use of the unitarity argument above and the possibility of strong $V_R$ dependence in this channel remains. We note that if $\nu_R$’s are sufficiently massive as to decay inside a HERA detector, the game is totally different as the SM background is now drastically reduced. It has in fact been shown by Buchmüller et al.\[7\] that the $W_R$ search range is significantly enhanced (to over 700 GeV for 120 GeV $\nu_{R}$’s) in this case.

(v) A last question one might ask is ‘what is the mass of the $Z'$ associated with the $W_R$ in the LRM?’ In general, the masses of these two particles are related, in the absence of mixing, via the expression\[3\]
\[
\frac{M_{W_R}^2}{M_{Z'}^2} = \frac{(1 - x_w)\kappa^2 - x_w}{\rho_R(1 - x_w)\kappa^2}
\]  

where the parameter \(\rho_R\) takes on the value 1(2) if the \(SU(2)_R\) breaking sector consists solely of Higgs doublets(triplets). (The triplet scheme is favored in the see-saw scenario for neutrino masses.) From this we see that unless the \(SU(2)_R\) breaking sector is somewhat unusual, the \(Z'\) will always be more massive than the \(W_R\). While \(W_R\) search limits may be sensitive to \(V_R\), however, those for \(Z'\) are not although they too are subject to uncertainties in \(\kappa\) and the \(Z'\) leptonic branching fraction. For \(\kappa = 1\) and \(Z'\) decays to SM fermions only, the CDF published limit[8] from the 1988-89 run of 412 GeV on a \(Z'\) with SM couplings would translate into a indirect, but \(V_R\)-independent, lower limit on \(M_{W_R}\) of only 302(214) GeV for \(\rho_R = 1(2)\). An incomplete analysis of the CDF electron data from run Ia places the corresponding lower limit of 495 GeV on a \(Z'\) with SM couplings would imply the \(V_R\)-independent lower limit on \(M_{W_R}\) of 371(263) GeV for \(\rho_R = 1(2)\). While these results are instructive the bounds we obtain are relatively weak and could be significantly loosened if \(\rho_R\) were greater than 2 and/or the \(Z'\) leptonic branching fraction was suppressed.

The strongest published bound on the \(W_R\) mass from direct Tevatron searches is that of the CDF Collaboration[8] obtained from their 1988-89 data by combining their electron and \(\mu\) samples: \(M_{W_R} \geq 520\) GeV. Their analysis assumes HMRSB parton distributions[9], \(\kappa = 1\), \(V_L = V_R\), \(B = 1/12\), with \(M_{\nu_R} < 15\) GeV and \(\nu_R\) appearing as \(E\) or \(p_t\). (The D0 Collaboration has recently reported a corresponding preliminary limit of \(M_{W_R} \geq 600\) GeV from the 1992-93 Tevatron run Ia with essentially identical assumptions[10].) With data from Tevatron run Ia currently being analyzed and the 1993-94 run Ib soon to begin in earnest, we would like to address the issue of how these existing limits, as well as the limits obtainable from the new data would be modified if these assumptions are loosened. In what follows, we will still assume that the \(\nu_R\) is sufficiently light so that neither the leptonic branching fraction
nor the $\nu_R$ signature are significantly effected. (Of course, we still can take these $\nu_R$’s to be sufficiently massive in order to avoid $\mu$-decay constraints while maintaining their ‘stability’ as far as collider searches are concerned.) For simplicity we will assume $B$ to be directly obtainable from a calculation including only SM final states once finite top-quark mass and three-loop QCD corrections are applied. (To be definitive, we assume $m_t = 160$ GeV and take $\alpha_s(M_Z) = 0.123$ which we then run up to $M_{W_R}$ using the three-loop renormalization group equations.) We thus will address the sensitivity of the Tevatron searches to variations in $\kappa$ as well as $V_R$. In our analysis, all production cross sections will be calculated assuming the CTEQ1M\cite{11} parton distribution functions as well as a ‘K-factor’ arising from QCD corrections\cite{12}.

Let us first deal with varying $V_R$ assuming $\kappa = 1$; we will return to the more sophisticated case below. In general, the elements of $V_R$ are determined by three angles and a number of phases. In order to demonstrate the sensitivity of the Tevatron $W_R$ search to variations in $V_R$, it is sufficient to assume only a single phase is present. We first generate a single set of these parameters and calculate the absolute squares of the nine elements in $V_R$, $|(V_R)_{ij}|^2$. We next calculate the parton level processes $q_i\bar{q}_j \rightarrow W_R \rightarrow \ell\nu_R$ and weight them by the corresponding parton luminosities evaluated at $Q^2 = M^2_{W_R}$. When these are scaled by the squares of the elements of $V_R$ and summed over $i, j$ a final total cross section is obtained for a fixed $W_R$ mass. $M_{W_R}$ is then increased until the experimental limiting value is reached. For the 1988-89 run, we use the CDF limit curve as presented in their paper\cite{8}. For runs Ia and Ib, we will simply rescale this CDF curve by the corresponding ratios of the integrated luminosities. This approximation does not allow, however, for improvements in the detector acceptance or backgrounds analyses. Since we are more interested in how the $W_R$ search reach changes as $V_R$ is varied we feel this is a reasonable simplification for this kind of analysis.
The above procedure needs to be repeated many times via a Monte Carlo so that an adequate coverage of the $V_R$ parameter space volume is obtained. This can be judged by increasing the number of generated points in this space by an order of magnitude and observing the sensitivity of the resulting limits to this variation. For a fixed value of $\kappa$, we find that $10^6$ points proves to be quite adequate to cover the entire $V_R$ parameter space volume. Once the $W_R$ mass limit for each of the generated points in the $V_R$ parameter space is determined we cluster them in bins of 2 GeV and present the results as a histogram over the $W_R$ mass. In an alternate approach, one can imagine instead using the Monte Carlo to generate the squares of four of the elements of $V_R$ and then using unitarity to obtain the others. This analysis would then assume that the squares of the $V_R$ elements would have flat distributions instead of the corresponding flat distributions for the angles and phases themselves. The results of these two approaches would yield qualitatively similar results.

Fig. 1a shows the results of this procedure for the CDF 1988-89 Tevatron data sample with $\kappa = 1$. Several features of this figure, in addition to the rather long tail to the left of the peak, are important to observe: $(i)$ A reasonably large fraction of the ‘events’ lie close to the upper end of the distribution; in fact, 23.5% lie at or above 500 GeV. This means that for a sizeable fraction of the parameter space volume the actual $W_R$ mass reach is not too much different than what would be obtained if $V_R = V_L$. $(ii)$ 29.8% of the ‘events’ lie below 400 GeV, the nominal HERA search limit. This would imply, based only upon this set of data, that HERA may still have a sizeable chance to be able to observe RHC even if $\nu_R$ is light. $(iii)$ A statistically significant enhancement is observed in the region near $M_{W_R} = 360$ GeV. This arises from a situation where $(V_R)_{us}$ is big and takes advantage of the fact that the $u\bar{s}$ parton luminosity is the second largest. $(iv)$ Although it is unlikely, there is a small chance, 0.61%, that $M_{W_R}$ may lie at or below 300 GeV.

The generic shape of this distribution persists for increased integrated luminosities
(as well as for different values of $\kappa$). Fig. 1b(c) shows the corresponding results for run Ia(Ib); in the Ib case, an integrated luminosity of 75 $pb^{-1}$ has been assumed. From Fig. 1b we see that if no $W_R$ candidates are observed after the data is analyzed, the probability that HERA can observe RHC (for the case of light $\nu_R$!) is still non-zero, but quite small, i.e., only 0.23%. Note that the distribution has elongated as well as flattened and the ‘$u\bar{s}$’ enhancement still persists near 470 GeV although it appears to be somewhat smaller.

Increasing the luminosity further to the run Ib case(Fig. 1c) we see that these general trends continue. At the 75 $pb^{-1}$ level, we see that there are no events below about 460 GeV implying that RHC would not be observable at HERA if the Tevatron data shows no hint of $W_R$ with this integrated luminosity.

What happens when $\kappa \neq 1$? The case where $V_R = V_L$ is rather simple and is shown in Fig. 2 where the mass reach for the three Tevatron runs is plotted as a function of $\kappa$. Note that for $0.55 \leq \kappa \leq 1$, which is the theoretically expected range, the mass reach can vary by as much as 100 GeV. One possible way of dealing with arbitrary $\kappa$ is to present results similar to the above for some representative values, e.g., in Figs. 3a-c, we show what happens for $\kappa = 0.85$. Essentially, to a first approximation, all of the curves in Fig. 1 are simply shifted to the left, i.e., to lower values of $W_R$. As a second approach, taking the theoretical bias into account, we may imagine treating $\kappa$ in the above range as a free parameter and placing it on an equal footing with the various angles and phases in $V_R$ as part of the Monte Carlo. To do this, we increase the number of points in the $V_R$ parameter space by 2 and generate an equal number of $\kappa$ values for which we also assume a flat distribution. The result of this approach is shown in Figs. 4a-c for the three Tevatron runs. Allowing $\kappa$ to vary within the parameter Monte Carlo totally changes the shape of the anticipated $W_R$ mass reach distribution resulting from ‘$\kappa$ smearing’. In addition to the tail which goes down to rather low $M_{W_R}$ values, these figures show two sizeable enhancements. The one at
larger $M_{W_R}$ results from the case where $(V_R)_{ud}$ is large but $\kappa < 1$ reduces the limit from its maximum allowed value. In the case of the 1988-89 run, e.g., the maximum search reach for large $(V_R)_{ud}$ is reduced, on average, about 60-70 GeV which explains the position of the peak. Note that the approximate position of the peak relative to the largest $M_{W_R}$ value stays roughly constant as the integrated luminosity is increased. The somewhat smaller peak at lower $M_{W_R}$ is the result of the large $(V_R)_{us}$ possibility as well as feed-down from the case of large $(V_R)_{ud}$ when $\kappa$ is close to 0.55. We note that as the integrated luminosity increases these two peaks separate and the one at larger $M_{W_R}$ becomes more pronounced, although its height is not increased, while the smaller one is reduced to being nearly a shoulder on the tail of the low mass end of the distribution. This results in an increased skewness of the mass reach distribution. Also, as the luminosity increases the apparent width of these distributions change; we can see this by calculating the average value and standard deviation of the $W_R$ mass reach for these three cases. We find $M_{W_R} = 397.7 \pm 62.2, 540.5 \pm 76.4, 629.8 \pm 82.1$ GeV for the 1988-89, Ia, and Ib runs respectively.

As an application of the above analysis, we briefly consider the model of Gronau and Wakaizumi(GW) in which b-quark decays occur only through the exchange of $W_R$’s[13] and $\nu_R$ is relatively light. Assuming the form of $V_R$ as originally suggested in their model, we can now calculate the Tevatron mass reach as a function of $\kappa$ as shown in Fig. 5. The rather large values obtained here can be easily traced back to the large size of $(V_R)_{ud}$ in this scenario. Similarly, we can determine a upper bound on the $W_R$ mass in their model by demanding agreement with the most recent determination of $V_{cb}$[14], which is also shown in Fig. 5. Combining these two constraints we see that the 1988-89 CDF Tevatron data forces $M_{W_R} > 560$ GeV and $\kappa > 1.35$ while the anticipated results from run Ia will increase these limits to $M_{W_R} > 750$ GeV and $\kappa > 1.85$ assuming no signal events are observed. One may argue that although such large values of $\kappa$ may be a priori allowed, they are perhaps
unnaturally large and are certainly outside of the range anticipated in grand unified models. Clearly, data from Tevatron run Ib would only push both these quantities to even higher values assuming no signal events are observed. We may conclude from these considerations that for this model to remain viable a different form of $V_R$ must be assumed than what was originally suggested.

In summary, we have analyzed the sensitivity of Tevatron searches for $W_R$ to various assumptions about the parameters of the LRM, in particular, the value of $\kappa$ and the form or the right-handed mixing matrix, $V_R$. Hopefully, $W_R$ will be sufficiently light as to been observed in the next round of collider experiments.

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Figure Captions

Figure 1. Histogram of the $W_R$ mass reach at the Tevatron assuming $\kappa = 1$ employing the CTEQ1M parton distributions as well as a ‘K-factor’ from QCD corrections. Results are shown for the 1988-89 Tevatron run(a), as well as for Tevatron runs (b) Ia and (c) Ib. In the run Ib case, an integrated luminosity of $75 \text{ pb}^{-1}$ is assumed.

Figure 2. Mass reach as a function of $\kappa$ for the 1988-89 Tevatron run(dots) as well as for run Ia(dash) and run Ib(dash-dots) assuming that $V_R = V_L$.

Figure 3. Same as Fig. 1 but for $\kappa=0.85$.

Figure 4. Same as Fig. 1 but now $\kappa$ is allowed to vary within the Monte Carlo along with the elements of $V_R$ over the range $0.55 \leq \kappa \leq 1$ in accordance with theoretical expectations.

Figure 5. Mass reach as a function of $\kappa$ for the 1988-89 Tevatron run(dots) as well as for run Ia(dash) assuming that $V_R$ takes the form as given by the Gronau and Wakaizumi model. The solid line is the 95% CL upper bound on the $W_R$ mass in their model.
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