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Model dependence of W_R searches at the Fermilab Tevatron

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We explore the sensitivity of the ongoing Fermilab 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 DESY HERA searches for right-handed currents.

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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) [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 $W_R^{\pm}$. This model, in its more modern, supersymmetric version, can be nicely embedded into an SO(10) grand unified theory (GUT) structure which yields correct predictions for $\sin^2\theta(M_Z)$ and $\alpha_s(M_Z)$, interesting relationships among neutrino masses, and which allows for the possibility that W_R can be lighter than a few TeV [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 Fermilab Tevatron. As we will see, these considerations will have important implications for the RHC searches at DESY HERA as well.

In order to establish limits on the masses 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, as follows.

(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 [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 $\kappa \geq 0.55$. Within the GUT context, however, κ is either very close to unity or lies in the range $0.55 \leq \kappa \leq 1$. The implication of the size of κ for W_R Tevatron collider searches is quite obvious as the production cross section is quadratic in κ. 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, ν_R? Clearly, if neutrinos are Dirac fields, then ν_R is simply a part of the four-component ν spinor and is thus essentially massless. However, if the rather attractive seesaw mechanism [4] is invoked, ν_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 μ decay experiments [5] 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, ν_R's are heavy, this situation changes drastically. For example, if ν_R's are more massive than a few hundred MeV, then they cannot be produced as final states in K, π, or μ decay, thus avoiding the low-energy bounds. If ν_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 ν_R mass, the second lepton and both jets may be quite close in ΔR. 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 high-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 supersymmetric (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 [6] 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 ν_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 ν_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 ν_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]

$$\frac{M_{W_R}^2}{M_{Z'}^2}=\frac{(1-x_w)\kappa^2-x_w}{\rho_R(1-x_w)\kappa^2}\ , \tag{1}$$

where the parameter ρ_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 seesaw 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 κ and the Z' leptonic branching fraction. For $\kappa=1$ and Z' decays to SM fermions only, the Collider Detector Facility (CDF) published limit [9] from the 1988–1989 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 which 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 ρ_R were greater than 2 and/or the Z' leptonic branching fraction were suppressed.

As discussed above, there are many addition constraints on the mass of W_R that one may wish to apply before performing the Monte Carlo study below. For example, Langacker and Sankar [6] have performed a very detailed analysis of the constraints on the LRM that arise from rare low-energy processes in addition to the K_L-K_S mass difference discussed above. As is well known, these constraints can be quite strong but are highly dependent upon assumptions we make about other sectors of the LRM, in particular, the symmetry-breaking sector and its corresponding mass spectrum. The existence of, e.g., light charged Higgs bosons or neutral Higgs bosons with small flavor-changing interactions can lead to a great relaxation in these constraints. Other W_R mass bounds can arise from radiative correction analyses of precision measurements, which make use of, e.g., CERN Large Electron-Positron Collider (LEP), μ lifetime, and W boson mass data [8]. Within a fixed symmetry-breaking scenario, one can turn a limit on the Z' mass and $Z-Z'$ mixing angle into a lower limit on the W_R mass. For example, choosing a minimal scalar sector involving $SU(2)_R$ breaking via triplets and $SU(2)_L$ breaking via a single bidoublet, and assuming that the W_R does not contribute to μ decay, the LEP constraints can be shown to lead to a lower limit of $M_{W_R}\simeq 650$ GeV for $\kappa=1$, as demonstrated by Langacker's analysis in [8]. (Other analyses obtain similar bounds depending on the data set they use.) However, if we give up the assumption of minimality (as we must to generate the observed fermion mass spectrum) and/or allow additional degrees of freedom to contribute significantly to loops (as can occur in many versions of the LRM), this type of bound can be lost entirely. In the analysis we present below, since we are only interested in *direct* searches for the W_R, we will not assume that these additional potential constraints are applicable. However, we must remember that within certain versions of the LRM they can be quite important.

The strongest published bound on the W_R mass from direct Tevatron searches is that of the CDF Collaboration [9] obtained from their 1988-1989 data by combining their electron and μ samples: $M_{W_R}\geq 520$ GeV. Their analysis assumes Harriman-Martin-Roberts-Sterling set B (HMRSB) parton distributions [10], $\kappa=1$, $V_L=V_R$, and $B=\frac{1}{12}$, with $M_{\nu_R}<15$ GeV and ν_R appearing as missing energy ($\not{E}$) or missing transverse momentum ($\not{p}_t$). (The D0 Collaboration has recently reported a corresponding preliminary limit of $M_{W_R}\geq 600$ GeV from the 1992–1993 Tevatron run Ia with essentially identical assumptions [11].) With data from Tevatron run Ia currently being analyzed and the 1993–1994 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 ν_R is sufficiently light so that neither the leptonic branching fraction nor the $\not{p}_t$ signature are significantly affected. (Of course, we still can take these ν_R's to be sufficiently massive in order to avoid μ-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 κ as well as V_R. In our analysis, all production cross sections will be calculated assuming the (CTEQ set 1*M*) (CTEQ1M) [12] parton distribution functions as well as a "*K* factor" arising from QCD corrections [13].

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 $q_i\bar{q}_j \to W_R \to l\nu_R$ 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 1988–1989 run, we use the CDF limit curve as presented in their paper [9]. 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 simulation 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 κ, 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 simulation 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.

Figure 1(a) shows the results of this procedure for the CDF 1988–1989 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" lies close to the upper end of the distribution; in fact, 23.5% lies at or above 500 GeV. This means that for a sizable fraction of the parameter space volume the actual W_R mass reach is not too much different from what would be obtained if $V_R=V_L$.

(ii) 29.8% of the events lies below 400 GeV, the nominal HERA search limit. This would imply, based only upon this set of data, that HERA may still have a sizable chance to be able to observe RHC even if ν_R is light.

(iii) A statistically significant enhancement is observed

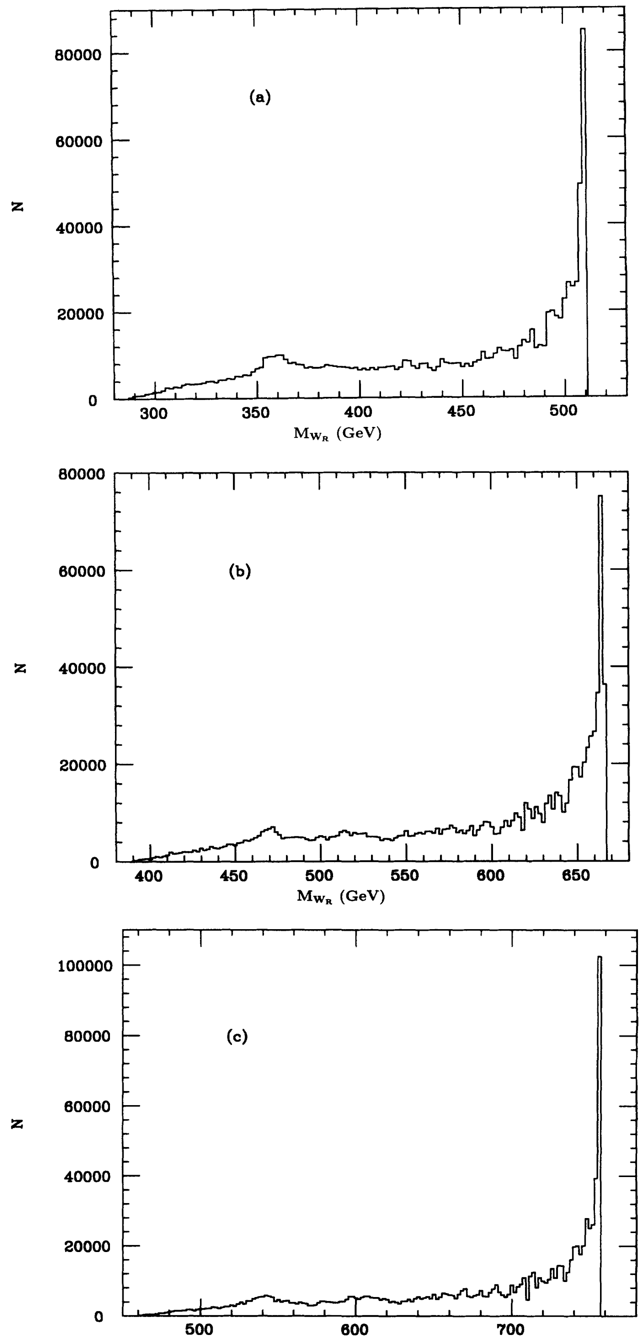

FIG. 1. Histogram of the W_R mass reach at the Tevatron assuming $\kappa=1$ employing the CTEQ1M parton distributions as well as a "*K* factor" from QCD corrections. Results are shown for (a) the 1988–1989 Tevatron run, as well as for Tevatron runs (b) Ia and (c) Ib. In case of run Ib an integrated luminosity of 75 pb^{-1} is assumed.

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 κ). Figure 1(b) [Fig. 1(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. 1(b) 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 ν_R) is still nonzero, 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. 1(c)], 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 show 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 κ. 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 κ is to present results similar to the above for some representative values, e.g., in Figs. 3(a)–3(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 κ 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 simulation. To do this, we increase the number of points in the V_R parameter space by 2 and generate an equal number of κ values for which we also assume a flat distribution. The result of this approach is shown in Figs. 4(a)–4(c) for the three Tevatron runs. Allowing κ to vary within the parameter Monte Carlo simulation totally changes the shape of the anticipated W_R mass reach distribution resulting from "κ smearing." In addition to the tail which goes down to rather low M_{W_R} values, these figures show two sizable enhancements. The one at larger M_{W_R} results from the

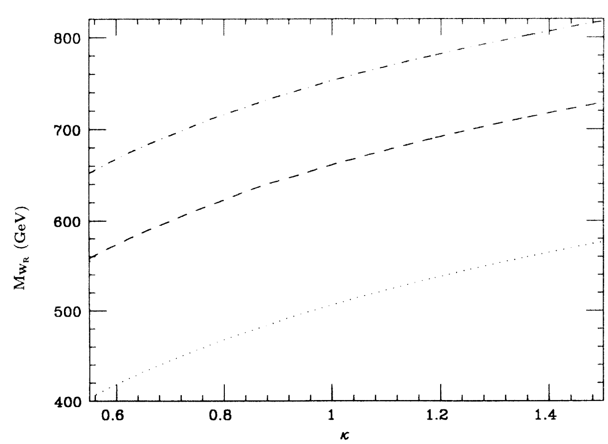

FIG. 2. Mass reach as a function of κ for the 1988–1989 Tevatron run (dotted) as well as for run Ia (dashed) and run Ib (dot-dashed) assuming that $V_R=V_L$.

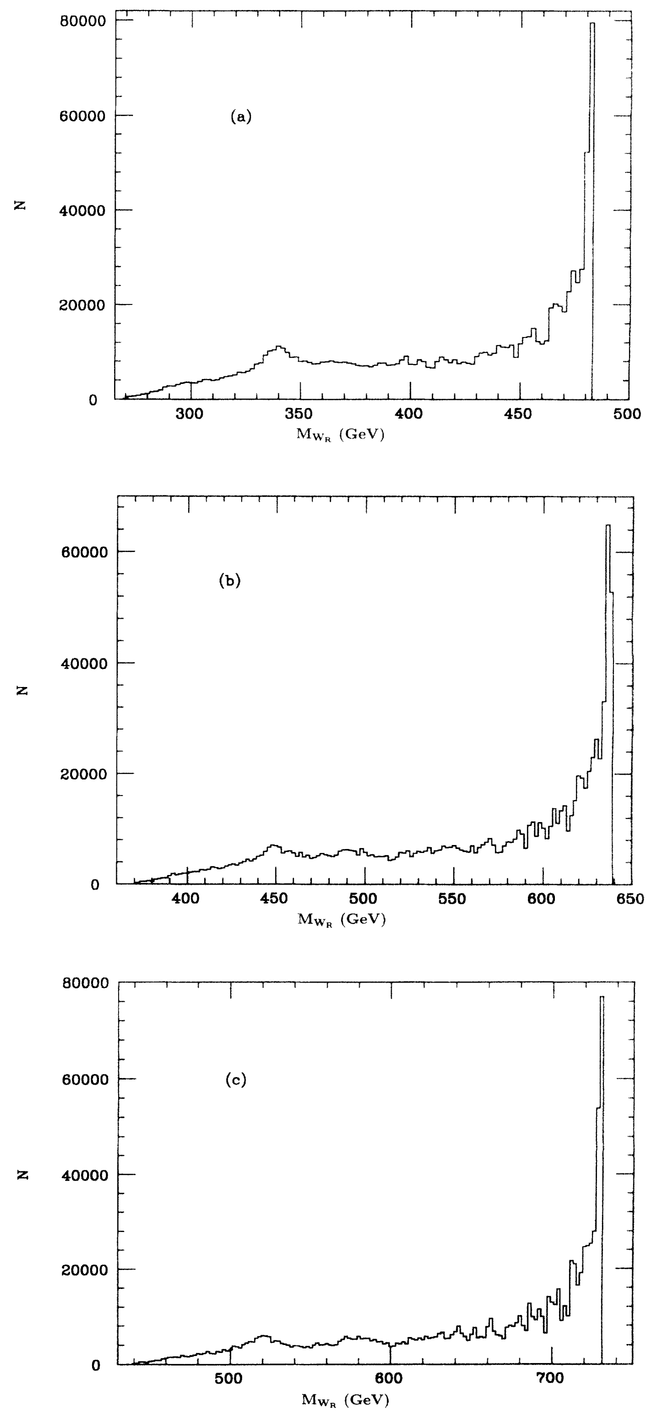

FIG. 3. Same as Fig. 1 but for $\kappa=0.85$.

case where $(V_R)_{ud}$ is large but $\kappa < 1$ reduces the limit from its maximum allowed value. In the case of the 1988–1989 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 κ 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 widths 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 ± 76.4, and 629.8 ± 82.1 GeV for the 1988–1989, Ia, and Ib runs, respectively.

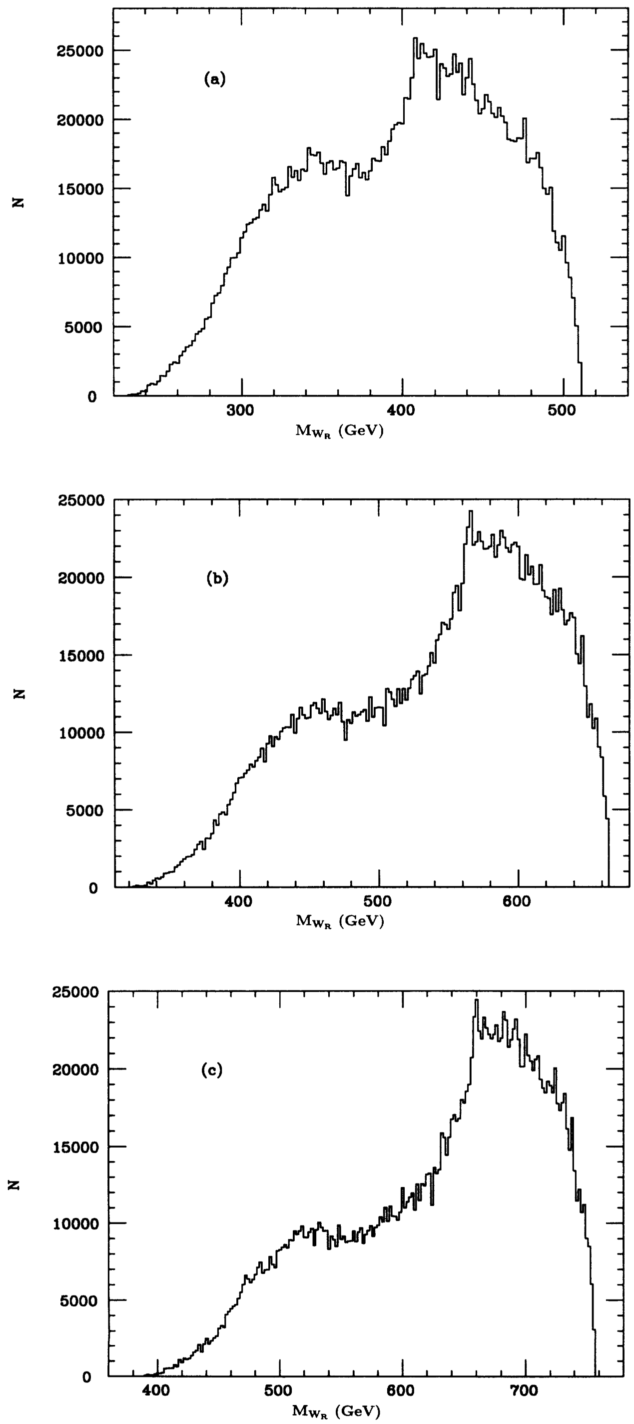

FIG. 4. Same as Fig. 1 but now κ is allowed to vary within the Monte Carlo simulation along with the elements of V_R over the range $0.55 \le \kappa \le 1$ in accordance with theoretical expectations.

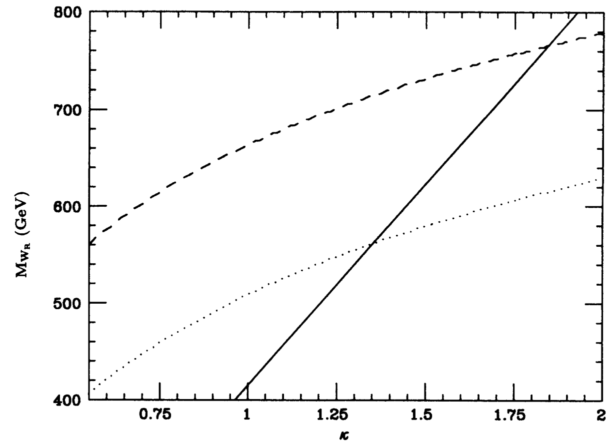

FIG. 5. Mass reach as a function of κ for the 1988–1989 Tevatron run (dotted) as well as for run Ia (dashed) assuming that V_R takes the form as given by the Gronau and Wakaizumi model. The solid line is the 95% C.L. upper bound on the W_R mass in their model.

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 [14] and ν_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 κ 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 an *upper* bound on the W_R mass in their model by demanding agreement with the most recent determination of V_{cb} [15], which is also shown in Fig. 5. Combining these two constraints, we see that the 1988–1989 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 κ may be *a priori* allowed, they are perhaps unnaturally large and are certainly outside 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 from what was originally suggested must be assumed.

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 κ and the form of the right-handed mixing matrix, V_R. Hopefully, W_R will be sufficiently light so as to be observed in the next round of collider experiments.

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[1] For a review and original references, see R. N. Mohapatra, *Unification and Supersymmetry* (Springer, New York, 1986).

[2] See, for example, N. G. Deshpande, E. Keith, and T. G. Rizzo, Phys. Rev. Lett. **70**, 3189 (1993), and references therein.

[3] See, for example, the recent work by J. L. Hewett and T. G. Rizzo, Phys. Rev. D **45**, 161 (1992); **47**, 4981 (1993); T. G. Rizzo, *ibid.* **47**, 956 (1993); **48**, 4236 (1993); **48**, 4470 (1993); M. Cvetic and P. Langacker, *ibid.* **46**, 14 (1992); **46**, 4943 (1992); M. Cvetic, P. Langacker, and B. Kayser, Phys. Rev. Lett. **68**, 2871 (1992).

[4] M. Gell-Mann, P. Ramond, and R. Slansky, in *Supergravity,* Proceedings of the Workshop, Stony Brook, New York, 1979, edited by P. van Nieuwenhuizen and D. Freedman (North-Holland, Amsterdam, 1980); T. Yanagida, in *Proceedings of the Workshop on Unified Theories and Baryon Number in the Universe,* Tsuhuba, Japan, 1979, edited by A. Sawada and A. Sugamoto (KEK Report No. 79-18, Tsuhuba, 1979); R. N. Mohapatra and G. Senjanovic, Phys. Rev. Lett. **44**, 912 (1980).

[5] A. Joddido *et al.*, Phys. Rev. D **34**, 1967 (1986); **37**, 237 (1988); J. Imazato *et al.*, Phys. Rev. Lett. **69**, 877 (1992).

[6] See, for example, P. Langacker and S. U. Sankar, Phys. Rev. D **40**, 1569 (1989); G. Beall, M. Bander, and A. Soni, Phys. Rev. Lett. **48**, 848 (1982).

[7] See, for example, W. Buchmüller *et al.*, in *Physics at HERA,* Proceedings of the Workshop, Hamburg, Germany, 1992, edited by W. Buchmüller and G. Ingleman (DESY, Hamburg, 1992), pp. 1003 and 1991; T. G. Rizzo, Phys. Rev. D **46**, 3751 (1992); F. Cornet, in *High Energy Physics in the 1990's,* Proceedings of the Summer Study, Snowmass, Colorado, 1988, edited by S. Jensen (World Scientific, Singapore, 1989).

[8] There have been several such analyses in the literature. See, for example, J. Polack and M. Zralek, Phys. Lett. B **276**, 492 (1992); Phys. Rev. D **46**, 3871 (1992); W. Buchmüller and C. Greub, Nucl. Phys. **B381**, 109 (1992); P. Langacker, talk given at the Workshop on Physics at Current Accelerators and Supercolliders, Argonne National Laboratory, 1993 (unpublished).

[9] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **67**, 2609 (1991); **68**, 1464 (1992); see also the CDF Collaboration talk given at the 9th Topical Workshop on Proton-Antiproton Collider Physics, Tsukuba, Japan, 1993 (unpublished).

[10] P. N. Harriman, A. D. Martin, R. G. Roberts, and W. J. Sterling, Phys. Rev. D **42**, 798 (1990).

[11] D0 Collaboration talk given at the 9th Topical Workshop on Proton-Antiproton Collider Physics [9].

[12] CTEQ Collaboration, J. Botts *et al.*, Phys. Lett. B **304**, 159 (1993).

[13] R. Hamberg, J. van Neervan, and T. Matsuura, Nucl. Phys. **B359**, 343 (1991).

[14] M. Gronau and S. Wakaizumi, Phys. Rev. Lett. **68**, 1814 (1992).

[15] D. Besson, V. Luth, and W. Venus, talks given at the XVI International Symposium on Lepton-Photon Interactions, Cornell University, 1993 (unpublished).