**New Probes for Extended Gauge Structures at HERA**

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**Abstract**

Doncheski and Hewett have recently shown that the ratio of neutral current to charged current cross sections, \( R = \sigma_{NC}/\sigma_{CC} \), can provide a more sensitive probe for the existence of heavy leptoquarks at HERA than the usual procedure which makes use of neutral current asymmetries. The apparent reason for this is that the Standard Model expectations for both of these cross sections are modified by the existence of such particles in a semi-coherent manner. In this paper we apply this technique to extended electroweak models whose spectrum contains both a \( W' \) and a \( Z' \). We find that measurements of \( R \) can, for some models, substantially increase the HERA search range for new gauge bosons beyond that which can be probed using the more conventional asymmetries.
The start-up of the HERA ep collider opens a new regime in which to explore for physics beyond the Standard Model (SM) \cite{1}. As such, it is important to be able to extend the search range for potential new physics as much as possible given the limitations of luminosity and center of mass energy. For example, previous to the recent work of Doncheski and Hewett (DH) \cite{2}, it had been thought that HERA could search for the leptoquarks arising in $E_6$ models \cite{3} up to masses comparable to the machine’s center of mass energy, $\sqrt{s}=314$ GeV, even for relatively weak leptoquark coupling strengths in comparison to electromagnetism. Such searches could be performed either by direct production or by hunting for deviations from the SM predictions for the values of various neutral current asymmetries \cite{4}. DH have, however, shown that it will possible to look for still heavier leptoquarks (with masses even as large as 800 GeV) provided their coupling strength is not too small relative to electromagnetism. The key to their analysis was to notice that the SM prediction for the ratio of neutral to charged current cross sections for unpolarized beams, $R = \sigma_{NC}/\sigma_{CC}$, is modified in a semi-coherent manner by the existence of leptoquarks and that various systematic errors, such as those due to luminosity and structure function uncertainties, mostly cancel in such a ratio.

The purpose of this paper is to explore whether other sorts of new physics, in particular, models with extended gauge sectors, can be more sensitively probed using the ratio $R$. While the possibility of using HERA to search for a new gauge boson, $W'$ or $Z'$, has been widely discussed in the literature \cite{5}, such analyses have failed to examine the coherent influence of these two particles simultaneously in models where both are present, hence making use of the DH technique. Thus in this paper we will seek to explore whether the ratio $R$ can extend the previously obtained search ranges for new gauge bosons at HERA. We will then compare these new limits with what may be obtainable via direct production searches at the Tevatron. We will find that at least for some extended models, the 95% CL
search limits obtainable indirectly from HERA are more than comparable to those arising from the parallel direct searches at the Tevatron. As we will see, an important ingredient in this analysis is a relationship between the $W'$ and $Z'$ masses.

Since $R$ will clearly be most sensitive to the existence of new gauge bosons when both a $W'$ and a $Z'$ are present, we will restrict our attention to extended gauge models where both kinds of particles are predicted to exist. (We have checked that in models with only a $Z'$ or a $W'$ that the mass limits obtainable from the ratio $R$ are comparable or inferior to the more standard results obtained via the examination of various polarization asymmetries as one would naively expect.) To be specific, we will restrict our attention to the three models which follow: (i) the Left-Right Symmetric Model (LRM)\[6\], wherein the $W'$ couples to right-handed currents and the only free parameters (other than the $Z'$ mass) are the ratio of right-handed to left-handed gauge couplings, $\kappa = g_R/g_L$, and the structure of the $SU(2)_R$-breaking scalar sector as expressed through the $W'$ and $Z'$ mass relationship

$$\frac{M_{W_2}^2}{M_{Z_2}^2} = \frac{(1 - x_w)\kappa^2 - x_w}{\rho_R(1 - x_w)\kappa^2}$$

where $M_{W_2}$ and $M_{Z_2}$ are the $W'$ and $Z'$ masses respectively, $x_w = \sin^2\theta_w$, and $\rho_R$ takes on the value 1(2) if the $SU(2)_R$ breaking sector consists of Higgs doublets(triplets). (In this equation, and in the various gauge model couplings we will assume for numerical purposes that $x_w=0.2325$, which is its effective value at the weak scale[7].) In calculating matrix elements, we will assume that the flavor-mixing matrix for the right-handed currents has essentially the same structure as the conventional Kobayashi-Maskawa matrix for left-handed currents in the sense that it is nearly diagonal. (We remind the cautious reader that this need not be the case.) (ii) the 'Un-unified' Model of Georgi, Jenkins, and Simmons (GJS) \[8\] in which the quarks and leptons couple to different $SU(2)$ gauge sectors. The two new gauge
bosons in this model are purely left-handed and degenerate in mass to a very high level of accuracy. Their couplings depend only upon a single mixing-angle parameter, \(0.22 < s_\phi < 0.99\). (iii) the model of Bagneid, Kuo, and Nakagawa (BKN) \[9\], in which the \(W'\) and \(Z'\) are essentially degenerate, as in the GJS case, but couple differently to the third generation than the first two. This model has no additional free parameters and both the \(W'\) and \(Z'\) are purely left-handed.

Although this is not an exhaustive list of models it is fairly representative of those existing in the literature; for detailed descriptions of these models we refer the interested reader to the original references. Some of these other models, which we will not discuss here, are clearly distinguishable from the SM since they predict that the exchange of a \(W'\) will lead to new particle production at the leptonic and/or hadronic vertex; see for example \[10\].

To calculate the ratio \(R\) we first note that both \(\sigma_{NC}\) and \(\sigma_{CC}\) appearing in the definition of \(R\) are unpolarized cross sections and we will assume an equal incoming flux of both \(e^+\) and \(e^-\) beams, i.e., the cross sections are charge averaged. In order to separate neutral current from charged current events, we employ the same kinematic cuts as DH; to remove the major part of the photon pole and to avoid the region where structure function uncertainties are largest we make the restriction \(0.1 \leq x \leq 1\). Given a fixed value of \(x\) we then further restrict the variable \(y\) to the range

\[
\max(0.1, y_{\text{min}}) \leq y \leq \min(1, y_{\text{max}}),
\]

(2)

where \(y_{\text{max, min}}\) are defined in terms of either a \(p_T\) cut on the outgoing electron in the neutral current case or a missing \(p_T\) cut, due to the outgoing neutrino, in the charged current case:

\[
y_{\text{max, min}} = \frac{1}{2} \left[ 1 \pm \sqrt{1 - \frac{4(p_T^{\text{cut}})^2}{xs}} \right].
\]

(3)
This cut not only helps us to separate the events into the NC and CC categories but also helps to increase the influence of the new heavy particles we have introduced (be they new gauge bosons or leptoquarks) and further reduces the relative contribution of the photon pole. DH make use of the following specific $p_T$ cuts: $p_T(e) > 5$ GeV for neutral currents and $p_T(\nu) > 20$ GeV for charged currents. We employ the Harriman et al., HMRS-B\cite{11} parton distributions as our default in performing our calculations but we have checked that other distributions, such as those of Morfin and Tung \cite{12} do not lead to results different than those quoted below by more than 5%. The equations for the various differential cross sections we need to evaluate have been given completely elsewhere\cite{2, 3, 5} and so will not be given explicitly here. These various cross sections are first calculated within the SM in order to obtain the ratio $R$ and then again within the context of various extended models for different values of the model parameters and as a function of the $Z'$ mass, $M_{Z'}$. (The corresponding $W'$ mass is then given in terms of the model-dependent mass relationships discussed above.) The value of $R$ obtained within the extended model is then compared with SM expectations via a $\chi^2$ analysis. Since most of the systematic errors in $R$ are expected to cancel in the taking the ratio of cross sections, the dominant error in $R$ will be purely statistical and easily calculated for a fixed integrated luminosity, $L$:

$$\frac{\delta R}{R} = \frac{1}{\sqrt{N_{NC}}} \oplus \frac{1}{\sqrt{N_{CC}}},$$

(4)

with $N_{NC}$ and $N_{CC}$ simply given by $N_{NC,CC} = L\sigma_{NC,CC}$. The ‘$\oplus$’ in the above equation implies that the errors are to be added in quadrature. The value of the $Z'$ mass is then raised from some small value until the deviation from the expectations of the SM reach the 95% CL; this particular value of $M_{Z'}$ (and correspondingly $M_{W'}$) is then the search limit which we quote below.
Fig. 1 shows the limits that we obtain by this procedure for the various models discussed above as functions of the HERA integrated luminosity per $e^\pm$ beam. We first note that although the couplings of the GJS model depend on the parameter $s_\phi$, the limits we obtain are independent of this parameter. The reason for this is that all factors of $s_\phi$ cancel in the product of couplings which appear in the matrix element and the $s_\phi$ dependence of the $Z'$ and $W'$ widths, appearing in the corresponding propagators, is relatively unimportant as these particles are exchanged in the t-channel. We also note that the limits we obtain from the ratio $R$ are highly model dependent. In the case of the LRM, we explicitly display the results where the $SU(2)_R$ breaking sector consists only of scalar doublets. The corresponding limits for breaking via isotriplets are smaller and can be obtained approximately by simply scaling the isodoublet results by a factor of 0.85.

How do these results compare to the corresponding limits which can be obtained from asymmetry measurements? A recent analysis from the Snowmass 1990 Summer Study for these same models[5] that assumed 80% beam polarization and an integrated luminosity of 400 pb$^{-1}$ (distributed equally among the $e^\pm_{L,R}$ beams) obtained the following limits on $M_{Z_2}$: 520 GeV for the GJS model, 380 GeV for the LRM with $\kappa=1$, and 350 GeV for the model of BKN. (The limits in the GJS model were also found to be $s_\phi$ independent in this case for the same reasons as above. Of course, no assumption about the interrelation of the $W'$ and $Z'$ masses was necessary to obtain these asymmetry results.) Comparing with Fig. 1, we see that the limits obtainable from $R$ without beam polarization and equivalent total integrated luminosity are substantially larger in both the GJS and BKN cases than what is obtainable using asymmetries but only comparable limits are found in the LRM case assuming $\kappa=1$ and isodoublet breaking of $SU(2)_R$. Thus we see, at least for the models we have examined, that the ratio $R$ does at least as well, and in most cases better, than asymmetries in probing the extended gauge sector provided we can input some relationship between the $W'$ and $Z'$
masses.

The improved limits on new gauge bosons obtainable from $R$ now allow HERA to be competitive with, and in some cases superior to, the Tevatron in probing extended gauge sectors. This is illustrated in Fig.2 which shows the search limits for the GJS model at the Tevatron as a function of $s_{\phi}$ for various integrated luminosities. (In obtaining these limits we have used the electron and muon efficiencies as reported by the CDF collaboration [13] and we reproduce their quoted search limits for the new gauge bosons of other extended electroweak gauge models within the errors associated with structure function uncertainties.) Unlike the situation at HERA, the Tevatron limits are seen to be relatively sensitive to the value of $s_{\phi}$ even though the $s_{\phi}$ dependence cancels in the product of quark and lepton couplings as it does in ep collisions. The reason for this is that the production rate, e.g., for lepton pairs, is also quite sensitive to the $s_{\phi}$ dependence of the $Z'$ width as the $Z'$ is now exchanged in the s-channel and appears as a resonance in the parton level subprocess. (The same is true for the production of a lepton plus neutrino final state in the case of $W'$). For values of $s_{\phi}$ near the extrema of the allowed range, the widths of the $Z'$ and $W'$ become quite large thus suppressing the leptonic production cross section. The actual limits we show in Fig.2 are those which arise from $W'$ production as the cross section times branching ratio is about an order of magnitude larger in this case than the corresponding one for the $Z'$. We then can simply use the fact that $M_{Z_2} = M_{W_2}$ for the GJS model to quote a limit on the $Z'$ and compare with the corresponding results obtained for HERA. A last caveat for the case of the Tevatron is the assumption that the $Z'$ and $W'$ only decay into SM particles when calculating total widths. As discussed above, the limits we obtain at the Tevatron are quite sensitive to the $Z'$ and/or $W'$ widths. If additional decay modes are available for the $Z'$ and/or $W'$ the cross section times branching ratio will be reduced resulting in a weakening of the limits we show in the figures. Thus, for each model, we only show the best that can be done at the Tevatron
for a fixed integrated luminosity. In the case of the GJS model, this leads us to conclude that HERA is a better probe of the extended gauge sector than the Tevatron even if the HERA integrated luminosity per beam is substantially smaller. For example, with only a modest $50 \, pb^{-1}/e^\pm$ beam at HERA, we can obtain a limit on the $Z'$ mass in the GJS model of 640 GeV independently of the value of $s_\phi$. To cover this same range of parameters at the Tevatron would require integrated luminosities in the neighborhood of $100 \, pb^{-1}$ or higher. As integrated luminosities increase at both machines, the HERA limits pull far ahead of those obtainable at the Tevatron. Of course, to truly make a comparison we would need to know the time evolution of the integrated luminosity at both colliders.

The situation is less clear for the other two models. In the BKN case, since there are no additional free parameters, we show in Fig.3 the search limit for a $Z'$ or $W'$ as a function of the Tevatron integrated luminosity for the same set of assumptions as in the GJS model case discussed above. Note that the search limit rises almost linearly with the log of the integrated luminosity. For example, assuming an integrated luminosity of $50 \, pb^{-1}$ per beam at HERA the search limit we obtain from Fig.1 is 430 GeV. To reach the same limit at the Tevatron would only require an integrated luminosity of $7 \, pb^{-1}$, not far from the present value. In general, we find that the Tevatron and HERA do comparably well for this model provided the $Z'$ and $W'$ do not have additional decay modes which would contribute substantially to their total widths. If such modes do exist, then HERA will provide the stronger limit for the BKN model case as well as the GJS case.

The situation for the LRM is a bit more complex since the relationship between the $W'$ and $Z'$ masses is no longer so trivial as in either the GJS or BKN models. Just as in either of these scenarios, however, the Tevatron limit on the $W'$ mass will be substantially stronger than the corresponding one for the $Z'$. Fig.4a shows the explicit limit on $M_{W_2}$ as a function of $\kappa$ for different integrated luminosities at the Tevatron. Assuming either
the isodoublet or isotriplet mechanism for $SU(2)_R$ breaking, these limits on the $W'$ can be converted to ones on the $Z'$ which are shown in Figs.4b and 4c. Fig.4d explicitly shows the relationship between the $Z'$ and $W'$ masses in the LRM for both $SU(2)_R$ breaking scenarios needed to obtain Figs.4b and 4c from Fig.4a. If we search for the $Z'$ in this model directly via the lepton pair signature at the Tevatron, we would instead obtain the result shown in Fig.4e which assumes for simplicity that $\kappa=1$. We see that even in the case where $SU(2)_R$ breaking occurs via triplets, the indirect limits on the $Z'$ using the $W'$ data and the mass relationships is at least as strong as the direct $Z'$ search limit. Comparing with Fig.1 for HERA, we observe that for the LRM case the Tevatron limit on the $Z'$ mass is always as good or better than what is obtainable at HERA using the ratio $R$ for either of the two $SU(2)_R$ symmetry breaking scenarios.

In this paper we have attempted to extend the search limits for new gauge bosons at HERA by using the ratio $R$ introduced by Doncheski and Hewett to search for leptoquarks with masses in excess of the HERA center of mass energy. The main results of this analysis are as follows:

$(i)$ For the GJS model, the HERA limits were substantially improved by using the ratio $R$ in comparison to the usual asymmetry technique and were found to be independent of the parameter $s_\phi$. For this model, HERA was shown to provide a stronger constraint on the $Z'$ mass than the Tevatron.

$(ii)$ In the case of the BKN model, HERA limits were somewhat improved via the $R$ ratio so that the Tevatron and HERA limits were now found to be roughly comparable in their abilities to explore for new gauge bosons. The Tevatron limits would prove inferior to those obtained from HERA if the new gauge bosons were to decay substantially into non-SM final states.

$(iii)$ For the LRM case, the HERA limits were not substantially altered by making
use of $R$. The *indirect* Tevatron limits on the $Z'$ mass which followed from the $W'$ and $Z'$ mass relationship were always superior to those obtainable at HERA. The *direct* $Z'$ search limits at the Tevatron were *also* shown to be superior to what is obtainable at HERA. This situation *might* be substantially modified if non-SM final states resulted in significant changes in the expectations for the $Z'$ and $W'$ total widths.

(iv) Clearly the ratio $R$ provides a useful tool in probing for extended gauge sectors at HERA when both a $W'$ and a $Z'$ are present, doing as well as or better than neutral current polarization asymmetries in all the cases we have examined. Of course, to employ the $R$ ratio technique to search for new gauge bosons the models we examine *must* predict a relationship between the $Z'$ and $W'$ masses.

Perhaps such signatures at HERA will provide the first evidence for new physics beyond the Standard Model.

ACKNOWLEDGEMENTS

The author would like to thank JoAnne Hewett and Mike Doncheski for discussions related to this work and Wesley Smith for his continual encouragement to explore the physics at HERA. This research has been supported in part by the U.S. Department of Energy under contracts W-31-109-ENG-38 and W-7405-ENG-82.
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Figure Captions

Figure 1. 95% CL limits on the $Z'$ mass as a function of the HERA integrated luminosity arising from the ratio $R$. The solid(dashed) curve corresponds to the GJS(BKN) model while the dashdot(dotted) curve is for the LRM with $\kappa=2(1)$ assuming $SU(2)_R$ breaking via isodoublet scalars.

Figure 2. 95% CL search limits for the $Z'$ in the the GJS model as a function of the parameter $s_{\phi}$ at the Tevatron for several different integrated luminosities assuming current electron and muon efficiencies. From top to bottom the first four curves are for 1000, 400, 100, and 25 pb$^{-1}$, while the bottom dotted curve represents the current limits.

Figure 3. Same as Fig.2 but for the $Z'$ of the BKN model as a function of the integrated luminosity.

Figure 4. (a) Same as Fig.2 but for the $W'$ in the LRM as a function of the parameter $\kappa$. The limits obtainable indirectly on the $Z'$ of the LRM using the results of (a) and the $W',Z'$ mass relationship for $SU(2)_R$ breaking via (b)doublets or (c)triplets of Higgs scalars. (d)The ratio of the $Z'$ and $W'$ masses in the LRM as a function of $\kappa$ assuming doublet (solid curve) or triplet(dashdot curve) breaking of $SU(2)_R$ used in obtaining Figs.4b and 4c from Fig.4a. (e)The direct $Z'$ search limit at the Tevatron for the LRM as a function of the integrated luminosity assuming that $\kappa=1$. 

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