Constraints on New Physics From Tevatron Dijet Data

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Abstract

New results from the CDF Collaboration on the invariant mass distribution of dijet events observed at the Tevatron are used to constrain the masses and couplings of new gauge bosons ($W'$ and $Z'$) as well as fundamental diquarks which can occur in some extended electroweak models. In the case of new gauge bosons, these new bounds are then compared to existing limits which arise from searches for the leptonic decay modes of these particles at the Tevatron.

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Although the Standard Model (SM) has enjoyed enormous success in explaining present data\cite{1}, it is generally believed that it cannot be the whole story as it leaves too many unanswered questions. Models which go beyond the standard scenario trying to address some of these issues usually predict the existence of new degrees of freedom, as yet unobserved, in the mass range not far above that of the conventional $W$ and $Z$. Some of these states may eventually be produced at existing or planned colliders.

One of the most common classes of such extended models predicts an enlargement of the SM gauge symmetry and thus new $Z'$ and/or $W'$ gauge bosons. These have been searched for, with so far negative results, both directly at hadron colliders via their leptonic decay modes\cite{2, 3} and indirectly at LEP\cite{4} through the effects of mixing. Since new gauge bosons generally have substantial couplings to both quarks and leptons\cite{5}, searches in the $Z', W' \rightarrow 2 \text{jets}$ channel also need to be carried out as these are complimentary to the more conventional ones involving only final state leptons, eor\(\mu\). Searches of this kind are, of course, more difficult due to the presence of large QCD backgrounds, but these are not impossible to overcome as has been shown by the UA2 Collaboration in the case of ordinary $W$ and $Z$ production\cite{6}.

Recently, the CDF Collaboration has made a precise measurement of the dijet invariant mass spectrum at the Tevatron\cite{7} and performed a comparison with the predictions of QCD at Next-to-Leading-Log (NLL) order for various structure function choices. From this analysis they were able to place limits on the production of ‘narrow’ dijet resonances over a broad mass range. (Here, by ‘narrow’ we mean that the width to mass ratio, $\Gamma/M$, of a resonance is less than 0.1.) To display the power of these measurements, they then showed that axigluons\cite{8}, an octet of strongly coupled massive gauge bosons which are predicted in a chiral version of QCD, were excluded over a large range of hypothetical masses. Of course, other particles which can couple to pairs of quarks and/or gluons which sufficient strength
might now also be excluded by this same set of data.

The purpose of the present work is to examine what additional constraints, if any, this new Tevatron dijet data places on the existence of new gauge bosons, $Z'$ and $W'$, and fundamental diquarks (which can appear, for example, in some $E_6$ models\cite{9}) and how these new limits compare with those already obtained by searches using only leptonic channels\cite{3}. As we will see, the dijet data does yield improved bounds on new gauge bosons for certain classes of extended gauge models particularly those in which the new $W'$ or $Z'$ is either strongly coupled to quarks or possess a large hadronic branching fraction. There are, of course, many extended electroweak models on the market so that the particular set of examples we have chosen below are meant only to be representative and not exhaustive.

Our procedure, for a given model, is to calculate the production cross section times hadronic branching fraction($\sigma B_h$) for the new gauge boson(or diquark) in the narrow width approximation as a function of its mass and then perform a comparison with the limits as quoted by CDF. To be specific, we performed these calculations assuming a top-quark mass of 150 GeV, $\sin^2 \theta_w = 0.2325\cite{1}$, and have employed the MTS1 set of parton distribution functions of Morfin and Tung\cite{10}. In addition, we also included a ‘K-factor’ in the $W'$ and $Z'$ production process as given by the work\cite{11} of Hamberg et al. as well as full three-loop QCD corrections\cite{12} to the $W'$ and $Z'$ decays. To be concrete, we have also assumed that these new particles can decay only into the conventional fermions of the SM and that any CKM-like matrices required by the extended model are essentially diagonal. We have also neglected any possible mixing between the $W'$, $Z'$ and the conventional gauge bosons of the SM as suggested by data from LEP\cite{1}, muon decay, and radiative corrections analyses.

We will considered the new gauge bosons from the following models in our discussion below: $(i)$ The Left-Right Symmetric Model(LRM)\cite{13}, which predicts the existence of both
a $Z'$ and a $W'$. Essentially the only free parameter in this scenario is the ratio of the right- to left-handed gauge couplings, $\kappa = g_R/g_L$. For the $Z'$ analysis we take $\kappa = 1$, while for the $W'$ case we allow $\kappa$ to vary over its `natural' range 0.55 to 1.5. The reason for this lower bound is that $\kappa$ is constrained by the structure of the model to values greater than $\tan \theta_w$ at which point the couplings of the $Z'$ become singular. We remind the reader that the embedding of this model into a larger GUT framework, such as SO(10), automatically leads to the prediction that $\kappa \leq 1$. Of course, phenomenologically, such a constraint need not apply but we may generally expect that $\kappa$ should not be very different than unity. In comparing with searches involving final state leptons, we assume that the leptonic decay of the $W'$ is unhindered by the existence of a large mass for the right-handed neutrino. (ii) The `Alternative' Left-Right Model(ALRM)[14], which also predicts both a $W'$ and a $Z'$ but where the $W'$ cannot be produced singly in hadronic collisions as it carries a non-zero Lepton number as well as negative R-parity. (iii) The superstring-'inspired', Effect Rank-5 Models(ER5M)[9], predict only a $Z'$ whose couplings critically depend on a parameter $-\pi/2 \leq \theta \leq \pi/2$. We will take two representative values for $\theta$ below corresponding to the so-called models $\chi(\theta = -\pi/2)$ and $\psi(\theta = 0)$. As examples of somewhat more `unconventional' extended electroweak theories, we consider (iv) the model of Foot and Hernandez(FH)[15], wherein an additional $Z'$ arises from the breaking of an extended color group, such as $SU(4)_C$ or $SU(5)_C$. The $Z'$ in this scenario is quite strongly coupled to $q \bar{q}$ and simultaneously only weakly coupled to lepton pairs. As a second example of models of this class, we examine the predictions of (v) the `Un-Unified' Model(UUM)[16] of Georgi et al. wherein quarks and leptons couple to the gauge fields belonging to distinct $SU(2)$ groups. The $W'$ and $Z'$ couplings in this model depend on a single parameter, $s_{\phi}$, which essentially lies in the range 0.35-0.95. Unlike the case of other scenarios, the $W'$ and $Z'$ are predicted to be highly degenerate in this model. As a final choice, we consider(vi) a pseudo-model wherein the $W'$ and $Z'$ are just heavier
versions of the conventional SM gauge bosons, which we refer to as the Sequential Standard Model (SSM), and is often used by experimentalists as a test case of extended electroweak models.

The results of our analysis for new gauge bosons searches in the dijet channel are shown in Figs. 1a-b and 2a-c for MTS1 structure functions. (Note that our results are not greatly modified by other structure function choices as long as the corresponding CDF bounds are used simultaneously.) One thing we notice immediately is that the constraints on $W'$s will be stronger than those on $Z'$s. This is to be expected as, within a generic model, the $W'$ couplings are generally somewhat larger than those of the corresponding $Z'$ and both particles have comparable hadronic branching fractions. We see this already in the case of the SM where the ratio of the $W$ to $Z$ production cross sections at the Tevatron (with appropriate leptonic branching fractions!) is of order 10. From Fig. 1a we see that, unfortunately, for most extended models, the CDF dijet data do not further restrict the existence of a $Z'$ beyond what was already obtained from the dilepton channel. The results for the two examples of the ER5M are quite representative as other values of the parameter $\theta$ lead to quantitatively similar results. However, for the FH model, we see that the mass region between 260 and 600 GeV is now essentially excluded. When combined with the previously obtained limits from single jet production\cite{15} we can now conclude that the entire mass range below 600 GeV is excluded for a $Z'$ in this model. For the LRM with $\kappa=1$ and SSM, the dijet data rule out only a small mass region, 480-560 GeV; the corresponding limits from the dilepton channel searches for these models are 376 and 422 GeV, respectively\cite{3, 17}. We note that in the LRM case, if $\kappa$ were relatively close to 0.55, its theoretical lower bound, stronger limits on the $Z'$ mass may be obtainable but the results we show are not significantly altered for, say, $\kappa=0.7$.

The situation improves somewhat for the $Z'$ in the UUM as shown in Fig.1b. For
smaller values of the parameter $s_\phi$, the $W'$ and $Z'$ in this model have reasonably strong couplings to quarks so that it is this region of the parameter space that one would hope to constrain by dijet data. Fig.1b ignores, for the moment, that the $W'$ and $Z'$ in this model are degenerate and displays the cross sections limits for the $Z'$ only. We will see below what happens in the case where $Z'$ and $W'$ results are combined for this model. From the figure we see that no constraints are found for $s_\phi=0.8$ or 0.9 but reasonable bounds are obtained for smaller $s_\phi$ values. With $s_\phi=0.4$, masses as large as 760 GeV are excluded whereas for $s_\phi=0.5$ (0.6,0.7), the mass range 260-630 (370-600, 470-580) GeV is excluded. We will compare these to the bounds obtained from the dilepton data below.

Fig.2a shows the limits obtainable from the CDF dijet data for $W'$s arising from both the SSM and LRM models. For the LRM with $\kappa=1.5$, we see that the mass region below 620 GeV is completely excluded whereas for $\kappa=1$ (0.55) only the mass range 260-600 (490-560) is now eliminated. The limit obtained in the SSM is identical to that of the LRM with $\kappa=1$. The corresponding lower limits on the $W'$ mass from leptonic channel searches are 595 (520, 411) GeV for $\kappa=1.5$ (1, 0.55) and thus we see that the dijet data can be used successfully to extend these previously known bounds. We remind the reader that the bounds presented here assume a right-handed CKM matrix which is at least approximately diagonal and that all limits, from either the dijet or leptonic channels would be substantially degraded if this assumption were invalid. Fig.2b shows that the constraints obtainable on the $W'$ of the UUM are not only generally stronger than what can be obtained in other models but are also stronger than the UUM $Z'$ limits themselves as discussed above. If we *combine* the $W'$ and $Z'$ UUM production cross sections and make use of the prediction that the $W'$ and $Z'$ are expected to be highly degenerate in this model we arrive at Fig.2c. While limits are still not obtained in this case for $s_\phi=0.9$, other choices for this parameter do result in significant bounds. For $s_\phi=0.4$ (0.5, 0.6), masses below 830 (760, 680) GeV are completely excluded.
by the dijet data while the corresponding lower bounds from the leptonic channels are 411 (455, 493) GeV. Thus the dijet data results in a substantial improvement in the search limits for the new gauge bosons of this model for this particular range of the $s_\phi$ parameter. For $s_\phi=0.7 (0.8)$, the mass range 220-615 (450-580) GeV is now excluded with the corresponding lower bounds from the leptonic searches being 522(534) GeV. For $s_\phi=0.9$, the leptonic data yield a limit of 503 GeV.

Thus we see the general result that for many models, particularly those that predict the existence of a $W'$ or or a $Z'$ with rather strong couplings to $q\bar{q}$, the Tevatron dijet data can be used to greatly supplement limits which are obtained solely from searches for leptonic decay modes. Generally, however, models which only predict a $Z'$ and which can be embedded in a ‘conventional’ GUT are not very constrained by this data.

We now turn our attention to the situation of a scalar diquark, $h$, whose parton-level production cross section is given in [18] for the case where we identify $h$ with the spin-0, $Q=-1/3$, color-triplet object in $E_6$ models. There are two possible choices for the Yukawa couplings of such a particle given the structure of the $E_6$ superpotential, $W$; these are usually written as [9]: $\lambda_9 Q^c Q h + \lambda_{10} u^c d^c h$. In either case, generation indices are suppressed and the values of the Yukawa couplings are a priori unknown. Since our diquark is being produced in hadronic interactions where $u$- and $d$-quark distributions dominate, we will assume in our discussion below that the diquark under consideration couples primarily only to the quarks of the first generation. If the dominant Yukawa couplings of the diquark were instead to the quarks of the other generations, the resulting production cross sections would be substantially reduced. The usual procedure in the literature [9] is to scale both the unknown Yukawa couplings, $\lambda_9, \lambda_{10}$, to the strength of the electromagnetic interactions, i.e., $\lambda^2_{9,10}/4\pi = \alpha F_{9,10}$, and treat $F_{9,10}$ as unknowns. If these $F$’s are of order unity or less, we then find that the diquark is a very narrow resonance with $\Gamma_h/m_h$ of order 0.01. Because of isospin algebra,
we find that the width and production cross section of \( h \) are both a factor of 4 times larger when \( F_9=1 \) then when \( F_{10}=1 \) (in the narrow width approximation), so we will specifically focus on this case. Fig.3 shows \( h \)'s production cross section, assuming \( F_9=1 \) and \( F_{10}=0 \), also assuming a constant ‘K-factor’ of 1.33 included to account for anticipated but as yet uncalculated enhancements due to NLL QCD. (Of course, the hadronic branching fraction for this particle is identically unity.) Shown for comparison is the CDF bound from the dijet data under the assumption that \( \Gamma/M=0.01 \) with MTS1 structure functions. As we can see immediately, even for electromagnetic coupling strengths, the data puts hardly any constraint as yet on the existence of \( E_6 \) diquarks. If, however, \( F_9 \) were significantly larger, say, \( F_9=3 \), we see that diquarks as massive as 570 GeV would be ruled out by the CDF dijet data. Limits on scalar diquarks are thus seen to be highly sensitive to our assumptions about the size of these unknown Yukawa couplings and the estimated size of the effective ‘K-factor’ in the production process. We anticipate, however, that a several-fold increase in integrated luminosity at the Tevatron, as is expected from the 1992-3 run, will be able to eliminate the possibility of diquarks, with electromagnetic coupling strength to the first generation of quarks, up to substantially large masses of order 600 GeV or more.

The results of our analysis can be summarized by the following observations:

(i) \( Z'' \)'s are generally less highly constrained by the dijet data than are \( W'' \)'s. In models which predict only a \( Z' \) and that can be embedded in a ‘conventional’ GUT scenario, such as in the ER5M case, essentially no new constraints on particle masses are obtained. Limits on the \( W' \) of both the LRM and SSM are found to be significantly improved over what is obtained by using the dilepton data alone.

(ii) Substantial improvement in the limits on new gauge boson masses are obtained for both the FH and the UUM cases as these scenarios predict that the \( Z' \) and/or \( W' \) is relatively strongly coupled to \( q\bar{q} \), at least over a reasonable range of model parameters.
(iii) For ‘$E_6$-like’ diquarks with electromagnetic strength Yukawa couplings to first generation quarks, no limits are obtained. However, a rather modest increase in the Tevatron integrated luminosity would result in rather significant bounds being obtained. Of course, the assumption of somewhat stronger Yukawa couplings leads to rather stringent constraints from existing data. To fully quantify these bounds, QCD corrections to the diquark production process need to be performed.

Hopefully a positive signature for new gauge bosons will be found in the near future and give us a glimpse of physics beyond the Standard Model.

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Figure Captions

Figure 1. Cross-section times hadronic branching fraction for $Z'$ production at the Tevatron. (a) From top to bottom, the monotonically falling curves correspond to the FH, SSM, LRM, ALRM, $\psi$, and $\chi$ models respectively while the upper(lower) wavy dotted line corresponds to the CDF upper limits assuming $\Gamma/M=0.05(0.01)$. (b) Same as (a), but for the UUM. The top solid curve corresponds to $s_\phi = 0.4$ with each subsequently lower curve reflecting an increase in $s_\phi$ by 0.1.

Figure 2. Same as Fig. 1 but for $W'$ production. (a) Comparison of the predictions for the LRM with the CDF bounds assuming the parameter $\kappa$ takes the values 1.5(dash-dots), 1(solid), or 0.55(dashes). The SSM prediction is identical to that for the LRM with $\kappa = 1$. (b) Same as Fig. 1b but for the $W'$ of the UUM scenario.(c) Same as (b) but assuming that the UUM $W'$ and $Z'$ are degenerate.

Figure 3. Production cross section times hadronic branching fraction for a spin-0, $Q=-1/3$, color triplet diquark of the $E_6$ type with its Yukawa couplings scaled to electromagnetic strength, assuming a K-factor of 1.33, and $F_{10}=0$, $F_9=1$ (solid) or 3 (dashes). The CDF bound for a narrow resonance, $\Gamma/M=0.01$, is also shown.