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SEARCHING FOR THE $Z' \rightarrow WW \rightarrow \ell\nu + jet + jet$ SIGNAL
AT HADRON COLLIDERS*

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ABSTRACT

We examine the feasibility of detecting in hadron-hadron collisions via the decay mode $Z' \rightarrow WW \rightarrow \ell\nu + jet + jet$ a new Z' boson of the type suggested by E_6 superstring models. We find that for a typical set of parameters the Z' signal is near two orders of magnitude smaller than the background for the production of single W bosons plus associated jets. We, therefore, conclude that such a Z' can not be observed in this decay mode at the present or planned hadron colliders.

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Introduction

We present a full Monte Carlo study, including detector simulation, of the production and decay of a new Z' boson in hadron-hadron collisions. In a previous parton level analysis^{1,2} we found that although the background from single W production plus associated jets is at first sight gigantic, there are kinematic regions that enhance the $Z' \rightarrow WW \rightarrow \ell\nu + jet + jet$ signal relative to the background making them comparable³. However, we find that at the hadron level the misidentification of particles within jets and the finite resolution of detectors smears the $W \rightarrow jet + jet$ decay reducing the Z' signal by an additional order of magnitude relative to the background. We conclude, therefore, that a new Z' with the couplings expected from E_6 superstring models can not be detected by its $Z' \rightarrow WW \rightarrow \ell\nu + jet + jet$ decay mode at foreseeable hadron colliders.

The great challenge at hadron colliders is to disentangle any new physics that may be present from the ordinary QCD background. An important final state in hadron-hadron collisions consists of a large transverse momentum lepton and neutrino plus two accompanying jets. It is one of the relevant signals for WW production, and also a signature for Higgs detection. Experimentally the signal consists of a large transverse momentum charged lepton (e or μ), a large amount of missing transverse energy from the neutrino, and a pair of jets resulting from the hadron decay, $W \rightarrow q\bar{q}$, of one of the W bosons. One would hope to be able to perform “jet spectroscopy” on the two jets and reconstruct the W mass and momentum.

Using a parton-shower Monte-Carlo model we generate Z' events in addition to the WW continuum for proton-proton collisions at a center-of-mass energy of 40 TeV and attempt to “observe” the Z' in this sample of events. We then generate single W events and examine whether or not the Z' signal is still visible above this background. Present day string theories allow for the presence of new gauge interactions near the weak scale. In particular, a new neutral gauge boson is a possibility not ruled out by existing experiments.

Even if a new Z' were discovered via the “gold plated” purely leptonic decay mode, $Z' \rightarrow \ell^+ + \ell^-$, a measurement of the $Z'WW$ vertex would give independent information on the pattern of symmetry breaking.

Z' Production at the parton level

In Ref.[1] we performed a parton level analysis of the production of a new Z' boson in proton-proton collisions via the subprocess $q + \bar{q} \rightarrow Z' \rightarrow WW$. We concentrated on the decay mode $WW \rightarrow \ell\nu + q\bar{q}$ and estimated the backgrounds from single W production by examining the exact 2-to-3 parton level expressions^{4,5} for $q + \bar{q} \rightarrow W + q\bar{q}$, $q + g \rightarrow W + gq$, etc. . For definiteness we took $M_{Z'} = 1 \text{ TeV}$, $\Gamma_{Z'} = 25 \text{ GeV}$, and Z' couplings from a minimal superstring inspired model^{2,6,7}. At the parton level we found that with a judicious choice of cuts one could significantly enhance the signal relative to the background. In particular, selecting the transverse momentum of the charged lepton, the neutrino, and the outgoing partons to be greater than 70 GeV and $p_T^W > 430 \text{ GeV}$ resulted in a signal to background of order one near the Z' mass peak at the SSC energy of 40 TeV. Here we use precisely the same model for Z' production with the parameters as given in Ref.[1], including the maximal $Z'WW$ mixing allowed by the present day values of the gauge boson masses in the standard model and perform the analysis at the hadron level.

Event Generation at the Hadron Level

We have used ISAJET⁸ to generate proton-proton collision events at collider energies. The Born term cross section for the WW continuum^{9,10}, $q\bar{q} \rightarrow WW$, *plus* Z' production is inserted into ISAJET which then generates additional partons perturbatively using the “leading pole” approximation to QCD. Final state partons then “fragment” into hadrons according to the Field-Feynman¹¹ prescription and we have used EHLQ¹² structure functions (set 1). (We used DO¹³ structure functions with $Q = 2M_W$ in Ref.[1]. It resulted in an enhancement of the production cross section by a typical factor ~ 1.4 .) In addition, QCD background events are generated using ISAJET and the order α_s single W cross

sections: $q + \bar{q} \rightarrow W + g$, $q + g \rightarrow W + q$, and $\bar{q} + g \rightarrow W + \bar{q}$. In all cases gluon radiation off both initial and final state partons is included. (We have generated W bosons with pseudorapidities in the range $|\eta| < 4$.) We have compared the results from ISAJET with FIELDJET¹⁴ which is another parton-shower Monte Carlo event generator and both models agree in the observables we have examined. (Backgrounds like $q + \bar{q} \rightarrow WZ \rightarrow l\nu + q\bar{q}$ are negligible compared to the QCD background, although the WZ contribution is $\sim 20\%$ of the WW continuum.)

Events are analyzed by dividing the solid angle for pseudorapidity in the range $|\eta| < 4$ into 960 cells, each cell having size $\delta\eta\delta\phi = 0.2 \times 15^\circ$. A single cell has an energy (the sum of the energies of all the particles that hit the cell *excluding* neutrinos) and a direction given by the coordinates of the center of the cell. From this we compute the transverse energy of each cell and sum all cells to form the global transverse energy of the event. Cells with transverse energy less than $E_T^{min} = 1.0$ GeV are then ignored and “clusters” of cells are formed by including in a cluster all cells with a common side. Clusters have an energy given by the sum of the energy of each cell in the cluster and a momentum $\vec{P}_{cluster}$ given by the vector sum of the momenta of each cell in the cluster. The invariant mass of a cluster is simply $M_{cluster} = \sqrt{E_{cluster}^2 - P_{cluster}^2}$. Finally, clusters are ordered by the total transverse energy of all the cells in the cluster with the leading cluster having the highest $E_T^{cluster}$. We trigger on events that have a charged lepton in the range $|\eta| < 4$ with a transverse momentum, p_T^ℓ , greater than 10 GeV. The cross section for the production of a $Z' \rightarrow WW$ in which one W decays into $e\nu$ and $p_T^\ell > 10$ GeV in proton-proton collisions at the SSC energy of 40 TeV is about $2.7 \times 10^{-5} nb$. We also require that the missing transverse momentum, $\cancel{p}_T$, be greater than 10 GeV and that the leading cluster have $E_T^{cluster} > 10$ GeV. (The average missing transverse energy for events containing a Z' is 211 GeV.) We could further enhance the signal relative to the background by increasing the cut on p_T^ℓ , but instead we will accomplish this by examining the clusters. Fig. 1(a) and Fig. 1(b) show the mass, $M_{cluster}$, and transverse energy, $E_T^{cluster}$, distribution of

the leading cluster for proton-proton collisions at the SSC energy of 40 TeV. For events containing a Z' , $\langle M_{cluster} \rangle = 86 \text{ GeV}$ and $\langle E_T^{cluster} \rangle = 472 \text{ GeV}$. Fig. 1(c) gives the distribution of the transverse momentum formed by the charged lepton and the missing transverse momentum, where

$$\vec{p}_T^{\ell p} = \vec{p}_T^\ell + \vec{p}_T. \quad (1)$$

In all Figures of this paper we denote the signal, *i.e.*, the contribution of the WW continuum with (*without*) a new Z' boson by WWZ' (WW). QCD refers to the production of a single W boson plus associated jets (*i.e.*, the QCD background). Whereas Z' indicates pure Z' events and is given for comparison. All plotted cross sections correspond to $pp \rightarrow e\nu + cluster + anything$.

Only the 2-to-2 matrix elements, $q + \bar{q} \rightarrow W + g$, $q + g \rightarrow W + q$, and $\bar{q} + g \rightarrow W + \bar{q}$ have been included exactly with additional partons being radiated in the “leading pole” approximation. Nevertheless, we believe that our estimates of, for example, the $W + jet + jet$ backgrounds are reliable. Had we included only the Born term $q + \bar{q} \rightarrow W$ with additional partons radiated in the “leading pole” approximation then, for example, the observable in Fig. 1(c) would correspond to a situation in which a gluon is radiated at a large angle which is where the “leading pole” approximation breaks down. On the other hand, by including the exact 2-to-2 subprocesses one reproduces correctly the dominant contribution and the “leading pole” approximation can be trusted to appropriately “smear” the events. Still care must be taken in generating the tails of the single W distributions (*i.e.*, the backgrounds) in Fig. 1. To insure good statistics one must be convinced that a sufficient number of events have been generated at, for example, large $p_T^{\ell p}$. We believe that the results we present here are the best estimates to date for the single W backgrounds. Further confidence in our background estimates is gained by comparing the leading cluster mass distribution with the exact parton level $W + jet + jet$ result^{4,5} (the *exact* curve in Fig. 1(a), obtained with the EHLQ¹² structure functions but with $Q = 2M_W$). Here we

compute the jet-jet invariant mass at the parton level with $\delta r < 0.9$, where δr is the two jet separation in the azimuthal angle pseudorapidity plane, $(\delta r)^2 = (\delta\phi)^2 + (\delta\eta)^2$. This corresponds to a maximum jet separation of around 50° , which is roughly the separation between two of our clusters.

Analysis

Ideally one would like to reconstruct the invariant mass of the Z' from its decay products; lepton, neutrino, and jets. The first problem one encounters, however, is the fact that the neutrino is not detected. Its presence must be inferred by examining the missing transverse momentum, $\vec{p}_T$. If we set the neutrino transverse momentum equal to the missing transverse momentum,

$$\vec{p}_T^\nu = \vec{p}_T, \quad (2)$$

and *assume* that the charged lepton and the neutrino are the result of a W decay (and neglect the W width) then the longitudinal momentum of the neutrino is given by one of the two solutions:

$$p_L^\nu = \frac{1}{2(p_T^\ell)^2} \left(A p_L^\ell \pm E_\ell \sqrt{A^2 - 4(p_T^\ell)^2 (p_T^\nu)^2} \right), \quad (3)$$

where E_ℓ , p_L^ℓ , and p_T^ℓ , are the energy, longitudinal momentum, and transverse momentum, respectively, of the charged lepton, and p_T^ν is the transverse momentum of the neutrino. The quantity A is given by

$$A = M_W^2 + 2\vec{p}_T^\ell \cdot \vec{p}_T^\nu = M_W^2 + 2p_T^\ell p_T^\nu \cos(\phi_{\ell\nu}), \quad (4)$$

where $\phi_{\ell\nu}$ is the azimuthal angle between the transverse momentum vectors of the charged lepton and the neutrino. If we pick one of the solutions in (3) then, on the average, half the time we will miss the true momentum of the neutrino. In our analysis we include both choices and thus count each event twice. This two-fold ambiguity, however, turns out not to be the limiting factor in reconstructing the Z' mass which is computed from

$$M_{Z'}^2 = M_W^2 + M_{q\bar{q}}^2 + 2E_W E_{q\bar{q}} - 2\vec{p}_T^W \cdot \vec{p}_T^{q\bar{q}} - 2p_L^W p_L^{q\bar{q}}, \quad (5)$$

where

$$\vec{p}_T^W = \vec{p}_T^\ell + \vec{p}_T^\nu, \quad (6)$$

$$p_L^W = p_L^\ell + p_L^\nu, \quad (7)$$

and

$$E_W = \sqrt{(p_T^W)^2 + (p_L^W)^2 + M_W^2}. \quad (8)$$

The largest uncertainty in computing the Z' mass comes from the assumption in (2) that the missing transverse momentum gives the neutrino transverse momentum *and* from the determination of mass, $M_{q\bar{q}}$, and momentum, $\vec{p}_{q\bar{q}}$, of the quark-antiquark system into which one of the W bosons hadronically decays. The energy of this system is given by

$$E_{q\bar{q}} = \sqrt{(p_T^{q\bar{q}})^2 + (p_L^{q\bar{q}})^2 + M_{q\bar{q}}^2}. \quad (9)$$

At the hadron level this system manifests itself as jets and it is difficult to find the correct jets among the associated hadronic debris in the event. If we identify jets as clusters, then there are, on the average, many jets per event (the mean number of clusters in a sample of pure Z' events at the SSC is 27!). If we simply take the highest two E_T clusters then quite often we miss the true W decay products or we include additional hadrons not associated with the decay. This misidentification results in a further smearing out of the true Z' width. With our definition of clusters the best choice is to simply take $M_{q\bar{q}} = M_{cluster}$ and $\vec{p}_{q\bar{q}} = \vec{p}_T^{cluster}$ and to reconstruct the Z' mass from the charged lepton momentum, the missing transverse momentum, and the leading cluster. For a sample of pure Z' events this results in an observed Z' mass of ~ 1025 GeV with a full width of ~ 200 GeV.

The average transverse momentum of the W bosons that result from $Z' \rightarrow WW$ decay is about 465 GeV resulting in an average opening angle between the $q\bar{q}$ pair resulting from the hadronic decay $W \rightarrow q\bar{q}$ of about 30° ¹⁰. The clusters we have defined are rather “fat” and quite often the leading cluster contains most of the decay products of the $q\bar{q}$ system. One sees a clear peak in the leading cluster mass at the mass of the W boson for the

sample of WWZ' events in Fig. 1(a) and a smooth background from the single W events. In addition, there is a slight bump in the distribution of transverse energy of the leading cluster in Fig. 1(b) at about 500 GeV which is $1/2$ the energy of the produced Z' .

The assumption in (2) and the uncertainty associated with the choice of which hadrons to include when one reconstructs the mass of the Z' results in an “observed” Z' width of about 200 GeV compared with the actual generated width of 25 GeV. Such a large induced width prohibits one from seeing a bump in the reconstructed Z' mass distribution shown in Fig.1(d) (except for pure Z' events, of course). Furthermore, the background from single W production is more than two orders of magnitude larger than the WWZ' signal.

We have tried several other ways of determining $M_{q\bar{q}}$ and $\vec{p}_{q\bar{q}}$ including taking the leading *two* clusters, the leading *three* clusters, and the leading cluster *plus* the cluster closest to it in opening angle. The peak of the Z' mass distribution changes somewhat with the choice, but in all cases the width remains roughly the same. Here one is really limited by not knowing precisely which hadrons to include in reconstructing the Z' mass.

When a large transverse momentum single W is produced and decays leptonically it is unlikely that any of the associated clusters has the mass of a W boson. On the other hand, when a pair of large transverse momentum W bosons is produced in decay of a Z' and one of them decays leptonically it is quite likely that the other one will produce a leading cluster with a mass near M_W . As it is clear from Fig.1(a) one can enhance the signal to background ratio by restricting the leading cluster to have a mass near M_W . Fig. 2 shows three of the distributions of Fig. 1 plotted for a sample of events with the leading cluster mass in the range $60 < M_{cluster} < 100$ GeV. This cut retains most of the WW and WWZ' events containing a leading cluster with large transverse energy as can be seen by comparing the distributions in Fig. 1(b) with those in Fig.2(a) around 500 GeV. In contrast, the reconstructed Z' mass distribution in Fig.2(c) starts to show for the WWZ' events a signal around 1 TeV for the first time.

When two W bosons are produced in the decay of a heavy Z' the transverse momentum of one of the W bosons tends to balance the transverse momentum of the other. This leads to a correlation in transverse energy of the leading cluster and $p_T^{\ell\cancel{p}}$. A large $p_T^{\ell\cancel{p}}$ arises from a large transverse momentum W which in turn implies that the recoil W also has large transverse momentum which it can then supply to the leading cluster. If we further restrict ourselves to events with $p_T^{\ell\cancel{p}} > 400$ GeV, as in Fig.3, then few of the WWZ' events that have a large leading cluster E_T are removed. The leading cluster transverse energy distributions for the WW and WWZ' events are almost identical in Fig. 2(a) and Fig.3(a) around $E_T^{cluster} = 500$ GeV. On the other hand, the reconstructed Z' mass distribution in Fig.3(b) now shows a clear peak near 1 TeV. Unfortunately, the WWZ' signal is still well (a factor ~ 30) below the background from single W production.

Fig. 3(b) represents the best signal to background ratio we could accomplish at the hadron level without drastically reducing the signal. The cuts we have used are not exactly the same as those we applied in our parton level analysis, but they have the same effect of isolating two high transverse momentum W bosons. The hadron level results in Fig.3(b) can be compared to the parton level estimates in Fig.2(a) of Ref.[1]. The hadron and parton level figures are similar except that the WWZ' signal to background ratio near the Z' peak is worse by a factor of ≈ 15 at the hadron level.

Summary and Conclusions

Our analysis illustrates the difficulty of reconstructing a $W \rightarrow q\bar{q}$ decay in proton-proton collisions using “jet spectroscopy”. One always has an uncertainty as to which hadrons to include and which to exclude. For large transverse momentum W bosons the situation is a bit easier and we are able to preferentially select W bosons by requiring the leading cluster to have large E_T and to have a mass near M_W . A large transverse momentum W quite often decays into two nearby jets with at least one of them also having large transverse momentum¹⁰. Selecting events with $60 < M_{cluster} < 100$ GeV and

$p_T^{\ell p} > 400 \text{ GeV}$ (or equivalently $E_T^{cluster} > 400 \text{ GeV}$) gives our best signal to background ratio. These cuts are not exactly the same, but they have the same effect as those used in our parton level analysis¹. As expected the hadron level analysis yields about an order of magnitude smaller signal to background ratio than the parton level analysis^{1,3,4,5}.

Our method of reconstruction the Z' mass from the lepton, missing transverse momentum and the leading cluster is different from previously used methods^{15,16}. An alternative procedure is to trigger on a large transverse momentum lepton and then include the leading jet opposite to the lepton and combine it with a second jet. The second jet is chosen by examining all jet pairs and selecting the pair that is closest to the mass of the W boson. Actually our method leads to similar results because quite often our leading cluster is opposite the charged lepton. On the other hand, we prefer our method for two reasons. It is simpler and the backgrounds from single W production are smooth distributions. Care must be taken not to choose a selection criterion that so biased in favor of a WW topology that it produces a peak in the single W background.

Our results indicate that a new Z' of the E_6 superstring inspired type^{2,3,6,7,17} that we have considered can not be seen via its decay mode, $Z' \rightarrow WW \rightarrow \ell\nu + jets$, at present or planned colliders. Although we have presented our results for a particular choice of parameters, this choice was already optimistic and near the present experimental limits². The cross section for Z' production at the SSC would have to be at least ~ 50 times larger if it were to be seen in this decay mode (*i.e.*, the Z' cross section in this channel and for the region analysed would have to be greater than $\sim 1\text{pb}$ at the SSC), which is unlikely but not impossible^{18,19}.

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Figure Captions

Fig.1 (Distributions for all generated events)

- a) Leading cluster mass
- b) Leading cluster transverse energy
- c) Lepton+"missing momentum" transverse momentum
- d) Reconstructed Z' mass

Fig.2 (Distributions for all events with $60 < M_{\text{leading cluster}} < 100$ GeV)

- a) Leading cluster transverse energy
- b) Lepton+"missing momentum" transverse momentum
- c) Reconstructed Z' mass

Fig.3 (Distributions for all events with $60 < M_{\text{leading cluster}} < 100$ GeV and
transverse momentum of the lepton+"missing momentum" system > 400 GeV)

- a) Leading cluster transverse energy
- b) Reconstructed Z' mass

Fig. 1

Fig. 2

Fig. 3