Extraction of Coupling Information From $Z' \rightarrow jj$

THOMAS G. RIZZO
High Energy Physics Division
Argonne National Laboratory
Argonne, IL 60439

Abstract

An analysis by the ATLAS Collaboration has recently shown, contrary to popular belief, that a combination of strategic cuts, excellent mass resolution, and detailed knowledge of the QCD backgrounds from direct measurements can be used to extract a signal in the $Z' \rightarrow jj$ channel in excess of $6\sigma$ for certain classes of extended electroweak models. We explore the possibility that the data extracted from $Z$ dijet peak will have sufficient statistical power as to supply information on the couplings of the $Z'$ provided it is used in conjunction with complimentary results from the $Z' \rightarrow \ell^+\ell^-$ ‘discovery’ channel. We show, for a 1 TeV $Z'$ produced at the SSC, that this technique can provide a powerful new tool with which to identify the origin of $Z'$s.

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The observation of a new neutral gauge boson, $Z'$, at the SSC and/or LHC would be an extremely clear signature for the existence of new physics beyond the Standard Model (SM). Many analyses have shown [1] that such particles are copiously produced at these hadron supercolliders and would be easily detected via their leptonic decay up to masses of order several TeV for most extended electroweak model (EEM) scenarios. Of course once the $Z'$ is detected it would be mandatory to determine its various couplings in order to determine, if possible, from which EEM it arose. Quite generally, this has proven to be a more difficult task than one might at first suspect and has lead to a number of possible approaches advocated in the literature during the last three years [2]. These various techniques have included the use of rare decay modes, initially polarized proton beams to produce new asymmetries, associated production of the $Z'$ together with other gauge particles, and determining the polarization of final state $\tau'$s. All of these analyses have neglected the possibility that hadronic $Z'$ decays could be used to obtain coupling information since it is commonly believed [3] that the conventional backgrounds ($B$) from QCD are so large as to render this mode unobservable.

Recently, Henriques and Poggioli (HP) of the ATLAS Collaboration [4] have shown that a combination of strategic cuts, good dijet mass resolution, and detailed determination of the QCD background in the dijet invariant mass neighborhood near the $Z'$ can be used to extract a signal ($S$) in excess of 6$\sigma$ at the LHC for a $Z'$ with a mass of 2 TeV with SM-like couplings. If a determination of the $Z' \to jj$ production cross section, $\sigma_{jj}$, can be combined with the corresponding lepton-pair cross section, $\sigma_\ell$, (which is the $Z'$ discovery channel), new information on the $Z'$'s couplings would be obtained. The purpose of this paper is to analyze this approach for a 1 TeV $Z'$ at the SSC, within the context of several EEM. (We choose this mass value in order to make a comparison with the analyses in [2].) For this rather low $Z'$ mass, we find there is sufficient statistics available to extract coupling information for at least some of these EEM’s assuming an integrated luminosity of $\mathcal{L} = 10 fb^{-1}$, corresponding
to one ‘standard SSC’ year. Other models, however, lead to too small a value for $S/\sqrt{B}$ and would require significantly larger values of $\mathcal{L}$ before useful information could be extracted.

As a first step in this analysis, it is important to remember that the dominant phase space regions occupied by the QCD and $Z'$ induced dijets are quite different. Because of the presence of $u$- and $t$-channel poles in the $2 \rightarrow 2$ and $2 \rightarrow 3$ parton level QCD processes, most of these dijet are at small $p_t$ and prefer large values of absolute pseudorapidity, $\eta$. Due to the approximate $1 + \cos^2 \theta^*$ distribution of the $Z'$ dijets, strong cuts on both the jet $p_t$ and $\eta$ will substantially increase $S/\sqrt{B}$. Of course, if our cuts are too strong we loose on statistics.

As a compromise, for a 1 TeV $Z'$, we employ the cuts $p_t \geq 200$ GeV and $-1 \leq \eta_{j_1,j_2} \leq 1$ which are similar to those used by ATLAS. These cuts provide us with jets which are highly isolated and highly central. In order to generate the QCD background numerically and incorporate, at least approximately, the order $\alpha_s^3$ corrections, we employ Next-to-Leading Order (NLO) parton distributions with a renormalization scale set to minimize these higher order effects when only the Born-level calculation is performed: $\mu = M_{jj}/4 \cosh(0.7 \eta_*)$, with $\eta_*$ being the rapidity of either jet in the parton center of mass frame. This choice of $\mu$ was explicitly found to minimize the deviation from the Born calculation due to $\alpha_s^3$ corrections at Tevatron energies by the authors of Ref. and also seems to work just as well as SSC/LHC energies. Lastly, we rescale these cross sections by a phenomenological ‘K-factor’ of 1.1. The result of this procedure reproduces the order $\alpha_s^3$ results with our kinematic cuts at the level of 10%, about the same as the uncertainty in the parton luminosities (see below). (Of course, when the actual procedure we envision is performed, this QCD background will be measured so that we would no longer need rely on the perturbative calculations presented here but we can make use of the data directly. Since no data exists to show how our analysis works, these best we can do is to use ‘simulated’ data to mimic what we expect to see at the SSC.) For a 1 TeV $Z'$, we generate events in the dijet invariant mass range $0.5 \leq M_{jj} \leq 1.5$
TeV subject to the cuts above. Since dijets involving top(t) quarks may appear somewhat different that those initiated by the lighter quarks and/or gluons in the final state (since the top probably decays before fragmentation is complete), we ignore subprocesses that lead to final state top quarks in this analysis. We note here that the effect of our cuts is to increase $S/B$ to the level of order 0.1-1%.

The dijet signal that arises from the $Z'$ production and decay within a given model is calculated in the usual manner but also includes a two-loop, QCD-corrected ‘K-factor’ in the production process\cite{8} as well as QCD corrections to the $Z'$ decays to $q\bar{q}$ \cite{9}. These signal events are subjected to the same cuts as are the QCD background and, of course, only $Z'$ decays to pairs of lighter quarks are considered. For numerical purposes, we assume a t-quark mass of 150 GeV, an effective $\sin^2 \theta_w$ of 0.2325 \cite{10} in EEM couplings, and take $\alpha_s(M_Z) = 0.117$ \cite{10} which we allow to run via the 3-loop renormalization group equations.

To account for the imperfect nature of all supercollider detectors, both the pure $Z'$ signal as well as the QCD background must be smeared by the dijet mass resolution. Since the width-to-mass ratio for most $Z'$'s is generally in the range $0.01 \leq \Gamma_{Z'}/M_{Z'} \leq 0.05$, we anticipate that the dominant effect of the finite mass resolution will be to smear out the $Z'$ peak and reduce its statistical significance. For most SSC/LHC detectors, the anticipated jet energy resolution is expected to be of order\cite{11} $50%/\sqrt{E} \oplus 2\%$ which leads to an effective dijet mass resolution of approximately $\Delta M_{jj}/M_{jj} = 0.034$, as in the ATLAS analysis, which can be seen to be comparable to the $Z'$ width-to-mass ratio. We will use this value in our analysis below. HP have shown in detail how modifying the mass resolution influences the ratio of $S/B$ and we anticipate that our results would not be drastically altered if small deviations from our assumed value were to occur.

Once both the QCD and $Z'$ differential cross sections are calculated and combined using the above description, we integrate it over the allowed ranges of $\eta$ as well as $\cos \theta^*$.
subject to the requirement that the jets have $p_t \geq 200$ GeV. This result is further integrated over dijet invariant mass bins of width 25 GeV, which is comparable to the resolution for dijets with pair masses near $M_{Z'}$, and multiply by the integrated luminosity; Gaussian statistical fluctuations are included for each mass bin. At this point, all we have succeeded in doing is generating a ‘set of data’ to which rather strict cuts have been applied. As one might expect, a plot of this ‘data’ would show no apparent structure in the neighborhood of 1 TeV as we will see below.

We now deviate a bit from the HP analysis and make use of the fact that the mass and width of the $Z'$ will already be determined with reasonably high precision from the dilepton data before we go hunting in dijets, i.e., we assume that the $Z'$ has already been discovered. The reason that this is important for our dijet analysis is that the leptonic data tell us where to look in dijet invariant mass and the approximate size of the ‘signal region’. Since we want this region to be at least $\pm 2\Gamma_{Z'}$ wide (roughly speaking) and we are assuming a $M_{Z'}$ of 1 TeV, we will define the signal region to be within 100 GeV of 1 TeV for all EEM’s. We now look at our ‘data’ outside of this signal region; we find it convenient at this point to introduce the dimensionless variable $x_{jj} = M_{jj}/M_{Z'}$. One finds that by rescaling our ‘data’ by $x_{jj}^5$, the resulting distribution becomes reasonably flat in $x_{jj}$ except for the range $0.5 \leq x_{jj} < 0.7$ where the effects of the strong $p_t$ and $\eta$ cuts become noticeable. Because we need to determine the background as precisely as possible outside the signal region, we do not include this $x_{jj}$ range in our fit. Next, we take our rescaled ‘data’ and fit to a polynomial outside the signal region; our best $\chi^2/d.o.f.$ (which is EEM dependent but quite close to unity in all cases) results for a fit to a polynomial of degree 7 whose coefficients (and associated errors) are obtained by least-squares using the singular value decomposition technique in the usual way. The use of a polynomial of a larger degree does not result in an improvement in our $\chi^2/d.o.f.$ Next, we extrapolate into the signal region using this polynomial fit and
subtract our QCD background which, hopefully, will result in a dijet $Z'$ ‘peak’ provided the $Z'$'s couplings are sufficiently strong and enough statistics are available.

At this point we've rendered the $Z'$ bump in dijets ‘visible’ and we fit the peak to a Gaussian and/or a relativistic Breit-Wigner. In either case, we let the amplitude, width, and position of the maximum float and obtain a best fit from a second $\chi^2$ analysis. We then can either integrate under the fitted peak, use the narrow-width approximation, or simply count the excess of events in the signal region to obtain the total number of $Z' \rightarrow jj$ events.

Even if the $Z'$ can be observed in the dijet channel, we cannot use our determination of the integrated cross section directly to obtain coupling information for a number of reasons. (i) As an absolute number of events, our result suffers from a number of systematic uncertainties, e.g., variations in the structure functions and machine integrated luminosity. (ii) Our observable depends explicitly on the width of the $Z'$, i.e., it depends on what final states are allowed in $Z'$ decay. To alleviate such problems we propose to take the ratio of the number of fitted $Z'$-induced dijet events to the number of $Z'$-induced dileptons. This quantity, $R$, essentially measures the ratio $\sigma_{jj}/\sigma_{\ell\ell}$, subject to the various cuts, is independent of luminosity uncertainties, and as we will see is extremely weak in its dependence on the choice of structure functions. To be specific, we define the lepton-pair cross section, $\sigma_{\ell\ell}$, to include a cut of $-2.5 \leq \eta_{\ell} \leq 2.5$ on both outgoing leptons. Except for the various cuts then, $R$ tells us the ratio of the dijet to leptonic widths of the $Z'$ in the narrow width approximation.

We should, of course, convince the reader that $R$ is worth determining, i.e., that it is sensitive to the $Z'$ couplings. To this end we must examine a number of specific EEM’s; we consider four representative examples in what follows. (i) The Left Right Symmetric Model(LRM) [12] with the ratio of right-handed to left-handed couplings, $\kappa = g_R/g_L$, set to unity; (ii) The Alternative version of the LRM, which we denote by ALRM [13]; (iii) The
$E_0$ rank-5 models (ER5M) \cite{14}, which contains a free parameter, $-\pi/2 \leq \theta \leq \pi/2$, which determines all of the $Z'$ couplings to fermions; and (iv) a $Z'$ with the same couplings as the $Z$ of the SM, which we call SSM. This list is far from exhausting the set of models on the market at present. Fig. 1a shows the ratio $R$ as a function of $\theta$ in the ER5M case for two different structure function choices. We see that $R$ is quite sensitive to $\theta$ but that possible deviations due to structure functions cancel almost entirely in taking the ratio; this has been confirmed numerically by examining the results obtained through the use of several other structure function sets. Fig. 1b shows the corresponding dependence of the ratio $R$ on the parameter $\kappa$ in the LRM; we again see that $R$ is quite sensitive to variations in the fermionic couplings and very insensitive to the choice of parton densities. (We again remind the reader that this ratio involves cross sections to which the above cuts have been applied and where top-quark final states are ignored.) For the LRM with $\kappa = 1$ (ALRM, SSM) we obtain $R = 30.5(3.92, 18.9)$ for the MTS1 set of parton densities of Morfin and Tung \cite{6} which we now take as our default. Clearly, the values of $R$ range over more than an order of magnitude for the various models we’ve considered thus demonstrating its sensitivity to the possible $Z'$ couplings. We have found that the range of allowed values for $R$ in other models could be much greater. If $R$ can be reliably determined by using the dijet data we will have a new piece of the $Z'$ coupling puzzle. It remains to be seen whether we can in fact perform this feat.

Let us use the LRM as a test case. Fig. 2a shows the number of dijet events, $N_{jj}$, in each 25 GeV mass bin as a function of $x_{jj}$ for our range of interest; the errors are contained within the crosses and no apparent evidence for a $Z'$ is yet visible. We note, as discussed above, that for $x_{jj} \geq 0.7$ the distribution has a positive second derivative but that this begins to change below $x_{jj} \simeq 0.7$ due to our cuts. Rescaling $N_{jj}$ by $x_{jj}^5$ (and an overall trivial constant) leads to Fig. 2b where we see that this rescaled distribution, $N_{jj}^0$, differs
significantly from unity only for small $x_{jj}$ and is only weakly $x_{jj}$ dependent otherwise as advertised. (We note that modifying the power of $x_{jj}$ in the rescaling procedure by a small amount in an attempt to further flatten this distribution will not effect the results of our fit since the ‘gross’ $x_{jj}$-dependence has already been accounted for.) We see that this rescaling has finally allowed the statistical fluctuations in the data to become visible for the first time although the $Z'$ still remains hidden. Now the values of $N^0_{jj}$, together with the associated errors, are fit outside the signal region by our degree 7 polynomial, extrapolated into the range $0.9 \leq x_{jj} \leq 1.1$ and subtracted. The result is shown in Fig. 3a which displays the number of excess dijet events, $N_{jj}^{\text{exc}}$, as a function of $x_{jj}$ as well as the best fit of this excess to a Gaussian(G) and a relativistic Breit-Wigner (BW), as described above. Our result is quite similar to that obtained in the ATLAS analysis even though the effects of particle fragmentation and detailed detector properties have not been included in the present analysis. For the BW(G) case, the fitted peak is located at 995(994) GeV with a width of 65(34) GeV; the actual width of this $Z'$ used as input into our analysis is 20.6 GeV. Thus we see that the effect of the finite mass resolution and fitting procedure is to broaden the peak (as well as flatten it). If we follow this identical procedure for the SSM case, we arrive at Fig. 3b. Here, for the BW(G) fit we obtain a peak position of 999 (1001) GeV with a width of 57(31) GeV, the actual input value being 30.2 GeV. Since the underlying parton-level process is of the BW type, we might be somewhat biased in favor of this particular choice. We find, however, that the Gaussian fit has a slightly better $\chi^2$.

Knowing the number of $Z'$-induced lepton pair events from our previous analysis\cite{15}, we can sum the appropriate excess event distributions and arrive at the extracted values for the ratio $R$ for both the LRM and SSM cases. By just counting the excess events, we obtain $R_{LRM} = 40.7 \pm 4.6$ and $R_{SSM} = 22.5 \pm 2.4$, both of which are quite close to the theoretical expectations above. (Note the tendency of these values to lie on the high side of the actual
expected values.) In the LRM case, if we force a fit to the model parameter space, this result allows us to place a constraint on the value of the parameter $\kappa$ by comparison theoretical expectations for this model shown in Fig. 1b. At the $3\sigma$ level, we learn that $0.83 \leq \kappa \leq 1.11$. If, instead, we integrate the number of events under the fitted peak, we find a somewhat smaller pair of results: $R_{LRM} = 34.9 \pm 4.0$ and $R_{SSM} = 20.4 \pm 2.2$ for the Gaussian fit. For the LRM, this results in a corresponding bound with essentially the same range as above but now at the 95% CL.

Before continuing, we would again like to stress the important role played by the leptonic data in this analysis. (i) The leptonic data has told us where to look in dijet invariant mass for the $Z'$ and has given us its approximate width (after de-convoluting the dilepton pair mass resolution). (ii) The leptonic data allows us to normalize our dijet results which removes luminosity and structure function uncertainties and provides us with a new observable, which is independent of other potentially exotic modes that the $Z'$ might possess, and is highly sensitive to the $Z'$’s couplings.

What happens if we perform the analysis above for the other models? Fig. 4 shows the predicted number of $Z'$-induced dijet events in the mass bin containing the $Z'$ peak as a function of the parameter $\theta$ in the ER5M. As can be easily seen, for all of these models this value is at least 4-5 times smaller than those for the LRM and SSM shown in the fits in Fig. 3. In fact, for all values of $\theta$, this ‘excess’ is below $\simeq 1.6\sigma$ in significance and is very probably unobservable at this level of integrated luminosity. A similar situation arises in the ALRM case where the bin with the $Z'$ dijet peak contains only 3044 events, approximately a factor of 7 below the LRM case, and is comparable to that found for the ER5M.

To show what happens for these less fortunate cases, less us consider the ER5M with $\theta = -\pi/2$, which is referred to as ‘model $\chi$’ in the literature. We choose this case as it essentially has the largest number of excess events expected in the bin containing the $Z'$
peak of all the ER5M’s and also predicts a value larger than the ALRM case. In other word, if we cannot extract a signal for model $\chi$, we cannot do it for any ER5M or for the ALRM. Following the same procedure as above leads to the excess event distribution shown in Fig. 5a. We see no apparent excess of any significance in the region near $x_{jj} = 1$. (Of course, we can always try and force a BW or G fit in this region but the result would have a terribly bad $\chi^2$.) Thus we conclude that $Z''$’s from the ER5M or ALRM would not be visible in dijets without significantly more integrated luminosity. To achieve the same $S/\sqrt{B}$ as in either the SSM or LRM cases would require an increase in $\mathcal{L}$ by at least a factor of 25; of course such a large value is not necessary to render the $Z'$ dijet peak visible. To demonstrate this, we show in Fig. 5b the number of excess events in dijets for model $\chi$ again, but with a factor of ten increase in integrated luminosity, $100 fb^{-1}$. (We remind the reader that we are aided by the fact that we know from the dilepton data the approximate location of the peak.) Now that $Z'$ peak is ‘visible’ after background subtraction, we can perform a fit, shown in Fig. 5b, as in the SSM and LRM cases and extract a value by simply counting the number of excess events, $R_\chi = 12.7 \pm 2.7$, to be compared with the theoretical value of 9.6. (We again see that the value we extract tends to be systematically high.) Furthermore, at the 95% CL, we find that even this meager data disallows values of $\theta$ between $12^\circ$ and $36^\circ$. If, instead, we integrated under the Gaussian fit we would obtain a similar result: $R_\chi = 12.2 \pm 2.6$, with a similar range of $\theta$ now being disallowed at 95% CL: $9^\circ \leq \theta \leq 39^\circ$.

A summary of the analysis presented here is as follows:

(i) We have shown that the $Z' \to jj$ peak can be observable with high significance, for a 1 TeV $Z'$, at the SSC given an integrated luminosity of $10 fb^{-1}$ at least for some classes of extended electroweak models. It would appear that more massive $Z''$’s or $Z'''$’s of the same mass but arising from other models might also be observable provided sufficient integrated luminosity were available. We consider the fact that the $Z'$ will already be known to exist
from the dilepton data, with a given mass and width, to be of extreme importance in this type of analysis. The value of tight $p_t$, $\eta$, and dijet mass cuts, together with excellent dijet mass resolution, was also shown to be of great significance is obtaining a dijet data set with which to explore $Z'$ properties. The importance of obtained detailed data on the QCD background away from the the resonance region so that a precise background subtraction can be performed cannot be overly emphasized.

(ii) If sufficient statistics become available, the number of excess dijet events remaining after QCD background subtraction can be used, in combination with the leptonic data, to determine the ratio $R$. $R$ was seen to be quite sensitive to model couplings yet insensitive to parton structure function, luminosity, and $Z'$ decay mode uncertainties. $R$ was shown to be capable or restricting the allowed range of the parameter spaces of both the LRM and the ER5M. When combined with other probes of the $Z'$ fermionic couplings, a complete determination might now be obtainable.

(iii) One may possibly be able to extend the procedure developed here to other $Z'$ decay modes provided tagging techniques with high efficiencies are found.

Hopefully, the $Z'$ will be there for us to explore.

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Figure Captions

Figure 1. Predicted values of $R$ in the (a)ER5M as a function of $\theta$ and in the (b)LRM as a function of $\kappa$. The solid curve is the result of using the Morfin-Tung MTS1 parton densities while the dashed curve is the result of using the HMRSB densities of Harriman et al..

Figure 2. (a) The number of dijet events in 25 GeV wide mass bins produced at the SSC as a function of $x_{jj}$ in the invariant mass region near the 1 TeV $Z'$ of the LRM after the cuts described in the text have been applied. An integrated luminosity of $10 \, fb^{-1}$ has been assumed. The errors are totally contained within the crosses. (b) Same as (a), but rescaled by a factor of $x_{jj}^5$ and an overall trivial constant.

Figure 3. Invariant mass distribution, in 25 GeV wide bins, of the excess dijet events due to the $Z'$ of the (a)LRM and (b)SSM after QCD background subtraction at the SSC assuming the same integrated luminosity as in Fig. 2. The solid(dash-dotted) curve is the result of performing a best fit to the excess assuming a Gaussian(Breit-Wigner) shape for these events.

Figure 4. Predicted number of signal dijet events at the SSC in the 25 GeV wide invariant mass bin containing the $Z'$ peak, assuming an integrated luminosity of $10 \, fb^{-1}$, in the ER5M as a function of $\theta$.

Figure 5. Same as Fig. 3, but for the ER5M $\chi$ assuming an integrated luminosity of (a) $10 \, fb^{-1}$ and (b) $100 \, fb^{-1}$. In the second case, both Gaussian(solid) and Breit-Wigner(dash-dotted) fits to the peak are also shown.