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Extraction of Z' Coupling Data From $Z' \to jj$ at the LHC and SSC*

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Abstract

A recent analysis has shown that it may be possible at the SSC to extract information about Z' couplings via the decay $Z' \to jj$. This technique was found to be useful for some extended electroweak models provided the Z' is relatively light. In the present paper, we generalize this procedure to the LHC and to Z''s which are more massive than 1 TeV.

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ABSTRACT

A recent analysis has shown that it may be possible at the SSC to extract information about Z' couplings via the decay $Z' \to jj$. This technique was found to be useful for some extended electroweak models provided the Z' is relatively light. In the present paper, we generalize this procedure to the LHC and to Z''s which are more massive than 1 TeV.

Probing the nature of a newly discovered particle at a hadron supercollider can be a difficult problem and one that is critical to address. For example, if a Higgs-like object is discovered it will be extremely important to determine if it is the conventional Higgs of the Standard Model(SM), one of the Higgs' of the Minimal Supersymmetric Standard Model, or some other more exotic beast. A similar situation would apply to the discovery of a new gauge boson(Z')-to try and identify *which* Z' has been discovered. This issue has attracted much attention in the literature[1] during the past fews years with various techniques being proposed to extract information on the Z''s couplings to fermions. Since all of these schemes suffer from some form of weakness it is clearly of some importance to have as much artillery available as possible when assaulting the Z'.

It has recently been shown that it may be possible, at least for relatively light Z''s arising from certain classes of extended electroweak models(EEM), to use the $Z' \to jj$ mode as a potential source of coupling data[2,3]. The main difficulty with this channel is the enormous background which arises from QCD even after very tight selection cuts are applied to the data in the dijet invariant mass range which the Z' is already known to occupy. Sufficient statistical power must be available to fit the dijet mass distribution quite precisely outside the signal region before a background subtraction can be performed. Only then is it possible to have any hope of seeing excess events due to the Z', provided of course that the Z''s couplings are sufficiently strong. The usefulness of the dijet channel to probe the Z''s couplings can be quantified by the resulting statistical significance, $S/\sqrt{B}$, of the Z' peak. The purpose of the present work is to extend this previous analysis to both the LHC and to Z''s with larger masses. We will see that the canonical order of magnitude higher integrated luminosity available at the LHC will allow the dijet channel to be a useful probe of Z' couplings for a much larger range of masses than does the SSC.

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We begin by a quick overview of the analysis as presented in Ref. 3. We assume that a Z' has already been discovered via it's leptonic modes so that it's mass and width are relatively well determined. We remind the reader that for most EEM the Z''s width to mass ratio is usually rather small, $\Gamma/M_{Z'} \leq 0.05$, so that excess dijets from the Z' will occupy a rather narrow invariant mass range. To reduce QCD backgrounds we demand that both jets are very central and have high p_t's, *i.e.*, $-1 \leq \eta_{j_1,j_2} \leq 1$ and $p_t \geq 0.2M_{Z'}$ and we concentrate on the data in the dijet mass range near the Z', *i.e.*, $0.7 \leq x_{jj} \leq 1.5$, where $x_{jj} = M_{jj}/M_{Z'}$ with M_{jj} being the dijet invariant mass. For smaller values of x_{jj}, outside the above range, the shape of the mass distribution is perturbed significantly by our cuts while for larger values of x_{jj} there is a loss is statistics. Since no real data exists, both signal and background are generated numerically using a improved Born calculation[4] for the QCD dijet background and a two-loop, QCD-corrected 'K-factor' for the Z' production process[5]. QCD corrections to the Z' decay were also included and several different NLO parton distributions were employed to ascertain the sensitivity of the results to variations in these distributions. Both the signal and background were smeared assuming a dijet mass resolution of $\Delta M_{jj}/M_{jj} = 0.034$, integrated over bins of width $0.025M_{Z'}$, following the ATLAS analysis[2], and provided with Gaussian statistical fluctuations. Since almost all of the Z'-induced dijets should lie within the range $M_{Z'} \pm 2\Gamma$, we define the range $0.9 \leq x_{jj} \leq 1.1$ to be the signal regime and fit the 'data' outside this range by a degree-7 polynomial (once it is rescaled by a factor of x_{jj}^3). Polynomials of higher degree fail to improve the $\chi^2/d.o.f.$ of the fit. The fitted background is then extrapolated into the signal regime and subtracted from the 'data' leaving a potential Z'-induced event excess. This excess dijet distribution is then fit to either a Gaussian or Breit-Wigner shape and integrated to determine the total number of $Z' \to jj$ events. Clearly, if the number of signal events is too small in comparison to the background no obvious excess will be observed. Since the total number of events is sensitive to a number of overall systematic uncertainties (*e.g.*, the integrated luminosity and the choice of parton distributions) as well as being sensitive to what we assume the Z' can to, we will normalize the number of $Z' \to jj$ events we find to the number of Z'-induced dilepton events in the discovery channel which defines the ratio R. (These leptons are assumed to have rapidities in the range $-2.5 \leq \eta \leq 2.5$.) If $S/\sqrt{B}$ is too small, R will suffer from large errors and we will learn little or nothing about the Z''s couplings.

Fig. 1 shows two examples of where this technique works quite well for a 1 TeV Z' at the SSC assuming an integrated luminosity of 10 fb^{-1}, *i.e.*, for the Left-Right Model(LRM)[6] with $\kappa = g_R/g_L = 1$ and a Z' with SM-like couplings(SSM). For the LRM(SSM) the extracted value of R from the 'data' is $34.9 \pm 4.0(20.4 \pm 2.2)$ while theory predicts 30.5(18.9). In the LRM case, this converts to the 95% CL bound on the parameter κ: $0.83 \leq \kappa \leq 1.11$. Of course, the method works well only because the statistical significance of the Z' dijet peak is quite high, $S/\sqrt{B} > 7$, for these two particular cases. For other models one finds that $S/\sqrt{B}$ is much smaller even for much greater integrated luminosities. This arises mainly from the fact that for most models the Z' couplings to fermion pairs is somewhat smaller than in either the LRM or SSM examples. The Alternative version of the Left-Right Model(ALRM) and the E_6 effective Rank-5 models(ER5M)[7,8], which are described by a parameter θ, are

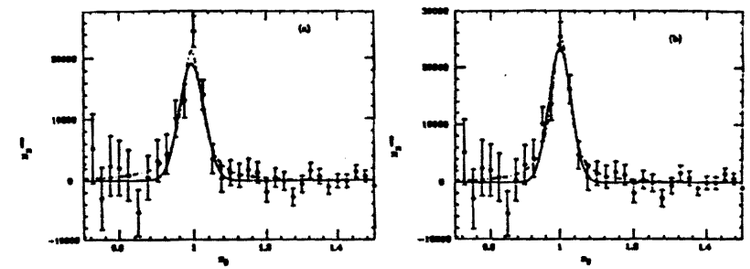

Fig. 1: Invariant mass distribution, in 25 GeV wide bins, of the excess dijet events due to the Z' of the (a)LRM and (b)SSM after QCD background subtraction at the SSC assuming the same integrated luminosity of 10 fb^{-1}. The solid(dash-dotted) curve is the result of performing a best fit to the excess assuming a Gaussian(Breit-Wigner) shape for these events.

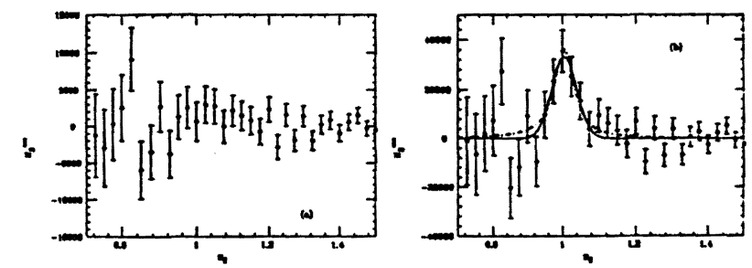

Fig. 2: Same as Fig. 1, but for the ER5M χ assuming an integrated luminosity of (a) $10fb^{-1}$ and (b) $100fb^{-1}$. In the second case, both Gaussian(solid) and Breit-Wigner(dash-dotted) fits to the peak are also shown.

reasonably representative of models in this class. For all values of θ one finds that a 1 TeV Z' at the SSC would be essentially impossible to observe in the dijet channel unless the integrated luminosity was significantly larger than 10 fb^{-1}. Fig. 2 shows this explicitly for the case $\theta = -\pi/2$, which is usually referred to as model χ in the literature. Among the ER5M, χ has essentially the largest dijet cross-section which implies that for other values of θ the situation can be significantly worse. The Z'_χ peak is not visible with only 10 fb^{-1} but is much more respectable for 100 fb^{-1} of luminosity. However, even in this case, the extracted value of R from the 'data', $R = 12.7 \pm 2.7$, is found to not only agree with the theoretical prediction for this model, $R = 9.6$, but with the predictions of *all* ER5M with θ's outside the range $9^\circ \leq \theta \leq 39^\circ$. Thus although the increased integrated luminosity has helped us to observe the Z', it's not sufficient to provide us with a precise enough determination of R which we need for model discrimination. Clearly, this implies that a value of $S/\sqrt{B} > 5-6$ is a *minimum* requirement to use this technique.

If we use this minimal criterion as a guidepost for our ability to use R as a model discriminator, we can ask how well our procedure works for other models, at the LHC, or for more massive Z''s. These possibilities are addressed by the results shown in Figs. 3a-f and Figs. 4a-b to which we now turn. From Fig. 3a we see that the dijet analysis can be applied to a 2 TeV LRM Z' at the SSC provided the integrated luminosity available is increased to about 25 fb^{-1}. Z''s of somewhat greater mass would appear to be quite hopeless requiring more than 10 standard years of running to accumulate adequate statistics. At the LHC, however, we see from Fig. 3b that the factor of 10 larger design luminosity may allow us to use R as a model discriminator for masses approaching 3 TeV in the LRM case after a few years of running. (It is important to note that the slopes of the LHC curves are steeper than those for the SSC due to the LHC's lower value of $\sqrt{s}$.) Figs. 3c-d show a very similar story for the SSM Z' since its production cross section is comparable to but slightly larger than that for the LRM. For the ALRM Z' case, shown in Figs. 3e-f, the situation is entirely different however. We see that R can probably never be determined at the SSC, even for a Z' mass of 1 TeV, due to the small cross section (although an upper bound might be obtainable). At the LHC, a 1 TeV Z' arising from this model might be probed after several years of running but for larger masses our dijet technique will surely fail.

The situation for the ER5M is not qualitatively different from the ALRM case, as one might expect, but is still somewhat sensitive to the value of the parameter θ. For the χ-type Z', we see from Fig. 4a that the SSC with an integrated luminosity of 100 fb^{-1} just barely manages to satisfy our 'minimal' criteria constraint, which is why R was perhaps not as precisely determined as well as we would have liked in the discussion above. Larger Z' masses are clearly hopeless at the SSC. At the LHC, from Fig. 4b, we see that the couplings of a 1 TeV Z'_χ has a reasonably good chance of being probed by the present dijet analysis after only 2-3 years of running at the canonical luminosity. Larger masses seem to be essentially impossible. As noted above, the χ case is realistically the most optimistic of all the ER5M. To show this explicitly, we consider a different ER5M which has often been discussed in the literature, called η. (This corresponds to choosing the parameter $\theta = cos^{-1}\sqrt{5/8}$.) Figs. 4c-d show us directly that for a 1 TeV Z'_η, neither collider will be able provide us with coupling

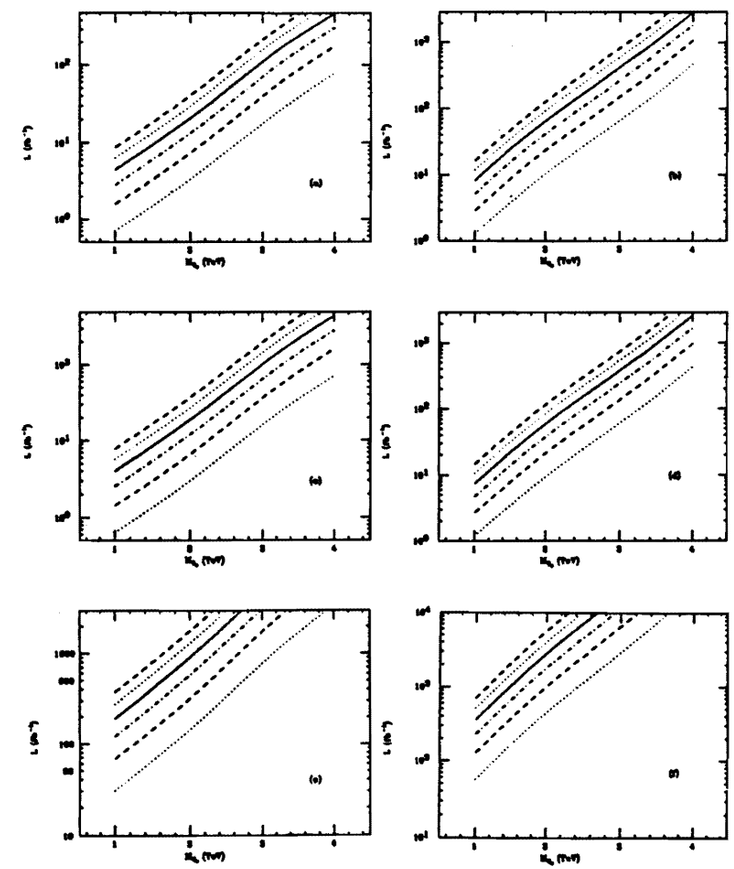

Fig. 3: Lines of constant $S/\sqrt{B}$ in the luminosity-Z' mass plane. From bottom to top, the lines correspond to $S/\sqrt{B}$ =2, 3, 4, 5, 6, and 7 for the LRM at the (a) SSC and (b) LHC, for the SSM at the (c) SSC and (d) LHC, or for the ALRM at the (e) SSC and (f) LHC.

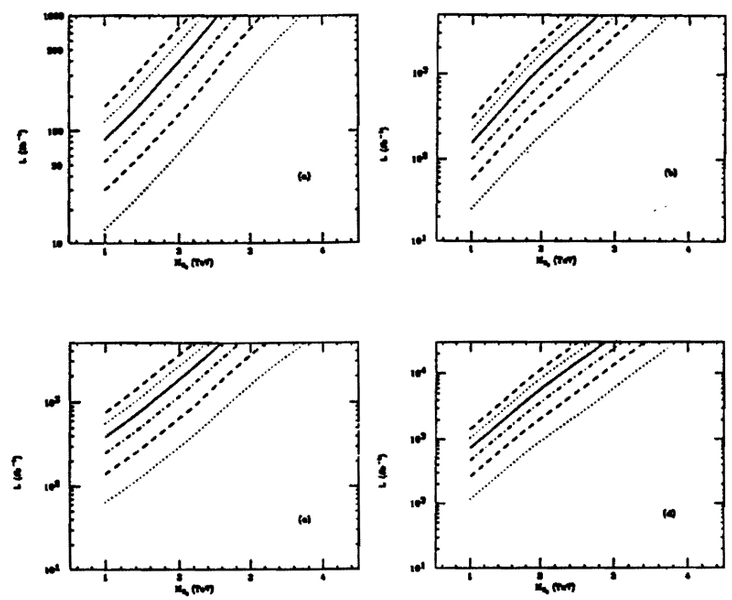

Fig. 4: Same as Fig. 3 but for the ER5M χ at the (a) SSC and (b) LHC, and for the ER5M η at the (c) SSC and (d) LHC.

information with less than a decade of running! This clearly demonstrates the shortfall of this technique, *i.e.*, it can only be applied for relatively light Z''s and even then only for certain classes of EEM in which the Z' has relatively strong couplings to fermion pairs.

Once a new particle is produced at the SSC/LHC, our work is just beginning. We must go beyond discovery and be able to determine just what it is that has been found. Although the procedure that we've described above cannot be used for a Z' originating from an arbitrary EEM if it is overly massive, it does add an important ingredient into the mix of techniques with which the Z''s couplings can be probed at hadron supercolliders.

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