PROBING NEW GAUGE BOSON COUPLINGS AT HADRON SUPERCOLLIDERS

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

and

Ames Laboratory and Department of Physics, Iowa State University, Ames, Iowa 50011, USA

ABSTRACT

Once it is discovered, the determination of the various couplings of a new neutral gauge boson at a hadron supercollider will not be an easy task. We review several recent studies that have begun to examine this issue for both the SSC and LHC.

1. Introduction

If a new neutral gauge boson($Z_2$) is discovered at either the SSC or LHC we will want to know more about it than the fact that it exists. Since many models in the literature predict such particles, we will want to know which $Z_2$ we have discovered. To accomplish this goal one must probe the couplings of the $Z_2$. This will not be an easy task since only a few of the properties of the $Z_2$ are easily measurable at hadron supercolliders. During the past 1-2 years there have been some initial attempts to address this problem and they will be reviewed in the discussion below.

2. Observables and Analyses

Neither the SSC or LHC detectors will have much difficulty in making clean measurements of the mass($M_2$), width($\Gamma$), production cross section($\sigma$), and forward-backward asymmetry($A_{FB}$) for a $Z_2$ in the TeV mass range via the lepton-pair production channel. If this is the only information available then identifying the $Z_2$ will be difficult but not impossible provided that certain theoretical prejudices are indeed realized in nature and sufficient statistics are available. Within a given extended gauge model, $\Gamma$ (and, hence $\sigma$) will be sensitive to what final states are kinematically allowed in $Z_2$ decay since such models require the existence of exotic particles in addition to those present in the Standard Model(SM). If one assumes that the $Z_2$ can decay only to the SM particles it is possible to get an excellent handle on the nature of the $Z_2$ couplings using the above data alone. However, such an analysis could be spoiled by the potential contributions of these exotics to $\Gamma$ or by the influence of a small mixing
between the $Z_2$ and the SM $Z$. One can show that for a class of models, the probability that some of these new degrees of freedom contribute substantially to $\Gamma$ is small since it is very likely that they are more massive than $M_2/2$ and are thus kinematically forbidden to appear as decay products. Fig. 1a shows this explicitly for the case of the exotic fermions in $E_6$ Effective Rank-5 Models. Since the exotics and the $Z_2$ have their masses generated by the same vev and all of the particle couplings are determined once the $E_6$ angle $-90^\circ \leq \theta \leq +90^\circ$ is fixed, the only free parameter for each exotic particle is the size of its Yukawa coupling. This can be bounded in the usual way by demanding tree-level unitarity in exotic particle scattering amplitudes mediated by $Z_2$ exchange. One then can determine what fraction of the allowed range for the Yukawa couplings will permit the exotics to participate in $Z_2$ decay resulting in Fig. 1a; comparable bounds are obtainable for the exotics in other models. Generally, however, the existence of additional $Z_2$ decay modes remains a concern for analyses using only the observables listed above.

Fig. 1. (a) Probability that a $Z_2$ can decay into the exotic fermions $h, E, S^c$(solid), $N$(dash-dot), or $N^c$(dash) in $E_6$ models. (b)$\chi^2$ fit to the value of $\theta$ for the model discussed in the text; the solid(dashed) curve corresponds to a $Z - Z_2$ mixing angle of 0.01(-0.01).

Similarly, it can also be shown that if the magnitude of the $Z - Z_2$ mixing angle is small($\leq 0.01$, as might be expected for a heavy $Z_2$), then this will have little effect on our ability to determine extended model couplings using only the data above; this is demonstrated by an explicit example in Fig. 1b for an $E_6$ model $Z_2$ with $\theta = 0$(model $\psi$) and a $M_2=3$ TeV at the SSC for an integrated luminosity of $10 fb^{-1}$. Here, we perform a $\chi^2$ fit to determine the value of $\theta$ obtainable from the above data using the properties of the SDC detector assuming the absence of mixing when it is in fact present and assuming decays to SM fermions only. (We remind the reader that, once specified, the value of $\theta$ uniquely fixes all of the $Z_2$ couplings.) We see that the best-fit value of $\theta$ as well as its 95% CL allowed range(corresponding to the gap between the curves along the dotted line) are only slightly altered by mixing angles as large as 0.01. We note that other models show more or less the same sensitivity to finite mixing.

In order to circumvent the potential problems in coupling determinations associated with theoretical uncertainties in the value of $\Gamma$ we must search for new observables
which are insensitive to this quantity. One possibility is to examine 3-body decays such as $Z_2 \rightarrow W^\pm l^\mp \nu$ and $Z_2 \rightarrow Zl^+l^-$. For a relatively light $Z_2$ with a mass less than 1-2 TeV, the number of events of this type is generally in the range $10^2 - 10^4$ at both the SSC and LHC so that significant statistics can be accumulated once SM backgrounds are removed. The ratios of the number of these kinds of events to ordinary lepton-pair events is thus not too small and is $\Gamma$ independent. In particular, one defines the ratios $r_{l\nu W} = \Gamma(Z_2 \rightarrow W^\pm l^\mp \nu)/\Gamma(Z_2 \rightarrow l^+l^-)$ and $r_{\nu\nu Z} = \Gamma(Z_2 \rightarrow Z\nu\bar{\nu})/\Gamma(Z_2 \rightarrow l^+l^-)$ whose values are shown for a number of different models in Fig. 2a assuming $M_2=1$ TeV and no $Z - Z_2$ mixing. (For a discussion of the individual specific models shown, see Ref. 4.) Most models predict values for these ratios that lie along the solid line provided the $Z_2$ has generation-independent couplings and its corresponding generator commutes with those of $SU(2)_L$; this is indeed the case for most GUT-inspired models. By satisfying these two conditions one finds that $r_{l\nu W}$ and $r_{\nu\nu Z}$ become simultaneously correlated and bounded. Scenarios not satisfying these conditions will lie elsewhere on the plot.

Fig. 2. (a) $r_{l\nu W}$ and $r_{\nu\nu Z}$ for several different extended gauge models as discussed in the text. (b) $r_{l\nu W}$ including the effects of $Z - Z_2$ mixing as described in the text.

If mixing does occur these conditions are no longer satisfied as the generator coupling to the $Z_2$ now has a small piece proportional to $T^3_L$. This does not significantly influence the resulting value of $r_{\nu\nu Z}$, but $r_{l\nu W}$ can be greatly modified since mixing turns on an additional resonant diagram involving the now non-zero $Z_2 W^+W^-$ coupling. This can result in a substantial increase in the value of $r_{l\nu W}$ as shown in Fig. 2b for the $E_6$ model case as a function of $\theta$ (x-axis) and the ratio of the two Higgs-doublets vevs, $\tan\beta$ (y-axis) assuming $M_2=1$ TeV. Here we see that mixing can induce values for $r_{l\nu W}$ of order unity or larger for a broad region of parameter space. The result of mixing for a model lying along the solid curve in Fig. 2a would then be a shift to the right without any appreciable shift up or down. While discovering a $Z_2$ whose values of these ratios place it in the lower right-hand part of Fig. 2a would be difficult to interpret (something exotic and/or non-zero mixing), a value of $r_{\nu\nu Z} \geq 0.06$ would be a clear indication that something unusual has been found. (Unfortunately, $r_{\nu\nu Z}$ has a very serious SM background from $2Z$ production that is very difficult to deal with.) A study of the SM backgrounds for the above 3-body channels, including the decays of the final
state $W$ and $Z$, has recently been done by del Aguila et al. for a number of different extended models. These authors conclude that the $Z_2\to e\bar{\mu}$ plus missing energy final states are reasonably sensitive to $Z_2$ couplings and are statistically powerful provided that $M_2$ is less than about 1.5 TeV. 

As a last point we mention that in some extended models the $Z_2$ is accompanied by a $W_2$ with a comparable mass; in a large fraction of cases the two particles are almost exactly degenerate so that $W_2$ cannot participate in $Z_2$ decay. (Of course, the mere observation of a $W_2$ will tell us a great deal about the nature of the extended model and in most cases the $W_2$ production cross section is larger than that of the $Z_2$ making it likely that $W_2$’s might be observed first as was the case for the SM gauge bosons.)

In the Left-Right Symmetric Model(LRM) however, there is a region of parameter space which allows $Z_2\to W^+_2 W^-_2$ the rate for which depends on the nature of $SU(2)_R$ breaking and the ratio of the $SU(2)_L$ and $SU(2)_R$ coupling constants, $\kappa$. A somewhat larger range of parameters allows for the corresponding 3-body decay $Z_2\to W^\pm_2 l^\mp\nu$. An observation of either of these modes will provide us much needed information on the extended gauge sector. For a further discussion of these possibilities see Refs. 4 and 7.

Another possibility, which has a long history and has been recently resurrected, is to measure the polarization asymmetry, $A$, of taus coming from the decay $Z_2\to\tau^+\tau^-$. The advantage of this observable is that, in the narrow-width approximation, it directly probes the leptonic $Z_2$ couplings and is very insensitive to structure function and luminosity uncertainties: $A = -2v_\tau a_\tau / (v_\tau^2 + a_\tau^2)$. Fig. 3a shows the strong sensitivity of $A$ to the mixing parameter $\theta$ discussed above for $E_6$ models. Unfortunately, observing $\tau$ pairs at hadron supercolliders is difficult due to substantial backgrounds from $t\bar{t}$ and $W^+W^-$ pairs as well as conventional QCD 2-jet production all of which must be drastically reduced before the value of $A$ can be reliably determined; this problem has been recently addressed for the SDC by Anderson et al. These authors have shown (for a $Z_2$ arising from the $E_6$ model discussed above with $M_2=1$ TeV) that a judicious choice

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Fig. 3. (a) $\tau$ polarization asymmetry, $A$, as a function of $\theta$ for the case discussed in the text. (b) Left-right asymmetry, $A_{LR}$, at the SSC for both the $E_6$ model with $M_2=1$(solid) or 2(dotted) TeV and the LRM for $M_2=1$(dashed) or 2(dot-dashed) TeV as discussed in the text.
of cuts can reject as much as 97% of the background and provides a determination of \( A \) at the 10% level assuming a luminosity of 10 \( fb^{-1} \). (After these cuts only 6% of the \( \tau \)-pairs from \( Z_2 \) decay remain but, since event rates are high, enough statistics remains available.) Unfortunately, for a heavier \( Z_2 \) it is unlikely that \( \tau \) polarization data will be very useful as the signal to background ratio is substantially smaller even if larger luminosities were available. These authors hypothesize that a better choice of cuts may help this situation; clearly more work on this observable is needed.

If polarized proton beams become available at either the SSC or LHC, then other asymmetries such as the left-right asymmetry, \( A_{LR} \) (defined in a manner similar to what is discussed for \( e^+e^- \) collisions), can be constructed which are comparable in magnitude to the more conventional \( A_{FB} \). Fiandrino and Taxil\(^9\) have recently shown that such asymmetries are quite sensitive to the choice of extended model as well the values of model parameters, such as \( \theta \) in the \( E_6 \) scenario, as shown in Fig. 3b. (In this plot, \( \beta = 90^\circ - \theta \) and \( \alpha \) is related to the parameter \( \kappa \) of the LRM.) Unfortunately, even if such asymmetries were reliably determined for the dilepton invariant mass region near \( M_2 \) they would be difficult to interpret in terms of model couplings in a more than a qualitative fashion due to the very large uncertainties currently present in the polarized parton densities. The authors of Ref. 8 are optimistic, however, that new polarized scattering data anticipated from RHIC may alleviate at least some of these difficulties.

3. Conclusions

As can be seen from the discussion above, the identification of new \( Z_2 \) gauge bosons at hadron supercolliders remains a serious problem especially if the mass of this particle exceeds 2 TeV. Clearly, much more work will be needed to address the issues raised here before hadron supercolliders are turned on later in the decade.

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