THE EFFECTS OF DETECTOR DESCOPING AND NEUTRAL BOSON MIXING ON NEW GAUGE BOSON PHYSICS AT THE SSC*

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Abstract

We examine how the abilities of an SDC-like detector to discover and identify the origin of a new neutral gauge boson are affected by $Z_1 - Z_2$ mixing and by variations in detector parameters such as lepton pair mass resolution, particle identification efficiency, and rapidity coverage. Also examined is the sensitivity of these results to variations in structure function uncertainties and uncertainties in the machine integrated luminosity. Such considerations are of importance when dealing with the issues of detector descoping and design.

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1. INTRODUCTION

If a new neutral gauge boson \(Z_2\) exists in the TeV mass range and has couplings to both \(q\bar{q}\) and \(e^+e^-\) at electroweak strength or larger, it will be copiously produced and detected at hadron supercolliders such as the SSC\(^1\) and LHC\(^2\). Once a \(Z_2\) is observed at these colliders, the real challenge begins: determining the extended electroweak model from which the \(Z_2\) originated. To meet this challenge, all possible information about the couplings of the \(Z_2\) must be gathered\(^3,4\) and unfortunately, hadron colliders provide few tools with which to work. In our earlier analysis\(^3\), we began to address these issues for a real SSC detector, the SDC\(^5\). Specifically, we examined the capability of the SDC to (i) directly determine the various couplings of the \(Z_2\) and (ii) determine the maximum value of the \(Z_2\) mass for which adequate statistical power is available to distinguish new neutral gauge bosons from two different extended electroweak models. The latter is referred to as the ID-limit. The measurable quantities used in this analysis are the new gauge boson mass \((M_2)\), the width \((\Gamma_2)\), the production cross section \((\sigma)\) for the reaction 
\[pp \rightarrow Z_2 \rightarrow \ell^+\ell^-\],
and the leptonic forward-backward asymmetry \((A_{FB})\) of the \(Z_2\), folded together with the anticipated SDC detector properties such as rapidity coverage, lepton-pair mass resolution, and particle identification efficiency, as well as the luminosity uncertainty of the SSC and the theoretical uncertainties due to our lack of detailed knowledge of the parton distribution functions.

The purpose of the present work is to re-examine our previous results in order to explore their sensitivity to possible variations in the capabilities of the SDC detector, improvements in our knowledge of the parton densities and the integrated machine luminosity, as well as to mixing between the \(Z_2\) and the Standard Model (SM) \(Z\)-boson. These considerations are particularly relevant when dealing with
Before discussing the main issues of this paper, we first briefly comment on
the influence of another assumption on our results; the omission of possible contri-
butions to $\Gamma_2$ arising from the existence of any new particles not contained in the
SM. Most extended electroweak models contain various exotic particles into which
the $Z_2$ may also decay. For example, in $E_6$ theories each generation lies in the $27$
representation, which contains the standard fermions, a right-handed neutrino, and
11 additional fields. These additional fields are comprised of the following: a color-
triplet, iso-scalar, $Q = -1/3$ fermion denoted by $h$; a color singlet, $Q = 0$, and $-1$, 
isodooublet denoted by $N$, and $E$, respectively, and their conjugate fields; and a
color singlet, iso-singlet, neutral fermion, designated by $S^c$. Most of these exotic
fermions acquire their masses from the same vacuum expectation value (vev) that
generates the $Z_2$ mass, and hence it is reasonable to expect that the exotics will
have masses of the same order as $M_2$. (We note that if the same argument were
applied to the SM, then the electron and top-quark masses should both be similar
to the mass of the SM $Z$-boson.) Using perturbative unitarity constraints from
the tree-level exotic fermion scattering via $Z_2$ exchange, $F\bar{F} \rightarrow F\bar{F}$, bounds on
the exotic fermion masses can be obtained in a manner similar to the constraints
issues of detector descoping and design. We will see below that, for a limited
class of models, our previous conclusions could be modified by as much as $\approx$
26% from variations in the above detector and machine characteristics, while the
incorporation of neutral gauge boson mixing does not significantly alter our results.
This paper is organized such that we first examine the effects of detector descoping,
neglecting gauge boson mixing, and then we investigate the contributions of mixing,
using a set of default detector parameters. We refer the interested reader to Ref. 3
for the full details of our analysis procedure.
obtained on heavy fermion masses in the SM. One may then ask, given the allowed range for the exotic fermion masses, what is the likelihood that $Z_2 \rightarrow F\bar{F}$ is kinematically allowed? This probability is presented in Fig. 1 for the superstring-inspired $E_6$ effective rank-5 models (ER5M), where the $Z_2$ couplings depend upon a parameter $-90^\circ < \theta < 90^\circ$. In the figure, the solid curve represents the percentage of parameter space that allows $Z_2 \rightarrow h\bar{h}, E\bar{E}$, or $S^c\bar{S}^c$, the dash-dotted curve corresponds to $Z_2 \rightarrow N\bar{N}$, and the dashed curve to $Z_2 \rightarrow N^c\bar{N}^c$. Note that the probability that the $Z_2$ decays into any single pair of exotics in these $E_6$ models is quite small, $\lesssim 8\%$. A more detailed analysis could lead to an even smaller probability that $Z_2 \rightarrow F\bar{F}$ is kinematically allowed.

We also note that the $Z_2$ production cross section into lepton pairs, $\sigma$, also depends on the total width of the $Z_2$ and suffers some of the same ambiguities mentioned above, although to a somewhat lesser degree. However, $\sigma$ can still be a valuable model discriminator. For example, the observation of an 8 TeV $Z_2$ alone would rule out entire classes of models.

2. EFFECTS OF DETECTOR DESCOPING

To be as specific as possible, we will limit our descoping discussion to three extended electroweak models: the Left-Right Symmetric Model (LRM) with the ratio of right-handed to left-handed coupling constants given by $g_R/g_L = 1$, the Alternative Left-Right Model (ALRM), and the Sequential Standard Model (SSM). The details of these models are also summarized in Ref. 3. This particular choice was made because these models are fairly representative and contain no free parameters once the $Z_2$ mass ($M_2$) is known (if $Z_1 - Z_2$ mixing is neglected), and if decays only to standard model fermions are allowed. For numerical purposes,
we will assume an integrated luminosity ($\mathcal{L}$) of $10\text{fb}^{-1}$ at the SSC, corresponding to one ‘standard year’ of run time, and take the S1 set of Morfin-Tung parton distribution functions\cite{12} to be our canonical set in the calculations.

The default $^5$ set of detector parameters that we use are:

$$
\epsilon_e = 0.85 \pm 0.04,
$$

$$
|\eta_\ell| \leq 2.5,
$$

$$
\delta M_{\ell\ell} = 0.01 M_{\ell\ell},
$$

$$
\frac{\delta \mathcal{L}}{\mathcal{L}} = 0.07,
$$

$$
\frac{\delta s}{s} = 0.10 \text{ with } M_{\ell\ell} = 4 \text{ TeV},
$$

(2.1)

where $\epsilon_e$ is the electron identification efficiency, $\eta_\ell$ is the pseudorapidity coverage for leptons, $\delta M_{\ell\ell}$ is the mass resolution for lepton pairs, $\delta \mathcal{L}/\mathcal{L}$ is the relative uncertainty in the SSC integrated luminosity, and $\delta s/s$ is the relative error in cross section and forward-backward asymmetry at $M_{\ell\ell} = 4 \text{ TeV}$ due to structure function uncertainties. We note in passing that the energy dependent term in the lepton pair mass resolution is essentially irrelevant when dealing with new gauge bosons in the TeV mass range.

We first examine how the search limits for new gauge bosons arising from the above three models are modified. In setting the search limits we demand the observation of $10 e^+e^-$ events arising from the $Z_2$ which are clustered in invariant mass, with $\leq 1$ event from background sources. For the default values of the parameters in Eq. (2.1), the $M_2$ discovery limits previously obtained$^3$ are 6.60 TeV (SSM), 6.10 TeV (LRM), and 6.95 TeV (ALRM). Figures 2a-c show the percentage change in the discovery limits as (a) the value of $\epsilon_e$, (b) the pseudorapidity cut

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on final state electrons, and (c) the overall normalization of the production cross section are altered. These figures demonstrate that the percentage change in the search limit is essentially model independent due only to availability of statistics. To confirm that there is nothing special about the three extended models we have chosen to analyze in detail, Fig. 2a also shows the percentage change of the search reach to modifications in $\epsilon_e$ for the superstring-inspired $E_6$ model $\psi$ (corresponding to $\theta = 0^\circ$). One sees that the results obtained for this model are very similar to the other three discussed above. In this figure, we see that a shift in $\epsilon_e$ of $\pm 0.10$, for example, can modify the search reach by $-5$ to $+4\%$. Looking at the electron pseudorapidity dependence in Fig. 2b, we see that (i) the discovery reach is not significantly improved when the $\eta_\ell$ coverage is increased (since the leptons from $Z_2$ decay are highly central) and (ii) the percentage change in the search limit is somewhat model dependent when the $\eta_\ell$ coverage is decreased. This is due to a modification in the lepton angular distribution as the fermion couplings of the $Z_2$ are varied. In summary, while increasing $\epsilon_e$ and $\eta_{\ell}^{max}$ could improve the $Z_2$ search limits by at most $\simeq 4\%$, a reduction in these quantities, if combined, could result in a $10 - 12\%$ decrease. Figure 2c shows that an uncertainty in the overall normalization of $\sigma$ does not significantly alter the $Z_2$ discovery capability.

We now turn to the issue of model identification. Table I shows the set of ID-limits for the three models above (comparing two at a time), assuming the default values of the parameters in Eq. (2.1). For each model in the first column on the left, corresponding to the $Z_2$ actually produced at the SSC, we find the maximum value of $M_2$ for which we can determine, at the 95% CL, that the produced $Z_2$ is not from another model. The numbers in the Table correspond to the six possible ID-limits that can be defined for these three distinct models.
Figures 3a-f show how the results in Table I are altered as each of the parameters in Eq. (2.1) are shifted from their default values. For the six possible pairs of models, the percentage change in the ID-limits is presented as a function of the value of (a) $\epsilon_e$, with the uncertainty in $\epsilon_e$ ($\delta \epsilon_e$) kept fixed at $\pm 0.04$, (b) the error in electron identification efficiency, $\delta \epsilon_e$, with $\epsilon_e$ kept fixed at its default value 0.85, (c) the pseudorapidity coverage for leptons, (d) the mass resolution for lepton pairs, $\delta M_{\ell\ell}/M_{\ell\ell}$, (e) the luminosity uncertainty $\delta \mathcal{L}/\mathcal{L}$, and (f) the parton distribution uncertainty $\delta s/s$.

We see from the figures that the dependence of the ID-limits on $\epsilon_e$ is roughly model independent, as one would expect. As $\epsilon_e$ varies by $\pm 0.10$ away from 0.85 (with $\delta \epsilon_e$ fixed), the ID-limits change at most by 6%. If $\epsilon_e$ is, however, fixed at 0.85 and $\delta \epsilon_e$ is allowed to vary, a significant loss in the ID-limit can occur, depending on the model, if $\delta \epsilon_e$ is poorly known. We have also checked that nothing is gained in the ID-limit by decreasing $\delta \epsilon_e$ below 0.04 (for $\epsilon_e = 0.85$). As $\eta_\ell$ is varied, we again see that nothing is gained by increasing the pseudorapidity coverage (since the leptons are almost entirely central), but that very substantial, albeit model dependent, losses in the ID-limits occur if too strong a cut is made. Unlike $\epsilon_e$, where the effect is mainly statistical, a reduction in $\eta_\ell$ coverage not only reduces the statistics, but also causes a reduction in the value of $A_{FB}$, which is an important ingredient in distinguishing the $Z_2$ couplings. Decreasing the value of the mass resolution constant term by a factor of 3 gives at most a $\simeq 2\%$ in the ID-limits, while an increase in the mass resolution by a factor of 2 can cost more than $\simeq 4\%$. We see that the ID-limits are generally insensitive to variations in $\delta \mathcal{L}/\mathcal{L}$ away from 0.07 with changes of at most $\pm 2\%$ as $\delta \mathcal{L}/\mathcal{L}$ varies from 0.03 to 0.10. There is a strong model dependence in the percentage change in the ID-limits as $\delta s/s$ is
reduced below its default value of 0.10. However, the resulting increase is at most a few percent, even if our knowledge of structure functions in the $M_{\ell\ell}$ range near $\simeq 4$ TeV improves by a factor of 5.

In Table II we compare the relative gains and losses in the identification limits due to the simultaneous variation of the input parameters to the following extreme values,

\begin{align*}
0.80 & \leq \epsilon_e \leq 0.90, \\
0.02 & \leq \delta \epsilon_e \leq 0.08, \\
2.0 & \leq \eta_{\ell} \leq 3.0, \\
0.005 & \leq \delta M_{\ell\ell}/M_{\ell\ell} \leq 0.020, \\
0.03 & \leq \delta \mathcal{L}/\mathcal{L} \leq 0.10, \\
0.02 & \leq \delta s/s \leq 0.15.
\end{align*}

The resulting modifications of the ID-limits are clearly quite model dependent. However, one general feature stands out; note that the possible loss in model determination is twice as large as the possible gain for each case. While in most cases there is only a modest increase in identification capability, there is the potential for significant losses if the detector characteristics are severely weakened. One must keep in mind, however, that the model identification ability is only reduced, and not destroyed altogether by detector descoping.
3. CONTRIBUTIONS FROM GAUGE BOSON MIXING

Here we address the possible influence that mixing between the new neutral
gauge boson and the SM $Z$-boson may have on our previous results.\textsuperscript{13} To be specific,
we consider the effect that such mixing has on the determination\textsuperscript{3} of the parameter
$\theta$ in $E_6$ models. Recall that the value of this parameter completely determines all
fermionic couplings of the $Z_2$ in these theories. Defining the weak eigenstates as
$Z$ and $Z'$, the orthogonal transformation
\begin{align}
Z_1 &= Z \cos \phi + Z' \sin \phi, \\
Z_2 &= -Z \sin \phi + Z' \cos \phi, 
\end{align}
\tag{3.1}
diagonalizes the $Z - Z'$ mass matrix, and produces the physical states $Z_1, Z_2$ with
masses $M_1, M_2$. $Z_1$ is then the state which is currently being probed at LEP.
Stringent bounds on this mixing can be placed from neutral current data, with the
result\textsuperscript{14} that $|\phi| \lesssim 0.02$.

The effects of mixing are presented in Figs. 4a-b. Here we show a $\chi^2$ fit to the
data on $\sigma$, $\Gamma_2$, and $A_{FB}$ as a function of the $E_6$ parameter $\theta$, assuming that a 3
TeV $Z_2$ is produced from the two representative cases: (a) model $\psi$ with $\theta = 0^\circ$,
and (b) model $\chi$ with $\theta = -90^\circ$. In these figures, the solid curves represent the $\theta$
determination when the produced $Z_2$ is mixed with the SM $Z$-boson with a value
of $\phi = -0.01$ and the dashed curves correspond to $\phi = 0.01$. Of course, since we
don’t know the value of $\phi$, \textit{a priori}, the fit is performed with $\phi = 0$. Thus, we
are probing the error that would be introduced in our fit to the value of $\theta$ for case
where $\phi$ is actually non-vanishing, by assuming that $\phi = 0$. The horizontal dotted
line shows the 95% CL limit on the determined range of $\theta$. For model $\psi$ with
$\phi = -0.01$ (0.01), the $\chi^2$ minimum is located at $\theta = -2^\circ$ (5$^\circ$), and the 95% CL
determined range of $\theta$ is $-24^\circ$ to $46^\circ$ ($-20^\circ$ to $42^\circ$), respectively. Comparing these shifts to our previous results\(^3\) for the case where $\phi = 0$ ($\chi^2$ minimum at $\theta = 0^\circ$ and $-22^\circ \leq \theta \leq 45^\circ$ at 95\% CL), it is clear that even for such maximal values of mixing, there is little effect. The contributions from mixing are even smaller in the case of model $\chi$, where for $\phi = -0.01$ (0.0, 0.01), the 95\% CL range of $\theta$ is $-114^\circ$ to $-66^\circ$ ($-115^\circ$ to $-66^\circ$, $-117^\circ$ to $-67^\circ$), and the minimum is located at $\theta = -90^\circ$ for all three possible values of $\phi$. We conclude that our previously obtained results are robust.

4. CONCLUSIONS

In summary, we have examined the consequences of variation in detector and machine characteristics and of neutral boson mixing in the model determination of new neutral gauge bosons at hadron supercolliders. We have found that upgrades in the detector parameters over the SDC default values, do not yield substantial improvements in $Z_2$ model differentiation, but a severe descoping could cause appreciable deterioration in the discovery and model identification ability. Our results also show that the incorporation of $Z - Z'$ mixing does not significantly change the resulting determination of the $Z_2$ couplings.

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Table I

ID-limits in TeV for the various extended models discussed in the text, assuming the default set of parameters in Eq. (2.1).

| Produced $Z_2$ | $Z_2$ Hypothesis |
|----------------|------------------|
|                | SSM   | LRM   | ALRM  |
| SSM            | $-$   | 5.05  | 5.95  |
| LRM            | 5.35  | $-$   | 6.10  |
| SSM            | 6.25  | 6.50  | $-$   |
Table II

Percentage gains and losses in ID-limits for the six pairs of models in Table I if the input parameters are altered simultaneously.

| Model        | Gain(%) | Loss(%) |
|--------------|---------|---------|
| LRM/ALRM     | 2.1     | −3.1    |
| LRM/SSM      | 5.6     | −12.4   |
| ALRM/LRM     | 3.8     | −6.6    |
| ALRM/SSM     | 5.2     | −11.3   |
| SSM/LRM      | 9.8     | −25.6   |
| SSM/ALRM     | 5.3     | −11.8   |
FIGURE CAPTIONS

1) The probability that the decay $Z_2 \to F \bar{F}$ is kinematically allowed for $F = h, E, S^c$ (solid curve), $F = N$ (dash-dotted curve), and $F = N^c$ (dashed curve) in $E_6$ models.

2) Sensitivity to $Z_2$ discovery limits to variations in the (a) electron identification efficiency and (b) pseudorapidity coverage for final state leptons, for the ALRM (dashed-dotted), SSM (dashed), LRM (solid), and the $E_6$ string-inspired model $\psi$ (dotted).

3) Sensitivity of the ID-limits to variations in the following detector parameters for the six pairs of models displayed in Table I. (a) $\epsilon_e$ is varied with $\delta \epsilon_e$ fixed at 0.04. From top to bottom, ALRM/LRM, ALRM/SSM, LRM/ALRM, SSM/ALRM, LRM/SSM, and SSM/LRM, where the first model listed corresponds to the actual $Z_2$ that is produced and the second to the $Z_2$ hypothesis. (b) $\delta \epsilon_e$ is varied while $\epsilon_e$ is fixed at 0.85 for, from top to bottom, LRM/ALRM, SSM/ALRM, ALRM/SSM, ALRM/LRM, LRM/SSM, and SSM/LRM. (c) Percentage change in ID-limits for variations in the $\eta_{cut}$ on leptons away from the default value. From top to bottom on the left-hand side of the figure, the curves are for LRM/ALRM, LRM/SSM, ALRM/LRM, SSM/LRM, ALRM/SSM, and SSM/ALRM. (d) Variations in the constant term of the lepton pair mass resolution for, from top to bottom on the right-hand side, ALRM/LRM, LRM/ALRM, LRM/SSM, SSM/LRM, ALRM/SSM, and SSM/ALRM. (e) Changes in the luminosity uncertainty for, from top to bottom on the left-hand side, SSM/LRM, LRM/SSM, ALRM/SSM, ALRM/LRM, LRM/ALRM, and SSM/ALRM, where the last two sets of models coincide. (f) Alterations
in the structure function uncertainty for, from top to bottom, SSM/LRM, LRM/SSM, ALRM/LRM, SSM/ALRM, ALRM/SSM. Here there is no change for the set LRM/ALRM.

4) The $\chi^2$ determination of $\theta$, as described in the text, for a 3 TeV $Z_2$ from $E_6$ models (a) $\psi (\theta = 0^\circ)$ and (b) $\chi (\theta = -90^\circ)$, including $Z - Z'$ mixing with $\phi = -0.01(0.01)$ corresponding to the solid (dashed) curves.