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ANL-HEP-PR-92-34

June 1992

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 descopeing and design.

* Work supported by the U.S. Department of Energy, Division of High Energy Physics, Contracts W-31-109-ENG-38 and W-7405-Eng-82.

† Research supported by an SSC Fellowship from the Texas National Research Laboratory Commission

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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 SSC¹ 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 (Γ_2), the production cross section (σ) 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 issues of detector descopeing and design. We will see below that, for a limited class of models, our previous conclusions could be modified by as much as $\simeq 26\%$ 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 descopeing, 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.

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 contributions to Γ_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,⁶ 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 , iso-doublet 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^{7,8} 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 obtained on heavy fermion masses in the SM.⁷ 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, σ , 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, σ 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)⁹ with the ratio of right-handed to left-handed coupling constants given by $g_R/g_L = 1$, the Alternative Left-Right Model (ALRM),¹⁰ and the Sequential Standard Model (SSM).¹¹ 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 10fb^{-1} at the SSC, corresponding to one ‘standard year’ of run time, and take the S1 set of Morfin-Tung parton distribution functions¹² to be our canonical set in the calculations.

The default⁵ set of detector parameters that we use are:

$$\begin{aligned}
\epsilon_e &= 0.85 \pm 0.04, \\
|\eta_\ell| &\leq 2.5, \\
\delta M_{\ell\ell} &= 0.01 M_{\ell\ell}, \\
\frac{\delta \mathcal{L}}{\mathcal{L}} &= 0.07, \\
\frac{\delta s}{s} &= 0.10 \text{ with } M_{\ell\ell} = 4 \text{ TeV},
\end{aligned} \tag{2.1}$$

where ϵ_e is the electron identification efficiency, η_ℓ 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 ≤ 1 event from background sources. For the default values of the pa-

rameters in Eq. (2.1), the M_2 discovery limits previously obtained³ 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 ϵ_e , (b) the pseudorapidity cut 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 ϵ_e for the superstring-inspired E_6 model ψ (corresponding to $\theta = 0^\circ$).⁶ 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 ϵ_e of ± 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 η_ℓ 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 η_ℓ 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 ϵ_e and η_ℓ^{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 σ 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-limits³ 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) ϵ_e , with the uncertainty in ϵ_e ($\delta\epsilon_e$) kept fixed at ± 0.04 , (b) the error in electron identification efficiency, $\delta\epsilon_e$, with ϵ_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 ϵ_e is roughly model independent, as one would expect. As ϵ_e varies by ± 0.10 away from 0.85 (with $\delta\epsilon_e$ fixed), the ID-limits change at most by 6%. If ϵ_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 η_ℓ 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 ϵ_e , where the effect is mainly statistical, a reduction in η_ℓ 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,

$$\begin{aligned}
0.80 &\leq \epsilon_e \leq 0.90, \\
0.02 &\leq \delta\epsilon_e \leq 0.08, \\
2.0 &\leq \eta_\ell \leq 3.0, \\
0.005 &\leq \delta M_{\ell\ell}/M_{\ell\ell} \leq 0.020, \\
0.03 &\leq \delta\mathcal{L}/\mathcal{L} \leq 0.10, \\
0.02 &\leq \delta s/s \leq 0.15.
\end{aligned}
\tag{2.2}$$

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 descopings.

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.¹³ To be specific, we consider the effect that such mixing has on the determination³ of the parameter θ 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

$$\begin{aligned} Z_1 &= Z \cos \phi + Z' \sin \phi, \\ Z_2 &= -Z \sin \phi + Z' \cos \phi, \end{aligned} \tag{3.1}$$

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 result¹⁴ that $|\phi| \lesssim 0.02$.

The effects of mixing are presented in Figs. 4a-b. Here we show a χ^2 fit to the data on σ , Γ_2 , and A_{FB} as a function of the E_6 parameter θ , assuming that a 3 TeV Z_2 is produced from the two representative cases: (a) model ψ with $\theta = 0^\circ$, and (b) model χ with $\theta = -90^\circ$. In these figures, the solid curves represent the θ 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 ϕ , *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 θ for case where ϕ is actually non-vanishing, by assuming that $\phi = 0$. The horizontal dotted line shows the 95% CL limit on the determined range of θ . For model ψ with $\phi = -0.01$ (0.01), the χ^2 minimum is located at $\theta = -2^\circ$ (5°), and the 95%

CL determined range of θ is -24° to 46° (-20° to 42°), respectively. Comparing these shifts to our previous results³ for the case where $\phi = 0$ (χ^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 χ , where for $\phi = -0.01$ (0.0, 0.01), the 95% CL range of θ is -114° to -66° (-115° to -66° , -117° to -67°), and the minimum is located at $\theta = -90^\circ$ for all three possible values of ϕ . 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 descopng 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.

ACKNOWLEDGEMENTS

This research was supported in part by awards granted by the Texas National Research Laboratory Commission and by the U.S. Department of Energy under contracts W-31-109-ENG-38 and W-7405-ENG-82.

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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 $Z_2 \rightarrow F\bar{F}$ 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 ψ (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) ϵ_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 ϵ_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 η_{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 χ^2 determination of θ , as described in the text, for a 3 TeV Z_2 from E_6 models (a) ψ ($\theta = 0^\circ$) and (b) χ ($\theta = -90^\circ$), including $Z - Z'$ mixing with $\phi = -0.01(0.01)$ corresponding to the solid (dashed) curves.

PROBABILITY THAT Z_2 CAN DECAY TO EXOTIC PAIRS

Figure 1

SDC Z_2 DISCOVERY LIMITS

Figure 2a

Figure 2b

Figure 2c

SDC Z_2 IDENTIFICATION LIMITS

Figure 3a

Figure 3b

Figure 3c

Figure 3d

Figure 3e

Figure 3f

Figure 4a

Figure 4b

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