Searches for New Gauge Bosons at Future Colliders *

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ABSTRACT

The search reaches for new gauge bosons at future hadron and lepton colliders are summarized for a variety of extended gauge models. Experiments at these energies will vastly improve over present limits and will easily discover a Z' and/or W' in the multi-TeV range.

I. INTRODUCTION

The discovery of new gauge bosons, Z', W', would be the cleanest signature for new physics beyond the Standard Model(SM) and would signal an extension of the gauge group by an additional factor such as $U(1)$ or $SU(2)$. Present direct searches for such particles at the Tevatron[1] suggest that, if they exist, their masses are in excess of several hundreds of GeV. It is thus the role of future colliders to search for a new Z' or W' at or above the TeV scale. In this paper we provide an overview and comparison of the capability of future hadron and lepton machines to discover these particles.

The search reach at a collider for new gauge bosons is somewhat model dependent due to the rather large variations in their couplings to the SM fermions which are present in extended gauge theories currently on the market in the literature. This implies that any overview of the subject is necessarily incomplete. Hence, we will be forced to limit ourselves to a few representative models. In what follows, we chose as examples the set of models recently discussed by Cvetic and Godfrey[2] so that we need to say very little here about the details of the coupling structure of each scenario. To be specific we consider (*i*) the E_6 effective rank-5 model(ER5M), which predicts a Z' whose couplings depend on a single parameter $-\pi/2 \leq \theta \leq \pi/2$ (with models ψ, χ, I, and η denoting specific θ values); (*ii*) the Sequential Standard Model(SSM) wherein the new W' and Z' are just heavy versions of the SM particles (of course, this is not a true model in the strict sense but is commonly used as a guide by experimenters); (*iii*) the Un-unified Model(UUM), based on the group $SU(2)_\ell \times SU(2)_q \times U(1)_Y$, which has a single free parameter $0.24 \leq s_\phi \leq 1$; (*iv*) the Left-Right Symmetric Model(LRM), based on the group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which also has a free parameter $\kappa = g_R/g_L$ of order unity which is just the ratio of the gauge couplings and, lastly, (*v*) the Alternative Left-Right Model(ALRM), based on the same extended group as the LRM but now arising from E_6, wherein the fermion assignments are modified in comparison to the LRM due to an ambiguity in how they are embedded in the **27** representation.

In the case of a W' we will restrict ourselves to the specific example of the LRM, *i.e.*, W_R, although both the UUM and ALRM have interesting W' bosons. The W' in the UUM is quite similar to that of the SSM apart from its overall coupling strength and the size of its leptonic branching fraction. The W' in the ALRM cannot be singly produced via the Drell-Yan mechanism since it carries non-zero lepton number and negative $R-$parity[4]. In what follows $Z-Z'$ and $W-W'$ mixing effects will be ignored which is an excellent approximation for any new gauge bosons in the multi-TeV mass range.

II. Z' SEARCHES AT HADRON COLLIDERS

In what follows we will limit our discussion to the most conventional discovery channels involving Z' and W' decays to charged lepton pairs and charged leptons plus missing E_t, respectively. Regrettably, this leaves vast and fascinating territories untouched wherein, *e.g.*, the new gauge boson decays to dijets, pairs of SM gauge bosons, or leptonic W' decay modes not involving missing E_t. These possibilities require further study particularly at the LHC.

Both Z' and W' search reaches are conventionally obtained using the narrow width approximation with some additional corrections to account for detector acceptance's(A) and efficiencies(ϵ). In this case the number of expected events(N) is simply the product $N = \sigma B_l A\epsilon\mathcal{L}$, where σ is the production cross section, B_l is the leptonic branching fraction and $\mathcal{L}$ is the machine's integrated luminosity. A 5σ signal is assumed to be given by 10 signal events with no background; this is logically consistent since an extremely narrow peak in the dilepton mass can have only an infinitesimal background underneath it. Detailed detector simulations for both the Tevatron and LHC[5] validate this approximation as a good estimator of the true search reach at least for the more `traditional' models. (The reader should be reminded to be careful when employing this approximation in all models since the Z' may not always be sufficiently narrow and Drell-Yan continuum backgrounds may become relevant.) In the Z' case, we need only know the various fermionic couplings for a fixed value of the Z' mass to obtain σ. Traditionally, one also assumes that the Z' can *only* decay to pairs of SM fermions in order to obtain B_l. It is important to note that in many models, where the Z' can also decay to exotic fermions and/or SUSY particles this *overestimates* B_l and, thus, the search reach. In obtaining our results for 10 signal events we combine both the electron and muon decay channels. With these assumptions, Figures 1 and 2 show the discovery reaches of the 60 TeV pp (LSGNA) collider and TeV33 for the Z' bosons of both the ER5M and the LRM, while Table I shows the summary of results for the other models as well as for the LHC and the higher energy 200 TeV (PIPETRON) colliders. The corresponding figures for the LHC can be found in Ref.[6].

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Here we see that TeV33 will allow us to approach the 1 TeV mass scale for Z' bosons for the first time. Note that in the case of the 60 and 200 TeV machines the higher $q\bar{q}$ luminosities in the $p\bar{p}$ mode leads to a significantly greater ($\simeq 30-50\%$) search reach.

If the above estimate of the leptonic branching fraction is wrong, how badly are the reaches affected? To get a feeling for this, consider reducing the value of B_l by a factor of two from the naive estimate given by decays to only SM fermion pairs. (In the E_6 case, this roughly corresponds to allowing the Z' to decay into SUSY partners as well as the exotic fermions with some phase space suppression[4].) Semi-quantitatively, the reduction in reach for each collider is found to be roughly model independent and approximate results are given in the last line of Table I. As can be seen from these values the `hit' taken can be significant in some cases. However, unless B_l is very much smaller than the naive estimate it is clear that the multi-TeV mass range will remain easily accessible to future hadron colliders.

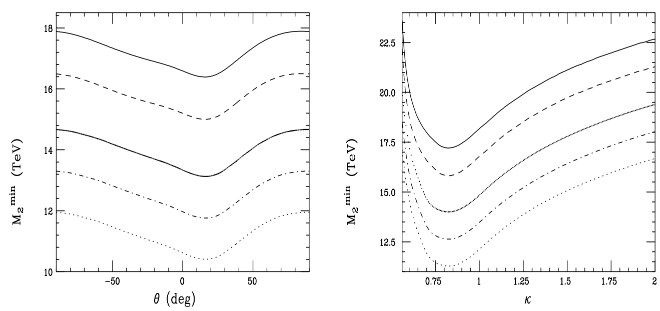

Figure 1: Z' search reaches at the 60 TeV pp collider(LSGNA) for E_6 models as a function of θ and the LRM as a function of κ. From bottom to top the curves correspond to integrated luminosities of 50, 100, 200, 500 and 1000 fb^{-1}, respectively. MRSA$'$ parton densities are assumed.

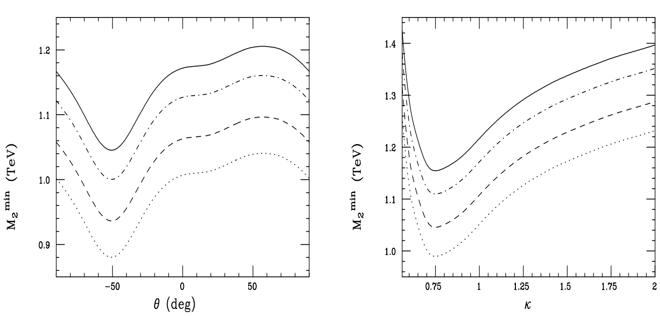

Figure 2: Same as the previous figure, but now for the Tevatron running at 2 TeV. From top to bottom the integrated luminosities are assumed to be 100, 50, 20 and 10 fb^{-1}, respectively.

III. W' SEARCHES AT HADRON COLLIDERS

Unlike the Z' case, the corresponding W_R searches via the Drell-Yan process have many subtleties even when we assume that the missing E_t mode is accessible and dominant. The canonical search assumes that the $q'\bar{q}W_R$ production vertex has SM strength, implying (*i*) $\kappa = 1$ and (*ii*) $|V_{L_{ij}}| = |V_{R_{ij}}|$, *i.e.*, the elements of the RH CKM mixing matrix, V_R, are the same as V_L, and, as in the Z' case, (*iii*) that the W_R leptonic branching fraction is given by its decay to SM fermions only. Of course violations of assumptions (*i*) and (*iii*) are easily accounted for in a manner similar to the Z' case discussed above. If assumption (*ii*) is invalid, a significant search reach degradation can easily occur as a result of modifying the weight of the various parton luminosities which enter into the calculation of the production cross section. At the pp colliders such as the LHC, we do not expect that surrendering (*ii*) will cost us such a very large penalty since the W_R production process already occurs through the annihilation of sea$\times$valence quarks. On the otherhand, W_R production is a valence$\times$valence process at the $p\bar{p}$ colliders such as the Tevatron so we might anticipate a more significant reach reduction in this case.

Fig.2 of Ref.[6] summarizes the W_R search reach situation at both the Tevatron and the LHC where the narrow width approximation has been employed. In particular this figure shows that the reduction of reach at the LHC due to variations in V_R is rather modest whereas it is far more significant at the Tevatron. Figure 3 compares the W_R production rates at the 60 and 200 TeV colliders for both pp and $p\bar{p}$ modes assuming $\kappa = 1$. In both cases we see that the maximum reach degradation resulting from variations in V_R is far more severe in the $p\bar{p}$ than pp mode. For both the 60 and 200 TeV colliders the search reach is $\simeq 25\%$ higher in the case of $p\bar{p}$. It is also interesting to compare the rates expected for the $p\bar{p}$ and pp modes for a fixed value of $\sqrt{s}$ and W_R mass(M_R). For example, at the 60(200) TeV machine and $M_R = 12(60)$ TeV, the production rates are found to be 6.62, 1.90, and 0.4(0.588, 0.168 and 0.04) fb in the $p\bar{p}$, pp, and V_R `worst case' modes.

Assuming $V_R = V_L$ for the 60 TeV collider, Figure 4 compares the κ dependence of the reach for both the pp and $p\bar{p}$ modes for different integrated luminosities. Table II summarizes all of our results for W_R search reaches at various colliders.

IV. Z' SEARCHES AT LEPTON COLLIDERS

It is more than likely that a Z' will be too massive to be produced directly at the first generation of new lepton colliders. Thus searches at such machines will be indirect and will consist of looking for deviations in the predictions of the SM in as many observables as possible. Layssac *et al.*[2] have shown that the deviations in the leptonic observables due to the existence of a Z' are rather unique. Since the Z' is not directly produced, lepton collider searches are insensitive to the decay mode assumptions that we had to make in the case of hadron colliders. In the analysis presented here we consider the following standard set of observables: σ_f, A_{FB}^f, A_{LR}^f, $A_{pol}^{FB}(f)$ where f labels the fermion in the final state and, special to the case of

Table I: Z' search reaches at hadron colliders in TeV. For the LRM, $\kappa = 1$ is assumed while for the UUM, we take $s_\phi = 0.5$. Decays to only SM fermions is assumed. The luminosities of the Tevatron, LHC, 60 TeV and 200 TeV colliders are assumed to be 10, 100, 100 and 1000 fb^{-1}, respectively. The last line in the Table is the approximate reduction in reach in TeV due to a decrease in B_l by a factor of 2.

Model	LHC	60 TeV (pp)	60 TeV ($p\bar{p}$)	200 TeV (pp)	200 TeV ($p\bar{p}$)	TeV33
χ	4.49	13.3	17.5	43.6	63.7	1.00
ψ	4.14	12.0	17.1	39.2	62.3	1.01
η	4.20	12.3	17.9	40.1	64.8	1.03
I	4.41	12.9	15.2	42.1	56.0	0.88
SSM	4.88	14.4	20.6	45.9	68.7	1.10
ALRM	5.21	15.0	22.5	49.9	74.7	1.15
LRM	4.52	13.5	18.9	43.2	64.6	1.05
UUM	4.55	13.7	19.7	43.5	65.1	1.08
Hit	0.33	1.5	1.8	4.9	6.3	0.05

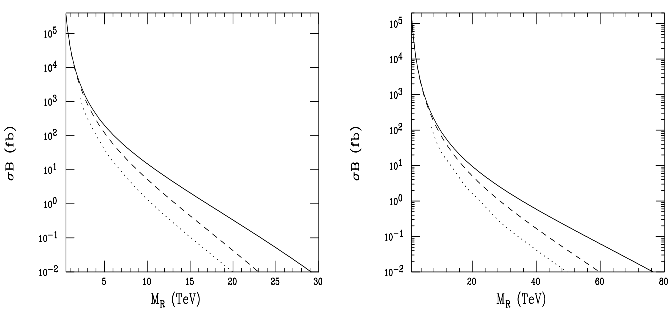

Figure 3: W_R production cross sections for $\kappa = 1$ at the 60 and 200 TeV colliders. B_l is assumed to be given by decays to the SM fermions only. The solid(dashed) curve corresponds to $p\bar{p}(pp)$ collisions with $V_L = V_R$ while the dotted curve corresponds to the lowest cross section in either case due to the most pessimistic choice of the V_R mixing matrix elements.

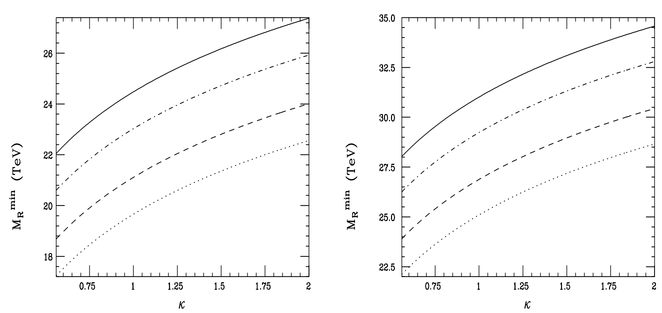

Figure 4: W_R search reaches at the 60 TeV LSGNA collider in the pp(left) and $p\bar{p}$(right) modes as functions of κ assuming $V_R = V_L$. From top to bottom the curves correspond to integrated luminosities of 1000, 500, 200 and 100 fb^{-1}, respectively.

Table II: W_R search reaches of hadron colliders in the missing energy mode in TeV. $\kappa = 1$ and decays to only SM fermions is assumed. WC(worst case) refers to the set of V_R elements that yield the lowest production cross section. The luminosities are as in the previous Table.

Machine	$V_L = V_R$	V_R (WC)
TeV33	1.2	$\simeq 0.5$
LHC	5.9	5.1
60 TeV (pp)	19.7	$\simeq 16$
60 TeV ($p\bar{p}$)	25.1	$\simeq 16$
200 TeV (pp)	64.7	$\simeq 52$
200 TeV ($p\bar{p}$)	82.9	$\simeq 52$

the tau, $< P_\tau >$ and P_τ^{FB}. Note that beam polarization plays an important role in this list of observables, essentially doubling its length.

In this paper we present a preliminary analysis wherein charged leptons as well as $b-$, $c-$, and $t-$quarks are considered simultaneously in obtaining the discovery reach. The basic approach follows that of Hewett and Rizzo[3] and is outlined in the review of Cvetic and Godfrey[2], but now includes angular cuts, initial state radiation(ISR) in the e^+e^- case but ignored for $\mu^+\mu^-$ collisions at the Large Muon Collider(LMC), finite identification efficiencies, systematics associated with luminosity and beam polarization(P) uncertainties. For e^+e^- colliders we take $P = 90\%$ while for the LMC we can trade off a smaller effective P through modifications[7] in the integrated luminosity. The angular cuts applied in all cases were assumed to be the same. Generically we find that ISR lowers the search reach by $15-20\%$ while finite beam polarization increases the reach by $15-80\%$ depending on the specific model and the machine energy, *i.e.*, the increase is smaller at larger values of $\sqrt{s}$.

Figures 5 and 6 display sample results of this analysis at the 500 GeV NLC and 5 TeV Next-to-Next Linear Collider(NNLC)

Table III: Indirect Z' search reaches of lepton colliders in TeV employing all observables. The integrated luminosities of the NLC500, NLC1000, NLC1500, NNLC and LMC are assumed to be 50, 100, 100, 1000 and 1000 fb^{-1}, respectively.

Model	NLC500	NLC1000	NLC1500	NNLC 5 TeV	LMC 4 TeV
χ	3.21	5.46	8.03	23.2	18.2
ψ	1.85	3.24	4.78	14.1	11.1
η	2.34	3.95	5.79	16.6	13.0
I	3.17	5.45	8.01	22.3	17.5
SSM	3.96	6.84	10.1	29.5	23.2
ALRM	3.83	6.63	9.75	28.4	22.3
LRM	3.68	6.28	9.23	25.6	20.1
UUM	4.79	8.21	12.1	34.7	27.3

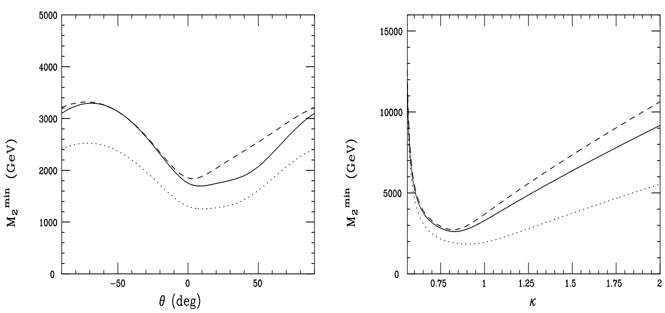

Figure 5: Indirect Z' search reaches at the 500 GeV NLC for E_6 models as a function of θ and the LRM as a function of κ including initial state radiation. The dotted(solid, dashed) curve corresponds to the values obtained using leptonic(leptonic plus $b-$quark, all) observables. A luminosity of 50 fb^{-1} has been assumed.

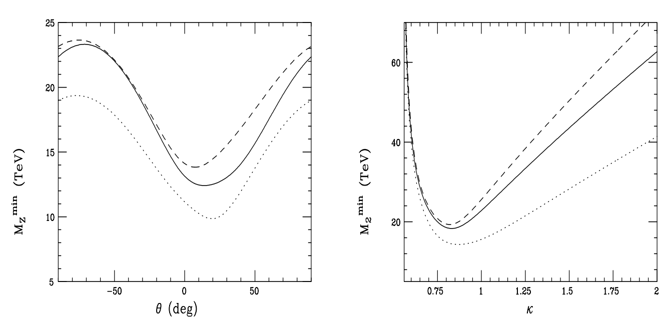

Figure 6: Same as the previous figure but now for the 5 TeV NNLC assuming an integrated luminosity of 1000 fb^{-1}.

for a Z' of either the ER5M or LRM type. In particular, these plots show how the introduction of additional observables associated first with b and then with c and t lead to an increased reach. Note that the inclusion of c and t in comparison to the leptons plus b case leads to only a rather mild increase in the reach for the E_6 case with a somewhat larger result on the average for the LRM. One reason for this is that the $Q = 2/3$ quarks have vanishing vectorial couplings for all values of the parameter θ and completely decouple from the Z' in the case of model I (which corresponds to $\theta \simeq -52.24°$) so that there is no additional sensitivity obtained in this case when the c and t are included. Table III summarizes our results for the search reaches of the various colliders for all of the above models. It is interesting to note that for the LMC the lack of significant ISR and the smaller polarization/luminosity are found to essentially cancel numerically in their affect on the Z' search reach.

In principle the NLC can be run in the polarized e^-e^- collision mode with a luminosity comparable to that for e^+e^-. Since both e^- beams are polarized, the *effective* polarization is larger and, due to the large Moller cross section, there is significant sensitivity to the existence of a Z'[8]. Unfortunately, an analysis of this situation including the effects of ISR is not yet available but a preliminary study by Cuypers[8] indicates that the *ratio* of search reaches in the e^+e^- and e^-e^- modes is stable under the modifications induced by ISR. We thus repeat the previous e^+e^- analysis neglecting ISR and also perform the complementary e^-e^- analysis with the same cuts, efficiencies *etc* and then take the ratio of the resulting reaches for a given extended gauge model. The results of this analysis for NLC500 are shown in Table IV. Here we see that in general the e^-e^- reach is superior to that obtained in the e^+e^- mode when only the leptonic final states are used, consistent with the results obtained in Ref.[8]. However, as soon as one adds the additional information from the quark sector, e^+e^- regains the lead in terms of Z' mass reach. Combining the leptonic and quark data together in the e^+e^- case always results in a small value for the ratio. Of course, once the anxiously awaited e^-e^- analysis including ISR becomes available we need to verify these results directly.

Table IV: Ratio of e^-e^- to e^+e^- indirect Z' search reaches at a 500 GeV NLC with an integrated luminosity of 50 fb^{-1} in either collision mode. ISR has been ignored. The columns label the set of the final state fermions used in the e^+e^- analysis.

Model	ℓ	$\ell+b$	$\ell+b,c,t$
χ	1.10	0.900	0.896
ψ	1.20	0.711	0.673
η	1.07	0.813	0.650
I	1.06	0.813	0.813
SSM	1.30	0.752	0.667
ALRM	1.20	1.12	0.909
LRM	1.02	0.483	0.432
UUM	0.891	0.645	0.496

V. ACKNOWLEDGEMENTS

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