SLAC-PUB-7365
December 1996

Extended Gauge Sectors at Future Colliders: Report of the New Gauge Boson Subgroup

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ABSTRACT

We summarize the results of the New Gauge Boson Subgroup on the physics of extended gauge sectors at future colliders as presented at the 1996 Snowmass workshop. We discuss the direct and indirect search reaches for new gauge bosons at both hadron and lepton colliders as well as the ability of such machines to extract detailed information on the couplings of these particles to the fermions and gauge bosons of the Standard Model.

To appear in the *Proceedings of the 1996 DPF/DPB Summer Study on New Directions for High Energy Physics-Snowmass96*, Snowmass, CO, 25 June-12 July, 1996.

[1]Work supported by the Department of Energy, contract DE–AC03–76SF00515.

1 Introduction

1.1 Overview

One of the most important goals of existing and future colliders is to establish the gauge group which fully describes the strong and electroweak interactions. Current precision measurements[1] as well as direct collider searches[2], both of which probe the physics at the 'electroweak' (100 GeV) scale, support the hypothesis that this group is that of the Standard Model(SM): $SU(3)_c \times SU(2)_L \times U(1)_Y$. Many scenarios have been proposed over the last 25 years in which the SM is just an effective low energy version of a somewhat more complex gauge structure which exists at higher energies. If any of these ideas have any validity and the associated scale is not far above the multi-TeV range then future colliders should find direct evidence for its existence. There are many reasons why the discovery of such a new scale would be important. Perhaps the most obvious is the observation that we cannot extrapolate the physics we currently see to extremely high energies, such as the Planck or a hypothetical GUT scale, without knowing all that is happening in our own neighborhood that we are just beginning to probe. Clearly, the discovery of a new gauge boson, such as a Z' or W', would be the cleanest signature for new physics beyond the SM.

It is impossible in a brief review to cover all possible models with new gauge bosons. We note that extensions of both the strong and electroweak sectors have been proposed in a variety of forms. For example, extending the conventional QCD $SU(3)_c$ group to $SU(3)_1 \times SU(3)_2$ leads to scenarios which predicts new strongly interacting particles such as axigluons[3], colorons[4], and topgluons[5] depending upon how the quarks transform under the two $SU(3)$'s. Other possibilities include extending the color group to larger factors, such as $SU(5)_c$[6]. *All* of these extensions result in particles which are new gauge bosons in the strictest sense. As the physics of such states are covered in New Interactions Subgroup report[7], we will limit our discussion below to extensions of the SM electroweak group. Even with this constraint, the number of potential models remains very large.

Extended Gauge Models(EGMs) can be divided into two very broad classes depending upon whether or not they originate from a GUT group, such as $SO(10)$ or E_6. *Generally*, the new gauge bosons from GUT-inspired scenarios have generation-independent couplings (in the same sense as the W and Z of the SM), whereas this need not be true for non-unifiable models. Also, *generally*, the extension of the SM group structure induces additional anomalies which cannot be cancelled by using the conventional SM fermions alone. This implies the almost all EGMs also contain additional exotic matter particles, such as leptoquarks, with masses comparable to those of the new gauge bosons themselves. In what follows, we will limit our discussion almost exclusively to a small set of sample models of either class that have been recently reviewed by Cvetic and Godfrey[8].

The search reach at a collider as well as our ability to extract coupling information for a new gauge boson is somewhat model dependent due to the rather large variations in their couplings to the SM fermions. 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 $\psi(\theta = 0)$, $\chi(\theta = -\pi/2)$, $I(\theta = -\cos^{-1}\sqrt{3/8})$, and $\eta(\theta = \cos^{-1}\sqrt{5/8})$ denoting specific common cases discussed in the literature; (*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 $0.24 \leq s_\phi \leq 0.99$; (*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 ($\kappa = g_R/g_L \geq 0.55$) 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[9]. In what follows $Z-Z'$ and $W-W'$ mixing effects will be generally ignored which is an excellent approximation for any new gauge bosons in the multi-TeV mass range.

1.2 Why a Z' Might Be Light

While it is interesting to consider EGMs on their own merits, they are only of true phenomenological interest if their associated scale is within the range accessible to existing or future colliders. In principle, the new scale could lie anywhere between the electroweak scale and the Planck scale. If it is far from current energies then the associated new physics could only be observed indirectly. Why might we expect this scale to be 'nearby'? In a contribution to these proceedings, Lykken[10] examined this issue for the case of a new $U(1)'$ gauge group within the general context of SUSY-GUTS and String Theory with weak-scale supersymmetry, extending the work of Cvetic and Langacker[11].

One of the essential ingredients of this scenario is the idea of radiative symmetry breaking. It is easy to imagine that the breaking of the $U(1)'$ might be triggered by the renormalization group(RG) running of some exotic fermion fields which drive the mass squared of some exotic scalar field negative. *However*, due to the logarithmic nature of the RG running it would not seem very likely that the Z' mass would naturally lie in the few TeV region or below without some fine tuning of parameters. In fact, in scenarios of this kind, one finds that the Z' mass naturally lies instead in the $10^8 - 10^{16}$ GeV range for typical GUT models.

In the MSSM, symmetry breaking is induced by the vev's of the two Higgs doublets $H_{U,D}$. To break $U(1)'$, we require the introduction of some number of SM singlet fields of which at least one gets a vev. In models with two or more singlets getting vev's, D flatness imposes a relationship between these vev's (apart from corrections of order the soft SUSY breaking

Model	Leptophobic $U(1)'$?	$Q'_H \neq 0$?
Faraggi I [12]	no	–
Faraggi II [13]	yes	no
Faraggi et al [14]	no	–
Chaudhuri et al [15]	yes	no
Hockney-Lykken [16]	yes	no
Flipped SU(5) [17]	yes	yes

Table 1: Partial survey of string models for naturally light Z' candidates which are leptophobic from Ref.10.

scale) but does not relate them to the vev's of $H_{U,D}$. This implies that the Z' mass and the electroweak scale are not directly related and the Z' could naturally be quite massive. On the otherhand, if only one singlet (S) gets a vev and either or both of $H_{U,D}$ carry $U(1)'$ charges then the doublet and singlet vev's are directly related through the requirement of D flatness. If the soft mass for S, m_S^2, is of order the weak scale (as is the case for all SUSY breaking soft terms) then the vev of S is also of order the electroweak scale. The Z' mass then becomes calculable in terms of the vev's, which are no longer independent, the gauge couplings, and the $U(1)'$ charges of the singlet and doublet fields.

To this scenario certain phenomenological constraints need to be added in that (i) the Z' has to be sufficiently massive as to have avoided current searches and (ii) either the $Z - Z'$ mixing angle must be reasonably small, of order 10^{-3}, or the Z' couplings to leptons are suppressed ($i.e.$, the Z' is leptophobic). This second constraint arises from the excellent agreement between leptonic precision measurements at SLD and LEP and the predictions of the SM. If the Z' is not leptophobic, this constraint implies an additional strong constraint between the $U(1)'$ charges of S, Q'_S, and the Higgs doublets, Q'_H. Cvetic and Langacker[11] did not find an acceptable string model of this type amongst those presented in the literature; of course only a handful of such models are known so far. (We recall that within these string models all of the $U(1)'$ charges are completely specified.) Given the severity of the constraint this is probably not surprising. Lykken examined the possibility of a leptophobic Z' in the string context with the additional requirement that Q'_H be non-zero. His results are shown in Table 1.2. As can be seen, only Flipped $SU(5)$ is a potential candidate theory but a detailed study[10] shows that the particle embedding necessary to generate a large top Yukawa coupling lead to flavor changing neutral currents generated by Z' exchange. Lykken concludes that a leptophobic Z' satisfying our constraints is less natural in string theory than the more conventional kind of Z'. Finally, Lyyken further reminds us that the $U(1)'$ leads to potentially large D-term contributions to the squark and slepton masses which can be of order 250 GeV. If so this implies rather significant modifications in the sparticle mass spectrum in comparison to either minimal supergravity or gauge-mediated low energy breaking models.

2 Collider Search Reaches For New Gauge Bosons

The search capabilities for new gauge bosons of existing and future accelerators as been discussed by many authors and has been most recently summarized by Fig. 1 from Cvetic and Godfrey[8]. More recent work along these lines was presented as this meeting[18] which generalize and extend previous results. The discussion for hadron and lepton colliders are presented in subsequent sections.

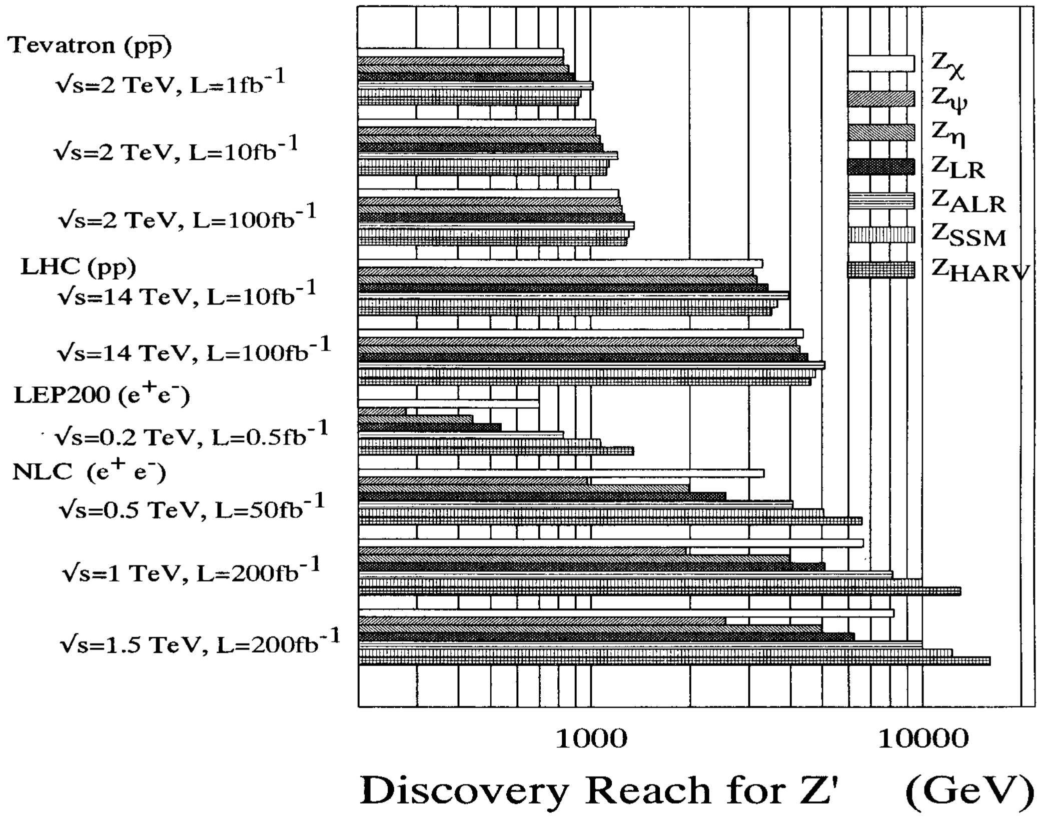

Figure 1: Tevatron and LHC bounds are based on 10 events in the $e^+e^- + \mu^+\mu^-$ channels; decays to SM final states only is assumed. LEP and NLC bounds are 99% CL using the observables σ_l, R^{had}, A^l_{LR} and A^{had}_{LR}.

2.1 Hadron Colliders

In what follows we will mostly limit our analysis to the conventional discovery channels involving Z' and W' decays to charged lepton pairs and charged leptons plus missing E_t, respectively. Regrettably, this leaves many 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. (Toback[19] has partially remedied this situation for the Tevatron as will be discussed below.) These possibilities require further study particularly at the LHC.

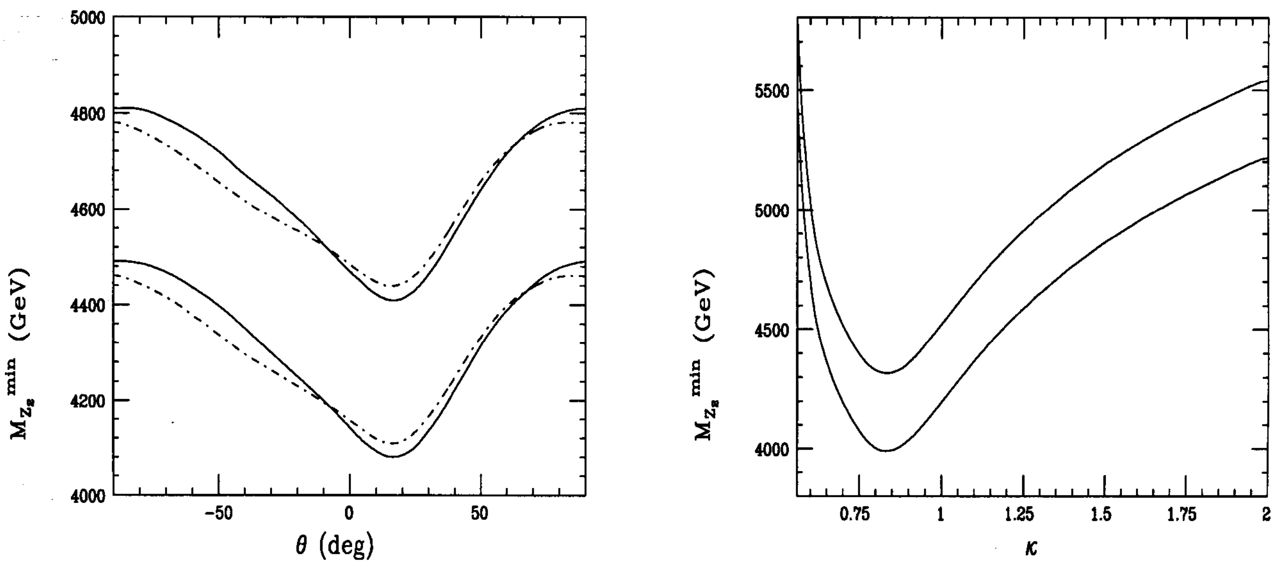

Figure 2: Z' search reaches at the 14 TeV LHC for E_6 models as a function of θ(left) and for the LRM as a function of κ(right). The curves on the left(right) correspond to integrated luminosities 100 and 200(50 and 100) fb^{-1}, respectively.

Traditionally, both Z' and W' search reaches are obtained through the use of 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 distribution can have only an infinitesimal background underneath it. Detailed detector simulations for both the Tevatron and LHC[20] validate this approximation as a good estimator of the true search reach at least for the more 'traditional' models where the Z' and W' are relatively narrow.

To obtain the search reach in the Z' case, we need to know the various fermionic couplings for a fixed value of the Z' mass to obtain σ. Traditionally, one also assumes that the Z' can

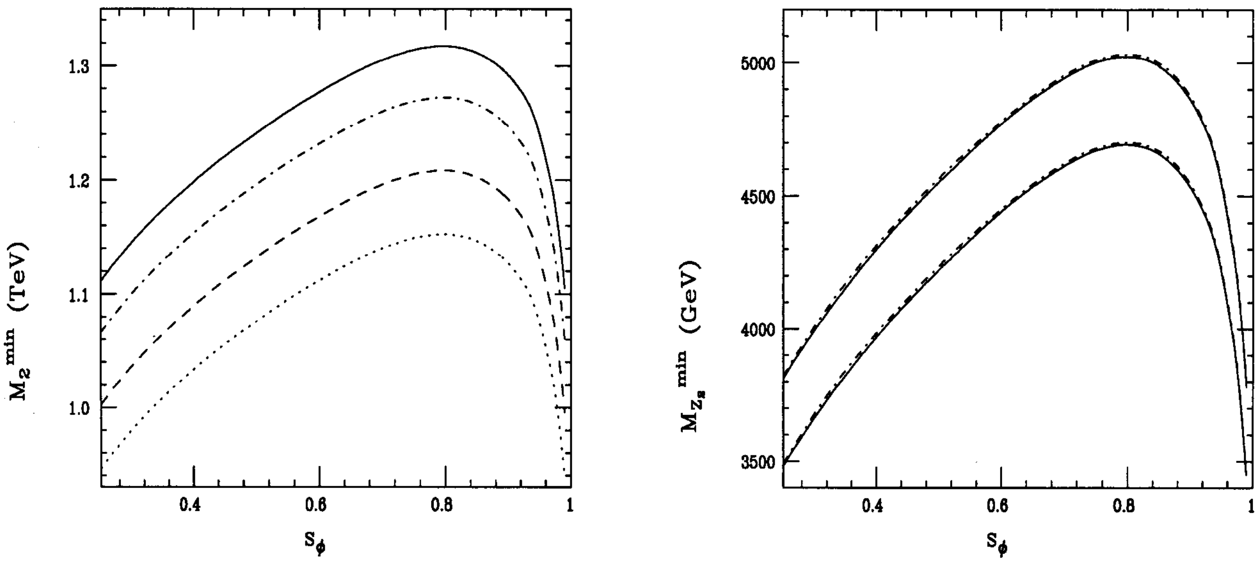

Figure 3: Same as the previous figure, but now for the UUM. On the left are the results for the Tevatron running at 2 TeV. From top to bottom the integrated luminosities are assumed to be 100, 50, 20 and 10 fb^{-1}, respectively. On the right are the corresponding LHC results for 50 and 100 fb^{-1}.

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, Figure 2 shows the discovery reaches for the Z' of the ER5M and the LRM at the LHC whereas Figure 3 shows the corresponding reaches for the UUM Z' at both the Tev33 and the LHC. The full set of figures for other models/colliders can be found in Ref.[18, 21]. Table 2.1 contains a summary of all of these results. 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.

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

Table 2: 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.

If the above estimate of the leptonic branching fraction is wrong, how seriously are the search reaches compromised? To get a feeling for this, consider reducing the value of B_l by a factor of two from the naive estimate given by the assumption that the Z' 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[9].) 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 2.1. 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.

Unlike the Z' case, the corresponding W_R searches in the LRM via the Drell-Yan process

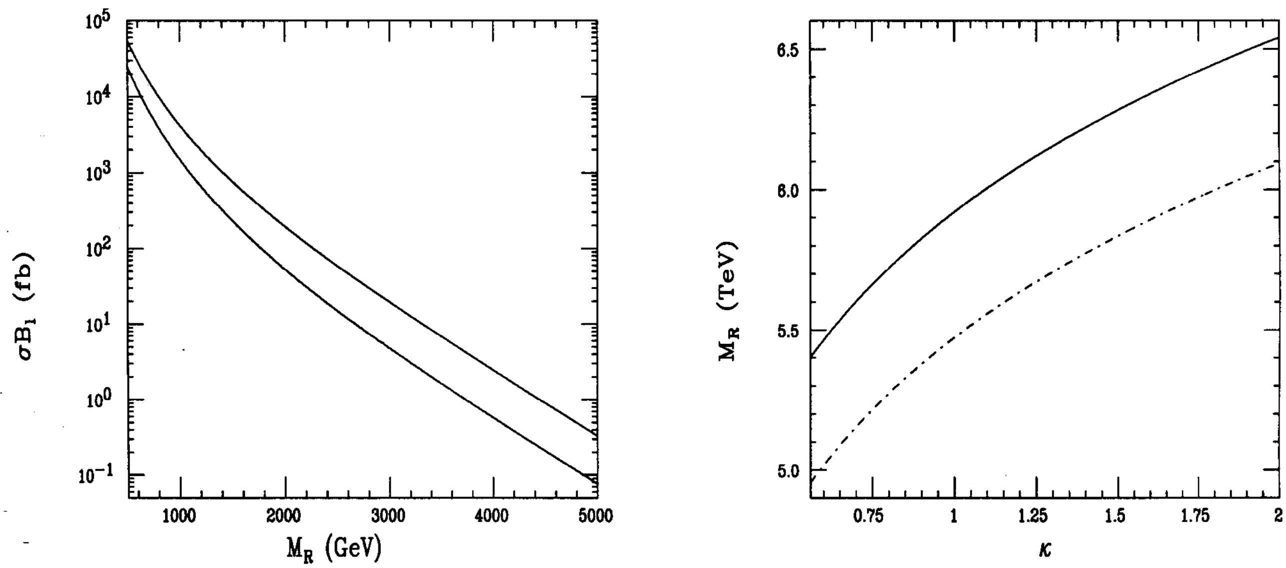

Figure 4: W_R production cross section times leptonic branching fraction at the LHC(left) for $\kappa = 1$ assuming $V_L = V_R$(top) or the worst case values(lower) of V_R. Also shown is the search reach for W_R vs. κ(right) at the LHC with $V_L = V_R$ for luminosities of 50 and 100 fb^{-1}.

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. If the conventional W' decay modes are suppressed, it may also be wise to search for the WZ final state as discussed by [19].

In models where both a W' and a Z' exist there is generally a direct relationship between their masses. For example, in the UUM case the W' and Z' are predicted to be degenerate, whereas in the LRM there is a non-trivial relationship:

$$\frac{M_{Z_R}^2}{M_{W_R}^2} = \frac{\kappa^2(1-x_w)\rho_R}{\kappa^2(1-x_w)-x_w}\,, \tag{1}$$

where $\rho_R = 1(2)$ signal symmetry breaking of $SU(2)_R$ by right-handed Higgs doublets(triplets) and $x_w = \sin^2\theta_w$. A measurement of the W' to Z' mass ratio will tell us a fair amount about the underlying gauge theory extension.

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	$\simeq 52$

Table 3: W_R search reaches of hadron colliders in the lepton plus 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.

Fig. 4 summarizes the W_R search at 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.

The corresponding figures for the complete set of results at other colliders can be found in Ref.[18, 21]; Table 2.1 summarizes these findings. We note that for the case of W_R, if we let $B_\ell \rightarrow B_\ell/2$, the search reach at the LHC is reduced by $\simeq$ 450 GeV for values of κ in the range $0.55 \leq \kappa \leq 2$.

2.2 Lepton Colliders: Indirect Searches

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.*[8] 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.

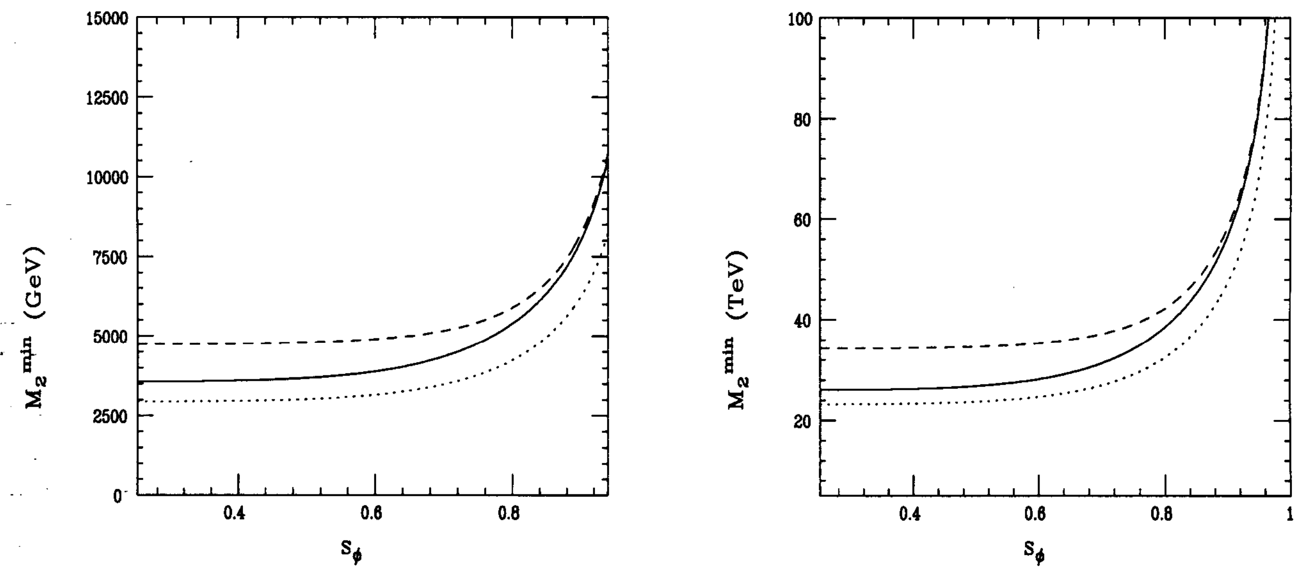

Figure 5: Indirect Z' search reaches for the UUM at the 500 GeV NLC(left) and for a 5 TeV e^+e^- NNLC collider(right) including initial state radiation. The dotted(solid, dashed) curve corresponds to the values obtained using leptonic(leptonic plus $b-$quark, all) observables. A luminosity of 50(1000) fb^{-1} has been assumed for the NLC(NNLC).

In the analysis by Rizzo presented at this meeting[18], the following standard set of observables were employed: 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 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. This was a first pass preliminary analysis wherein charged leptons as well as $b-$, $c-$, and $t-$quarks are considered simultaneously in obtaining the discovery reach. [Note: the results presented by Rizzo in the Snowmass workshop Subgroup summary talk did not include the c and t quark contributions.] The basic approach follows that of Hewett and Rizzo[22] and is outlined in the review of Cvetic and Godfrey[8], 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 $P = 90\%$ was assumed while for the LMC one can trade off a smaller effective P through modifications[23] in the integrated luminosity. The angular cuts, efficiencies, systematic errors, *etc*, applied in all cases were assumed to be the same. This is probably extremely optimistic for the LMC since it is unclear whether a microvertex detector with suitable b and c identification efficiencies is possible in that collider environment. Generically one find that ISR *lowers* the search reach by $15 - 20\%$ while beam polarization *increases* the reach by $15 - 80\%$ depending on the specific model and the machine energy, *i.e.*, the increase is found to be smaller at larger values of $\sqrt{s}$.

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

Table 4: Indirect Z' search reaches of lepton colliders in TeV employing all observables including the effects of ISR. The integrated luminosities of the NLC500, NLC1000, NLC1500, NNLC and LMC are assumed to be 50, 100, 100, 1000 and 1000 fb^{-1}, respectively.

Figure 5 displays a set of sample results of this analysis at the 500 GeV NLC and 5 TeV Next-to-Next Linear Collider(NNLC) for a Z' of the UUM 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. Table 2.2 summarizes all these 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.

It is possible to extend this technique to more exotic extended gauge models which do not obey family universality; a good example of this is the Z' in topcolor-assisted technicolor models[24] which is expected to lie below $\simeq 3$ TeV and above $\simeq 1.5$ TeV based on constraints from precision measurements[25]. The exact couplings depend upon a single free parameter, s_θ. Fig. 6 shows that the search reach for this Z' at the NLC is in excess of 4.7 TeV for all values of this parameter. Note the important role played by charm and top quark final states in obtaining this high reach.

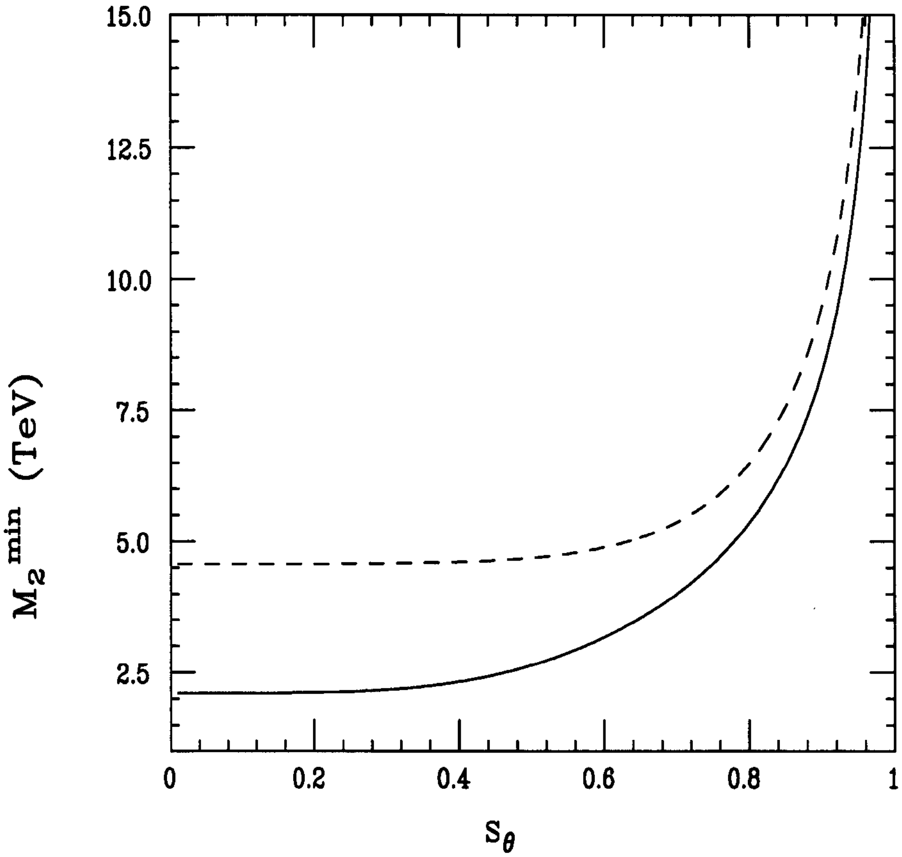

Figure 6: Search reach for the Z' in topcolor models at the 500 GeV NLC with an integrated luminosity of 50 fb^{-1}. The solid line includes data from the e, μ, τ and b finals states; the dashed curve also includes data on c and t.

A parallel analysis of the capability of lepton colliders to indirectly discover a Z' was performed by Godfrey[26] with a slightly different set of assumptions and observables, neglecting the effects of ISR. Numerically, the two analyses agree at the semi-quantitative level once the ISR contributions are taken into account. This is important in that it demonstrates that the Z' search reach is not extremely sensitive to the detailed nature of the assumptions of a particular analysis as long as they are fairly reasonable. A very interesting part of

Godfrey's analysis was a detailed examination of the various contributions which led to the χ^2 used in setting the search reach. For the 500 GeV NLC, this is nicely displayed in Fig. 7 for four different Z' models with the Z' mass set to 2 TeV. The figure shows the variation in the size of the individual χ^2 contributions is very significant. However, it also shows that the importance of the polarization asymmetries when information from various final state flavors are combined together.

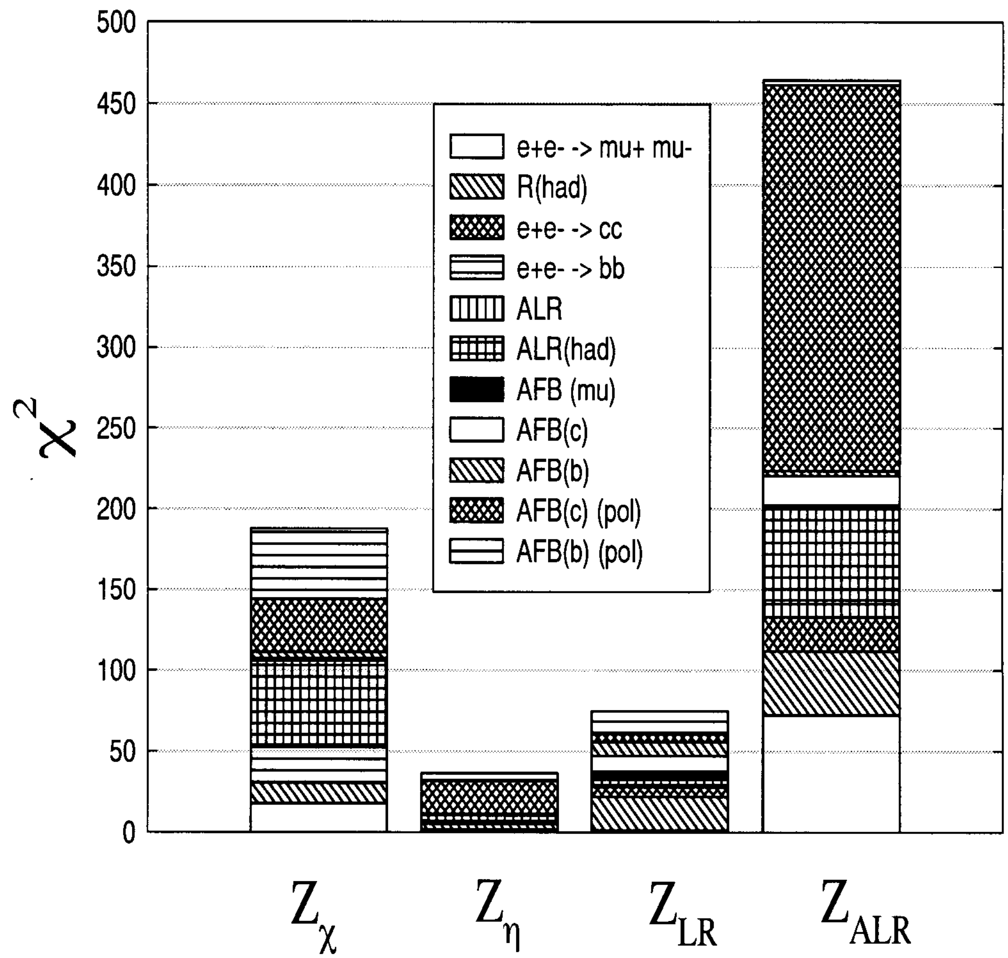

Figure 7: Contributions to the total χ^2 for a number of different observables used in the indirect Z' searches in e^+e^- colliders. The specific values are for the 500 GeV NLC with a luminosity of 50 fb^{-1}, $P = 100\%$, and a Z' mass of 2 TeV.

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'[27]. Unfortunately, an analysis of this situation including the effects of ISR was not available at the time of the meeting but a preliminary study by Cuypers[27] presented there indicated that the *ratio* of search reaches in the e^+e^- and e^-e^- modes might be stable under the modifications induced by ISR. Assuming this to be true, Rizzo[18] thus repeated the previous e^+e^- analysis *neglecting* ISR and also performed the complementary e^-e^- analysis with the same cuts, efficiencies, *etc*, and then took the ratio of the resulting reaches for a given extended gauge model. The results of this analysis for NLC500 are shown in Table 2.2. 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.[27]. 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.

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

Table 5: 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.

Of course, we need to verify these results directly; in a contribution to these proceedings, Cuypers examined the influence of a number of systematic effects in the searches for Z''s in the purely leptonic processes $e^+e^- \to \mu^+\mu^-$ as well as in Bhabha and Moller scattering[28]. He has now demonstrated that for these processes the effects of ISR modify the Z' search reaches by essentially the same amount $\simeq 15\%$. Cuypers also showed that the systematic uncertainties in both beam polarization (since both beams are polarized) and angular resolution (due to the t-channel pole) are far more important in Moller scattering than in $e^+e^- \to \mu^+\mu^-$. In fact, for Bhabha scattering, Cuypers has found that the angular resolution is the largest source of systematic error. Including all systematic effects, Bhabha scattering was found to be the least sensitive to the existence of a Z'. A comparison of the sensitivities of these three processes to a new Z' at a 500 GeV NLC with $P = 90\%$ is shown in Fig. 8.

A W' can also be produced in pairs in e^+e^- annihilation via s-channel γ, Z, Z' exchanges and some model-dependent t-channel exchange. For example, in the LRM(UUM), a heavy

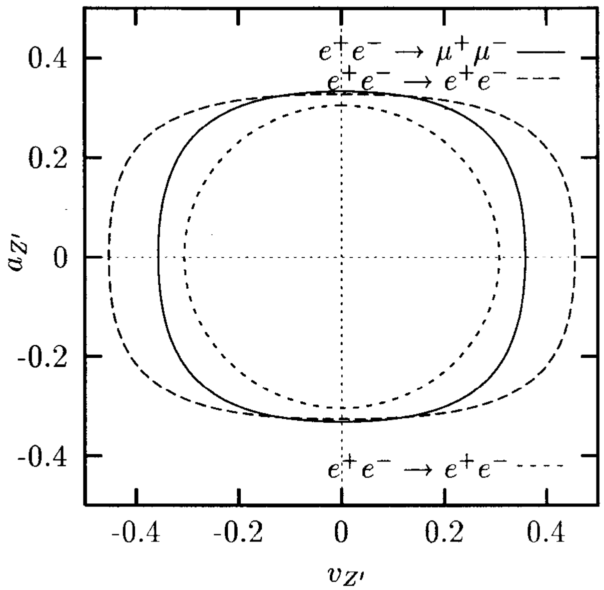

Figure 8: Contours of observability at 95% CL for the reduced Z' couplings including the effects of ISR, polarization and luminosity uncertainties, as well as the angular resolution of the detector. These results are for a 500 GeV NLC with $P = 90\%$ with a luminosity of 50(25) fb^{-1} in the $e^+e^-(e^-e^-)$ mode.

right-handed (massless left-handed) neutrino is exchanged in the t-channel. While the cross sections for this process are large[29], the kinematic reach for direct production is rather poor $\leq \sqrt{s}/2$. In the LRM, it is also possible to produce like-sign W_R pairs in e^-e^- collisions if the right-handed neutrino is a Majorana particle[30]. Of course, the reach is the same as in e^+e^- collisions. One possible way to extend the direct discovery range is to produce one on-shell and one off-shell W'[31]. In this case W' masses as large as $\simeq 0.8\sqrt{s}$ can be reached. Another possibility is to employ the γe collision mode where the W' is produced in association with some other fermion; in the LRM case this pushes the reach almost up to the kinematic limit: $m_{W_R} + m_N \leq \sqrt{s}$, where m_N is the mass of the right-handed neutrino[32]. It is clear from this discussion that for a more massive W', we need to perform an indirect search as has just been discussed in the case of a Z'.

Since virtual W''s are not conventionally exchanged in $e^+e^- \to f\bar{f}$ processes, it is difficult to obtain indirect mass limits. One possibility, explored by Hewett[33] in a first pass analysis for these proceedings, is the famous 'neutrino-counting' process $e^+e^- \to \nu\bar{\nu}\gamma$. In the SM, this reaction proceeds though the 'subprocess' $e^+e^- \to \nu\bar{\nu}$, which occurs via $s-$channel Z and $t-$channel W exchanges and an additional photon is then allowed to be emitted by any charged leg. In models with new W' and Z' gauge bosons there will be additional graphs that can lead to modifications in the SM result. For a given W' mass, the corresponding Z' mass is fixed by a model dependent relationship as discussed above. The SM W and W' are treated as contact interactions in this first approximation. Thus in the LRM (assuming Dirac neutrinos) or the UUM we need only specify κ or s_ϕ as well as $M_{W'}$ to perform the complete calculation if we neglect any possible mixing among the gauge bosons. Unfortunately, this radiative process is suppressed in comparison to the usual fermion pair rate by an additional power of α as well as by three-body phase space, though these are somewhat offset by the appearance of large logarithms. We might thus expect that the available statistical power may not be able to provide much of a search reach, but it is clear that any extension beyond $M_{W'} \geq \sqrt{s}$ is important.

To render the process observable (and also to make the cross section finite by removing infrared and colinear divergences), the photon energy is assumed to be $\geq 0.05\sqrt{s}$ and to make an angle with the electron or positron beam directions $\geq 20°$, which should be well inside the NLC detector. What observables are useful in obtaining constraints? In addition to the total cross section, we can form the Left-Right asymmetry, A_{LR}, using the initial beam polarization. In the SM, the value of A_{LR} is close to unity due to the rather strong influence of the W. Unfortunately, for interesting W' masses this situation is not altered and one finds that A_{LR} is not useful. One can also, in principle, use the energy and angular distributions of the final state photon; however, a short analysis demonstrates the the by far dominant influence here is just QED in the W/W' contact interaction approximation. We are thus left with only the total cross section as the only useful observable.

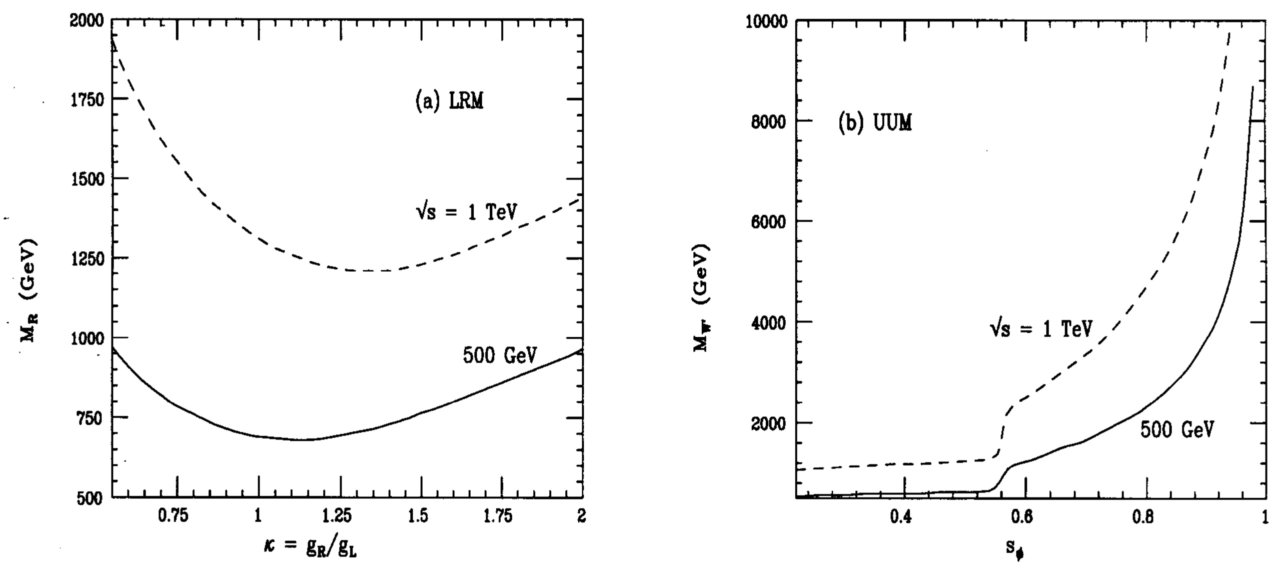

Figure 9: 95% CL lower bound on the W' in (a) the LRM as a function of κ and (b) the UUM as a function of s_ϕ. In each case the lower(upper) curve corresponds to a center of mass energy of 500 GeV(1 TeV) and an integrated luminosity of 50(200) fb^{-1}.

The results of Hewett's analysis for the exclusion reach of this process for a new W' can be seen in Fig. 9 for both the LRM and the UUM cases. This figure show the minimum value of the W' mass as a function of either κ or s_ϕ for NLC collider energies of 500 GeV and 1 TeV and luminosities of 50 and 200 fb^{-1} respectively. For the LRM case, the limits range from $\simeq$ 680 GeV to $\simeq$ 975 GeV above the kinematic limit in the $\sqrt{s}$=500 GeV case for $0.55 \leq \kappa \leq 2$. For the case of a 1 TeV collider the corresponding reach ranges from 1200 to 1950 GeV. For the UUM with small values of s_ϕ, the reach is found to not be significantly greater than $\sqrt{s}$. As s_ϕ grows beyond 0.5, the leptonic couplings of the W' and Z' increase and the reach increases dramatically to several times $\sqrt{s}$ for both the 500 GeV and 1 TeV NLC. For both models we see that reasonable exclusion reaches are obtainable. The influence of the contact interaction approximation will be examined in a future analysis[34].

3 Extraction of Coupling Information

Once a new gauge boson is found a new era begins, *i.e.*, to ascertain all of its properties. Only if we know as much as possible about the new Z'/W' will we be able to determine its origin within a more general extended gauge model. Both hadron and lepton colliders can play important and complementary roles in reaching this goal. Each has its own strength and weaknesses and are discussed separately.

3.1 Hadron Colliders

The determination of the couplings of a Z' at a hadron collider is a highly non-trivial task due to both large backgrounds and limited statistics. In our discussion below, we focus on the determination of Z' couplings to the SM fermions at the LHC. Certainly the same problems are to be faced at other hadron colliders. The recent review of Z' physics by Cvetic and Godfrey[8] shows that in an idealized world, without backgrounds or systematic errors to worry about, the LHC will be able to do a reasonable job at extracting the couplings of a new Z' if its mass is not too much greater than 1 TeV by combining a series of different measurements in a simultaneous fit. What we really want to know is how well this program can be performed by a real LHC detector.

At first glance it would appear that statistics should *not* be a problem at, *e.g.*, the LHC with a luminosity of $100 fb^{-1}$, but this is not always true. While the typical search reach for a Z' at the LHC is near 5 TeV this would give us only a few events. To even begin to *analyze* a Z' requires more than 100 events in the discovery channel. This tells us that it is unlikely that we will ever gain sufficient information about a Z' much heavier than about 3-3.5 TeV[20] unless it had a particularly large production cross section or significantly more luminosity were to be available. In reality, the reach for coupling analysis is far inferior to the 3-3.5 TeV range at the LHC.

When a Z' is discovered, both ATLAS and CMS will easily measure its mass, total width(Γ_{tot}), and its production cross section in the leptonic channel(σ_l), which in the narrow width approximation is given by $\sigma(q\bar{q} \rightarrow Z')B_l(= \Gamma(Z' \rightarrow \ell^+\ell^-)/\Gamma_{tot})$. Unfortunately, this last observable *cannot* be used to extract coupling information since the value of B_l

depends not only on the conventional quark and lepton couplings to the Z'(which we want to determine) but also on possible decays to SUSY partners, exotic states, *etc.* Fortunately, however, the product $\sigma_l \Gamma_{tot}$ is decay mode independent and will tell us something about the overall Z' coupling strength. Of course, the production of a Z' at the LHC in the real world does not look like the narrow width approximation but more like Fig. 10, so that resolution effects need to be deconvoluted and efficiencies and backgrounds accounted for before this product of observables can be readily determined.

This observation reminds us that past analyses of the extraction of Z' coupling information at hadron colliders have not accounted for detector issues and have systematically relied on the narrow width approximation. (It is also generally assumed that there will be little uncertainty due to variations in the parton densities. This may be a valid assumption in 10 years time when the LHC begins analyzing data!) Before a Z' is found at the LHC we need to revisit these older analyses and try to understand how well the proposed observables can be measured in a more realistic situation. We began this exercise at the Snowmass workshop and report below on some of our results and observations. A complete model-independent coupling extraction analysis through the use of detector simulations for the LHC is still some years away from being demonstrated.

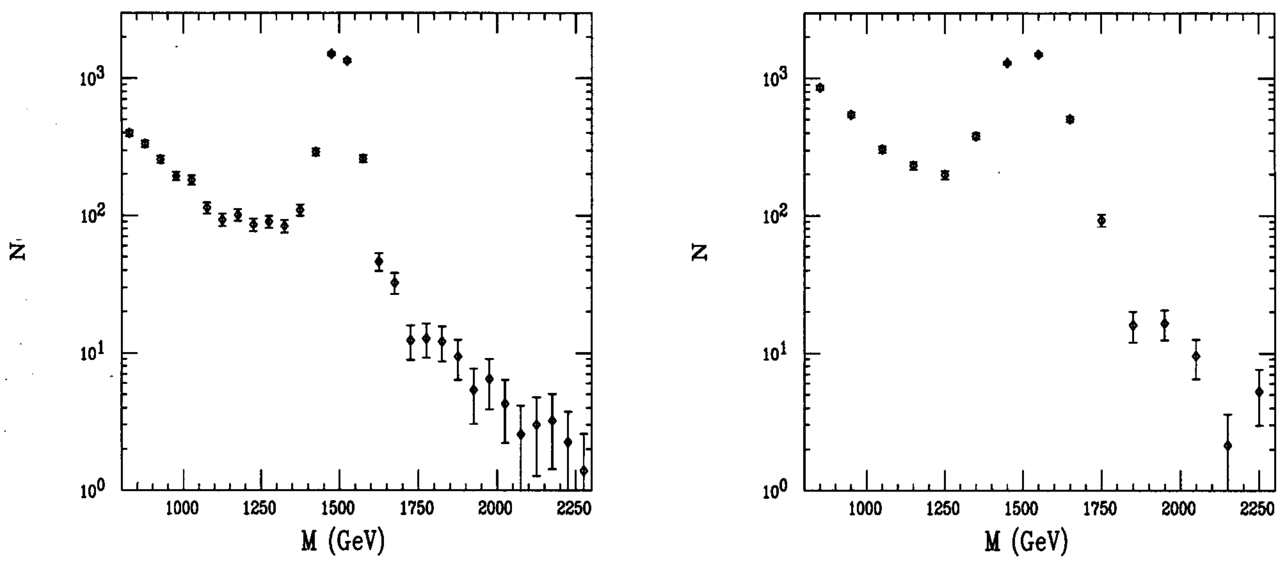

Figure 10: Simulation of a typical Z' lepton pair invariant mass distribution assuming $M_{Z'}$=1.53 TeV for electrons(left) and muons(right) smeared with the ATLAS(CMS) resolutions at the LHC assuming a luminosity of $100 fb^{-1}$ and $|\eta_l| \leq 2.5$. The bin size is 50(100) GeV; only Drell-Yan backgrounds are included.

Since the lepton-pair channel is the discovery channel for a Z', it is obvious that we should try to extract as much information as possible there. Several observables have been proposed[35]:

- The forward-backward asymmetry, A_{FB};
- The rapidity ratio, r_{y1}, the ratio of cross sections in the central rapidity region in comparison to larger rapidities;
- The τ polarization asymmetry, A_τ, in $Z' \to \tau^+\tau^-$;
- The various polarization asymmetries that can be formed if at least one polarized proton beam is available. Clearly, this possibility also relies on having excellent knowledge of the polarized parton densities of the proton at $Q^2 \simeq 1$ TeV^2. It would seem that such observables will not be used in the first round effort to disentangle Z' couplings.

Note that all these observables are *ratios* of cross sections and are thus less subject to systematic uncertainties and are also independent of the Z' decay modes. Since we are assuming that hundreds of Z' events are available the measurements of these observables are not statistics limited. In principle, we would like to have available Monte Carlo studies of each of these quantities including detector simulations. This work was initiated during the workshop.

A_{FB} is perhaps the most well-studied of this set of observables for purposes of coupling extraction but again generally only in the narrow width limit. Unfortunately, as a function of the dilepton mass, A_{FB} will look more like Fig. 11 when it is first measured and not a simple number as given by the narrow width estimate.

To proceed one needs to cut away as much of the underlying Drell-Yan background as possible without too much of a loss in statistics. A mass cut such as $M_{Z'} \pm (1-2)\Gamma_{tot}$ is found to be most useful. For the sample model in Fig. 10, a cut of $\pm(2)\Gamma_{tot}$ captures about 60(72)% of the Z' with a background contamination of less than about 2% for electron pairs. (For wider Z''s, as well as for muon pairs, the backgrounds could be significantly worse and tighter invariant mass cuts should be applied.) The events remaining after this cut can then be plotted vs. rapidity as has been done in the analysis of Wulz[20] with the full CMS detector simulation. It is clear from Figures 12 and 13, that the Z''s are reasonably distinguishable even with a mass of 3 TeV. However, it is not so easy to go from *real data* that may look like these plots to the extraction of coupling information. (Remember that we want to do more than distinguish models, we want to get at the Z' couplings.) As before, resolutions can be deconvoluted, but the background's contribution to the asymmetry may be potentially large. Numerically, however, the narrow width approximation works fairly well in practise and gives reasonable results at the level of $10-15\%$ for both the rapidity-integrated asymmetry as well as the dependence of A_{FB} on rapidity. Fig. 14 shows a direct comparison between Monte Carlo A_{FB} 'data' generated using a simplified simulation of the ATLAS detector and the narrow width approximation expectations for a typical Z'. At least

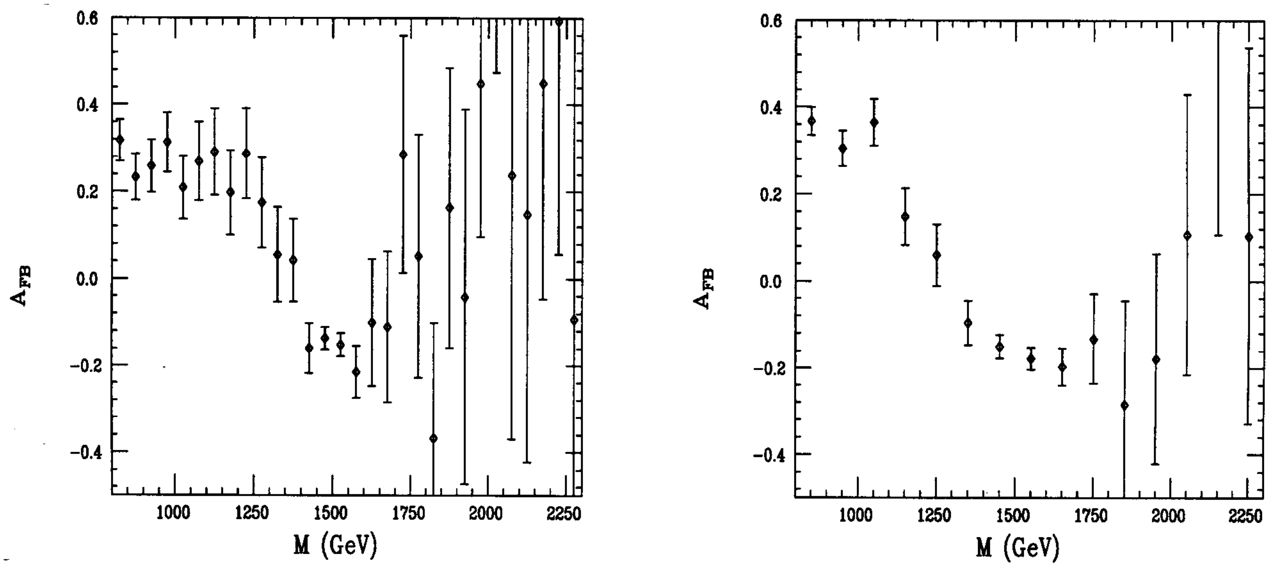

Figure 11: Simulation of the A_{FB} for a typical Z' with a mass of $M_{Z'}$=1.53 TeV for electrons(left) and muons(right) smeared with the ATLAS(CMS) resolutions at the LHC assuming a luminosity of $100 fb^{-1}$ and $0.3 \leq |\eta_l| \leq 2.5$. The bin size is 50(100) GeV; only Drell-Yan backgrounds are included. The low η region is removed to eliminate ambiguous hemisphere assignments for the leptons.

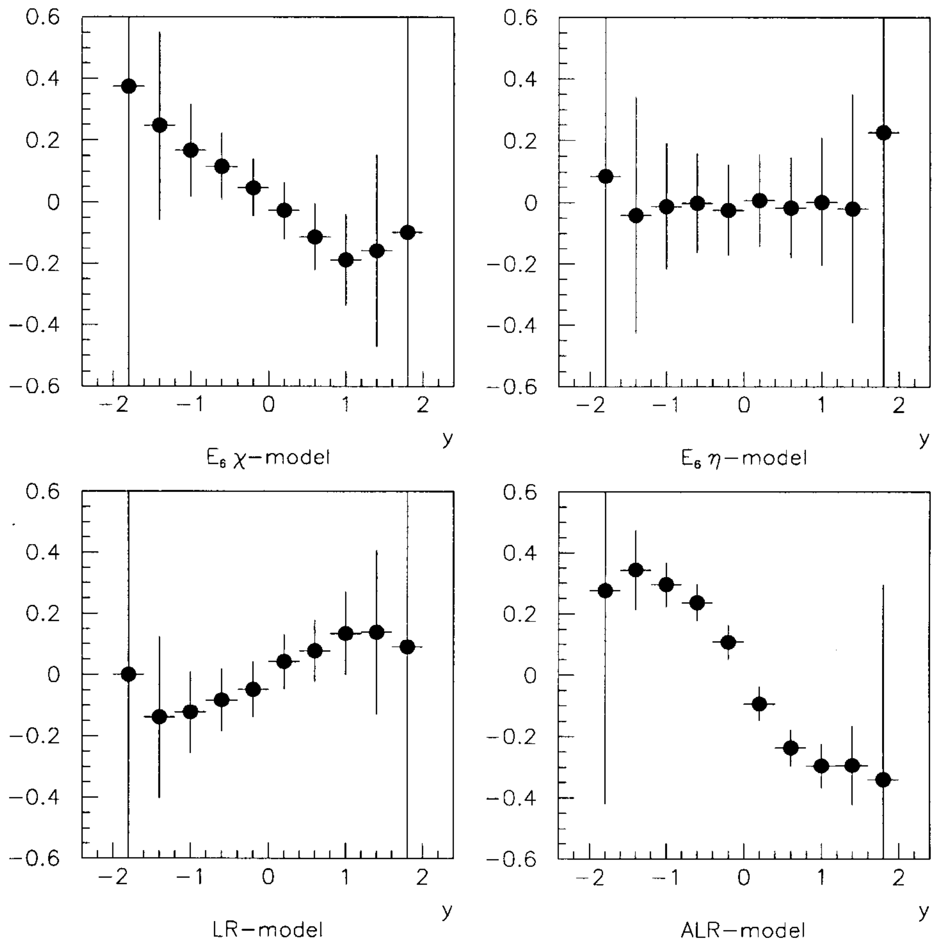

Figure 12: Simulation of the Z' forward-backward asymmetries for different models as a function of rapidity(y) assuming $M_{Z'} = 2$ TeV as seen by the CMS detector in the dimuon channel. Signal and background have been integrated over the lepton pair mass range $M_{Z'} \pm \Gamma_{tot}$.

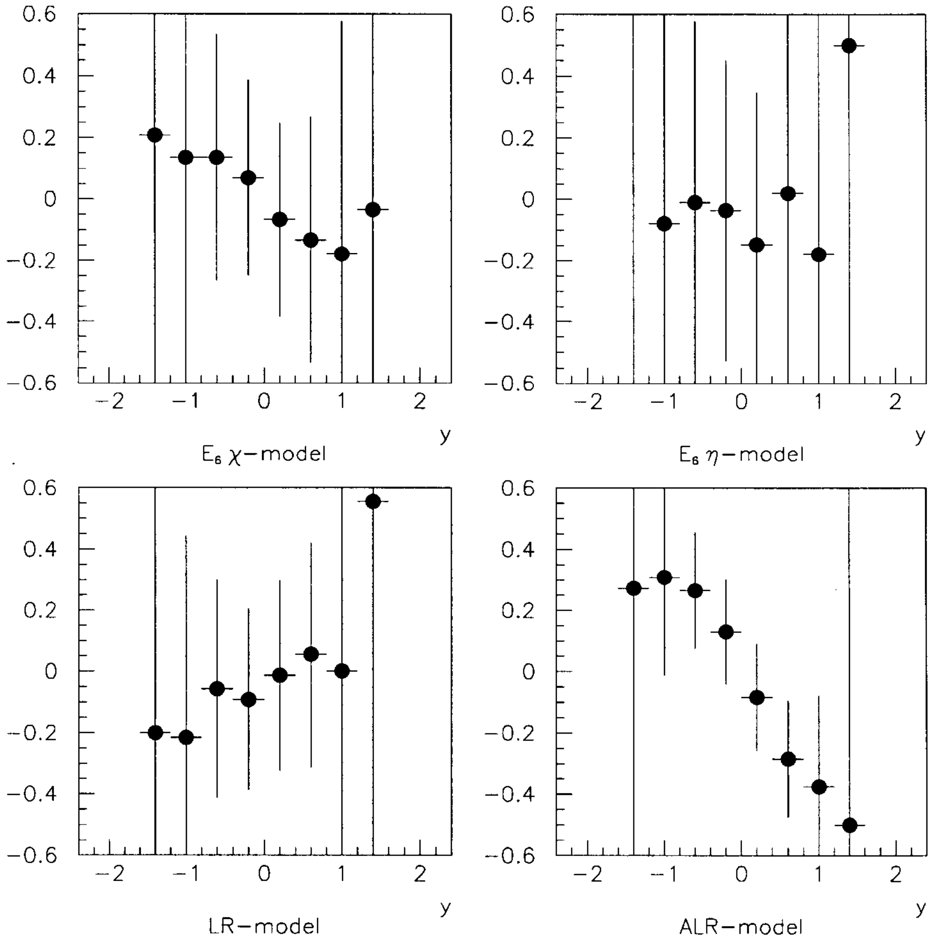

Figure 13: Same as the previous figure but now for $M_{Z'} = 3$ TeV.

for this observable the narrow width method works well within the statistics; we have verified that this result also holds for other models.

The rapidity ratio, r_{y1}, provides a complementary probe of the Z' couplings. The relevant quantity to measure is the rapidity dependence of Z' production cross section. Fig. 14 shows a comparison between the simplified ATLAS simulation and the narrow width approximation expectation which has been rescaled to go through the first Monte Carlo point. (Remember, we loose about 40% of our events due to the invariant mass cut on the lepton pair.) This result indicates that the narrow width approach does not do a very good job at getting the right shape for this distribution which results in values of r_{y1} which are systematically high by as much as 30% or more when this method is used. An examination of several other models with random Z' masses and couplings shows similar qualitative results. Of course, we would need a more thorough simulation to verify these results and we would like to expand the study to many more models.

One might ask how the narrow width approximation can do so well in the case of A_{FB} but perform rather poorly for r_{y1}. It is clear that what is happening in the A_{FB} case, since ratios of two cross sections at the *same* rapidity are taken, is that the excesses predicted by the narrow width method are cancelling out when the ratio is taken. Since the ratios at *different* rapidities are used in r_{y1} this cancellation does not occur.

In the narrow width approximation, assuming universality, A_τ provides a direct determination of the ratio of the left- and right-handed leptonic couplings of the Z'. In principle, this is a very sensitive probe of the Z' couplings, *e.g.*, in the ER5M as we vary the parameter θ, A_τ takes on its entire allowed range of values and is generally large in magnitude. The technique is essentially that employed by LEP to extract this same quantity for the SM Z, however here we have to apply it in a hadronic environment. To study the $Z' \to \tau^+\tau^-$ requires good triggering for τ-pairs with a excellent background rejection to get a clean sample. Studies by the CMS Collaboration indicate that these basic requirements can be achieved at a luminosity of 10^{33} at the LHC. A preliminary analysis of the use of A_τ to extract Z' coupling information was performed some years ago by Anderson, Austern and Cahn[36] for the SSC. They concluded that a reasonable determination of A_τ might be possible for a Z' with a mass near 1 TeV but that backgrounds became too serious if the mass were much larger. It would be very interesting and important to repeat this analysis for the LHC with a semi-realistic detector simulation to see if it remains valid.

Other observables have been proposed to probe Z' couplings:

- Associated Z' production, *i.e.*, $pp \to Z'V$ where $V = W, Z$ or γ. For different choices of V different combinations of the Z' couplings are being probed. The observable of interest here is the cross section ratio $R_V = \sigma(pp \to Z'V, Z' \to \ell^+\ell^-)/\sigma(pp \to Z' \to \ell^+\ell^-)$, wherein the $Z' \to \ell^+\ell^-$ branching fraction drops out.

- Rare Z' decays such as the 3-body mode $Z' \to W\ell\nu_\ell$. The relevant observable here is the ratio of branching fractions, $r_{Wl\nu}$, for the $W\ell\nu_\ell$ final state scaled to the $\ell^+\ell^-$ discovery mode.

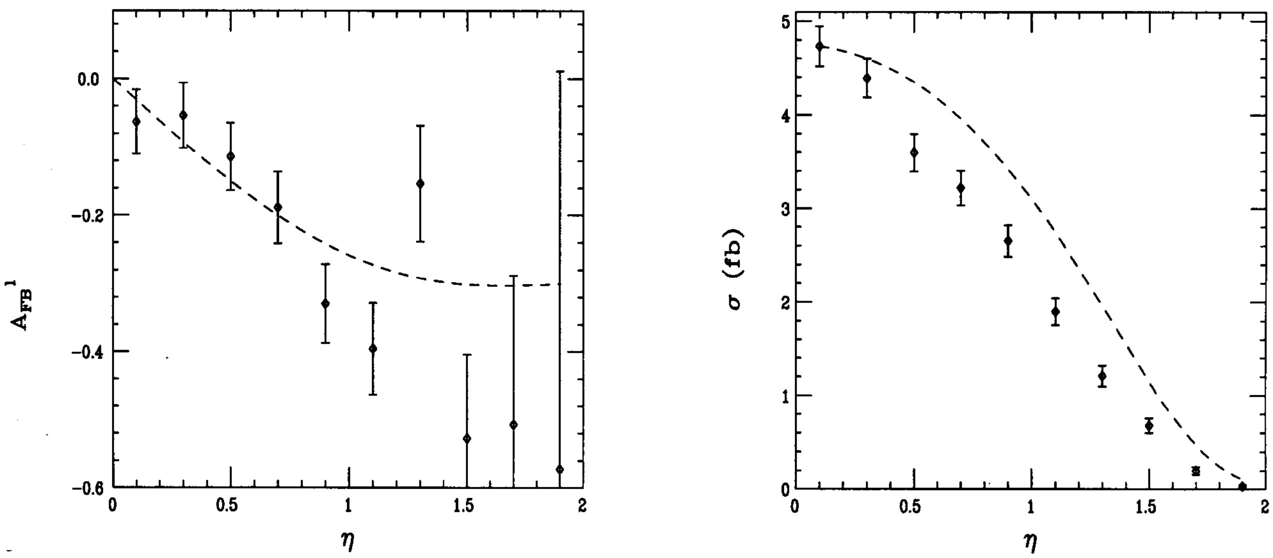

Figure 14: A typical comparison of narrow width approximation expectations with a simulation for an ATLAS-like detector in the $Z' \to e^+e^-$ mode assuming a luminosity of $100 fb^{-1}$ at the LHC. The Z' mass is 1.53 TeV. On the left(right) is $A_{FB}(\sigma)$ as a function of rapidity. The dashed curve is the narrow width result which has been rescaled in the σ case to go through the first data point. Only events in the mass bin $M_{Z'} \pm \Gamma_{tot}$ are included.

- The ratio of cross sections for $pp \to Z' \to jj$ compared to $pp \to Z' \to \ell^+\ell^-$.

The immediate problem with the first two ideas is one of rate. For example, a 1 TeV Z' in the ER5M has a value of R_γ in the 0.001-0.007 range for photon E_t's greater than 50 GeV with $|\eta_\gamma| \leq 2.5$. Both R_Z and R_W have similar magnitudes. Using leptonic W, decay modes alone would compromise these measurements since the rates would be far too low. However,if the $Z, W \to jj$ modes are used we need to cleanly separate the two classes of events, thus requiring excellent hadronic mass resolution. While providing a reasonably clean signature, it does not seem too likely that associated production will be of much use for Z' masses too far above 1 TeV due to a rapid fall off in statistics. A Monte Carlo analysis of these processes at the LHC needs to be performed.

The quantity $r_{Wl\nu}$ is generally found to be somewhat larger than R_V for most EGM's and reasonable rates may be obtainable for Z' masses as large as 1.5-2 TeV. The problem here is background since there is no $Z' \to \ell^+\ell^-$ in the final state to separate this from related SM processes. S/B grows rapidly with increasing Z' mass and it is unlikely that this mode can be used far above 1 TeV. Again, a Monte Carlo study of this and related processes at the LHC would be very useful.

$Z' \to jj$ may be useful provided good resolution is available. The statistics is excellent but the QCD backgrounds are enormous. This possibility has already been explored in the somewhat tamer Tevatron environment by both the CDF and D0 Collaborations[37, 7] and has been briefly discussed by ATLAS[38]. It is clear that more detector studies need to be done to insure the usefulness of this mode.

3.2 Lepton Colliders

If a Z' is sufficiently light that we can produce it directly at a lepton collider, the determination of its various properties will be straightforward. We need only to repeat the successful programs of SLC and LEP for the SM Z over again at a higher energy. As noted above, however, it may be most likely that a Z' will be too massive to undertake such a program at least at the first generation lepton colliders so that we can only make use of the same indirect signatures discussed above to sniff out the Z' couplings. As we will see below, a major piece of the puzzle will be supplied if a hadron collider, such as the LHC, tells us the Z' mass before coupling extraction analyses begin at lepton colliders.

In a contribution to these proceedings, Riemann[39] analyzed the capability of future e^+e^- colliders operating below the Z' resonance to measure the $Z\bar{f}f$ couplings, where $f = \ell, b, c$. Her analysis implicitly assumed that the mass of the Z' was already known and was used as an input into the numerical extraction of couplings. Fig. 15 shows the capability of the NLC running at different energies to measure the leptonic couplings of the Z' in the LRM and ER5M χ as the gauge boson mass is varied. It's clear from this analysis that with reasonable luminosities the NLC will be able to extract leptonic coupling information for Z' masses up to $2 - 3\sqrt{s}$. (We recall that the *search reach* was found to be $6 - 10\sqrt{s}$.) These results

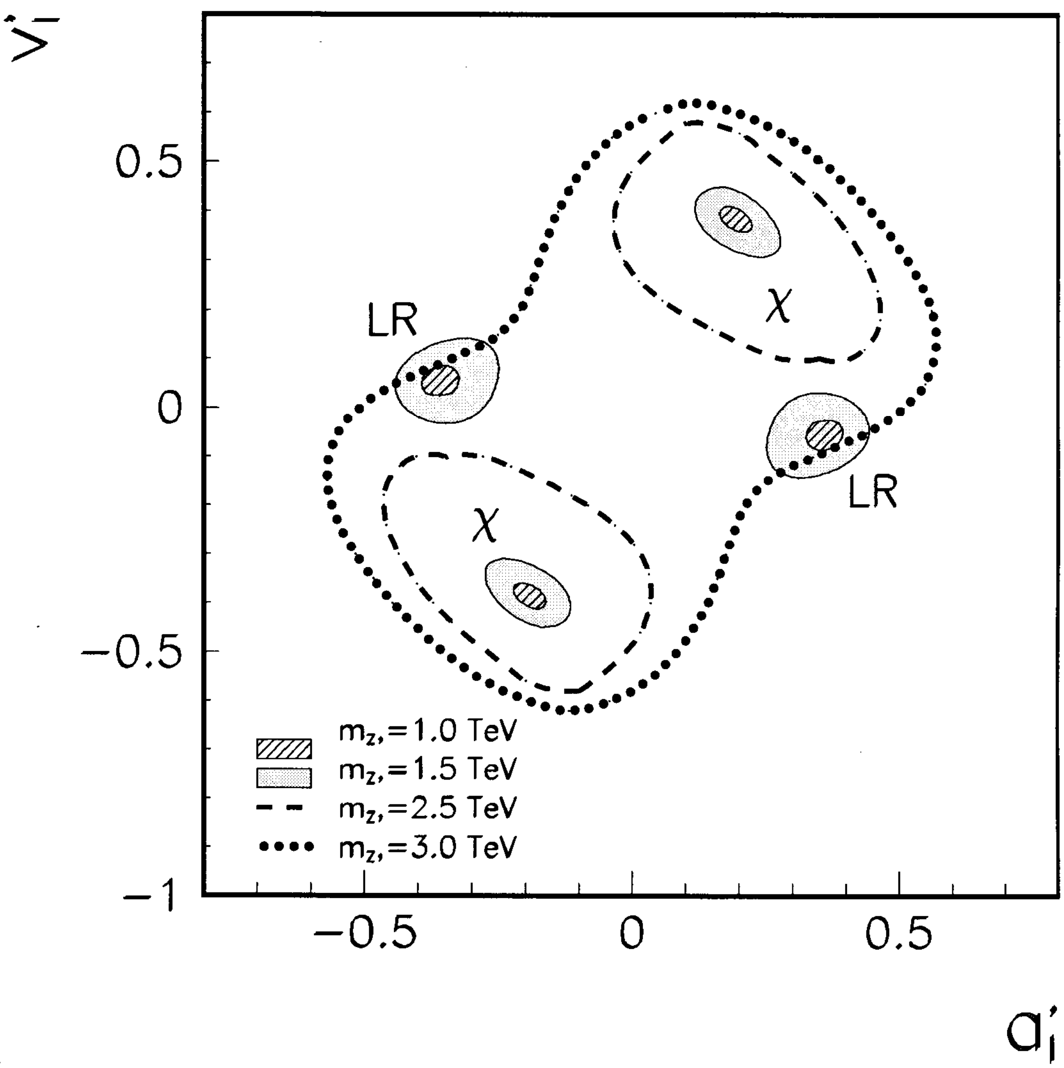

Figure 15: 95% CL contours for v_l' and a_l' for a 500 GeV NLC with a luminosity of $50 fb^{-1}$. The Z' is taken to be in the χ or LRM with a 1(1.5) TeV mass corresponding to the hatched(shaded) area. The dashed(dotted) contours are 95% CL limits on the $Z'll$ couplings for the χ case and a mass of 2.5(3) TeV. A beam polarization of 80% has been assumed.

are essentially statistics limited, there being few sizeable sources for systematic errors in the purely lepton mode.

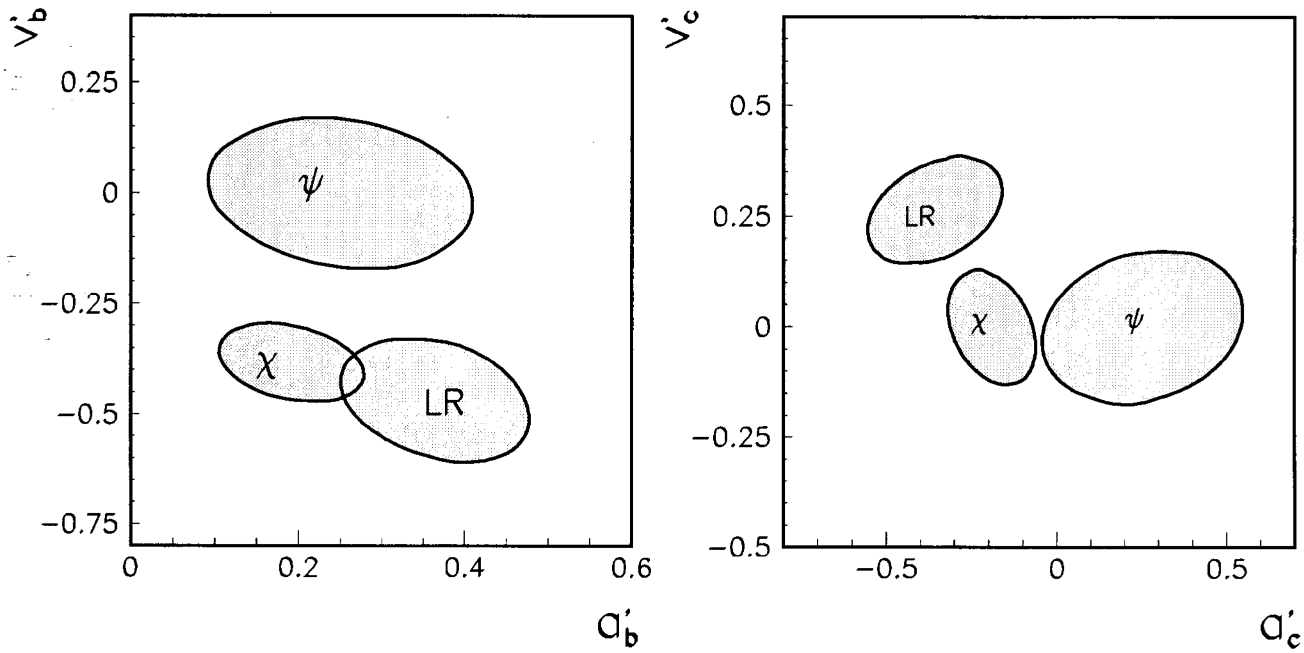

Figure 16: Model discrimination at 95% CL, for a 1 TeV Z' at a 500 GeV NLC with $50 fb^{-1}$ of luminosity; on the left(right) for bottom(charm) quarks assuming a systematic uncertainty in observables of 1(1.5)%. A $b(c)$-tagging efficiency of 60(40)% has been assumed together with a beam polarization of 80%.

Riemann goes further in her analysis to take on the more daunting task of constraining the c and b quark couplings of the Z'. As she correctly points out, the size of the systematic errors for the measurements on these final states is rather critical to this program. For example, for a $Z_\chi(Z_\psi)$ with a 1 TeV mass, the size of the allowed region in the $v'_b - a'_b(v'_c - a'_c)$ plane approximately doubles at a 500 GeV NLC with a luminosity of 50 fb^{-1} if a systematic error of 1(1.5)% is added to all relevant observables. However, as Fig. 16 shows, the NLC will still be able to extract coupling information and distinguish various models using the c, b final states.

What if the Z' mass were not *a priori* known? It is clear in this circumstance that measurements taken at a single value of $\sqrt{s}$ will not be able to disentangle Z' mass and coupling information. The reason is straightforward: to leading order in $s/M_{Z'}^2$, rescaling all of the couplings and the value of Z' mass by a common factor would leave all of the observed deviations from the SM invariant. In this approximation, the Z' exchange appears only as a contact interaction. Thus as long as $\sqrt{s} < M_{Z'}$, the only potential solution to this problem lies in obtaining data on the deviations from the SM predictions at several different values of $\sqrt{s}$ and combining them together in a single fit. In a presentation at this workshop, Rizzo[40] reported a first benchmark analysis of this kind in which data from different values

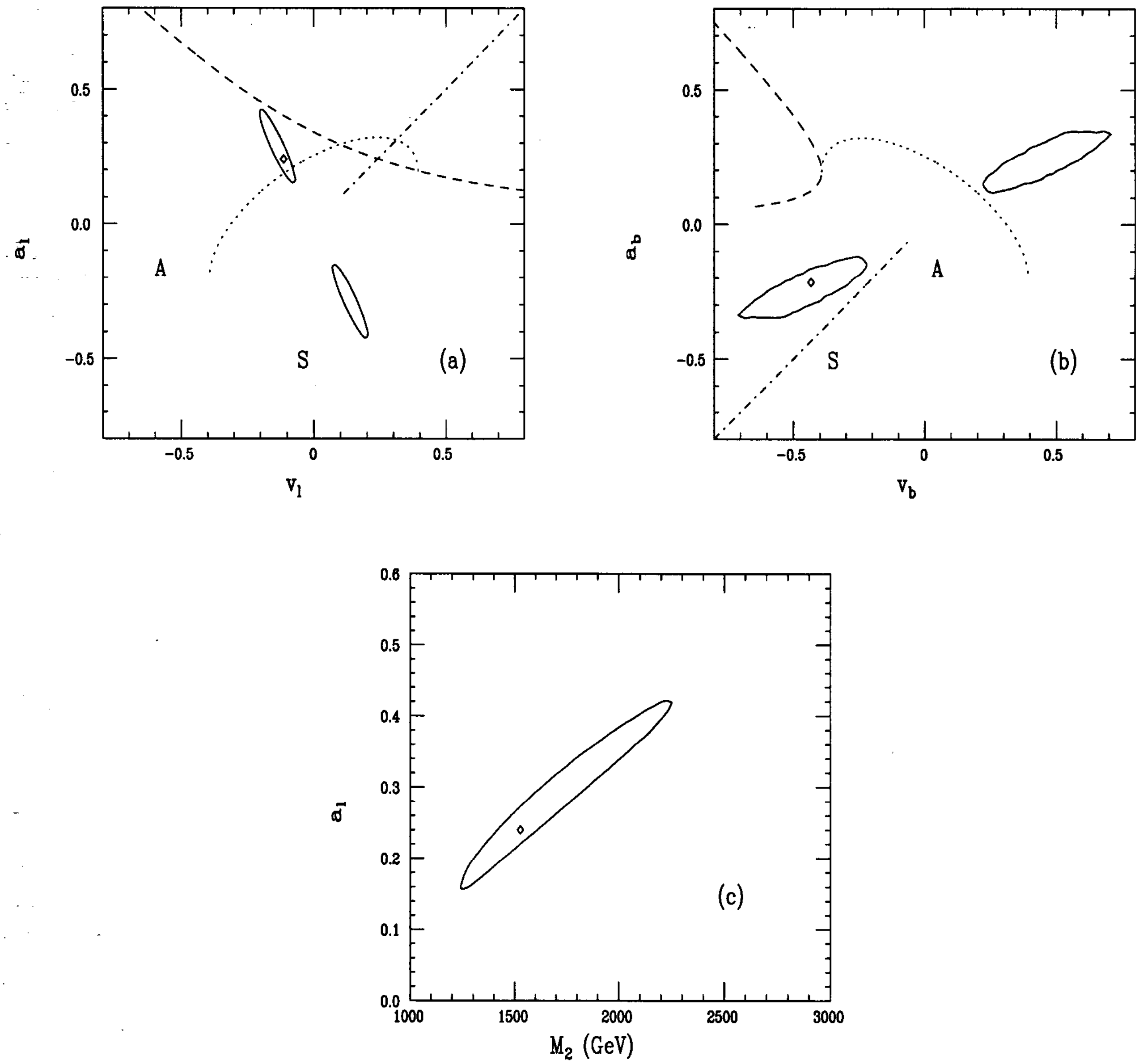

Figure 17: 95% CL allowed regions for the extracted values of the (a) lepton and (b) b-quark couplings for a Z' with randomly generated mass and couplings compared with the predictions of the E_6 model(dotted), the Left-Right Model(dashed), and the Un-unified Model(dash-dot), as well as the Sequential SM and Alternative LR Models(labeled by 'S' and 'A', respectively.) (c) Extracted Z' mass; only the $a_\ell > 0$ branch is shown. In all cases the diamond represents the corresponding input values. Here we seer that the couplings of this Z' do not correspond to those of any of our favorite models.

of $\sqrt{s}$ are combined. Only the leptonic and b-quark couplings to the Z' were considered. For Z' masses in the 1.5-2 TeV range which were *a priori* unknown, this analysis found that combining data taken at 500, 750 and 1000 GeV was sufficient to determine the 4 unknown couplings as well as the Z' mass. To insure model-independence, the mass and couplings were chosen *randomly* and *anonymously* from rather large ranges.

A sample result of this procedure is shown in Fig. 17. The three figures correspond to two-dimensional projections of the full five dimensional $(v_l', a_l', v_b', a_b', M_{Z'})$ 95% CL fit. The following standard set of observables were employed: σ_f, A_{FB}^f, A_{LR}^f, $A_{pol}^{FB}(f)$ where $f = \ell, b$ labels the fermion in the final state and, special to the case of the tau, $< P_\tau >$ and P_τ^{FB}. Universality amongst the generations was also assumed. While none of the couplings are extremely well determined we learn enough to rule out all conventional extended gauge models as the origin of this particular Z'. Note that knowledge of both the leptonic and $b-$quarks couplings was required to rule out the case of an E_6 Z'. Fig. 18 shows how these results significantly improve if the the Z' mass becomes known; one now performs a four dimensional fit instead of five.

3.3 W' Couplings

The model-independent extraction of the couplings of a new W' have not attracted as much attention in the literature as has the Z' case although several of the same techniques can be used. For example, the A_{FB} of the decay lepton from W' decay can tell us a great deal about the W' couplings. However, assuming these couplings are essentially chiral (as they are in all conventional models with a W'), as is well known this asymmetry will not be able to distinguish left-handed from right-handed couplings. As suggested by Cvetic and Godfrey[8], the associated production of a W' with a SM W will only occur at a reasonable rate if the W' has a substantial coupling to left-handed fields. For example, in the LRM, WW' associated production cannot occur in the limit of zero gauge boson mixing if the quarks are assumed to be massless. In the Un-unified Model, however, the cross section for this process is rather large since the W' couples in a left-handed manner. Similarly, rare decay modes such as $W' \to Wf\bar{f}$ will not occur if the W' is purely right-handed. It would be quite beneficial if a model-independent analysis of the W''s couplings could be performed.

Another way to get a handle on W' couplings, particularly if the traditional lepton plus missing energy final state is suppressed, is to search for the decay $W' \to WZ$. This decay is particularly sensitive to the detailed structure of the extended gauge model. This analysis has already been done at the Tevatron by CDF for Run I[41] and has been extended for these proceedings by Toback[19] for the $W \to e\nu, Z \to jj$ decay mode. The W' was assumed to have SM-like couplings to the initial $q\bar{q}$.

Apart from explicit factors which may appear at the $W'WZ$ vertex, the decay rate for $W' \to WZ$ scales as $M_{W'}^5$ in the large W' mass limit. This is easily understood in that the W' is actually coupling to the longitudinal components of the SM W and Z in this limit. Clearly, perturbation theory for the W' width would become meaningless before the W' mass exceeds

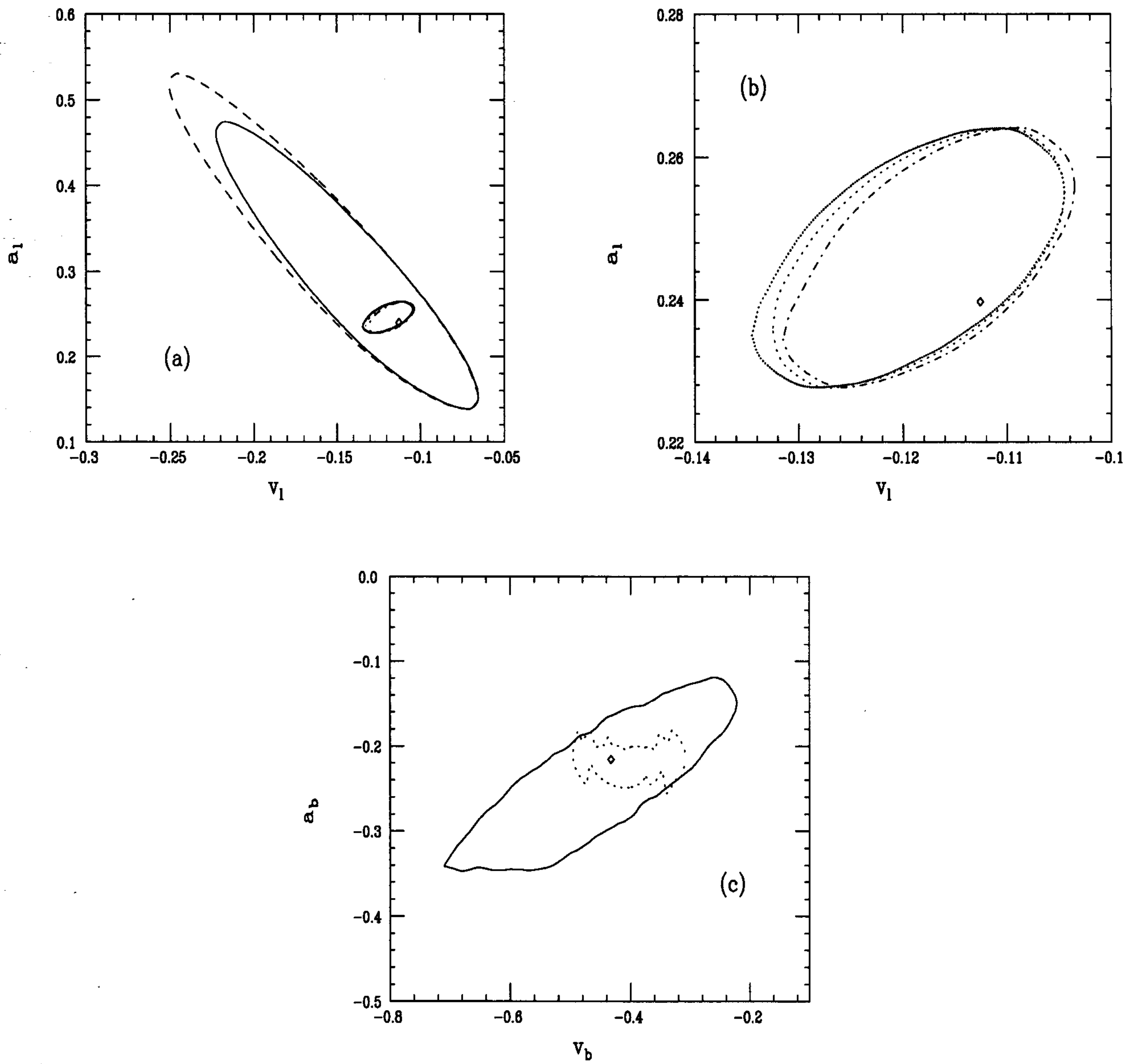

Figure 18: (a) Expanded lobe(solid) from the previous figure; the dashed curve shows the same result but for $P = 80\%$. The smaller ovals, expanded in (b) apply when the Z' mass is known. Here, in (b), $P = 90(80)\%$ corresponds to the dash-dot(dotted) curve while the case of $P = 90\%$ with $\delta P/P = 5\%$ corresponds to the square-dotted curve. (c) Expanded lobe(solid) from the previous figure (b); the dotted curve corresponds to the case when $M_{Z'}$ is known.

values of order 1 TeV. A similar story applies to decays of the type $Z' \to WW$. Fortunately, in most realistic extended gauge models, the $W'WZ$ and $Z'WW$ vertex is only generated via $W - W'/Z - Z'$ mixing produced when we go over from the weak to mass eigenstate basis. In this case, the overall $W'WZ[Z'WW]$ vertex is proportional to this mixing angle, which is generically of order $(M_W/M_{W'})^2[(M_Z/M_{Z'})^2]$. The growth in the $W' \to WZ$ and $Z' \to WW$ widths is thus significantly dampened and scales linearly with the mass of the new gauge boson.

Assuming that the $W - W'$ mixing angle is just the ratio $(M_W/M_{W'})^2$, Toback shows that TeV33 has a significant sensitivity to this mode for W' masses up to about 525 GeV for an integrated luminosity of $30 fb^{-1}$. A similar sensitivity was found for the $Z \to WW$ mode. It would be interesting to extend this study to the LHC.

4 Summary/Outlook

The physics of extended gauge sectors is particularly rich. Analyses have evolved to the point where detector considerations are becoming increasingly important. Many of the problems associated with the determination of the couplings of new gauge bosons now have to be faced with specific detector capabilities in mind. Although much work has been done, there is still a lot to be done along the directions begun here. Hopefully they will be completed before new gauge bosons are discovered.

5 Acknowledgements

The author would like to thank all of the members of this subgroup, as well as the entire New Phenomena group, for making the Snowmass meeting successful.

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