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Determination of the Z' Mass and Couplings Below Threshold at the NLC

Thomas G. Rizzo[1]

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309 USA

ABSTRACT

We investigate the capability of the NLC to indirectly determine both the mass as well as the couplings to leptons and b-quarks of a new neutral gauge boson below direct production threshold. By using data collected at several different values of the collider center of mass energy, we demonstrate how this can be done in an anonymous and model-independent manner. The procedure can be easily extended to the top and charm quark couplings.

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1 Introduction

A new neutral gauge boson, Z', is the most well-studied of all exotic particles and is the hallmark signature for extensions of the Standard Model(SM) gauge group. If such a particle is found at future colliders the next step will be to ascertain its couplings to fermions. At hadron colliders, a rather long list of observables has been proposed over the years to probe these couplings–each with its own set of drawbacks and limitations [1]. It has been shown, at least within the context of E_6-inspired models, that the LHC($\sqrt{s} = 14$ TeV, $100 fb^{-1}$) should be able to extract useful information on all of the Z' couplings for $M_{Z'}$ below $\simeq 1-1.5$ TeV. (N.B., that this analysis included only statistical errors and should be redone.) At the NLC, when $\sqrt{s} < M_{Z'}$, a Z' manifests itself only indirectly as deviations in observables, *e.g.*, cross sections and asymmetries from their SM expectations. Fortunately the list of useful precision measurements that can be performed at the NLC is reasonably long and the expected large beam polarization(P) plays a very important, perhaps crucial, role. In the past, analyses of the ability of the NLC to extract Z' coupling information in this situation have taken for granted that the value of $M_{Z'}$ is already known from elsewhere, *e.g.*, the LHC [1]. Here we address the more complex issue of whether it is possible for the NLC to obtain information on the couplings of the Z' if the mass were for some reason *a priori* unknown. In this case we would not only want to determine all fermionic couplings but in addition the Z' mass as well.

If the Z' mass were unknown it would appear that the traditional NLC Z' coupling analyses would become problematic. Given data at a fixed value of $\sqrt{s}$ which shows deviations from the SM due to a Z', one would not be able to *simultaneously* extract the value of $M_{Z'}$ as well as the corresponding couplings. The reason is clear: to leading order in $s/M_{Z'}^2$, rescaling all of the couplings and the value of $M_{Z'}$ by a common factor would leave 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 deviations in observables from the SM at *several*, distinct $\sqrt{s}$ values and combining them into a single fit. Here we report on the first analysis of this kind, focussing on observables involving only leptons and/or b-quarks. In performing such an analysis there are many questions that one can raise: how many $\sqrt{s}$ values are needed? How do we distribute the luminosity($\mathcal{L}$) to optimize the results? Can such an analysis be done while maintaining model-independence? In this *initial* study we begin to address these and some related questions.

2 Analysis

In order to proceed with this benchmark study, we will make a number of simplifying assumptions and parameter choices. These can be modified at a later stage to see how they influence our results. In this analysis we consider the following ten observables: $\sigma_{\ell,b}$, $A_{FB}^{\ell,b}$,

$A_{LR}^{\ell,b}$, $A_{pol}^{FB}(\ell,b)$, $< P_\tau >$, and P_τ^{FB}. Other inputs and assumptions are as follows:

e,μ,τ universality	ISR with $\sqrt{s'}/\sqrt{s} > 0.7$
$P = 90\%$, $\delta P/P = 0.3\%$	$\delta\mathcal{L}/\mathcal{L} = 0.25\%$
$\epsilon_b = 50\%$, $\Pi_b = 100\%$	$\lvert\theta\rvert > 10^\circ$
$\epsilon_{e,\mu,\tau}(\sigma) = 100\%$, $\epsilon_\tau(P_\tau) = 50\%$	$\delta A/A = 0.3\%$
Neglect t-channel terms in $e^+e^- \to e^+e^-$	

Of special note on this list are (i) a b-tagging efficiency(ϵ_b) of 50% for a purity(Π_b) of 100%, (ii) the efficiency for identifying all leptons is assumed to be 100%, although only 50% of τ decays are assumed to be polarization analyzed, (iii) a 10° angle cut has been applied to all final state fermions, and (iv) a strong cut to events with an excess of initial state radiation(ISR) has also been made. (v) A small systematic error associated with the various asymmetry measurements has also been included. In addition to the above, final state QED as well as QCD corrections are included, the b-quark and τ masses have been neglected, and the possibility of $Z-Z'$ mixing has been ignored. Since our results will generally be statistics limited, the role played by the systematic uncertainties associated with the parameter choices above will generally be rather minimal.

To insure model-independence, the values of the Z' couplings, *i.e.*, $(v,a)_{\ell,b}$, as well as $M_{Z'}$, are chosen *randomly* and *anonymously* from rather large ranges representative of a number of extended gauge models. Monte Carlo data representing the above observables is then generated for several different values of $\sqrt{s}$. At this point, the values of the mass and couplings are not 'known' *a priori*, but will later be compared with what is extracted from the Monte Carlo generated event sample. Following this approach there is no particular relationship between any of the couplings and there is no dependence upon any particular Z' model. (We normalize our couplings so that for the SM Z, $a_\ell = -1/2$.) Performing this analysis for a wide range of possible mass and coupling choices then shows the power as well as the limitations of this technique.

To get an understanding for how this procedure works in general we will make two case studies for the Z' mass and couplings, labelled here by I and II. There is nothing special about these two choices and several other parameter sets have been analyzed in comparable detail to show that the results that we display below are rather typical. To begin we generate Monte Carlo data at $\sqrt{s}$ =0.5, 0.75 and 1 TeV with associated integrated luminosities of 70, 100, and 150 fb^{-1}, respectively, and subsequently determine the 5-dimensional 95% CL allowed region for the mass and couplings from a simultaneous fit using the assumptions listed above. This 5-dimensional region is then projected into a series of 2-dimensional plots which we can examine in detail. Figs. 1 and 2 show the results of our analysis for these two case studies compared with the expectations of a number of well-known Z' models [1]. Several things are immediately apparent-the most obvious being that two distinct allowed regions are obtained from the fit in both cases. (The input values are seen to lie nicely inside one of them.) This two-fold ambiguity results from our inability to make a determination of the overall sign of *one* of the couplings, *e.g.*, a_ℓ. If the sign of a_ℓ were known, only a single allowed region would appear in Figs. 1a-b and 2a-b and a unique coupling determination would be obtained. Note that this *same* sign ambiguity arises in SLD/LEP data for the SM Z and is only removed through the examination of low-energy neutrino scattering. Secondly, we see that the leptonic couplings are somewhat better determined than are those of the b-quark, which is due to the fact that the leptonic observables involve only leptonic couplings, while those for b-quarks involve both types. In addition, there is more statistical power available in the lepton channels due to the assumption of universality and the leptonic results employ two additional observables related to τ polarization. Thirdly, we see from Figs. 1a-b the importance in obtaining coupling information for a number of different fermion species. If only the Fig. 1a results were available, one might draw the hasty conclusion that an E_6-type Z' had been found. Fig. 1b clearly shows us that this is not the case. Evidently *neither* Z' corresponds to any well-known model. Lastly, as promised, the Z' mass is determined in both cases, although with somewhat smaller uncertainties in case II. We remind the reader that there is nothing special about these two particular cases.

Of course, the clever reader must now be asking the question 'why use 3 different values of $\sqrt{s}$, why not 2 or 5?' This is a very important issue which we can only begin to address here. Let us return to the mass and couplings of case I and generate Monte Carlo 'data' for only $\sqrt{s}$=0.5 and 1 TeV with $\mathcal{L}$= 100 and 220 fb^{-1}, respectively, thus keeping the total $\mathcal{L}$ the *same* as in the discussion above. Repeating our analysis we then arrive at the '2-point' fit as shown in Fig. 3a; unlike Fig. 1a, the allowed region does not close and extends outward to ever larger values of v_ℓ, a_ℓ. The corresponding Z' mass contour also does not close, again extending outwards to ever larger values. We realize immediately that this is just what happens when data at only a single $\sqrt{s}$ is available. For our fixed $\mathcal{L}$, distributed as we have done, we see that there is not enough of a lever arm to simultaneously disentangle the Z' mass and couplings. Of course the reverse situation can also be just as bad. We now generate Monte Carlo 'data' for the case I mass and couplings in 100 GeV steps in $\sqrt{s}$ over the 0.5 to 1 TeV interval with the same total $\mathcal{L}$ as above but now distributed as 30, 30, 50, 50, 60, and 100 fb^{-1}, respectively. We then arrive at the '6-point' fit shown in Fig. 3b which suffers a problem similar to Fig. 3a. What has happened now is that we have spread the fixed $\mathcal{L}$ too thinly over too many points for the analysis to work. This brief study indicates that a proper balance is required to simultaneously achieve the desired statistics as well as an effective lever arm to obtain the Z' mass and couplings. It is important to remember that we have *not* demonstrated that the '2-point' fit will never work. We note only that it fails with our specific fixed luminosity distribution for the masses and couplings associated with cases I and II. It is possible that for 'lucky' combinations of masses and couplings a 2-point fit will suffice. Clearly, more work is required to further address this issue.

How do these results change if $M_{Z'}$ *were* known or if our input assumptions were modified? Let us return to case I and concentrate on the allowed coupling regions corresponding to a choice of negative values of $v_{\ell,b}$; these are expanded to the solid curves shown in Figs. 4a and 4c. The large dashed curve in Fig. 4a corresponds to a reduction of the polarization to 80%

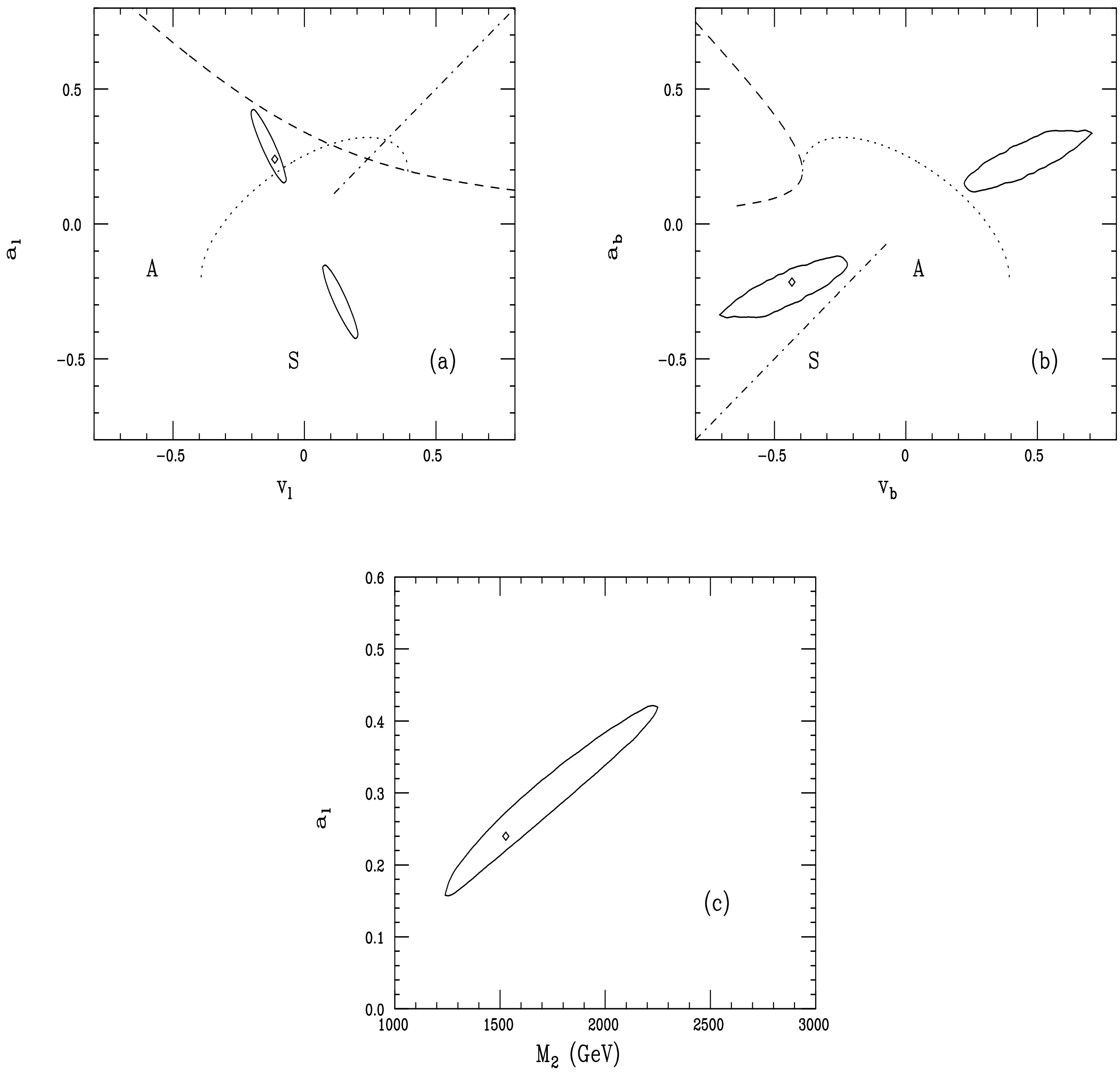

Figure 1: 95% CL allowed regions for the extracted values of the (a) lepton and (b) b-quark couplings for the Z' of case I compared with the predictions of the E_6 model(dotted), the Left-Right Model(dashed), and the Un-unified Model(dash-dot), as well as the Sequential SM and Alternative LR Models(labeled 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.

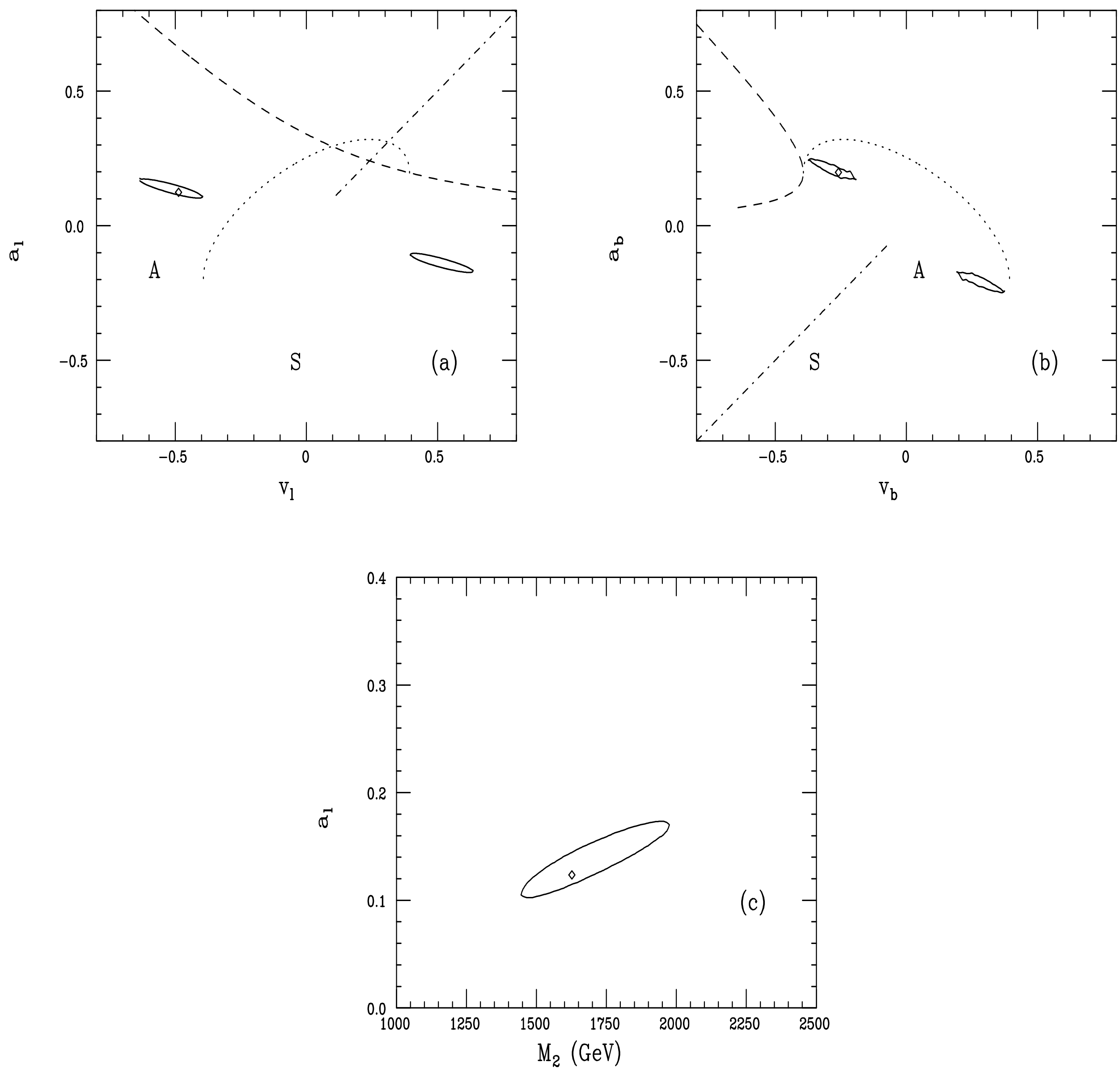

Figure 2: Same as Fig. 1 but for a different choice of Z' mass and couplings referred to as case II in the text.

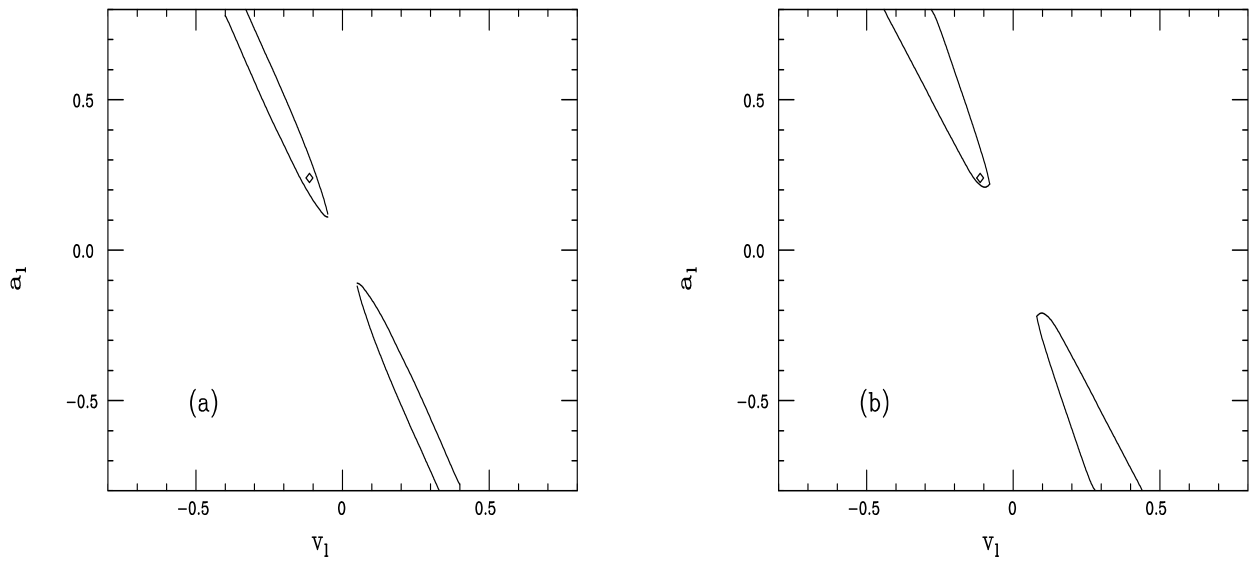

Figure 3: Failure of the method in case I when data is taken at (a) too few ('2-point' fit) or (b) too many ('6-point' fit) different center of mass energies for the same total integrated luminosity as in Figs. 1 and 2. The luminosities are distributed as discussed in the text.

with the same relative error as before. While the allowed region expands the degradation is not severe. If the Z' mass were known, the 'large' ellipses shrink to the small ovals in Fig. 4a; these are expanded in Fig. 4b. This is clearly a radical reduction in the size of the allowed region! We see that when the mass is known, varying the polarization or its uncertainty over a reasonable range has very little influence on the resulting size of the allowed regions. From Fig. 4c we see that while knowing the Z' mass significantly reduces the size of the allowed region for the b couplings, the impact is far less than in the leptonic case for the reasons discussed above. Figs. 5a and 5b show that case I is not special in that similar results are seen to hold for case II.

What happens for larger Z' masses or when data at larger values of $\sqrt{s}$ becomes available? Let us assume that the 'data' from the above three center of mass energies is already existent, with the luminosities as given. We now imagine that the NLC increases its center of mass energy to $\sqrt{s}$= 1.5 TeV and collects an additional 200 fb^{-1} of integrated luminosity. Clearly for Z' masses near or below 1.5 TeV our problems are solved since an on-shell Z' can now be produced. Thus we shall concern ourselves with Z' masses in excess of 2 TeV. Figs. 6a-d show the result of extending our procedure–now using 4 different $\sqrt{s}$ values, again for two distinct choices of the Z' mass and couplings. These '4-point' results are a combined fit to the data at all four center of mass energies. (Only one of the allowed pair of ellipses resulting from the overall sign ambiguity is shown for simplicity.) Note that the Z' input masses we

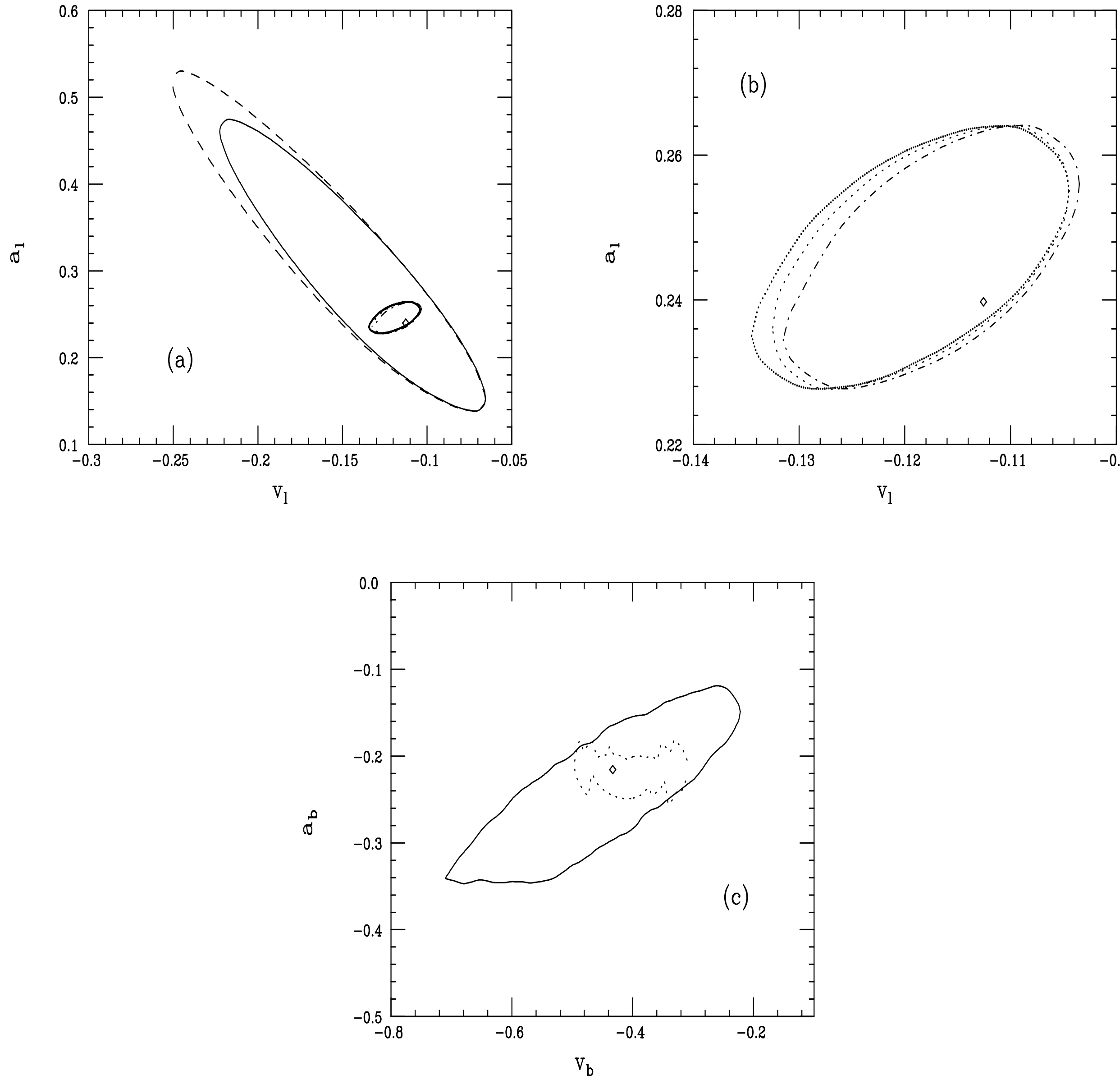

Figure 4: (a) Expanded lobe(solid) from Fig. 1a; the dashed curve shows the same result but for $P = 80\%$. The smaller ovals, expanded in (b) apply when the Z' mass is known. Here, in (b), $P = 90(80)\%$ corresponds to the dash-dot(dotted) curve while the case of $P = 90\%$ with $\delta P/P = 5\%$ corresponds to the square-dotted curve. (c) Expanded lobe(solid) from Fig.1b; the dotted curve corresponds to the case when $M_{Z'}$ is known.

have chosen are well in excess of 2 TeV where the LHC may provide only very minimal information on the fermion couplings [1]. Clearly by using the additional data from a run at $\sqrt{s}$=1.5 TeV this technique can be extended to perform coupling extraction for Z' masses in excess of 2.5 TeV. The maximum 'reach' for the type of coupling analysis we have done is not yet known. It seems likely, based on these initial studies, that the extraction of interesting coupling information for Z' masses in excess of 3 TeV seems possible for a reasonable range of parameters.

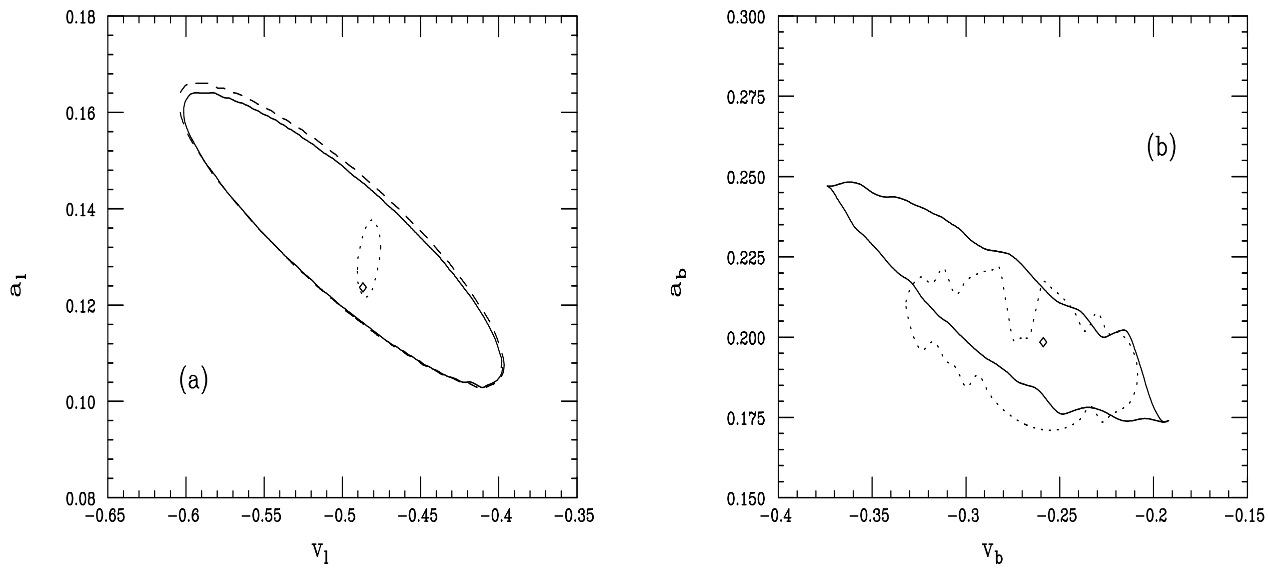

Figure 5: (a) Expanded lobe(solid) from Fig. 2a; the dashed curve shows the same result but for P = 80%. The smaller dotted oval, applies when the Z' mass is known and P = 90%. (b) Expanded lobe(solid) from Fig. 2b; the dotted curve corresponds to the case when $M_{Z'}$ is known.

3 Outlook and Conclusions

In this paper we have shown that it is possible for the NLC to extract information on the Z' couplings to leptons and b-quarks even when the Z' mass is not *a priori* known. The critical step for the success of the analysis was to combine the data available from measurements performed at several different center of mass energies. For reasonable luminosities the specific results we have obtained suggest, but do not prove, that data sets at at least 3 different energies are necessary for the procedure to be successful.

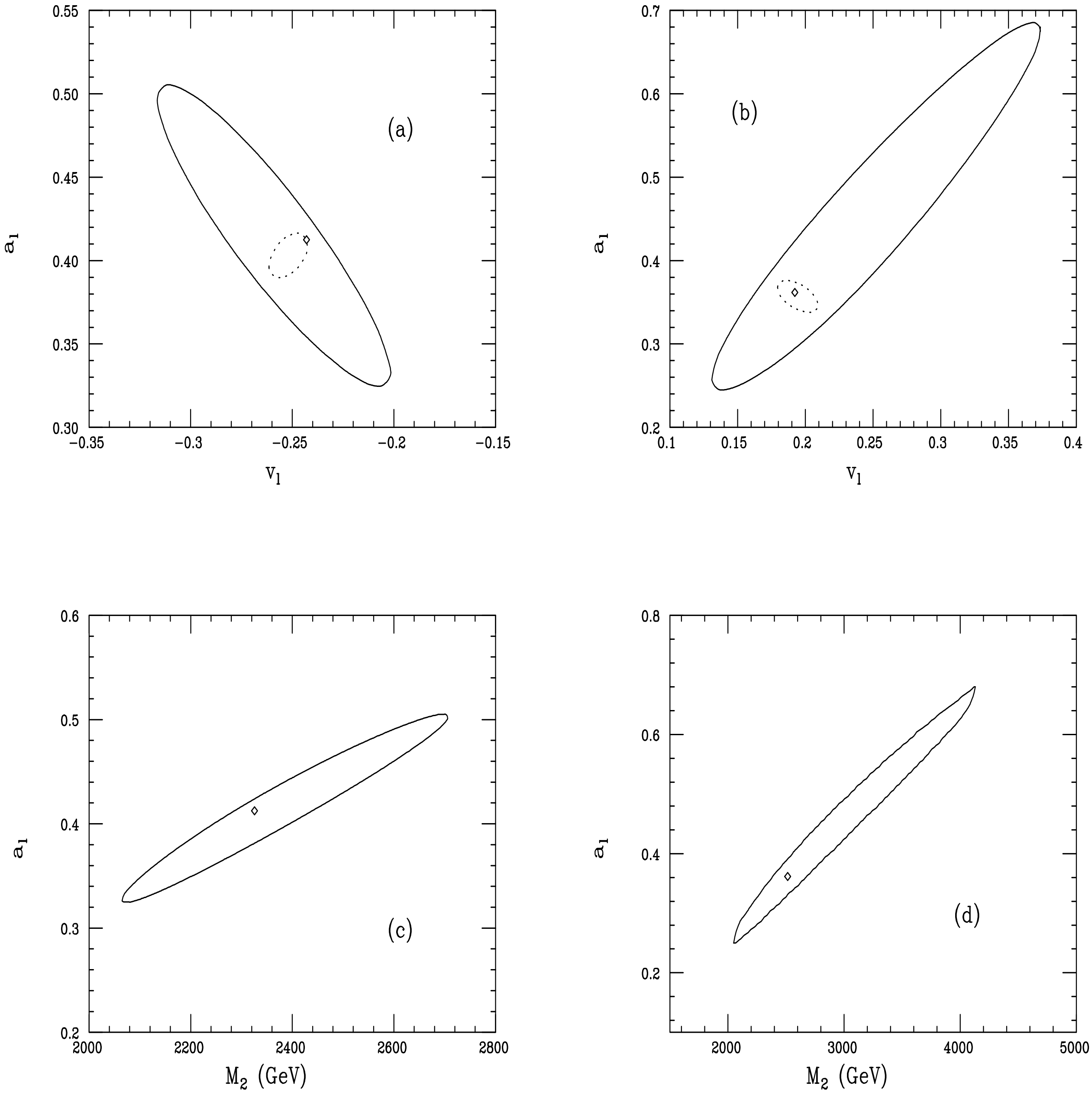

Figure 6: Lepton coupling determination for Z''s with masses of (a) 2.33 TeV and (b) 2.51 TeV when the mass is unknown(solid) and known(dotted). (c) and (d) are the corresponding mass determinations which result from the five-dimensional fit. These results include an additional 200 fb^{-1} of luminosity taken at a center of mass energy of 1.5 TeV.

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References

[1] For a complete set of references and a recent review of the physics of new gauge bosons see, M. Cvetic and S. Godfrey, Carleton University report OCIP/C-95-2, 1995, a part of the DPF long-range planning study to be published in *Electroweak Symmetry Breaking and Physics Beyond the Standard Model*, eds. T. Barklow, S. Dawson, H. Haber, and J. Seigrist (World Scientific 1996). See also, A. Djouadi, talk given at the *Workshop on Physics and Experiments with Linear Colliders*, Morioka-Appi, Japan, Sept. 8-12, 1995, hep-ph/9512311; J. Layssac *et al.*, hep-ph/9602327; A. Leike and S. Riemann, to appear in the *Proceedings of the Physics with* e^+e^- *Linear Colliders Workshop*, Annecy-Gan Sasso-Hamburg, 1995, ed. P. Zerwas, hep-ph/9604321 and hep-ph/9607306.