Search Limits for Extra Neutral Gauge Bosons at High Energy Lepton Colliders^{*}

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ABSTRACT

We study and compare the discovery potential for heavy neutral gauge bosons (Z') at the various e^+e^- and $\mu^+\mu^-$ colliders that have been proposed. Typical search limits for the e^+e^- colliders are $2 - 10 \times \sqrt{s}$ with the large variation reflecting the model dependence of the limits. The search limits for the $\mu^+\mu^-$ colliders are slightly lower. Polarization and flavour tagging are important in realizing the highest discovery limits possible. Because the search limits are based on indirect inferences of deviations from standard model predictions, they are sensitive to systematic errors.

I. INTRODUCTION

Extended gauge symmetries and the associated heavy neutral gauge bosons, Z', are a feature of many extensions of the standard model such as grand unified theories, Left-Right symmetric models, and superstring theories. If a Z' were discovered it would have important implications for what lies beyond the standard model. It is therefore important to study and compare the discovery reach for extra gauge bosons at the various facilities that are under consideration for the future. Included in the list of proposed facilities considered at the Snowmass'96 workshop are high energy e^+e^- and $\mu^+\mu^-$ colliders. In this report we update previous studies [1, 2, 3, 4, 5] to include these high energy lepton colliders.

II. MODELS

Quite a few models predicting extra gauge bosons exist in the literature. We will present search limits for several of these models which, although far from exhaustive, form a representative set for the purposes of comparison. The models chosen for study are listed below but for details we direct the interested reader to ref. [2] and references therein.

(i) Effective rank-5 models originating from E₆ grand unified theories are conveniently labelled in terms of the decay chain E₆ → SO(10) × U(1)_ψ → SU(5) × U(1)_χ × U(1)_ψ → SM × U(1)_{θE₆}. Thus, the Z' charges are given by linear combinations of the U(1)_χ and U(1)_ψ charges resulting in the Z'-fermion couplings:

$$g_{Z'}(Q_{\chi}\cos\theta_{E_6} + Q_{\psi}\sin\theta_{E_6}) \tag{1}$$

where θ_{E_6} is a free parameter which lies in the range $-90^\circ \le \theta_{E_6} \le 90^\circ$. Specific models of interest are model

 χ ($\theta_{E_6} = 0^\circ$) corresponding to the extra Z' of SO(10), model ψ ($\theta_{E_6} = 90^\circ$) corresponding to the extra Z' of E_6 , and model η ($\theta_{E_6} = \arctan - \sqrt{5/3}$) corresponding to the extra Z' arising in some superstring theories.

- (ii) The Left-Right symmetric model (LRM) extends the standard model gauge group to SU(2)_L × SU(2)_R × U(1). It has a parameter κ with 0.55 ≤ κ² ≡ (g_R/g_L)² ≤ 1 2. We assume κ = 1 in our analysis which corresponds to strict left-right symmetry.
- (iii) The Alternative Left-Right Symmetric model (ALRM) originates from E_6 GUT's and is also based on the electroweak gauge group $SU(2)_L \times SU(2)_R \times U(1)$. Here the assignments for $T_{3L(R)}$ differ from that of the usual LRM due to an ambiguity in how the fermions are embedded in the 27 representation of E_6 .
- (iv) The "sequential" Standard Model (SSM) consists of a Z' which is just a heavy version of the SM Z^0 boson with identical couplings. Although it is not a realistic model it is often used as a benchmark and for purposes of comparison.
- (v) The Harvard Model (HARV) is based on the gauge group $SU(2)_l \times SU(2)_q \times U(1)_Y$, i.e., left-handed leptons (quarks) transform as doublets under $SU(2)_l$ ($SU(2)_q$) and singlets under $SU(2)_q$ ($SU(2)_l$), and right-handed fields are singlets under both groups. This model has a parameter ϕ which lies in the range $0.22 \leq \sin \phi \leq 0.99$. We take $\sin \phi = 0.5$ in our calculations. The Z' is purely left handed in this model.

There are numerous other models in the literature predicting Z''s but the subset described above have properties reasonably representative of broad classes of models, at least for the purposes of comparing search limits of high energy colliders.

III. CALCULATIONS AND RESULTS

At e^+e^- colliders searches for Z''s are indirect, being inferred from deviations from the standard model predictions due to interference between the Z' propagator and the γ and Z^0 propagators [6]. This is similar to PEP/PETRA seeing the standard model Z^0 as deviations from the predictions of QED. The basic process is $e^+e_{\lambda}^- \rightarrow f\bar{f}$ where f could be leptons (e, μ, τ) or quarks (u, d, c, s, b, t) and λ denotes the $e^$ polarization. The cross section for the basic process is given by:

$$\frac{d\sigma_L}{d\cos\theta} = \frac{\pi\alpha^2}{4s} \left\{ |C_{LL}|^2 (1+\cos\theta)^2 + |C_{LR}|^2 (1-\cos\theta)^2 \right\}$$
(2)

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where

$$C_{ij} = -Q_f + \frac{C_i^e C_j^j}{c_w^2 s_w^2} \frac{s}{(s - M_Z)^2 + i\Gamma_Z M_Z} + \frac{(g_{Z'}/g_{Z^0})^2 C_i^{e'} C_j^{f'}}{c_w^2 s_w^2} \frac{s}{(s - M_{Z'})^2 + i\Gamma_{Z'} M_{Z'}} (3)$$

where the C_i^f are the SM Z^0 couplings and the $C_i^{f'}$ are the Z' couplings. For right-handed electrons make the substitutions $C_{LL} \rightarrow C_{RR}$ and $C_{LR} \rightarrow C_{RL}$. From these expressions we can obtain everything else we need. For example, the total differential cross section is just

$$\frac{d\sigma}{d\cos\theta} = \frac{1}{2} \left[\frac{d\sigma_L}{d\cos\theta} + \frac{d\sigma_R}{d\cos\theta} \right]$$
(4)

and the various polarized or unpolarized total cross sections can be obtained by integrating these expressions. The spin averaged (unpolarized) cross section is given by:

$$\sigma = \frac{\pi \alpha^2}{3s} [|C_{LL}|^2 + |C_{RL}|^2 + |C_{RL}|^2 + |C_{RR}|^2]$$
(5)

From the basic reactions a number of observables can be used to search for the effects of Z''s:

- σ^f the cross section to specific final state fermions
- $R^{had} = \sigma^{had} / \sigma_0$ the ratio of the hadronic to the QED point cross section
- A_{FB}^{f} the forward-backward asymmetry to fermion f in the final state;

$$A_{FB} = \frac{\left[\int_{0}^{1} - \int_{-1}^{0}\right] d\cos\theta \frac{d\sigma}{d\cos\theta}}{\left[\int_{0}^{1} - \int_{-1}^{0}\right] d\cos\theta \frac{d\sigma}{d\cos\theta}}$$
(6)

• A_{LR}^{f} — the left-right asymmetry with fermion f in the final state;

$$A_{LR}^{f} = \frac{\sigma(e_{L}^{-}) - \sigma(e_{R}^{-})}{\sigma(e_{L}^{-}) - \sigma(e_{R}^{-})}$$
(7)

- A_{LR}^{had} the left-right asymmetry with hadrons in the final state
- $A_{FB}^{f}(pol)$ the polarized forward-backward double asymmetry with fermion f in the final state;

$$A_{FB}^{f}(pol) = \frac{(\sigma_{L}^{F} - \sigma_{R}^{F}) - (\sigma_{L}^{B} - \sigma_{R}^{B})}{(\sigma_{L}^{F} - \sigma_{R}^{F}) + (\sigma_{L}^{B} - \sigma_{R}^{B})}$$
(8)

• P_{τ} — the tau polarization

In these expressions we generally take the index $f = \mu$, τ , c, b and had ='sum over all hadrons' to indicate the final state fermions.

To obtain discovery limits for new physics, which in this case means evidence for extra neutral gauge bosons, we look for

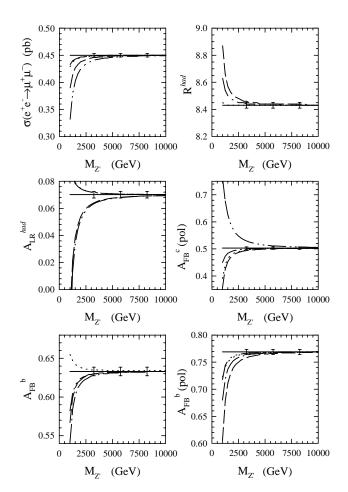


Figure 1: Some e^+e^- observables showing their standard model values and their values for a Z' as a function of $M_{Z'}$ for $\sqrt{s} = 500$ GeV. The solid line is the standard model value, the dashed line is for Z_{χ} , the dotted line for Z_{η} , the dot-dashed line for Z_{LR} and the dot-dot-dash line for Z_{ALR} . The error bars are based on the statistical error assuming an integrated luminosity of 50 fb⁻¹.

statistically significant deviations from standard model expectations. In Fig. 1 a number of observables are shown with their standard model values and for various Z''s as a function of the Z' mass. The error bars are based on the statistics expected in the standard model. (Note that there is a cheat here in that I did not include c and b-quark tagging efficiences in the statistical errors so that in reality some of the error bars should really be bigger than what is shown.) What is important to note here is that the different observables have different sensitivities to the different models. For example, of the models shown, $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ is most sensitive to Z_{ALR} while R^{had} is most sensitive to Z_{χ} . Similarly, $A_{FB}^c(pol)$ is most sensitive to Z_{ALR} while $A_{FB}^b(pol)$ is most sensitive to Z_{χ} . Therefore to have the highest possible reach for the largest number of possible models it is important to include all possible observables.

We quantify the sensitivity to an extra gauge boson by com-

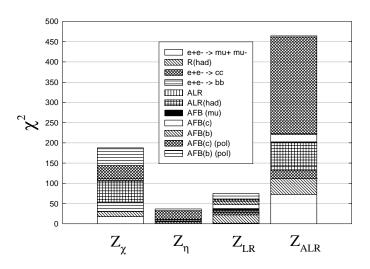


Figure 2: The contributions to χ^2 for the observables $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, R^{had} , $\sigma(e^+e^- \rightarrow c\bar{c})$, $\sigma(e^+e^- \rightarrow b\bar{b})$, A^{μ}_{LR} , A^{had}_{LR} , A^c_{FB} , A^b_{FB} , A^c_{FB} (pol), and A^b_{FB} (pol) for models Z_{χ} , Z_{η} , Z_{LR} , and Z_{ALR} . These are based on $\sqrt{s} = 500$ GeV, L=50 fb⁻¹, and $M_{Z'} = 2$ TeV. The χ^2 is based solely on the statistical error. We assume 100% polarization and do not include finite c and b-quark detection efficiencies.

paring the predictions for various observables assuming the presence of a Z' to the predictions of the standard model and constructing the χ^2 figure of merit;

$$\chi^2 = \sum_i \left(\frac{\mathcal{O}_i^{Z'} - \mathcal{O}_i^{SM}}{\delta \mathcal{O}_i^{SM}} \right)^2 \tag{9}$$

where the sum is over observables included in the χ^2 and δO is the experimental error of the observable. The contributions of some observables to the χ^2 for Z_{χ} , Z_{η} , Z_{LR} , and Z_{ALR} are shown in figure 2. There are several points to note from this figure. First, we again see that the observables have different sensitivities to the various models so that it is important to consider as many observables as possible. Second, the polarization asymmetries are in many cases the most sensitive observables so that polarization is potentially very important for searches for Z''s. And finally, flavour tagging can contribute a considerable amount of information.

To obtain "discovery" limits for the e^+e^- case we include the eighteen observables: σ^{μ} , σ^{τ} , σ^{c} , σ^{b} , R^{had} , A^{μ}_{FB} , A^{τ}_{FB} , A^{c}_{FB} , A^{b}_{FB} , A^{μ}_{LR} , A^{τ}_{LR} , A^{had}_{LR} , A^{c}_{LR} , A^{b}_{LR} , A^{μ}_{FB} (pol), A^{c}_{FB} (pol), A^{c}_{FB} (pol), and P_{τ} . For the $\mu^+\mu^-$ case we included the ten observables that did not involve polarized electrons. In calculating the χ^2 we assumed 90% electron polarization, 35% *c*-tagging efficiency and 60% *b*-tagging efficiency. The 99% C.L. discovery limits are shown in figure 3. Only statistical errors are considered in obtaining the limits shown.

Because search limits obtained at e^+e^- colliders are indirect, based on deviations from the standard model in precision measurements, they are sensitive to both statistical and systematic errors. If, for example, the NLC integrated luminosity is reduced from 50 fb⁻¹ to 10 fb⁻¹ (200 fb⁻¹ to 50 fb⁻¹) for the 500 GeV (1 TeV) case, the search limits are reduced by about 33%. Including a 5% systematic error in cross section measurements due to, for example, luminosity uncertainties, and a 2% systematic error in asymmetries where systematic errors partially cancel, typically reduces these numbers by 30% although in some cases (the SSM) it can reduce the limits by up to 50%. Clearly, systematic errors will have to be kept under control for high precision measurements. Finally, we did not include initial rate radiation (ISR). Rizzo has found that including ISR can lower the search reach by 15–20% [7].

One sees that the discovery limits obtained at e^+e^- colliders can be quite substantial although they can be quite model dependent. For example, for the Z_{ψ} , $C'_L = \pm C'_R$ so that either C'_V or $C'_A = 0$. For \sqrt{s} sufficiently far away from the Z^0 pole deviations are dominated by $Z^0 - Z'$ and $\gamma - Z'$ interference which is proportional to $C^2_V C'_V{}^2 + 2C_V C_A C'_V C'_A + C^2_A C'_A{}^2$. Since for the photon $C_A = 0$, when C'_V is also equal to 0 deviations from the standard model become small.

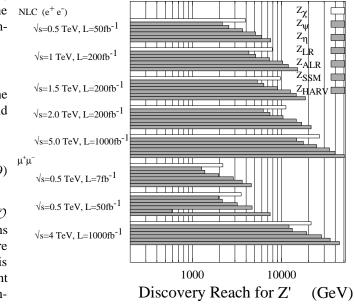


Figure 3: Search limits for extra neutral gauge bosons at high energy lepton colliders. The criteria for obtaining these limits are described in the text.

IV. SUMMARY

In this report we have shown that high luminosity lepton colliders can put limits on the existence of extra gauge bosons via deviations of measurements from their standard model values. The so called discovery limits can be many times the centre of mass energy of the collider. Polarization and flavour tagging are important in realizing the highest discovery limits possible. Since bounds on Z''s are based on precision measurements they are quite sensitive to measurement errors. Given the high statistics, to achieve the highest possible discovery limits, it will be crucial to minimize systematic errors. Finally, we note that while the non-observation of deviations from the SM will put constraints on the existence of Z''s, if deviations are found, disentangling the underlying physics will be far from trivial.

V. ACKNOWLEDGEMENTS

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