Signatures of Extended Gauge Sectors in $e^+e^- \to \nu\bar{\nu}\gamma^*$

JoAnne L. Hewett

Stanford Linear Accelerator Center, Stanford, CA 94309, USA

Abstract

The ability of high energy e^+e^- colliders to indirectly probe the existence of heavy new charged gauge bosons via their exchange in the reaction $e^+e^- \to \nu\bar{\nu}\gamma$ is investigated. It is shown that examination the resulting photon energy spectrum with polarized beams can extend the W' search reach above the center of mass energy.

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ABSTRACT

The ability of high energy e^+e^- colliders to indirectly probe the existence of heavy new charged gauge bosons via their exchange in the reaction $e^+e^- \to \nu\bar{\nu}\gamma$ is investigated. It is shown that examination the resulting photon energy spectrum with polarized beams can extend the W' search reach above the center of mass energy.

Extended gauge sectors are a feature in many scenarios of physics beyond the Standard Model (SM). Perhaps the most appealing set of enlarged electroweak models are those which arise in supersymmetric grand unified theories (GUTs), such as SO(10) and E_6. However, more complex gauge structures are also present in several non-GUT scenarios, including models of composite gauge bosons, horizontal interactions, and topcolor assisted technicolor. The existence of new gauge bosons is the hallmark of such theories and the discovery of such particles would provide uncontested evidence for new physics with an extended gauge sector, and the study of their couplings would provide a diagnostic tool in determining the underlying theory.

The conventional search strategy for new gauge bosons at hadron colliders is through their direct production and subsequent decay to lepton pairs, *i.e.*, the Drell-Yan mechanism. Present bounds[1] on the mass of a new neutral gauge boson, Z', from the Tevatron are generally in the range $M_{Z_2} \gtrsim 500 - 700$ GeV, with the exact value being dependent on the specific extended model. This search reach is expected[2] to increase by ~ 300 GeV with 1fb^{-1} of luminosity. The Z' discovery potential at the LHC is in the mass range of $4 - 5$ TeV. The corresponding Tevatron bound[3] on the mass of a new charged boson, W', is 720 GeV; this limit assumes that the W' has SM strength couplings and that it decays into a light and stable neutrino which manifests itself in the detector as missing E_T. The LHC discovery reach[2] for a heavy charged boson, with the same assumptions, is ~ 5.9 TeV with 100 fb^{-1}. These bounds are invalidated if the W' decays into a heavy neutrino[3], or as discussed below, can be seriously degraded for some regions of parameter space in specific extended electroweak models.

At e^+e^- colliders direct production of new gauge bosons is kinematically limited by the available center of mass energy, and hence different search tactics are necessary. Such machines, however, easily allow for Z' indirect searches for the case $M_{Z_2} > \sqrt{s}$ by looking for deviations from SM expectations for cross sections and asymmetries associated with fermion pair production[2, 4]. This is similar to the exploration of the modifications of QED predictions due to the SM Z boson at PEP/PETRA. The bounds obtained in this manner[2] are

greatly model dependent, but lie in the general range of $2 - 5$ TeV for $\sqrt{s} = 500$ GeV with 50 fb^{-1}. It has been believed that W' searches may only proceed via direct production, with the most promising process, $e^+e^- \to W'W'^* \to W'jj$, resulting in a discovery reach[5] of $M_{W'} \simeq 0.8\sqrt{s}$. Indirect W' signals are thought to be inaccessible as charged gauge bosons do not contribute to $e^+e^- \to f\bar{f}$ ($f \neq \nu$).

Here we explore the neutrino counting reaction, $e^+e^- \to \nu\bar{\nu}\gamma$, to determine if the W' search reach can be extended to masses above $\sqrt{s}$. In the SM, this process proceeds through s-channel Z and t-channel W exchange with the photon being radiated from every possible charged particle. Although the resulting cross section suffers from an additional factor of α and from 3-body phase space suppression (as compared to fermion pair production), it still has a reasonable value[6], of order a few pb at a 500 GeV NLC. In extended gauge models it is modified by both s-channel Z' and t-channel W' exchange. The influence of additional Z' exchange alone has been previously examined[7] in E_6 GUTs models at SLC/LEP energies, where the effects were found to be small due to the close proximity of the SM Z resonance.

We examine the effect of two extended electroweak models on this reaction. The first is the Left-Right Symmetric Model (LRM)[8], based on the gauge group $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$, which has right-handed charged currents, and hence restores parity at a higher mass scale. This model contains the free parameter $\kappa \equiv g_R/g_L$, which represents the ratio of the right- to left-handed coupling strengths and lies in the range $0.55 \lesssim \kappa \lesssim 2.0$. Strict left-right symmetry dictates that $\kappa = 1$. It has been shown[9] that a light right-handed mass scale ($M_R \sim 1$ TeV) is consistent with coupling constant unification in supersymmetric SO(10) GUTs. A direct mass relationship between the right-handed charged and neutral gauge bosons is present and is given by

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

where $\rho_R = 1(2)$ probes the symmetry breaking of the $SU(2)_R$ by right-handed Higgs doublets (triplets) and $x_w = \sin^2\theta_w$. The fermionic Z_R couplings are fixed and can be written as $(g/2c_w)(\kappa - (1 + \kappa)x_w)^{-1/2}[x_w T_{3L} + \kappa(1 - x_w)T_{3R} - x_w Q]$, with $T_{3L(R)}$ being the fermion's left-(right-) handed isospin, and Q is the fermion electric charge. In this study, we assume that the neutrinos are light and Dirac in nature. We note the existence of a right-handed Cabbibo-Kobayashi-Maskawa (CKM) matrix in this model, which need not be the same as the corresponding left-handed mixing matrix. This can degrade the W_R search capability in hadronic collisions[10], as the weights of the various parton densities which enter the production cross

section can be dramatically altered. For example, this could reduce the current Tevatron W_R mass bounds by up to a factor of ~ 2.

The second model we consider is the un-unified model (UUM)[11], which is based on the gauge group $SU(2)_q \times SU(2)_\ell \times U(1)_Y$, where the quarks and leptons transform under their own $SU(2)$. In this case the additional heavy W and Z are approximately degenerate, $M_{W_H} \simeq M_{Z_H}$. The Z_H fermionic couplings take the form $c_w[T_{3q}/\tan\phi - \tan\phi T_{3\ell}]$, where $T_{3q(\ell)}$ is the $SU(2)_{q(\ell)}$ third component of isospin, and ϕ is a mixing parameter which is constrained to the range $0.24 \lesssim \sin\phi \lesssim 0.99$. Note that the additional neutral and charged currents are purely left-handed in this case.

In this preliminary study we employ the point interaction approximation for the W_i boson exchange diagrams in $e^+e^- \to \nu\bar\nu\gamma$. This approximation is reasonable for the heavy W' contribution as we are considering the case $M_{W'} > \sqrt{s}$, but it is known[12] to break down for the SM W for center of mass energies above the Z pole. An exact calculation will be presented elsewhere[13]. In this approximation the $e^+e^- \to \nu\bar\nu\gamma$ differential cross section can then be cast in the form[7] (after integration over the angle of the final state photon)

$$\frac{d\sigma}{dx} = \frac{\alpha}{\pi x}\left[(2 - 2x + x^2)\ln\frac{1+\delta}{1-\delta} - x^2\delta\right]\sigma_M^{\nu\bar\nu}(x)\,, \quad (2)$$

where $x = 2E_\gamma/\sqrt{s}$ and $\delta = \cos\theta_{\min}$ with $\theta_{\min}$ being the minimum angle between the initial electron beam and the outgoing γ allowed by the experimental cuts. In our analysis we take $\theta_{\min} = 20°$ and $E_\gamma > 0.1E_{\text{beam}}$. The angular cut corresponds to a conservative estimate of the acceptance of a typical NLC detector[6] and is effective in removing background from the process $e^+e^- \to e^+e^-\gamma$, while the minimum photon energy ensures the finiteness of the cross section by removing the infrared and collinear divergences. $\sigma_M^{\nu\bar\nu}(x)$ is the cross section for the subprocess $e^+e^- \to \nu\bar\nu$ evaluated at the center of mass energy $M^2 = s(1 - x)$.

We now evaluate the $e^+e^- \to \nu\bar\nu$ subprocess cross sections for polarized beams in our two extended electroweak models. In the LRM these are given by

$$\sigma_L(x) = \frac{G_F^2 M^2}{6\pi}\left[1 - 2M_{Z_1}^2\sum_i C_i(v_i^L + a_i^L)F_i\right.$$

$$+ \left. 2N_\nu M_{Z_1}^4\sum_{i,j}(v_i^L v_j^L + a_i^L a_j^L)(C_iC_j + \tilde{C}_i\tilde{C}_j)P_{ij}\right]$$

$$\sigma_R(x) = \frac{G_F^2 M^2}{6\pi}\left[\left(\frac{\kappa M_L}{M_R}\right)^4\right. \quad (3)$$

$$- \left(\frac{\kappa M_L}{M_R}\right)^2 2M_{Z_1}^2\sum_i \tilde{C}_i(v_i^R + a_i^R)F_i$$

$$+ \left. 2N_\nu M_{Z_1}^4\sum_{i,j}(v_i^R v_j^R + a_i^R a_j^R)(C_iC_j + \tilde{C}_i\tilde{C}_j)P_{ij}\right]$$

Here, $N_\nu = 3$ represents the number of light neutrino species,

$$F_i = \frac{M^2 - M_{Z_i}^2}{D_i}\,,$$

$$D_i = (M^2 - M_{Z_i}^2)^2 + (\Gamma_i M_{Z_i})^2\,, \quad (4)$$

$$P_{ij} = \frac{(M^2 - M_{Z_i}^2)(M^2 - M_{Z_j}^2) + (\Gamma_i M_{Z_i})(\Gamma_i M_{Z_j})}{D_i D_j}\,.$$

The polarized couplings of the electron to the Z_i are related to the unpolarized couplings v_i and a_i by

$$v_i^{L,R} = \frac{1}{2}(v_i + \lambda a_i)\,,$$

$$a_i^{L,R} = \frac{1}{2}(a_i + \lambda v_i)\,, \quad (5)$$

with $\lambda = +1(-1)$ for left-(right-)handed electrons. C_i and $\tilde{C}_i$ represent the couplings of ν_L and ν_R, respectively, to the Z_i. (Note that $\tilde{C}_1 = 0$.) The couplings are normalized as

$$\mathcal{L} = \frac{g}{2c_w}\bar{e}\gamma_\mu(v_i - a_i\gamma_5)eZ_i^\mu\,. \quad (6)$$

In evaluating these subprocess cross sections we neglect mixing between the SM and heavy gauge bosons.

The corresponding subprocess cross sections in the UUM are

$$\sigma_L(x) = \frac{G_F^2 M^2}{6\pi}\left\{\left[1 + \left(\frac{t_\phi M_L}{M_H}\right)^2\right]^2\right.$$

$$- 2M_{Z_1}^2\left[1 + \left(\frac{t_\phi M_L}{M_H}\right)^2\right]\sum_i C_i(v_i^L + a_i^L)F_i$$

$$+ \left. 2N_\nu M_{Z_1}^4\sum_{i,j}(v_i^L v_j^L + a_i^L a_j^L)C_iC_jP_{ij}\right\}\,, \quad (7)$$

$$\sigma_R(x) = \frac{G_F^2 M^2}{6\pi}2N_\nu M_{Z_1}^4\sum_{i,j}(v_i^R v_j^R + a_i^R a_j^R)C_iC_jP_{ij}\,.$$

We first examine the resulting unpolarized E_γ distribution. Figure 1a displays this spectrum for the SM, LRM, and UUM, corresponding to the solid, dashed, and dotted curves, respectively, for various values of the parameters. It is clear from the figure that the differences between the SM and the extended models is very small; in fact the SM and the LRM are indistinguishable on this scale. In order to better quantify the influence of the new gauge bosons, we present in Fig. 1b the ratio of the difference between the differential cross section in the extended model from that of the SM to the SM, i.e., $(d\sigma - d\sigma_{SM})/d\sigma_{SM}$. We see that the effects of the extended electroweak sector are at most at the few percent level. Examination of the E_γ distribution with polarized beams yields similar results.

In determining the W' search reach we make use of the differential cross section as well as the left-right asymmetry. For finite polarization, P, these quantities can be written as

$$\sigma(\pm P) = \frac{1}{2}(1 \pm P)\sigma_L + \frac{1}{2}(1 \mp P)\sigma_R\,, \quad (8)$$

and

$$A_{LR} = P\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}. \tag{9}$$

In our calculations we take the polarization to be 90%. We divide the photon energy spectrum into 10 bins of equal size and perform a χ^2 analysis according to usual prescription,

$$\chi^2 = \sum_i \left[\frac{\mathcal{O}_i - \mathcal{O}_i^{SM}}{\delta\mathcal{O}_i}\right]^2, \tag{10}$$

for our two observables (denoted as $\mathcal{O}_i$) $d\sigma/dx$ and A_{LR}. We include statistical errors only, such that $\delta\sigma = \sigma/\sqrt{N}$ and $\delta A = \sqrt{(1 - P^2 A^2)/P^2 N}$ for finite polarization, with N being the number of events in each bin. Surprisingly, we find that the left-right asymmetry contributes very little to the overall value of χ^2. The resulting 95% C.L. search reach for heavy charged gauge bosons is presented in Fig. 2 for (a) the LRM as a function of κ and (b) the UUM as a function of $\sin\phi$ for $\sqrt{s} = 0.5$ TeV with 50 fb^{-1} of luminosity and $\sqrt{s} = 1$ TeV with 200 fb^{-1}. In the LRM we see that the search reach for W_R is expanded to at most $2 \times \sqrt{s}$. This does not compete with the discovery potential at the LHC, however it is independent of assumptions about the right-handed CKM mixing matrix. In the UUM, the W_H discovery reach barely extends above $\sqrt{s}$ for small values of $\sin\phi$. However, for larger values of $\sin\phi$ the reach grows to several times $\sqrt{s}$ due to the increase in the leptonic couplings for $\sin\phi > 0.5$. At this stage it is difficult to decouple the effects from the charged gauge boson from that of the neutral Z'. Once the W and W' contact approximation is removed[13] we expect that appropriate cuts coupled with an examination of the photon angular distribution will distinguish the W' contribution from that of the Z'.

In conclusion, we have performed a preliminary study of the reaction $e^+e^- \rightarrow \nu\bar{\nu}\gamma$ in two extended gauge models and have found that it does probe the indirect effects of a heavy charged gauge boson. Although the results presented here do not directly compete with the discovery reach for such particles at the LHC, they do provide proof of demonstration that it is possible to observe W' signals with masses is excess of $\sqrt{s}$ at e^+e^- colliders. This reaction could also serve as a diagnostic tool by providing information on the couplings of the new charged gauge boson.
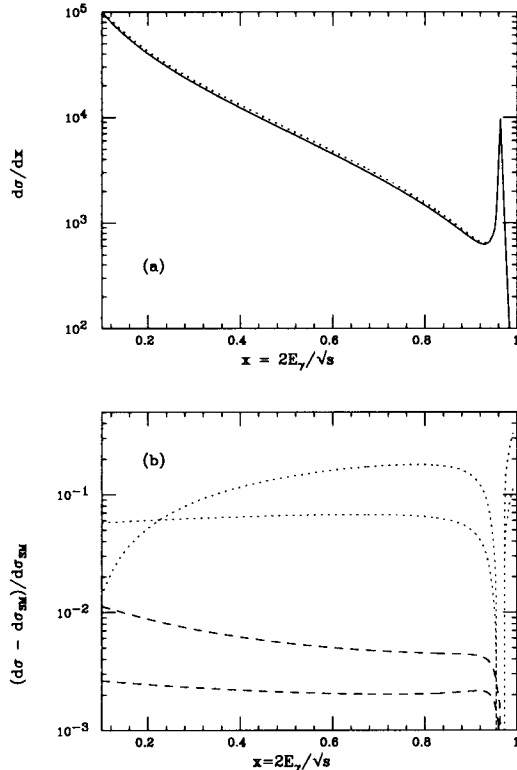

Figure 1: (a) The photon energy spectrum for the SM (solid curve), LRM with $\kappa = 2$ and $M_R = 750$ GeV (dashed), and UUM with $\sin\phi = 0.6$ and $M_H = 1$ TeV (dotted). (b) The ratio of the difference of the E_γ spectrum in the extended model from the SM to the SM for the LRM with $\kappa = 2$ and $M_R = 750(600)$ GeV corresponding to the bottom (top) dashed curves, and for the UUM with $\sin\phi = 0.6$ and $M_H = 1(0.6)$ TeV represented by the bottom (top) dotted curves.
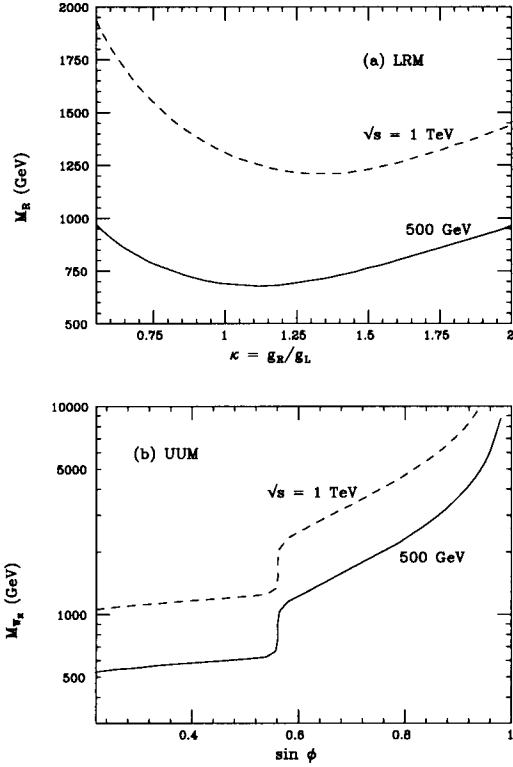
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Figure 2: 95% C.L. discovery reach for a new charged gauge boson via the reaction $e^+e^- \to \nu\bar{\nu}\gamma$ in (a) the LRM as a function of κ (b) the UUM as a function of $\sin\phi$ for $\sqrt{s} = 500$ GeV with 50 fb^{-1} (solid curve) and 1 TeV with 200 fb^{-1} (dashed curve).

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