

Searching for a W' at the Next-Linear-Collider using Single Photons*

Stephen Godfrey, Pat Kalyniak and Basim Kamal

*Ottawa-Carleton Institute for Physics
Department of Physics, Carleton University, Ottawa, ON K1S 5B6, Canada*

Arnd Leike

LMU, Sektion Physik, Theresienstr. 37, D-80333 München, Germany

Abstract. We examine the sensitivity of the process $e^+e^- \rightarrow \nu\bar{\nu} + \gamma$ to additional W -like bosons which arise in various models. The process is found to be sensitive to W' masses up to several TeV.

INTRODUCTION

There have been many studies of processes sensitive to additional Z -like bosons (Z 's) but comparatively few studies pertinent to W 's (see for instance [1,2]), especially at e^+e^- colliders. Why? Firstly, there are fewer models which predict W 's. Secondly, at LEP II energies, the W' signal is rather weak. Hence direct searches have been limited to hadron colliders and the W' -quark couplings are poorly constrained in some models.

In this contribution we present preliminary results of an investigation of the sensitivity of the process $e^+e^- \rightarrow \nu\bar{\nu} + \gamma$ to W' bosons in various models. Our results are obtained by measuring the deviation from the standard model expectation. Interesting discovery limits are obtained for center-of-mass e^+e^- energy of 500 GeV or higher – *Next-Linear-Collider* (NLC) energies.

Direct searches have been performed and indirect bounds have been obtained for W 's in a few models, the details of which are given later. Bounds for the Left-Right Symmetric Model (LRM) and Sequential Standard Model (SSM) can be found in [3]. They are obtained from the non-observation of direct production of W 's at the Tevatron and from indirect μ -decay constraints. For the LRM (with equal left- and right-handed couplings) CDF obtains $M_{W'} \gtrsim 650$ GeV and for the SSM, D0 finds

*) Supported in part by the Natural Sciences and Engineering Research Council of Canada.

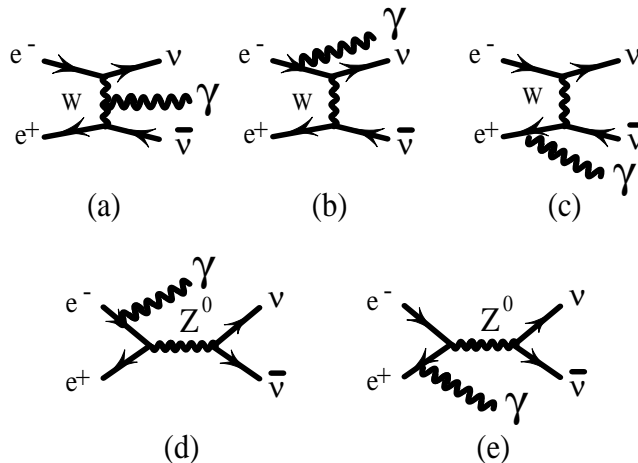


FIGURE 1. The Feynman diagrams contributing to the SM process.

$M_{W'} \gtrsim 720$ GeV. From μ -decay, the LRM W' is constrained to $M_{W'} \gtrsim 550$ GeV [4]. A naive leading order analysis for the SSM yields a bound of between 900 GeV and 1 TeV. One expects a somewhat higher bound than for the LRM since, in μ -decay, there will be a W - W' interference term. The major limitation in this method is the uncertainty in the W mass.

The LHC will have a discovery reach in the TeV range [5]. The search is analogous to that done at the Tevatron, except for the higher energy and luminosity. On the down side, one has pp instead of $p\bar{p}$, which means no valence-valence contribution in the large Feynman- x region. For the LRM, the magnitude of the effect will depend also on the W' -quark couplings which are unknown. Therefore it is hard to make predictions a-priori concerning discovery limits. The NLC search nicely sidesteps the above problem as no W' -quark couplings enter. Other LHC disadvantages include a lack of initial state quark polarizability, parton distribution dependence and large QCD corrections. The latter problems will affect the ability to pin down the W' couplings. Hence, the complimentary nature of the cleaner NLC measurement is obvious despite the LHC's high energy reach.

BASIC PROCESS

The basic process under consideration is:

$$e^-(p_1) + e^+(p_2) \rightarrow \gamma(p_3) + [\nu(p_4) + \bar{\nu}(p_5)], \quad (1)$$

where the square brackets indicate that since the neutrinos are not observed, we effectively only have single photon production. The diagrams representing the leading Standard Model (SM) contribution are shown in Fig. 1. The W' (Z') contributions are obtained by replacing $W \rightarrow W'$, $Z \rightarrow Z'$ in the SM diagrams. Then one must include all interferences between SM and beyond-SM diagrams in the squared amplitude.

The resulting squared amplitude is quite short, including spin dependence which comes out automatically when expressing the result in terms of the left- and right-handed couplings. The result is quite general and includes an arbitrary number of W' 's and Z' 's.

MODELS

We have considered three models having W' 's which contribute to our process and are briefly described below.

Sequential Standard Model: This is the simplest W' -containing extension of the SM, although not well motivated by theory. One has an extra W' which is heavier than the SM one, but which has identical couplings.

Left-Right Symmetric Model: In this model [6], the symmetry $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ is obeyed, giving rise to a W' and a Z' . The W' is purely right-handed; we do not consider mixing between the SM and beyond-SM bosons. The pure SM couplings remain unchanged and we take the new right-handed neutrinos to be massless. In principle they could be very heavy as well, but this would lead to decoupling of the W' from our process and we would be effectively left with a Z' model, which is not the principal interest of this study.

Two parameters arise; ρ and κ . For symmetry breaking via Higgs doublets (triplets) $\rho = 1$ (2). κ is defined by $\kappa = g_R/g_L$ and thus measures the relative strength of the $W'l\nu_l$ and $Wl\nu_l$ couplings. It lies in the range [2,7]

$$0.55 \lesssim \kappa \lesssim 2 . \quad (2)$$

More specifically, we have the coupling

$$W'l\nu = i \frac{g\kappa}{\sqrt{2}} \gamma^\mu \frac{1 + \gamma_5}{2} , \quad (3)$$

suggesting that larger values of κ will lead to larger deviations from the SM. In addition, we have the relation

$$M_{Z'}^2 = \frac{\rho\kappa^2}{\kappa^2 - \tan^2 \theta_W} M_{W'}^2 , \quad (4)$$

so that $\rho = 1$ leads to a lighter Z' mass for fixed $M_{W'}$, which should yield a bigger effect versus $\rho = 2$.

Un-Unified Model (UUM): The UUM [8] obeys the symmetry $SU(2)_q \times SU(2)_l \times U(1)_Y$, again leading to a W' and a Z' . Both new bosons are left-handed and generally taken to be approximately equal in mass. There are two parameters: a mixing angle ϕ , which represents a mixing between the charged bosons of the two $SU(2)$ symmetries, and $x = (u/v)^2$, where u and v are the VEV's of the two scalar multiplets of the model. The relation $M_{Z'} \simeq M_{W'}$ follows in the limit $x/\sin^2 \phi \gg 1$ and the parameter x may be replaced by $M_{W'}$, so that only ϕ enters as a parameter

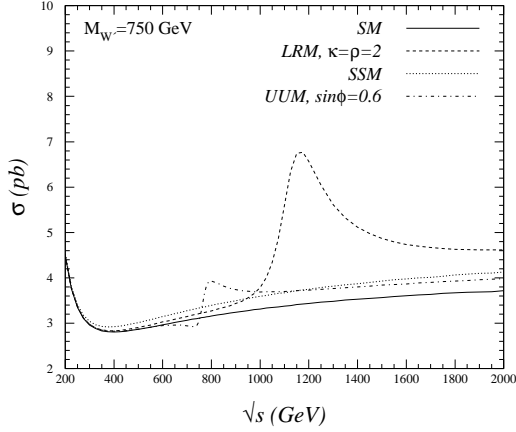


FIGURE 2. Unpolarized total cross section versus center-of-mass energy in the SM, LRM, SSM and UUM.

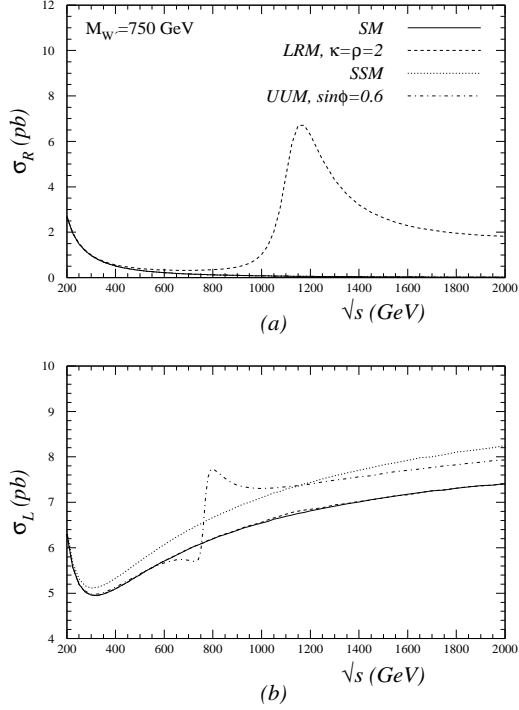


FIGURE 3. As Fig. 2, except for (a) right-handed; (b) left-handed e^- beam.

for determining mass discovery limits. The leptonic couplings may be inferred from the Lagrangian

$$\mathcal{L}_{\text{lept}} = -\frac{g \sin \phi}{2 \cos \phi} [\sqrt{2} \bar{\psi}_{\nu_l} \gamma_\mu \psi_{l,L} W_2^{+,\mu} + (\bar{\psi}_{\nu_l} \gamma_\mu \psi_{\nu_l,L} - \bar{\psi}_l \gamma_\mu \psi_{l,L}) Z_2^\mu], \quad (5)$$

where $\psi_L = \frac{1}{2}(1 - \gamma_5)\psi$. The existing constraint on ϕ is [1]

$$0.24 \lesssim \sin \phi \lesssim 0.99. \quad (6)$$

CROSS SECTIONS

As inputs, we take $M_W = 80.33$ GeV, $M_Z = 91.187$ GeV, $\sin^2 \theta_W = 0.23124$, $\alpha = 1/128$, $\Gamma_Z = 2.49$ GeV. Let E_γ , θ_γ denote the photon's energy and angle in the e^+e^- center-of-mass, respectively. No binning or transverse momentum cuts have been explicitly introduced at this point. However, we have restricted the range of E_γ , θ_γ as follows:

$$E_\gamma > 10 \text{ GeV}, \quad 10^\circ < \theta_\gamma < 170^\circ, \quad (7)$$

so that the photon may be detected cleanly. As well, the angular cut eliminates the collinear singularity arising when the photon is emitted parallel to the beam.

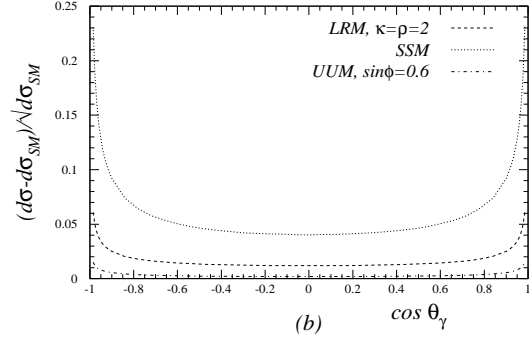
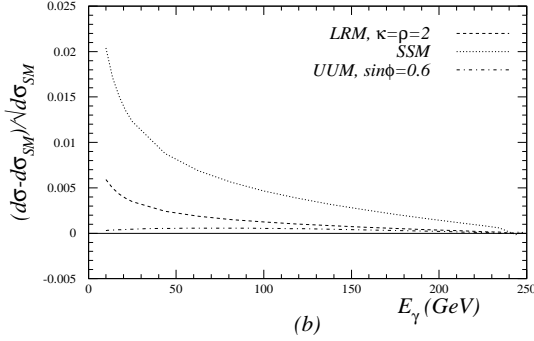
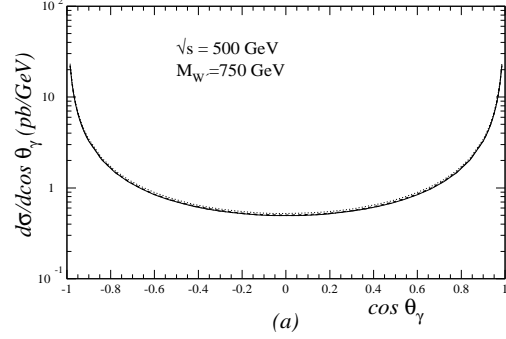
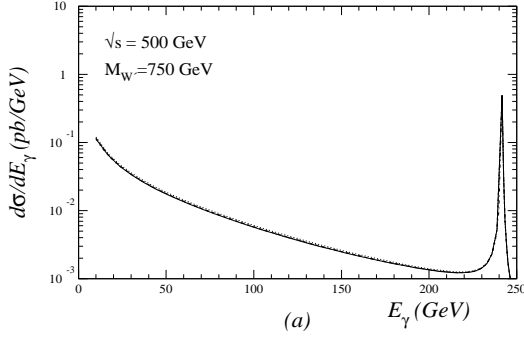


FIGURE 4. (a) Cross section and (b) relative statistical significance of the deviation from the SM versus photon energy.

FIGURE 5. (a) Cross section and (b) relative statistical significance of the deviation from the SM versus $\cos \theta_\gamma$.

Figure 2 shows the total unpolarized cross section versus center-of-mass energy for the SM, LRM (taking $\kappa = \rho = 2$), SSM and UUM (taking a representative value of $\sin \phi = 0.6$). Throughout, we use $M_{W'} = 750$ GeV. Figure 3 shows the same, except for pure right- and left-handed e^- beams. The peaks are due to the Z 's in the LRM and UUM. As expected, the LRM gives a large effect when the e^- is right-handed while the SSM and UUM give a larger effect for a left-handed e^- . The fact that the SM right-handed cross section goes to zero for large \sqrt{s} indicates W (t -channel) dominance well above the Z pole.

In Figure 4(a), we plot the differential cross section with respect to E_γ for \sqrt{s} of 500 GeV. The peak in the photon distributions is due to the radiative return to the Z resonance. At higher energies, there are additional peaks in the E_γ spectrum due to Z 's. We see that most of the contribution comes from the lower E_γ range. This must be weighted with the deviation from the SM in order to gauge the relative statistical significance of the various energy regions. This is done in Figure 4(b) where $(d\sigma/dE_\gamma - d\sigma_{SM}/dE_\gamma)/\sqrt{d\sigma_{SM}/dE_\gamma}$ is plotted as a function of E_γ . Indeed, we see that one benefits little from the region E_γ above ~ 200 GeV in all models.

In Figure 5 we plot the the differential cross section with respect to $\cos \theta_\gamma$ and the corresponding relative statistical significance. We see that both the cross section and relative statistical significance are peaked in the forward/backward direction and the distributions are very nearly symmetric in $\cos \theta_\gamma$. In Figures 4(b) and 5(b),

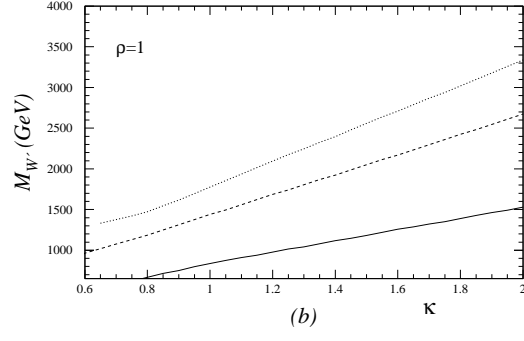
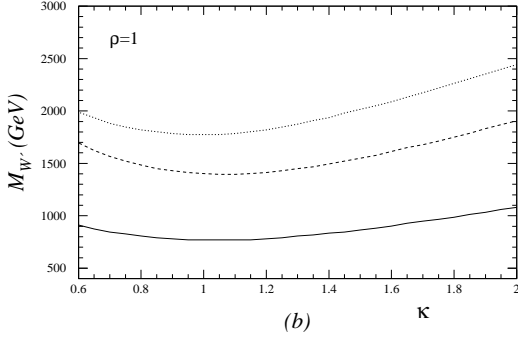
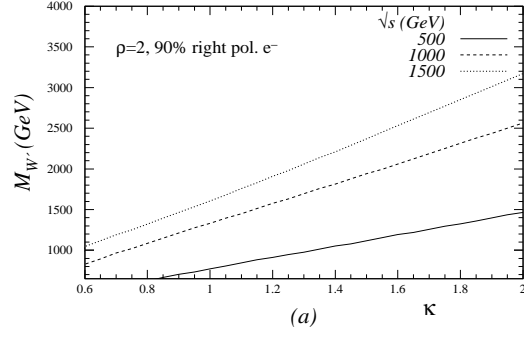
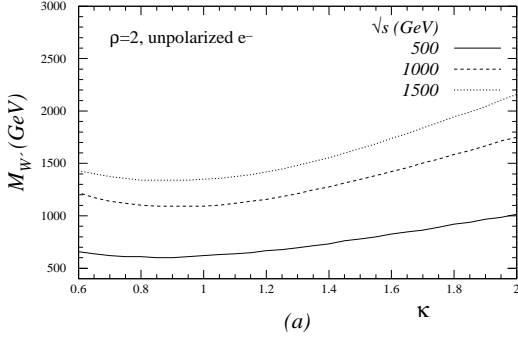


FIGURE 6. W' 95% C.L. discovery limits versus κ in the LRM obtained with unpolarized beam for (a) $\rho = 2$; (b) $\rho = 1$.

FIGURE 7. As Fig. 6, except with 90 percent right-polarized electron beam.

the overall normalization is unimportant. Experimentally, some binning scheme will be adopted and each bin will carry a weight proportional to the beam luminosity.

NLC W' MASS DISCOVERY LIMITS

For \sqrt{s} of 500 GeV, we take an integrated luminosity of $50fb^{-1}$ and for \sqrt{s} of 1 TeV and 1.5 TeV we take $200fb^{-1}$. For the polarized limits we take half the above luminosities assuming equal running in both polarization states (of the e^- beam). We assume 90% e^- polarization unless otherwise stated.

In obtaining limits, we have imposed the additional cut:

$$E_\gamma < E_{\gamma,\max} , \quad (8)$$

in order to cut out the high energy events, especially those near the Z pole, which are insensitive to W' s and Z' s. It was found that $E_{\gamma,\max}$ of 200, 350 and 500 GeV for \sqrt{s} of 500 GeV, 1 TeV and 1.5 TeV, respectively, lead to the best limits in general, although the limits were not very sensitive to moderate variations in $E_{\gamma,\max}$. The limits are given at 95% confidence level and are calculated for all three energies.

Figure 6 presents the W' mass discovery limits obtainable with an unpolarized beam for the LRM, plotted versus κ for $\rho = 1, 2$. Depending on \sqrt{s} , ρ and κ , they range from 600 GeV to 2.5 TeV. The predicted dependence on κ and ρ is

TABLE 1. W' 95% C.L. discovery limits obtained in the SSM, LRM ($\kappa = \rho = 2$) and the UUM ($\sin \phi = 0.6$), assuming 90 percent e^- polarization (unless otherwise stated) and using 1/2 the unpolarized luminosity for the left and right cases.

\sqrt{s} (GeV)	Model	Unpolarized e^- Limit (TeV)	Left Pol. e^- Limit (TeV)	Right Pol. e^- Limit (TeV)	100% L/R Pol. Limit (TeV)
500 (50 fb $^{-1}$)	SSM	2.45	2.45	1.15	2.45
	LRM	1.0	<0.75	1.45	2.05
	UUM	0.65	0.65	0.55	0.65
1000 (200 fb $^{-1}$)	SSM	4.55	4.5	2.15	4.55
	LRM	1.75	<1	2.55	4.5
	UUM	1.3	1.3	1.15	1.3
1500 (200 fb $^{-1}$)	SSM	5.2	5.15	2.45	5.2
	LRM	2.15	<1.25	3.2	6.2
	UUM	1.85	1.85	1.65	1.85

generally observed, except at low κ where we notice a moderate *increase* in the limits, even though the W' couplings have weakened. We attribute this effect to the Z' , whose couplings are enhanced (but its mass increased) in the low κ region. This is evidenced by the appreciable improvement in the bounds for low κ and $\rho = 1$. Figure 7 demonstrates the improvement in bounds in the moderate to large κ region obtained when a (90%) polarized right-handed e^- beam is used. The beam polarization picks out the LRM W' and suppresses the SM W . Increase of the polarization can lead to even higher limits as shown in the rightmost column of Table 1, where limits are tabulated for all three models.

The highest limits are obtained for the SSM in most scenarios, except when $\sin \phi$ is large, as indicated in Figure 8 which shows the limits in the UUM versus $\sin \phi$. We observe a turn-on in sensitivity for $\sin \phi \gtrsim 0.62$ at $\sqrt{s} = 500$ GeV and 1 TeV, while for $\sqrt{s} = 1.5$ TeV this occurs for $\sin \phi \gtrsim 0.73$. The interference term may play a role in this behaviour. From another perspective, for fixed $\sin \phi$, one may observe sudden changes in sensitivity as \sqrt{s} is varied as can be seen from the changing of the sign of the effect on the cross section in Figs 2,3. The result is that for $0.62 \lesssim \sin \phi \lesssim 0.72$, we obtain better limits at $\sqrt{s} = 1$ TeV than we do at $\sqrt{s} = 1.5$ TeV.

For both the UUM and the SSM, where the W' s are left-handed, there is little benefit from polarization. The reason is that all the effect comes from the left-handed e^- initial state, which also dominates the unpolarized cross section. After folding in the luminosity decrease associated with running in a particular polarization state, all benefits are lost.

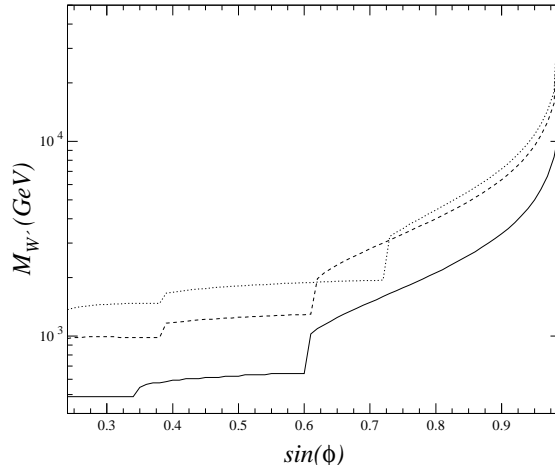


FIGURE 8. 95% C.L. discovery limits versus $\sin(\phi)$ in the UUM; lines as in Fig. 6.

SUMMARY AND OUTLOOK

The usefulness of the process $e^+e^- \rightarrow \nu\bar{\nu} + \gamma$ in searching for W 's has been demonstrated and should be complimentary to direct searches at the LHC. The results of our study will be extended to include cuts on the transverse momentum of the photon to reduce backgrounds (primarily from radiative Bhabha scattering with undetected e^+e^-) and to examine the effect of binning. All remaining backgrounds will have to be included in the final analysis of the data and are currently under investigation, but are not expected to significantly affect our limits. Other models are also under consideration.

REFERENCES

1. Barger, V., and Rizzo, T., *Phys. Rev.* **D41**, 946 (1990).
2. Hewett, J., SLAC-PUB-7441, June 1996, hep-ph/9704292.
3. Particle Data Group (Caso, C., et al.), *Eur. Phys. J.* **C3**, 1 (1998).
4. Barenboim, G., Bernabéu, J., Prades, J., and Raidal, M., *Phys. Rev.* **D55**, 4213 (1997).
5. For a review, see: Cvetič, M., and Godfrey, S., "Discovery and Identification of Extra Gauge Bosons," in *Electro-weak Symmetry Breaking and Beyond the Standard Model*, eds. Barklow, T., et al., World Scientific, 1995, hep-ph/9504216.
6. Mohapatra, R.N., *Unification and Supersymmetry*, New York: Springer, 1986, and original references therein.
7. Parida, M., and Raychaudhuri, A., *Phys. Rev.* **D26**, 2364 (1982); Chang, D., Mohapatra, R., and Parida, M., *Phys. Rev.* **D30**, 1052 (1984).
8. Georgi, H., Jenkins, E.E., and Simmons, E.H., *Phys. Rev. Lett.* **62**, 2789 (1989); **63**, 1540(E) (1989).