2.6 Anomalous Gauge Boson Couplings

Although the Standard Electroweak Model has been verified to astounding precision in recent years at LEP and SLC, one important component has not been tested directly with significant precision: the non-Abelian self couplings of the weak vector gauge bosons. Deviations of non-abelian couplings from expectation would signal new physics, perhaps arising from unexpected loop corrections involving propagators of new particles. In addition, as will be discussed in Chapter 8, precise measurements of WWV couplings, where $V = \gamma$ or Z, can provide important information on the nature of electroweak symmetry breaking. Recent results from CDF and D0 indicate the presence of triple gauge boson couplings, but have not yet reached a precision better than order unity [75]. Upcoming measurements at LEP II, at an upgraded Tevatron and at the LHC will improve upon this precision considerably, but cannot the match the expected precision of a 500 GeV NLC, much less that of a 1.0 or 1.5 TeV NLC. There exist indirect constraints on the anomalous couplings from the precision electroweak measurements at the Z^0 resonances, in particular, from the fact that loop diagrams involving weak vector bosons are seen to take the values expected in the Standard Model. However, the ambiguities in the calculation of these diagrams call for more direct measurements [76].

In this brief report we restrict attention mainly to measurement of possibly anomalous WWV couplings via the process $e^+e^- \to W^+W^-$, but much work has been done on other processes that involve non-abelian couplings in e^+e^- annihilation, including $ZZ\gamma$, $Z\gamma\gamma$, $WWZZ$, and $WWWW$ [75]. In addition, many of these couplings can also be measured independently using the e^-e^-, $e^-\gamma$ and $\gamma\gamma$ options for the NLC. We will describe one common parametrization of anomalous WWV couplings, summarize present and expected pre-NLC measurements of WWV couplings, and discuss in more detail what can be done at the NLC.

2.6.1 Parametrization

In parametrizing anomalous couplings, we follow the notation of Ref. [4] in which the generic effective Lagrangian for the WWV vertex is written:

$$\begin{aligned} L_{WWV}/g_{WWV} \;=\; & i\,g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W^\dagger_\mu V_\nu W^{\mu\nu}) + i\,\kappa_V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{i\,\lambda_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_{\ \nu}V^{\nu\lambda} \\ & - g_4^V W^\dagger_\mu W_\nu(\partial^\mu V^\nu + \partial^\nu V^\mu) + g_5^V\epsilon^{\mu\nu\rho\sigma}(W^\dagger_\mu \overleftrightarrow{\partial}_\rho W_\nu)V_\sigma + \tilde{\kappa}_V W^\dagger_\mu W_\nu \tilde{V}^{\mu\nu} \\ & + \frac{i\,\tilde{\lambda}_V}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_{\ \nu}\tilde{V}^{\nu\lambda}\;, \end{aligned} \tag{2.11}$$

where $W_{\mu\nu} \equiv \partial_\mu W_\nu - \partial_\nu W_\mu$, $V_{\mu\nu} \equiv \partial_\mu V_\nu - \partial_\nu V_\mu$, $(A\overleftrightarrow{\partial}_\mu B) \equiv A(\partial_\mu B) - (\partial_\mu A)B$, and $\tilde{V}_{\mu\nu} \equiv \frac{1}{2}\epsilon_{\mu\nu\rho\sigma}V^{\rho\sigma}$. The normalization factors are defined for convenience to be $g_{WW\gamma} \equiv -e$ and $g_{WWZ} \equiv -e\cot\theta_W$. The 7 coupling parameters defined in Eq. 2.11 for each of γ and Z include the C and P violating couplings g_5^V as well as the CP-violating couplings $g_4^V, \tilde{\kappa}_V, \tilde{\lambda}_V$. In most studies and in this one, such terms are neglected. At tree level in the Standard

Model $g_1^V = \kappa_V = 1$ and $\lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$. The couplings in Eq. 2.11 should properly be written as form factors with momentum-dependent values. This complication is of little importance at an e^+e^- collider where the WW center of mass energy is well defined, but it must be borne in mind for other processes, particularly those measurable at hadron colliders.

We follow the common convention in defining $\Delta g_1^Z \equiv g_1^Z - 1$ and $\Delta\kappa_V \equiv \kappa_V - 1$. The W electric charge fixes $g_1^\gamma(q^2 \to 0) \equiv 1$. In perhaps more familiar notation, one can express the W magnetic dipole moment as $\mu_W \equiv \frac{e}{2\,M_W}(1 + \kappa_\gamma + \lambda_\gamma)$ and the W electric quadrupole moment as $Q_W \equiv -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma)$.

In any model with new physics at high energy that couples to the W boson, the anomalous couplings will be induced at some level. A useful way to represent this effect is to write an $SU(2) \times U(1)$-invariant effective Lagrangian to represent the effects of the new physics, and then to couple this to the weak vector bosons by gauging the symmetry. In the literature, this has been done using both linear and nonlinear effective Lagrangians [76, 77, 78]. Typically, the anomalous couplings predicted in such models are suppressed by factors of M_W^2/Λ^2, where Λ is a multi-TeV scale, or by factors $\alpha_w/4\pi$. These lead to typical values of the anomalous couplings below 10^{-2} and make it difficult to observe these couplings before directly observing the new physics itself. In the Standard Model one expects loop contributions of $O(10^{-3}$ [79]. In the supersymmetry model, one might expect loop contributions, depending on the values of the supersymmetry parameters [80].

For the present discussion, we use a linear realization with the additional constraint of equal couplings for the U(1) and SU(2) terms in the effective Lagrangian that contribute to anomalous triple gauge boson couplings. This gives an effective lagrangian with two free parameters, which we will take to be K_γ and λ_γ. This restriction is called the 'HISZ scenerio' [81]. This restriction of the parameter space has recently been applied to comparative studies of the anomalous W couplings at colliders [75]. It is important to note, however, that studies of $e^+e^- \to W^+W^-$ at the NLC can also test this hypothesis by independently determining the γ and Z couplings to the W [82].

2.6.2 Present and Expected Pre-NLC Measurements

The only present direct measurements of WWV couplings come from the CDF and D0 Experiments [75] at the Tevatron, which have searched for WW, WZ, and $W\gamma$ production. The WW and WZ searches have yielded $O(1)$ candidates and the $W\gamma$ searches have yielded $O(10)$ candidates, consistent with expectation. These observations have led to limits on the corrections to the coupling parameters of order unity. For example, D0 sets a 95% CL range $-1.8 < \Delta\kappa_\gamma < 1.9$ assuming $\lambda_\gamma = 0$ or a range $-0.6 < \lambda_\gamma < 0.6$ assuming $\kappa_\gamma = 0$ (both limits assume $\Lambda = 1$ TeV in the appropriate form factors).

One expects significant improvement at LEP II [83], once the accelerator exceeds the W-pair threshold energy. Techniques similar to those described below will be applied to $e^+e^- \to W^+W^-$ events at c.m. energies ranging from threshold at $\approx$160 GeV to $\approx$195 GeV.

Assuming no anomalous couplings are observed after an integrated luminosity of 500 pb^{-1}, 95% CL limits on individual couplings (all others set to zero) of $O(0.1)$ are expected.

After the Main Injector upgrade has been completed, it is expected that the Tevatron will collect O(1-10) fb^{-1} of data. (Further upgrades in luminosity are also under discussion.) If 10 fb^{-1} is achieved, it is expected [75] that limits on $\Delta\kappa_\gamma$ and λ_γ will be obtained that are competitive with those from LEP II with 500 pb^{-1}.

Finally, one expects the LHC accelerator to turn on sometime before the NLC and to look for the same signatures considered at the Tevatron. The planned luminosity and c.m. energy, however, give the LHC a large advantage over even the Main Injector Tevatron in probing anomalous couplings. The ATLAS Collaboration has estimated [24] that with 100 fb^{-1}, one can obtain (in the HISZ scenario) 95% CL limits on $\Delta\kappa_\gamma$ and λ_γ in the range 5-10 $\times\ 10^{-3}$. We should note that these studies do not yet include helicity analysis on the W bosons.

2.6.3 Measurements in W Pair Production at the NLC

The fact that the expected LHC limits improve dramatically upon those of a high-luminosity Tevatron indicates the importance of center-of-mass energy. This reflects the fact that, in the effective Lagrangian description, the anomalous couplings arise from higher-dimension effective interactions.

The NLC has an added advantage over hadron colliders in reconstructing W pair events due to absence of spectator partons. To a good approximation, full energy and momentum conservation constraints can be applied to the visible final states. Thus an $e^+e^- \to W^+W^-$ event can ideally be characterized by five angles: the production angle Θ_W of the W^- with respect to the electron beam, the polar and azimuthal decay angles θ^* and ϕ^* of one daughter of the W^- in the W^- reference frame, and the corresponding decay angles $\overline{\theta}^*$ and $\overline{\phi}^*$ of one of the W^+ daughters. In practice, initial-state photon radiation and final-state photon and gluon radiation (in hadronic W decays) complicate the picture. So does the finite width of the W. Nevertheless, for the studies below, we will characterize $e^+e^- \to W^+W^-$ events by these five angles and fit distributions in the angles to obtain values of anomalous couplings.

At high energies, the $e^+e^- \to W^+W^-$ process is dominated by t-channel ν_e exchange, leading primarily to very forward-angle W's where the W^- has an average helicity near minus one. This makes the bulk of the cross section difficult to observe with precision. However, the amplitudes affected by the anomalous couplings are not forward peaked; the central and backward-scattered W's are measurably altered in number and helicity by the couplings. W helicity analysis through the decay angular distributions provides a powerful probe of anomalous contributions. Most studies, including those discussed here, restrict attention to events for which $|\cos\Theta_W| < 0.8$. Not surprisingly, the most powerful channel to use is one in which one W decays leptonically (to $e\nu$ or $\mu\nu$) and the other hadronically ($\approx 30\%$ of all $e^+e^- \to W^+W^-$ events) Although one gains statistics when both W's decay hadronically, one loses considerable discriminating power from being unable to purely tag the charge of the W daughter quarks. The channel in which both W's decay leptonically suffers from both poor statistics and kinematic ambiguities due to two undetected neutrinos. For the leptonic *vs* hadronic channel, the lepton energy carries important information for kinematic reconstruction. For simplicity, most studies have not yet attempted to incorporate $W \to \tau\nu$ decays.

Figure 2.38 (taken from Ref. [84]) shows 95% CL exclusion contours in the plane λ_γ *vs* $\Delta\kappa_\gamma$ in the HISZ scenario for different c.m. energies and integrated luminosities (0.5 fb^{-1} at 190 GeV, 80 fb^{-1} at 500 GeV, and 190 fb^{-1} at 1500 GeV). These contours are based on ideal reconstruction of W daughter pairs produced on mass-shell with no initial-state radiation. The contours represent the best one could possibly do. A previous study [82] assuming a very high-performance detector but including initial-state radiation and a finite W width found some degradation in these contours, primarily due to efficiency loss when imposing kinematic requirements to suppress events far off mass-shell or at low effective c.m. energies. Nevertheless, one attains a precision of $O(10^{-3})$ at NLC(500) and $O(\text{few} \times 10^{-4})$ at NLC(1500). Another nice feature of coupling studies at NLC is the ability to disentangle couplings in models more general than HISZ via tuning of the electron beam polarization, as shown in Ref. [82].

A study [85] undertaken for this workshop has examined the effects of detector resolution on achievable precisions. One might expect *a priori* that the charged track momentum resolution would be most critical since the energy spectrum for the W-daughter muons peaks at a value just below the beam energy, falling off nearly linearly with decreasing energy. One might also expect the hadron calorimeter energy resolution to be important in that it affects the energy resolution of jets to be identified with underlying W-daughter quarks. Indeed, one finds that these resolutions do matter, but that the nominal resolution parameters assumed for the purposes of this workshop are quite adequate. A significant source of degradation in sensitivity to anomalous couplings comes from initial state photon radiation, aggravated by beamsstrahlung, the presence of which is difficult to establish in a single lepton-jets event, given the undetected neutrino. In this respect, the four-jets channel in which both W's decay hadronically, is more promising. Further investigation of this channel is in progress.

In summary, the studies reviewed in this section confirm the power of the NLC to extract anomalous couplings. We expect some degradation in coupling parameters precision from the ideal case due to the underlying physical phenomena of initial state photon radiation and the finite W width and a smaller degradation from the imperfection of matching detected particles to primary W daughters, but these effects are not serious and should be straightforward to incorporate in a real measurement.

2.6.4 Measurements in Other Reactions at the NLC

In addition, the NLC allows measurements of non-Abelian gauge boson couplings in other channels [75]. The process $e^+e^- \to Z\gamma$ probes $ZZ\gamma$ and $Z\gamma\gamma$ couplings, and processes such as $e^+e^- \to WWZ$ probe quartic couplings. The $WW\gamma$ and WWZ couplings can be probed independently via the processes $e^+e^- \to \nu\overline{\nu}\gamma$ and $e^+e^- \to \nu\overline{\nu}Z$, respectively.

Similar measurements can be carried out at e^-e^-, $e^-\gamma$ and $\gamma\gamma$ colliders, where the expected reduction in luminosity is at least partly compensated by other advantages [82, 86]. For example, the process $\gamma e^- \to W^-\nu_e$ probes the $WW\gamma$ coupling, independent of WWZ effects. The polarization asymmetry in this reaction reverses as the energy of the collisions is varied, and the location of this zero-crossing provides a sensitive probe of λ_γ [87]. The reaction $\gamma\gamma \to W^+W^-$ also separates effects of the γ couplings from those of the Z, and also probes the 4-boson $WW\gamma\gamma$ vertex. The power of this facility is enhanced by its ability to polarize both incoming beams [82].

2.6.5 Conclusions

Although there will have been a number of measurements of anomalous coupling parameters from LEP II, the Tevatron, and the LHC before the turn-on of the NLC, the precisions on the values of the couplings attainable with the NLC will quickly overwhelm the previous measurements. Moreover, the higher the accessible energy at NLC, the more dramatic the improvement will be. Figure 2.39 (taken from Ref. [88]) shows a useful comparison among these accelerators. The enormous potential of the NLC is apparent.

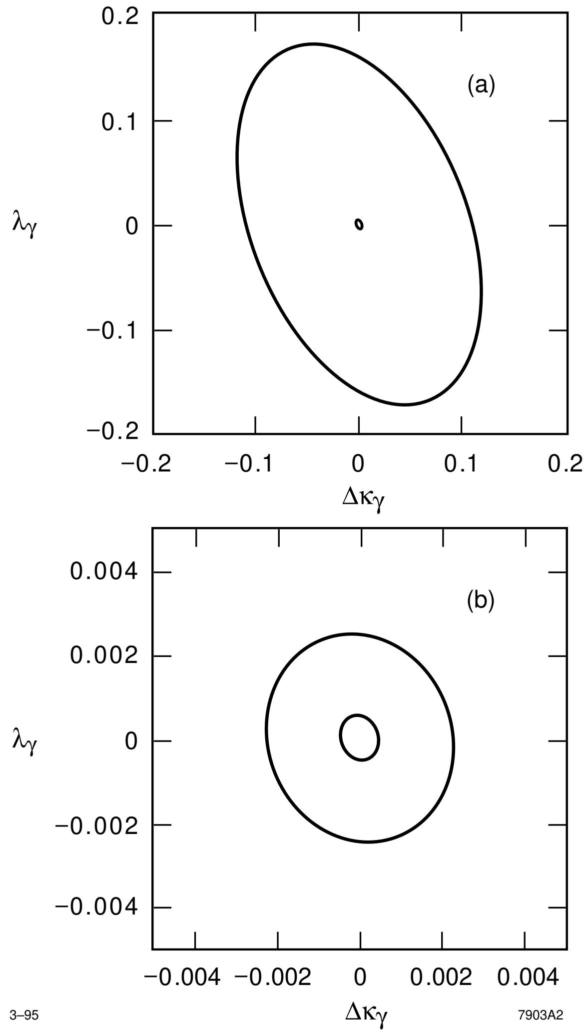

Figure 2.38: 95% CL contours for $\Delta\kappa_\gamma$ and λ_γ in the HISZ scenario. The outer contour in (a) is for $E_{CM} = 190$ GeV and 0.5 fb^{-1}. The inner contour in (a) and the outer contour in (b) is for $E_{CM} = 500$ GeV with 80 fb^{-1}. The inner contour in (b) is for $E_{CM} = 1.5$ TeV with 190 fb^{-1}.

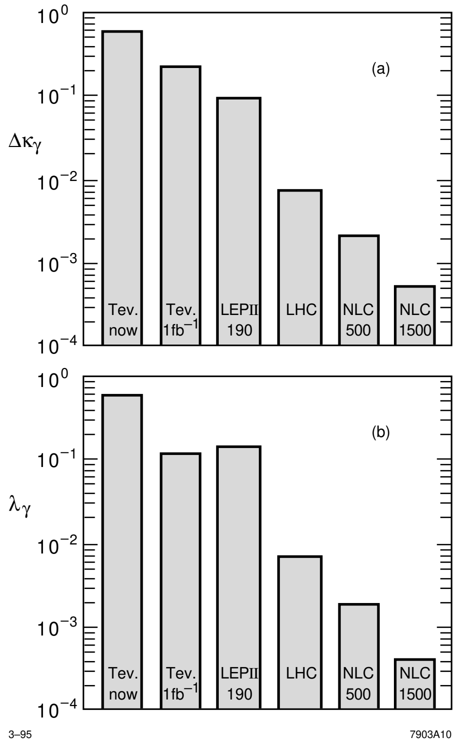

Figure 2.39: Comparison of representative 95% CL upper limits on $\Delta\kappa_\gamma$ and λ_γ for present and future accelerators.