Anomalous Gauge Boson Couplings

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ABSTRACT

The measurement of anomalous gauge boson self couplings is reviewed for a variety of present and planned accelerators. Sensitivities are compared for these accelerators using models based on the effective Lagrangian approach. The sensitivities described here are for measurement of "generic" parameters κ_V, λ_V, *etc.*, defined in the text. Pre-LHC measurements will not probe these coupling parameters to precision better than $O(10^{-1})$. The LHC should be sensitive to better than $O(10^{-2})$, while a future NLC should achieve sensitivity of $O(10^{-3})$ to $O(10^{-4})$ for center of mass energies ranging from 0.5 to 1.5 TeV.

I. INTRODUCTION

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 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 internal structure or loop corrections involving propagators of new particles. In addition, as is discussed elsewhere in these proceedings[1], precise measurements of gauge boson self interactions provide important information on the nature of electroweak symmetry breaking.

Recent results from CDF and D0 are consistent with nonvanishing values of triple gauge boson couplings, but have not yet reached a precision better than order unity. Upcoming measurements at LEP II and later at an upgraded Tevatron will improve upon this precision by an order of magnitude. The Large Hadron Collider (LHC) should do better by more than another order of magnitude. A 500 GeV Next Linear Collider (NLC) improves still further upon the LHC precision, and a 1.5 TeV NLC probes even smaller couplings, of order 10^{-4}. The alternative colliding modes of an NLC machine, e^-e^-, $e^-\gamma$, and $\gamma\gamma$, also provide useful and often complementary information on anomalous couplings. In principle, a $\mu^+\mu^-$ collider would provide comparable sensitivity to a corresponding NLC e^+e^- machine of the same center of mass (c.m.) energy, as long as luminosities, beam polarization, and detector backgrounds are also kept comparable, requirements that seem daunting at the moment. It should be noted, though, that given the increased sensitivity to anomalous couplings that comes with higher c.m. energies, a 4 TeV $\mu^+\mu^-$ collider would be a powerful machine indeed for studying gauge boson self-interactions.

This article focuses on *direct* measurements of anomalous couplings, typically via diboson production. There also exist indirect, model-dependent limits, obtained from virtual corrections to precisely measured observables and inferred parameters, such as $(g-2)_\mu$, the neutron electric dipole moment, and "oblique" Z parameters. Depending on assumptions, *e.g.*, depending on what one considers "natural", one can obtain limits from $O(10^{-2})$ to $O(1)$ [2].

In the following sections, an overview is given of common parametrizations of anomalous gauge boson couplings, followed by discussions of sensitivities to anomalous parameters provided by various accelerators. Conclusions follow at the end.

II. PARAMETRIZATION

Anomalous gauge boson couplings can be parametrized in a variety of ways. One can define "generic" parameters that describe in the most general way the allowed forms of gauge-boson vertices. This generic form has many free parameters, some of which violate discrete symmetries. To deal with this multitude of parameters it is convenient to apply an effective Lagrangian approach, assume certain symmetries are respected, and expand in terms of given operator dimensions. This approach has the virtue of imposing relations among the many otherwise-arbitrary parameters, and allowing an *a priori* estimate of the relative importance of different contributions.

In defining a generic set of anomalous couplings, we follow the notation of ref. [3] in which the effective Lagrangian for the WWV vertex is written:

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

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 14 (7×2) general coupling parameters allow for C/P-violating (g_5^V), and CP-violating (g_4^V, $\tilde{\kappa}_V$, $\tilde{\lambda}_V$) terms. In most studies such terms are neglected. In the standard model at tree level $g_1^V = \kappa_V = 1$ and $\lambda_V = g_4^V = g_5^V = \tilde{\kappa}_V = \tilde{\lambda}_V = 0$. It should be noted that these couplings are, in general, form factors with momentum-dependent values. This complication is of little importance at an e^+e^- collider where the WW c.m. energy is well defined, but it must be borne in mind at hadron colliders where couplings are simultaneously probed over large energy ranges[4]. To observe the momentum dependence directly at a hadron collider requires a nominal c.m. energy comparable to the form factor scale parameter $\Lambda_{\rm FF}$.

We follow a 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, in the static limit one can express the W magnetic dipole moment as

$$\mu_W \quad \equiv \quad \frac{e}{2\,M_W}(1 + \kappa_\gamma + \lambda_\gamma)$$

and the W electric quadrupole moment as

$$Q_W \quad \equiv \quad -\frac{e}{M_W^2}(\kappa_\gamma - \lambda_\gamma).$$

In addition, one can investigate the tri-boson coupling at the $V_\mu(P) \to Z_\alpha(q_1)\gamma_\beta(q_2)$ vertex (with $V = \gamma, Z$) for which the following general vertex function can be written:

$$
\begin{aligned}
\Gamma^{\alpha\beta\mu}_{Z\gamma V} \quad = \quad \tfrac{s-M_V^2}{M_Z^2}\Big[\quad & h_1^V(q_2^\mu g^{\alpha\beta} - q_2^\alpha g^{\mu\beta}) + \\
& \frac{h_2^V}{M_Z^2} P^\alpha (P\cdot q_2 g^{\mu\beta} - q_2^\mu P^\beta) + \\
& h_3^V \epsilon^{\mu\alpha\beta\rho} q_{2_\rho} + \\
& \frac{h_4^V}{M_Z^2} P^\alpha \epsilon^{\mu\beta\rho\sigma} P_\rho q_{2_\sigma} \Big]
\end{aligned}
$$

where h_i^V are anomalous couplings (zero in the Standard Model at tree level). The couplings h_1^V and h_2^V are CP-violating and are typically ignored in studies. As is true for the generic WWV coupling parameters, these parameters are, in general, momentum-dependent form factors.

There are two common approaches taken in relating these generic parameters to those of effective Lagrangians that go beyond the Standard Model. Both approaches involve classifying Lagrangian terms according to the energy dimensions of the operators involved, where each term beyond dimension 4 is suppressed by a power of a large mass parameter Λ that characterizes the scale of new physics: $L_{\rm eff} = L_{\rm SM} + L_{\rm NR}$ where $L_{\rm NR}$ is non-renormalizable in finite order:[5, 6]

$$
\begin{aligned}
L_{NR} \quad \equiv \quad & \frac{1}{\Lambda}\sum_i \alpha_i^{(5)} O_i^{(5)} + \\
& \frac{1}{\Lambda^2}\sum_i \alpha_i^{(6)} O_i^{(6)} + \ldots
\end{aligned}
$$

where O_i^N are local operators of dimension N and $\alpha_i^{(N)}$ are dimensionless couplings. Since odd-dimension operators do not contribute to gauge boson self interactions, one begins with dimension-6 operators and typically assumes that dimension-8 operators can be neglected.

In the so-called linear realization, (in which the Standard Model is recovered in the limit $\Lambda \to \infty$), one includes in the Lagrangian an explicit Higgs doublet field and its associated covariant derivative. Terms are then separated into those affecting gauge-boson two-point functions, which have been well tested at LEP/SLC, and those leading to non-standard triple gauge boson couplings. One generally expects in this model suppressions of dimension-6 anomalous triple gauge terms by $O(M_W^2/\Lambda^2)$. It has been shown[7], however, that no renormalizable underlying theory can generate these terms at tree level. One requires loops and thereby incurs an additional suppression of $O(\frac{1}{16\,\pi^2})$. In this scheme it is difficult to observe large anomalous trilinear couplings without directly observing the new physics itself. In contrast, anomalous quartic couplings can be generated at tree level and may therefore be substantially larger than the anomalous trilinear couplings. In the most widely used linear realization, one assumes (somewhat arbitrarily) 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. One also neglects C, P, and CP-violating terms in the Lagrangian. This leads to the

"HISZ Scenario", named after the authors[8], and involves only two free parameters, commonly taken to be κ_γ and λ_γ. In this scenario, the following relations hold:

$$\begin{aligned}
\Delta\kappa_Z &= \frac{1}{2}(1-\tan^2\theta_W)\Delta\kappa_\gamma \\
\Delta g_1^Z &= \frac{1}{2\,\cos^2\theta_W}\Delta\kappa_\gamma \\
\lambda_Z &= \lambda_\gamma
\end{aligned}$$

For reference, a "relaxed" HISZ scenario is sometimes used (see LEP II studies below) in which the $U(1)$ and $SU(2)$ couplings are *not* equated, a scenario that then involves three free parameters.

In the second common approach to effective Lagrangians, one constructs a nonlinear field from would-be Goldstone Bosons which give masses to the W and Z Bosons[9]. Without an explicit Higgs doublet in the model, one must encounter new physics at the few-TeV scale in a process such as longitudinal W-W scattering, which would otherwise violate unitarity. This non-linear approach is discussed in detail elsewhere in these proceedings[1]. For completeness, salient features are outlined here.

A non-linear field is defined via

$$\Sigma \equiv e^{i\vec{w}\cdot\vec{\sigma}/v}$$

with covariant derivative:

$$D_\mu\Sigma = \partial_\mu\Sigma + \frac{i}{2}gW_\mu^a\sigma^a\Sigma - \frac{i}{2}g'B_\mu\Sigma\sigma_3$$

where w_i represent the Goldstone fields, σ_i are the Pauli spin matrices, and $v = 246$ GeV is the electroweak symmetry breaking scale. From these fields and covariant derivatives, an effective Lagrangian is constructed, for which the following dimension-6 terms give anomalous WWV couplings:

$$\begin{aligned}
&-ig\frac{v^2}{\Lambda^2}L_{9L}Tr[W^{\mu\nu}D_\mu\Sigma D_\nu\Sigma^\dagger] \quad + \\
&-ig'\frac{v^2}{\Lambda^2}L_{9R}Tr[B^{\mu\nu}D_\mu\Sigma^\dagger D_\nu\Sigma]
\end{aligned}$$

In this scheme, the coupling parameters L_{9L} and L_{9R} are expected to be $O(1)$. They can be mapped onto the generic set of parameters defined above via the relations:

$$\begin{aligned}
\Delta g_1^Z &= \frac{e^2}{2\,c_W^2 s_W^2}\frac{v^2}{\Lambda^2}\,L_{9L} \\
\Delta\kappa_\gamma &= \frac{e^2}{2\,s_W^2}\frac{v^2}{\Lambda^2}\,(L_{9L}+L_{9R}) \\
\Delta\kappa_Z &= \frac{e^2}{2\,c_W^2 s_W^2}\frac{v^2}{\Lambda^2}\,(L_{9L}\,c_W^2 - L_{9R}\,s_W^2)
\end{aligned}$$

where $s_W^2 = \sin^2\theta_W$ and $c_W^2 = \cos^2\theta_W$. In the non-linear scheme there are no λ_V terms at the dimension 6 level. It should be noted that one obtains the full HISZ scenario with $\lambda_\gamma = 0$ by setting $L_{9R} = L_{9L}$.

III. PRESENT LIMITS ON ANOMALOUS GAUGE COUPLINGS

The best present direct measurements of WWV couplings come from hadron collider experiments – the UA2 experiment at the CERN S$p\bar{p}$S[10] and the CDF and D0 experiments at the Fermilab Tevatron[11, 12, 13]. UA2 has searched for $W\gamma$ production, while CDF and D0 have searched for $W\gamma$, WW and WZ production. Preliminary CDF and D0 results with $\sim$ 100 pb^{-1} of Run 1 data have resulted in $O(5)$ WW candidates per experiment in the dilepton channel and $O(100)$ $W\gamma$ candidates per experiment in the e and μ channels, consistent with SM expectations. From these data, the absence of an excess of such events has resulted in 95% C.L. bounds on coupling parameters of the order of unity, as shown in Fig. 1. (Also shown are limits from the CLEO experiment determined from measurements of B($b \to s\gamma$)[14].) For example, from $W\gamma$ data, D0 sets 95% C.L. limits of $|\Delta\kappa_\gamma| < 1.0$ assuming $\lambda_\gamma = 0$ and $|\lambda_\gamma| < 0.3$ assuming $\Delta\kappa_\gamma = 0$ (both results assume $\Lambda = 1.5$ TeV in the appropriate form factors). In the static limit, these constraints on $WW\gamma$ anomalous couplings can be related to higher-order EM moments of the W boson - the magnetic dipole moment and electric quadrupole moment, both of which are predicted to be non-zero in the SM. These experimental results exclude the simultaneous vanishing of μ_W and Q_W in excess of 95% C.L..

Preliminary results from CDF and D0 on limits on WWV anomalous couplings from $WW \to \ell\nu jj$ production from Run 1 data are comparable to those obtained from $W\gamma$ production. Limits from the WW dilepton channel are approximately 60% higher from each experiment. Since WW/WZ production is sensitive to both $WW\gamma$ and WWZ couplings, and delicate gauge cancellation between the two is required by the SM, these results are interesting because they provide the first *direct* evidence of the existence of the WWZ coupling – i.e. $g_1^Z = \kappa^Z = 0$ is excluded in excess of 99% C.L..

CDF, D0 and the L3 and DELPHI experiments at LEP have also obtained direct limits on $Z\gamma V$ anomalous couplings[15, 16, 17]. The SM predicts these couplings to be zero at tree level. At the Tevatron, the $Z\gamma \to \ell\ell\gamma$ ($\ell = e,\mu$) channel has been used, and more than $O(10)$ of $Z\gamma$ candidates have been observed in Run 1 data. The L3 experiment has searched in the lepton channel as well as the $\nu\bar{\nu}\gamma$ channel. D0 has also searched in this latter channel, and extracted the most stringent preliminary 95% C.L. limits of $|h_{30,10}^V| < 0.9$ for $h_{40,20}^V = 0$ and $|h_{40,20}^V| < 0.2$ for $h_{30,10}^V = 0$, for $\Lambda = 0.5$ TeV. The limits from the $\ell\ell\gamma$ channels from each experiment are approximately a factor of two less stringent than that obtained from the $\nu\bar{\nu}\gamma$ channel D0 result, as shown in Fig. 2.

IV. WHAT CAN LEP II SAY?

One expects significant improvement at LEP II[18, 19], as the accelerator raises its energy to well above the W-pair production threshold. Results from the recent Physics at LEP II Workshop[18] will be summarized here. In the workshop study, the relaxed HISZ scenario was used. Three free parameters

$\alpha_{W\phi}$, $\alpha_{B\phi}$, and α_W were considered, which can be related to the generic set via the relations:

$$\begin{aligned}\Delta\kappa_\gamma &= \alpha_{W\phi} + \alpha_{B\phi} \\ \Delta\kappa_Z &= \alpha_{W\phi} - \tan^2\theta_W \alpha_{B\phi} \\ \Delta g_1^Z &= \frac{1}{\cos^2\theta_W}\alpha_{W\phi} \\ \lambda_\gamma &= \lambda_Z = \alpha_W\end{aligned}$$

(If one requires $\alpha_{W\phi} = \alpha_{B\phi}$, one recovers the full HISZ scenario.)

As for hadron colliders, lepton colliders provide sensitivity to anomalous couplings through studies of diboson production. One important advantage of lepton colliders, though, is the ability to reconstruct accurately the full kinematics of the W pair events because of the 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 $\bar{\theta}$ and $\bar{\phi}$ of a W^+ daughter. 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, one finds that the five reconstructed angles remain robust observables for studying anomalous couplings.

There are three main topologies to consider, those in which both W's decay hadronically, in which one decays hadronically, the other leptonically, and in which both decay leptonically. The fully hadronic topology has the advantages of abundance (45.6%) and fully measured kinematics, but has the disadvantage of poorly determined charge signs for the W's and especially their decay products. Since much of the sensitivity to anomalous couplings comes from the pronounced forward-backward charge asymmetry of the W's (distribution in Θ_W), this disadvantage is a serious one. The mixed hadronic/leptonic topology has the disadvantages of lower abundance (29.2%, counting only e, μ decays) and of more poorly measured kinematics, due to the missing neutrino. This latter disadvantage is largely offset, however, by the power of kinematic constraints, including energy/momentum constraints and (optionally) mass constraints on reconstructed W's. The considerable advantage of the mixed topology lies in unambiguous determination of the individual W electric charges and the charge of one decay product. There does remain, however, a two-fold ambiguity in decay angles of the hadronic final state. The purely leptonic topology suffers badly from its low abundance (10.5%, counting e, μ and τ decays) and from the very poorly known kinematics, given two missing neutrinos. Even after imposing energy/momentum constraints and forcing both W masses to reconstruct to the nominal value, one is still left with a two-fold ambiguity in resulting angles.

In the LEP II study, a number of fitting methods were considered in order to extract anomalous couplings from measured angular distributions, methods based on helicity-density matrices, maximum likelihood, and moments of multi-dimensional distributions. The maximum likelihood technique was found to be most effective, and results from that method are shown here. For the purely hadronic and the mixed topologies, more than one choice of measured distributions for fitting was considered. Table I [18, 20] shows expected 1 standard deviation errors on each α parameter when only that parameter is allowed to vary. The numbers represent integrated luminosities of 500 pb^{-1} at 176 and 190 GeV, respectively. For comparison, the "ideal" sensitivity is also shown, for which all five angles are reconstructed perfectly with no ambiguity. From this table it's clear that the mixed topology, using all five reconstructed angles provides the best sensitivity. It's also clear that even a modest increase in energy improves sensitivity significantly. From these numbers, one can expect ultimate sensitivities (95% C.L.) to anomalous couplings parameters at somewhat better than $O(10\%)$. It should be noted that when more than one coupling parameter is varied at a time, correlations degrade these limits significantly. The absence of beam polarization at LEP makes separation of $WW\gamma$ from WWZ couplings more difficult than should be possible at the NLC, as discussed below.

V. WHAT CAN THE TEVATRON WITH THE MAIN INJECTOR SAY?

After the Main Injector upgrade has been completed, it is expected that the Tevatron will collect $O(1\text{-}10)$ fb^{-1} of data. (Further upgrades in luminosity are also under discussion.) If 10 fb^{-1} is achieved, it is expected[13, 21] that limits on $\Delta\kappa_\gamma$ and λ_γ will be obtained that are competitive with those from LEP II with 500 pb^{-1} at $\mathrm{E_{CM}}$ = 190 GeV.

In the Main Injector era, the Tevatron also provides a unique opportunity for observing the SM prediction of the existence of a radiation amplitude zero in $W\gamma$ production[22]. Direct evidence for the existence of this amplitude zero in $W\gamma$ production can be obtained by studying the photon $-$ W-decay lepton rapidity correlation, or equivalently, the photon-lepton rapidity difference distribution[23]. Because of the fact that the LHC will be a *pp* machine and because of severe QCD corrections at very high energies, this will be an extremely difficult measurement at the LHC.

Limits on $Z\gamma V$ couplings for the same integrated luminosity, in the $\nu\bar{\nu}\gamma$ channel are anticipated to be $|h^V_{30,10}| < 0.024$ for $h^V_{40,20} = 0$ and $|h^V_{40,20}| < 0.0013$ for $h^V_{30,10} = 0$, for $\Lambda = 1.5$ TeV at 95% C.L.. For the $\ell\ell\gamma$ channel, the limits on $Z\gamma V$ anomalous couplings are expected to be approximately a factor of two less stringent than this.

VI. WHAT CAN THE LHC SAY?

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% C.L. limits on $\Delta\kappa_\gamma$ and λ_γ in the range 5-10 $\times$ 10^{-3}. It should be noted that these studies do not yet include helicity analysis on the W bosons. A study of WZ production at the LHC, in the all-lepton decay channel[13, 25], obtained similar results. For the $W\gamma$ channel, the limits on λ_γ are comparable, while the limits on $\Delta\kappa_\gamma$ are approximately a factor of 10 times weaker.

The limits on $Z\gamma V$ couplings that are achievable at the LHC with the same integrated luminosity are $|h^V_{30,10}| < 5 \times 10^{-3}$ for $h^V_{40,20} = 0$ and $|h^V_{40,20}| < 9 \times 10^{-4}$ for $h^V_{30,10} = 0$, for $\Lambda = 1.5$ TeV[13]. It should be borne in mind that these limits depend strongly upon the assumed form factor scale Λ.

VII. WHAT CAN THE NLC SAY?

A high-energy NLC will be able to replicate the measurements of anomalous WWV couplings expected at LEP II, but with two important advantages: much higher energy and high beam polarization. The increased energy allows dramatic improvement in sensitivity, reflecting the fact that, in the effective Lagrangian description, the anomalous couplings arise from higher-dimension effective interactions. The beam polarization allows a clean separation of effects due to $WW\gamma$ and WWZ interactions. As at LEP II, one relies on reconstructing (with additional help from kinematic constraints) the five production / decay angles characterizing an $e^+e^- \to W^+W^-$ event. The resulting angular distributions are then fitted to extract anomalous couplings.

At high energies in the Standard Model, 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 detailed studies to date have restricted attention to events for which $|\cos\Theta_W| < 0.8$ and to the mixed topology where one W decays hadronically and the other leptonically.

Fig. 3 (taken from ref. [26]) shows results from one such study. The figure depicts 95% C.L. 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 (ISR). The contours represent the best one can do. Another study[27] 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). As mentioned above, the polarizable beams at NLC allow one to disentangle couplings that have correlated effects on observables in accelerators with unpolarized beams. This feature facilitates studying models more general than, say, the HISZ scenario with only two free parameters. Fig. 4 (taken from ref. [26]) shows expected 95% C.L. exclusion contours in the $\Delta\kappa_\gamma$–$\Delta\kappa_Z$ plane when $\Delta\kappa_\gamma$, λ_γ, $\Delta\kappa_Z$, and λ_Z are allowed to vary freely. The outer contour is for unpolarized beams, while the inner contour where correlation is much reduced demonstrates the discrimination available with 90% beam polarization. Results consistent with these have been found by other recent studies[28, 29].

A more recent study [30] undertaken for the 1995-1996 NLC workshop[31] has examined the effects of realistic 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. Preliminary work indicates, however, that an NLC detector can tolerate a broad range in charged track momentum and hadron calorimeter energy resolutions without significant degradation of precision on extracted anomalous couplings. This insensitivity to detector resolutions stems from the power of an over-constrained kinematic fit in determining the five event angles.

One expects some degradation in coupling parameters precision from the ideal case due to the underlying physical phenomena of initial state radiation[32] and the finite W width and a smaller degradation from the imperfection of matching detected particles to primary W daughters. The potentially largest effect comes from initial state radiation. With precise luminosity monitors, such as those in present LEP detectors, for which luminosity *vs* effective c.m. energy can be tracked, straightforward corrections for ISR, including beamstrahlung, should be feasible. One doesn't expect dramatic degradation in sensitivity from any of the above complications.

Preliminary work suggests that the 4-jet channel $jjjj$ can contribute significantly to anomalous couplings measurements, as long as charge confusion in the detector is well understood. In regard to ISR, this channel has the important advantage of allowing reliable event-by-event determination of missing photon energy, using kinematic constraints, a technique that works only poorly in the $jj\ell\nu$ channel[30]. If one could reliably tag a $c(\bar{c})$ quark jet, at least one of which occurs in 75% of the $jjjj$-channel events, one would expect further improvements in sensitivity. This channel merits additional study. The purely leptonic $\ell\nu\ell\nu$ channel is remarkably clean, but poor statistics and ambiguous kinematics make this channel intrinsically less sensitive than the $jj\ell\nu$ and $jjjj$ channels[33].

An NLC e^+e^- collider also allows measurement of non-Abelian gauge boson couplings in channels[13] other than $e^+e^- \to W^+W^-$. The process $e^+e^- \to Z\gamma$ probes $ZZ\gamma$ and $Z\gamma\gamma$ couplings, and processes such as $e^+e^- \to WWZ$ and $e^+e^- \to ZZZ$ probe quartic couplings[34, 35]. The $WW\gamma$ and WWZ couplings can be probed independently via the processes $e^+e^- \to \nu_e\bar{\nu}_e\gamma$ and $e^+e^- \to \nu_e\bar{\nu}_e Z$, respectively[36, 37].

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[27, 38]. For example, the processes $\gamma e^- \to W^-\nu_e$ and $\gamma\gamma \to W^+W^-$ probe the $WW\gamma$ coupling, independent of WWZ effects. The polarization asymmetry in the former reaction reverses as the energy of the collisions is varied, and the location of the zero-crossing provides a probe of λ_γ[39]. Similarly, the process $e^-\gamma \to Ze^-$ probes the $ZZ\gamma$ vertex[39]. In the process $e^-\gamma \to W^-Z\nu_e$, one obtains sensitivity to WWZ, $WW\gamma$, and $WWZ\gamma$ couplings. In particular, the parity-violating coupling g_5^V can be probed[40]. More power comes from the ability to polarize *both* incoming beams with these alternative colliders. An e^-e^- collider has moreover the special capability of producing isospin-2 intermediate states, such as in $e^-e^- \to \nu\nu W^-W^-$[41]. The similar reactions $e^-e^- \to e^-\nu W^-Z$ and $e^-e^- \to e^-e^-ZZ$ turn out to be powerful probes for anomalous quartic couplings[38]. Table II shows a sampling of processes and gauge couplings that can be studied at alternate colliders associated with the NLC.

VIII. CONCLUSIONS

In the coming years, data from LEP II and an upgraded Tevatron should provide sensitivities to various anomalous gauge boson couplings of $O(10^{-1})$, an order of magnitude better than present direct measurements from the Tevatron. The LHC should greatly improve on this sensitivity, probing to better than $O(10^{-2})$. An NLC at 500 GeV c.m. energy would do still better, reaching $O(10^{-3})$, while a 1.5 TeV NLC would achieve sensitivities of $O(10^{-4})$. Fig. 5 (taken from ref. [42]) shows a useful comparison among these accelerators. The enormous potential of LHC and especially that of a high-energy NLC are apparent. In general, the LHC and NLC are complementary: the e^+e^- collider (and associated alternative e^-e^-, $e^-\gamma$, $\gamma\gamma$ colliders) allow precision measurement of helicity amplitudes at well-determined c.m. energy, while the pp collider allows less precise probing of couplings at higher energies. Both machines should probe energy scales of a few TeV and should add decisively to our understanding of gauge boson self interactions.

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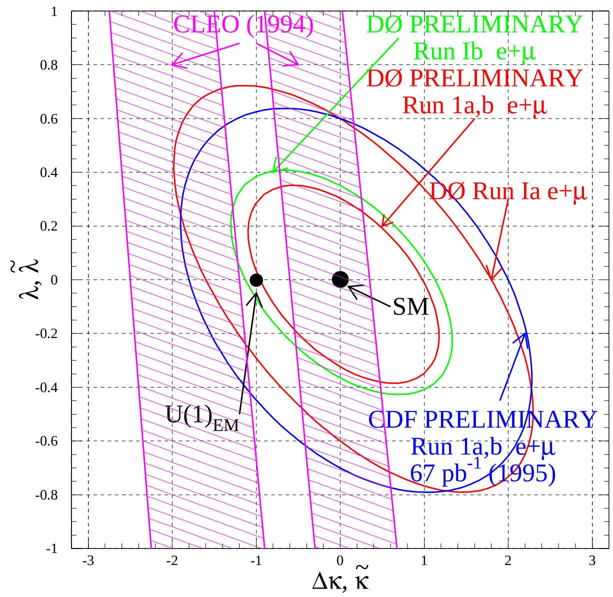

Figure 1: CDF and D0 95% C.L. contours for WWV anomalous couplings for Λ = 1.5 TeV. Also shown are the CLEO limits from $b \rightarrow s\gamma/B \rightarrow K^*\gamma$.

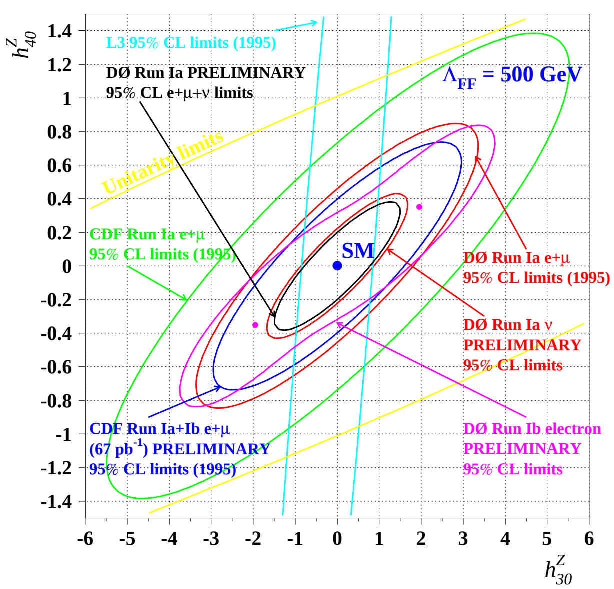

Figure 2: CDF and D0 95% C.L. contours for $Z\gamma V$ anomalous couplings for Λ = 0.5 TeV

Table I: Estimated 1 s.d. errors on anomalous couplings obtainable at LEP II with 500 pb^{-1} at each c.m. energy.

Model	Channel	Angular data used	176 GeV	190 GeV
$\alpha_{B\phi}$	$jj\ell\nu$	$\cos\theta$	0.222	0.109
		$\cos\theta$, $(\cos\theta_l, \phi_l)$	0.182	0.082
		$\cos\theta$, $(\cos\theta_l, \phi_l)$, $(\cos\theta_j, \phi_j)_{\rm folded}$	0.159	0.080
	$jjjj$	$\vert\cos\theta\vert$	0.376	0.149
		$\vert\cos\theta\vert$, $(\cos\theta_{j_1}, \phi_{j_1})_{\rm folded}$, $(\cos\theta_{j_2}, \phi_{j_2})_{\rm folded}$	0.328	0.123
	$\ell\nu\ell\nu$	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$, 2 solutions	0.323	0.188
	Ideal	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$	0.099	0.061
$\alpha_{W\phi}$	$jj\ell\nu$	$\cos\theta$	0.041	0.027
		$\cos\theta$, $(\cos\theta_l, \phi_l)$	0.037	0.023
		$\cos\theta$, $(\cos\theta_l, \phi_l)$, $(\cos\theta_j, \phi_j)_{\rm folded}$	0.034	0.022
	$jjjj$	$\vert\cos\theta\vert$	0.098	0.054
		$\vert\cos\theta\vert$, $(\cos\theta_{j_1}, \phi_{j_1})_{\rm folded}$, $(\cos\theta_{j_2}, \phi_{j_2})_{\rm folded}$	0.069	0.042
	$\ell\nu\ell\nu$	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$, 2 solutions	0.096	0.064
	Ideal	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$	0.028	0.018
α_W	$jj\ell\nu$	$\cos\theta$	0.074	0.046
		$\cos\theta$, $(\cos\theta_l, \phi_l)$	0.062	0.038
		$\cos\theta$, $(\cos\theta_l, \phi_l)$, $(\cos\theta_j, \phi_j)_{\rm folded}$	0.055	0.032
	$jjjj$	$\vert\cos\theta\vert$	0.188	0.110
		$\vert\cos\theta\vert$, $(\cos\theta_{j_1}, \phi_{j_1})_{\rm folded}$, $(\cos\theta_{j_2}, \phi_{j_2})_{\rm folded}$	0.131	0.069
	$\ell\nu\ell\nu$	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$, 2 solutions	0.100	0.064
	Ideal	$\cos\theta$, $(\cos\theta_1, \phi_1)$, $(\cos\theta_2, \phi_2)$	0.037	0.022

Table II: A sampling of processes and associated gauge boson couplings measurable at e^-e^-, $\gamma\gamma$, and $e^-\gamma$ colliders.

Process	Couplings probed
$e^-e^- \to e^-\nu W^-$	$WW\gamma$, WWZ
$e^-e^- \to e^-e^-Z$	$ZZ\gamma$, $Z\gamma\gamma$
$e^-e^- \to e^-\nu W^-\gamma$	$WW\gamma$, WWZ
$e^-e^- \to \nu\nu W^-W^-$	$WWWW$
$e^-e^- \to e^-\nu W^-Z$	$WWZZ$
$e^-e^- \to e^-e^-ZZ$	$ZZZZ$
$\gamma\gamma \to W^+W^-$	$WW\gamma$
$\gamma\gamma \to W^+W^-Z$	WWZ, $WW\gamma$
$\gamma\gamma \to ZZ$	$ZZ\gamma$, $Z\gamma\gamma$
$\gamma\gamma \to W^+W^-W^+W^-$	$WWWW$
$\gamma\gamma \to W^+W^-ZZ$	$WWZZ$
$e^-\gamma \to W^-\nu$	$WW\gamma$
$e^-\gamma \to e^-Z$	$ZZ\gamma$, $Z\gamma\gamma$
$e^-\gamma \to W^+W^-e^-$	WWZ, $WW\gamma$, $WWZ\gamma$
$e^-\gamma \to W^-Z\nu$	WWZ, $WW\gamma$, $WWZ\gamma$

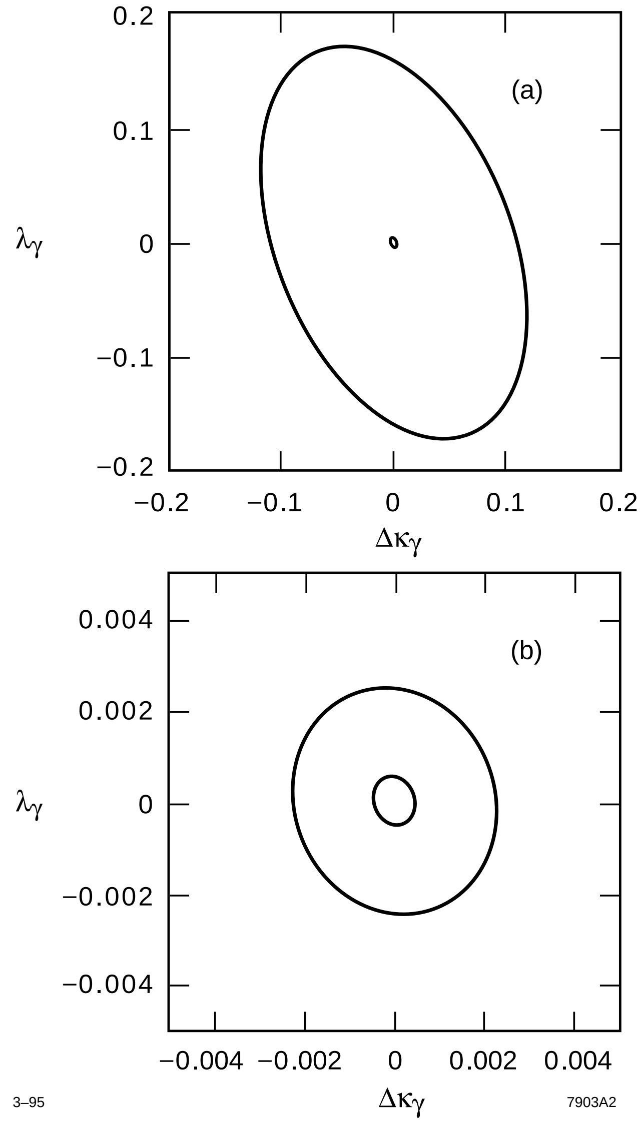

Figure 3: 95% C.L. contours for $\Delta\kappa_\gamma$ and λ_γ in the HISZ scenario. The outer contour in (a) is for $\mathrm{E_{CM}}$ = 190 GeV and 0.5 fb^{-1}. The inner contour in (a) and the outer contour in (b) is for $\mathrm{E_{CM}}$ = 500 GeV with 80 fb^{-1}. The inner contour in (b) is for $\mathrm{E_{CM}}$ = 1.5 TeV with 190 fb^{-1}.

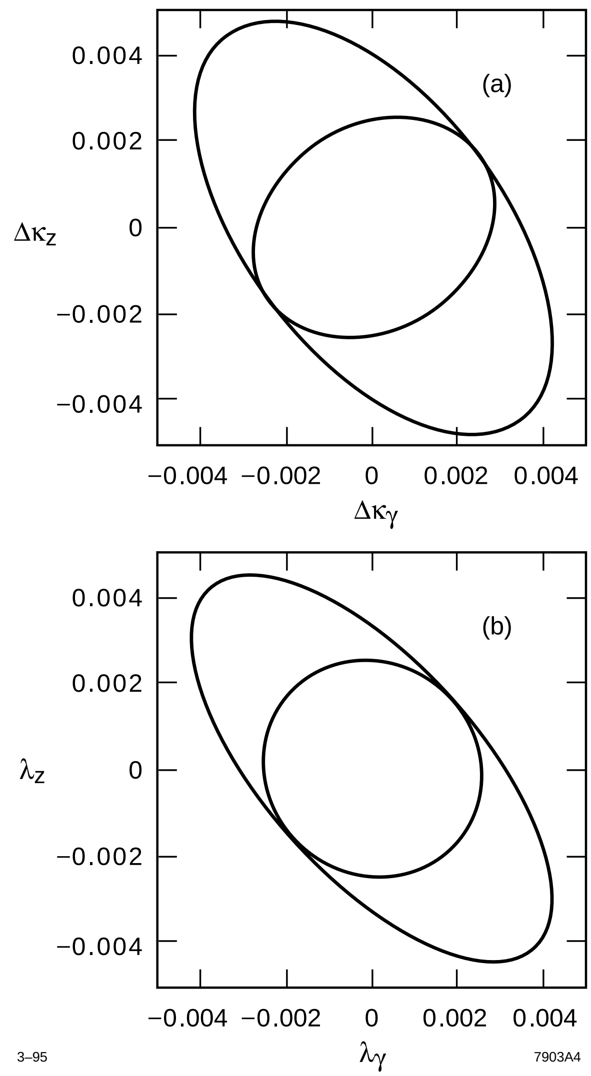

Figure 4: 95% C.L. contours for $\Delta\kappa_\gamma$ and $\Delta\kappa_Z$ and for λ_γ and λ_Z for simultaneous fits of $\Delta\kappa_\gamma$, $\Delta\kappa_Z$, λ_γ, λ_Z at $\mathrm{E_{CM}}$ = 500 GeV with 80 fb^{-1}. The outer contours are for 0% initial state electron polarization and the inner contours are for 90% polarization.

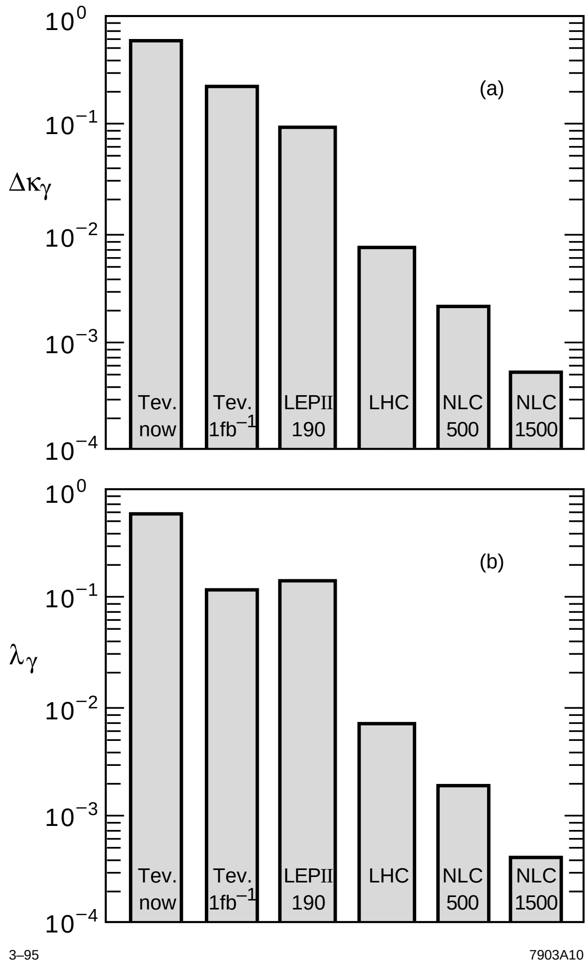

Figure 5: Comparison of representative 95% C.L. upper limits on $\Delta\kappa_\gamma$ and λ_γ for present and future accelerators.