Effects of Detector Resolution on Measurement of Anomalous Triple Gauge Boson Couplings

Keith Riles

Randall Laboratory
University of Michigan
Ann Arbor, MI 48109-1120

ABSTRACT

This article describes a study of detector resolution effects in the measurement of anomalous gauge boson couplings, specifically the extraction of WWZ and $WW\gamma$ parameters from the process $e^+e^- \rightarrow W^+W^-$ with $WW \rightarrow \ell\nu q\overline{q}'$. A computer program `wwv`, available on the World Wide Web, has been written to carry out this study and is described. Preliminary work indicates that determination of anomalous couplings does not depend critically upon detector performance, but more study is needed to understand how to correct for large effects due to initial state photon radiation. Determination of anomalous couplings is found to be insensitive to detector smearing over a broad range of assumed resolutions. The effects of initial state radiation, however, lead to substantial losses in efficiency from kinematic requirements or demand a detailed understanding of initial state radiation and beamsstrahlung photon energy spectra.

1 Introduction

Studies in recent years[1, 3] have demonstrated the tremendous potential of a high-energy e^+e^- collider for precise determination of anomalous triple gauge boson couplings. In particular, the process $e^+e^- \rightarrow W^+W^-$ followed by $WW \rightarrow \ell\nu q\overline{q}'$ promises to provide unmatched sensitivity to $WWV(V = \gamma Z)$ couplings[13]. This study addresses the question of whether realistic detector performance significantly degrades the expected precision in these couplings measurements. Important effects of initial state radiation and finite W width are considered.

It is assumed that the reader is familiar with the conventional parametrization of Hagiwara *et al.*[4] in which WWV couplings are defined in terms of parameters κ_V, λ_V, *etc.*. For the purposes of this study, the full HISZ[5] scenario will be used, in which only two parameters (taken to be $\Delta\kappa_\gamma$, λ_γ) are free to vary.

In keeping with the guidelines of the NLC workshop studies, no explicit detector simulation has been performed. Instead, 4-vectors representing momenta / energies of detectable particles (charged leptons, stable hadrons) have been smeared according to a standard prescription[12]. This smearing includes reduced acceptance in forward detector regions. One expects *a priori* that the most important resolution for $WW \to \mu\nu q\overline{q}'$ events is that for reconstructed charged particle momentum, since the muon energy spectrum peaks near the beam energy. In addition, for both $WW \to e\nu q\overline{q}'$ and $WW \to \mu\nu q\overline{q}'$ one might expect the hadron calorimeter energy resolution for hadronic jets to be important. The "nominal" parameters describing these two resolutions (given below) are used as a benchmark against which both degraded and improved resolutions are compared. For reference, charged particle momentum resolution is taken to have the form (assuming a solenoidal magnetic field):

$$\frac{\delta p_\perp}{p_\perp} \quad = \quad a \quad \times \quad p_\perp$$

with $p_\perp$ in GeV and where $a = 2.0 \times 10^{-4}$ (multiple scattering effects are unimportant in this measurement). Hadron calorimeter energy resolution is taken to have the form

$$\frac{\delta E}{E} \quad = \quad \frac{A}{\sqrt{E}} \quad \oplus \quad B$$

with E in GeV, where $A = 45\%$ and $B = 50\%$, and where the A and B errors are combined in quadrature. In addition to this nominal benchmark, two others were defined: a "perfect particle detector" for which the momenta of charged leptons and stable hadrons are detected with full efficiency and perfect resolutions and an "ideal daughter detector" for which the momenta of W daughter partons are measured perfectly (meaning measurement of neutrino / charged lepton / quark momenta and determination of lepton charge but not of quark charges).

The `pythia` Monte Carlo program[8] has been used for $e^+e^- \to W^+W^-$ event generation; hadronization of quarks is carried out via the Lund algorithm. Although the `pythia` program has been shown in LEP II studies[7] to lack the precision in radiative corrections of other recent $e^+e^- \to W^+W^-$ generators developed for LEP II, it serves as a useful and convenient platform for isolating the effects of detector resolution and the predominant effects of initial state radiation. For the studies described here only $e^+e^- \to W^+W^-$ events with $|\cos\Theta_W| < 0.8$ were generated. This restriction is motivated not only by the difficulty in accurately reconstructing W's in the forward direction, but also by the dominance of the cross section in forward regions by the t-channel ν_e exchange diagram which is not affected by anomalous WWV couplings. Restricting attention to the centrally produced W's has only a small effect on the statistical precision of extracted couplings.

In section 2, the procedure used in this study is described in detail. Results will be shown in section 3, and section 4 contains a summary and some discussion.

The study described in this article was carried out using the `wwv` fortran program which can be accessed via the World Wide Web at the following URL:

`http://www-personal.umich.edu/~kriles/wwv/wwvdoc.html`

The source code is provided both in a `patchy` cards file and as a `tar` archive file containing extracted fortran code and common block files. In addition, programs for plotting differential cross sections and for fitting to idealized self-generated distributions are included in the `patchy` source code. Scripts for running these programs on a `unix` operating system are also provided.

2 Procedure

It is conventional and convenient to define the topology of a $e^+e^- \to W^+W^-$ event via five angles (neglecting initial state radiation): polar production angle Θ_W of the W^-; the decay polar and azimuthal angles θ^*_ℓ, ϕ^*_ℓ of the charged lepton w.r.t. its parent W's lab-frame direction in the W rest frame; and the analogous decay angles $\overline{\theta}^*_q$ and $\overline{\phi}^*_q$ of one quark in its parent W's rest frame. No quark-charge tagging is assumed here; hence there is an ambiguity ($\overline{\theta}^*_q \leftrightarrow \pi - \overline{\theta}^*_q$ and $\overline{\phi}^*_q \leftrightarrow \overline{\phi}^*_q + \pi$) that requires folding the hadronic decay angle distributions. The basic procedure used in the `wwv` program can be described quite simply:

- Loop over events...
  - Identify W pair candidate events and classify decays
  - Reconstruct and store five W production / decay angles per event
- Fit stored angular distributions to extract couplings parameters

The different steps in this procedure are detailed in this section.

2.1 Event Selection and Reconstruction

For this study, only very simple criteria have been used to select $WW \to q\overline{q}' q''\overline{q}'''$ events. This is largely because the events should in reality be easy to find with very little background. The leptons will generally be highly energetic and isolated. The hadronic jets are straightforward to reconstruct. Background from other four-fermion processes $e^+e^- \to \ell\nu q\overline{q}'$ have been considered in ref.[3] and found to be controllable with invariant mass requirements on the reconstructed W candidates. No backgrounds have been considered in this study.

Charged leptons are subjected to the tracking / calorimeter efficiencies and resolutions described in ref[12]. In addition, this study requires the leptons be isolated by at least 15 degrees from any other charged particle with momentum greater than 1 GeV and that the lepton energy lie between 90% of the kinematically allowed minimum and 110% of the kinematically allowed maximum for a lepton from W decay when no initial state radiation is present and the W width vanishes. The extra 10% of allowed energy range is meant to accommodate detector resolution and radiation and width effects.

Once the lepton candidate has been identified, additional requirements are imposed on the remaining detected particles to ensure consistency with the presence of hadronic W

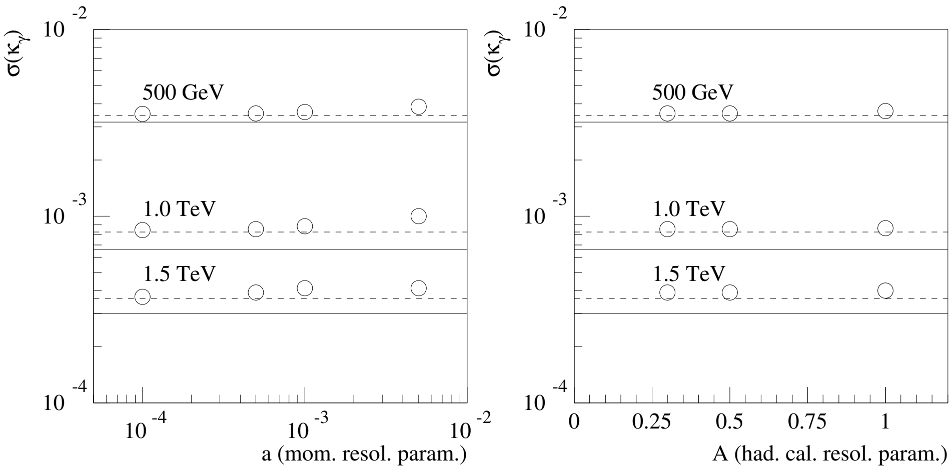

Figure 1: *Idealized Case:* Measurement precision for $\Delta\kappa_\gamma$ at various c.m. energies and for various detector resolution parameters, as explained in the text. All values are for 4000 accepted events with $|\cos\Theta_W| < 0.8$. The solid lines at each energy represent the ideal W-daughter detector with the same angular binning, while the dashed lines represent a perfect particle detector. Events have been generated with no initial state radiation and with $\Gamma_W = 0$.

decay. Aside from a single identified lepton, the event must contain at least 3 charged tracks, 3 neutral particles, charged particle energy greater than 5% of E_{CM}, total neutral energy greater than 2.5% of E_{CM}, and charged + neutral energy greater than 20% of E_{CM}. (These energies exclude the lepton's contribution.)

All detected particles, excluding the lepton, are subjected to a jet finding algorithm that forces two jets to be found. Two algorithms are available in `wwv`: the JADE[6] method with a varying y_{min} cutoff and a separation according to thrust axis hemispheres in the c.m. frame of the detected particles. The two algorithms are found to give nearly identical results. The thrust axis separation is used in what follows.

After the lepton and two hadronic jets have been identified, their four vectors are subjected to an algorithm to determine the five production / decay angles described above. A number of algorithm choices are available in `wwv`. The first is based on ref.[2] in which one assumes that the lepton momentum and the 3-velocities of the jets are measured perfectly. One also assumes that the leptonically decaying W is on mass shell ($\Gamma_W = 0$) and that there is no initial state radiation present. A second algorithm is based on a least-squares constrained kinematic fit[9], using lepton and jet resolutions. A number of kinematic fitting options have been implemented. The two W masses may vary independently, they may vary together, or they may be forced to equal the nominal W mass. In addition, the fit may allow a massless photon radiated along the beam direction.

For generated events with no ISR and with $\Gamma_W = 0$, the four different algorithms above (no photon assumed along beam direction) give very similar results over large ranges in detector resolution. In the study of these events, no photon radiation is assumed in the kinematic fit, and the W masses float independently. For generated events with ISR and $\Gamma_W \neq 0$, the different algorithms vary considerably in effectiveness. In the study of these events, the W masses float together, and a massless photon is assumed along the beam direction.

2.2 Parameter Fitting

Once the sets of five production / decay angles have been determined for all selected $WW \rightarrow \ell\nu q\overline{q}'$ candidate events, the angles are binned into a 5-dimensional distribution for a subsequent maximum likelihood fit to a detector-smeared differential cross section that depends on anomalous couplings parameters. The differential cross section formulae are taken from ref.[4]. For convenience in comparing to previous studies, the HISZ[5] scenario is used here.

The treatment of detector smearing is non-trivial in the fit to the 5-dimensional angular distribution. The `wwv` program allows two approaches based on migration matrices that transform true production / decay angles into measured angles. The first approach assumes independent smearing among the five single-angle distributions, allowing a factorized transformation consisting of products of five two-dimensional migration matrices. The second approach does not assume independent smearing and uses a ten-dimensional migration matrix. This second approach was found to be less prone to biasing central values of fitted parameters and is used in what follows.

There is a considerable CPU/memory penalty, however, in using the unfactorized migration matrix. For the computer used in this study (Hewlett Packard 715/80 Workstation), memory was the more severe constraint. For 5-dimensional fitting the binning chosen was $(10 \times 3 \times 3 \times 2 \times 2)^2$) for the true / reconstructed variables Θ_W, $\cos\theta^*_\ell$, ϕ^*_ℓ, $\cos\overline{\theta}^*_q$, and $\overline{\phi}^*_q$, respectively. To reduce errors coming from non-linear variation of cross sections within a single bin, multiple sampling in uniform subdivisions is allowed for each dimension. In addition, since the differential cross sections are exactly quadratic in the couplings, full matrix element evaluation for each bin need only be done during initialization, after which a set of coefficients is calculated for each bin to allow rapid recalculation of differential contributions for arbitrary coupling values.

One other technical point concerns the polar production angle Θ_W. The differential cross section formulae are provided in ref.[4] with respect to $\cos\Theta_W$. These formulae give very sharply peaked distributions in the forward direction. Consequently, to reduce non linearity across bins, the fitting is performed directly in Θ_W instead of $\cos\Theta_W$.

3 Results

Results are given below for two distinct cases. The first concerns analysis of idealized $e^+e^- \rightarrow W^+W^-$ events generated by the `pythia` program with no initial state photon radiation and

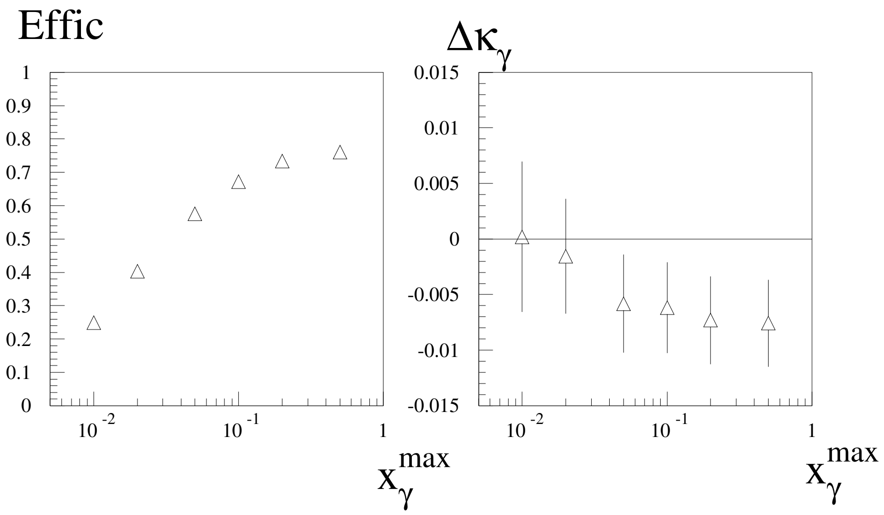

Figure 2: Efficiency and bias on fitted $\Delta\kappa_\gamma$ plotted *vs* the minimimum allowed true c.m. energy of the W pair. The error bars indicate the statistical error from the fit to candidates in a sample of 4000 $e^+e^- \to W^+W^-$ events generated with initial state radiation and $\Gamma_W \neq 0$ at a nominal c.m. energy of 500 GeV.

with $\Gamma_W = 0$. The second concerns the more realistic case with initial state radiation and finite W width. In the first case, detector resolution and the details of the kinematic fitting play only a small role, thanks to the power of kinematic constraints. In the second case, on the other hand, detector resolution and the kinematic fitting approach both take on greater importance, as the kinematic constraints weaken.

3.1 Idealized Case: $\Gamma_W = 0$ and no ISR

Consider first the idealized case of no initial state radiation and vanishing W width. In this study 4000 $e^+e^- \to W^+W^-$ events were generated with $|\cos\Theta_W| < 0.8$ at c.m. energies of 500, 1000, and 1500 GeV. These correspond to integrated luminosities of approximately 10, 50, and 130 fb^{-1}, respectively. The events were kinematically fitted with equal floating W masses and with no missing photon along the beam direction. The resulting distributions in production / decay angles were fitted to obtain $\Delta\kappa_\gamma$ in the HISZ scenario with λ_γ fixed to zero. The procedure was repeated for a variety of charged particle momentum resolution and hadron calorimeter energy resolution parameters. The unfactorized 10-dimensional migration matrix with binning described above was used to account for detector smearing in the fit.

Figures 1a-b shows the resulting statistical errors on the fitted $\Delta\kappa_\gamma$ values for the different tracking and calorimeter resolutions. The dashed lines indicate what could be achieved with this procedure for a *perfect particle detector*. The solid lines indicate what could be achieved with an *ideal W daughter detector* in which the charged lepton and initial quark momenta are known exactly. The striking feature of Figure 1 is that the precision on $\Delta\kappa_\gamma$ is quite

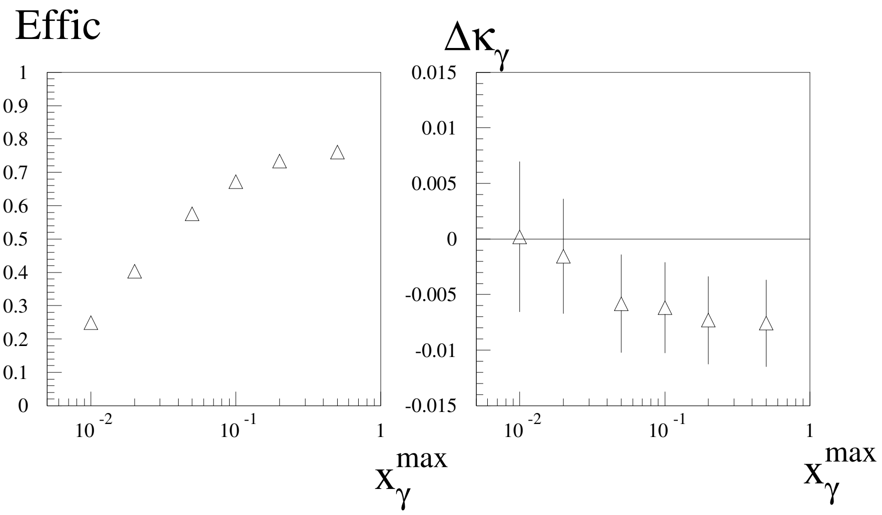

Figure 3: Efficiency and bias on fitted $\Delta\kappa_\gamma$ plotted *vs* the maximum allowed fraction of c.m. energy obtained for the fitted energy of a photon undetected along the beam direction. The error bars indicate the statistical error from the fit to candidates in the sample of 4000 $e^+e^- \rightarrow W^+W^-$ events generated with initial state radiation and $\Gamma_W \neq 0$ at a nominal c.m. energy of 500 GeV.

insensitive to detector resolution. This is an indication of the power of the constrained kinematic fitting when initial state radiation is not present.

3.2 Inconvenient reality: $\Gamma_W \neq 0$ and ISR

Introducing initial state radiation and finite W width considerably spoils the idealized case above. The degradation comes from several sources. First, the Breit-Wigner spread in W masses detracts from an otherwise powerful kinematic constraint. Second, the emission of an undetected photon along the beam direction distorts the kinematics of the visible decay products. A kinematic fit assuming full energy/momentum conservation necessarily obtains incorrect production / decay angles. Third, the emission of the the photon leads to a reduced effective c.m. energy for the produced W pair, leading to a distorted spectrum in actual production / decay angles from that expected at the nominal beam c.m. energy.

Since initial state radiation is strongly peaked toward zero photon energy, one can maintain a high efficiency by excluding specifically those events with c.m. energies far below the nominal value. Figure 2a shows the efficiency obtained by the standard reconstruction / fitting procedure, including detector smearing effects, for 4000 events containing ISR and $\Gamma_W \neq 0$ at a nominal c.m. energy of 500 GeV. The efficiencies are plotted *vs* the minimum allowed true c.m. energy of the W pair. Figure 2b shows the bias in the fitted $\Delta\kappa_\gamma$ value obtained from directly fitting these events. The error bars indicate the errors obtained in the associated fit to the passing candidates (*not* the error on the bias itself). As expected, one can eliminate bias in the central value with a modest loss of efficiency if one can cut

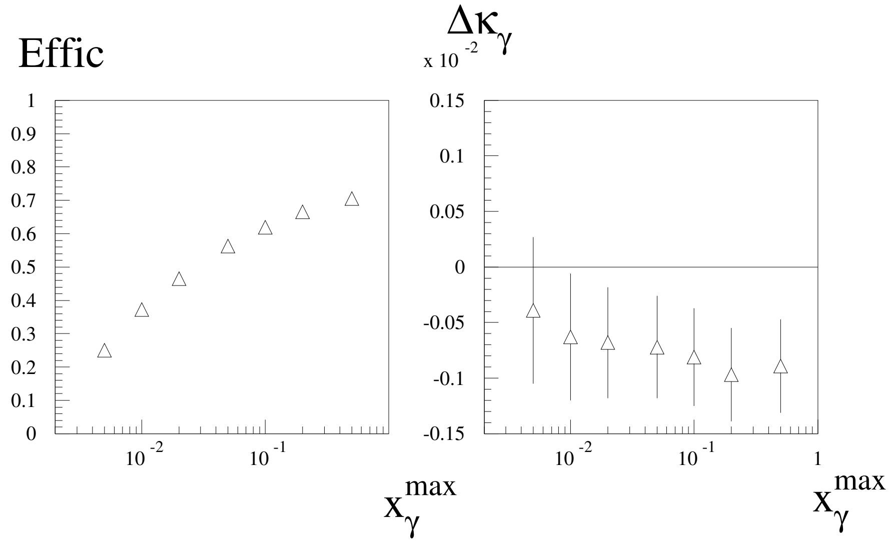

Figure 4: Same quantities as for Figure 3 but at a nominal c.m. energy of 1500 GeV. Notice that the vertical scale in the righthand plot is 10 times smaller than in Figure 3.

directly on the true W pair c.m. energy.

The problem, of course, is making a cut based on reconstructed observables. Two approaches have been tried. One uses a "χ^2" parameter that measures the deviation of the two reconstructed W masses from nominal values, as described in ref.[2]. Another approach, which seems to give slightly better efficiency for the same bias and which is used in the following, comes from performing a kinematic fit to the event while allowing a missing photon along the beam direction. The fitted photon energy is then required to be less than a fraction x_γ^{max} of the nominal c.m. energy. Figure 3a shows the efficiency obtained for the 4000 events at 500 GeV plotted *vs* x_γ^{max}. Figure 3b shows the resulting biases in fitted $\Delta\kappa_\gamma$ values plotted *vs* x_γ^{max}. One suffers a large efficiency loss to obtain a bias much smaller than the statistical error in these samples. Figures 4a-b show the analogous quantities for a sample of 4000 generated events at a nominal c.m. energy of 1500 GeV. At the higher energy, it is more difficult to eliminate bias with modest efficiency loss.

In order to understand the effect of varying detector resolution on these biases and couplings errors, values of $x_\gamma^{max} = 0.02(.01)$ were chosen for events at 500(1500) GeV, and the above fitting procedure was repeated for different track momentum and calorimeter energy resolution parameters. Figures 5a-b show the resulting errors on $\Delta\kappa_\gamma$ as the momentum and energy resolutions are varied over large ranges. In contrast to Figures 1a-b, detector resolution does matter. However, improving detector resolution beyond what has been chosen to be nominal for this workshop is not justified by these plots.

4 Summary and Discussion

The effects of initial state radiation, finite W width, and realistic detector resolution on measurement of anomalous gauge boson couplings in the process $e^+e^- \to W^+W^-$ (with $WW \to \ell\nu q\overline{q}'$) have been studied. The effects of initial state radiation are found to be most important. Although very poor charged-track momentum resolution can degrade the measurements of anomalous couplings, it appears that the nominal resolutions chosen for this workshop are adequate, even for a 1.5 TeV linear collider.

The main difficulty in kinematically fitting the $WW \to \ell\nu q\overline{q}'$ events with a photon along the beam direction is the inevitable degradation in photon energy resolution due to the presence of the undetected neutrino; attempting to fit for the photon energy event by event can have only limited success. This approach has been attempted in this study and found to lead to substantial efficiency loss for acceptably low bias. Another approach would entail fitting the observed differential cross sections to underlying $\mathrm{E_{CM}}$-dependent differential cross sections weighted by the $\mathrm{E_{CM}}$-dependent beam luminosity. This has the drawback of requiring accurate knowledge of beamsstrahlung effects, but recent work[10] indicates that precise luminosity monitors combined with fine-grained central calorimetery can give reliable estimates of integrated luminosity *vs* effective c.m. energy.

This study had considered only the $WW \to \ell\nu q\overline{q}'$ channel. A recent preliminary study for this workshop[11] indicates that the four-jets $WW \to q\overline{q}'q''\overline{q}'''$ chanel may be more promising than first thought. The W^+/W^- separation is clean enough and the four-jets branching ratio product high enough that comparable statistical power to the $WW \to \ell\nu q\overline{q}'$ channel is feasible, even when individual quark tagging is not reliable. It would be desirable to carry out a detailed study of the four-jets channel, including initial state radiation and detector smearing. With the greater kinematic information available in a four-jets event, fitting for the energy of a missing photon along the beam direction may prove more informative about true W pair c.m. energy. Taking into account photon radiation, the $WW \to q\overline{q}'q''\overline{q}'''$ channel may in the end provide greater sensitivity to couplings than the $WW \to \ell\nu q\overline{q}'$ channel.

ACKNOWLEDGEMENTS

The author wishes to thank T. Barklow, J. Brau, M. Einhorn, S. Godfrey, M. Pohl, and D. Strom for useful discussions.

References

[1] T.L. Barklow, in *Physics and Experiments with Linear Colliders*, eds. R. Orava *et al.*, World Scientific, vol. 1, p 423.

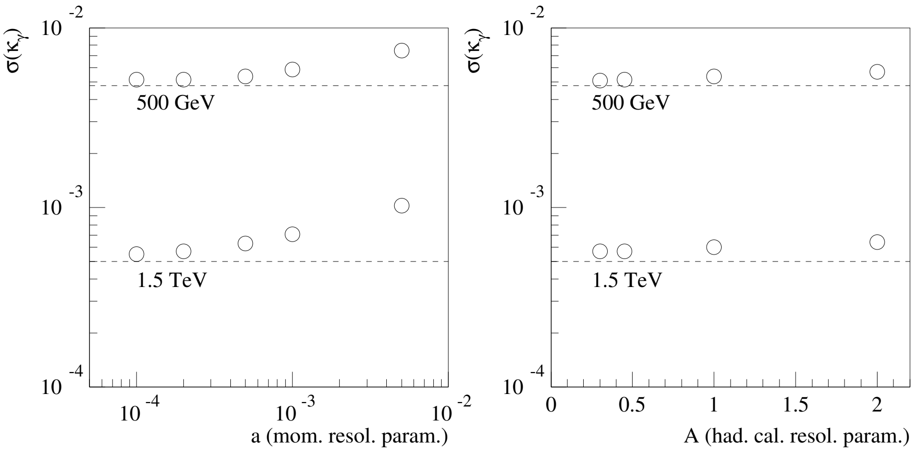

Figure 5: Measurement precision for $\Delta\kappa_\gamma$ at two c.m. energies and for various detector resolution parameters, as explained in the text. For events at nominal c.m. energy of 500 GeV, the fraction of c.m. energy assigned to a kinematically fitted photon missing along the beam direction is required to be less than 0.02. Foe events at 1500 GeV, the maximum fraction is 0.01. Events have been generated with initial state radiation and with $\Gamma_W \neq 0$.

[2] T.L. Barklow, in *Proceedings of the International Symposium on Vector Boson Self-Interactions*, eds. U. Baur, S. Errede, and T. Müller, Amer. Inst. Press, p. 307.

[3] M. Gintner, S. Godfrey, and G. Couture, contributed paper to these proceedings.

[4] H. Hagiwara, R.D. Peccei, and D. Zeppenfeld ***Nuc. Phys.*** **B282**, 253 (1987)

[5] H. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld ***Phys. Lett.*** **B283**, 353 (1992)

[6] JADE Collaboration, W. Bartel *et al.*, Z. Phys. **C33** 23 (1986).

[7] D. Bardin *et al.*, in *Physics at LEP II*, V. 2, p. 3, CERN 96-01 (1996).

[8] H.U. Bengtsson and T. Sjöstrand, Comp. Phys. Comm. **43** 367 (1987).

[9] B.P. Roe, "Probability and Statistics in Experimental Physics", Springer-Verlag, New York 1992.

[10] D. Strom, presentation at SLAC meeting of this Workshop.

[11] D. Strom, presentation at BNL meeting of this Workshop.

[12] See chapters on detector parameters and simulations in the Workshop Summary Document

[13] See chapter on anomalous gauge boson couplings in the Workshop Summary Document