SLAC-PUB-7153
May 1996

Probing Weak Anomalous Top Quark Couplings with Final State Gluons at the NLC

Thomas G. Rizzo[1]

Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309 USA

ABSTRACT

The rate and corresponding gluon jet energy distribution for the process $e^+e^- \to t\bar{t}g$ are sensitive to the presence of anomalous dipole-like couplings of the top to the photon and Z at the production vertex. For sizeable anomalous couplings of this type substantial deviations from the expectations of the Standard Model are likely. We explore the capability of the NLC to discover or place bounds on these types of top quark couplings. The resulting constraints are found to be quite complementary to those which arise from direct probes of the top quark production vertex.

To appear in *Physics and Technology of the Next Linear Collider*, eds. D. Burke and M. Peskin, reports submitted to Snowmass 1996.

[1]Work supported by the Department of Energy, contract DE–AC03–76SF00515.

1 Introduction

The Standard Model(SM) has provided a remarkably successful description of almost all available data involving the strong and electroweak interactions. In particular, the discovery of the top quark at the Tevatron with a mass[1], $m_t = 175 \pm 9$ GeV, close to that anticipated by fits to precision electroweak data is indeed a great triumph. However, the fact that R_b(and perhaps A_b) remains[2] more than $3.3(1.8)\sigma$ from SM expectations may be providing us with the first indirect window into new physics. In fact, this apparent deviation in b-quark couplings from the SM expectations could indicate that some new physics is interacting with the third family as a whole. Since the top is the most massive fermion, it is believed by many that the detailed physics of the top quark may be significantly different than what is predicted by the SM. This suggestion makes precision measurements of all of the top quark's properties mandatory.

Perhaps the most obvious and easily imagined scenario is one in which the top's couplings to the SM gauge bosons, *i.e.*, the W, Z, γ, and g, are altered. This possibility, extended to all of the fermions of the third generation, has attracted a lot of attention over the last few years[3]. In the case of the electroweak interactions involved in top pair production in e^+e^- collisions, the lowest dimensional gauge-invariant operators representing new physics that we can introduce take the form of dipole moment-type couplings to the γ and Z. The anomalous magnetic moment-type operators, which we can parameterize by a pair of dimensionless quantities, $\kappa_{\gamma,Z}$, are CP-conserving. The corresponding electric dipole moment terms, parameterized as $\tilde{\kappa}_{\gamma,Z}$, are CP-violating. The shift in the three-point $t\bar{t}\gamma$ and $t\bar{t}Z$ interactions due to the existence of these anomalous couplings can be written as

$$\delta\mathcal{L} = \frac{i}{2m_t}\bar{t}\sigma_{\mu\nu}q^\nu \left[e(\kappa_\gamma^t - i\tilde{\kappa}_\gamma^t\gamma_5)A^\mu + \frac{g}{2c_w}(\kappa_Z^t - i\tilde{\kappa}_Z^t\gamma_5)Z^\mu\right] t\,, \tag{1}$$

where e is the proton charge, g is the standard weak coupling constant, $c_w = cos\theta_W$, and q is the γ or Z's four-momentum. Gauge invariance will also lead to new four-point interactions involving two gauge bosons and the top, *e.g.*, $t\bar{t}\gamma\gamma, ZZ, Z\gamma, W^+W^-$, but they will not concern us here as we will only work to leading order in the electroweak interactions. In most cases gauge invariance will relate any $t\bar{t}Z,\gamma$ anomalous couplings to others involving the tbW vertex. Escribano and Masso[3] have shown that in general all of the anomalous three-point couplings involving the neutral gauge bosons can be unrelated even when the underlying operators are SM gauge invariant. Thus in our analysis we will treat $\kappa_{\gamma,Z}^t$ and $\tilde{\kappa}_{\gamma,Z}^t$ as independent free parameters. (Of course, within any particular new physics scenario the anomalous couplings will no longer be independent.) As has been discussed in the literature[3], if any of the anomalous couplings are sufficiently large their effects can be directly probed by top pair production. The purpose of the present work is to consider the sensitivity of the process $e^+e^- \to t\bar{t}g$ to non-zero values of the $t\bar{t}Z,\gamma$ anomalous couplings.

2 Analysis

In the present analysis we consider how the 'normalized' gluon energy distribution,

$$\frac{dR}{dz} = \frac{1}{\sigma(e^+e^- \to t\bar{t})} \frac{d\sigma(e^+e^- \to t\bar{t}g)}{dz}, \tag{2}$$

where $z = 2E_g/\sqrt{s}$, can be used to constrain anomalous top couplings to the γ and Z. (We work only to lowest order in α_s.) Note that the anomalous couplings will contribute to *both* the numerator and denominator of the expression of dR/dz. This implies that the sensitivity of R to very large values(with magnitudes ≥ 1) of the anomalous couplings is quite small. However, for the range of anomalous couplings of interest to us significant sensitivity is achieved. We follow the procedure given in Ref.[4] which also supplies the complete formulae for evaluating this gluon energy distribution.

In comparison to Ref.[4], the present analysis has been extended in two ways. (i) We allow for the possibility that two of the four anomalous couplings may be simultaneously non-zero. (ii) We lower the cut placed on the minimum gluon jet energy, E_g^{min}, in performing energy spectrum fits. The reasons for employing such a cut are two-fold. First, a minimum gluon energy is required to identify the event as $t\bar{t}g$ and not just $t\bar{t}$. The cross section for $e^+e^- \to t\bar{t}g$ itself is infra-red singular though free of co-linear singularities due to the finite top quark mass. Second, since the top decays rather quickly, $\Gamma_t \simeq 1.45$ GeV for $m_t = 175$ GeV, we need to worry about 'contamination' from the additional gluon radiation generated off of the b-quarks in the final state subsequent to top decay. Such events can be effectively removed from our sample if we require that $E_g^{min}/\Gamma_t >> 1$. In our past analysis we were very conservative in our choices for E_g^{min} in order to make this ratio as large as possible, *i.e.*, we assumed $E_g^{min} = 37.5(200)$ GeV for a 500(1000) GeV NLC. It is now believed that we can with reasonable justification soften these cuts at least as far as 25(50) GeV for the same center of mass energies[5], with a possible further softening of the cut at the higher energy machine not unlikely. Due to the dramatic infra-red behaviour of the cross section, this change in the cuts leads not only to an increased statistical power, since more events are included in the fit, but also to a longer lever arm to probe those events with very large gluon jet energies which have the most sensitivity to the presence of anomalous couplings. As one might expect, we find constraints on the anomalous couplings which are somewhat stronger than what was obtained in our previous analysis[4].

As in our previous work this analysis is based on a Monte Carlo approach. We generate data simulating the scaled gluon energy spectrum, dR/dz, in fixed energy bins accounting for only the statistical errors assuming the SM to be correct. A fit is then performed to these generated data samples allowing the values of the various anomalous couplings to float. In general, one can perform a four parameter fit allowing all of the parameters $\kappa^t_{\gamma,Z}$ and $\tilde{\kappa}^t_{\gamma,Z}$ to be simultaneously non-zero. Here, for simplicity we allow only two of these couplings to be simultaneously non-vanishing, *i.e.*, we consider anomalous top couplings to the photon and Z separately. The first results of this analysis are shown in Figs.1a-b and Figs. 2a-b

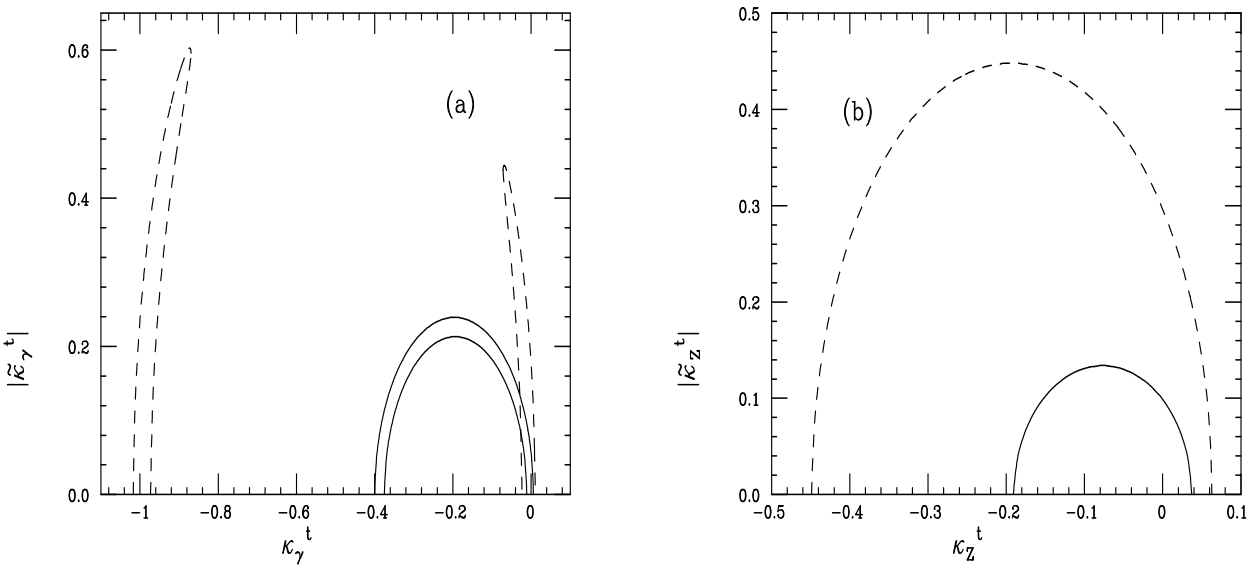

Figure 1: 95% CL allowed regions obtained for the anomalous couplings at a 500(1000) GeV NLC assuming a luminosity of 50(100) fb^{-1} lie within the dashed(solid) curves. The gluon energy range $z \geq 0.1$ was used in the fit. Only two anomalous couplings are allowed to be non-zero at a time.

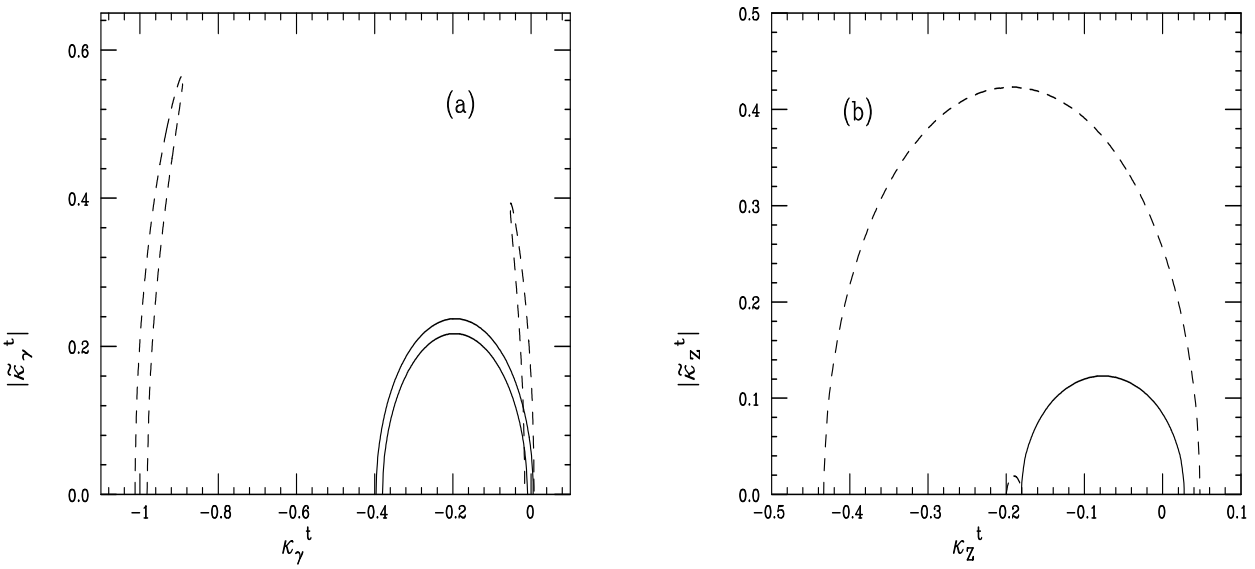

Figure 2: Same as Fig. 1 but now doubling the integrated luminosity to 100(200) fb^{-1} for the 500(1000) GeV NLC.

which compare a 500 and 1000 GeV NLC at two different values of the integrated luminosity. For the 500(1000) GeV case, the minimum gluon jet energy, E_g^{min}, was set to 25(50) GeV corresponding to $z \geq 0.1$. A fixed energy bin width of Δz=0.05 was chosen in both cases so that at 500(1000) GeV 8(15) bins were used to cover the entire spectrum. In either case the constraints on the anomalous $t\bar{t}\gamma$ couplings are seen to be stronger qualitatively than the corresponding $t\bar{t}Z$ ones. In the former case the allowed region is essentially a long narrow circular band, which has been cut off at the top for the $\sqrt{s}$ =500 GeV NLC. In the latter case, the allowed region lies inside a rather large ellipse. We see from these figures that to increase the sensitivity to anomalous couplings it is far better to go to higher center of mass energies than to simply double the statistics of the sample. The 1 TeV results are seen to be significantly better than those quoted in Ref.[4] due to lower value of E_g^{min}.

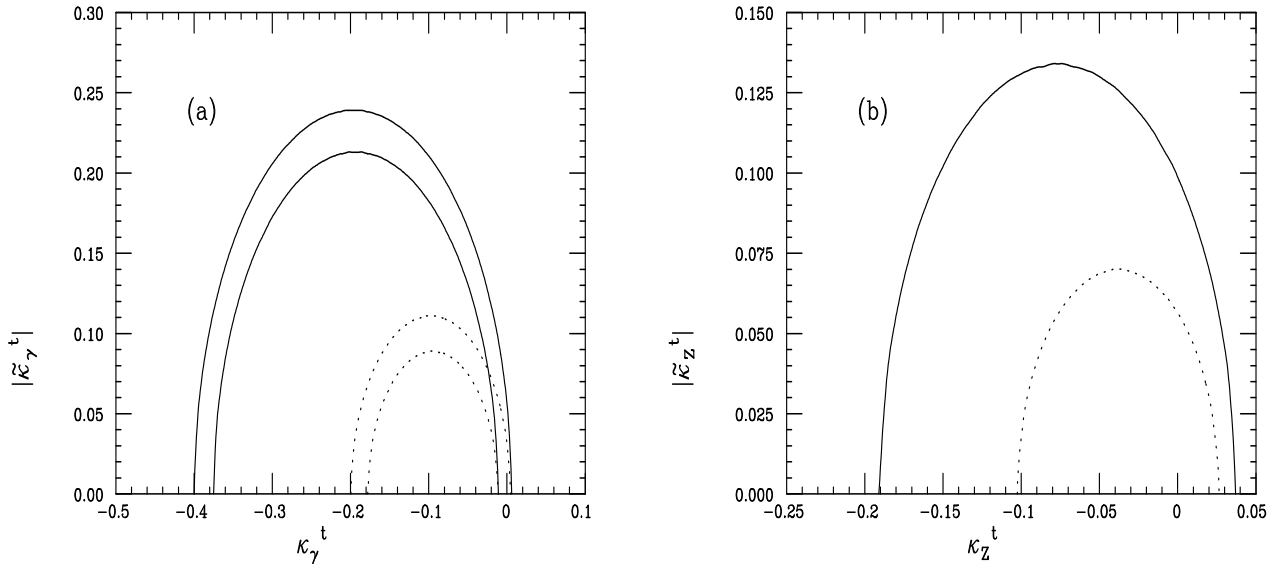

Figure 3: Same as Fig. 1 but now for a 1 (1.5) TeV NLC assuming an integrated luminosity of 100(200) fb^{-1} corresponding to the solid(dotted) curve.

A similar pattern is shown in Figs. 3a-b and 4a-b which display and compare the result of our fits at center of mass energies of 1 and 1.5 TeV for two different integrated luminosities. Note that the 1 TeV solid curves shown in Figs. 1 and 2 are expanded by a change of scale of roughly a factor of 2 in Figs. 3 and 4. Again we see that the anomalous photon couplings are far more constrained than are those of the Z and that an increase in energy far outweighs additional luminosity if increased sensitivity is desired. Fig. 5 shows that for a 1 TeV collider a further reduction in E_g^{min} to 25 GeV from 50 GeV does not significantly improve our anomalous coupling constraints for either γ or Z.

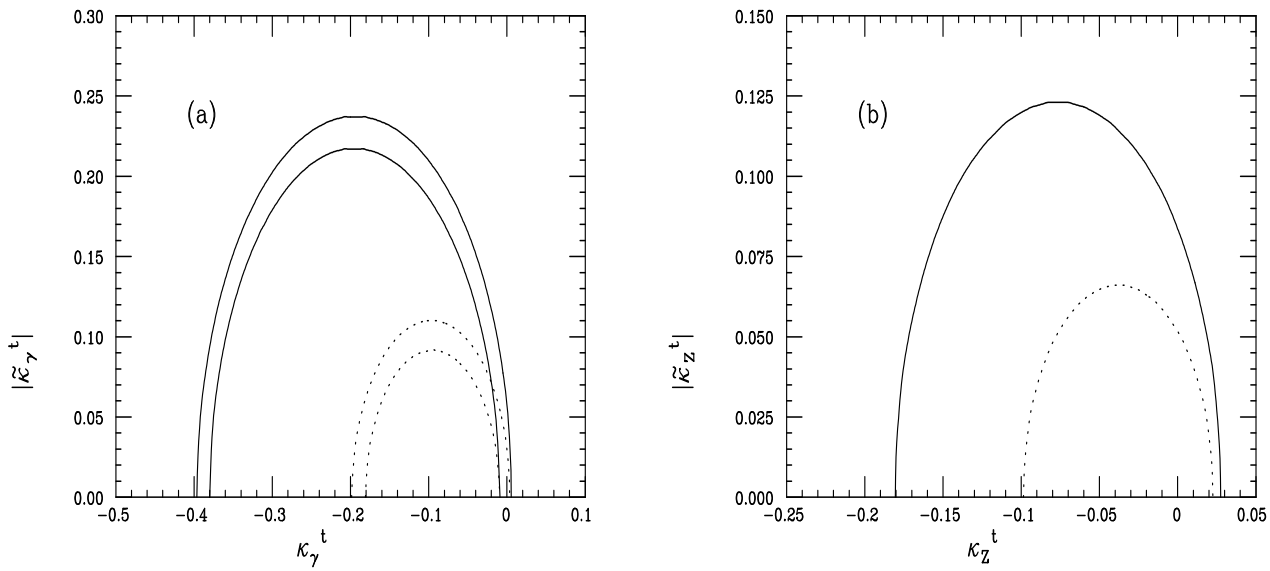

Figure 4: Same as Fig. 3 but now for luminosities of 200(300) fb^{-1} at a 1(1.5) TeV collider corresponding to the solid(dotted) curve.

3 Discussion and Conclusions

In this report we have shown that the process $e^+e^- \to t\bar{t}g$ can be used to obtain stringent limits on the anomalous dipole-like couplings of the top to both γ and Z through an examination of the associated gluon energy spectrum. Such measurements are seen to be complementary to those which directly probe the $t\bar{t}$ production vertex. By combining both sets of data a very high sensitivity to the anomalous couplings can be achieved.

ACKNOWLEDGEMENTS

The author would like to thank P. Burrows, A. Kagan and J.L. Hewett for discussions related to this work.

References

[1] H.H. Williams, talk given at the *Workshop on High Energy Physics at the LHC*, Fermilab, March 28-30, 1996.

[2] See, for example, the LEP/SLD Working Group report LEPEWWG/96-01, March 1996.

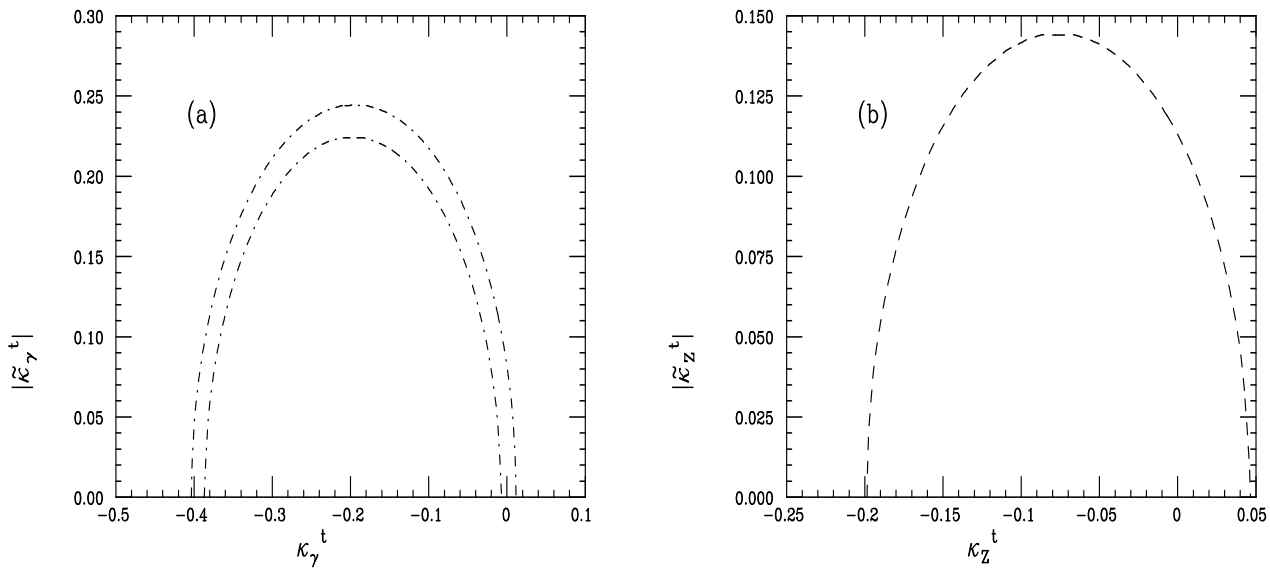

Figure 5: Same as Fig. 3 for the 1 TeV NLC with a 100 fb^{-1} of integrated luminosity but now with a gluon jet cut of $z \geq 0.05$.

[3] There has been an enormous amount of work in this general subject area; see for example: A. Grifols and A. Mendez, Phys. Lett. **B255**, 611 (1991) and erratum Phys. Lett. **B259**, 512 (1991); B. Ananthanarayan and S.D. Rindani Phys. Rev. Lett. **73**, 1215 (1994); G. Köpp *et al.*, Z. Phys. **C65**, 545 (1995); F. del Aguila and M. Sher, Phys. Lett. **B252**, 116 (1990); R. Escribano and E. Masso, Phys. Lett. **B301**, 419 (1993)and Nucl. Phys. **429**, 19 (1994); W. Bernreuther, O. Nachtmann and P. Overmann, Phys. Rev. **D48**, 78 (1993); G. Couture, Phys. Lett. **B305**, 306 (1993) and Phys. Lett. **B272**, 404 (1991); G. Domokos *et al.*, Phys. Rev. **D32**, 247 (1985); T.G. Rizzo, Phys. Rev. **D51**, 3811 (1995) and Phys. Rev. **D53**, 2326 (1996); J. Reid, M. Samuel, K.A. Milton and T.G. Rizzo, Phys. Rev. **D30**, 245 (1984). See also, P.D. Acton *et al.*, OPAL Collaboration, Phys. Lett. **B281**, 305 (1992); D. Buskulic *et al.*, ALEPH Collaboration, Phys. Lett. **B297**, 459 (1992); G. Kane, G.A. Ladinsky and C.P. Yuan, Phys. Rev. **D45**, 124 (1992); C.P. Yuan, Phys. Rev. **D45**, 782 (1992); D. Atwood, A. Aeppli and A. Soni, Phys. Rev. Lett. **69**, 2754 (1992); M. Peskin, talk presented at the *Second International Workshop on Physics and Experiments at Linear e^+e^- Collider*, Waikoloa, HI, April 1993; M. Peskin and C.R. Schmidt, talk presented at the *First Workshop on Linear Colliders*, Saariselkä, Finland, September 1991; P. Zerwas, *ibid.*; W. Bernreuther *et al.*, in *Proceedings of the Workshop on e^+e^- Collisions at 500 GeV, The Physics Potential*, (DESY, Hamburg) ed. by P. Igo-Kemenes and J.H. Kühn, 1992; A. Djouadi, ENSLAPP-A-365-92 (1992); M. Frigeni and R. Rattazzi, Phys. Lett. **B269**, 412 (1991); R.D. Peccei, S. Persis and X. Zhang, Nucl. Phys. **B349**, 305 (1991); D.O. Carlson, E. Malkawi and C.-P. Yuan, Phys. Lett. **B337**, 145 (1994);

J.L. Hewett and T.G. Rizzo, Phys. Rev. **D49**, 319 (1994); T.G. Rizzo, Phys. Rev. **D50**, 4478 (1994); D. Atwood, A. Kagan and T.G. Rizzo, Phys. Rev. **D52**, 6264 (1995); K. Cheung, Phys. Rev. **D53**, 3604 (1996); P. Haberl, O. Nachtmann and A. Wilch, Phys. Rev. **D53**, 4875 (1996).

[4] T.G. Rizzo, SLAC-PUB-95-6758, to appear in Phys. Rev. **D53**.

[5] L. Orr, private communication.