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Using Final State Gluons as Probes of Anomalous Top Quark Couplings at the NLC

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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 as well as to the gluon itself. For sizeable anomalous couplings substantial deviations in the shape and magnitude of the gluon spectrum from the expectations of the Standard Model are anticipated. We explore the capability of the Next Linear Collider to either discover or place bounds on these types of top quark couplings through measurements of the gluon energy distribution. The resulting constraints are found to be quite complementary to those obtained using other techniques.

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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], $m_t = 175 \pm 6$ GeV, close to that anticipated by fits to precision electroweak data, is indeed a great triumph. However, the fact that both R_b and A_b remain[2] approximately 2σ away 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 allows one to speculate that perhaps all of the members of the third generation might couple to some kind of new physics. Independent of these potential discrepancies with the SM, 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, non-renormalizable 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 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. Clearly, analogous interactions may also be anticipated for the top couplings with gluons which is directly involved in top production at hadron colliders. The shift in the three-point $t\bar{t}\gamma, Z, g$ interactions due to the existence of these anomalous couplings can be written as

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

where e is the proton charge, $g(g_s)$ is the standard weak(strong) coupling constant, T_a are the color generators, $c_w = \cos\theta_W$, and q is the γ, g or Z's four-momentum. Gauge invariance will also lead to new four-point interactions involving two gauge bosons and the top, *e.g.*, $t\bar{t}gg$ and $t\bar{t}W^+W^-$, but they will not concern us here as we will only work to leading order in the strong and electroweak interactions. In most cases gauge invariance will relate any of the trilinear $t\bar{t}Z, \gamma$ 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 all κ's and $\tilde{\kappa}$'s as independent free parameters. Of course, within any particular new physics scenario the anomalous couplings will no longer be completely independent. For example, if the new physics generated an effective dimension-6 operator which coupled to top via its hypercharge quantum number, we would find the

relation

$$\kappa_\gamma^t = \frac{-\kappa_Z^t}{2sin^2\theta_w}\,, \tag{2}$$

between the photon and Z anomalous magnetic dipole couplings with an identical expression holding for the electric dipole couplings. (A similar but somewhat different result occurs if the new operator coupled instead to the top quark's weak isospin in which case $\sin^2\theta_w \to -\cos^2\theta_w$ in the expression above.)

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 at either e^+e^- or hadron colliders. 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 any of these anomalous couplings.

2 Analysis I: Chromoelectric and Chromomagnetic Moments

The basic cross section formulae and analysis procedure for either anomalous strong or electroweak dipole couplings can be found in Ref.[4]. The essential observation of our analysis is that the presence of anomalous top couplings *at either vertex* modifies the shape of the gluon energy spectrum in the $e^+e^- \to t\bar{t}g$ process. An example of this is shown in Fig. 1 in the case of anomalous $t\bar{t}g$ couplings for $\sqrt{s} = 500$ and 1000 GeV. (In this figure, $z = 2E_g/\sqrt{s}$, where E_g is the gluon jet energy.) Here, we will go beyond the initial studies that exist in the literature in several ways; in the case of anomalous chromomagnetic and chromoelectric we have done the following: (i) we generalize the form of the $t\bar{t}g$ coupling to allow for the possibility of a sizeable chromoelectric moment, $\tilde{\kappa}$. The incorporation of $\tilde{\kappa} \neq 0$ into the expressions for the differential cross section in Ref.[4] is rather straightforward and can be accomplished by the simple substitution $\kappa^2 \to \kappa^2 + \tilde{\kappa}^2$ made universally. Note that since a non-zero value of $\tilde{\kappa}$ produces a CP-violating interaction it appears only quadratically in the expression for the gluon energy distribution since this is a CP-conserving observable. Thus, in comparison to κ, we anticipate a greatly reduced sensitivity to the value of $\tilde{\kappa}$. (ii) We use updated expectations for the available integrated luminosities of the NLC at various center of mass energies as well as an updated efficiency($\simeq 100\%$) for identifying top-quark pair production events. Both of these changes obviously leads to a direct increase in statistical power compared to Ref.[4] (iii) Perhaps, even more importantly, we soften the cut placed on the minimum gluon jet energy, E_g^{min}, in performing the energy spectrum fits.

The reasons for having such a cut are two-fold. First, a minimum gluon energy is required to identify the event as $t\bar{t}g$. The cross section 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, we need to worry about 'contamination' from the additional gluon radiation off of the b-quarks in the final state. 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 overly conservative

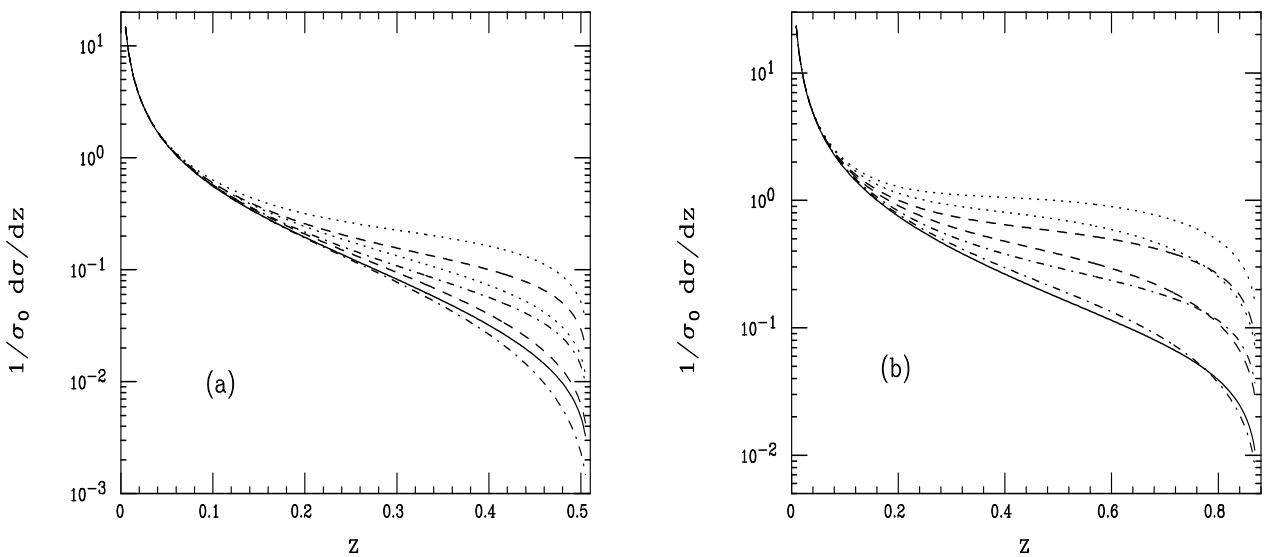

Figure 1: Gluon jet energy spectrum assuming $\alpha_s = 0.10$ for $m_t = 175$ GeV at a center of mass energy of (a) 500 GeV or (b) 1 TeV NLC. The upper(lower) dotted, dashed, and dot-dashed curves correspond to κ values of 3(-3), 2(-2), and 1(-1) respectively while the solid curve is conventional QCD with $\kappa = 0$.

in our choices for E_g^{min} in order to make this ratio as large as possible, *i.e.*, we assumed $E_g^{min} = 50(200)$ GeV for an NLC with a center of mass energy of 500(1000) GeV. It is now believed that we can with reasonable justification soften these cuts to at least as low a value as 25(50) GeV for the same center of mass energies[5], with a potential further softening of the cut at the higher energy machine being possible. Due to the dramatic infra-red behaviour of the cross section, this change in the cuts leads not only to an increased statistical power but also to a longer lever arm to probe events with very large gluon jet energies which have the most sensitivity to the presence of anomalous couplings. Combining all these modifications, as one might expect, we find constraints which are substantially stronger than what was obtained in our previous analysis[4].

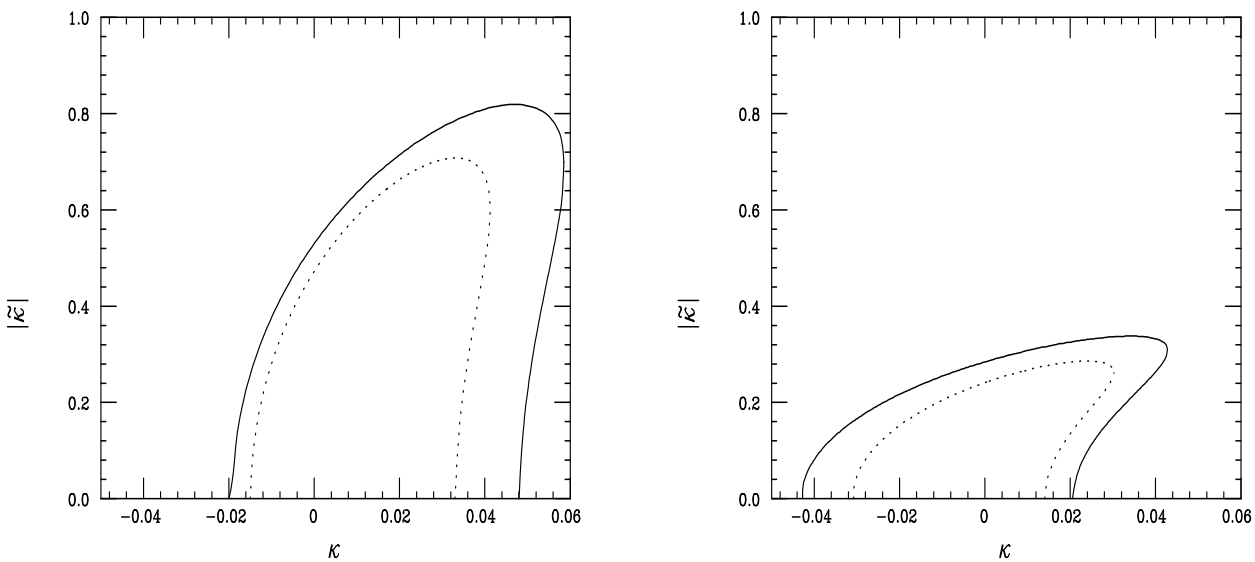

Figure 2: 95% CL allowed region in the $\kappa - \tilde{\kappa}$ plane obtained from fitting the gluon spectrum: on the left above E_g^{min}=25 GeV at a 500 GeV NLC assuming an integrated luminosity of 50(solid) or 100(dotted) fb^{-1}; on the right for a 1 TeV collider with E_g^{min}=50 GeV and luminosities of 100(solid) and 200(dotted) fb^{-1}. Note that the allowed region has been significantly compressed downward in comparison to lower energy machine.

As in Ref.[4], our analysis follows a Monte Carlo approach employing statistical errors only. For a given e^+e^- center of mass energy, a binned gluon jet spectrum is generated for energies above E_g^{min} assuming that the SM is correct. The bin widths are fixed to be $\Delta z = 0.05$ where $z = 2E_g/\sqrt{s}$ for all values of $\sqrt{s}$, with the number of bins thus determined by the values of the top mass(m_t=175 GeV), $\sqrt{s}$ and E_g^{min}. As an example, at a 500 GeV NLC with E_g^{min}=25 GeV, there are 8 energy bins for the gluon energy spectrum beginning at $z = 0.10$; the last bin covers the range above $z = 0.45$. After the Monte Carlo data samples are generated, we perform a fit to the general expressions for the $\kappa - \tilde{\kappa}$ dependent spectrum and obtain the 95% CL allowed region in the $\kappa - |\tilde{\kappa}|$ plane. Note that only the absolute

value of $\tilde{\kappa}$ occurs due to reasons given above.

Fig. 2 shows the results of this procedure for a 500 GeV NLC with a cut of E_g^{min}=25 GeV for two different integrated luminosities. As expected, excellent constraints on κ are now obtained but those on $\tilde{\kappa}$ are more than an order of magnitude weaker. A doubling of the integrated luminosity from 50 to 100 fb^{-1} decreases the size of the allowed region by about 40%. We note that in the published study only extremely poor constraints on κ were obtained at a 500 GeV e^+e^- collider, $-1.98 \leq \kappa \leq 0.44$, due to the presence of a degenerate minima in the χ^2 distribution. Now, with the both the increased luminosity and top-tagging efficiencies, as well as the longer lever arm in energy, these previous difficulties are circumvented.

Going to a higher energy leads to several simultaneous effects. First, since the cross section approximately scales like $\sim 1/s$ apart from phase space factors, a simple doubling of the collider energy induces a reduction in statistics unless higher integrated luminosities are available to compensate. Second, the sensitivity to the presence of non-zero anomalous couplings is enhanced at higher energies, roughly scaling like $\sim \sqrt{s}$ for κ and, correspondingly, like $\sim s$ for $\tilde{\kappa}$ *assuming* the same available statistics at all energies. In Fig. 2 also we show the results of our analysis at a 1 TeV NLC for E_g^{min}=50 GeV. (Note that in our previous analysis, we obtained the 95% CL bound $-0.12 \leq \kappa \leq 0.21$ for this center of mass energy and an integrated luminosity of 200 fb^{-1}.) For E_g^{min}=50 GeV, the energy range was divided into 15 $\Delta z = 0.2$ bins beginning at $z = 0.10(0.05)$ with the last bin covering the range $z \geq 0.80$. We see from these figures that by going to higher energy we drastically compress the allowed range of $\tilde{\kappa}$ while the improvement for κ is not as great. Lowering the energy cut is seen to lead to a far greater reduction in the size of the 95% CL allowed region than is a simple doubling of the integrated luminosity.

3 Analysis II: Anomalous Electroweak Dipole Moments

In this analysis we consider our observable to be the full, 'normalized' gluon energy distribution,

$$\frac{dR}{dz} = \frac{1}{\sigma(e^+e^- \to t\bar{t})} \frac{d\sigma(e^+e^- \to t\bar{t}g)}{dz}, \tag{3}$$

We note that now, unlike the previous case, the electroweak anomalous couplings will contribute differently 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 since their contributions effectively cancel in the ratio. However, for the range of anomalous couplings of interest to us here significant sensitivity is achieved. We follow the procedure as given in Ref.[4] which also supplies the complete formulae for evaluating this gluon energy distribution when the $t\bar{t}\gamma, Z$ vertex is modified by the existence of anomalous couplings.

In comparison to our previous work, 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) As in the previous section, we lower the cut placed on the minimum gluon jet energy, E_g^{min}, in performing energy spectrum fits. In the published analysis we were again 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, for the reasons described above. As in the case of the the anomalous strong couplings, we generate 'data' following the Monte Carlo approach as described in the last section.

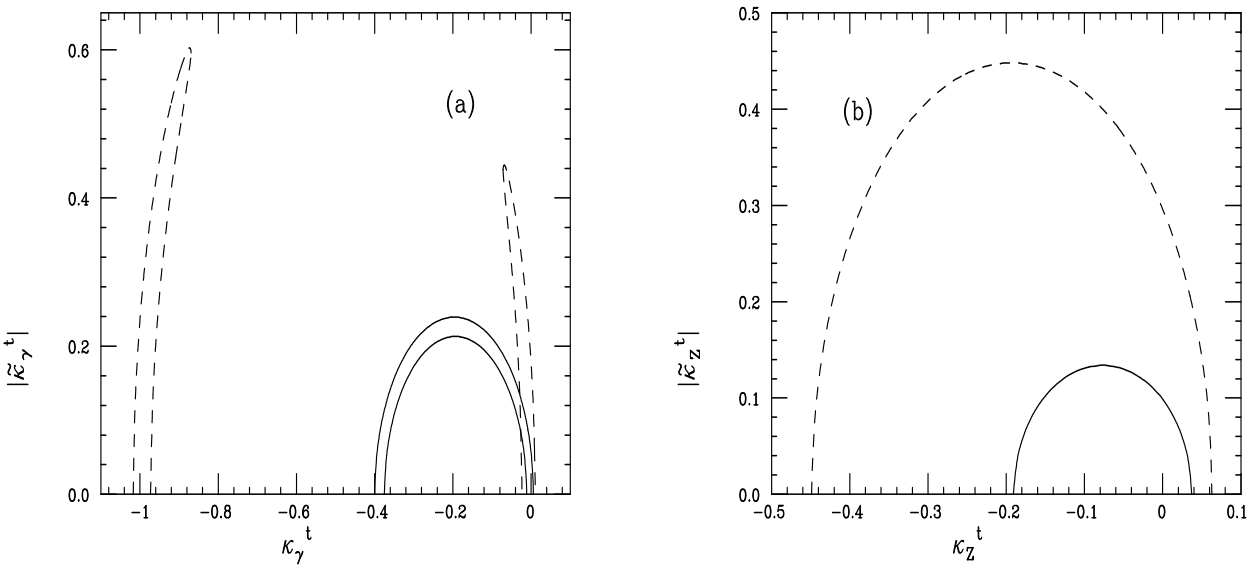

Figure 3: 95% CL allowed regions obtained for the anomalous couplings at a 500(1000) GeV NLC assuming a luminosity of 50(100) fb^{-1} lie within the dashed(solid) curves. The gluon energy range $z \geq 0.1$ was used in the fit. Only two anomalous couplings are allowed to be non-zero at a time.

A fit is then performed with these 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-zero, *i.e.*, we consider anomalous top couplings to the photon and Z separately. The results of this analysis are shown in Figs.3a-b and Figs. 4a-b which compare a 500 and 1000 GeV NLC at two different values of the integrated luminosity. As above, 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

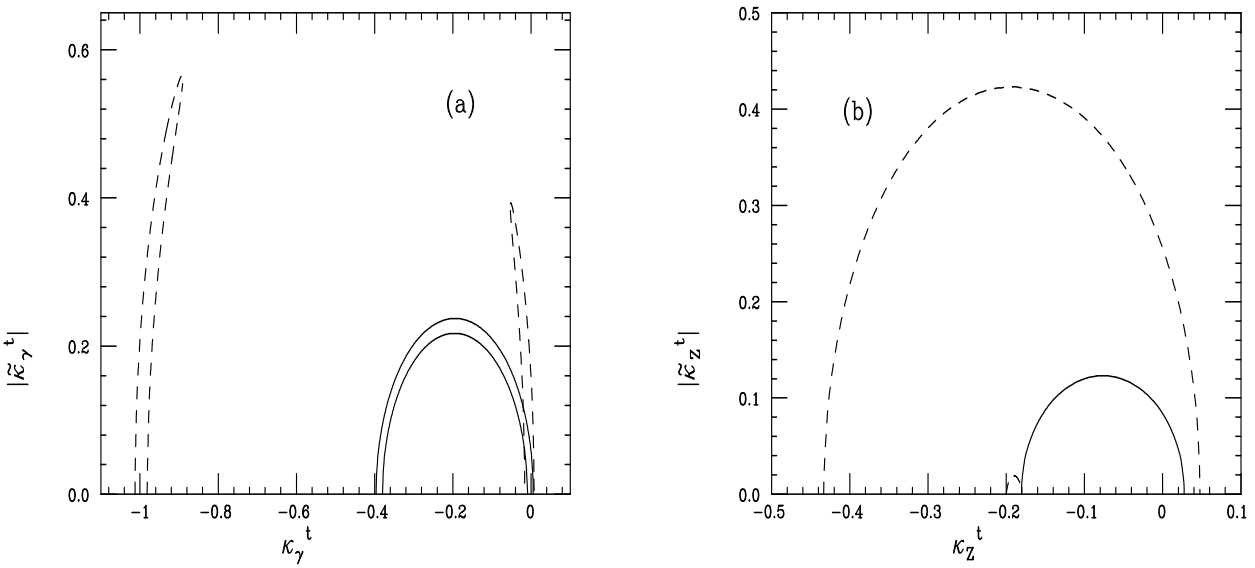

Figure 4: Same as Fig. 3 but now doubling the integrated luminosity to 100(200) fb^{-1} for the 500(1000) GeV NLC.

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}. Note that with data from only a single center of mass energy available there can be some ambiguity in the values of the anomalous couplings. By combining data from two different energies such ambiguities can be completely removed and the size of the allowed region shrinks drastically, as can be seen in Fig.5.

4 Discussion and Conclusions

In this paper 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 γ, g 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 at hadron and e^+e^- colliders. By combining both sets of data a very high sensitivity to the anomalous couplings can be achieved. The value of the cut on the gluon energy was shown to play a key role in obtaining strong bounds on these anomalous couplings. These results may be strengthened in the future if we find that the E_g^{min} cut can be further softened.

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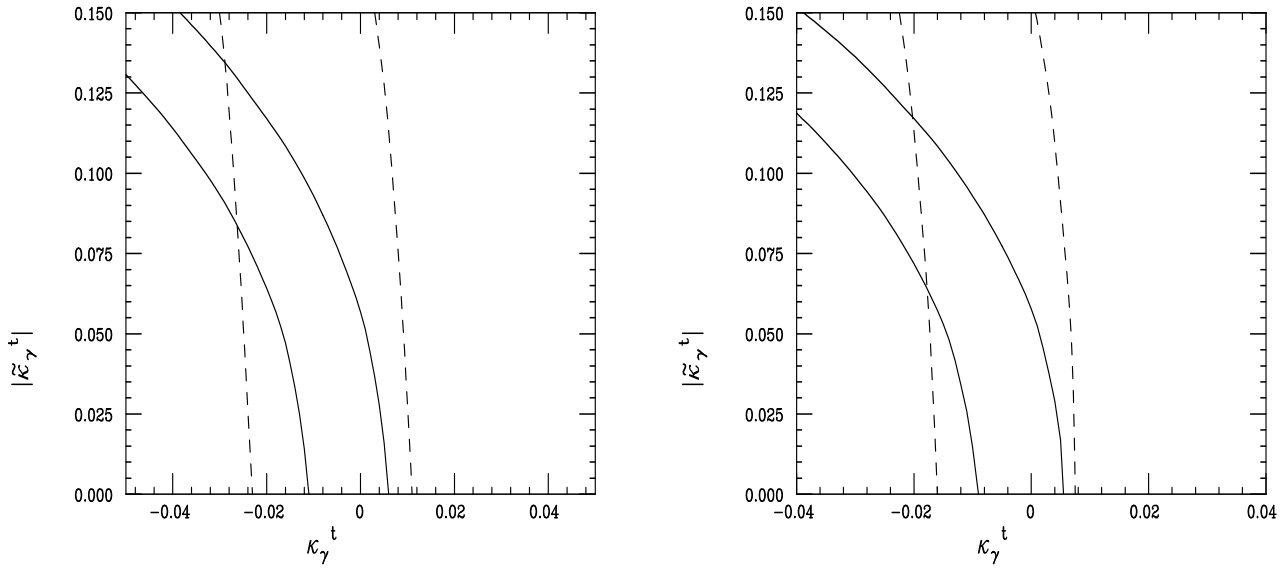

Figure 5: Expanded view of the overlapping regions from Fig.3a(4a) shown on the left(right).

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