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Probing the Top Quark Production and Decay Vertices at a 400 GeV e^+e^- Collider[1]

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Abstract

A high energy e^+e^- linear collider (NLC) is an ideal tool for probing the structure of the $\gamma t\bar{t}$, $Zt\bar{t}$, and $Wt\bar{b}$ vertices to look for effects both within and beyond the standard model. In this talk we discuss how to use the high level of top quark polarization at the NLC to disentangle its production and decay vertices, and we make some estimates of limits on anomalous couplings that can be reached for realistic NLC parameters.

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The CDF evidence for a top quark of mass around 174 GeV [1] indicates that the top quark couples more strongly to the electroweak symmetry breaking sector than any other known particle, and much more strongly than any of the other quarks. This suggests that the top may play a special role in the generation of the quark masses, or at least it may offer hints to this mass generation. Thus, we should try to study its properties as precisely as possible. Due to the clean event environment and the possibility of initial-state polarization, a high energy e^+e^- linear collider would be an ideal tool for extracting the properties of the top quark. There have already been detailed analyses of the top quark production at threshold at the Next Linear Collider (NLC), where the mass and width can be measured to considerable accuracy [2]. In this talk we will give some initial results of an analysis of the top quark above threshold. In particular we will concentrate on extracting the couplings of the top quark at the NLC [3].

The most general top quark couplings can be written in terms of form factors in the production and decay vertices. The $t \to W^+ b$ decay vertex is

$$i\mathcal{M}^{W\mu} = i\frac{g}{\sqrt{2}}\Big\{\gamma^\mu[F_{1L}^W P_L + F_{1R}^W P_R] + \frac{i\sigma^{\mu\nu}q_\nu}{2m_t}[F_{2L}^W P_R + F_{2R}^W P_L]\Big\}. \qquad (1)$$

At tree level in the standard model $F_{1L}^W = 1$ and all other form factors are zero. The antitop form factors are identical to these in the limit of CP invariance. Similarly, the $\gamma, Z \to t\bar{t}$ production vertices are

$$i\mathcal{M}^{i\mu} = ie\Big\{\gamma^\mu[Q_V^i F_{1V}^i + Q_A^i F_{1A}^i \gamma_5] + \frac{i\sigma^{\mu\nu}q_\nu}{2m_t}[Q_V^i F_{2V}^i + Q_A^i F_{2A}^i \gamma_5]\Big\}\ , \qquad (2)$$

where the superscript is $i = \gamma, Z$. In this formula $Q_V^\gamma = Q_A^\gamma = \frac{2}{3}$, $Q_V^Z = (\frac{1}{4} - \frac{2}{3}s^2)/sc$, and $Q_A^Z = (-\frac{1}{4})/sc$, so that at tree level in the standard model $F_{1V}^\gamma = F_{1V}^Z = F_{1A}^Z =$

1 and all the others are zero. In the limit of CP invariance $F^i_{2A} = F^i_{3A} = 0$. The form factors are typically corrected by a few percent or less from QCD and electroweak loops. Thus, any large deviations would indicate new physics, which may occur if the top quark is strongly coupled to the symmetry breaking sector [4].

In the present analysis we will study the process $e^+e^- \to t\bar{t} \to b\ell^+\nu\bar{b}q\bar{q}$ at the parton level without detector resolution effects, hadronization, or initial-state radiation. These will be included in the future. We use the complete helicity amplitudes [5] for the event in the zero-width approximation for the top quark and the W and with $m_b = 0$. The top quark mass is set to its nominal value of $m_t = 174$ GeV. The form factors can be obtained from a maximum likelihood fit using all of the information available in the helicity angles of the top quarks and their decay products in the sample of $t\bar{t}$ events. Here we estimate the sensitivity possible in such an analysis at the NLC.

We will present our results for an integrated luminosity of 100 fb^{-1}. This is an optimistic value for one year of running and is more likely characteristic of a few years worth of data. Of course, the estimated errors will simply scale as $(\int \mathcal{L}dt)^{-1/2}$. For simplicity in this analysis we will just keep events where one of the W's decays hadronically and the other leptonically to an electron or a muon. This allows complete reconstruction of the event with little background. The resulting branching fraction is then $2 \times (2/9) \times (6/9) = 30\%$. In addition, as a crude model of the detector efficiency we require that all of the partons except the neutrino must lie within $|\cos\theta_{\rm lab}| < 0.8$. The bottom quarks are assumed to be tagged and signed, but the ambiguity in the sign of the decay angle of the $W \to q\bar{q}$ decay has been included. At the NLC the backgrounds to this process are quite small; the dominant one is radiative W pair production.

Table 1: Number of $t\bar{t}$ pairs.

	50 fb^{-1} e_L	50 fb^{-1} e_R	100 fb^{-1} unpol.
Total	42403	20488	62891
$\times$ BR	12564	6070	18634
$\times$ cuts	3981	1891	5872

In table 1 we show the number of $t\bar{t}$ pairs produced at 400 GeV center-of-mass energy and 100 fb^{-1} integrated luminosity, along with the effects of the branching fraction and the angular cuts. In addition we show the breakdown if the collider is run with 50 fb^{-1} each of left-handed and right-handed electrons at 90% polarization. The table shows that the acceptance cut reduces the event sample by a factor of about 0.3 beyond that of the branching fraction. To explain this we plot the cross section in units of R as a function of the top production angle for 90% left-polarized electrons, including the subprocess cross sections for top quarks of specific helicities. From this figure we see that the electron helicity typically carries through to the top quark, with the top quark produced strongly peaked in the forward direction. Thus, good forward detector coverage is very important for obtaining the most complete event information. However, we must emphasize that events that are neglected here, such as ones with a missing quark jet, may still be used in a less complete analysis for constraining the form factors. In addition, the purely hadronic $t\bar{t}$ mode

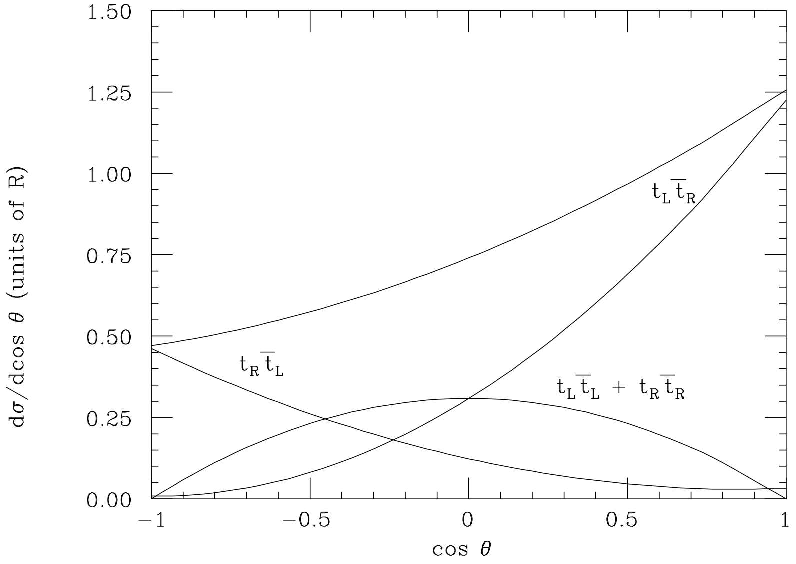

Fig. 1: $t\bar{t}$ cross section.

may also be usable in the e^+e^- event environment.

Figure 1 also shows that electron polarization will be an important tool in studying top quarks at the NLC. We exhibit this in figure 2 where we plot the 95% confidence level contours for F_{1V}^Z and F_{1A}^Z with all other form factors set to their standard model values. The dotted (dotdashed) curves are obtained from the 50 fb^{-1} of events with 90% L (R) polarized electrons, while the solid band is obtained from the measurement of $A_{LR} = (\sigma_L - \sigma_R)/(\sigma_L + \sigma_R)$. Note that the A_{LR} measurement is very important for constraining F_{1V}^Z, gaining almost a factor of two in sensitivity over an unpolarized event sample. On the other hand, the absolute total cross section is quite insensitive to these form factors[3].

[3]The total cross section is, however, important for constraining the $t\bar{t}$ production magnetic moment form factors.

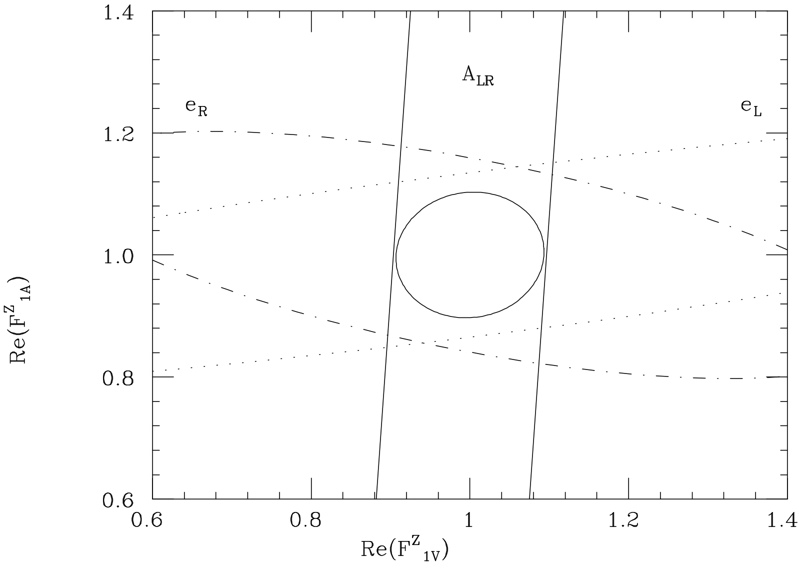

Fig. 2: 95% Confidence level contours.

The polarization of the top quarks can also be used in constraining the decay form factors. The standard method for obtaining F_{2L}^W is by measuring the ratio $W_{\text{long.}}/W_{\text{trans.}}$ of polarized W's in top quark decays [6]. This simply requires fitting to the polar angle of the decay products of the W in its rest frame. However, for polarized top quarks, the top decay angles are also correlated with the W polarization, offering further constraints. To gauge the importance of these effects we made a one parameter fit to F_{2L}^W, using 1) 50 fb^{-1} each of L and R polarized electrons with a complete event analysis; 2) 100 fb^{-1} of unpolarized electrons with a complete event analysis; and 3) the same events, but analyzing only the W-decay polar angle information. The 95% confidence limits are 1) $\pm.080$, 2) ±0.098, 3) ±0.114. Thus, a complete likelihood analysis can increase the sensitivity by a factor of 1.4. However, the W-decay angle analysis should still be useful for events where

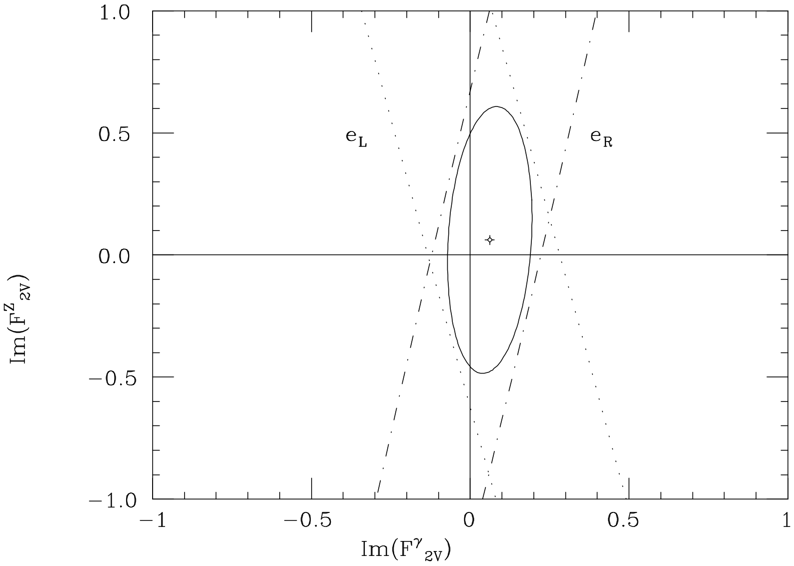

Fig. 2: 95% Confidence level contours.

complete reconstruction is impossible.

A likelihood fit can also be used to search for transverse polarization effects. Transverse polarization can arise within the standard model at the one-loop level from absorptive QCD and electroweak diagrams [7]. In the formalism used here these loop effects contribute to the imaginary parts of the form factors. In figure 3 we show the sensitivity to the imaginary parts of F_{2V}^Z and F_{2V}^γ around their one-loop QCD values for 50 fb^{-1} each of L and R polarized electrons. This plot suggests that a factor of 4 in statistics is still needed to confidently infer a nonzero value for the form factors.

In this talk we have investigated the sensitivity to the top production and decay vertices of a likelihood analysis using the complete event reconstruction at the NLC.

Further work will include experimental resolution effects, non-$t\bar{t}$ backgrounds, and more efficient ways to use all of the $t\bar{t}$ events. Implications for detector design are important because simply increasing coverage to $|\cos\theta_{\rm lab}| < 0.9$ from 0.8 increases the statistics by a factor of ~ 2.

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