Probing Form Factors in Top Quark Pair Production at $e^-e^+$ Colliders

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ABSTRACT

We describe how to probe new physics through large CP violation effects and non-standard $Z$-t-$\bar{t}$ couplings via the scattering process $e^-e^+ \rightarrow t\bar{t}$.

Large CP violating effects are required to have the cosmological baryon asymmetry produced at the weak phase transition. If such effects exist, can they be probed at electron colliders? How well can the form factors of the $Z$-t-$\bar{t}$ coupling be measured in both the $e^-e^+ \rightarrow t\bar{t} \rightarrow b\bar{l}\nu_l\bar{b}$ and $e^-e^+ \rightarrow t\bar{t} \rightarrow b\bar{l}\nu_l\bar{b}qq'$ decay modes? What are the preferred energies and luminosities for detecting large CP violating effects and measuring the form factors governing the $Z$-t-$\bar{t}$ interaction? We addressed these issues at this conference.

The most general form factors for the coupling of $t$ and $\bar{t}$ with either of the vector bosons $\gamma$ or $Z$ can be derived from the lagrangian

\begin{equation}
\mathcal{L}_{\text{int}} = g \left[ Z_{\mu} \bar{t} \gamma^{\mu} \left( F_1^{Z(L)} P_- + F_1^{Z(R)} P_+ \right) t - \frac{1}{v} \partial_{\nu} Z_{\mu} \bar{t} \sigma^{\mu\nu} \left( F_2^{Z(L)} P_- + F_2^{Z(R)} P_+ \right) t \right. \\
+ \partial^\mu Z_{\mu} \bar{t} \left( F_3^{Z(L)} P_- + F_3^{Z(R)} P_+ \right) t + A_{\mu} \bar{t} \gamma^{\mu} \left( F_1^{\gamma(L)} P_- + F_1^{\gamma(R)} P_+ \right) t \\
\left. - \frac{1}{v} \partial_{\nu} A_{\mu} \bar{t} \sigma^{\mu\nu} \left( F_2^{\gamma(L)} P_- + F_2^{\gamma(R)} P_+ \right) t + \partial^\mu A_{\mu} \bar{t} \left( F_3^{\gamma(L)} P_- + F_3^{\gamma(R)} P_+ \right) t \right]
\end{equation}

where $P_\pm = \frac{1}{2}(1 \pm \gamma_5)$, $i\sigma^{\mu\nu} = -\frac{1}{2}[\gamma^\mu, \gamma^\nu]$, and $v \sim 250$ GeV is the vacuum expectation value. Since we ignore the masses of the incoming electron and positron, the $F_3$ form factors in Eq. (1) do not contribute.

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If the form factor $D$, defined as $D_{[\gamma,Z]} \equiv \frac{2}{v}(F_2^{[\gamma,Z]}(L) - F_2^{[\gamma,Z]}(R))$, is not zero, the theory is CP violating. Specifically, the difference between the $RR$ and $LL$ cross sections is linearly dependent on $D$ through

$$(RR - LL) \propto \Re \left[ \left( \frac{A_Z}{s - m_Z^2} + \frac{A_\gamma}{s} \right) D^*_Z \right],$$

where

$$A_{[\gamma,Z]} = F_1^{[\gamma,Z]}(L) + F_1^{[\gamma,Z]}(R) - \frac{2m_t}{v} \left( F_2^{[\gamma,Z]}(L) + F_2^{[\gamma,Z]}(R) \right),$$

the “$^*$” indicates complex conjugation, and $\Re$ takes the real part of its argument. (In this work the photon is assumed to preserve its Standard Model (SM) behavior, namely, $D_\gamma = 0$.) $LL$, $RR$, $LR$, $RL$ respectively denote the production rates for $t_L\bar{t}_L$, $t_R\bar{t}_R$, $t_L\bar{t}_R$, $t_R\bar{t}_L$ events, where $L$ labels a left–handed helicity and $R$ labels a right–handed helicity. From Eq. (2) one can construct a quantity sensitive to CP violation, $A_1 \equiv \frac{LL-RR}{LL+RR}$, to measure the real part of $D$. The imaginary part of $D$ can be examined by studying the transverse polarization of the top quark pairs perpendicular to the scatter plane. The advantage of determining the polarization states of the $t\bar{t}$ pairs is that one can measure $A_1$ instead of $A_2 \equiv \frac{LL-RR}{LL+RR+LR+RL}$ (which may lose some of its effectiveness due to the dilution acquired by having a larger denominator from the $RL$ and $LR$ events) when studying CP violation.

To observe CP violation with $A_1 \sim 10^{-2}$, as in Weinberg’s model, in top quarks of $m_t = 140$ GeV, requires a luminosity of about $3 \times 10^4$ fb$^{-1}$ at $\sqrt{s} = 500$ GeV (i.e., about $2 \times 10^7$ $t\bar{t}$ pairs are required).

Below we present bounds that represent a 90% and 68% confidence level on the range for determining the form factors of the $Z$-$t\bar{t}$ interaction. (The 90% (68%) confidence level roughly represents a 3.3 (1) standard deviation error.) These bounds were obtained using MINUIT to fit the polar angle distribution of the top quark as generated for the NLC ($\sqrt{s}=500$ GeV, with 50 fb$^{-1}$ integrated luminosity) with no constraints on the kinematics. We expect 30,000 $t\bar{t}$ events for $m_t = 140$ GeV, but if we focus on the mode where the two $W$’s decay leptonically to $\mu^\pm$ or $e^\pm$, there is a branching ratio reduction to 1,500 events. These 1,500 events were collected into twenty bins for the fit. Allowing only one form factor to vary at a
time, the results indicate that within the 90% (68%) confidence limit, it should be possible to find $F_1^{(L)}$ to within about 20% (6%), while $F_1^{(R)}$ can only be known to within roughly 40% (13%). The $F_2$ form factors are zero at the Born level in the SM, and the fit indicates that their values can be known to within about $0.0^{+0.148}_{-0.043}$ ($0.0^{+0.022}_{-0.015}$) at a confidence level of 90% (68%).

Using our knowledge of the polarization behavior of the top quark to untangle some of the form factors before comparing them with data, it may be possible to improve these bounds. Performing the same procedures as we did with the unpolarized cross section, we bin 750 events from the unconstrained $LR$ sample and use MINUIT to fit for $F_1^{Z(L)}$ and find $0.395 \pm 0.014$ at the 68% confidence level, which is roughly 2% better than the fit from the unpolarized distribution. Further improvement in the form factor determination can come from the increased statistics (by about a factor of 7) obtained by including the events from $e^-e^+ \rightarrow t\bar{t} \rightarrow l + \text{jets}$ in the analysis. For the $l + \text{jets}$ mode, where the branching ratios take 9,000 unpolarized events from the original 30,000, the results indicate that within the 90% (68%) confidence limit, it should be possible to find $F_1^{(L)}$ to within about 8% (3%), while $F_1^{(R)}$ can be known to within roughly 18% (5%). In this case the $F_2$ form factors can be known to within about $\pm0.008$ ($\pm0.03$) at a confidence level of 90% (68%).

A 1 TeV machine can do better than a 500 GeV machine in determining $F_1^{(L,R)}$ because the relative sizes of the $RR$ and $LL$ rates become smaller compared to the total event rate, however, for the same reason a 1 TeV machine makes the CP asymmetry measurement more difficult.

In reality, the initial state electron or positron at high energies will radiate photons along the beam axis either due to initial state radiation (ISR) or beamstrahlung. Such radiation tends to move along the beam direction such that neither the center–of–mass energy nor the boost of the $t\bar{t}$ pair is known. Despite this, the effects of ISR are such that half of the time the center–of–mass energy of the $t\bar{t}$ pair is very close to the beam energy. Furthermore, it is possible to design experiments such that the beamstrahlung is minimized, so we only consider the ISR effect. We
checked that it is possible to solve for the momentum of the top quark in both the
\[ e^- e^+ \rightarrow t\bar{t} \rightarrow b\bar{l} + \nu_{l} \bar{b} q q' \] and \[ e^- e^+ \rightarrow t\bar{t} \rightarrow b\bar{l} + \nu_{l} b \bar{l} - \nu_{l} \] decay modes.[

Even including the effects of ISR, the kinematics of the top quark can be
reconstructed in the dilepton modes. The advantage of a high energy machine
in this regard is that the top quark is highly boosted, making it easy to select
the correct \( b \) quark (not the \( \bar{b} \)) associated with the \( W^+ \) to reconstruct the top
momentum. We have found that the probability of choosing the wrong \( b \) quark
is less than a percent at \( \sqrt{s} = 500 \text{ GeV} \) and \( m_t = 140 \text{ GeV} \). Determining the top
quark kinematics when one \( W \) boson decays hadronically while the other \( W \) boson
decays leptonically is even less complicated.

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