Probing Anomalous Top Quark Couplings at NLC

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(with T. Han, Z.-H. Lin, J.-X. Wang and X. Zhang)

1. Motivation

- SM has been successful in describing EW. It is quite possible that SM is only an effective theory which breaks down at higher energies as the structure of the underlying physics emerges.
- There are reasons to believe that the deviation from the SM might first appear in the interactions involving the third-generation fermions. The heavier fermions are more sensitive to the new physics and the new interactions will dominantly act on the third family.
- Take a model-independent approach to explore the physics in the Higgs and the top-quark sector. A linearly realized effective lagrangian to dimension-six operators.
- The observability of the signal from the new interactions over the SM at e^-e^+ colliders for anomalous coupings $t\bar{t}H$, $\gamma t\bar{t}$, $Zt\bar{t}$ and tWb with c.m. energies $\sqrt{s} = 0.5 - 1$ TeV will be discussed.

1.5 TeV

2. Effective Interactions

In the case of linear realization, the new physics is parameterized by higher dimensional operators which contain the SM fields and are invariant under the SM gauge group, $SU_c(3) \times SU_L(2) \times U_Y(1)$. Below the new physics scale Λ, the effective Lagrangian can be written as

$$\mathcal{L}_{eff} = \mathcal{L}_0 + \frac{1}{\Lambda^2}\sum_i C_i O_i + \mathcal{O}(\frac{1}{\Lambda^4})$$

where $\mathcal{L}_0$ is the SM Lagrangian. O_i are dimension-six operators which are $SU_c(3) \times SU_L(2) \times U_Y(1)$ invariant and C_i are constants which represent the coupling strengths of O_i .

Furthermore,

- To the order of $1/\Lambda^2$, *the fermion and the Higgs boson equations of motion* can be used to list the operators but the equations of motion of the gauge bosons can not.
- All the operators O_i are Hermitian and the coefficients C_i are real.

CP-even operators

Up to dimension-6, contribute to $Zb\bar{b}$, $Wt\bar{b}$, $Zt\bar{t}$, $\gamma t\bar{t}$ and $t\bar{t}H$, $t\bar{t}HZ$ and $t\bar{t}H\gamma$.

$$
\begin{aligned}
O_{t1} &= (\Phi^\dagger\Phi - \frac{v^2}{2})\left[\bar{q}_L t_R \widetilde{\Phi} + \widetilde{\Phi}^\dagger \bar{t}_R q_L\right], \\
O_{t2} &= i\left[\Phi^\dagger D_\mu \Phi - (D_\mu\Phi)^\dagger\Phi\right] \bar{t}_R\gamma^\mu t_R, \\
O_{Dt} &= (\bar{q}_L D_\mu t_R) D^\mu \widetilde{\Phi} + (D^\mu\widetilde{\Phi})^\dagger (\overline{D_\mu t_R} q_L), \\
O_{Db} &= (\bar{q}_L D_\mu b_R) D^\mu \Phi + (D^\mu\Phi)^\dagger (\overline{D_\mu b_R} q_L), \\
O_{tW\Phi} &= \left[(\bar{q}_L\sigma^{\mu\nu}\tau^I t_R)\widetilde{\Phi} + \widetilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}\tau^I q_L)\right] W^I_{\mu\nu}, \\
O_{tB\Phi} &= \left[(\bar{q}_L\sigma^{\mu\nu} t_R)\widetilde{\Phi} + \widetilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu} q_L)\right] B_{\mu\nu}, \\
O_{bW\Phi} &= \left[(\bar{q}_L\sigma^{\mu\nu}\tau^I b_R)\Phi + \Phi^\dagger(\bar{b}_R\sigma^{\mu\nu}\tau^I q_L)\right] W^I_{\mu\nu}, \\
O^{(1)}_{\Phi q} &= i\left[\Phi^\dagger D_\mu \Phi - (D_\mu\Phi)^\dagger\Phi\right] \bar{q}_L\gamma^\mu q_L, \\
O^{(3)}_{\Phi q} &= i\left[\Phi^\dagger\tau^I D_\mu \Phi - (D_\mu\Phi)^\dagger\tau^I\Phi\right] \bar{q}_L\gamma^\mu\tau^I q_L, \\
O_{qB} &= \left[\bar{q}_L\gamma^\mu D^\nu q_L + \overline{D^\nu q_L}\gamma^\mu q_L\right] B_{\mu\nu}, \\
O_{qW} &= \left[\bar{q}_L\gamma^\mu\tau^I D^\nu q_L + \overline{D^\nu q_L}\gamma^\mu\tau^I q_L\right] W^I_{\mu\nu}, \\
O_{tB} &= \left[\bar{t}_R\gamma^\mu D^\nu t_R + \overline{D^\nu t_R}\gamma^\mu t_R\right] B_{\mu\nu},
\end{aligned}
$$

K. Whisnant et.al. Phys. Rev. D56, 467, (1997)
G. Gounaris et al. Z. Physik C76, 333. (1997)

CP-odd operators

Up to dimension-6, contribute to $t\bar{t}H$, $t\bar{t}HZ$ and $t\bar{t}H\gamma$

$$\overline{O}_{t1} = i(\Phi^\dagger\Phi - \frac{v^2}{2})\left[\bar{q}_L t_R \widetilde{\Phi} - \widetilde{\Phi}^\dagger \bar{t}_R q_L\right],$$

$$\overline{O}_{t2} = \left[\Phi^\dagger D_\mu \Phi + (D_\mu\Phi)^\dagger \Phi\right] \bar{t}_R \gamma^\mu t_R,$$

$$\overline{O}_{Dt} = i\left[(\bar{q}_L D_\mu t_R) D^\mu \widetilde{\Phi} - (D^\mu \widetilde{\Phi})^\dagger (\overline{D_\mu t_R} q_L)\right],$$

$$\overline{O}_{tW\Phi} = i\left[(\bar{q}_L \sigma^{\mu\nu} \tau^I t_R)\widetilde{\Phi} - \widetilde{\Phi}^\dagger (\bar{t}_R \sigma^{\mu\nu} \tau^I q_L)\right] W^I_{\mu\nu},$$

$$\overline{O}_{tB\Phi} = i\left[(\bar{q}_L \sigma^{\mu\nu} t_R)\widetilde{\Phi} - \widetilde{\Phi}^\dagger (\bar{t}_R \sigma^{\mu\nu} q_L)\right] B_{\mu\nu},$$

$$\overline{O}^{(1)}_{\Phi q} = \left[\Phi^\dagger D_\mu \Phi + (D_\mu\Phi)^\dagger \Phi\right] \bar{q}_L \gamma^\mu q_L,$$

$$\overline{O}^{(3)}_{\Phi q} = \left[\Phi^\dagger \tau^I D_\mu \Phi + (D_\mu\Phi)^\dagger \tau^I \Phi\right] \bar{q}_L \gamma^\mu \tau^I q_L.$$

Yang + Young Phys. Rev. D56, 5907 (1997)

The standard notation is :

q_L the third family left handed doublet fermion,

Φ the Higgs doublet,

$W_{\mu\nu}$ the SU(2) gauge boson field tensor,

$B_{\mu\nu}$ the U(1) gauge boson field tensor,

D_μ the appropriate covariant derivative.

	$t\bar{t}H$	$t\bar{t}HZ$	$t\bar{t}H\gamma$
SM	1	0	0
✓ $O_{t1}, \overline{O}_{t1}$	1		
O_{t2}		$1/v$	
$\overline{O}_{t2}$	E/v		
✓ $O_{Dt}, \overline{O}_{Dt}$	E^2/v^2	E/v^2	E/v^2
$O_{tW\Phi}, \overline{O}_{tW\Phi}$		E/v^2	E/v^2
$O_{tB\Phi}, \overline{O}_{tB\Phi}$		E/v^2	E/v^2
$O^{(1)}_{\Phi q}$		$1/v$	
$\overline{O}^{(1)}_{\Phi q}$	E/v		
$O^{(3)}_{\Phi q}$		$1/v$	
$\overline{O}^{(3)}_{\Phi q}$	E/v		

Table 1: The energy-dependence of dimension-six operators for couplings $t\bar{t}H$, $t\bar{t}HZ$ and $t\bar{t}H\gamma$. An overall normalization v^2/Λ^2 has been factored out.

	$Zb\bar{b}$	$Wt\bar{b}$	$Zt\bar{t}$	$\gamma t\bar{t}$
SM	1	1	1	1
$O_{\Phi q}^{(1)}$	1		1	
$O_{\Phi q}^{(3)}$	1	1	1	
O_{Db}	E/v	E/v		
$O_{bW\Phi}$	E/v	E/v		
O_{qB}	E^2/v^2		E^2/v^2	E^2/v^2
O_{qW}	E^2/v^2	E^2/v^2	E^2/v^2	E^2/v^2
O_{t2}			1	
O_{Dt}		E/v	E/v	
$O_{tB\Phi}$			E/v	E/v
$O_{tW\Phi}$		E/v	E/v	E/v
O_{tB}			E^2/v^2	E^2/v^2

Table 2: The energy-dependence of dimension-six operators for couplings $Zb\bar{b}$, $Wt\bar{b}$, $Zt\bar{t}$ and $\gamma t\bar{t}$. An overall normalization v^2/Λ^2 has been factored out.

3. Bounds on the nonstandard couplings

- *Bounds from the process $Z \to b\bar{b}$*

The ratio of hadronic decay width at Z pole is defined as

$$R_b \equiv \frac{\Gamma(Z \to b\bar{b})}{\Gamma(Z \to \text{hadrons})}.$$

$R_b^{SM} = 0.2158(2)$

$R_b^{exp} = 0.21656(74)$

By using of the observable, we obtain the bounds at the 1σ (3σ) level as

$$-1 \times 10^{-2}\,(-2 \times 10^{-2}) < \frac{v^2}{\Lambda^2}C_{qW} < -1 \times 10^{-4}\,(1 \times 10^{-2}),$$

$$-2 \times 10^{-2}\,(-5 \times 10^{-2}) < \frac{v^2}{\Lambda^2}C_{qB} < -3 \times 10^{-4}\,(2 \times 10^{-2}),$$

$$5 \times 10^{-5}\,(-4 \times 10^{-3}) < \frac{v^2}{\Lambda^2}C_{\Phi q}^{(1)} < 4 \times 10^{-3}\,(8 \times 10^{-3}),$$

$$5 \times 10^{-5}\,(-4 \times 10^{-3}) < \frac{v^2}{\Lambda^2}C_{\Phi q}^{(3)} < 4 \times 10^{-3}\,(8 \times 10^{-3}).$$

For $\Lambda = 1$ TeV,

$$-0.16\,(-0.33) < C_{qW} < -0.16 \times 10^{-2}\,(0.16),$$

$$-0.33\,(-0.82) < C_{qB} < -0.49 \times 10^{-2}\,(0.33),$$

$$0.82 \times 10^{-3}\,(-0.07) < C_{\Phi q}^{(1)} < 0.07\,(0.15),$$

$$0.82 \times 10^{-3}\,(-0.07) < C_{\Phi q}^{(3)} < 0.07\,(0.15).$$

We have also examined the constraints from the bottom quark FB asymmetries $A_{FB}^{(b)}$ and obtained a weaker bounds than R_b does.

- *The unitarity limits*

The unitarity limits (given by G.J. Gounaris *et al.*) for $\Lambda \approx 3 - 1$ TeV: Z. Physik C 76, 333 (1997)

$$|C_{t1}|\frac{v^2}{\Lambda^2} \simeq 1.0 - 3.0, \qquad |C_{t2}|\frac{v^2}{\Lambda^2} \simeq 0.29 - 2.6,$$
$$C_{Dt}\frac{v^2}{\Lambda^2} \simeq 0.07 - 0.63 \ \text{ or } \ C_{Dt}\frac{v^2}{\Lambda^2} \simeq -(0.04 - 0.40),$$
$$|C_{tW\Phi}|\frac{v^2}{\Lambda^2} \simeq 0.02 - 0.15\ , \quad |C_{tB\Phi}|\frac{v^2}{\Lambda^2} \simeq 0.02 - 0.15\ ,$$
$$C_{tB}\frac{v^2}{\Lambda^2} \simeq 0.04 - 0.34 \ \text{ or } \ C_{tB}\frac{v^2}{\Lambda^2} \simeq -(0.03 - 0.29).$$

For $\Lambda \approx 1$ TeV:

$$|C_{t1}|\frac{v^2}{\Lambda^2} \simeq 3.0, \qquad |C_{t2}|\frac{v^2}{\Lambda^2} \simeq 2.6,$$
$$C_{Dt}\frac{v^2}{\Lambda^2} \simeq 0.63 \ \text{ or } \ C_{Dt}\frac{v^2}{\Lambda^2} \simeq -0.40,$$
$$|C_{tW\Phi}|\frac{v^2}{\Lambda^2} \simeq |C_{tB\Phi}|\frac{v^2}{\Lambda^2} \simeq 0.15\ .$$

Currently, there are no significant experimental constraints on the CP-odd couplings involving the top-quark sector.

4. $e^+e^- \to t\bar{t}H$

We show the relevant Feynman diagrams for $t\bar{t}H$ production. The four-particle vertex should be paid more attention, since there is no such vertex in the SM but exists in the effective couplings due to gauge invariance.

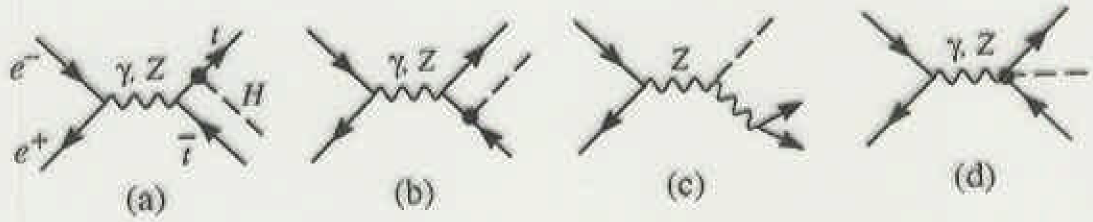

Figure 1: Feynman diagrams for $e^+e^- \to t\bar{t}H$ production. (a)-(c) are those in the SM. The dots denote the contribution from new interactions.

We evaluate the diagrams including interference effects, employing a helicity amplitude pakage

We have not included the QCD corrections to the signal process.

To show the sensitivity to the nonstandard couplings we choose two typical operators as follow:

- $O_{t1} = (\Phi^\dagger\Phi - \frac{v^2}{2})\left[\bar{q}_L t_R \widetilde{\Phi} + \widetilde{\Phi}^\dagger \bar{t}_R q_L\right]$,
  which corrects directly to Yukawa coupling and is energy independent.
- $O_{Dt} = (\bar{q}_L D_\mu t_R) D^\mu \widetilde{\Phi} + (D^\mu \widetilde{\Phi})^\dagger (\overline{D_\mu t_R} q_L)$,
  which corrects to $t\bar{t}H$ as well as $t\bar{t}HZ$ and $t\bar{t}H\gamma$ and is most sensitive to energy scale.

It is informative to study how the cross sections change versus the couplings, for

- $C_{t1}v^2/\Lambda^2$ from -0.16 to 0.16 or $C_{Dt}v^2/\Lambda^2$ from -0.40 to 0.40.
- c.m. energy $\sqrt{s}$ from 0.5 TeV to 1 TeV.
- the Higgs mass from 120 MeV to 140 MeV.

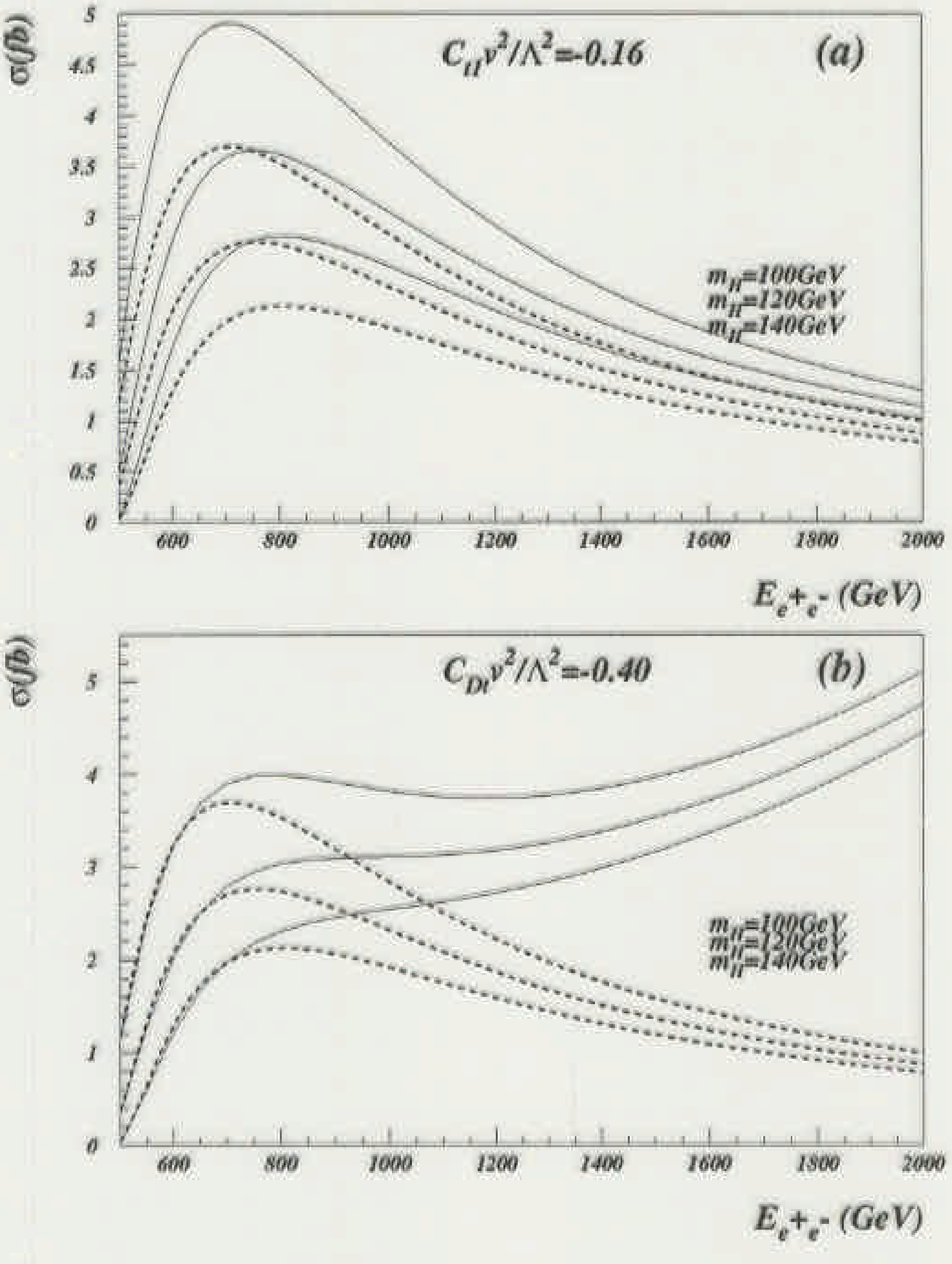

Figure 2: Total cross section for $e^+e^- \to t\bar{t}H$ production versus the e^+e^- c. m. energy for $m_H = 100$, 120 and 140 GeV, with (a) for O_{t1} and (b) for O_{Dt}. The dashed curves are for the SM expectation.

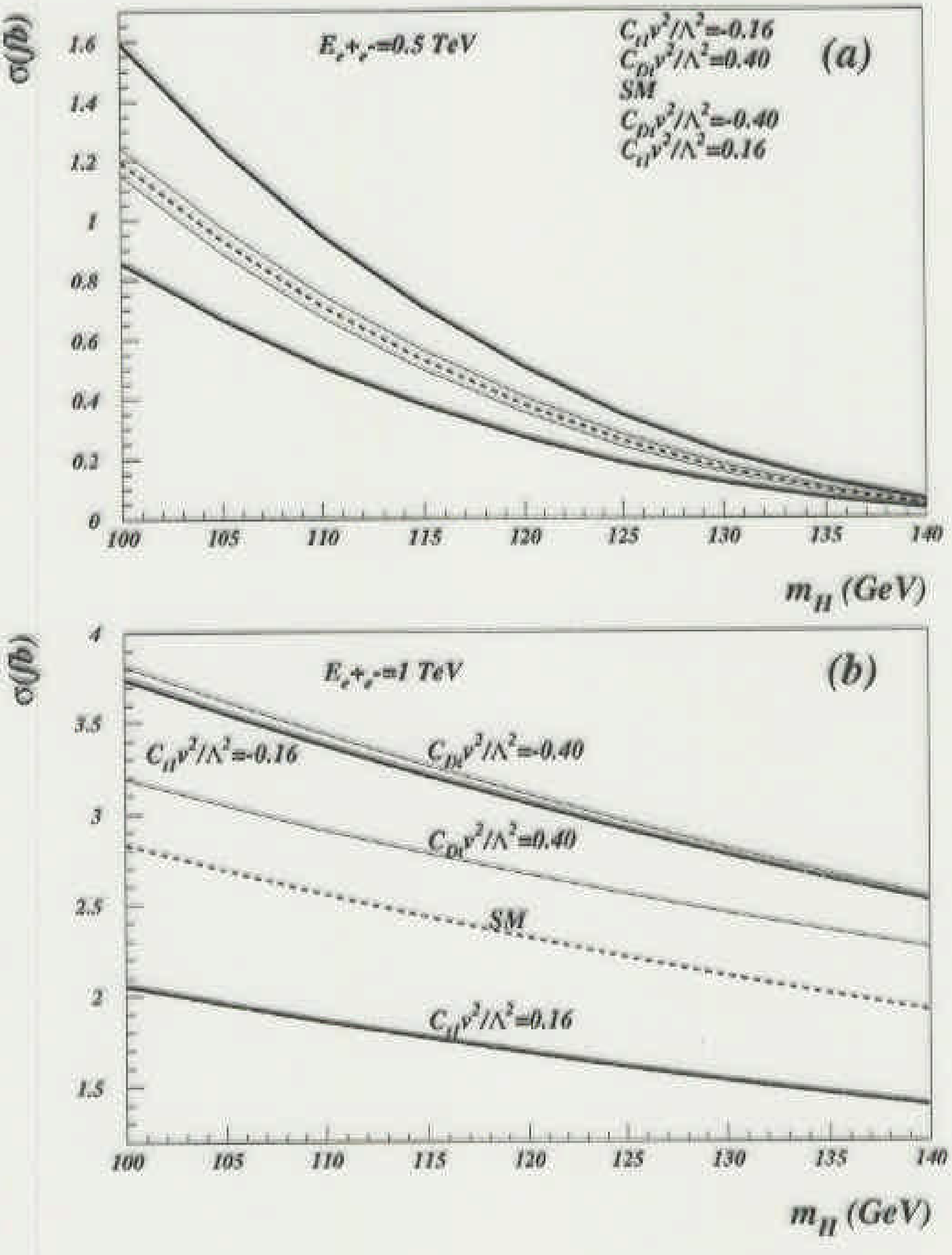

Figure 3: Total cross section for $e^+e^- \to t\bar{t}H$ production versus m_H (a) for $\sqrt{s} = 0.5$ TeV and (b) for $\sqrt{s} = 1$ TeV. The dashed curves are for the SM expectation.

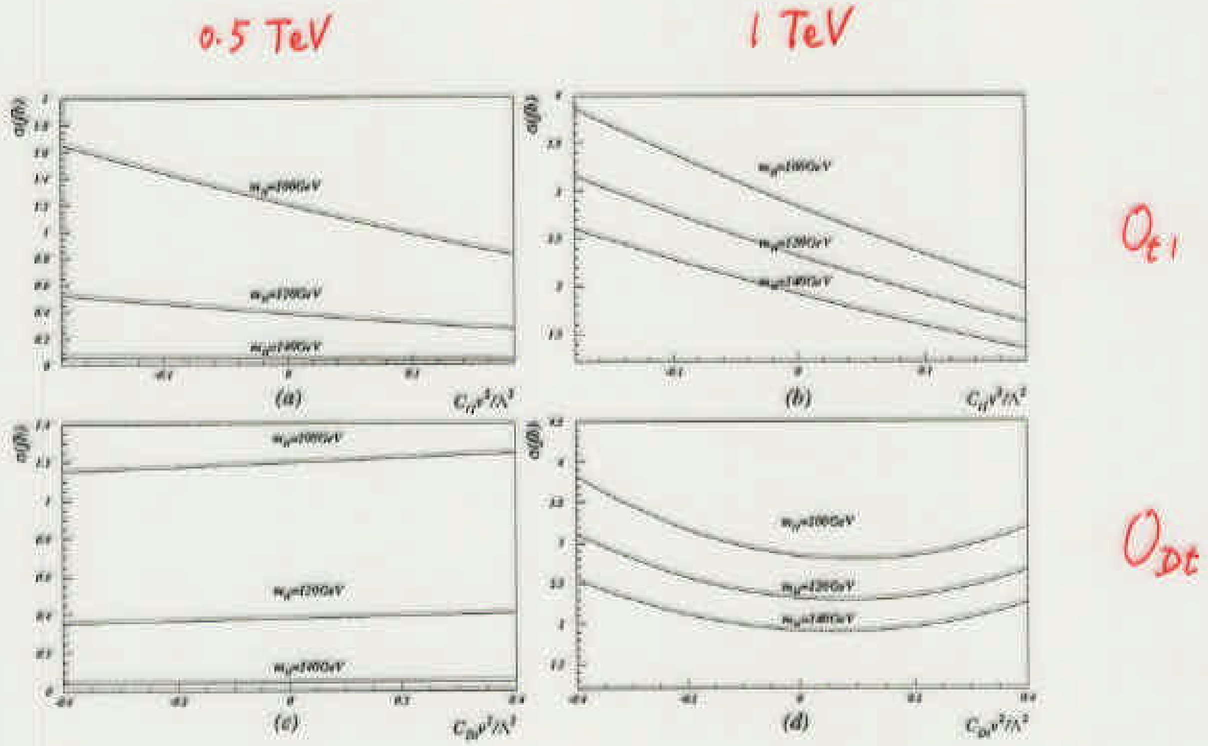

Figure 4: Total cross section for $e^+e^- \to t\bar{t}H$ production versus the couplings (a) for O_{t1} and $\sqrt{s} = 0.5$ TeV ; (b) for O_{t1} and $\sqrt{s} = 1$ TeV ; (c) for O_{Dt} and $\sqrt{s} = 0.5$ TeV ; (d) for O_{Dt} and $\sqrt{s} = 1$ TeV with $m_H = 100,\ 120,\ 140$ GeV.

Due to the interference effects, cross sections decrease as C_{t1} increases and are essentially linearly dependent upon the coupling. The effect due to the operator O_{Dt} is insignificant at $\sqrt{s} = 0.5$ TeV, while at higher energies the contribution from O_{Dt} is substantial and the quadratic terms become important quickly.

Sensitivity to the Non-standard Couplings

We consider the identification of the final state from $t\bar{t}H$ including the branching ratios and the detection efficiencies.

- The branching ratio of the leading decay mode $H \to b\bar{b}$ is about 80% $\sim$ 50% for the mass range of 100 $\sim$ 130 GeV.
- Assume 65% efficiency for a single b-tagging to identify four b-jets in the final state.
- Include both the leptonic decay $(e^{\pm}, \mu^{\pm})$ and the pure hadronic decay for $W^{\pm}$ from $t\bar{t}$. These amount about 85% of the $t\bar{t}$ events.
- Impose certain selective acceptance cuts (the cut efficiency would not less than 50%).

With the above event selection, We estimate an efficiency factor ϵ_S for detecting $e^+e^- \to t\bar{t}H$ to be

$$\epsilon_s = 10 - 30\%,$$

and a factor ϵ_B for reducing QCD and EW background to be

$$\epsilon_B = 10\%.$$

The background cross sections for QCD (σ_{QCD}), electroweak (σ_{EW}) and $e^+e^- \to t\bar{t}H$ in the SM (σ_{SM}) at selective energies without branching ratios and cuts included are listed in

	σ_{SM}	σ_{EW}	σ_{QCD}
$\sqrt{s}$(500 GeV)	0.38	0.19	0.84
$\sqrt{s}$(1 TeV)	2.32	0.79	1.93
$\sqrt{s}$(1.5 TeV)	1.36	0.62	1.54

Table 3: Background cross sections σ_{SM}, σ_{EW} and σ_{QCD} in units of fb at selective energies for $m_H = 120$ GeV.

To estimate the luminosity (L) needed for probing the effects of the non-standard couplings, we define the significance of a signal rate (S) relative to a background rate (B) in terms of the Gaussian statistics,

$$\sigma_S = \frac{S}{\sqrt{B}}$$

for which a signal at 95% (99%) confidence level (C.L.) corresponds to $\sigma_S = 2$ (3).

In the present CP-even operators, the $t\bar{t}H$ cross section (σ) would be thus modified from the SM expectation. The event rates are calculated as

$$S = L(|\sigma - \sigma_{SM}|)\epsilon_S \quad \text{and} \quad B = L\left[\sigma_{SM}\epsilon_S + (\sigma_{QCD} + \sigma_{EW})\epsilon_B\right].$$

We then obtain the luminosity required for observing the effects.

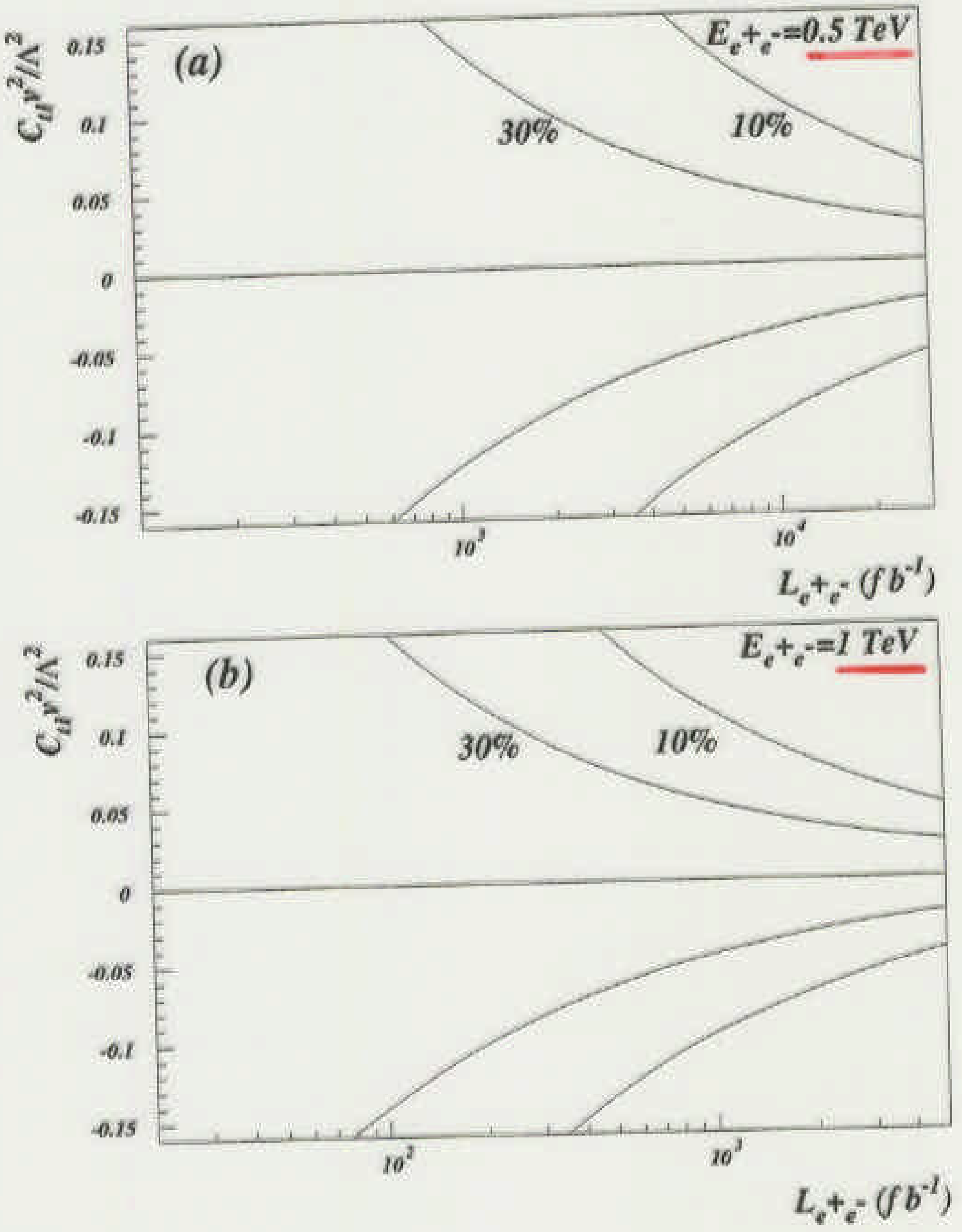

Figure 5: Sensitivity to the anomalous couplings O_{t1} versus the integrated luminosity for a 95% confidence level limits at (a) $\sqrt{s} = 0.5$ TeV and (b) $\sqrt{s} = 1$ TeV, with $m_H = 120\ GeV$.

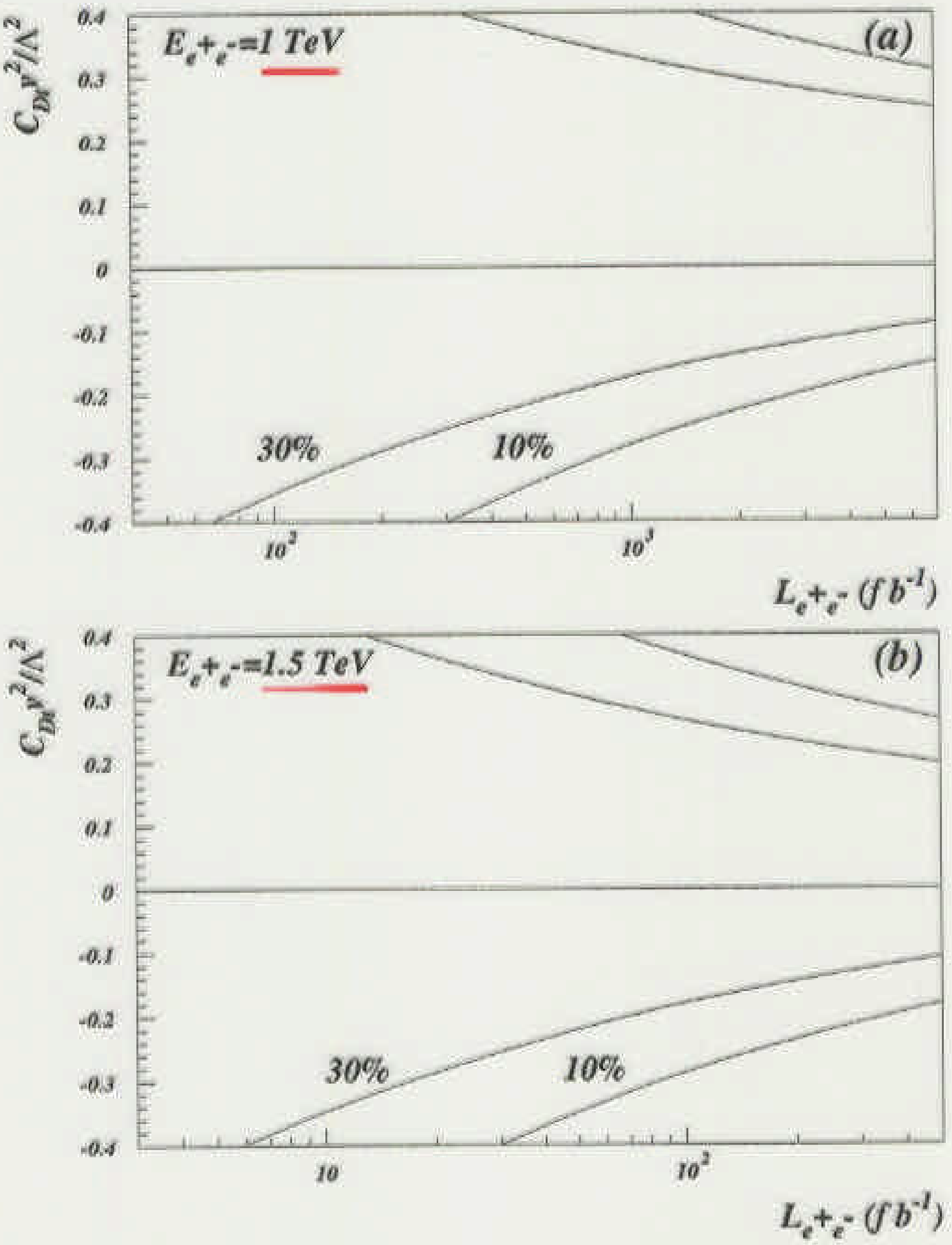

Figure 6: Sensitivity to the anomalous couplings O_{Dt} versus the integrated luminosity for a 95% confidence level limits at (a) $\sqrt{s}$ = 1 TeV and (b) $\sqrt{s}$ = 1.5 TeV, with m_H = 120 GeV.

We see that at a 0.5 TeV collider, one would need rather high integrated luminosity to reach the sensitivity to the non-standard couplings; while at a collider with a higher c.m. energy one can sensitively probe those couplings with *a few hundred* fb^{-1} luminosity.

Some kinematical distributions are discriminative for the signal and backgrounds. We plotted three distributions for O_{Dt},

- $d\sigma/dE_t$, E_t is the energy of top quark.
- $d\sigma/dm_{t\bar{t}}$, $m_{t\bar{t}}$ is the invariant mass of the $t\bar{t}$ system.
- $d\sigma/d\cos\theta_H$, θ_H is the angle of Higgs with respect to the electron beam direction.

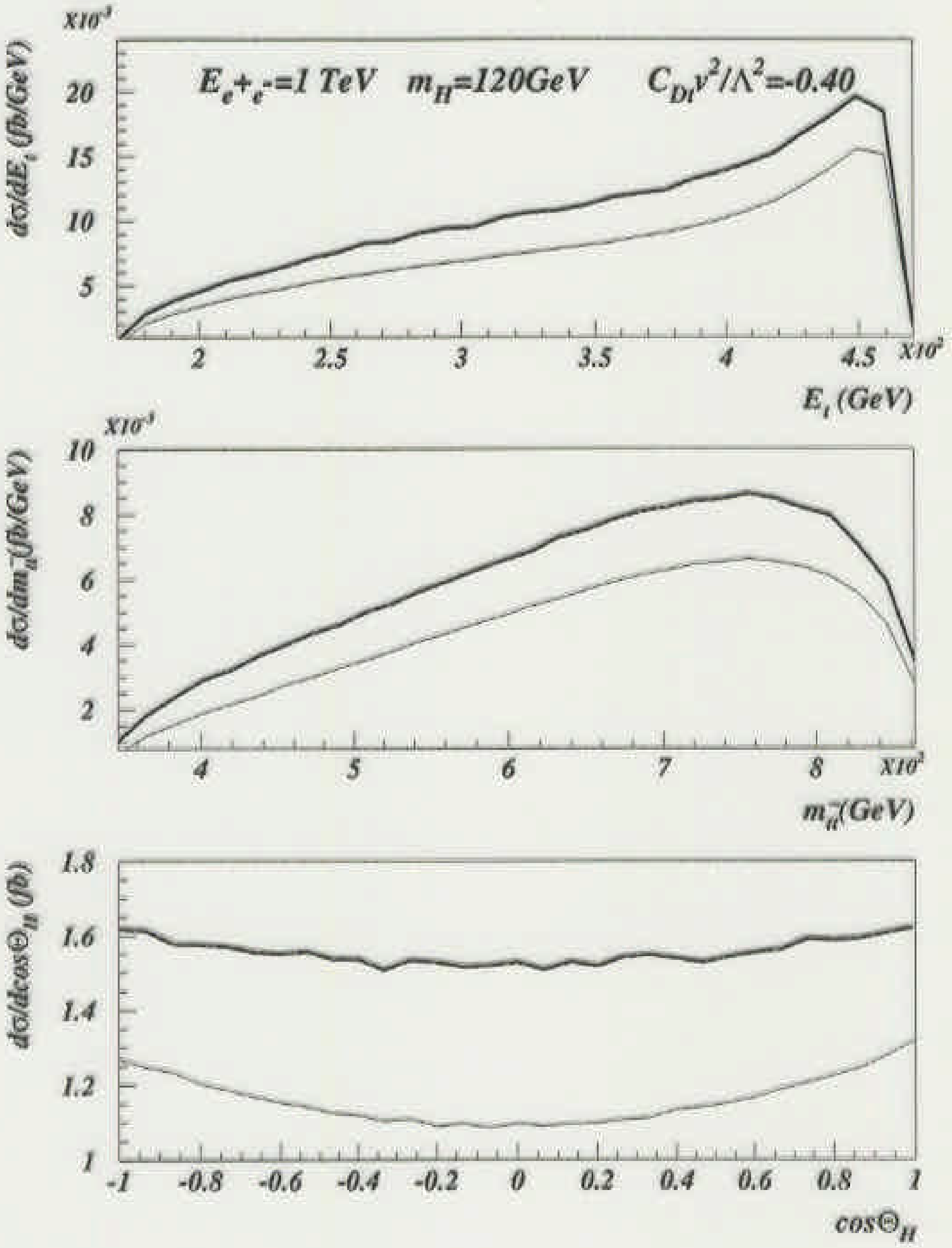

Figure 7: Kinematical distributions for $d\sigma/dE_t$, $d\sigma/dm_{tt}$, and $d\sigma/d\cos\theta_H$ with $m_H = 120$ GeV and for $\sqrt{s} = 1$ TeV. The thick line is for $C_{Dt}v^2/\Lambda^2 = -0.40$ and the thin line is for the Standard Model.

CP-violating effects

If there exist effective CP-odd operators beside the SM interaction, then CP will be violated in the Higgs and top-quark sector.

The CP-violating effect can be parameterized by a cross section asymmetry as

$$A_{CP} \equiv \frac{\sigma((p_1 \times p_3) \bullet p_4 < 0) - \sigma((p_1 \times p_3) \bullet p_4 > 0)}{\sigma((p_1 \times p_3) \bullet p_4 < 0) + \sigma((p_1 \times p_3) \bullet p_4 > 0)}$$

where p_1, p_3 and p_4 are the momenta of the incoming electron, top quark and anti-top quark, respectively. The 1σ statistical error for N_+ and N_- are $\sqrt{N}_+$ and $\sqrt{N}_-$ respectively, where N_+ is the number of the events for $(p_1 \times p_3) \bullet p_4 > 0$. and N_- is the number of the events for $(p_1 \times p_3) \bullet p_4 < 0$. Then the error for $N_+ - N_-$ is $\sqrt{(\sqrt{N}_+)^2 + (\sqrt{N}_-)^2}$. Noting that $\sqrt{(\sqrt{N}_+)^2 + (\sqrt{N}_-)^2} = \sqrt{N}$, we get the definition of the confident level for two σ as

$$\frac{N_- - N_+}{\sqrt{N}} = 2.$$

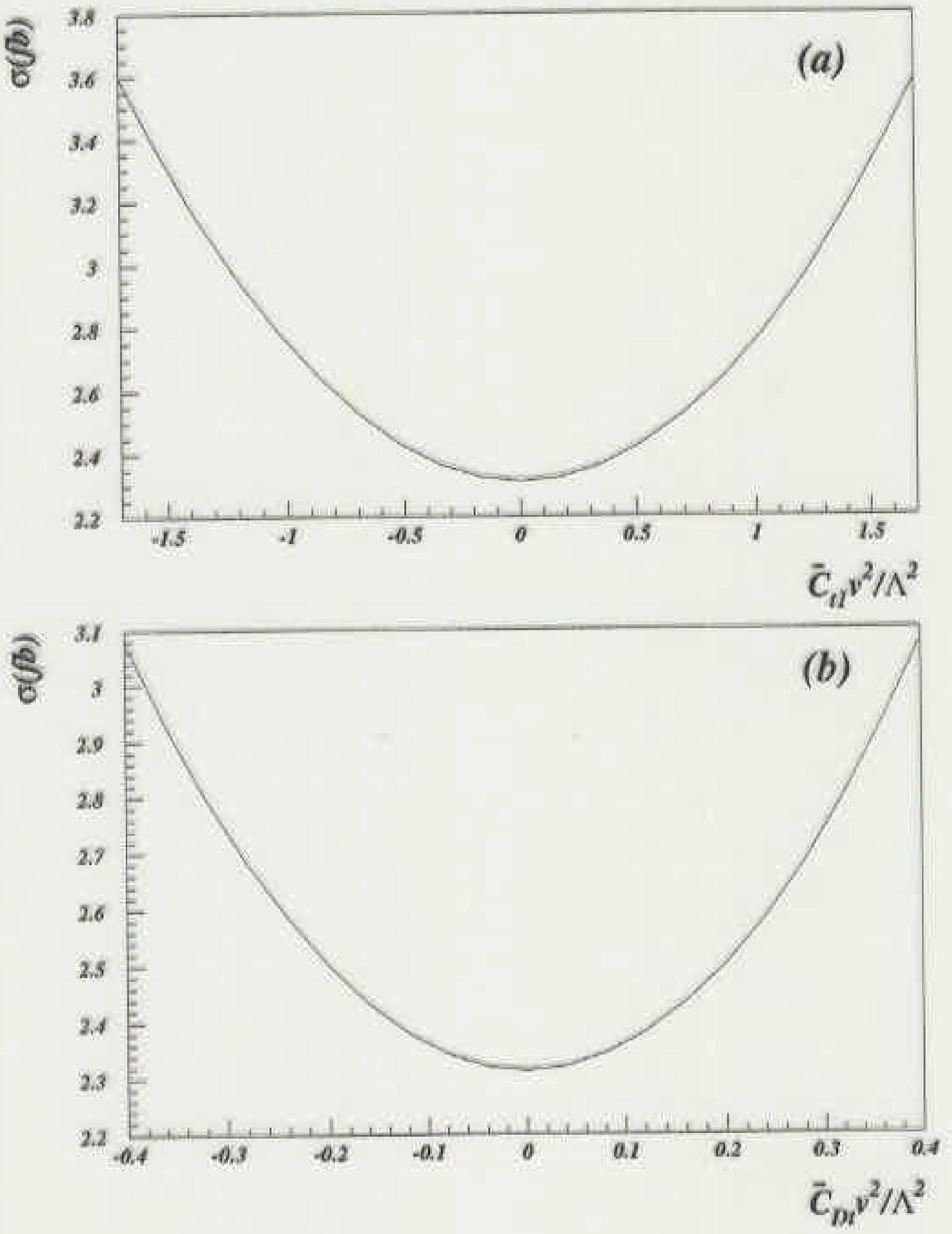

Figure 8: The total cross section versus CP-odd couplings for $m_H = 120$ GeV, $\sqrt{s} = 1$ TeV.

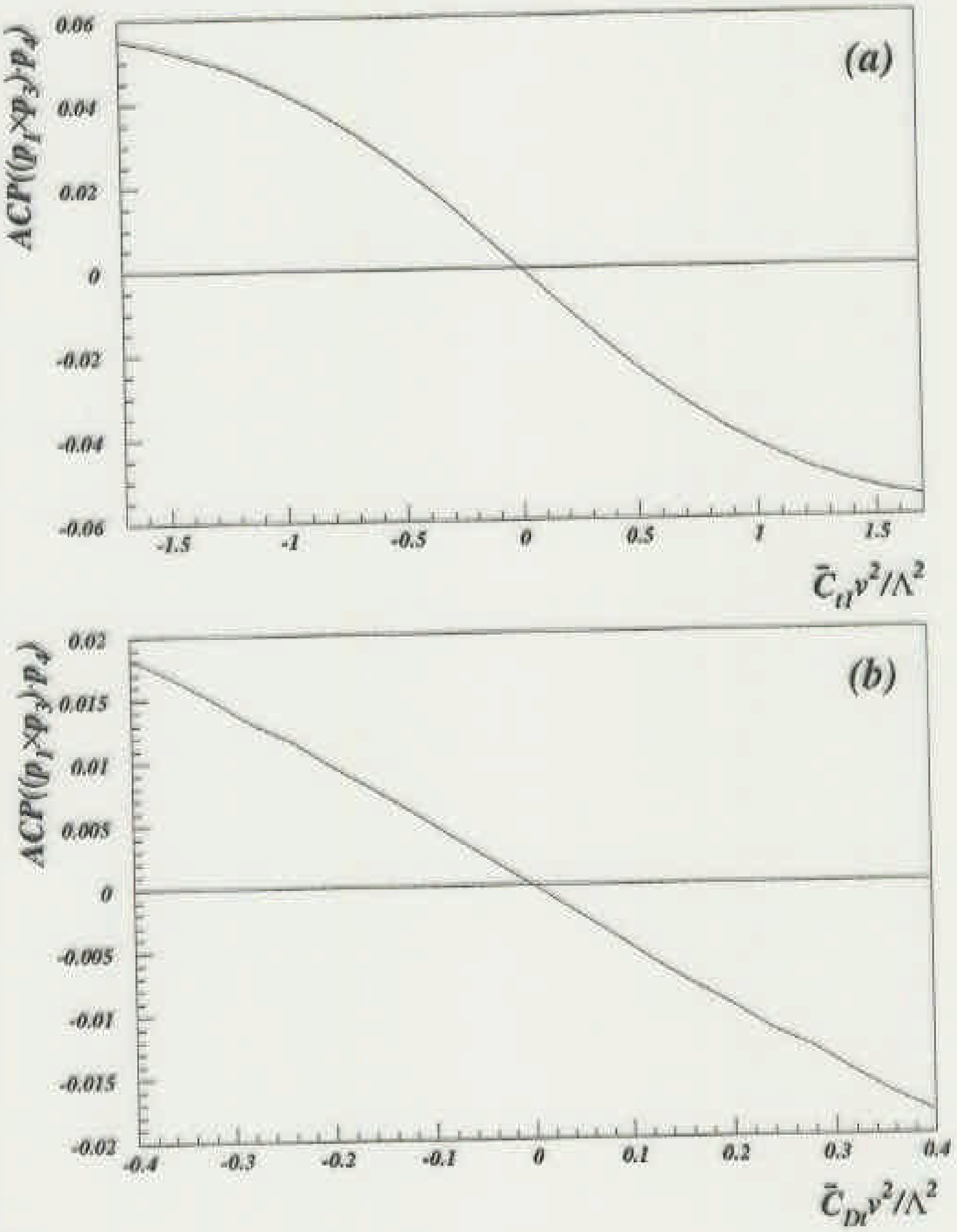

Figure 9: The CP asymmetry A_{CP} versus CP-odd couplings for $m_H = 120$ GeV, $\sqrt{s} = 1$ TeV.

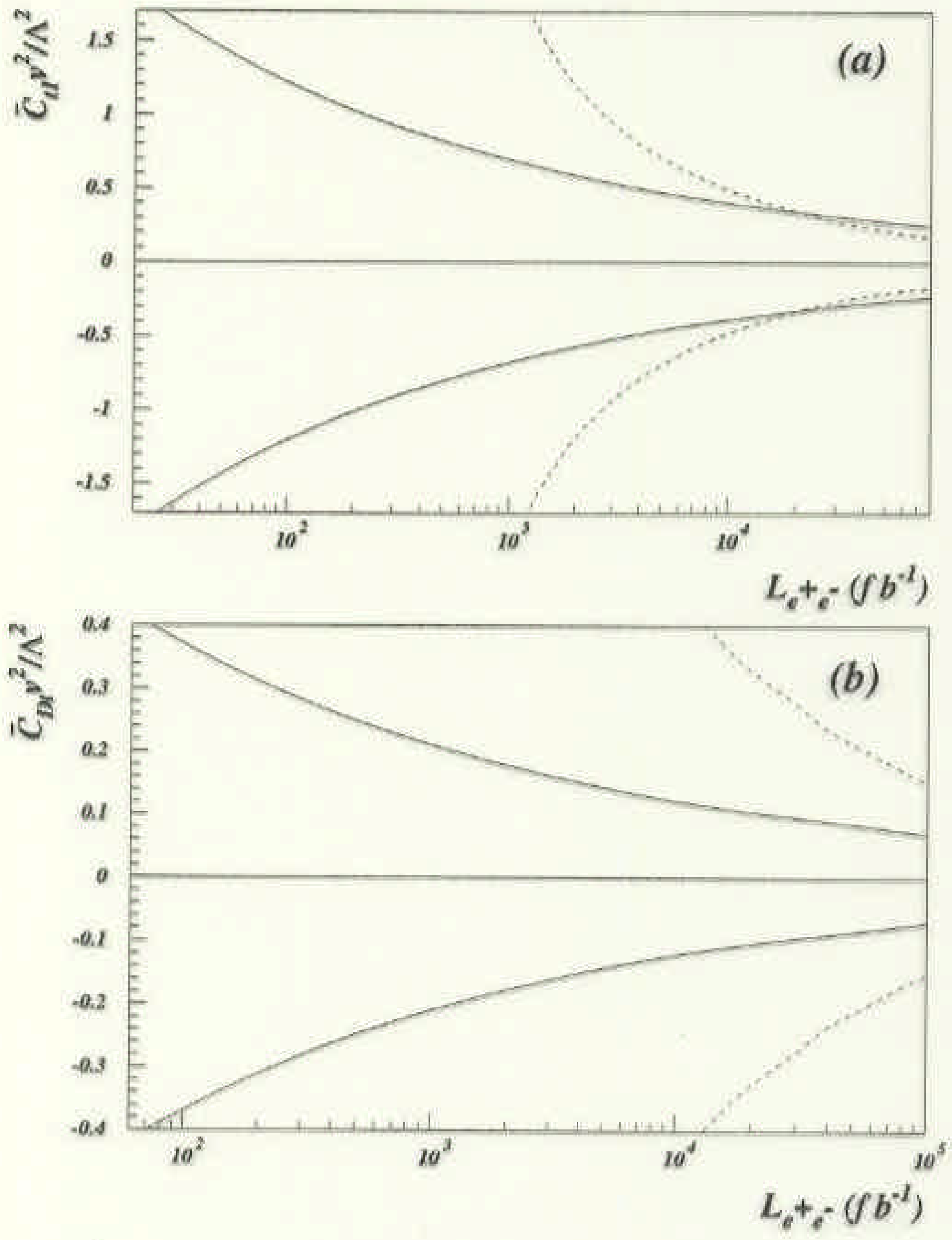

Figure 10: Sensitivity to the anomalous CP-odd couplings versus the integrated luminosity for a 95% confidence level limits and for 30% of detection efficiency at $\sqrt{s} = 1$ TeV , with $m_H = 120$ GeV. The solid line is for the total cross section and the dash line is for the CP asymmetry A_{CP}.

One can find that

- The cross sections depend on CP-odd couplings approximately quadratically due to that the corrections to the cross sections come from the squared terms of matrix elements and there is essentially no large interference between the SM and new operators.
- A_{CP} depends on the couplings linearly since it comes from interference terms.
- The effects on the total cross section due to CP-odd operators are much stronger than that on A_{CP}. In other words, the direct observation of the CP asymmetry would need much higher luminosity to reach.

6. Conclusions

- We have considered a general effective lagrangian to dimension-six operators including CP violation effects. Constrants on some of the couplings has been derived from $Z \to b\bar{b}$ data.
- We have studied the process $e^+e^- \to t\bar{t}H$ to explore the non-standard couplings of a Higgs boson to the top-quark. For the future LC, the intergrated luminosities needed are about $O(1000, 100, 10\ fb^{-1})$ for $\sqrt{s} = 0.5, 1.0, 1.5$ TeV.
- We have studied in detail the effects of anomalous couplings ($\gamma t\bar{t}$, $Zt\bar{t}$ and tWb) on $t\bar{t}$ spin correlations in the top pair production as well as the top quark decay processes with three bases (helicity, beam line and off-diagonal bases). Our results show that with a c.m. energy $\sqrt{s} \sim 0.5 - 1$ TeV and a high luminosity of $100 - 1000\ fb^{-1}$, the anomalous couplings $\gamma t\bar{t}$, $Zt\bar{t}$ and tWb may be sensitivelly probed.