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Top-spin analysis of new scalar and tensor interactions in $e^+ e^-$ collisions with transverse beam polarization

B ANANTHANARAYAN[1], MONALISA PATRA[1,*] and SAURABH D RINDANI[2]

[1]Centre for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India
[2]Theoretical Physics Division, Physical Research Laboratory, Navrangpura, Ahmedabad 380 009, India
*Corresponding author. E-mail: monalisa@cts.iisc.ernet.in

Abstract. The top polarization at the International Linear Collider (ILC) with transverse beam polarization is utilized in the $e^+e^- \rightarrow t\bar{t}$ process to probe interactions of the scalar and tensor type beyond the Standard Model and to disentangle their individual contributions. Confidence level limits of 90% are presented on the interactions with realistic integrated luminosity and are found to improve by an order of magnitude compared to the case when the spin of the top quark is not measured. Sensitivities of the order of a few times 10^{-3} TeV^{-2} for real and imaginary parts of both scalar and tensor couplings at $\sqrt{s} = 500$ and 800 GeV with an integrated luminosity of 500 fb^{-1} and completely polarized beams are shown to be possible.

Keywords. International Linear Collider; transverse beam polarization.

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1. Introduction

Discoveries made in Large Hadron Collider will be complemented by the electron positron collider, the planned International Linear Collider (ILC), with the availability of both transverse and longitudinal beam polarization. New physics (NP) in $t\bar{t}$ production is estimated in a model-independent parametrization by introducing higher-dimensional operators consistent with gauge invariance. Probing of CP violation due to S, P and T type beyond Standard Model (BSM) interactions using 4-Fermi interactions is done with transverse polarization (TP), see e.g., ref. [1]. Azimuthal asymmetries involve the linear combination given by

$$S + \frac{2c^t_{\rm A} c^e_{\rm V}}{c^t_{\rm V} c^e_{\rm A}} T. \tag{1}$$

The following discussion is an extension of the final-state spin analysis in $t\bar{t}$ production [2].

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Longitudinal polarization of ∼80% for electron and ∼60% for positron beam expected at ILC can be converted to TP by spin rotators with practically no depletion [3]. TP picks out a spatial direction, and along with the beam direction defines a plane, giving access to azimuthal asymmetries, to probe NP due to additional observables [4].

2. Effective Lagrangian

There are various tree-level-generated operators presenting the widest window into physics beyond SM which directly contribute to $e^+e^- \to t\bar{t}$. The Lagrangian takes the form:

$$\mathcal{L}^{4\mathrm{F}} = \sum_{i,j=\mathrm{L,R}} \left[S_{ij}(\bar{e}P_i e)(\bar{t}P_j t) + T_{ij}\left(\bar{e}\frac{\sigma_{\mu\nu}}{\sqrt{2}}P_i e\right)\left(\bar{t}\frac{\sigma^{\mu\nu}}{\sqrt{2}}P_j t\right)\right], \quad (2)$$

where $P_{\mathrm{L,R}}$ are respectively the left- and right-chirality projection matrices.

3. Cross-section

Retaining the new couplings to linear order, with the superscripts denoting the respective signs of the e^+ and e^- TP [2]

$$\begin{aligned}\frac{\mathrm{d}\sigma^{\pm\mp}}{\mathrm{d}\Omega} &= \frac{\mathrm{d}\sigma^{\pm\mp}_{\mathrm{SM}}}{\mathrm{d}\Omega} \mp \frac{h\alpha\beta}{\pi s^2}\left[\frac{s^{3/2}}{2}m_{\mathrm{t}}\sin\theta\left(\mathrm{Im}\,T\sin\phi\right.\right.\\ &\qquad\left.\left. - \frac{1}{2}z'(\mathrm{Re}\,S - 2\beta\mathrm{Re}\,T\cos\theta)\cos\phi\right)\right]\\ &\quad \pm \frac{\alpha\beta}{4\pi s(s-M_{\mathrm{Z}}^2)}\\ &\quad \times\left[3h\beta m_{\mathrm{t}}c_{\mathrm{A}}^t c_{\mathrm{A}}^e\cos\theta\sin\theta\sin\phi s^{3/2}\mathrm{Im}\,T\right.\\ &\qquad -\frac{3}{2}m_{\mathrm{t}}s^{3/2}\sin\theta\left\{\left(\beta c_{\mathrm{A}}^e c_{\mathrm{V}}^t\mathrm{Im}\,S + 2c_{\mathrm{V}}^e(\beta c_{\mathrm{A}}^t - hc_{\mathrm{V}}^t)\mathrm{Im}\,T\right)\sin\phi\right.\\ &\qquad\left.\left. + z'hc_{\mathrm{V}}^e c_{\mathrm{V}}^t(\mathrm{Re}\,S - 2\beta\ \mathrm{Re}\,T\cos\theta)\cos\phi\right\}\right], \quad (3)\end{aligned}$$

when $\beta = \sqrt{1-4m_{\mathrm{t}}^2/s}$, and c_{V}^i, c_{A}^i are the couplings of Z to e^-e^+ and $t\bar{t}$.

4. Extraction of new physics

The transversely polarized beams along with the rich structure of helicity-dependent part, allows to isolate the couplings. The generic form of the azimuthal asymmetries calculated for the top polarization-dependent part are:

$$A_1(\theta) = \frac{1}{\sigma^{\mathrm{SM}}(\theta)}\left[\int_0^{\pi}\frac{\mathrm{d}\sigma_{\mathrm{NP}}}{\mathrm{d}\Omega}\mathrm{d}\phi - \int_{\pi}^{2\pi}\frac{\mathrm{d}\sigma_{\mathrm{NP}}}{\mathrm{d}\Omega}\mathrm{d}\phi\right]$$

$$A_2(\theta) = \frac{1}{\sigma^{\rm SM}(\theta)}\left[\int_0^{\pi/2}\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega}\,{\rm d}\phi - \int_{\pi/2}^{3\pi/2}\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega}\,{\rm d}\phi + \int_{3\pi/2}^{2\pi}\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega}\,{\rm d}\phi\right],$$

where

$$\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega} = \left.\frac{{\rm d}\sigma}{{\rm d}\Omega}\right|_{h=1} - \left.\frac{{\rm d}\sigma}{{\rm d}\Omega}\right|_{h=-1}$$

$$\sigma^{\rm SM}(\theta) = \left[\int_0^{2\pi}\frac{{\rm d}\sigma_{\rm SM}}{{\rm d}\Omega}\,{\rm d}\phi\right].$$

The θ-integrated version of the asymmetries are:

$$A_1(\theta_0) = \frac{1}{\Delta\sigma^{\rm SM}(\theta_0)}\left[\int_{-\cos\theta_0}^{\cos\theta_0}\left(\int_0^{\pi}\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega}\,{\rm d}\phi - \int_{\pi}^{2\pi}\frac{{\rm d}\sigma_{\rm NP}}{{\rm d}\Omega}\,{\rm d}\phi\right){\rm d}\cos\theta\right],$$

where

$$\Delta\sigma^{\rm SM}(\theta_0) = \left[\int_{-\cos\theta_0}^{\cos\theta_0}\left(\int_0^{2\pi}\frac{{\rm d}\sigma_{\rm SM}}{{\rm d}\Omega}\,{\rm d}\phi\right){\rm d}\cos\theta\right].$$

The choice of the asymmetries chosen is justified below.

$$\begin{aligned} A_1^{+-}(\theta) &= \frac{1}{\sigma^{\rm SM}(\theta)}\frac{2m_{\rm t}\alpha\beta\sin\theta}{\pi\sqrt{s}} \\ &\quad\times\left[-2 + \frac{3s}{s-M_{\rm Z}^2}\left(c_{\rm V}^e c_{\rm V}^t + \beta c_{\rm A}^e c_{\rm A}^t\cos\theta\right)\right]{\rm Im}\,T, \\ A_2^{+-}(\theta) &= \frac{1}{\sigma^{\rm SM}(\theta)}\frac{2m_{\rm t}\alpha\beta\sin\theta}{\pi\sqrt{s}} \\ &\quad\times\left[-1 + \frac{3s}{2(s-M_{\rm Z}^2)}c_{\rm V}^e c_{\rm V}^t\right](2\,{\rm Re}\,T\beta\cos\theta - {\rm Re}\,S)\,. \end{aligned}$$

5. Numerical results

The asymmetries are calculated assuming the ideal condition with 100% beam polarization for e^- as well as e^+ at $\sqrt{s} = 500$ GeV and 800 GeV respectively for an integrated luminosity of 500 fb^{-1}. The results are here presented for the $(+-)$ case (figure 1). The asymmetries are used to calculate 90% CL limits that can be obtained with ILC with an integrated luminosity $\mathcal{L}$ of 500 fb^{-1}, and $\sqrt{s} = 500$ GeV and 800 GeV.

$$\mathcal{C}_{\rm limit} = \frac{1.64}{|A|\sqrt{N_{\rm SM}}}. \quad (4)$$

6. Selection of polarized top

In the rest frame of the top, the angular distribution of a given decay product is given by

$$\frac{1}{\Gamma}\frac{{\rm d}\Gamma}{{\rm d}\cos\theta} = \frac{1}{2}(1-\kappa\cos\theta),$$

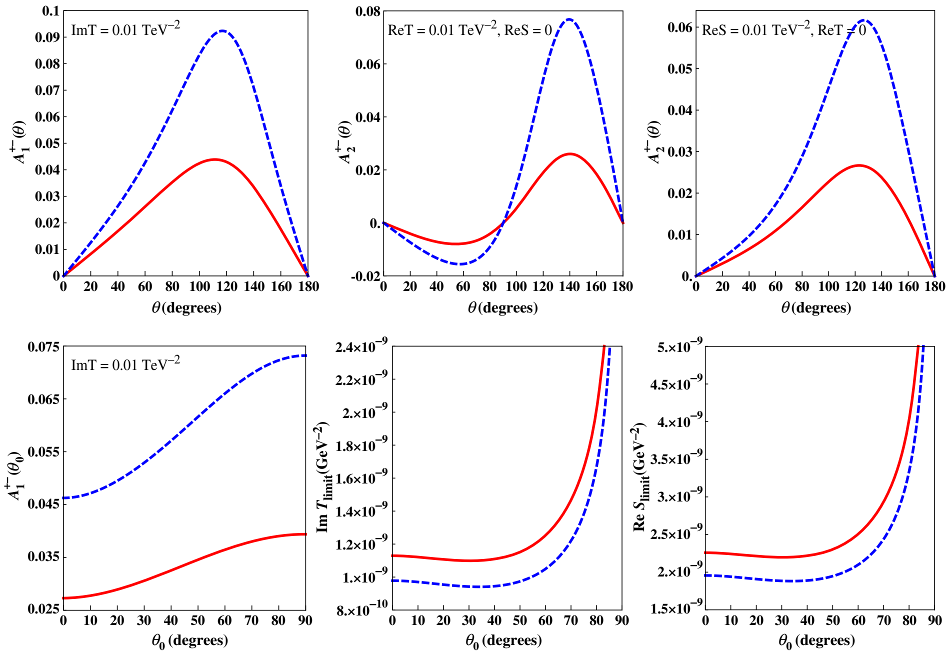

Figure 1. The various asymmetries $A_1^{+-}(\theta)$, $A_2^{+-}(\theta)$ as a function of θ and $A_1^{+-}(\theta_0)$ as a function of θ_0 for different values of S and T at $\sqrt{s} = 500$ GeV (red solid line) and $\sqrt{s} = 800$ GeV (blue dashed line). 90% CL limit obtained on S and T obtained for an integrated luminosity of 500 fb^{-1} is also plotted as a function of θ_0.

where θ is the angle between the momentum of the decay product and top spin quantization axis, and κ is the spin analysing power for a given decay channel. The particles with the highest spin analysing power are the lepton and the down-type quark from W boson decay.

A measurement of the distribution is performed and the events are classified depending on whether $\cos\theta$ is positive or negative, giving two event samples, one with dominantly positive helicity tops and the other with dominantly negative helicity tops.

7. Conclusions

The $t\bar{t}$ process in the presence of NP contributions due to S and T interactions at leading order is considered. On analysis of the top quark spin, it becomes possible to disentangle the contributions of S and T, which was not possible when no final-state spin was measured. With an integrated luminosity of 500 fb^{-1} and realistic beam polarizations, the limits on real and imaginary parts for T and S are of order 10^{-3} TeV^{-2} at $\sqrt{s} = 500$ and 800 GeV, an order of magnitude better compared to the previous case [2].

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