Top Quark Spin Polarization in $e\gamma$ Collision

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We investigate the degree of spin polarization of single top quarks in the $e\gamma$ collision via the process $e^+\gamma \rightarrow t\bar{b}\nu_e$. Dominant spin fractions and spin asymmetries for the various top quark spin bases are investigated. We show that $e^+$-beam direction is the favorite top quark spin decomposition axis. It is found to be comparable with the ones in $pp$ and $ep$ collisions.

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I. INTRODUCTION

The top quark is the heaviest fermion in the Standard Model. Its mass is at the electroweak symmetry-breaking scale. Due to its large mass its weak decay time is much shorter than the typical time for the strong interactions to affect its spin [1]. Therefore the information on its polarization, is not disturbed by hadronization effects but transferred to the decay products. Within the standard model, the dominant decay of the top quark is $t \rightarrow W^+b$.

The angular distributions of the top quark decay products are determined by the momentum and spin state of the top quark itself. It is believed that top quark physics will be crucial to understand the structure of Standard Model and existence of new physics beyond. Detailed discussions on top quark spin polarization properties will contribute future researches on this subject.

In this work we investigate top quark spin polarization along the direction of various spin bases for the single production in $e^+\gamma$ collision via the process $e^+\gamma \rightarrow t\bar{b}\nu_e$. The research and development on linear $e^+e^-$ colliders have been progressing and the physics potential of these future machines is under study. After linear colliders are constructed its operating modes of $e\gamma$ and $\gamma\gamma$ are expected to be designed [2, 3]. Real gamma beam is obtained through Compton backscattering of laser light off linear electron beam where most of the photons are produced at the high energy region. The luminosities for $e\gamma$ and $\gamma\gamma$ collisions turn out to be of the same order as the one for $e^+e^-$ [4], so the cross sections for photoproduction processes with real photons are considerably larger than virtual photon case. In our calculations we consider three different center of mass energies $\sqrt{s}=0.5, 1$ and 1.5 TeV of the parental linear $e^+e^-$ collider.

There are many detailed discussions in the literature for single top quark production and spin correlations in $pp$, $p\bar{p}$ and $ep$ collisions [2, 3, 5]. At $pp$ and $p\bar{p}$ colliders top quarks are produced $tt$ and single $t$ production modes. In double production case, spin up top quark and spin down anti-top quark are more likely produced and there are observable angular correlations among the decay products. $tt$ decay products in the final states give larger statistics than the single production case. On the other hand, final state in the single top case is relatively simple and may compensate for the smaller statistics [6]. In $ep$ collisions, top quark decay products in the final states are dominated by the single top production due to absence of the $tt$ production. Since single top production contains an electroweak process with produced top quarks coupled to a W boson, decay products of the final top quark gives a high angular correlation [7]. This is also the case in the $e^+\gamma$ collision. Moreover linear $e^+e^-$ collider or its $e\gamma$ mode provide a clean environment to study polarization phenomena of top quarks.

II. CROSS SECTIONS OF POLARIZED TOP QUARKS

In $e^+e^-$ linear colliders a hard photon beam can be produced by Compton backscattering of laser light off linear electron or positron beam. We consider the case in which the photon beam is obtained by Compton backscattering off linear electron beam and the positron beam directly takes part in the subprocess. The spectrum of the backscattered photons is given by [4].

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helicity for top quark spin. The spin four-vector of a top quark is defined by

\[ s^\mu_t = \left( \frac{\vec{p}_t \cdot \vec{s}}{m_t}, \frac{\vec{p}_t \cdot \vec{s}}{m_t(E_t + m_t)} \hat{p}_t \right) \]  

(4)

where \((s^\mu_t)_{RF} = (0, \vec{s})\) in the top quark rest frame. The laboratory frame is the \(e^+e^-\) center of mass system where the cross section is performed. We consider four different top spin direction in the laboratory frame: the incoming positron beam, photon beam directions and outgoing \(\bar{b}\) direction and also the helicity basis. \(\vec{s}\) should be obtained by a Lorentz boost from laboratory frame:

\[ \vec{s} = \lambda \frac{\vec{p}^*}{|p^*|}, \quad \lambda = \pm 1. \]

(5)

Here \(\vec{p}\) is the momentum of the particle moves along the top spin direction in the laboratory frame and \(p^*\) is the momentum observed in the rest frame of the top quark.

In Table I-III polarized cross sections, dominant spin fractions and spin asymmetries are given for the various top quark spin bases. It is shown from these tables that \(e^+\)-beam direction gives the highest degree of polarization: 94% at \(\sqrt{s} = 0.5\) TeV, 88% at \(\sqrt{s} = 1\) TeV and 86% at \(\sqrt{s} = 1.5\) TeV. Its energy dependence is significant. In relatively low energies, helicity will not give the best description of the spin of a massive fermion like top quark. Therefore other spin bases may give a better description of top quark spin. In our case favorite spin basis is the \(e^+\)-beam spin decomposition axis. When energy increases top quark gradually becomes ultrarelativistic and spin fraction in the helicity basis grows. This behaviour is shown from Table I-III. Spin fraction for the helicity basis increases with energy: 60%(L) at \(\sqrt{s} = 0.5\) TeV, 66%(L) at \(\sqrt{s} = 1\) TeV and 69%(L) at \(\sqrt{s} = 1.5\) TeV. At the energy region we have considered speed of the top quarks are not ultrarelativistic therefore helicity is not the favorite spin basis.

It is straightforward to obtain similar results for anti top quarks with the process \(e^-\gamma \rightarrow \bar{b}\nu_e\). In this case favorite spin basis is the \(e^-\)-beam spin decomposition axis. Same results at Table I-III for the spin fractions are obtained.
with the interchange of the bases; $e^+\text{-beam} \leftrightarrow e^-\text{-beam}$, $\bar{b}\text{-beam} \leftrightarrow b\text{-beam}$. But the spin orientations should be reversed; spin up $\leftrightarrow$ spin down, $L \leftrightarrow R$.

Another useful quantity about spin-induced angular correlations is the spin asymmetry

$$A_{\uparrow \downarrow} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$  \hspace{1cm} (6)

Here subscript up arrow $\uparrow$ (down arrow $\downarrow$) stands for spin up $\lambda = +1$ (spin down $\lambda = -1$) and $N$ represents number of event for the corresponding spin. The angular distribution of the top quark decay involves correlations between top decay products and top quark spin:

$$\frac{1}{\Gamma_T} \frac{d\Gamma}{d\cos\theta} = \frac{1}{2} (1 + A_{\uparrow \downarrow} \alpha \cos\theta)$$  \hspace{1cm} (7)

Here the dominant decay chain of the top quark in the standard model $t \rightarrow W^+b(W^+ \rightarrow l^+\nu, \bar{d}u)$ is considered. $\theta$ is defined as the angle between top quark decay products and the top quark spin quantization axis in the rest frame of the top quark. $\alpha$ is the correlation coefficient and $\alpha = 1$ for $l$ or $\bar{d}$ which leads to the strongest correlation. One can see from Table I that $e^+\text{-beam}$ basis improves the asymmetry a factor of 4.35 when compared to helicity basis at $\sqrt{s} = 0.5$ TeV. From Table II and III we see that this factor takes the value of 2.38 and 1.85 respectively.

In order to get an idea about the influence of spin polarization on transverse momentum $P_T$ distributions of singly produced top quarks we plot Fig I-III. Similar features in the tables are reflected in the figures also; deviations of the $P_T$ distributions from the unpolarized (total) is the largest for helicity basis.

In our calculations phase space integrations have been performed by GRACE which uses a Monte Carlo routine.

III. CONCLUSIONS

We have shown that in the energy region $\sqrt{s} = 0.5-1.5$ TeV $e^+\text{-beam}$ direction provides a high degree of polarization. Considerable improvements have been obtained in the spin fractions and asymmetries with respect to helicity basis. Therefore a detailed analysis of top spin polarization and studying various spin bases in the $e^+\gamma$ collision is important and may contribute future researches.

Linear $e^+e^-$ collider and its $e^+\gamma$ mode provide a clean environment and the experimental cleanness is an advantage of e$\gamma$ collisions with respect to pp, $p\bar{p}$ and ep collisions. At hadron colliders the interacting particles are not the beam particles themselves. The reactions are initiated by one of many partons present in the incident hadron. So the energy and quantum state of the initial state are not fixed. On the other hand lepton colliders tend have much cleaner beams and lower backgrounds.

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FIG. 1: Transverse momentum $P_T^t$ distributions of the singly produced top quarks via process $e^+\gamma \rightarrow t\bar{b}\nu_e$ at center of mass energy $\sqrt{s} = 0.5$ TeV of the parental linear $e^+e^-$ collider. Dominant spin bases $\gamma$-beam down, $e^+$-beam up, helicity left, $b$-beam down and unpolarized (Total) case are drawn.

TABLE I: Polarized cross sections, dominant spin fractions and spin asymmetries for the various top quark spin bases in the production of single top process $e^+\gamma \rightarrow t\bar{b}\nu_e$ at center of mass energy $\sqrt{s} = 0.5$ TeV of the parental linear $e^+e^-$ collider.

| basis     | polarized cross sections (pb) | spin fractions | $\frac{N_1-N_\uparrow}{N_1+N_\uparrow}$ |
|-----------|-------------------------------|----------------|----------------------------------------|
| $e^+$-beam| 0.014                         | 94%↑           | 0.87                                   |
| $\gamma$-beam | 0.013                      | 86%↑           | -0.73                                  |
| $\bar{b}$-beam | 0.012                     | 78%↑           | -0.60                                  |
| helicity  | 0.009                         | 60%(L)         | -0.20                                  |

TABLE II: The same as table I but for $\sqrt{s} = 1$ TeV.

| basis     | polarized cross sections (pb) | spin fractions | $\frac{N_1-N_\uparrow}{N_1+N_\uparrow}$ |
|-----------|-------------------------------|----------------|----------------------------------------|
| $e^+$-beam| 0.044                         | 88%↑           | 0.76                                   |
| $\gamma$-beam | 0.038                     | 76%↑           | -0.52                                  |
| $\bar{b}$-beam | 0.034                     | 68%↑           | -0.36                                  |
| helicity  | 0.033                         | 66%(L)         | -0.32                                  |

TABLE III: The same as table II but for $\sqrt{s} = 1.5$ TeV.

| basis     | polarized cross sections (pb) | spin fractions | $\frac{N_1-N_\uparrow}{N_1+N_\uparrow}$ |
|-----------|-------------------------------|----------------|----------------------------------------|
| $e^+$-beam| 0.062                         | 86%↑           | 0.72                                   |
| $\gamma$-beam | 0.052                   | 72%↑           | -0.44                                  |
| $\bar{b}$-beam | 0.047                   | 65%↑           | -0.31                                  |
| helicity  | 0.050                         | 60%(L)         | -0.39                                  |
FIG. 2: The same as FIG. 1 but for $\sqrt{s} = 1 \text{ TeV}$.

FIG. 3: The same as FIG. 2 but for $\sqrt{s} = 1.5 \text{ TeV}$. 