Probing the Z' gauge boson with the spin configuration of top quark pair production at future e^-e^+ linear colliders

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(Received 13 November 2000; published 2 April 2001)

We explore the effects of extra neutral gauge bosons involved in the supersymmetric E_6 model on the spin configuration of the top quark pair produced at the polarized e^-e^+ collider. Generic mixing terms are considered including kinetic mixing terms as well as mass mixing. In the off-diagonal spin basis of the standard model, we show that the cross sections for the suppressed spin configurations can be enhanced with the effects of the Z' boson through the modification of the spin configuration of produced top quark pair enough to be measured in the linear colliders, which provides the way to observe the effects of the Z' boson and discriminate the pattern of gauge group decomposition. It is pointed out that the kinetic mixing may dilute the effects of mass mixing terms, and we have to perform the combined analysis.

DOI: 10.1103/PhysRevD.63.094010 PACS number(s): 13.88.+e, 12.60.Cn

I. INTRODUCTION

The existence of an extra U(1) gauge group is inevitable in many extended models derived by grand unified theories (GUTs) of higher ranked gauge group and superstring or M theory inspired models [1]. Moreover, the symmetry breaking scale for an extra U(1) might be as low as $\mathcal{O}(1)$ TeV in the context of supersymmetry to provide the solution of the μ problem [2], leading to the possibility to observe the effects of the extra heavy neutral gauge boson, Z' boson, at the future collider experiments. The latest bound of the Z' boson mass comes from a direct search at the $p\bar{p}$ collider via Drell-Yan production and subsequent decay to charged leptons [3]. Indirect constraints for the Z' boson mass and the Z-Z' mixing angles are obtained from high precision CERN e^+e^- collider LEP data at the Z peak energy and from various low energy neutral current experiment data [4–7]. Very recently it was indicated that a missing invisible width in Z decays at LEP 1 and a significantly negative S parameter observed in atomic parity violation of a Cs atom can be explained properly if the presence of a Z' boson is assumed [8]. Thus it is timely and interesting to search for an effective way to probe the effects of the Z' boson at future colliders.

As a larger class of Z' models is considered from the string perspective, meanwhile, it is natural to introduce a kinetic mixing term. The kinetic mixing is a threshold effect of string models at the string scale and can be generated by renormalization group (RG) evolution from the high energy scale to the scale that we study. Furthermore, it may yield significant effects on the phenomenologies of the Z' couplings to the SM sector [9].

In this paper, we study the effects of the Z' boson involved in the supersymmetric E_6 model in $e^-e^+\to t\bar{t}$ process at linear colliders (LCs) including the kinetic mixing term. Charges of the standard model (SM) fermions for the Z' boson are determined by gauge group decompositions, along with which the ψ, χ, and η models are defined at the low energy scale in the supersymmetric (SUSY) E_6 model framework. Here we take the decoupling limit of the exotic fermions. Since the asymmetry of the left- and right-handed couplings to the Z' boson characterizes each model, it is possible to distinguish models using the spin information of the top quark pair with the polarized initial e^-e^+ beams. We can read out the information of the polarization of top quark through the angular distribution of the decay products [10]. The large mass of the top quark prompts itself to decay before hadronization and the information of the top spin is free from the uncertainties of hadronization. The top quark pair is produced in a unique spin configuration at the polarized e^-e^+ collision, which reveals remarkable features [11,12] in the off-diagonal basis of the spin. Moreover, it is interesting to observe the polarization of the top quark to probe new physics in this basis, since the off-diagonal basis is model dependently defined.

The LC with $\sqrt{s}=500$ GeV is the best testing ground for studying $t\bar{t}$ production in the off-diagonal basis. If the c.m. energy is around at threshold of top pair production, the top spins are determined by the electron and positron momentum directions since the top quark pair is almost at rest. Then the off-diagonal basis cannot be defined. At high energy, $\sqrt{s}\gg m_t$, the spin basis is close to the usual helicity basis so that the angle $\xi\sim 0$. Thus it is hard to extract new physics effects from ξ although they exist.

This paper is organized as follows. In Sec. II, the extra neutral gauge bosons in the string inspired supersymmetric E_6 are briefly reviewed. In Sec. III, we present the formulas of the scattering amplitudes of the $e^-e^+\to t\bar{t}$ process with the Z' bosons in a generic spin basis of the top quark pair. The off-diagonal spin basis is defined and discussed as a way to probe the Z' boson through the spin configuration of the $t\bar{t}$ pair. In Sec. IV, a numerical analysis for each models is performed in the SM off-diagonal basis. Section V is devoted to a summary of the paper.

II. Z' BOSON IN THE SUPERSYMMETRIC E_6 MODEL

In the supersymmetric E_6 model, there are two additional U(1) factors beyond the SM gauge group since the rank of

TABLE I. U(1)′ charge assignment for the standard model fermions.

Model particles	ψ $f_V/\sqrt{5/72}$	$f_A/\sqrt{5/72}$	χ $2\sqrt{6}f_V$	$2\sqrt{6}f_A$	η $12f_V$	$12f_A$
ν	0	1	4	-1	6	-4
e	0	1	2	1	3	-1
u	0	1	2	1	3	-1
d	0	1	-2	1	-3	-1

the E_6 group is 6. The canonical decompositions of ψ and χ models are as follows:

$$E_6 \to SO(10)\times U(1)_\psi,$$

$$SO(10)\to SU(5)\times U(1)_\chi .$$

After the extra U(1) symmetries are spontaneously broken by the weak iso-singlet Higgs scalar(s), the gauge bosons Z_ψ and Z_χ corresponding to the groups $U(1)_\psi$ and $U(1)_\chi$, respectively, become massive but are not mass eigenstates in general. We call Z' a linear combination of Z_ψ and Z_χ parametrized by the mixing angle θ_E:

$$Z'(\theta_E)\equiv Z_\chi \cos\theta_E + Z_\psi \sin\theta_E , \tag{1}$$

which is relatively light enough to mix with the ordinary Z boson and relevant to the low energy phenomenology. The orthogonal mode to the Z' boson is assumed to be so massive that its effect is to be decomposed. In the case of $\theta_E=0$, the Z' mode is identified to the Z_χ boson; if $\theta_E=\pi/2$, the Z' mode is the Z_ψ boson. The η model and corresponding Z_η boson are defined by setting $\theta_E=\tan^{-1}(-\sqrt{5/3})$. Here we assume that exotic fermions are heavy enough to be decoupled.

In the effective rank-5 limit with only one extra neutral gauge boson, the interaction Lagrangian is described by

$$-\mathcal{L}_{\rm int}=\sum_f \bar{\Psi}_f\gamma^\mu\Big[g_3\lambda^\alpha G^\alpha_\mu + g_2 T^a{}_f W^a{}_\mu + g_1 Y_f B_\mu + g_1'\frac{1}{2}(f^f{}_{\rm V}-f^f{}_{\rm A}\gamma^5)Z'_\mu\Big]\Psi_f , \tag{2}$$

where Ψ_f is the fermion field with flavor f; λ^α and T^a are generators of the $SU(3)_C$ and $SU(2)_L$ gauge groups, respectively. The extra gauge coupling is expressed by $g_1'\equiv(1/\sqrt{\lambda})g_1$ with order 1 parameter λ. The exact value of λ depends upon the pattern of symmetry breaking and we set the value 1 in the numerical analysis. The couplings $f^f{}_V$ and $f^f{}_A$ are the vector and axial vector charges of the fermion for the $U(1)'$ group. The $U(1)'$ charge assignment is given in Table I in terms of the vector and axial vector couplings of Z' to fermions.

After the electroweak symmetry breaking, the gauge sector of the Lagrangian with the Z' boson is given by

$$\mathcal{L}_{\rm gauge}=\mathcal{L}_{\rm kinetic}+\mathcal{L}_{\rm mass}+\mathcal{L}_{\rm mix}, \tag{3}$$

where the kinetic term and the mass term are written as

$$\mathcal{L}_{\rm kinetic}=-\frac{1}{4}(\hat{F}^{\mu\nu}\hat{F}_{\mu\nu}+Z^{\mu\nu}Z_{\mu\nu}+Z'^{\mu\nu}Z'_{\mu\nu}), \tag{4}$$

$$\mathcal{L}_{\rm mass}=\frac{1}{2}(m_Z{}^2 Z^\mu Z_\mu + m_{Z'}{}^2 Z'^\mu Z'_\mu), \tag{5}$$

where $\hat{F}$, $Z_{\mu\nu}$, and $Z'_{\mu\nu}$ are the usual field strength tensor for the fields $\hat{A}_\mu$, Z_μ, and Z'_μ, respectively. The fields $\hat{A}_\mu$ and Z_μ are defined by

$$Z=c_W W_3 - s_W B,$$

$$\hat{A}=s_W W_3 + c_W B, \tag{6}$$

where the shortened notation $s_W=\sin\theta_W$ and $c_W=\cos\theta_W$ with the weak mixing angle θ_W. We write $\mathcal{L}_{\rm mix}$ including the gauge invariant kinetic mixing term,

$$\mathcal{L}_{\rm mix}=-\frac{\sin\chi}{2}Z'_{\mu\nu}B^{\mu\nu}+\delta M^2 Z'_\mu Z^\mu, \tag{7}$$

where $B^{\mu\nu}=\partial_\mu B_\nu - \partial_\nu B_\mu$ is the field strength tensor of the $U(1)_Y$ gauge boson.

The mass eigenstates (A,Z_1,Z_2) are obtained by diagonalizing the mass terms and kinetic terms with the transformation

$$\begin{pmatrix} A\\ Z_1\\ Z_2\end{pmatrix}=\begin{pmatrix}1 & 0 & c_W s_\chi\\ 0 & c_\zeta & -c_\zeta s_W s_\chi + s_\zeta c_\chi\\ 0 & -s_\zeta & c_\zeta c_\chi + s_\zeta s_W s_\chi\end{pmatrix}\begin{pmatrix}\hat{A}\\ Z\\ Z'\end{pmatrix}, \tag{8}$$

where

$$\tan 2\zeta \equiv \frac{-2c_\chi(\delta M^2 + m_Z^2 s_W s_\chi)}{m_{Z'}^2 - m_Z^2 s_W^2 s_\chi^2 + 2\delta M^2 s_W s_\chi}, \tag{9}$$

where $s_\chi=\sin\chi, c_\chi=\cos\chi$ and $s_\zeta=\sin\zeta, c_\zeta=\cos\zeta$. The lighter Z_1 boson is identified with the ordinary Z boson. We recast the Lagrangian in terms of the mass eigenstates Z_1 and Z_2 to obtain the interaction terms of $Z_i f\bar{f}$, $i=1,2$, as

$$\begin{aligned}-\mathcal{L}_{Z_i f\bar{f}}=&\frac{e}{2s_W c_W}\Bigg[\left(1+\frac{\alpha T}{2}\right)\sum_f \bar{\Psi}_f\gamma^\mu[(g_V^f+\zeta\tilde{f}_V^f) -(g_A^f+\zeta\tilde{f}_A^f)\gamma_5]\Psi_f Z_{1_\mu}+\sum_f \bar{\Psi}_f\gamma^\mu[(h_V^f-\zeta g_V^f) -(h_A^f-\zeta g_A^f)\gamma_5]\Psi_f Z_{2_\mu}\Bigg]\\ \equiv&\sum_f\sum_i \bar{\Psi}_f\gamma^\mu[V_i{}^f - A_i{}^f\gamma_5]\Psi_f Z_{i_\mu},\end{aligned} \tag{10}$$

where the SM couplings are modified by Z-Z' mixing effects

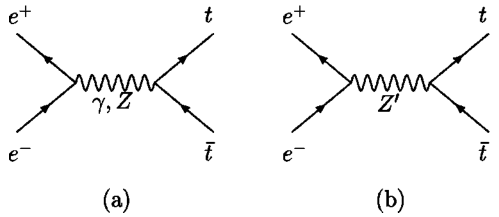

FIG. 1. Feynman diagrams for the $e^-e^+\to t\overline{t}$ process (a) in the standard model, (b) with the Z' boson.

$$g_A^f = T_3^f, \quad g_V^f = T_3^f - 2Q^f s_*^2, \tag{11}$$

and the extra U(1) couplings

$$\tilde{f}^f_{V,A} \equiv \frac{g'}{g}\frac{f^f_{V,A}}{\cos\chi},$$

$$h^f{}_V = \tilde{f}^f_V + \tilde{s}(T^f{}_3 - 2Q^f)\tan\chi, \tag{12}$$

$$h^f{}_A = \tilde{f}^f_A + \tilde{s}T^f{}_3 \tan\chi.$$

Effective weak mixing angles are defined by

$$s_*^2 = s_W^2 + \zeta\, c_W^2 s_W \tan\chi - \zeta^2 \frac{c_W^2 s_W^2}{c_W^2 - s_W^2}\left(\frac{M_2^2}{M_1^2} - 1\right),$$

$$\tilde{s} = s_W + \frac{s_W^3}{c_W^2 - s_W^2}\left(\frac{\alpha S}{4c_W^2} - \frac{\alpha T}{2}\right), \tag{13}$$

where the Peskin-Takeuchi variables S and T [13] are given by

$$\alpha S = 4\zeta c_W{}^2 s_W \tan\chi,$$

$$\alpha T = \zeta^2\left(\frac{M_2^2}{M_1^2} - 1\right) + 2\zeta s_W \tan\chi, \tag{14}$$

up to the leading order of ζ.

III. TOP QUARK PAIR PRODUCTION IN THE OFF-DIAGONAL BASIS

For the process

$$e^-(p_1,s_1) \quad e^+(p_2,s_2) \to t(k_1,r_1) \quad \overline{t}(k_2,r_2), \tag{15}$$

we have s-channel Feynman diagrams mediated by the photon, Z and Z' boson exchanges depicted in Fig. 1. In Eq. (15), p_i and k_i denote the momenta and s_i and r_i the polarizations of electrons and top quarks, respectively. In the center of momentum (c.m.) frame, we write the momenta as

$$p_1 = (E, E\hat{\mathbf{n}}), \quad p_2 = (E, -E\hat{\mathbf{n}}), \quad k_1 = (E,0,0,|\mathbf{k}|),$$
$$k_2 = (E,0,0,-|\mathbf{k}|), \tag{16}$$

where the unit vector $\hat{\mathbf{n}} = (-\sin\theta, 0, \cos\theta)$ indicates the spatial direction of the electron beam. We assume that the whole process is confined on the xz plane when taking the direction of the produced top quark to be z axis.

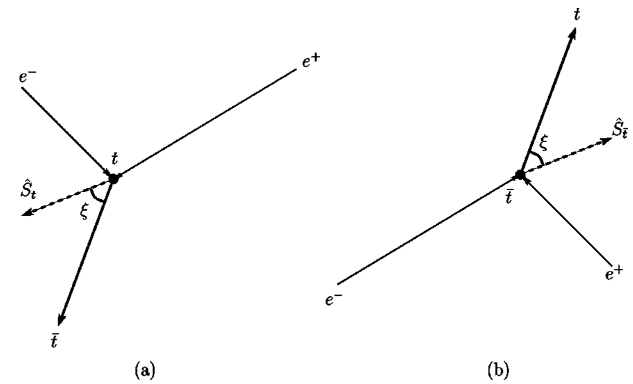

FIG. 2. Definition of generic top spin basis (a) in the top quark rest frame, (b) in the antitop quark rest frame.

We study the spin configuration of the top quark pair in a generic spin basis suggested in Ref. [11]. The spin states of the top quark and top antiquark are defined in their own rest frame by decomposing their spins along reference axes. The reference axis for the top quark is expressed by an angle ξ between the axis and the top antiquark momentum in the rest frame of the top quark as depicted in Fig. 2. The usual helicity basis is obtained by taking $\xi = \pi$. In this general spin basis, the explicit expression for spin four-vectors of the $t\overline{t}$ is given by

$$r_1 = \left(-\frac{|\mathbf{k}|}{m}\cos\xi, \sin\xi, 0, -\frac{E}{m}\cos\xi\right),$$

$$r_2 = \left(-\frac{|\mathbf{k}|}{m}\cos\xi, -\sin\xi, 0, \frac{E}{m}\cos\xi\right), \tag{17}$$

in the c.m. frame. It is to be notified that the spin vectors of the produced top quark pair lie in the production plane at the tree level if the CP invariance of the scattering amplitude is preserved.

We have the scattering amplitudes for each spin configuration of top quark pair produced by the left-handed polarized electron and right-handed polarized positron beams, including Z' effects,

$$\mathcal{M}(LR,\uparrow\uparrow) = -C_1 s(\cos\theta\sin\xi - 1/\gamma\sin\theta\cos\xi) + C_2 s\beta\sin\xi = -\mathcal{M}(LR,\downarrow\downarrow),$$

$$\mathcal{M}(LR,\downarrow\uparrow) = C_1 s(\cos\theta\cos\xi + 1 + 1/\gamma\sin\theta\sin\xi) - C_2 s\beta(\cos\theta + \cos\xi), \tag{18}$$

$$\mathcal{M}(LR,\uparrow\downarrow) = C_1 s(\cos\theta\cos\xi - 1 + 1/\gamma\sin\theta\sin\xi) + C_2 s\beta(\cos\theta - \cos\xi),$$

where $\beta \equiv \sqrt{1 - 4m_t{}^2/s}$ and $\gamma \equiv 1/\sqrt{1-\beta^2}$. The coefficients C_1 and C_2 are defined by $C_1 = P_{VV} + P_{VA}$ and $C_2 = P_{AV} + P_{AA}$, and the effective coupling strength of current-current interactions $P_{\alpha\beta}$ is given by

$$P_{VV}/\sqrt{N_c} \equiv e^2 Q_t Q_e D_0(s) + V_1{}^t V_1{}^e D_1(s) + V_2{}^t V_2{}^e D_2(s),$$

$$P_{VA}/\sqrt{N_c} \equiv -V_1{}^t A_1{}^e D_1(s) - V_2{}^t A_2{}^e D_2(s), \tag{19}$$

$$P_{AV}/\sqrt{N_c} \equiv -A_1{}^t V_1{}^e D_1(s) - A_2{}^t V_2{}^e D_2(s),$$

$$P_{AA}/\sqrt{N_c} \equiv A_1{}^t A_1{}^e D_1(s) + A_2{}^t A_2{}^e D_2(s),$$

where N_c is the number of colors and $Q_{t(e)}$ is the electric charge for the top quark (electron). D_0, D_1, and D_2 are the propagation factors for the photon, Z_1 and Z_2 bosons, respectively,

$$D_0(s) \equiv \frac{1}{s}, \quad D_1(s) \equiv \frac{1}{s-m_1^2}, \quad D_2(s) \equiv \frac{1}{s-m_2^2}, \tag{20}$$

while V_i^f and A_i^f are the model-dependent vector and axial vector couplings for fermion f and gauge boson i = photon, Z_1, Z_2, defined in Eq. (10).

The scattering amplitudes for the right-handed polarized electron and left-handed polarized positron are obtained in a similar manner:

$$\mathcal{M}(RL,\uparrow\uparrow) = C_1 s(\cos\theta \sin\xi - 1/\gamma \sin\theta \cos\xi) + C_2 s\beta \sin\xi$$
$$= -\mathcal{M}(RL,\downarrow\downarrow),$$

$$\mathcal{M}(RL,\downarrow\uparrow) = -C_1 s(\cos\theta\cos\xi - 1 + 1/\gamma \sin\theta \sin\xi)$$
$$+ C_2 s\beta(\cos\theta - \cos\xi), \tag{21}$$

$$\mathcal{M}(RL,\uparrow\downarrow) = -C_1 s(\cos\theta\cos\xi + 1 + 1/\gamma \sin\theta \sin\xi)$$
$$- C_2 s\beta(\cos\theta + \cos\xi).$$

There exist angles ξ_L and ξ_R such that the scattering amplitudes for the like-spin states of the top quark pair, $(\uparrow,\uparrow)$ and $(\downarrow,\downarrow)$, vanish for the left- and right-handed electron beams, respectively. From Eqs. (18) and (21), we find the angles ξ_L and ξ_R:

$$\xi_L(s,\theta) \equiv \arctan\left[\frac{\tan\theta}{\gamma(1-(C_2/C_1)\beta\sec\theta)}\right],$$

$$\xi_R(s,\theta) \equiv \arctan\left[\frac{\tan\theta}{\gamma(1+(C_2/C_1)\beta\sec\theta)}\right], \tag{22}$$

which are always defined in terms of the scattering angle θ. It is called the *off-diagonal basis* since only the scattering amplitudes for off-diagonal spin states are nonzero [11]. For given kinematics, the angles $\xi_{L,R}$ are determined by the model-dependent ratio (C_2/C_1), so $\xi_{L,R}$ depend upon the existence of new physics.

One more interesting feature of the off-diagonal basis is that the process into the $(\uparrow\downarrow)$ state for the left-handed electron beam and the $(\downarrow\uparrow)$ state for the right-handed one is dominant. This pure dominance is very stable under the one-loop QCD corrections where the soft gluon emissions dominate so that the QCD corrections are factored out. At high energy, the degree of this dominance is close to 100% [15].

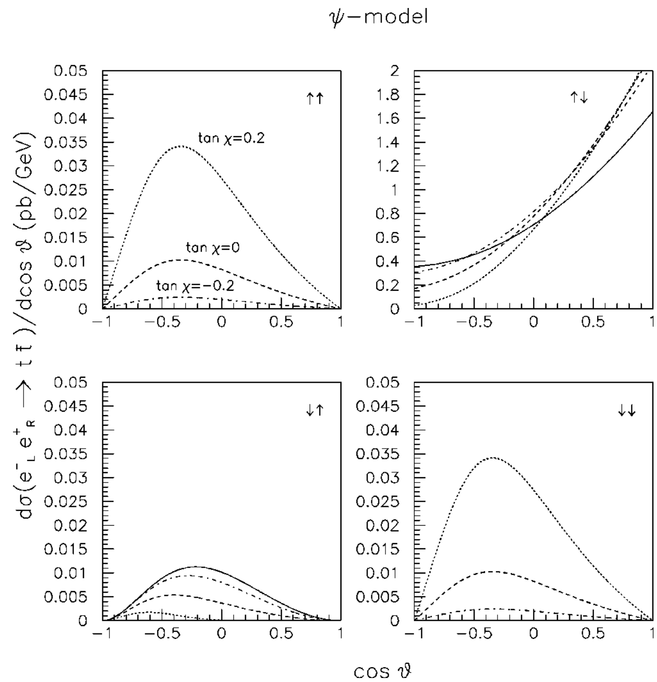

FIG. 3. The differential cross sections in the ψ model for the spin configuration of the top quark pair, drawn with respect to the scattering angle of the top quark at $\sqrt{s}=500$ GeV with the left-handed electron beam. The solid line denotes the SM prediction; the dashed line includes the Z' boson effects with the kinetic mixing $\tan\chi=0$, the dotted line with $\tan\chi=0.2$, and the dash-dotted line with $\tan\chi=-0.2$.

IV. ANALYSIS

In the off-diagonal basis, the scattering amplitudes of the like-spin states are identical to zero and so are the corresponding cross sections. Including new physics effects, the basis does not remain as the off-diagonal basis anymore and the characteristic features of the off-diagonal basis are modified through the model dependence of the angle $\xi_{L,R}$. The Z' boson exchange diagrams yield a deviation of the cross sections for like-spin states from zero. Therefore observation of sizable cross sections for like-spin states can be a ''smoking-gun'' signal of new physics.

In Figs. 3–5, we plot the differential cross sections for left-handed polarized electron beams with respect to the scattering angle in the ψ, χ, and η models, respectively. The SM predictions are denoted by solid lines. The dashed lines denote the model predictions with no kinetic mixing terms, the dotted lines the predictions with the kinetic mixing $\tan\chi=0.2$, and the dash-dotted lines with $\tan\chi=-0.2$. For the numerical analysis, we take $m_{Z'}=600$ GeV, the lower bound from the direct search by the Collider Detector at Fermilab (CDF) [3], and the mixing angles to be the latest bounds in Ref. [4] to maximize the new contributions. We have two lines for each prediction corresponding to the upper and lower limits of the Z-Z' mixing angle ζ, respectively.

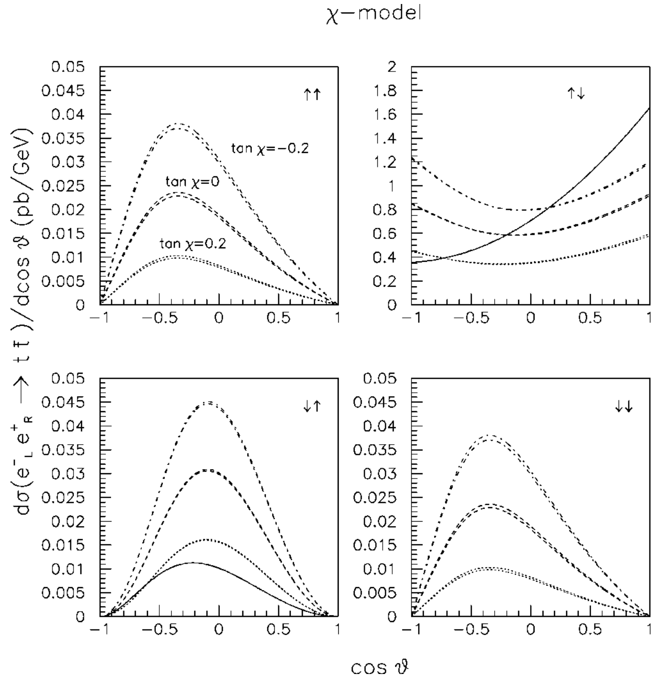

FIG. 4. The differential cross sections in the χ model for the spin configuration of the top quark pair, drawn with respect to the scattering angle of the top quark at $\sqrt{s}=500$ GeV with the left-handed electron beam. The solid line denotes the SM prediction; the dashed line includes the Z' boson effects with the kinetic mixing $\tan\chi=0$, the dotted line with $\tan\chi=0.2$, and the dash-dotted line with $\tan\chi=-0.2$.

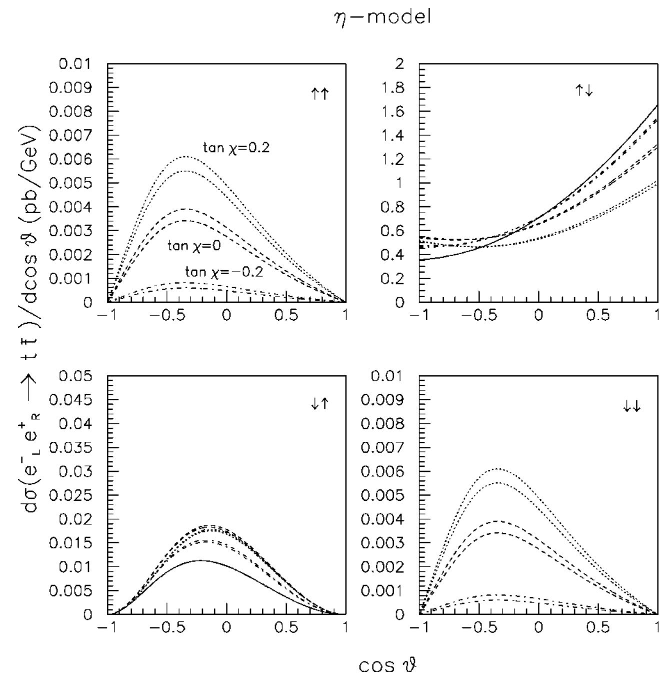

FIG. 5. The differential cross sections in the η model for the spin configuration of the top quark pair, drawn with respect to the scattering angle of the top quark at $\sqrt{s}=500$ GeV with the left-handed electron beam. The solid line denotes the SM prediction; the dashed line includes the Z' boson effects with the kinetic mixing $\tan\chi=0$, the dotted line with $\tan\chi=0.2$, and the dash-dotted line with $\tan\chi=-0.2$.

It is apparent from the figures that the cross sections $\sigma(\uparrow\uparrow)$ and $\sigma(\downarrow\downarrow)$ are nonzero with Z' boson effects, which can be as large as 10^{-2} pb, of order 1% of the total cross section of $t\bar{t}$ production. With the expected integrated luminosity $\int\mathcal{L}>50$ fb^{-1} for energy at $\sqrt{s}=500$ GeV, we will have more than 500 events for like-spin states, which is sufficient to examine the nonzero cross section. We also find that the pure dominance of $(\uparrow\downarrow)$ state is contaminated with Z' boson effects from the figures. Cross sections for states other than the $(\uparrow\downarrow)$ state increase with Z' boson effects in general. However, the pure dominance is essentially affected by the alteration of $\sigma(\uparrow\downarrow)$, since actually the total cross section is still dominated by the $(\uparrow\downarrow)$ state. We present the ratios of $\sigma(\uparrow\downarrow)/\sigma_{total}$ for each model in Table II.

Since the asymmetry of vector and axial vector charges to the Z' boson is a feature of the models, the forward-backward asymmetry of $t\bar{t}$ production can be a useful observable to discriminate models. The forward-backward asymmetry A_{FB} defined by

$$A_{FB}=\frac{\sigma_F-\sigma_B}{\sigma_F+\sigma_B} \tag{23}$$

increases with Z' boson effects in the ψ model while it decreases in the χ and η models from the figures. The η model is a mixture of ψ and χ models and behaves about halfway. The smallness of A_{FB} is a characteristic feature of the χ model. The asymmetry A_{FB} for each model is listed in Table II.

We find that the kinetic mixing derives a large shift in the observables. Here the kinetic mixing is taken to be $\tan\chi=\pm0.2$, which is the bound obtained in Ref. [14]. It is to be notified that the effects of the kinetic mixing term act on the effects of the Z' boson both constructively and destructively

TABLE II. The ratios of the cross section for the $(\uparrow\downarrow)$ spin state of the top quark pair to the total cross section of $e_L^- e_R^+\to t\bar{t}$ production in the SM off-diagonal basis and the forward-backward asymmetries are presented for the standard model and ψ, χ, and η models.

Models	$\tan\chi$	$\sigma(e_L^- e_R^+\to t_\uparrow \overline{t_\downarrow})/\sigma_{total}$	A_{FB}
SM		99.3%	0.4046
	0	98.5%	0.5539
ψ	0.2	95.6%	0.6796
	−0.2	99.2%	0.4703
	0	94.4%	0.0382
χ	0.2	95.4%	0.0886
	−0.2	93.6%	0.0056
	0	98.2%	0.2556
η	0.2	97.5%	0.2036
	−0.2	98.9%	0.3279

with respect to the sign of tan χ. The effects of the Z' boson may be diluted and even canceled by the kinetic mixing effects. For instance, the pure dominance of the $(\uparrow\downarrow)$ final state is almost recovered in the ψ model when $\tan\chi = -0.2$. In this case, the precise measurement of A_{FB} can still be evidence of the Z' boson. Hence it is essential to perform an analysis with more than two observables to probe the Z' effects and to discriminate the models.

V. SUMMARY AND CONCLUSIONS

We have explored the effects of the Z' boson arising in the supersymmetric E_6 model framework at $e^- e^+ \rightarrow t\bar{t}$ process, including the kinetic mixing terms. Considering the spin configuration of the produced top quark pair, we propose useful probes not only to search for the Z' boson but also to discriminate the models corresponding to the pattern of gauge group decomposition. Provided that we take the off-diagonal spin basis of the SM, the existence of nonzero cross sections for diagonal spin states $t_\uparrow \overline{t_\uparrow}$ and $t_\downarrow \overline{t_\downarrow}$ can be direct evidence of new physics. As a matter of fact, only one spin configuration is appreciable for the top quark pair in this basis and violation of such a pure dominance of a peculiar spin state is a signature of the Z' gauge boson, which is almost free from loop corrections. Alternatively, A_{FB} is an effectual observable to probe the Z' boson due to the asymmetry of left- and right-handed couplings of the Z' boson to fermions. Meanwhile, it is shown that the kinetic mixing effects results in a substantial shift in the observables discussed here. Moreover, changing the sign of the kinetic mixing term, its effects can be additive or subtractive to the mass mixing effects, by which it is possible that the Z' effects are wiped out. As a consequence, we conclude that a combined analysis with more than one observable is indispensable to study the structure of the Z' gauge boson.

ACKNOWLEDGMENTS

This work is supported in part by the BK21 program of the Ministry of Education for Seoul National University and by the Korea Research Foundation (KRF-2000-D00077).

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