Probing anomalous top quark interactions at the Fermilab Tevatron collider

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We study the effects of dimension-six operators contributing to the $gt\bar{t}$ vertex in top quark pair production at the Fermilab Tevatron collider. We derive both the limits from run 1 data and the potential bounds from future runs (runs 2 and 3). Although the current constraints are not very strong, the future runs are quite effective in probing these operators. We investigate the possibility of disentangling different operators with the $t\bar{t}$ invariant mass distribution and the top quark polarization asymmetry. We also study the effects of a different set of operators contributing to single top quark production via the $Wt\bar{b}$ coupling. We derive the current and potential future bounds on these anomalous operators and find that the upgraded Fermilab Tevatron collider can improve the existing constraints from R_b for one of the operators. [S0556-2821(98)07121-5]

I. INTRODUCTION

The phenomenological success of the standard model (SM) has significantly limited the possibility of new physics. However, some unanswered fundamental questions suggest that the SM will be augmented by new physics at higher energy scales. As the most massive fermion in the SM, the top quark is naturally regarded to be more sensitive to new physics than lighter fermions. Therefore, precision measurements of top quark properties offer one of the best possibilities to obtain information on new physics.

The measurements of top quark properties in run 1 at the Fermilab Tevatron have only small statistics. There is plenty of room for new physics to be discovered in similar measurements taken with higher luminosities. Such possibilities exist in the near future: Runs 2 and 3 of the Fermilab Tevatron collider should significantly improve the precision of the measurements of top quark properties [1], and provide better insight into new physics at higher energy scales.

There are numerous speculations on the possible forms of new physics. The fact that no single clear signal for deviation from the SM has been observed in any experiment strongly suggests that the new physics effects not too far above the electroweak scale should preserve the SM structure and at most modify it delicately. This suggests that any new particles which may exist will be too heavy to be produced at current, and quite possibly, near-future colliders, and thus the only observable effects of new physics at energies not too far above the SM energy scale could be in the form of anomalous interactions which will slightly affect the couplings of the SM particles. This reasoning leads to the effective Lagrangian approach in describing new physics effects. For the description of new physics in the top quark sector, there are

two effective Lagrangian approaches, which are formulated in terms of nonlinear [2] and linear realizations [3–7] of the electroweak symmetry, corresponding to the situations without and with a light Higgs boson, respectively. In this article, we choose the linear realization and parametrize the new physics effects in the top quark sector by dimension-six operators which are invariant under $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$. We will focus on the CP-conserving operators contributing to the anomalous $gt\bar{t}$ or $Wt\bar{b}$ coupling which can be directly probed at the upgraded Fermilab Tevatron collider through top pair and single top production, respectively.

The operators we consider describe the anomalous couplings of top quark with gauge and/or Higgs bosons and do not include top quark four-fermion ($q\bar{q}t\bar{t}$) contact terms, which have been investigated at the Fermilab Tevatron collider by Hill and Parke [8]. There have also been analyses of the phenomenology of an anomalous chromomagnetic dipole moment $gt\bar{t}$ coupling at the Fermilab Tevatron collider [9]. The operators considered in this paper will also induce such an anomalous chromomagnetic dipole moment coupling for $gt\bar{t}$, but at the same time give rise to other kinds of anomalous couplings via operators that obey the SM symmetries. Some of the operators contributing to the $Wt\bar{b}$ coupling also induce an anomalous $Zb\bar{b}$ coupling. Their effects on single top production cross section at the Fermilab Tevatron collider were evaluated in Refs. [6] and [10], with constraints derived from the earlier, less accurate data on $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$. Our systematical analyses in this paper also include these operators, but with a more complete calculation by considering all possible backgrounds and by

deriving the potential limits from the upgraded Fermilab Tevatron collider. We find that the operators which contribute to the $Zb\bar{b}$ coupling are strongly constrained and can no longer give rise to observable effects at the upgraded Fermilab Tevatron collider due to the good agreement of R_b with the SM value.

This paper is organized as follows. In Sec. II, we list the relevant dimension-six operators. In Sec. III we study the contribution of those operators to the $gt\bar{t}$ coupling and their effect on top pair production. We derive the limits on the coupling strengths set by run 1 and determine the limits which could be set by runs 2 and 3 if no new physics effects are observed. In Sec. IV, we present two methods to disentangle the effects between different operators contributing to the $gt\bar{t}$ coupling. One is studying the $t\bar{t}$ invariant mass distribution of the cross section, the other is measuring the asymmetry between left- and right-handed top events in top pair production. In Sec. V we evaluate the effects of those operators contributing to the $Wt\bar{b}$ coupling in single top production and derive the bounds which could be set by Runs 2 and 3. Finally, Sec. VI is devoted to conclusions.

II. LIST OF THE RELEVANT OPERATORS

We assume here that the new physics in the quark sector only resides in the interaction of the third family to gauge bosons and/or Higgs boson. The effective Lagrangian including the new physics effects can be written as [3]

$$\mathcal{L}_{\text{eff}}=\mathcal{L}_0+\frac{1}{\Lambda^2}\sum_i C_i O_i+O\left(\frac{1}{\Lambda^4}\right), \tag{2.1}$$

where $\mathcal{L}_0$ is the SM Lagrangian, Λ is the new physics scale, O_i are dimension-six operators which are $SU(3)_c\times SU(2)_L\times U(1)_Y$ invariant, and C_i are coupling constants which represent the strengths of O_i. Recently, the effective operators involving the third-family quarks were reclassified in Refs. [4–6] for the CP-conserving ones and in Ref. [7] for CP-violating ones. There are ten dimension-six CP-conserving operators which contribute to the $gt\bar{t}$ or $Wt\bar{b}$ coupling:

$$O_{tG}=[\bar{t}_R\gamma^\mu T^A D^\nu t_R+\overline{D^\nu t_R}\gamma^\mu T^A t_R]G^A_{\mu\nu}, \tag{2.2a}$$

$$O_{qG}=[\bar{q}_L\gamma^\mu T^A D^\nu q_L+\overline{D^\nu q_L}\gamma^\mu T^A q_L]G^A_{\mu\nu}, \tag{2.2b}$$

$$O_{tG\Phi}=[(\bar{q}_L\sigma^{\mu\nu}T^A t_R)\tilde{\Phi}+\tilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}T^A q_L)]G^A_{\mu\nu}, \tag{2.2c}$$

$$O_{qW}=[\bar{q}_L\gamma^\mu\tau^I D^\nu q_L+\overline{D^\nu q_L}\gamma^\mu\tau^I q_L]W^I_{\mu\nu}, \tag{2.2d}$$

$$O^{(3)}_{\Phi q}=i[\Phi^\dagger\tau^I D_\mu\Phi-(D_\mu\Phi)^\dagger\tau^I\Phi]\bar{q}_L\gamma^\mu\tau^I q_L, \tag{2.2e}$$

$$O_{Db}=(\bar{q}_L D_\mu b_R)D^\mu\Phi+(D^\mu\Phi)^\dagger(\overline{D_\mu b_R}q_L), \tag{2.2f}$$

$$O_{bW\Phi}=[(\bar{q}_L\sigma^{\mu\nu}\tau^I b_R)\Phi+\Phi^\dagger(\bar{b}_R\sigma^{\mu\nu}\tau^I q_L)]W^I, \tag{2.2g}$$

$$O_{t3}=i[(\Phi^\dagger D_\mu\Phi)(\bar{t}_R\gamma^\mu b_R)-(D_\mu\Phi)^\dagger\Phi(\bar{b}_R\gamma^\mu t_R)], \tag{2.2h}$$

$$O_{Dt}=(\bar{q}_L D_\mu t_R)D^\mu\tilde{\Phi}+(D^\mu\tilde{\Phi})^\dagger(\overline{D_\mu t_R}q_L), \tag{2.2i}$$

$$O_{tW\Phi}=[(\bar{q}_L\sigma^{\mu\nu}\tau^I t_R)\tilde{\Phi}+\tilde{\Phi}^\dagger(\bar{t}_R\sigma^{\mu\nu}\tau^I q_L)]W^I_{\mu\nu}, \tag{2.2j}$$

where $q_L=(t_L,b_L)$ denotes the third family left-handed quark doublet, Φ and $\tilde{\Phi}$ are the Higgs field and its charge conjugate $\tilde{\Phi}=i\tau_2\Phi^*$, $W_{\mu\nu}$ and $B_{\mu\nu}$ are the SU(2) and U(1) gauge boson field tensors, respectively, in the appropriate matrix forms, D_μ denotes the appropriate covariant derivatives, and $T^A=\lambda^A/2$ with λ^A $(A=1,\ldots,8)$ denoting the Gell-Mann matrices.

After electroweak symmetry breaking, the first three operators O_{tG}, O_{qG}, and $O_{tG\Phi}$ will induce anomalous $gt\bar{t}$ couplings which are given by

$$\mathcal{L}_{gt\bar{t}}=\frac{C_{tG}}{\Lambda^2}[\bar{t}\gamma^\mu P_R T^A\partial^\nu t+\partial^\nu\bar{t}\gamma^\mu P_R T^A t]G^A_{\mu\nu}$$

$$+\frac{C_{qG}}{\Lambda^2}[\bar{t}\gamma^\mu P_L T^A\partial^\nu t+\partial^\nu\bar{t}\gamma^\mu P_L T^A t]G^A_{\mu\nu}$$

$$+\frac{C_{tG\Phi} v}{\sqrt{2}\Lambda^2}(\bar{t}\sigma^{\mu\nu}T^A t)G^A_{\mu\nu}, \tag{2.3}$$

where $v=(\sqrt{2}G_F)^{-1/2}$ is the SM Higgs vacuum expectation value. Other operators will give rise to anomalous $Wt\bar{b}$ couplings which are given by

$$\mathcal{L}_{Wt\bar{b}}=\frac{C_{qW}}{\sqrt{2}\Lambda^2}W^+_{\mu\nu}(\bar{t}\gamma^\mu P_L\partial^\nu b+\partial^\nu\bar{t}\gamma^\mu P_L b)$$

$$+\frac{C^{(3)}_{\Phi q} g_2 v^2}{\sqrt{2}\Lambda^2}W^+_\mu(\bar{t}\gamma^\mu P_L b)-\frac{C_{Db} g_2 v}{2\Lambda^2}W^+_\mu(i\bar{t}P_R\partial^\mu b)$$

$$+\frac{C_{bW\Phi} v}{2\Lambda^2}W^+_{\mu\nu}(\bar{t}\sigma^{\mu\nu}P_R b)+\frac{C_{t3} g_2 v^2}{2\sqrt{2}\Lambda^2}W^+_\mu(\bar{t}\gamma^\mu P_R b)$$

$$+\frac{C_{Dt} g_2 v^2}{2\Lambda^2}W^+_\mu(i\partial^\mu\bar{t})P_L b$$

$$+\frac{C_{tW\Phi} v}{2\Lambda^2}W^+_{\mu\nu}(\bar{t}\sigma^{\mu\nu}P_L b), \tag{2.4}$$

where g_2 is the weak SU(2) gauge coupling. Note that the operators O_{qW}, $O^{(3)}_{\Phi q}$, O_{Db}, and $O_{bW\Phi}$ also induce $Zb\bar{b}$ couplings

TABLE I. Expected numbers of events and statistical errors for top pair production at runs 2 and 3. The combined statistical error is derived from the $\ell\ell$ and $\ell 3j/b$ channels.

Mode	Efficiency (%)	Purity S:B	Run 2		Run 3	
			No. events (with bkgd)	Statistical error (%)	No. events (with bkgd)	Statistical error (%)
$\ell\ell$	1.2	5:1	200	8.5	3000	2.2
$\ell 3j/b$	8.6	3:1	1600	3.3	24000	0.9
$\ell 4j/2b$	3.8	12:1	570	4.5	8600	1.2
Total				3.1		0.8

$$\mathcal{L}_{Zb\bar{b}} = \frac{C_{qW} c_W}{2\Lambda^2} Z_{\mu\nu}(\bar{b}\gamma^\mu P_L \partial^\nu b + \partial^\nu \bar{b}\gamma^\mu P_L b)$$

$$+ \frac{C_{\Phi q}^{(3)} v m_Z}{\Lambda^2} Z_\mu(\bar{b}\gamma^\mu P_L b)$$

$$+ \frac{C_{Db} m_Z}{2\sqrt{2}\Lambda^2} Z^\mu [i(\partial_\mu \bar{b} b - \bar{b}\partial_\mu b) - i\partial_\mu(\bar{b}\gamma_5 b)]$$

$$+ \frac{C_{bW\Phi} c_W v}{2\sqrt{2}\Lambda^2} Z_{\mu\nu}(\bar{b}\sigma^{\mu\nu} b), \quad (2.5)$$

where $c_W \equiv \cos\theta_W$, and thus will be subject to a constraint from R_b measurements.

III. TOP PAIR TOTAL CROSS SECTION

The number of top pair events produced at the Fermilab Tevatron collider will be different from the SM prediction if new physics exists in the top sector. Since the standard model cross section for top pair production is known, here we only need to evaluate the new physics contribution to the total cross section.[1] We can predict the number of reconstructed top pair events in the various decay channels (dilepton, single lepton plus jets, etc.) at the upgraded Fermilab Tevatron collider [1] by extrapolating from the run 1 results. We will calculate the new physics contribution to the cross section and derive bounds on the coupling strengths of the anomalous operators. For illustration, we will only present the bounds at the 2σ level.

A. Anomalous contribution to top pair production cross section

The dominant mechanisms of top quark pair production at hadron colliders are the QCD processes of quark-antiquark annihilation and gluon-gluon fusion. At the Fermilab Tevatron collider, the quark-antiquark annihilation process is dominant for $m_t = 175$ GeV. In the SM, several groups [11–

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[1]We assume that the new physics only affects the SM top quark couplings and that there is no exotic decay mode for top quark. Therefore the branching fractions of various final states in $t\bar{t}$ production are about the same as in the SM.

13] have calculated the cross section to the next-to-leading order by summing over soft gluons up to leading logarithms. More recently, soft-gluon resummation at the next-to-leading logarithmic level has also been performed [14].

We calculate the new physics contribution to the quark-antiquark annihilation process and neglect its effect in the gluon-gluon fusion process since its contribution to the cross section is small at the Fermilab Tevatron collider. For the on-shell t and $\bar{t}$, we obtain the effective $gt\bar{t}$ coupling arising from the dimension-six operators

$$\Gamma_{gt\bar{t}}^{\mu A} = T^A \left[\gamma^\mu F_V + \left(\gamma^\mu \gamma_5 - \frac{2m_t}{k^2} k^\mu \gamma_5 \right) F_A \right.$$
$$\left. + \frac{1}{2m_t}(p_{\bar{t}} - p_t)^\mu F_M \right], \quad (3.1)$$

where p_t and $p_{\bar{t}}$ are the momenta of the outgoing top quark and antiquark, respectively, and $k = p_{\bar{t}} + p_t$ is the momentum of the vector boson. The form factors are derived from the contributions of the new physics operators

$$F_V(k^2) = -\frac{k^2}{2}\left[\frac{C_{tG}}{\Lambda^2} + \frac{C_{qG}}{\Lambda^2}\right] + 2\sqrt{2}v m_t \frac{C_{tG\Phi}}{\Lambda^2}, \quad (3.2a)$$

$$F_A(k^2) = -\frac{k^2}{2}\left[\frac{C_{tG}}{\Lambda^2} - \frac{C_{qG}}{\Lambda^2}\right], \quad (3.2b)$$

$$F_M(k^2) = 2\sqrt{2}v m_t \frac{C_{tG\Phi}}{\Lambda^2}. \quad (3.2c)$$

The pseudoscalar coupling proportional to $k_\mu \gamma_5$ is related to the axial vector coupling by current conservation. It gives negligible contribution (proportional to the initial quark mass) to the process.

The new physics contribution to the parton-level cross section for $q\bar{q} \to t\bar{t}$ to order $1/\Lambda^2$ is found to be

$$\Delta\hat{\sigma}^{\text{new}}(\hat{s}) = \frac{2\alpha_s g_s \hat{\beta}}{27\hat{s}}[F_V(\hat{s})(3 - \hat{\beta}^2) + F_M(\hat{s})\hat{\beta}^2], \quad (3.3)$$

where $\hat{s}$ is the center-of-mass energy squared for the parton-level process and $\hat{\beta} = (1 - 4m_t^2/\hat{s})^{1/2}$. Notice that the axial

vector coupling does not contribute to the total cross section. We will discuss in Sec. IV how to measure this coupling.

The new physics contribution to the total hadronic cross section for top quark pair production is obtained by

$$\Delta \sigma_{t\bar{t}}^{\text{new}} = \sum_q \int_{\tau_0}^1 d\tau \frac{dL_{q\bar{q}}}{d\tau} \Delta \hat{\sigma}^{\text{new}}(\hat{s} = s\tau), \qquad (3.4)$$

where s is the $p\bar{p}$ center-of-mass energy squared, $\hat{s}$ the center-of-mass energy squared for the parton subprocess, and $\tau_0 = 4m_t^2/s$. The quantity $dL_{q\bar{q}}/d\tau$ is the parton luminosity defined by

$$\frac{dL_{q\bar{q}}}{d\tau} = \int_\tau^1 \frac{dx_1}{x_1} [f_q^p(x_1,\mu) f_{\bar{q}}^{\bar{p}}(\tau/x_1,\mu) + (q \leftrightarrow \bar{q})],$$

$$(3.5)$$

where f_q^p denotes the quark distribution function in a proton.

In our numerical calculation, we use the CTEQ3L parton distribution functions [15] with $\mu = \sqrt{\hat{s}}$. For $m_t = 175$ GeV, we obtain the new physics contribution to order $1/\Lambda^2$ to the total hadronic cross section in units of pb:

$$\Delta \sigma_{t\bar{t}}^{\text{new}} = \begin{cases} [-0.61(C_{tG} + C_{qG}) + 0.81 C_{tG\Phi}] (\Lambda/\text{TeV})^{-2} & \text{at } \sqrt{s} = 1.8 \text{ TeV}, \\ [-0.85(C_{tG} + C_{qG}) + 1.09 C_{tG\Phi}] (\Lambda/\text{TeV})^{-2} & \text{at } \sqrt{s} = 2 \text{ TeV}. \end{cases} \qquad (3.6)$$

B. Current bounds from run 1

Current bounds for the coupling strength of the operators can be derived from the available data on the cross section at run 1 of the Fermilab Tevatron collider. The production cross section measured by the Collider Detector at Fermilab collaboration with an integrated luminosity of 110 pb^{-1} is [16] $\sigma = 7.6^{+1.8}_{-1.5}$ pb for $m_t = 175$ GeV, which combines dilepton, lepton + jets and all-hadronic channels. The D0 collaboration gives [17,18] $\sigma = 5.9 \pm 1.7$ pb for $m_t = 172$ GeV. We use the (unofficial) combined result [18] of

$$\sigma_{t\bar{t}}^{\text{exp}} = 6.7 \pm 1.3 \text{ pb}. \qquad (3.7)$$

For the theoretical cross section in the SM, we adopt the most complete result currently available [14], which includes soft-gluon summation up to the next-to-leading logarithmic order:

$$\sigma_{t\bar{t}}^{\text{SM}} = 5.06^{+0.13}_{-0.36} \text{ pb} \qquad (3.8)$$

for $m_t = 175$ GeV at $\sqrt{s} = 1.8$ TeV. To make a comparison of the measured and standard model cross section, we have to take into account the present uncertainty of the top quark mass [19,20,18] which affects both the experimental and theoretical cross sections. Shifting m_t by ± 5 GeV changes the SM cross section by about $\pm 15\%$. The measured cross section also changes with m_t in the same direction but the dependence is weaker. The net effect is about 10% uncertainty in the difference of the two cross sections.

Combining all these uncertainties, the possible new physics contribution to the cross section is found to be

$$\Delta \sigma_{t\bar{t}}^{\text{new}} = \sigma^{\text{exp}} - \sigma^{\text{SM}} = 1.6 \pm 1.4 \text{ pb}, \qquad (3.9)$$

which gives a 2σ bound on the coupling strengths for $\Lambda = 1$ TeV

$$-7.2 < C_{tG} + C_{qG} - 1.33 C_{tG\Phi} < 2.0. \qquad (3.10)$$

If one of the dimension-six operators gives the dominant new physics contribution, we find

$$-7.2 < C_{tG}, C_{qG} < 2.0, \qquad (3.11)$$

$$-1.5 < C_{tG\Phi} < 5.4. \qquad (3.12)$$

We can see that the current bounds from run 1 are not very strong. If one defines the new physics scale Λ such that the magnitude of the coupling strengths are 1, then run 1 has excluded the existence of new physics below 400–800 GeV.

C. Expectations for runs 2 and 3

To determine the size of the couplings that can be probed in the upgraded Fermilab Tevatron collider, we must estimate the number of top events produced. In our analysis, runs 2 and 3 are defined as an integrated luminosity of 2 and 30 fb^{-1} at $\sqrt{s} = 2$ TeV. We use the SM cross section for $t\bar{t}$ production of 7.0 pb at $\sqrt{s} = 2$ TeV. At run 2 (run 3), the total number of the produced $t\bar{t}$ pairs is thus about 10^4 (2×10^5). A detailed analysis of the detection efficiencies and signal purity for the three modes, the dilepton ($\ell\ell$), lepton plus ≥ 3 jets with one b tag ($\ell 3j/b$), and lepton plus ≥ 4 jets with two b tags ($\ell 4j/2b$) can be found in Ref. [1]. They are shown in Table I.

In extracting the new physics contribution, various systematic uncertainties have to be taken into account besides the experimental systematic error. The present uncertainty in the theoretical $t\bar{t}$ cross section in the standard model is at the 5% level [14]. Additional error coming from the present error on m_t will be much reduced with the expected more precise determination of m_t (2.8 and 0.8 GeV are quoted for runs 2 and 3 [1]). We use the total systematic error of 5% and 1% for illustration. We also assume the same de-

TABLE II. Expected 2σ bounds at runs 2 and 3 for the operators contributing top pair production. If the three operators coexist, the limits for $|C_{tG}|$, etc. should be reinterpreted to those for $|C_{tG} + C_{qG} - 1.28 C_{tG\Phi}|$.

Systematic error	Run 2		Run 3	
	5%	1%	5%	1%
$|C_{tG}|$, $|C_{qG}|$	0.97	0.53	0.82	0.21
$|C_{tG\Phi}|$	0.75	0.41	0.64	0.17

tection efficiencies as the SM events for the new physics contribution.

Assuming no signal of new physics, the expected 2σ bound on the coupling strength of the operators are obtained as shown in Table II; bounds are listed for systematic uncertainties of both 5% and 1%. A large improvement in the systematic error does not lead to a corresponding decrease in the bound at run 2 because much of the error there still comes from the statistical uncertainty. At run 3 the error is dominated by the systematic uncertainty and the bound would be substantially smaller if the systematic uncertainty could be reduced to 1%. For $C_{tG} = C_{qG} = C_{tG\Phi} = 1$, these bounds correspond to the new physics scale Λ between 1 and 2.5 TeV. Although run 2 can improve the bounds from those at run 1, one needs a better understanding of the theoretical uncertainty for further significant improvement of the bound at run 3.

IV. DISENTANGLING DIFFERENT OPERATORS

In the preceding section we assumed the existence of one operator at a time and derived the bound for each operator from the event-number counting experiments at the future runs of the Fermilab Tevatron collider. But the counting experiments cannot distinguish the effects of different operators. If the operators coexist, their effects have to be disentangled by analyzing additional measurable quantities. Here we present two methods to distinguish the effects of different operators contributing to the $gt\bar{t}$ coupling; one is the $t\bar{t}$ invariant mass distribution of the cross section, and the other is the asymmetry between left- and right-handed top events in top pair production.

A. $t\bar{t}$ invariant mass distribution

The contribution of O_{tG} and O_{qG} is energy dependent and thus the behavior of the cross section versus the invariant $t\bar{t}$ mass differs from that predicted by the SM. On the other hand, the contribution of $O_{tG\Phi}$ is energy independent and gives the same $M(t\bar{t})$ distribution as the SM. This provides a method to distinguish the effects of O_{tG} and/or O_{qG} from that of $O_{tG\Phi}$.

The mass distribution is given by

$$\frac{d\sigma}{dM_{t\bar{t}}} \equiv \frac{d(\sigma^{SM} + \Delta\sigma^{new})}{dM_{t\bar{t}}}$$

$$= \frac{2M_{t\bar{t}}}{s}(\hat{\sigma}^{SM} + \Delta\hat{\sigma}^{new})\frac{dL_{q\bar{q}}}{d\tau}(\tau = M_{t\bar{t}}^2/s). \quad (4.1)$$

Figure 1 shows this distribution with and without the new physics contribution. It can be seen that the presence of $O_{tG\Phi}$ only alters the magnitude of the cross section, leaving the shape unchanged. The effect O_{tG} is energy dependent and is more prominent for larger $M_{t\bar{t}}$, giving some distortion in the invariant mass distribution. The result for O_{qG} is the same as that for O_{tG} and is not shown.
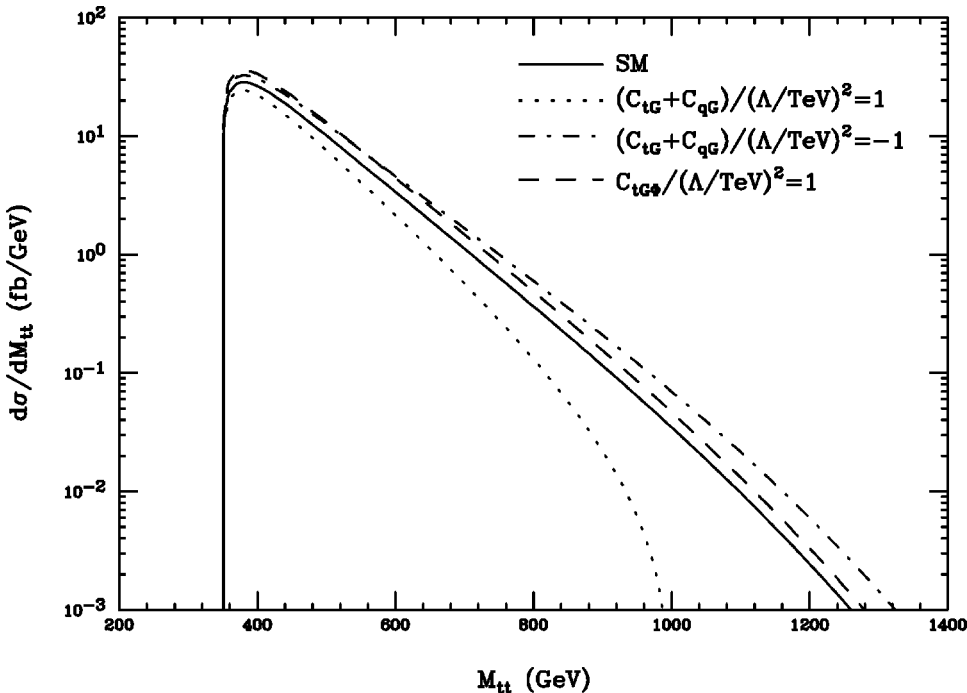

FIG. 1. Top pair invariant mass distribution in the SM (solid), with contributions from $O_{tG\Phi}$ (dashed) and with O_{tG} and/or O_{qG} (dotted and dash-dotted). The two curves for O_{tG}/O_{qG} correspond to different coupling strengths.
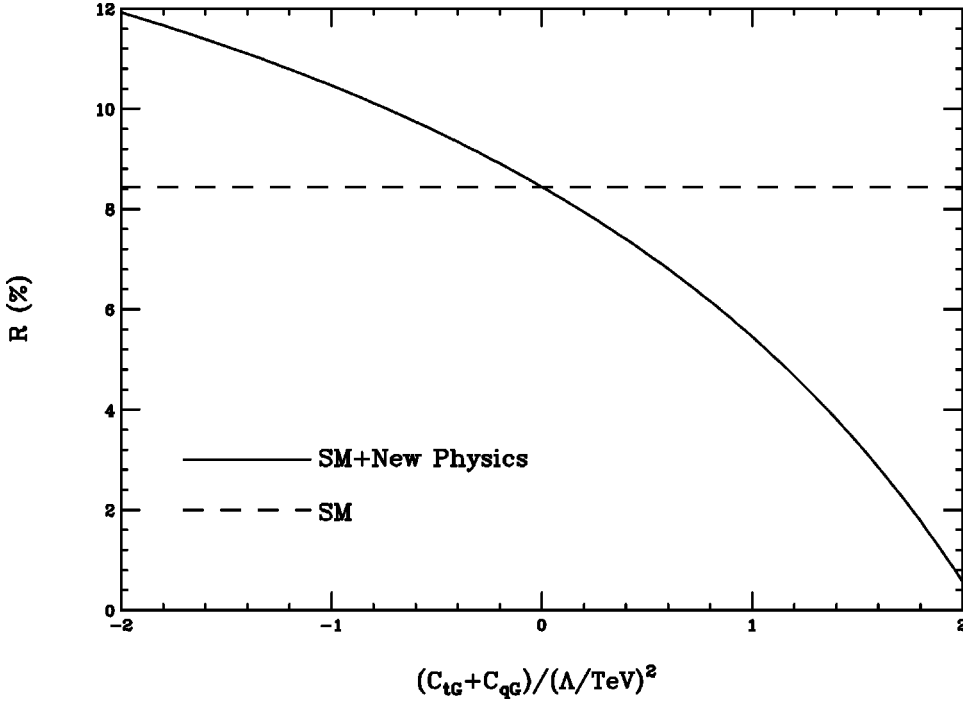
In order to quantify the shape of the distribution, we define the ratio of the high-mass vs low-mass $t\bar{t}$ events as follows:

$$R \equiv \frac{N(M_{t\bar{t}} > M_0)}{N(M_{t\bar{t}} < M_0)} = \frac{\sigma(M_{t\bar{t}} > M_0)}{\sigma(M_{t\bar{t}} < M_0)}, \qquad (4.2)$$

where $N(M_{t\bar{t}} > M_0)$ is the number of events for $M_{t\bar{t}} > M_0$, etc. The value of M_0 may be chosen to maximize sensitivity to the new physics. The ratio R is found to be a function of $C_{tG} + C_{qG}$. It thus provides independent information on new physics not contained in the total cross section. In particular, R will be the same as the SM prediction if only $O_{tG\Phi}$ is present.

Figure 2 shows the ratio R versus the coupling strength with and without the presence of O_{tG}. We have used $M_0 = 600$ GeV for illustration. We note that measuring this ratio will not only distinguish O_{tG} (or O_{qG}) from $O_{tG\Phi}$ but also determine the sign of the coupling constant C_{tG} (or C_{qG}).

B. Top polarization asymmetry

In Sec. III, we have evaluated the new physics contribution to the total top pair events summing over the spins of t and $\bar{t}$. Measurement of top polarization can give independent information for the new physics. In fact, the axial vector coupling F_A in Eq. (3.1) contributes with the opposite sign to left- and right-handed top quark cross sections, producing a nonzero polarization asymmetry without changing the total cross section.

Following Ref. [21], we define the asymmetry as

$$\mathcal{A} \equiv \frac{N_R - N_L}{N_R + N_L} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \qquad (4.3)$$

where N_R and N_L are the number of right- and left-handed top quarks, respectively. We do not require spin information on the $\bar{t}$. The polarization may be measured[2] through the angular distributions [22] of the leptonic events $t \to W^+ b \to \ell^+ \nu_\ell b (\ell = e, \mu)$. In the SM this asymmetry is too small to be observed at the Fermilab Tevatron collider, because QCD is invariant under parity and charge conjugation, and so the asymmetry arises only from the weak corrections [21]. Hence the asymmetry is a good observable for probing new physics.

The cross sections in Eq. (4.3) can be written as $\sigma_R = \sigma_{RL} + \sigma_{RR}$ and $\sigma_L = \sigma_{LR} + \sigma_{LL}$, with $\sigma_{\lambda_1 \lambda_2} \equiv \sigma(p\bar{p} \to t_{\lambda_1} \bar{t}_{\lambda_2} + X)$. Here λ_1 and λ_2 indicate the helicity states for t and $\bar{t}$, respectively. These are obtained by convoluting the parton-level cross section $\hat{\sigma}(q\bar{q} \to t\bar{t})$ with parton distribution functions as in Eq. (3.4). The parton-level cross section is expressed as

$$\hat{\sigma}_{\lambda_1 \lambda_2} = \hat{\sigma}^{SM}_{\lambda_1 \lambda_2} + \Delta \hat{\sigma}^{new}_{\lambda_1 \lambda_2}, \qquad (4.4)$$

where $\hat{\sigma}^{SM}_{\lambda_1 \lambda_2}$ and $\Delta \hat{\sigma}^{new}_{\lambda_1 \lambda_2}$ are the SM and new physics contribution, respectively. At tree level, these are given by

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[2]Anomalous tbW couplings may change the decay angular distribution. However, the three operators considered in this and the previous sections do not produce such couplings.

$$\hat{\sigma}_{LL}^{SM} = \hat{\sigma}_{RR}^{SM} = \frac{4\pi\alpha_s^2\beta}{27\hat{s}} \frac{2m_t^2}{\hat{s}}, \qquad (4.5a)$$

$$\hat{\sigma}_{LR}^{SM} = \hat{\sigma}_{RL}^{SM} = \frac{4\pi\alpha_s^2\beta}{27\hat{s}}, \qquad (4.5b)$$

and

$$\Delta\hat{\sigma}_{LL}^{new} = \hat{\sigma}_{RR}^{new} = \frac{1}{g_s}\left(2F_V + \frac{\beta^2\hat{s}}{2m_t^2}F_M\right)\hat{\sigma}_{LL}^{SM}, \quad (4.6a)$$

$$\Delta\hat{\sigma}_{LR}^{new} = \frac{2}{g_s}(F_V - \beta F_A)\hat{\sigma}_{LR}^{SM}, \qquad (4.6b)$$

$$\Delta\hat{\sigma}_{RL}^{new} = \frac{2}{g_s}(F_V + \beta F_A)\hat{\sigma}_{RL}^{SM}. \qquad (4.6c)$$

Here we see that $\Delta\hat{\sigma}_{LR}^{new}$ differs from $\Delta\hat{\sigma}_{RL}^{new}$ due to the existence of F_A, which will cause the asymmetry $\mathcal{A}$.

To order $1/\Lambda^2$, we can neglect the new physics contribution to the denominator in Eq. (4.3). Again we use the CTEQ3L parton distribution functions [15] with $\mu = \sqrt{\hat{s}}$. For $m_t = 175$ GeV, we obtain the asymmetry

$$\mathcal{A} = -0.098(C_{tG} - C_{qG})(\Lambda/\text{TeV})^{-2}. \qquad (4.7)$$

A cut on the $t\bar{t}$ invariant mass $M_{t\bar{t}} > M_0$ enhances the asymmetry but at the same time decreases the number of $t\bar{t}$ events.

The expected number of reconstructed $t\bar{t}$ events with top decay in the channel $t \to W^+ b \to \ell^+ \nu_\ell b (\ell = e, \mu)$ may be found in Table I, which implies the 1σ sensitivity for the asymmetry of $\sim 3\%$ and $\sim 1\%$ in magnitude at runs 2 and 3, respectively. Under the present constraints Eq. (3.11), the operators C_{tG} or C_{qG} can produce an asymmetry $\mathcal{A}$ as large as 30% assuming no cancellation between these two operators. Such a large asymmetry should be clearly observable in future runs. If no asymmetry is observed, one can put bounds on the operators

$$\frac{|C_{tG} - C_{qG}|}{(\Lambda/\text{TeV})^2} \le 1.3 \quad (0.4) \qquad (4.8)$$

for run 2 (run 3), which corresponds to $\mathcal{A} \le 4/\sqrt{N}$ (N is the total number of events). Although this bound is weaker than that obtained in Sec. III, it can be regarded as independent information because it does not depend on the coupling strength of $O_{tG\Phi}$.

Note that both of the observables in Secs. IV A and IV B distinguish the effects of O_{tG} or O_{qG} from that of $O_{tG\Phi}$. Furthermore, the two methods are complementary in that the ratio R in Eq. (4.2) depends on $C_{tG} + C_{qG}$, while the asymmetry $\mathcal{A}$ in Eq. (4.3) is sensitive to $C_{tG} - C_{qG}$. Therefore, separation of the effects of the three couplings is possible using the measurements discussed in this and the previous sections.

V. SINGLE TOP QUARK PRODUCTION

Now we examine the effects of the set of operators (2.2d)–(2.2j) which contribute to single top production. At the Fermilab Tevatron collider, this reaction occurs mainly through the s-channel W^* process $q'\bar{q} \to t\bar{b}$ and the W-gluon fusion process, which were studied extensively in the SM [24] and some of its extensions [25]. The s-channel W^* process, despite its relatively low cross section, is quite powerful for probing new physics because (i) the systematic error in the theoretical calculation of its cross section is small (its initial state effects can be measured in the similar Drell-Yan process $q'\bar{q} \to \ell \nu$), (ii) it can be isolated from other single top production processes at the upgraded Fermilab Tevatron collider by requiring that both jets in the final state be tagged as b jets [26]. The balance between statistics and systematics for the W^* process gives the result that its cross section can be measured to about the same precision as that for full single top cross section. So we choose the s-channel W^* process to probe the operators.[3]

Unlike the case of top pair production in which the efficiency for top selection can be predicted by extrapolating from run 1 experience, we will calculate the number of single top signal and backgrounds by Monte Carlo simulation. We will also take into account the fact that the top quark is polarized in its production.

A. Signal and backgrounds

For both t and b being on-shell, the new physics contribution to the $Wt\bar{b}$ vertex can be written as

$$\Gamma_{Wt\bar{b}}^\mu = -\frac{g_2}{\sqrt{2}}[\gamma^\mu(\kappa_{1L}P_L + \kappa_{1R}P_R) + p_t^\mu(\kappa_{2L}P_L + \kappa_{2R}P_R) + p_{\bar{b}}^\mu(\kappa_{3L}P_L + \kappa_{3R}P_R)], \qquad (5.1)$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$ and the form factors from new physics are given by

$$\kappa_{1L} = \frac{v^2}{\Lambda^2}\left[C_{tW\Phi}\frac{\sqrt{2}m_t}{g_2 v} + C_{\Phi q}^{(3)} - C_{qW}\frac{k^2}{g_2 v^2}\right], \quad (5.2a)$$

$$\kappa_{1R} = \frac{v^2}{\Lambda^2}\left[C_{bW\Phi}\frac{\sqrt{2}m_t}{g_2 v} + \frac{C_{t3}}{2}\right], \qquad (5.2b)$$

$$\kappa_{2L} = \frac{v}{\Lambda^2}\left[-C_{tW\Phi}\frac{\sqrt{2}}{g_2} - \frac{C_{Dt}}{\sqrt{2}} + C_{qW}\frac{m_t}{g_2 v}\right], \qquad (5.2c)$$

$$\kappa_{2R} = -\frac{v}{\Lambda^2}C_{bW\Phi}\frac{\sqrt{2}}{g_2}, \qquad (5.2d)$$

---

[3] The anomalous Wtb couplings may also be probed at the Fermilab Tevatron collider in the top quark decay $t \to Wb$ with spin analysis [23].

$$\kappa_{3L} = \frac{v}{\Lambda^2} \left[C_{tW\Phi} \frac{\sqrt{2}}{g_2} + C_{qW} \frac{m_t}{g_2 v} \right], \tag{5.2e}$$

$$\kappa_{3R} = \frac{v}{\Lambda^2} \left[\frac{C_{Db}}{\sqrt{2}} + C_{bW\Phi} \frac{\sqrt{2}}{g_2} \right], \tag{5.2f}$$

where $k = p_t + p_{\bar{b}}$.

The interference of the SM matrix element ($\mathcal{M}_{SM}$) with the new physics contribution ($\mathcal{M}_{new}$) for the W^* process $u + \bar{d} \to t + \bar{b}$ is given by [neglecting Kobayashi-Maskawa (KM) mixing]

$$\sum_{spins} \text{Re}[\mathcal{M}_{SM}^\dagger \mathcal{M}_{new}] = \frac{g_2^4}{2(\hat{s} - m_W^2)^2} [2\hat{u}(\hat{u} - m_t^2)\kappa_{1L}$$
$$- m_t \hat{t}\hat{u}(\kappa_{2L} - \kappa_{3L})] \tag{5.3}$$

for spin-summed matrix elements and

$$\text{Re}[\mathcal{M}_{SM}^\dagger \mathcal{M}_{new}]$$

$$= \begin{cases} \dfrac{g_2^4 \hat{t}\hat{u}}{2(\hat{s} - m_W^2)^2} \left[\dfrac{2m_t^2}{\hat{s} - m_t^2} \kappa_{1L} - m_t(\kappa_{2L} - \kappa_{3L}) \right] \\ \quad \text{for } h_t = +, \\[2mm] \dfrac{g_2^4}{(\hat{s} - m_W^2)^2(\hat{s} - m_t^2)} (\hat{s}\hat{u}^2) \kappa_{1L} \\ \quad \text{for } h_t = -, \end{cases} \tag{5.4}$$

for matrix elements with top quark helicity $h_t = \pm$. Here $\hat{s}$ is the parton c.m. energy squared and

$$\hat{t} = (p_u - p_t)^2 = -\frac{1}{2}(\hat{s} - m_t^2)(1 - \cos\theta^*), \tag{5.5a}$$

$$\hat{u} = (p_d - p_t)^2 = -\frac{1}{2}(\hat{s} - m_t^2)(1 + \cos\theta^*), \tag{5.5b}$$

where θ^* is the parton c.m. scattering angle. We have neglected the bottom quark mass. With this approximation, only one helicity of the quarks other than the top participate in the process and the contribution of κ_{iR} ($i = 1, 2, 3$), and hence that of the operators $O_{bW\Phi}$, O_{t3}, and O_{Db}, drops out.

For the W^* process, we look for events with $t \to W^+ b \to \ell^+ \nu b (\ell = e, \mu)$ and thus the signature is an energetic charged lepton, missing E_T, and double b-quark jets. We assumed silicon vertex tagging of the b-quark jet with 50% efficiency and the probability of 0.4% for a light quark jet to be misidentified as a b jet. The potential SM backgrounds are: (B1) the same W^* process in the SM, (B2) the quark-gluon fusion process $qg \to q' t \bar{b}$ where q' is misidentified as a b jet, (B3) processes involving a b quark in the initial state, $qb \to tq'$ and $gb \to tW$, (B4) $t\bar{t} \to W^- W^+ b\bar{b}$, (B5) $Wb\bar{b}$, and (B6) Wjj.

Let us discuss the backgrounds in turn. Background process (B2) contains an extra light quark jet and can only mimic our signal if the quark misses detection by going into the beam pipe. In our calculation of the W-gluon fusion process as a background, we impose $\eta(q') > 3$ and $p_T(q') < 10$ GeV for the light-quark jet. The $qb \to tq'$ background[4] is greatly reduced by requiring double b tagging. The process $gb \to tW$ can only imitate our signal if the W decays into two jets, where one jet is missed by the detector and the other is misidentified as a b quark, which should be negligible for the misidentification rate assumed here. Background process (B4) can mimic our signal if both W's decay leptonically and one charged lepton is not detected, which we assumed to occur if $|\eta(\ell)| > 3$ and $p_T(\ell) < 10$ GeV. Since we required two b jets to be present in the final state, the potentially large background process (B5) from Wjj is reduced to an insignificant level. In order to reduce the backgrounds $Wb\bar{b}$ and Wjj, we required the reconstructed top quark mass $M(bW)$ to lie within the mass range $|M(bW) - m_t| < 30$ GeV.

To simulate the detector acceptance, we made a series of cuts on the transverse momentum (p_T), the pseudorapidity (η), and the separation in the azimuthal angle-pseudorapidity plane [$\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$] between a jet and a lepton or between two jets. The cuts are chosen to be

$$p_T^\ell, \ p_T^b, \ p_T^{miss} \geq 20 \text{ GeV}, \tag{5.6a}$$

$$|\eta_b|, \ |\eta_\ell| \leq 2.5, \tag{5.6b}$$

$$\Delta R_{jj}, \ \Delta R_{j\ell} \geq 0.5. \tag{5.6c}$$

To make the analyses more realistic, we simulate the detector effects by assuming a Gaussian smearing from the energy of the final-state particles, given by

$$\frac{\Delta E}{E} = \begin{cases} 30\%/\sqrt{E} \oplus 1\% & \text{for leptons,} \\ 80\%/\sqrt{E} \oplus 5\% & \text{for hadrons,} \end{cases} \tag{5.7}$$

where $\oplus$ indicates that the energy-dependent and independent terms are added in quadrature and E is in GeV.

We have explicitly calculated backgrounds (B1) and (B2), and for the others used the analysis of Ref. [27]. After all cuts, the number of background events at run 2 (run 3) are found to be 38 (570), 2 (26), 1 (14), 4 (54), 60 (900), and 1 (21), respectively, for the six background processes described above. Here we see that after the cuts the backgrounds from processes (B2), (B3), (B4), and (B6) are

---

[4]There is a large uncertainty in the relative strengths of the qb and qg contributions to the background since the b-quark parton distribution is not a measured quantity, but is rather an entirely theoretical construction. Since both the qb and qg contributions after all cuts are a very small fraction of the total background, this uncertainty will not affect our results.

negligibly small. The number of total background events is 106 (1590) for run 2 (run 3). After the cuts, the number of signal events from new physics is found to be

$$
S = \begin{cases} (9C_{tW\Phi} + 5C_{\Phi q}^{(3)} - 11C_{qW} + 0.3C_{Dt})(\Lambda/\text{TeV})^{-2} & \text{at run 2,} \\ (135C_{tW\Phi} + 69C_{\Phi q}^{(3)} - 165C_{qW} + 4.5C_{Dt})[\Lambda/(\text{TeV})]^{-2} & \text{at run 3.} \end{cases} \tag{5.8}
$$

The effects of O_{Dt} are much smaller than those of the other three operators since it does not contribute to the form factor κ_{1L}, whose contribution is found to be much larger than those of the other form factors.

B. Improvement of the bounds with runs 2 and 3

From the results of the preceeding subsection, we obtain the bounds on the coupling strength of the operators from run 2 (run 3) if the new physics events are not observed at the 2σ level

$$
\frac{|C_{qW}|}{(\Lambda/\text{TeV})^2} \leq 2.1 \quad (0.50), \tag{5.9a}
$$

$$
\frac{|C_{\Phi q}^{(3)}|}{(\Lambda/\text{TeV})^2} \leq 4.6 \quad (1.2), \tag{5.9b}
$$

$$
\frac{|C_{tW\Phi}|}{(\Lambda/\text{TeV})^2} \leq 2.6 \quad (0.61), \tag{5.9c}
$$

$$
\frac{|C_{Dt}|}{(\Lambda/\text{TeV})^2} \leq 77 \quad (18), \tag{5.9d}
$$

where we again assumed the simple situation that cancellation among different operators does not take place.

As mentioned in Sec. II, the operators O_{qW}, $O_{\Phi q}^{(3)}$, O_{Db}, and $O_{bW\Phi}$ also affect the $Zb\bar{b}$ coupling and will be subject to an R_b constraint. The SM values of R_b and the latest experimental data are [28]

$$
R_b^{\text{SM}} = 0.2158, \quad R_b^{\text{exp}} = 0.2170(9). \tag{5.10}
$$

With the new physics contribution described in Eq. (2.5), R_b is given by

$$
R_b = R_b^{SM} \Bigg[1 + \frac{4s_W c_W}{e} \frac{v m_Z}{\Lambda^2} \bigg(C_{qW} \frac{c_W m_Z}{2v} - C_{\Phi q}^{(3)} \bigg)
$$
$$
\times \frac{v_b + a_b}{v_b^2 + a_b^2} (1 - R_b^{SM}) \Bigg], \tag{5.11}
$$

where we have neglected the bottom quark mass and thus the contributions of $O_{bW\Phi}$ and O_{Db}, which are proportional to m_b/m_Z, drop out. At the 2σ level, we obtain the bounds for the coupling strength by assuming that no cancellation between O_{qW} and $O_{\Phi q}^{(3)}$ takes place

$$
-0.8 < \frac{C_{qW}}{(\Lambda/\text{TeV})^2} < 0.2, \tag{5.12a}
$$

$$
-0.03 < \frac{C_{\Phi q}^{(3)}}{(\Lambda/\text{TeV})^2} < 0.13. \tag{5.12b}
$$

Since the dimension-six operators give a bad high-energy behavior, there is an energy scale above which they cease to be a valid description of new physics. Any process below the new physics scale Λ should not violate the unitarity limit. For a given Λ, this requirement can be translated to an upper limit on the coupling strengths C. These unitarity limits have been worked out by Gounaris *et al.* [5] in detail. For O_{Dt} and $O_{tW\Phi}$, the strongest limits are obtained from two-body $t\bar{t}$ scattering process. For $\Lambda = 1$ TeV, they are given by

$$
|C_{tW\Phi}| < 13.5, \tag{5.13a}
$$

$$
|C_{Dt}| < 10.4. \tag{5.13b}
$$

The limit on C_{Dt} is independent of Λ. That on $C_{tW\Phi}$ becomes somewhat weaker for larger Λ.

Comparing Eqs. (5.9) with Eqs. (5.12) and (5.13), we find the following.

(1) For the operators O_{qW} and $O_{\Phi q}^{(3)}$, future runs at the Fermilab Tevatron collider cannot improve the current bounds obtained from R_b, which place much stronger constraints on these operators. Hence their effects will not be observable at the Fermilab Tevatron collider, even for a luminosity of 100 fb^{-1}.

(2) The operator $O_{tW\Phi}$, currently subject only to weak bounds from unitarity, can be meaningfully probed at runs 2 and 3.

(3) The operator O_{Dt} cannot be probed at runs 2 and 3 much beyond the current bound from unitarity. For a higher integrated luminosity of 100 fb^{-1}, we found that the bound is $C_{Dt} < 9.8$ which is only slightly stronger than its current bound.

So we conclude that among the operators contributing to the $Wt\bar{b}$ coupling, only one operator ($O_{tW\Phi}$) can be meaningfully probed at the future runs of the Fermilab Tevatron collider.

VI. CONCLUSIONS

We have studied in the effective Lagrangian approach the ability of future runs at the Fermilab Tevatron collider in probing anomalous couplings of the top quark. We have

TABLE III. Current and future strongest upper bounds on the magnitude of coupling strength of some operators at 2σ level for $\Lambda = 1$ TeV. The current bounds are from unitarity requirement for $C_{tW\Phi}$ and C_{Dt}, from R_b for C_{qW} and $C_{\Phi q}^{(3)}$, and from run 1 data for C_{tG}, C_{qG}, and $C_{tG\Phi}$.

	Current bounds	Bounds from run 2	Bounds from run 3
$|C_{tG}|$, $|C_{qG}|$	7.2	1.0	0.8
$|C_{tG\Phi}|$	5.4	0.8	0.6
$|C_{qW}|$	0.2	2.1	0.5
$|C_{\Phi q}^{(3)}|$	0.03	4.6	1.2
$|C_{tW\Phi}|$	13.5	2.6	0.6
$|C_{Dt}|$	10.4	77	18

listed and analyzed the possible dimension-six CP-conserving operators involving the anomalous $gt\bar{t}$ or $Wt\bar{b}$ couplings which could be generated by new physics at a higher scale.

For the operators which give rise to an anomalous $gt\bar{t}$ coupling, we evaluated their effects in top pair production and derive the bounds both from run 1 and those expected from future runs. We found that the current constraints from run 1 are not very strong and that future runs can either discover the effects of these operators or significantly improve the current bounds. We also proposed two methods to disentangle the effects between different operators contributing to the $gt\bar{t}$ coupling: one is studying the energy distribution of the cross section and the other is measuring the asymmetry between left- and right-handed top events in top pair production.

For the operators which give rise to an anomalous $Wt\bar{b}$ coupling, we calculated their contribution to single top production at the upgraded Fermilab Tevatron collider and derived the bounds which could be obtained from runs 2 and 3. We found that future runs of the Fermilab Tevatron collider cannot effectively probe those operators which are currently subject to a tight constraint from R_b. For the operators which are not subject to the R_b constraint and are only constrained by unitarity, future runs of the Fermilab Tevatron collider can either discover the effects of or set stronger bounds on $O_{tW\Phi}$, while the best bound on O_{Dt} is still obtained from the unitarity constraint for any new physics scale.

In Table III we summarize the strongest upper bounds on the operators under consideration that currently exist or can be obtained in the future at the Fermilab Tevatron collider, for $\Lambda = 1$ TeV. The current bounds are from our results using either R_b or the run 1 data at the 2σ level, except for $C_{tW\Phi}$ and C_{Dt}, where the best current bounds come from the requirement of unitarity. We note that the current bounds on C_{qW} and $C_{\Phi q}^{(3)}$ obtained from R_b are better than those that can be obtained at run 3 at the Fermilab Tevatron collider.

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