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Nonuniversal correction to $Z\rightarrow b\bar{b}$ and single top quark production at Fermilab Tevatron

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New physics associated with the heavy top quark can affect top quark production and the partial decay width of $Z\rightarrow b\bar{b}$. In this paper, we examine the correlated effects of possible new physics on R_b measured at CERN LEP I and the single top quark production rate at the Fermilab Tevatron by using an effective Lagrangian technique. We point out that certain operators in the effective Lagrangian, constrained by the measured value of R_b, can lead to significant and potentially observable effects in single top quark production. [S0556-2821(97)50105-6]

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I. INTRODUCTION

An important issue in high energy physics is to understand the mechanism of mass generation. In the standard model, a fundamental complex Higgs scalar is introduced to break the electroweak symmetry and generate masses. However, arguments of triviality and naturalness suggest that the symmetry-breaking sector of the standard model is just an effective theory. The top quark, with a mass of the order of the weak scale, is singled out to play a key role in probing the new physics beyond the standard model [1].

If anomalous top quark couplings were to exist, their effects could show up in the top quark production rate [2], the partial decay width of $Z\rightarrow b\bar{b}$ measured at the CERN e^+e^- collider LEP [1,3], flavor-changing neutral current (FCNC) processes at low energies [4] and in top quark decays [5]. The new experimental value for $R_b=0.2178\pm0.0011$ [6] is higher than the standard model prediction of 0.2156 ± 0.0005 by 1.8σ. This still could be a possible first hint of new physics associated with the heavy top quark [7,8].

Recently with Hill, one of the authors (X.Z.) [9] studied the correlated effects of new dynamics, which sensitively involves the top quark, on R_b and the top pair production rate at the Tevatron. In this paper we will study the impact of possible new physics on the single top quark production rate at the Tevatron.

It was shown in Ref. [10] that the signal for single top production in $q\bar{q}\rightarrow t\bar{b}$ via a virtual s-channel W is potentially observable at the Fermilab Tevatron. The signal for this process is unobservable at the CERN Large Hadron Collider (LHC) because of the large background from $t\bar{t}$ production and single top quark production via W-gluon fusion [11]. Compared to the single top quark production via W-gluon fusion the process $q\bar{q}\rightarrow t\bar{b}$ has the advantage that the cross section can be calculated reliably because the quark and antiquark structure functions at the relevant values of x are better known than the gluon structure functions that enter in the calculation for the W-gluon cross section. The purpose of the paper is to show that certain types of new physics, after being constrained by the new value of R_b, can still show significant effects on the single top quark production rate at the Tevatron. In particular for operators that generate anomalous vertices with a q^2 dependence, one would naively expect new physics effects in single top production to be enhanced by a factor of $(m_t/m_Z)^2$ compared to new physics effects in R_b. Similar enhancement effects, in models of new physics used to explain R_b, could also be expected at LEP II [8,12].

The paper is organized as follows. In Sec. II, we discuss the phenomenology of $Z\rightarrow b\bar{b}$ and the single top production rate at the Fermilab Tevatron. In Sec. III, we summarize our results.

II. PHENOMENOLOGIES OF $Z\rightarrow b\bar{b}$ AND SINGLE TOP QUARK PRODUCTION RATE AT TEVATRON

In Ref. [9], several operators in the effective Lagrangian relevant to R_b were considered. Among them operators, $\mathcal{O}^1_{L,R}$ in the notation of Ref. [9] are relevant to the single top production. Since $b\rightarrow s\gamma$ strongly constrains the strength of the anomalous right-handed charged current for the third family [13], we focus here only on the operator $\mathcal{O}^1_L$. Explicitly,[1]

$$\mathcal{O}^1_L=\left(\overline{\psi_L}\gamma_\mu\frac{\tau^a}{2}\psi_L\right)(D_\nu F^{\mu\nu})^a, \qquad (1)$$

where $F^a_{\mu\nu}$ is the SU(2) field strength, $\psi_L=(t,b)_L$, $D_\mu=\frac{1}{2}[(\vec{D}_\mu)-(\overleftarrow{D}_\mu)]$ and

[1]Operator $\mathcal{O}^1_L$ can be reduced to four-Fermi operator by using equation of motion [9], which gives contact terms, such as $\overline{u}d\overline{t}b$. When calculating the cross section for process $q'\bar{q}\rightarrow t\bar{b}$, one gets the same matrix element with or without using the equation of motion.

$$\vec{D}_\mu=\vec{\partial}_\mu+igA^a_\mu\frac{\tau^a}{2}+ig'B_\mu\frac{Y}{2}.$$

This operator, modifying the Wtb couplings along with the $Zb\bar{b}$ vertex, could be generated in models where the top quark has a composite structure [14] and/or a soliton structure [15], in the strong extended technicolor (ETC) models [16] and in models where the top quark has new strong interactions [17]. It may also be generated in the weakly interacting theories, such as supersymmetry (SUSY) and multi-Higgs-boson models with relatively smaller coeffecients.

The effective Lagrangian is written as[2]

$$\mathcal{L}^{\rm eff}=\mathcal{L}^{\rm SM}+\frac{1}{\Lambda^2}[c_1\mathcal{O}^1_L], \tag{2}$$

where $\mathcal{L}^{\rm SM}$ is the Lagrangian of the standard model and Λ is the scale of new physics.

The Lagrangian $\mathcal{L}^{\rm eff}$ generates an effective $Zb\bar{b}$ and $Wt\bar{b}$ vertices. They are

$$Zb\bar{b}:\frac{-ig\gamma_\mu}{2\cos\theta_W}[g_L(1+\kappa_L)(1-\gamma_5)+g_R(1+\gamma_5)],$$

$$g_L=-\tfrac{1}{2}+\tfrac{1}{3}\sin^2\theta_W,$$

$$g_R=\tfrac{1}{3}\sin^2\theta_W,$$

$$\kappa_L=\frac{c_1M_Z^2\cos^2\theta_W}{2gg_L\Lambda^2}, \tag{3}$$

and

$$Wt\bar{b}:V_{tb}\frac{-ig}{2\sqrt{2}}[F_1\gamma_\mu(1-\gamma_5)],$$

$$F_1=1-\frac{c_1q^2}{g\Lambda^2}, \tag{4}$$

where $q=p_t+p_{\bar{b}}$ is the momentum of the W.

We now use the experimental value of R_b to constrain the parameters associated with the higher dimension operator, and then calculate its correction to the single top production rate. In the effective Lagrangian, c_1/Λ^2 can be extracted by using the formula [9]

$$\kappa_L=\frac{(R_b-R_b^0)}{R_b^0}\frac{g_L^2+g_R^2}{2g_L^2}, \tag{5}$$

where R_b and R_b^0 are the experimental value and the standard model prediction, respectively. The cross section for $p\bar{p}\to tbX$ is given by

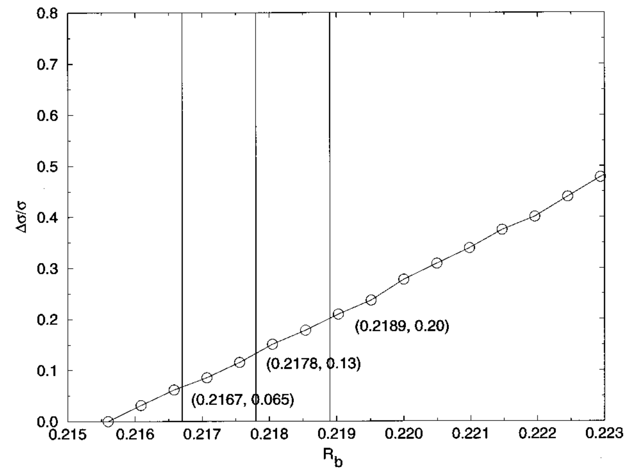

FIG. 1. The plot shows $\Delta\sigma/\sigma$ vs R_b, where $\Delta\sigma$ is the change in the single top quark production cross section in the presence of higher dimensional operators and σ is the standard model prediction. The numbers shown in the plot represent (R_b,$\Delta\sigma/\sigma$).

$$\sigma(p\bar{p}\to t\bar{b}X)=\int dx_1dx_2[u(x_1)\bar{d}(x_2)+u(x_2)\bar{d}(x_1)]\sigma(u\bar{d}\to t\bar{b}). \tag{6}$$

Here $u(x_i)$, $\bar{d}(x_i)$ are the u and the structure functions, x_1 and x_2 are the parton momentum fractions and the indices $i=1$ and $i=2$ refer to the proton and the antiproton. For the process

$$u(p_1)+\bar{d}(p_2)\to W^*\to\bar{b}(p_3)+t(p_4),$$

the spin and color averaged matrix element squared at the partonic level is given by (with $V_{tb}=V_{ud}\approx 1$)

$$|M|^2=32G_F^2\frac{M_W^4}{(q^2-M_W^2)^2}[F_1^2(p_1\cdot p_3)(p_2\cdot p_4)]. \tag{7}$$

We use the Martin-Roberts-Stirling set A′ (MRSA′) structure functions, given in Ref. [18], for our numerical calculation. In Fig. 1, we plot $\Delta\sigma/\sigma$ vs R_b, where $\Delta\sigma$ is the change in the single top quark production cross section in the presence of higher dimensional operators in the Lagrangian, and σ is the standard model cross section for single top quark production.

One can see from the figure that if one requires the new physics to bring the prediction of R_b to the central value of the experimental data, $R_b=0.2178$, then its correction to the single top rate is around 13%. Furthermore, if we fit R_b to the experimental value within 1 σ then the correction due to new physics to the single top production rate could be[3] 6–20%.

[2]We have not included the four-Fermi operators involving the top and bottom quarks [9], which can only indirectly affect R_b and the single top production rate at one-loop, but not directly as the operator, $\mathcal{O}^1_L$ does at the tree level.

[3]We have not included the QCD and Yukawa corrections [19] to the single top quark production rate. They will enhance the total rate, but not change the percentage of the new physics correction to the cross section.

III. CONCLUSION

In this paper, we have studied the correlated effects of new physics on R_b and the cross section of the single top quark production at the Fermilab Tevatron. Our results show that the correction to the single top quark production rate due to the new physics responsible for R_b could be 6–20% at the Tevatron. Given that the single top cross section (via $q'\overline{q}\to t\overline{b}$) can be measured at Tevatron Run 2 and Run 3 with a precision of 27 and 8%, respectively [20], our study here provides a theoretical argument for such a measurement in order to probe new physics beyond the standard model.

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