Non-Universal Correction To $Z \to b\bar{b}$
And Single Top Quark Production at Tevatron

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Abstract

New physics associated with the heavy top quark can affect top quark production and the partial decay width of $Z \to b\bar{b}$. In this paper, we examine the correlated effects of possible new physics on $R_b$ measured at LEP I and the single top quark production rate at 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 production.
1 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 LEP [1] [3], FCNC processes at low energies [4] and in top quark decays [5]. The new experimental value for $R_b = 0.2178 \pm 0.0011$ [6] is higher than the standard model prediction of $0.2156 \pm 0.0005$ by 1.8σ. This still could be a possible first hint of new physics associated with the heavy top quark [7, 8].

Recently with Chris Hill, one of the authors [9] (X. Zhang) 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 Tevatron. The signal for this process is unobservable at the LHC because of the large background from $t\bar{t}$ production and single top production via W-gluon fusion [11]. Compared to the single top 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 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 section II, we discuss the phenomenology of $Z \to b\bar{b}$ and the single top production rate at the Tevatron. In section III, we summarize our results.

## 2 Phenomenologies of $Z \to b\bar{b}$ and single top production rate at Tevatron

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

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

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

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

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 ETC models [16] and in models where the top quark has new strong interactions [17]. It may

$^1$[F.1] Operator $\mathcal{O}_L^1$ can be reduced to four-Fermi operator by using equation of motion [9], which gives contact terms, such as $\bar{u}d\bar{b}$. When calculating the cross section for process $q'\bar{q} \to tb$, one gets the same matrix element with or without using the equation of motion.
also be generated in the weakly interacting theories, such as SUSY and multi-Higgs models with relatively smaller coefficients.

The effective lagrangian is written as:

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

(2)

where \( \mathcal{L}^{\text{SM}} \) is the lagrangian of the standard model and \( \Lambda \) is the scale of new physics.

The lagrangian \( \mathcal{L}^{\text{eff}} \) generates an effective \( Zb\bar{b} \) and \( Wt\bar{b} \) vertices. They are

\[
\begin{align*}
Zb\bar{b} & : \quad \frac{-i g \gamma_{\mu}}{2 \cos \theta_W} [g_L (1 + \kappa_L) (1 - \gamma_5) + g_R (1 + \gamma_5)], \\
g_L & = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W, \\
g_R & = \frac{1}{3} \sin^2 \theta_W, \\
\kappa_L & = \frac{c_1 M_Z^2 \cos^2 \theta_W}{2 g g_L \Lambda^2};
\end{align*}
\]

(3)

and

\[
Wt\bar{b} : \quad V_{tb} \frac{-i g}{2 \sqrt{2}} [F_1 \gamma_{\mu} (1 - \gamma_5)], \\
F_1 & = 1 - \frac{c_1 q^2}{g \Lambda^2},
\]

(4)

where \( q = p_t + p_b \) 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 \( c_1 / \Lambda^2 \) can be extracted by using the formula:

\[
\kappa_L = \frac{(R_b - R_b^0) g_L^2 + g_R^2}{2 g_L^2},
\]

(5)

\footnote{We have not included the four-Fermi operators involving the top and bottom quarks, which can only indirectly affect \( R_b \) and the single top production rate at one-loop, but not directly as the operator, \( O^1_L \) does at the tree level.}
where $R_b$ and $R_b^0$ are the experimental value and the standard model prediction respectively. The cross section for $p\bar{p} \to t\bar{b}X$ is given by

$$\sigma(p\bar{p} \to t\bar{b}X) = \int dx_1 dx_2 [u(x_1)\overline{d}(x_2) + u(x_2)\overline{d}(x_1)]\sigma(ud \to t\overline{b}).$$

(6)

Here $u(x_i), \overline{d}(x_i)$ are the $u$ and the $\overline{d}$ 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

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

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

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

(7)

We use the 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 production cross section in the presence of higher dimensional operators in the lagrangian and $\sigma$ is the standard model cross section for single top 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 $\sigma$ then the correction due to new physics to the single top production rate could be $6 \sim 20\%$ [3].

3 Conclusion

In this paper, we have studied the correlated effects of new physics on $R_b$ and the cross section of the single top production at the Tevatron. Our results show that the correction to the single top

\footnote{[F.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.}
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 $q'\bar{q} \to t\bar{b}$) 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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4 Figure Caption

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 $\sigma$ is the standard model prediction. The numbers shown in the plot represent $(R_b, \Delta \sigma / \sigma)$. 
