Some Phenomenology of the Top Quark with Non-standard Couplings

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Abstract
In this talk I will discuss possible new physics associated with the top quark. We use higher dimension effective operators to represent the new physics and examine constraints on the operators from the phenomenology they predicted.
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I. Introduction
Because of the large mass of the top quark which signifies a sizable coupling to the electroweak symmetry breaking sector, it is possible that the top quark may play a key role in probing new physics. The works described below, which are performed in collaboration with Seungkoog Lee, Kerry Whisnant, and Xinmin Zhang, include the investigation of higher dimension operators and flavor changing neutral currents, both can be remnants of the physics took placed above the fermi scale. We examined constraints on the effective operators due to baryogenesis, collider physics, unitarity bounds, and certain static properties of leptons and hadrons. Due to space limitation, only a bare number of references will be given.

I will first summarize the constraints on physics at the fermi scale due to electroweak baryogenesis which is related to physics above the fermi scale. The observed ratio of baryon number density to entropy, \( \frac{n_B}{s} = (0.4 - 1.4) \times 10^{-10} \), can impose significant constraints on the standard model. Two constraints are particularly relevant to our discussion and both require the existence of new physics. One is that there should exist new sources of CP violation besides the complex phase of the CKM quark mixing matrix. With the CKM phase, the electroweak dynamics predicts a very small baryon number density which is of 10 orders of magnitude smaller than the observation. A second constraints is the bound on the Higgs boson mass. In order to prevent washout of the baryon number generated by the electroweak dynamics during the electroweak phase transition, the Higgs boson mass can not exceed 45\(GeV\) [1]. However, this bound conflicts with the LEP data [2] which put 58\(GeV\) as the lower limit of the Higgs boson mass.

II. Effective Lagrangian
New physics by the effective Lagrangian is a familiar approach [3]. Since the effective Lagrangian is free from specific models, it is a systematic way in searching for new physics. We assume that the non-standard top quark coupling has something to do with symmetry breaking, and is therefore associated with Higgs interactions. We have investigated in some detail the following lowest dimension operator,

\[ O = \frac{m_t}{v} c_t e^{i \xi} \left| \frac{\Phi^2}{\Lambda^2} - \frac{v^2}{2} \right| (t_t, b_t) \bar{t} \cdot \Phi t_r, \]

where \( c_t \) and \( \xi \) are unknown parameters. Adding this operator to the standard model Lagrangian, we obtain a modified top quark-Higgs boson coupling,

\[ L_H = \frac{m_t}{v} H \{ 1 + \delta (\cos \xi + i \sin \xi) + \cdots \} t, \quad \delta = c_t \frac{v^2}{\Lambda^2}. \]

In the following, we summarize the effect of the operator on several measurable quantities which allow us to constrain the parameters \( c_t \) and \( \xi \) and make predictions.

(II.A) **Extension of the Higgs mass bound** [4] [5]

One effect of the operator is to increase the bound of the Higgs mass from \( M_{H0}^2 \) to \( M_{H0}^2 + \frac{8v^2}{\Lambda^2} \), where \( M_{H0}^2 \) is subjected to the old bound of 45 GeV. The new bound can be as large as 180 GeV for \( \Lambda = 1 \) TeV. This new bound may also imply that the current LEP data allows a cutoff no higher than \( \Lambda = 3 \) TeV.

(II.B) **The baryon number to entropy ratio** [5]

The baryon number density to entropy ratio can be estimated as \( \frac{n_B}{s} \approx \kappa \alpha_W^4 \delta_{CP} F \), where \( F \), being of the order of 0.1, depends on the properties of the electroweak phase transition, and \( \kappa \) governing the rate of baryon number violation in the symmetric phase ranges from 0.5 to 20. The CP violation phase from the operator \( O \) is given by \( \delta_{CP} \sim c_t \sin \xi \frac{v^2}{2\Lambda^2} \). Using \( \Lambda = 1 \) TeV, we have \( \kappa c_t \sin \xi \geq 4 \times 10^{-2} \).

It should be noted that the electroweak baryogenesis calculation is only accurate to within a couple of order of magnitude. For instance, if the effect of QCD sphaleron is taken into account, the predicted baryon asymmetry will be suppressed by a factor of \( 10^{-2} \) and the above bound will be \( \kappa c_t \sin \xi \geq 4 \).

(II.C) **Electric dipole moments of electron and neutron** [5]

The operator \( O \) can contribute to the electric dipole moments of the fermion. First, a CP violating \( H \gamma \gamma \) coupling can be generated through the top quark loop diagram. Then the photon coupling to the fermion under consideration through a virtual H and \( \gamma \) one-loop process will produce the desired electric dipole moments,
\[ d_f \sim e \cdot Q_f^2 \frac{m_f}{v^2} \left( \frac{\alpha}{2\pi} \right) c_t \sin \xi \frac{1}{16\pi^2} \ln \frac{m_t^2}{m_H^2}, \]

where \( Q_f \) is the electric charge of the fermion in units of e. Using the constraints on the input parameters of the effective operator, we obtain \( d_e \sim \frac{2}{10} (10^{-28} - 10^{-30}) e \cdot cm \), where the experimental data is \( d_e^{\exp} = (-0.3 \pm 0.8) \times 10^{-26} e \cdot cm \). The neutron electric dipole moment is given by \( d_n \sim \frac{m_m}{m_e} d_e \sim \frac{1}{10} (10^{-26} - 10^{-28}) e \cdot cm \), and the experimental upper limit is \( d_n^{\exp} < 11 \times 10^{-26} e \cdot cm \). Both are one to two orders of magnitude below the experimental limit.

(II.D) **Phenomenology at high energy linear colliders**

The effective operator \( O \) has interesting consequences at the future high energy \( e^+e^- \) linear collider. For example, the cross section of \( e^+e^- \rightarrow t + \bar{t} + H \) is sensitive to the parameters of \( O \). For the top quark mass of 180 GeV and Higgs boson mass 100 GeV, about 20 events per year are predicted by the SM to be produced for an integrated luminosity of \( \int L = 20 \text{ fb}^{-1} \). The event can be identified by the spectacular final state \( W^+W^-b\bar{b}b\bar{b} \). Except for special values of the parameters the cross section value in the presence of the anomalous coupling can be distinguished from that of the standard model. We plotted the cross section versus \( \delta \) and \( \xi \). Fig. 1.

(II.E) **Bounds from unitarity**

We have also considered the unitarity constraints on the anomalous top quark Yukawa coupling. We performed a multichannel analysis of the helicity amplitudes of the six reactions \( t\bar{t} \rightarrow t\bar{t}, W^+_L W^-_L, Z_L Z_L, Z_L H, \) and \( HH \). In the analysis we also took into consideration the \( t\bar{t}HH \) anomalous vertex contained in \( O \). We plot the constraints of \( \delta \) versus \( \xi \) from the unitarity, baryogenesis, and the electric dipole moment of the neutron. Fig. 2.

Let us remark that an operator like \( O \) can be realized in a left-right model when the heavy right-handed degree of freedom is integrated out [5].

### III. Flavor changing neutral current

Non-universal electroweak interactions which couple only to the third generation can lead to flavor changing neutral currents (FCNC) due to quark mixing [7]. The strength of the FCNC depends on the individual quark mass mixing matrix elements. We can write the FCNC in the form

\[ j_{\mu}^{jk} = \bar{q}_j \gamma_\mu \left( g_{jk,L}^{\text{eff}} \Gamma_L + g_{jk,R}^{\text{eff}} \Gamma_R \right) q_k \]

\[ g_{jk,C}^{\text{eff}} = gc \left( \delta_{jk} + \kappa_{jk,C} \right), \]

\( C = L \) (R) means left- (right-) handed, \( \Gamma_L \) (\( \Gamma_R \)) are the left- (right-) handed chiral projection operator, \( \kappa_{jk,C} \) gives the strength of the flavor changing neutral current,
and \( g_L = -\frac{1}{2} + \frac{1}{3} \sin^2 \theta_W \), \( g_R = \frac{1}{3} \sin^2 \theta_W \) are the standard model couplings of \( Z \) to \( \overline{b}b \). The \( \kappa \) term can be induced by higher dimension effective operators. Since \( g_R \) is much smaller than \( g_L \), we will neglect the effect of the right-handed part. We take the following operators:

\[
O_1 = i [\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger] \overline{\Psi}_L \gamma^\mu \Psi_L
\]

\[
O_2 = i [\Phi^\dagger \overline{\tau} D_\mu \Phi - (D_\mu \Phi)^\dagger \overline{\tau}] \overline{\Psi}_L \gamma^\mu \overline{\tau} \Psi_L,
\]

where \( \overline{\Psi}_L = (\overline{t}_L, \overline{b}_L) \) is the left-handed third generation doublet. The effective Lagrangian is given by

\[
L_{\text{eff}} = L_{\text{SM}} + \frac{1}{\Lambda^2} (c_1 O_1 + c_2 O_2)
\]

After the spontaneous symmetry breaking and diagonalization of the quark mass matrix, an anomalous neutral current is obtained,

\[
\frac{g_2}{\cos \theta_W} \begin{bmatrix} \bar{d} & \bar{s} & \bar{b} \end{bmatrix} L U^{(d)}_{L} \begin{bmatrix} 0 & 0 & \Delta_L \end{bmatrix} U^{(d)}_{L} \begin{bmatrix} d \\ s \\ b \end{bmatrix} Z^\mu
\]

where \( g_2 \) is the \( SU(2) \) coupling, \( \Delta_L = \frac{v^2}{\Lambda^2} (c_1 + c_2) \), and \( U^{(d)}_{L} \) is the unitary rotation matrix which diagonalizes the left-handed down quark mass matrix. Note that the CKM mixing matrix is given by \( V_{\text{CKM}} = U^{(u)}_{L} U^{(d)}_{L} \), where \( U^{(u)}_{L} \) is the up quark rotation matrix. We see that the FCNC depends on both the new physics and the quark rotation matrix.

Since the individual quark rotation matrix is not known. We used a variant of the modified Fritzsch ansatz of the down quark rotation matrix

\[
\begin{bmatrix}
1 \\
(\frac{m_d}{m_s})^{1/2} e^{-i \alpha_q} \\
-(\frac{m_d(m_s+w_q)}{m_s m_b})^{1/2} e^{-i(\alpha_q+\beta_q)}
\end{bmatrix}
\begin{bmatrix}
(\frac{m_d}{m_s})^{1/2} e^{-i \alpha_q} \\
(\frac{m_d(m_s+w_q)}{m_s m_b})^{1/2} e^{-i(\alpha_q+\beta_q)} \\
(\frac{m_d(m_s+w_q)}{m_s m_b})^{1/2} e^{-i(\alpha_q+\beta_q)}
\end{bmatrix}
\]

where \( w_q \) is taken to be \( m_c, \alpha_q \) and \( \beta_q \) are responsible for the CP violation phase in the CKM mixing matrix.

The above effective Lagrangian can affect a number of low energy reactions. We refer to [8] for details.

We are investigating, in another approach to FCNC, the anomalous electro- and chromo-magnetic operators, \( tc\gamma \) and \( tcg \). The effective Lagrangian is taken to be

\[
\Delta L = \frac{1}{\Lambda} (\kappa^\gamma \epsilon \overline{t} \sigma_{\mu\nu} c F^{\mu\nu} + \kappa^g g_s \overline{t} \sigma_{\mu\nu} \overline{\lambda} \epsilon G^{\mu\nu}_{\mu\nu})
\]

Both \( \kappa^\gamma \) and \( \kappa^g \) can be constrained from \( b \to s + \gamma \) which has been observed experimentally. The anomalous \( tc\gamma \) coupling contributes to \( bs\gamma \) directly through a one-loop diagram and \( tcg \) contributes through QCD corrections.
The $t \to c + \gamma$ decay is easily observable by the presence of a high energy $\gamma$ which carries half of the top quark energy. There seems to be very little background. We are performing a simulation to study the background in detail. The process considered is the $t\bar{t}$ production in a high energy hadron collider. One of the top quarks decays into $c + \gamma$ and the other decays through the normal channel [10]. A sizable anomalous $tcg$ coupling can enhance the single top quark production at the Fermilab Tevatron which we are currently investigating.

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