Top Quark and Electroweak Symmetry Breaking Mechanism

C.–P. Yuan *Department of Physics and Astronomy, Michigan State University*
East Lansing, Michigan 48824 , USA

Abstract

After a brief comment on the role of top quark in models of electroweak symmetry breaking (EWSB), I shall discuss what we know about top quark interaction and how to improve that knowledge. Since bottom quark is the weak isospin partner of the top quark, its interaction with a scalar boson may also distinguish models of EWSB. We shown that Tevatron can provide useful information through the associated production of a scalar with a bottom quark pair.

1 Introduction

Two of the outstanding mysteries in electroweak theory are: (i) the cause of the electroweak symmetry breaking (EWSB), which gives masses to the weak gauge bosons $W^{\pm}$ and Z, and (ii) the origin of flavor symmetry breaking (FSB), which makes quarks and leptons have diverse masses. In the standard model (SM) of particle physics, both symmetry breaking mechanisms are accommodated by including a fundamental weak doublet of scalar (Higgs) boson. Because of the spontaneous symmetry breaking, the Higgs boson develops a vacuum expectation value (VEV) v, so that the weak gauge bosons gain their masses. Similarly, fermion gains mass via Yukawa interaction with Higgs boson. However, SM provides no explanation (i.e., no explicit dynamics) for the generation of mass.

The models of symmetry breaking beyond the SM can be characterized into two classes. One is the weakly interacting model (with elementary Higgs bosons), such as supersymmetry (SUSY) theory [1], another is the strongly interacting model (with composite Higgs bosons), such as Topcolor model [2]. In these models, top quark often plays a very special role in the EWSB and/or the FSB dynamics. For example, in the supergravity model, the electroweak symmetry is broken radiatively by corrections from top quark and top-squarks (superpartners of left- and right-handed top quark) in the self-energy of Higgs boson [3]. Because top quark is heavy ($\sim v/\sqrt{2}$), the running mass of the Higgs boson field becomes negative around TeV energy scale where the spontaneous symmetry breaking occurs. Thus, EWSB is driven by a heavy top quark. In the Topcolor-assisted Technicolor (TCATC) model [4], some unknown strong dynamics in the Techni-fermion sector induces electroweak symmetry breaking through the formation of the Techni-fermion condensation, which generates the masses of $W^{\pm}$ and Z gauge bosons. What is the role of top quark? In the usual extended Technicolor (ETC) model, fermions gain mass by interacting with ETC gauge bosons and Techni-fermions. It is a fine idea to generate masses for light fermions, but in order to give a large mass to the top quark, the mass of the ETC gauge boson has to be small. Unfortunately, in that case, the model would predict a large shift ($\Delta\rho$) in the ρ-parameter, and is not tolerable by data. This is a well known problem in ETC models. However, in the TCATC model, top quark plays a very special role to solve this problem of FSB. How does it work? In the TCATC model, top quark (and bottom quark) experiences a new strong gauge (Topcolor) interaction so that a heavy top quark pair can condensate and give a large (almost all) mass to top quark, while the condensate contributes only a little to the breaking of the electroweak symmetry. By this, it solves the $\Delta\rho$ problem and generates a more "natural" ETC model to describe the fermion mass spectrum. Obviously, the above ideas for either class of models will not work if the mass of the top quark were not large enough. In conclusion, it seems to be reasonable that a heavy top quark can play an important role in the electroweak symmetry breaking and/or flavor symmetry breaking dynamics.

With the discovery of the top quark by the CDF and DØ collaborations, it has become natural to consider its properties, such as its couplings to the other particles. By now, all the experimental data show excellent agreement with SM prediction. Does that imply new physics is not allowed and top quark interaction is determined? No, that is not the case. The present data does not exclude possible new physics. In the next section, I will discuss what data is telling us about the interaction of top quark.

2 Constraints From Low Energy Data

If we do not assume a SM top quark, do we know anything about the interactions of top from low energy data, such as the precision Z-pole data and bottom physics? Will there be any surprise from future collider data, such as the Fermilab upgraded Tevatron, CERN Large Hadron Collider (LHC), future Linear Collider (LC)? If yes, how to look for them? In this section, I will address the first question, and defer the others to the next section.

We can perform the study in a model-independent way by constructing an effective low energy theory that is consistent with the symmetry breaking pattern of the SM, i.e., the gauge symmetry $SU(3)_C \times SU(2)_L \times U(1)_Y$ is spontaneously broken down to $SU(3)_C \times U(1)_{em}$. A well established technique to construct a complete set of operators that respects the symmetries in expansion of energy is to build an electroweak chiral Lagrangian (EWCL), in which the $SU(2)_L \times U(1)_Y$ symmetry is non-linearly realized [5]. To simplify our study, we shall assume that the effect of heavy new physics is to only modify the couplings of W-t-b and Z-t-t without introducing any non-SM light field. In that case, the most general gauge invariant chiral Lagrangian [6], that includes the electroweak couplings of the top quark up to dimension four, contains terms such as

$$\frac{1}{\sqrt{2}}\left(1+\kappa_L^{\mathrm{CC}}\right)\overline{t_L}\gamma^\mu b_L \mathcal{W}_\mu^+, \qquad \frac{1}{\sqrt{2}}\kappa_R^{\mathrm{CC}}\overline{t_R}\gamma^\mu b_R \mathcal{W}_\mu^+,$$

$$\frac{1}{6}\left(3-4s_w^2+3\kappa_L^{\mathrm{NC}}\right)\overline{t_L}\gamma^\mu t_L \mathcal{Z}_\mu,$$

and

$$\frac{1}{6}\left(-4s_w^2+3\kappa_R^{\mathrm{NC}}\right)\overline{t_R}\gamma^\mu t_R \mathcal{Z}_\mu,$$

where κ's parameterize possible new physics. (Here, we do not include possible flavor-changing neutral current (FCNC) couplings, e.g. t-c-Z, or dimension five operators [6].) In general, the charged current coefficients can be complex with the imaginary part introducing a CP odd interaction, and the neutral current coefficients are real so that the effective Lagrangian is hermitian. In the unitary gauge, the *composite* fields $\mathcal{W}_\mu^\pm$, $\mathcal{Z}_\mu$, and $\mathcal{A}_\mu$ are reduced to $-gW_\mu^\pm$, $-\frac{g}{c_w}Z_\mu$, and $\frac{e}{s_w^2}A_\mu$, respectively, where $e = gs_w = g'c_w$ and $s_w = \sin\theta_w$, etc.

Top quark can only contribute to low energy observables through loop corrections. To concentrate on the interactions of top quark and EWSB sector, we shall only include those non-standard contributions (from the κ's) of the order $\frac{m_t^2}{16\pi^2 v^2}\ \ln\frac{\Lambda^2}{m_t^2}$, where Λ is a physical cutoff scale below which the effective Lagrangian is valid. (Here, Λ is taken to be $4\pi v \sim 3\,\mathrm{TeV}$.)

Since any contributions from the right-handed charged current coupling κ_R^{CC} are proportional to the bottom quark's mass m_b (which is much smaller than m_t), we can only obtain useful bounds for κ_L^{NC}, κ_R^{NC} and κ_L^{CC} from the Z-pole data at the LEP and the SLC, up to one loop level. However, κ_R^{CC} can be studied independently by using the CLEO measurement of the branching ratio (BR) of $b \to s\gamma$, in which κ_R^{CC} becomes the significant anomalous coupling. From the theoretical prediction [7] and the CLEO measurement $1\times 10^{-4} < BR(b \to s\gamma) < 4.2\times 10^{-4}$ [8], it was found [6] that $-0.037 < \kappa_R^{CC} < 0.0015$. Hence, κ_R^{CC} is strongly constrained for the case that there is no new light field contributing to the $b \to s\gamma$ data. With these observations, we study how κ_L^{NC}, κ_R^{NC} and κ_L^{CC} can be constrained by LEP/SLC data, which, under a few general assumptions, can be parameterized by 4-independent parameters: ϵ_1, ϵ_2, ϵ_3, and ϵ_b [9]. Namely, all the leading contributions of the non-standard couplings κ's are contained in the oblique corrections, i.e., the vacuum polarization functions of the gauge bosons, and the non-oblique corrections to the vertex b-b-Z . The non-standard contributions to the ϵ parameters are: $\delta\epsilon_1 = \frac{G_F}{2\sqrt{2}\pi^2}3m_t^2(-\kappa_L^{NC} + \kappa_R^{NC} + \kappa_L^{CC})\ln\frac{\Lambda^2}{m_t^2}$ and $\delta\epsilon_b = \frac{G_F}{2\sqrt{2}\pi^2}m_t^2\left(-\frac{1}{4}\kappa_R^{NC} + \kappa_L^{NC}\right)\ln\frac{\Lambda^2}{m_t^2}$. It is interesting to note that κ_L^{CC} does not contribute to ϵ_b up to this order ($m_t^2\ln\Lambda^2$). Given the above results we can then use the experimental values of the ϵ's to constrain the theoretical predictions. We find that precision data allows for all three non-standard couplings to be different from zero. There is a three dimensional boundary region for these κ's. The only coefficient that is constrained at the 95% confidence level (C.L.) is κ_L^{NC} which can only vary between -0.35 and 0.35. The other two can vary through the whole range (-1.0 to 1.0) although in a correlated manner [6]. (For instance, ϵ_b data implies $\kappa_R^{NC} \sim 4\kappa_L^{NC}$ for any κ_L^{CC}.) Furthermore, LEP/SLC data imposes $\kappa_L^{CC} \sim -\kappa_R^{NC}$ if κ_L^{NC} is close to zero. This conclusion holds for m_t ranging from 160 GeV to 180 GeV. Hence, the precision low energy data does not exclude the possibility of having anomalous top quark interactions with the gauge bosons.

Different models for the electroweak symmetry breaking sector can induce different relations among the κ's. These relations can in turn be used to discriminate between models by comparing their predictions with experimental data. To illustrate this point, consider a model [10] with $\kappa_L^{CC} = \frac{1}{2}\kappa_L^{NC}$ (due to an approximate custodial symmetry which ensures that ρ-parameter is close to one) and another model [11] with $\kappa_L^{CC} = 0$. The allowed range predicted by these two models lies along the line $\kappa_L^{NC} = 2\kappa_R^{NC}$ and $\kappa_L^{NC} = \kappa_R^{NC}$ (with,$-0.1 < \kappa_L^{NC} < 0.15$), respectively. If we imagine that any prescribed dependence between the couplings corresponds to a symmetry-breaking scenario, then, given the present status of low energy data, it may be possible to distinguish the above two scenarios if κ_L^{NC}, κ_R^{NC} and κ_L^{CC} are larger than 10%. One such model that predicts $\kappa_L^{CC} \sim 10\%$ can be found in Ref. [12].

In conclusion, we shown that new physics possibility (e.g., with non-zero κ's) is allowed by the current low energy data. Only direct measurement (not through loop effect) on κ's can conclusively test the interaction of top quark with gauge bosons. That means we have to study the direct production of the top quark at high energy colliders.

3 Direct Measurement of Top

While production of $t\bar{t}$ pairs provides an excellent opportunity to probe the top's QCD properties, in order to carefully measure the top's electroweak interactions it is also useful to consider single top production, in addition to studying the decay of the top quark in $t\bar{t}$ events.

Single top production at a hadron collider occurs dominantly through three sub-processes [13]. The W^* mode of production occurs when a quark and an anti-quark fuse into a virtual W boson, which then splits into a t and $\bar{b}$ quark. The W-gluon fusion mode occurs when a b quark fuses with a W^+ boson, producing a top quark. The tW^- mode occurs when a b quark radiates a W^-. The three single top production processes contain the t-b-W vertex of the SM, and thus are sensitive to the Cabibbo-Kobayashi-Maskawa (CKM) parameter V_{tb} in the SM and to any possible modification of this vertex from physics beyond the SM (e.g, that generating a non-zero $\kappa_{L,R}^{CC}$). The tW^- process is important at the LHC, but is highly suppressed at the Tevatron because of the massive W and t particles in the final state. In Ref. [13], a detailed analysis was carried out for the other two production processes at the Tevatron Run II energy (a $\bar{\mathrm{p}}\mathrm{p}$ collider with $\sqrt{S} = 2\,\mathrm{TeV}$), up to next-to-leading order (NLO) in QCD interaction. The predicted theoretical values and uncertainties of σ_{W^*} and σ_{Wg} (including single-t and single-$\bar{t}$ rates) are: $\sigma_{W^*} = 0.84$ pb $\pm$ 15.5% and $\sigma_{Wg} = 2.35$ pb $\pm$ 10.2%, for a 175 GeV top quark. The theoretical uncertainties from scale, parton distribution functions (PDF), and uncertainty in m_t (assuming $m_t = 175 \pm 2$ GeV) are found to be $\pm$5% ($\pm$4%), $\pm$2% ($\pm$3%), and $\pm$6% ($\pm$3%), for σ_{W^*} (σ_{Wg}). Hence, the total uncertainties obtained from adding these uncertainties in quadrature, linearly, and the result from the envelope method are $\pm$8% ($\pm$6%), $\pm$13% ($\pm$10%), and $\pm$15.5% ($\pm$10.2%), for σ_{W^*} (σ_{Wg}). To determine how well σ_{W^*} and σ_{Wg} can be measured *experimentally*, experimental systematic uncertainties must be included. Assuming a semi-leptonic top decay into an electron or muon, and the detection efficiencies of 9% for the W^* process and 33% for the W-gluon fusion process obtained from leading order (LO) studies, the projected statistical uncertainties for a 2 fb^{-1}(10 fb^{-1}) of integrated luminosity are $\pm$17% ($\pm$8%) and $\pm$5% ($\pm$2%) for measuring σ_{W^*} and σ_{Wg}, respectively. The corresponding total uncertainties (including theoretical and statistical uncertainties) are $\pm$23% ($\pm$17%) and $\pm$11% ($\pm$10%). In the SM, the square-root of the single-top cross section is proportional to $|V_{tb}|$. Hence, the expected uncertainty in measuring $|V_{tb}|$ is about $\pm$10% and $\pm$5% from the W^* and W-gluon fusion data, assuming $|V_{tb}|$ is close to 1. Furthermore, the relevant background rates (52 and 350 events, for a 2 fb^{-1}of luminosity) after the kinematic cuts are about the same as the signal rates (34 W^* and 345 W-gluon fusion events). It should be emphasized that the use of the LO backgrounds and efficiencies is an approximation, however we expect these estimates to correspond rather well to the true NLO results.

We note that the W-gluon fusion mode, within the SM, provides a way to directly measure the partial width of the top quark, $\Gamma(t \to W^+ b)$, through the effective-W approximation. Under this approximation, σ_{Wg} can be related to the width $\Gamma(t \to W^+b)$ by the equation [13]

$$\sigma_{Wg} \simeq \sum_{\lambda=0,+,-} \int dx_1\, dx_2\, f_\lambda(x_1)\, b(x_2) \left[\frac{16\pi^2 m_t^2}{\hat{s}(m_t^2 - M_W^2)}\right] \Gamma(t \to W_\lambda^+ b)\ ,$$

where $x_1 x_2 = \hat{s}/S$, $f_\lambda(x_1)$ is the distribution function for W bosons within the proton carrying momentum fraction x_1, $b(x_2)$ is the b quark PDF, and λ is the polarization of the W boson. Thus, if one has an experimental measurement of the W-gluon fusion rate, it can be combined with the known effective W distribution functions to extract the partial width. (We note that there is no similar relation between σ_{W^*} and $\Gamma(t \to W^+b)$.) This method relies on the fact that within the SM there are no FCNC interactions, and the CKM elements V_{ts} and V_{td} are very small; thus the t-channel single top production involves fusion of only the b parton with a W^+ boson[1]. Once this partial width has been extracted from a measurement of σ_{Wg}, it can be combined with a measurement of the branching ratio (BR) of $t \to W^+b$ (obtained from examining top decays within $t\bar{t}$ production) to get the top quark's full width ($\Gamma(t \to X)$, where X is anything) via the relation $\Gamma(t \to X) = \Gamma(t \to W^+b)/BR(t \to W^+b)$.

As also noted in Ref. [13] that because of the different sensitivities to different types of new physics effects of the two production modes, it is useful to consider the experimental data in the σ_{W^*}-σ_{Wg} plane. For example, σ_{W^*} is sensitive to the presence of a new heavy resonance contributing through s-channel diagram, while σ_{Wg} is sensitive to top quark FCNC interactions contributing through t-channel diagram. Comparison of the predictions of explicit models with the experimental point on this plane could be used to rule out or constrain these models. Furthermore, the tW^- mode of single top production is insensitive to the types of new physics mentioned above, and thus could provide a safe way to measure V_{tb}, provided enough statistics or a carefully tuned search strategy compensates for its low cross section.

In conclusion, it is important to study single top production at the Tevatron, in both the W^* and W-gluon fusion modes separately, as these two modes provide complimentary information about the top quark. Single top production provides an excellent opportunity to directly measure V_{tb}, and to

[1] Assuming a top mass of $m_t = 175$ GeV, including the non-zero contributions from $V_{td} = 0.009$ and $V_{ts} = 0.04$ increases the W-gluon fusion cross section by less than 0.5%.

search for possible signs of the new physics associated with the top quark. Besides all the potential physics discussed above, the Tevatron, as a $p\bar{p}$ collider, is unique for being able to test CP violation by measuring the production rates of single-top events. A nonvanishing asymmetry in the inclusive production rates of the single-t events and the single-$\bar{t}$ events signals CP violation [14]. Thus it can be used to constrain or detect this type of new physics.

While Tevatron can provide sensitive test to the coupling of t-b-W, it cannot say very much about the coupling of Z-t-t, which has to be studied at the LHC via the production of $Zt\bar{t}$, or at the LC through s-channel Z-diagram contribution. It is also possible that the same dynamics that modifies the three-point vertices of top quark also modifies its four-point vertices. This was discussed in Ref. [6].

4 From Bottom To Top

As argued earlier, top quark may play a special role in the mechanism of EWSB and/or FSB. One of such ideas is that some new strong dynamics may involve a composite Higgs sector to generate the EWSB and to provide a dynamical origin for the top quark mass generation (*e.g.,* the top-condensate/top-color models [2]). Another idea is realized in the supersymmetric theories in which the EWSB is driven radiatively by the large top quark Yukawa coupling with some fundamental Higgs bosons [1].

Since the third family b quark, as the weak isospin partner of the top, can have large Yukawa coupling with the Higgs scalar(s) in both composite and supersymmetric models, it was proposed in Ref. [15] to use the b quark as a probe of possible non-standard dynamics in Higgs and top sectors. Because of the light b mass relative to that of the top, the production of Higgs boson associated with b quarks ($\bar{\rm p}{\rm p}, {\rm pp} \to \phi b\bar{b} \to b\bar{b}b\bar{b}$) may be experimentally accessible at the Tevatron and the LHC, even though the large top mass could render associated Higgs production with top quarks ($\bar{\rm p}{\rm p}, {\rm pp} \to \phi t\bar{t}$) infeasible. This makes it possible for the Tevatron and the LHC to test various models in which the b-quark Yukawa coupling is naturally enhanced relative to the SM prediction. Using the complete tree level results of the signal and background rates (with an estimated QCD k-factor of 2), we derive the exclusion contour for the enhancement factor (in the coupling of $\phi b\bar{b}$ relative to that of the SM) versus the Higgs mass m_ϕ at the 95% C.L., assuming a signal is not found. We apply these results to analyze the constraints on the parameter space of both the composite models and the MSSM (in the large $\tan\beta$ region). For the composite Higgs scenario, we first consider the two-Higgs-doublet extension (2HDE) of top-condensate model [16] and then analyze the topcolor model, where the b quark Yukawa couplings are naturally large (about the same as the top quark Yukawa coupling, which is around 1) due to the infrared quasi-fixed-point structure and the particular boundary conditions for (y_b, y_t) at the compositeness scale. The Tevatron Run II with a 2 fb^{-1} of luminosity can exclude the entire parameter space of the simplest 2HDE of top-condensate model, if a signal is not found. For the topcolor model, the Tevatron Run II is able to detect the composite Higgs h_b or A_b up to ~ 400 GeV and the LHC can extend the mass range up to ~ 1 TeV.

To confirm the MSSM, it is necessary to detect all the predicted neutral Higgs bosons h, H, A and the charged scalars $H^\pm$. From LEP II, depending on the choice of the MSSM soft-breaking parameters, the current 95% C.L. bounds on the masses of the MSSM Higgs bosons are about 70 GeV for both the CP-even scalar h and the CP-odd scalar A. It can be improved at LEP II with higher luminosity and maximal energy, but the bounds on the Higgs masses will not be much larger than $\sim m_Z$ for an arbitrary $\tan\beta$ value. The Wh and WH associated production at the Tevatron can further improve these bounds, if a signal is not observed. At the LHC, a large portion of parameter space can be tested via $pp \to t\bar{t} + h(\to \gamma\gamma) + X$, and $pp \to h(\to ZZ^*) + X$, etc. A future high energy e^+e^- collider will fully test the MSSM Higgs sector through the reactions $e^+e^- \to Z + h(H)$, $A + h(H)$, H^+H^-, etc. We concluded [15] that studying the $\phi b\bar{b}$ channel at hadron colliders can further improve our knowledge on MSSM. The exclusion contours on the m_A-$\tan\beta$ plane of the MSSM shows that Tevatron and LHC are sensitive to a large portion of the parameter space via this mode. Therefore, it provides a complementary probe of the MSSM Higgs sector (including both the supergravity and the gauge-mediated SUSY breaking models) in comparison with that from LEP II. Thus, it is expected that experimental searches for this signature at the Tevatron and the LHC will provide interesting and important information about the mechanism of the electroweak symmetry breaking and the fermion mass generation. Fortunately, we shall have data very soon.

Acknowledgments

I thank the organizers for the warm hospitality, and V. Ilyin and A. Pukhov for introducing me Russia, a beauty country with many friendly people. I would also like to thank my collaborators: C. Balazs, D. Carlson, J.L. Diaz-Cruz, H.-J. He, G. Kane, G. Ladinsky, F. Larios, E. Malkawi, S. Mrenna, and T. Tait, from them I have learned a great deal about top quark physics. This work was supported in part by the NSF grant No. PHY-9802564.

References

[1] J.F. Gunion, H.E. Haber, G. Kane and S. Dawson, *The Higgs Hunter's Guide,* Addison-Wesley Pub., 1996 (2nd edition);
J.F Gunion, hep-ph/9801417, and references therein.

[2] C. Hill. hep-ph/9802216, and references therein.

[3] L. Ibanez, Nucl. Phys. B**218**, 514 (1983); J. Ellis, D. Nanopolous and K. Tamvakis, Phys. Lett. B**121**, 123 (1983); L. Alvare-Gaume, J. Polchinski and M. Wise, Nucl. Phys. B**221**, 495 (1983).

[4] K Lane, hep-ph/9805254, and references therein.

[5] S. Coleman, J. Wess and B. Zumino, Phys. Rev. **D177**, 2239 (1969); C.G. Callan, S. Coleman, J. Wess and B. Zumino, Phys. Rev. **D177**, 2247 (1969); S. Weinberg, Physica **96A**, 327 (1979).

[6] F. Larios, E. Malkawi, and C.-P. Yuan, hep-ph/9704288, and references therein.

[7] K. Fujikawa and A. Yamada, Phys. Rev. **D49**, 5890 (1994).

[8] M. Alam *et al.*, CLEO collaboration, Phys. Rev. Lett. **74**, 2885 (1995).

[9] G. Altarelli, R. Barbieri, and F. Caravaglios, hep-ph/9712368, and references therein.

[10] E. Malkawi and C.–P. Yuan, Phys. Rev. **D50**, 4462 (1994).

[11] R.D. Peccei, S. Peris and X. Zhang, Nucl. Phys. **B349**, 305 (1991).

[12] C.-X. Yue, Y.-P. Kuang and G.-R. Lu, Phys. Rev. **D56**, 291 (1997).

[13] T. Tait and C.-P. Yuan, hep-ph/9710372, and references therein.

[14] C.-P. Yuan, Mod. Phys. Lett. **A10**, 627 (1995).

[15] C. Balazs, J.L. Diaz-Cruz, H.J. He, T. Tait, and C.-P. Yuan, hep-ph/9807349, and references therein.

[16] M.A. Luty, Phys. Rev. D**41**, 2893 (1990); M. Suzuki, Phys. Rev. D**41**, 3457 (1990).