Top, Bottom Quarks and Higgs Bosons

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In this talk, I will discuss possible new physics effects that modify the interaction of Higgs boson(s) with top and bottom quarks, and discuss how to detect such effects in current and future high energy colliders.

1 Introduction

Two of the great mysteries in the elementary particle physics are the cause of the electroweak symmetry breaking (that generates masses for the weak gauge bosons $W^\pm$ and $Z$) and the origin of the flavor symmetry breaking (that generates masses for quarks and leptons). In the Standard Model (SM), both symmetry breaking mechanisms are explained by introducing a single Higgs boson doublet field. The $W$ and $Z$ bosons gain their masses from Goldstone boson mechanism and the fermions gain their massed from Yukawa interactions. In the SM, the mass of the Higgs boson can receive a large radiative correction that is proportional to the square of the cutoff scale beyond which new physics effect has to take place. In order for the SM to be a valid field theory all the way up to the Planck’s scale (about $10^{19}$GeV), the mass of the SM Higgs boson has to be somewhere around 130 GeV to 180 GeV (to satisfy the naturalness condition). Furthermore, to explain the diverse fermion mass spectrum, every fermion has to be assigned a different Yukawa coupling. The fact that the mass of the top quark is so large as compared to the other fermions and is close to the vacuum expectation value suggests that top is a

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special quark and it may play a role in the electroweak symmetry breaking. If that is the case, then the flavor symmetry breaking and the electroweak symmetry breaking mechanisms may be related. In this talk I will discuss two different classes of models – one is the strongly interacting models and another is the weakly interacting models. The typical strongly interacting models are Technicolor, top-condensate, topcolor and top-seesaw models, and the weakly interacting models are supersymmetry models, particularly, the minimal supersymmetric standard model (MSSM). In the former class of models, the electroweak symmetry breaking is generated dynamically and usually results in composite (in contrast to elementary) Higgs bosons. On the contrary, in the latter class of models, the electroweak symmetry breaking is generated spontaneously and results in elementary Higgs bosons. I shall take the topcolor model and the MSSM as two examples to discuss the phenomenology predicted by these two classes of models and to identify a few experiments at high energy colliders that can distinguish these models assuming some new physics signals are found.

2 Models

2.1 Topcolor model

In the topcolor model, the mass of the top quark is generated by topcolor dynamics that also contributes to the electroweak symmetry breaking and induces two composite Higgs boson doublets in its low energy effective theory. The physical (composite) scalars are $t$-Higgs ($H^0_t$), top-pions ($\pi^0_t, \pi^\pm_t$) and $b$-Higgs ($H^0_b, A^0_b, H^\pm_b$). Because the topcolor dynamics has to be strong enough to make top quark and antiquark to form condensate to generate the large top quark mass as well as to contribute to part of the weak boson masses, the Yukawa couplings of $t$-Higgs (or top-pions) with top quarks have to be large (at the order of 1). Furthermore, because the bottom quark is the isospin partner of the top quark, the

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strong topcolor dynamics that a left-handed top quark experiences
will also affect the bottom quark. Hence, the Yukawa coupling of
b-Higgs with bottom quarks have to be large as well. This should
be compared with the SM in which the Yukawa coupling of top
quark to the SM Higgs boson is about 1 while the coupling of bot-
tom quark is much less than 1 (about 1/50 at the 100 GeV scale).
In this model, tau lepton does not involve the topcolor dynamics
so that it does not directly couple to the composite scalars and its
Yukawa coupling vanishes. (Its mass has to be generated by other
mechanics, such as the technicolor dynamics. Again, this is differ-
ent from the SM prediction which is equal to $\sqrt{2}m_\tau/v$ where
$v$ is the vacuum expectation value ($\sim 246$ GeV) and $m_\tau$ is the mass of
tau. Hence, it is expected that the collider phenomenology of this
model will be significantly different from the SM.

As noted above, there are also charged Higgs bosons and top-
pions predicted in this model. Their couplings to the top, bottom,
and charm quarks are shown in the equation below:

$$
\mathcal{L}^{tc} = \frac{m_t \tan \beta}{v} \left[ i K_{UR}^{tt} K_{UL}^{tt} \bar{t}_R \pi_0^t + \sqrt{2} K_{UR}^{bb} \bar{b}_R \pi_0^t + i K_{UR}^{tc} K_{UL}^{tc} \bar{c}_R \pi_0^t + \frac{1}{\sqrt{2}} K_{UR}^{tb} K_{DL}^{tb} \bar{b}_R \pi_0^t + \text{h.c.} \right],
$$

(1)

where $\tan \beta = \sqrt{(v/v_t)^2 - 1}$ and $v_t \simeq O(60 - 100)$ GeV is the top-
pion decay constant; $K_{UL,R}$ and $K_{DL,R}$ are rotation matrices that
diagonalize the up- and down-quark mass matrices $M_U$ and $M_D$, 
i.e., $K_{UL}^\dagger M_U K_{UR} = M_U^{\text{dia}}$ and $K_{DL}^\dagger M_D K_{DR} = M_D^{\text{dia}}$, from which
the CKM matrix is defined as $V = K_{UL}^\dagger K_{DL}$. As shown in Ref.5,
a typical topcolor model, that is consistent with all the precision
low energy data, gives

$$
K_{UR}^{tt} \simeq 0.99 - 0.94, \quad K_{UR}^{tc} \simeq 0.11 - 0.33, \quad K_{UL}^{tt} \simeq K_{DL}^{tb} \simeq 1.\quad (2)
$$

As to be discussed later, the large flavor mixing between $t_R$ and
cR can lead to very distinct collider signatures. One example is to
induce a large single-top event rate6 at hadron colliders.
2.2 MSSM

In the MSSM, the electroweak symmetry is radiatively broken due to the contribution of the heavy top quark in loops. (It would not have worked if the top quark were not heavy enough.) Therefore, in this model, top quark also plays a special role in the electroweak symmetry breaking. Two Higgs doublet fields are required in the MSSM by the requirement of supersymmetry. Among the eight real fields, three of them are the Goldstone bosons which generate the masses of the weak gauge bosons and five of them are the two CP-even Higgs bosons \((h\) and \(H)\), one CP-odd Higgs boson \((A)\) and two charged Higgs bosons \((H^{\pm})\). Their couplings to the fermions are derived by demanding one Higgs doublet couple to the up-type fermions and another to the down-type fermions, which is similar to a type-II two-Higgs-doublet model\(^4\). For example, the tree level Yukawa couplings of \(A-b-b\) and \(A-t-t\) are \(\sqrt{2}m_b \tan \beta/v\), and \(\sqrt{2}m_t \cot \beta/v\), respectively, where \(\tan \beta\) is the ratio of the two vacuum expectation values. For a large \(\tan \beta\), the coupling of \(A-b-b\) can become \(O(1)\), while the coupling of \(A-t-t\) becomes very small. This pattern of the Yukawa couplings is not only different from that in the SM (where the top Yukawa coupling is much larger than the bottom Yukawa coupling) but also different from the top-color model (where both the top and bottom Yukawa couplings are \(O(1)\)). This difference is the crucial element that allows us to distinguish different classes of electroweak symmetry braking models by carefully examining the experimental data. We shall come back to this point in the next section.

A perfect supersymmetric theory cannot describe the Nature. (Otherwise, we would have seen various supersymmetric partners of the observed particles.) Hence, supersymmetry has to be broken. To incorporate the effect from the yet-to-be found supersymmetry breaking mechanism, the MSSM contains the soft-breaking sector in its Lagrangian to parameterize all such possibilities. One interesting possibility induced by a general soft-breaking sector is that
the top-squark and the charm-squark can be largely mixed to yield a sizable flavor mixing between top and charm.

In the soft breaking sector of the MSSM Lagrangian, the squark mass terms and the trilinear $A$-terms are written as

$$-\tilde{Q}^i(M^2_{\tilde{Q}})_{ij}\tilde{Q}_j - \tilde{U}^i(M^2_{\tilde{U}})_{ij}\tilde{U}_j - \tilde{D}^i(M^2_{\tilde{D}})_{ij}\tilde{D}_j$$

$$+(A^u_i\tilde{Q}_iH_u\tilde{U}_j - A^d_i\tilde{Q}_iH_d\tilde{D}_j + \text{c.c.}).$$

The squark mass matrices are generally $6 \times 6$ matrices, e.g.

$$\tilde{M}^2_u = \begin{pmatrix} M^2_{LL} & M^2_{LR} \\ M^2_{LR} & M^2_{RR} \end{pmatrix},$$

with

$$M^2_{LL} = M^2_{\tilde{Q}} + M^2_u + \frac{1}{6} \cos 2\beta (4m^2_w - m^2_z),$$

$$M^2_{RR} = M^2_{\tilde{U}} + M^2_u + \frac{2}{3} \cos 2\beta \sin^2 \theta_w m^2_z,$$

$$M^2_{LR} = A_u v \sin \beta / \sqrt{2} - M_u \mu \cot \beta,$$

where $M_{\tilde{Q}}, M_{\tilde{U}}$ and $A_u$ can all be non-diagonal in the flavor space. One such model can be generated by imposing a horizontal $U(1)_H$ symmetry, which is called the Type-B supersymmetry model in Ref. 7. Another way to generate the up-type squark mixings is to have a non-diagonal $A_u$ in the flavor space. Motivated by the charge-color-breaking (CCB) and vacuum stability (VS) bounds, we define at the weak scale

$$A'_u = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & x \\ 0 & y & 1 \end{pmatrix} A,$$

where $(x, y) = O(1)$ and $A'_u$ is $A_u$ in the super-CKM basis (where the quark mass matrix $M_u$ is diagonal). Hence, we have generated large flavor-mixings in the $\tilde{t} - \tilde{c}$ sector, which are consistent with all
low energy experimental flavor changing neutral current (FCNC) data and theoretical CCB/VS bounds. Without losing generality, we define the Type-A1 model as $x \neq 0$, $y = 0$ and Type-A12 model as $x = 0$, $y \neq 0$. It is obviously that in the former model $\tilde{c}_L$ decouples, and in the latter model $\tilde{c}_R$ decouples. (Here, we assume $M^2_{LL} \simeq M^2_{RR} \simeq \tilde{m}_0^2 I_{3 \times 3}$, for simplicity.) It has been shown in Ref. 7 that both Type-A and Type-B models can radiatively generate large flavor-mixing Yukawa couplings to quarks. The effect of these large flavor-mixing Yukawa couplings to the collider phenomenology will be discussed in section 4.

Figure 1: 95% C.L. discovery reach of the Tevatron Run II and the LHC for (a) the two Higgs doublet extension of top-condensate model and (b) the topcolor assisted technicolor model. Regions above the curves can be discovered. The top curves in (b) indicate the Yukawa coupling strength for various topcolor breaking scale $\Lambda$.
In Ref.\textsuperscript{8}, we calculated the cross sections of the $gg, q\bar{q} \to b\bar{b}\phi^0$ processes at the Tevatron and the LHC, where $\phi^0$ denotes a (pseudo-) scalar predicted in the strongly interacting topcolor model, the two Higgs doublet extension of top-condensate model\textsuperscript{9}, and the MSSM.

To suppress the large SM QCD backgrounds in the detection mode of $\phi^0 \to b\bar{b}$, a set of kinematic cuts has to be applied together with 3 or more $b$-tags. As shown in Fig.\textsuperscript{1}, for the class of strongly interacting models, the Tevatron Run II and the LHC are able to either exclude an entire model or a large part of the model parameters if the $\phi^0 b\bar{b}$ signal is not found experimentally. Likewise, for the class of weakly interacting models, such as the MSSM, a large portion of the supersymmetry parameters on the tan $\beta$ versus $m_A$ plane can be probed at the Tevatron and the LHC. However, because the coupling of $A-b-b$ can receive large (about a factor of 2) radiative corrections from the supersymmetric particle threshold effect and the QCD interaction, the precise region of tan $\beta$ as a function of $m_A$ that can be studied via the above processes will depend on other supersymmetry parameters, such as the $\mu$ parameter and the top-squark masses, cf. Fig.\textsuperscript{2} quoted from Ref.\textsuperscript{8}. Nevertheless, the constraint provided by this process on the tan $\beta - m_A$ plane is complementary to that provided by the associated production of the weak gauge boson and the Higgs boson.

If the mass of $\phi^0$ is large, it can be dominantly produced from the s-channel fusion process $b\bar{b} \to \phi^0$ at hadron colliders. The cross sections of this process for various models were also given in Ref.\textsuperscript{10}.

As noted in the previous section, to distinguish the strongly interacting from the weakly interacting models, one should also examine the production of $t\bar{t}\phi^0$ in addition to the $b\bar{b}\phi^0$ channel. Furthermore, to distinguish those two classes of models in the $b\bar{b}\phi^0$ channel, one can examine the tau lepton decay mode of $\phi^0$. (In the topcolor model, $b$-Higgs do not couple strongly to the tau lepton, while in the MSSM with a large tan $\beta$, the coupling of $\phi^0-\tau-\tau$ is
Figure 2: 95% C.L. exclusion contours in the $m_A$-$\tan \beta$ plane of the MSSM. The areas above the four boundaries are excluded for the Tevatron Run II with the indicated luminosities, and for the LHC with an integrated luminosity of 100 fb$^{-1}$. The soft supersymmetry breaking parameters were chosen uniformly to be 500 GeV in Fig. (a), while the inputs of the “LEP II Scan A2” are used for the Fig. (b) in which LEP II excludes the left area of the solid curve.
large.) We summarize this part of discussion in Table 1.

Table 1: Predictions of different classes of models on various data, where $\sigma(bb\phi^0)$ is the cross section of the $bb\phi^0$ event with $\phi^0$ representing the scalars predicted in the corresponding model, and $Br$ denotes the branching ratio.

| Data \ Model | Topcolor | MSSM with a large tan $\beta$ |
|--------------|----------|-------------------------------|
| $\sigma(bb\phi^0)$ | large | large |
| $\sigma(tt\phi^0)$ | large | small |
| $\frac{Br(\phi^0\rightarrow\tau^+\tau^-)}{Br(\phi^0\rightarrow bb)}$ | zero | $\frac{m_H^2}{3m_\phi^2}$ |

4. $c\bar{b} \rightarrow H^+$

If the mass of a charged Higgs boson is less than $\sim 170$ GeV, it can be studied via the decay process $t \rightarrow H^+b$ using the large data sample of the $tt$ pairs expected at the Tevatron and the LHC. For a heavy charged Higgs boson, the $H^+H^-$ pair production rate is usually small unless enhanced by some resonant effect. One such example is to have have a heavy neutral Higgs boson with mass larger than twice of $m_{H^+}$ in the MSSM. It can also be associated produced with a top quark via $gb \rightarrow H^+t$ [1], but again with a small rate. In [13], it was pointed out that $H^+$ can be produced via the s-channel process $cs \rightarrow H^\pm$ because of the large parton luminosities of charm and strange quarks at the LHC. Furthermore, if the flavor-mixing coupling of $c\cdot b$-$H^+$ can be large, then $H^+$ can also be produced via $cb \rightarrow H^\pm$.

In the topcolor model, the mass of top-pion $\pi_{t}^\pm$ is expected to be around the weak scale, and the typical values of the Yukawa
Figure 3: Cross sections for $\pi_t^\pm$ production: NLO (solid), the $q\bar{q}'$ (dashed) and $qg$ (dash-dotted) sub-contributions, and the LO (dotted). $qg$ cross sections are multiplied by $-1$.

couplings of top-pions are those given in Eqs. (1) and (2). To find out the typical production rates of the charged top-pions predicted by the topcolor model, we chose $\tan \beta = 3$ and $K_{UR}^{tc} = 0.2$. The results are shown in Fig. 3.

We note that for a given $m_{\pi_t}$, the allowed range of the Yukawa couplings has to be checked by comparing with low energy precision data. A recent study for the topcolor assisted technicolor model can be found in Ref. 13. To test this model’s prediction, we can study the single-top event signature from $c\bar{b} \to H^+ \to t\bar{b}$. The invariant mass distribution of the $t-\bar{b}$ system can reveal the existence of such a resonant, cf. Fig. 4. To truly test this model, one should also check that the polarization of the final state top quark is right-handed because of its couplings, cf. Eq. (1). In contrast, the top quark produced from the SM single top processes, either the s-
channel process $q\bar{q}' \rightarrow W^* \rightarrow t\bar{b}$ or the t-channel process $qb \rightarrow q't$, are almost one hundred percent left-handedly polarized.

Similarly, in the MSSM, a sizable flavor-mixing $c-b-H^+$ coupling can be radiatively generated through radiative correction arising from the large stop and scharm mixings. At the tree level, the coupling of $c-b-H^+$ is suppressed by the CKM matrix element $V_{bc}$ which is about 0.04. Hence, even with the large enhancement factor from a large $\tan\beta$, the tree level rate of $c\bar{b} \rightarrow H^+$ is still smaller than that of $c\bar{s} \rightarrow H^+$ at the Tevatron and the LHC because the parton luminosity of the strange quark is much larger than that of the bottom quark. As shown in Ref. [7], the Type-A supersymmetry models with the non-diagonal scalar trilinear $A$-term for the up-type squarks can enhance the $c-b-H^+$ coupling from the contribution of stop, scharm and gluino in loops. For $y = 0$ and $x \sim O(1)$ (i.e. Type-A1 model), the production rate of $c\bar{b} \rightarrow H^+$ can be increased by a factor of 2 to 5 as compared to its tree level rate, depending on

Figure 4: Distribution of $t-b$ invariant mass of the charged top-pion production.
Figure 5: $H^\pm$ production via $cb$ (and $cs$) fusions at hadron colliders.

the value of $x$. In Fig. 5, we show the single charged Higgs boson production rate for a typical choice of the supersymmetry parameters $(m_{\tilde{g}}, \mu, \tilde{m}_0) = (300, 300, 600)$ GeV, $(A, -A_b) = 1.5$ TeV, and $\tan\beta = (15, 50)$ with $x = 0.75$.

5 $t \to c\phi^0$

The flavor-mixing dynamics predicted by models can also be tested from the FCNC decay of the top quark, such as $t \to c\phi^0, c\gamma, cg$.

It is known that the SM branching ratio of the flavor-changing top decay $t \to ch^0$ is extremely small ($\sim 10^{-13} - 10^{-14}$), so that this process provides an excellent window for probing new physics. In the topcolor model the low energy precision data requires the mass of the top-pions not to be too small as compared to the top quark mass $m_t$. In case that $m_{\pi}^0 < m_t - m_c$, the decay process $t \to c\phi^0$ can occur at tree level, cf. Eq. (1), which can impose further
constraint on the model if such a signal is not found experimentally. A few recent studies on the other FCNC processes predicted by the topcolor model can be found in Ref. 15.

In the MSSM, the loop induced $t$-$c$-$h^0$ coupling can be greatly enhanced depending on the detailed parameters of the model. In Ref. 7, we showed that in the Type-A1 model this effect can be large. Assuming that the only dominant decay mode of the top quark is its SM decay mode, i.e. $t \rightarrow bW$, the decay branching ratio of $t \rightarrow ch^0$ is given by $\text{Br}[t \rightarrow ch^0] \simeq \Gamma[t \rightarrow ch^0]/\Gamma[t \rightarrow bW]$. As summarized in Table 2, $\text{Br}[t \rightarrow ch^0]$ can be as large as $10^{-3} - 10^{-5}$ over a large part of the supersymmetry parameter space where the mass of the lightest Higgs boson $h^0$ is around $110 - 130$ GeV. Since the LHC with an integrated luminosity of 100 fb$^{-1}$ can produce about $10^8$ $t\bar{t}$ pairs, it can have a great sensitivity to discover this decay channel and test the model predictions, by demanding one top decaying into the usual $bW^\pm$ mode and another to the FCNC $ch^0$ mode.

Table 2: $\text{Br}[t \rightarrow ch^0] \times 10^3$ is shown for a sample set of Type-A1 inputs with $(\tilde{m}_0, \mu, A) = (0.6, 0.3, 1.5)$ TeV and Higgs mass $M_{h^0} = 0.6$ TeV. The three numbers in each entry correspond to $x = (0.5, 0.75, 0.9)$, respectively.

| $m_{\tilde{g}}$ | $\tan \beta = 5$ | 20 | 50 |
|----------------|------------------|----|----|
| 100 GeV        | (.011, .10, .81) | (.015, .19, 4.6) | (.016, .21, 7.0) |
| 500 GeV        | (.011, .09, .41) | (.015, .13, 1.0) | (.016, .14, 1.2) |
6 Conclusion

Because the mass of the top quark is close to the weak scale, it may play an essential role in the breaking of the electroweak symmetry. Two classes of models — strongly interacting and weakly interacting models — are considered. In the topcolor model, the Yukawa couplings of the top quark are large. As an isospin partner of the top quark, the bottom quark can also experience large Yukawa interactions. With the possibility of having a large flavor-mixing between the (right-handed) top- and charm-quarks, the charged top-pions can be copiously produced via the s-channel $cb$-fusion process at high energy colliders, due to its large Yukawa coupling and the sizable parton luminosities. In the MSSM, the flavor symmetry is tightly connected to the supersymmetry breaking through the introduction of the soft breaking sector in the Lagrangian. To carefully study the flavor-mixing and the flavor changing neutral current processes can advance our knowledge on the supersymmetry breaking mechanism. This point was demonstrated in some production and decay processes. Although through out this talk, I only concentrated on the phenomenology at hadron colliders, some similar effects are also expected in the future Linear Colliders. For example, a polarized $\gamma\gamma$ collide can test the chirality of the Yukawa coupling of $b\rightarrow cH^+$ by studying the single charged Higgs boson production\cite{16}.

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