Scalars from Top-condensation Models at Hadron Colliders

Gustavo Burdman

*Department of Physics, University of Wisconsin, Madison WI 53706.*

We study the production and decay of neutral scalars and pseudo-scalars at hadron colliders, in theories where the top-quark mass is the result of a $t\bar{t}$ condensate. We show that the dominant decay channel for masses below the $t\bar{t}$ threshold is the flavor changing mode $tc$. This is a consequence of the non-universal nature of the underlying interactions in all top-condensation models and provides a model-independent signature of these scenarios. We show that an upgraded Tevatron is sensitive to a sizeable region of the interesting parameter space and that the LHC will highly constrain these models through this flavor violating channel.

PACS numbers: 12.60.Fr, 14.80.Cp, 12.60.Rc

---

The generation of a large fermion mass such as $m_t$ is a difficult problem in theories of dynamical Electroweak Symmetry Breaking (ESB). The idea of the top quark mass as a "constituent", dynamical mass generated by the presence of a condensate ($t\bar{t}$) addresses this problem, providing at the same time a source of dynamical ESB not requiring large amounts of new matter. In the original top-condensation standard model [1], the formation of the $t\bar{t}$ condensate is fully responsible for the masses of the standard model (SM) gauge bosons as well as for the dynamical generation of $m_t$. If the scale of the interaction driving the condensation is $\Lambda$, then at lower energies there is a scalar doublet, the top-Higgs, which acquires a vacuum expectation value (VEV). Just as in the SM, the Nambu-Goldstone bosons (NGB) are eaten by the $W$ and $Z$, leaving a neutral, CP-even scalar particle in the spectrum.

Although the original top condensation model fails to provide a natural picture of ESB, the idea that a $t\bar{t}$ condensate is responsible for the large "constituent" top quark mass is still appealing. The Pagels-Stokar formula relating the NGB decay constant to the cutoff scale $\Lambda$ and the dynamical top quark mass is [2]

$$f_{\pi_\tau}^2 \approx \frac{N_c}{8\pi^2} m_t^2 \ln \frac{\Lambda^2}{m_t^2},$$

where $N_c$ is the number of colors. From Eq. (1) it can be seen that obtaining the correct top quark mass and $f_{\pi_\tau} = v \approx 246$ GeV forces the cutoff scale to be $\Lambda \simeq 10^{15}$ GeV. This results in the need of extreme fine tuning of the coupling of the underlying gauge interaction (Topcolor), reproducing the naturalness problem of the SM we set out to solve in the first place. On the other hand, if $\Lambda \simeq \mathcal{O}(1)$ TeV we obtain $f_{\pi_\tau} \approx (70 - 80)$ GeV, not enough to fully break the electroweak symmetry. Thus, one can imagine that there is an additional source of ESB such that this deficit is covered. This is the case in the Topcolor Assisted Technicolor (TATC) scenario proposed by Hill [3], where Technicolor gives most of the $W$ and $Z$ masses. In addition, in this scenario Extended Technicolor (ETC) is invoked to generate fermion masses up to $\mathcal{O}(1)$ GeV, leaving the burden of most of $m_t$ to Topcolor.

In general, whatever the model invoked to supplement Topcolor in generating $\nu$, it results in an additional set of NGBs. A triplet of these new NGBs mixes with the one resulting from the breaking of the top quark chiral symmetry: one set is absorbed by the $W$ and the $Z$ and the other one, the so called top-pions, remains in the spectrum. In the TATC scenario the top-pions acquire masses in the range $m_{\pi_\tau} \simeq (100 - 300)$ GeV. The neutral CP-even state analogous to the $\sigma$ particle in low energy QCD, the top-Higgs, is a $t\bar{t}$ bound state and its mass can be estimated in the Nambu–Jona-Lasinio (NJL) model in the large $N_c$ approximation, to be

$$m_h \simeq 2m_t.$$

This estimate is rather crude and it should be taken as a rough indication of where the top-Higgs mass could be. Masses well below the $t\bar{t}$ threshold are quite possible and occur in a variety of cases [4].

The search for scalars from top-condensation models has been previously considered in the literature for the case of the charged top-pions from Topcolor [4]. In this paper, we will examine the prospects for the observation of the top-Higgs $h_t$ and the neutral top-pion $\pi_{\tau \nu}$ at hadron colliders. Most viable models of top condensation feature additional scalars. Here we concentrate on those that couple to $t\bar{t}$ since this endows them with a large Yukawa coupling

$$r \equiv \frac{m_t}{f_{\pi_\tau}}.$$

This implies that the cross sections in production mechanisms governed by the top-Yukawa coupling are enhanced by a factor of $r^2 \approx 10$ with respect to the equivalent SM
Higgs production processes \[1\]. Such is the case with gluon-gluon fusion, as well as the emission from a top quark line. On the other hand, the associated production with electroweak gauge bosons, the search channel for the SM Higgs boson at LEP and at the Tevatron, is suppressed by the factor \(r^2\) in the case of the top-Higgs production, a reflection of the fact that only a fraction of \(M_W\) and \(M_Z\) come from the top condensation mechanism.

Just as for the SM Higgs boson, the dominant production mechanism at hadron colliders is through gluon-gluon fusion. The fact that the cross section is \(r^2\) times larger than in the SM is of little help if the \(h_t\) and \(n_t^0\) decay modes are subjected to the same insurmountable backgrounds. A crucial observation is that the underlying interactions in top condensation models are non-universal and therefore do not possess a Glashow-Iliopoulos-Maiani (GIM) mechanism. This is an essential feature of these models due to the need to single out the top quark for condensation. For instance in TATC models the Topcolor gauge interactions are \(SU(3)_1 \times SU(3)_2\), which breaks down to the standard \(SU(3)_c\) of QCD at the TeV scale. Here the \(SU(3)_1\) couples strongly to the third generation quarks and becomes chiral-critical giving rise to \(\langle t\bar{t}\rangle \neq 0\). These non-universal gauge interactions result in Flavor Changing Neutral Current (FCNC) vertices of the heavy gauge bosons, the top-gluons, when one writes the interactions in the quark mass eigen-basis. As long as the top-gluons masses are in the several hundred GeV range and above, conflicts with low energy data are avoided \[3\]. Furthermore, the neutral scalar sector of Topcolor theories exhibits the same FCNC vertices. For instance, the off-diagonal top-Higgs couplings take the form

\[
\frac{m_t}{\sqrt{\sigma}} h_t \left\{ U_L^{(tt)} U_R^{(tc) \dagger} \bar{t}_L c_R + U_L^{(tc) \dagger} U_R^{(tt)} \bar{c}_L t_R \right\} + U_L^{(tt) \dagger} U_R^{(tu) \dagger} \bar{t}_L u_R + U_L^{(tu)} U_R^{(tt) \dagger} \bar{u}_L t_R \right\}. \tag{4}
\]

Here \(U_L\) and \(U_R\) are the left and right-handed up quark rotation matrices that diagonalize the up quark mass matrix. The Cabibbo-Kobayashi-Maskawa (CKM) matrix is given by \(V_{CKM} = U_L^{(t)} D_{L}^{(tb)} U_R^{(tb) \dagger}\), where \(D_{L}\) is the analogous matrix in the left-handed down quark sector. Thus, although the off-diagonal elements of \(U_L\) and \(U_R\) are not parameters measured independently, our knowledge of \(V_{CKM}\) and the quark masses allows us to estimate the most natural region of their parameter space. A simple assumption is that the diagonal elements of \(U_{L,R}\) and \(D_{L,R}\) are close to unity and that they are increasingly suppressed as one moves away from the diagonal. Independently of the nature and size of the off-diagonal suppression, this gives a prescription to estimate how large the elements of these matrices can be without the mediation of unnatural cancellations. Then, for instance, we have

\[
V_{cb} = U_L^{(uc) \dagger} D_{L}^{(db)} + U_L^{(cc) \dagger} D_{L}^{(sb)} + U_L^{(ct) \dagger} D_{L}^{(bb)} \nonumber \sim D_{L}^{(sb)} + U_L^{(ct) \dagger} \sim \mathcal{O}(\lambda^2), \tag{5}\]

and

\[
V_{ub} = U_L^{(uu) \dagger} D_{L}^{(db)} + U_L^{(cu) \dagger} D_{L}^{(sb)} + U_L^{(tu) \dagger} D_{L}^{(bb)} \nonumber \sim D_{L}^{(db)} + U_L^{(cu) \dagger} D_{L}^{(sb)} + U_L^{(tu) \dagger} \sim \mathcal{O}(\lambda^3), \tag{6}\]

where \(\lambda \approx 0.22\) is the Cabibbo angle in the Wolfenstein parametrization of \(V_{CKM}\). Then it is natural to assume \(U_L^{(tc)} \sim \mathcal{O}(\lambda^2)\) and that the \(\bar{u}_L t_R\) coupling in Eq. (4) can be neglected. On the other hand, there are no similar constraints on the off-diagonal elements of \(U_R\) unless something is known about \(m_t\), the mass matrix in the weak eigen-basis. For instance, it was shown in \[4\] that with the dynamically generated triangular textures proposed in \[5\], and assuming that the dynamical top quark mass makes up 99% of \(m_t\), one obtains the rather loose bound \(U_R^{(tc)} < 0.15\). Other, more specific realizations of the TATC scenario \[6\] suggest much smaller values of \(U_L^{(tc)}\), although still allow large values for \(U_R^{(tc)}\).

In Fig. 1 we plot the branching ratios of the top-Higgs vs. its mass. For the \(h_t \rightarrow t\bar{t}\) decay mode we use \(U_{tc} = 0.05\), a rather conservative value closer to \(\bar{t}\) than to the \(U_R^{(tc)}\) upper bound. As mentioned above, the

![FIG. 1. The top-Higgs branching fractions as a function of its mass. The solid line is the \(t\bar{t}\) decay mode, the dashed line is \(VV = (WW + ZZ)\), the dot-dash line corresponds to \(h_t \rightarrow (t\bar{t} + tc)\), the upper and lower dotted lines correspond to \(bb\) and \(gg\) respectively.](image-url)
with typical branching ratios of about 70%. Thus, for \( m_{tc} < 2m_t \), anomalous single top production in association with a charm jet could provide a clean signal for the discovery of the top-Higgs at the Fermilab Tevatron. Almost identical conclusions apply to the top-pions, where the only difference is the absence of the gauge boson decay channels, which causes the branching ratio to \( tc \) to be slightly higher. Top-pions with masses below the \( t\bar{t} \) threshold cause large negative deviations in the \( Z \rightarrow \bar{b}b \) vertex \([10]\) and unless some other contribution cancels them, they are in conflict with the current measurement of \( R_b \) from experiments at the \( Z \) pole. On the other hand, if such cancellations exist the top-pions could lie below \( 2m_t \) and be observed in the \( \pi^0 \rightarrow tc \) channel as well.

In Fig. 2, we plot the top-Higgs production cross section via gluon fusion times its branching ratio to \( (t\bar{c} + tc) \) for various values of the parameter \( U_{tc} \). For instance for values as small as \( U_{tc} = 0.02 \) a few hundred events are produced at the Tevatron in Run II. Thus the signal is expected to be sizeable even after assuming 60% \( b \)-tagging efficiency and the \( e, \mu \) decay modes of the \( W \). This is more so since the signal presents a narrow peak in the top-jet invariant mass distribution. The top-Higgs total width is

\[
\Gamma_{h_t} < 7 \text{ GeV}. \tag{7}
\]

Thus, the top-charm mass distribution will present a narrow resonance which should be observable above the smooth background. The main backgrounds for this process are \( Wjj \), with one of the light jets tagged as a \( b \)-jet; \( W\bar{b}b \), where one of the \( b \)-tags is missed; and the SM single top production. The number of events in the signal region is expected to be comparable for signal and background \([11]\) for intermediate values of \( U_{tc} \). To illustrate this point we plot in Fig. 3 the mass distribution for the top and the charm jet for \( m_{h_t} = 200 \) and 300 GeV, \( U_{tc} = 0.05 \), and the leading backgrounds \([12]\) \( Wjj \) and \( W\bar{b}b \), using the cuts of Ref. \([11]\). The signal is smeared assuming a resolution given by \( \Delta M_{tj}/M_{tj} = 0.80/\sqrt{M_{tj}} \), with \( M_{tj} \) in GeV. For instance, taking a region of \( \pm 2 \Delta M_{tj} \) around the peaks results in a significance \( S/\sqrt{B} = 10.6 \) for \( m_{h_t} = 200 \) GeV, and \( S/\sqrt{B} = 5.8 \) for \( m_{h_t} = 300 \) GeV, for \( 2 fb^{-1} \) of integrated luminosity. Although not a substitute for a complete background study, this already suggests that for rather natural values of \( U_{tc} \) the Tevatron in Run II will be sensitive to the top-Higgs and top-pions below the \( t\bar{t} \) threshold.

At the CERN Large Hadron Collider (LHC) the signal is considerably enhanced due to the dominance of partonic gluons, and although backgrounds can be very large (particularly \( t\bar{t} \) and \( Wcj \) \([11]\)) the signal should be observable in most cases. In Fig. 4, we plot the top-Higgs production cross section times the branching ratio to top-charm as a function of \( m_{h_t} \) and for various values of the parameter \( U_{tc} \). For instance, for \( m_{h_t} = 300 \) GeV and assuming the same \( b \)-tagging efficiency as for the Tevatron, as well as the \( e, \mu \) decay modes, there will be approximately 6000 events/\( fb^{-1} \). Thus the discovery of top-Higgses and top-pions at the LHC should be possible for a wide range of values of \( U_{tc} \).

There are other models of top-condensation that in principle give rise to GIM violating interactions and in which the scalar sector will also exhibit \( tc \) couplings similar to those in Eq. (4). However, they do not always lead to signals as large as the ones discussed above. An example is the Top see-saw model of Ref. \([13]\). Unlike in TATC, here the Topcolor interactions fully break the electroweak symmetry implying that \( r = 1 \), and therefore there is no enhancement in the production via gluon fusion. Moreover, now the \( WW \) and \( ZZ \) dominate the decay of the lightest CP even state, analogous to the Higgs, which has a very small branching ratio to the flavor changing \( tc \).
channel. On the other hand, the low energy theory of the Top see-saw scenario, contains CP-odd composite scalars that can be light enough to be produced via gluon fusion at the Tevatron and the LHC. Although this is not the most general scenario, it is the case for the region of parameter space for which the Top see-saw Higgs becomes light. In this case, these pseudo-scalar states could be below the threshold and, since they do not decay into the SM gauge bosons, they may also have a large branching fraction to the \( tc \) final state. Due to the suppression at the production end, the discovery of the CP-odd composite states of Top see-saw may be very challenging for the Tevatron in Run II. However, it should be a large signal at the LHC.

Finally, we comment on the possibility that the scalar mass, either for the top-Higgs or the top-pion, is above the \( tt \) threshold. In this case, the \( tt \) decay mode dominates overwhelmingly, making the flavor changing \( tc \) mode negligible at the Tevatron. The sensitivity of the LHC to the \( tc \) mode in this case will depend critically on the value of \( U_{tc} \). On the other hand, the effect of the top-condensation scalars on the \( tt \) cross section is very small, resulting for instance in a contribution of the order of \( \delta \sigma(tt)/\sigma(tt) \approx (1 - 2)\% \) at the Tevatron.

To summarize, we have seen that the gluon fusion production and subsequent flavor changing decay of a top-Higgs or a top-pion into the \( tc \) final state is likely to be the most important signal of top-condensation models at hadron colliders, as long as their masses are below the \( tt \) threshold. This is particularly the case if top-gluon masses are larger than 1 TeV. This is a rather model-independent occurrence and it is rooted in the GIM violating character of the underlying interactions, an essential feature of these models. The flavor changing decay mode resulting in anomalous single top production has a large branching ratio for most of the interesting values of the parameter space. Thus the Tevatron with a few \( fb^{-1} \) of integrated luminosity will be sensitive to Topcolor models, greatly constraining the value of \( U_{tc} \). Rather small values of \( U_{tc} \) can be explored at the LHC, as it can be seen in Fig. 4. In both cases a more detailed study of the background is warranted, in order to establish the sensitivity of each experiment in the \((U_{tc}, m_{h_{1}})\) parameter space.

The author thanks T. Han, R. Harris, D. Rainwater and especially S. Willenbrock for useful comments, and the Enrico Fermi Institute for its hospitality in the early stages of this work. This research was supported in part by the U.S. Department of Energy under Grant No. DE-FG02-95ER40896 and in part by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation.

[1] Y. Nambu, “New Theories In Physics”, Proc. XI Warsaw Symposium on Elementary Particle Physics, (ed. Z. Ajduk et al., publ. World Scientific, Singapore, 1989); V.A. Miransky, M.Tanabashi and M. Yamawaki, Phys. Lett. B221 (1989) 177; R.R. Mendel and V.A. Miransky, Phys. Lett. B 268 384 (1991); W.A. Bardeen, C.T. Hill and M.Lindner, Phys. Rev. D41 1647 (1990).
[2] H. Pagels and S. Stokar, Phys. Rev. D20, 2947 (1979).
[3] C. T. Hill, Phys. Lett. B345, 483 (1995).
[4] R. S. Chivukula, B. Dobrescu, H. Georgi and C. T. Hill, Phys. Rev. D59, 075003 (1999).
[5] H. J.-F. He and C. -P. Yuan, preprint MSUHEP-80801, hep-ph/9810367.
[6] G. Burdman, hep-ph/9611256 in Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass, CO, 25 Jun - 12 Jul 1996, eds. D. G. Cassel et al.
[7] G. Buchalla, G. Burdman, C. T. Hill and D. Kominis, Phys. Rev. D53, 5185 (1996).
[8] D. Kominis, Phys. Lett. B358, 312 (1995).
[9] K. Lane, Phys. Rev. D54, 2204 (1996); ibid, Phys. Lett. B433, 96 (1998).
[10] G. Burdman and D. Kominis, Phys. Lett.B403, 101 (1997); W. Loinaz and T. Takeuchi, preprint VIP-IPPA-98-7, hep-ph/9812377.
[11] T. Stelzer, Z. Sullivan and S. Willenbrock, Phys. Rev. D58, 094021 (1998); A. S. Belyaev, E. E. Boos and L. V. Dudko, Phys. Rev. D59, 075001 (1999).
[12] We use VECBOS, F.A. Berends, H. Kuijf, B. Tausk and W.T. Giele, Nucl. Phys. B357,32 (1991).
[13] B. Dobrescu and C. T. Hill, Phys. Rev. Lett. 81, 2634 (1998).
[14] F. Abe et al., the CDF collaboration, Phys. Rev. Lett. 82, 2038 (1999). For projections for the Tevatron in Run II see R. Harris, hep-ph/9609316 and hep-ph/9609318 in Proceedings of the 1996 DPF/DPB Summer Study on High-Energy Physics, Snowmass, CO, 25 Jun - 12 Jul 1996, eds. D. G. Cassel et al.