SEARCHING FOR $t \to ch^0$ OR $h^0 \to t\bar{c}$
AT $e^+e^-$ LINEAR COLLIDERS

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1. Why?

It is quite legitimate for one to ask: Why? Are there $t-c$–Higgs couplings in Nature? In the Standard Model (SM), tree level flavor changing neutral couplings (FCNC) of the Higgs boson are absent, while at the one–electroweak–loop level, it is still strongly suppressed by the G.I.M. mechanism. In “standard” two Higgs doublet models\(^1\) (called Model I and II), FCNC Higgs couplings are removed by design, and again suppressed by the G.I.M. mechanism at the one–loop level, since the charged Higgs contribution is rather similar to the $W$ boson contribution diagramatically.

However, we now know that the top is rather heavy, and so is the Higgs boson, which functions as the “agent of mass”. Their heaviness suggests that they may hold the key to the question of mass, and as new, undiscovered particles, their properties certainly call for thorough examination.

It was recently pointed out\(^2,3\) that, with more than one Higgs doublet, it is possible to have tree level FCNC Higgs couplings that satisfy the stringent low energy constraints, but are precisely the largest for the top quark. Two generic types of models are given. In Model III, which is basically a generalization of the model of Cheng and Sher\(^4\), FCNC Higgs couplings are of the form

$$\Delta f_{ij} \frac{\sqrt{m_i m_j}}{v} f_i f_j h^0,$$

where $v$ is the electroweak symmetry breaking scale, $f = u, d$ and $e$, and $\Delta$ is of order one. We have denoted the neutral Higgs boson with FCNC coupling generically as $h^0$. It can also be viewed as the lightest such Higgs of phenomenological concern. Note that Eq. (1) reduces to the usual $m_i/v$ for flavor diagonal couplings, while the given pattern is consistent with the quark mass and mixing hierarchies.\(^2\)

Model IV is constructed\(^2\) as a hybrid of Models I/II and III that eliminates FCNC Higgs couplings in the $d$ and $e$ type fermion sectors, but up type quarks have FCNC Higgs couplings of the form of Eq. (1). It is clear that the $t-c-h^0$ coupling is the largest possible one with 3 fermion generations in both Models III and IV.

Before one explores $t \to ch^0$ decays, it is prudent to check with whatever low energy constraint that is available. The FCNC Higgs couplings of Eq. (1)
are proportional to the geometric mean of the external fermion masses, and are thereby very suppressed in low energy processes. Nevertheless, the $d$ type quarks and charged leptons provide stringent constraints, the most notable ones are $K^0 - \bar{K}^0$ mixing, $B^0 - \bar{B}^0$ mixing and $\mu \to e\gamma$, and an earlier analysis lead to a not so stringent bound of $m_{h^0} \gtrsim 80$ GeV. It was recently pointed out that a two–loop mechanism makes $\mu \to e\gamma$ into a rather effective constraint for Model III, leading to a bound of $m_{h^0} \gtrsim 200$ GeV. Although still viable and interesting, the heaviness of the Higgs bosons makes phenomenology rather limited for the near future. However, Model IV is distinguished in the sense that FCNC couplings are decoupled from $d$ type quarks and charged leptons, by construction. In fact, in Model IV, $t - c - h^0$ coupling can be much larger than given by Eq. (1). Given that the $D^0 - \bar{D}^0$ mixing bound is rather poor, there is practically no limit on $m_{h^0}$ coming from low energy FCNC constraints! We remark that the present LEP limit on the neutral Higgs boson mass, $m_{H^0} \gtrsim 60$ GeV, is weakened in general two Higgs models.

The upshot is that, there is in fact little direct experimental constraint on $t - c - h^0$ couplings. If extra (more than one) scalar bosons exist, FCNC couplings of order $\sqrt{m_c m_t}/v$ or greater are conservative and reasonable. Note that since Model II is the Higgs sector of minimal SUSY (MSSM), tree level FCNC is absent in MSSM.

We shall take $t - c - h^0$ coupling as

$$\lambda_{ct} = \sqrt{m_c m_t}/v = \sqrt{G_F m_c m_t}$$

for illustration purposes. For the mass range $m_t = 50 - 200$ GeV, one finds

$$\frac{\lambda_{ct}}{g_2} = \sqrt{m_c m_t}/M_W \simeq 0.1 - 0.2,$$

i.e. weaker than the weak gauge coupling (of order 10–20% in relative strength).

2. Phenomenology

Phenomenological impact would depend on whether the top is lighter than $h^0$ and ...

2.1. $m_{h^0} < m_t < M_W + m_b$

One may think that CDF had ruled out this scenario long ago. In fact, the 1992 (1989) limit $m_t \gtrsim 91$ GeV is now upgraded by the new 92–93 run to roughly $m_t \gtrsim 110$ GeV by CDF and D0. Recall, however, that this is done by assuming the SM $BR(t \to b\ell\nu) \simeq 1/9$ for $\ell = e, \mu$. CDF and D0 in fact measure the effective cross section in the $\ell\nu +$ jets and $\ell\ell\nu\nu +$ jets signatures. Define $B_{h^0} = BR(t \to ch^0)$, i.e.

$$B_{h^0} = \frac{\Gamma(t \to ch^0)}{\Gamma(t \to bW^\ast) + \Gamma(t \to ch^0)} = \frac{R}{1 + R},$$

where $R$ is the ratio of the $t \to ch^0$ rate w.r.t. the SM $t \to bW^\ast$ rate. The counting rate at the Tevatron in these modes should be

$$N(\ell\nu +$ jets $) \equiv \mathcal{L} \times \sigma_{t\ell} \times \frac{8}{27} \times (1 - B_{h^0})(1 + \frac{1}{2}B_{h^0}) \times \epsilon,$$
and
\[ N(\ell\ell'\nu+\text{jets}) \approx L \times \sigma_{t\bar{t}} \times \frac{4}{81} \times (1 - B_{h^0})^2 \times \epsilon, \]

where \( \epsilon \) is the detector acceptance and efficiency for the respective modes. It is clear that if \( B_{h^0} \to 1 \), the \( m_t \) limit would weaken.

One might expect that \( B_{h^0} \) to be relatively small since from Eq. (2) the \( t-c-h^0 \) coupling is weaker than the \( SU(2) \) gauge coupling. However, in this mass range, \( t \to bW^* \) is a three body decay, while the \( t \to ch^0 \) decay is a two body process, and the smaller FCNC coupling in fact prevails. With the \( t-c-h^0 \) coupling of Eq. (2), \( R \) varies from more than 10 to order 1 as \( m_t \) goes from 50 GeV to 85 GeV.\(^2\) It can be considerably larger in Model IV since the coupling is unconstrained. Thus, \( B_{h^0} \) could be from 50% to more than 90%, and the \( m_t \) limit from CDF is considerably weakened. Note that the limit from the usually more stringent \( \ell\ell'\nu+\text{jets} \) mode weakens faster than the \( \ell\nu+\text{jets} \) mode.

With more accumulated data in the 92–93 run, one could weaken the assumptions on \( B_{s,l} \equiv BR(t \to \ell\nu+X) \) and explore the \( B_{s,l}-m_t \) plane. One would equivalently be “measuring” \( B_{h^0}(m_t) \). This is apparently not yet done, as the new searches seem to be aimed directly at a heavier (than 91 GeV) top, and tighter lepton \( p_T \) cuts have been applied.\(^7\) However, in case CDF and D0 do not recheck the light top option, or if they simply cannot rule out the possibility because \( B_{h^0} \to 1 \), the top quark with \( m_t \sim M_W \) will show up readily at LEP–II as it is turned on in a couple of years.

2.2. \( m_t > M_W + m_h, \ m_{h^0} \)

As \( m_t \) grows beyond the \( M_W \) threshold, \( B_{h^0} \) quickly drops since \( t \to bW \) becomes a two body process. The CDF/D0 search assuming SM branching ratios would then be valid. However, from Eq. (3), we see that in general \( B_{h^0} \sim 1\%, \ i.e. \) basically just the ratio of couplings involved in the respective processes. This branching ratio stays rather flat until one reaches the kinematic limit for \( t \to ch^0 \).\(^2\)

Although the top would be found by CDF/D0, searching for \( t \to ch^0 \) at 1% level would be impossible for the Tevatron, and may be very difficult even for the SSC/LHC. Here, we are interested in whether the 500 GeV \( e^+e^- \) Linear Collider could be of use. The typical benchmark is to assume 10 fb\(^{-1} \) in integrated luminosity, which corresponds to order of \( 10^4 \ t\bar{t} \) pairs. The single most important aspect of Linear Collider capabilities for this purpose is the \( b \) tagging efficiency. SLD has demonstrated \( b \)–tagging efficiencies at the 60–70% level.\(^8\) This is because of the very small beam spot size and superb micro–vertex capabilities. Let us consider two strategies. Using \( t \to \ell\nu+X \) as tag, one expects several thousand clean top events, where the event kinematics can be used to project out 3 jets with \( M_{jjj} \) consistent with \( m_t \). Assuming \( b \) tagging efficiency to be order 0.5, one expects a few events that are consistent with \( t \to ch^0 \to cb\bar{b} \). The expected background from \( t \to bW \to bc\bar{b} \) is 10 times smaller, but actual background rejection has to be further studied. The second method is to demand three \( b \)–jets. Again, background suppression has to be studied, but one expects to retain 10–30 \( t \to cb\bar{b} \) events. However, the six jet event signature is quite entangled, and much work would be needed to be able to utilize the higher statistics.
Clearly, 100 fb$^{-1}$ would be more desirable. Together with the available handles of $m_t$ known to 1 GeV, and perhaps the knowledge of $m_{h^0}$, the $b$–tagging capability at the Linear Collider certainly would make the search for $t \rightarrow ch^0$ easier.

2.3. $m_{h^0} > m_t$

The competing modes would be $h^0 \rightarrow b\bar{b}$, $t\bar{t}$ and $WW$, $ZZ$, but $h^0 \rightarrow t\bar{c}$ may well be dominant, especially if $m_t \lesssim m_{h^0} \lesssim 2m_t$, $2M_W$. For example, for $m_{h^0} = 160$ GeV and $m_t = 130$ GeV, the two allowed modes $h^0 \rightarrow t\bar{c}$ and $b\bar{b}$ are comparable. Since the top quark is presumably already found, detection of $h^0 \rightarrow t\bar{c}$ should be straightforward at the Linear Collider. Note, however, that Higgs production cross sections (scalar, pseudoscalar, charged) are modified in multi–Higgs models.

3. Summary

FCNC $t \rightarrow ch^0$ decays may not be as rare as Standard Model prescribes. Such couplings are not ruled out by known physics, and since the top and Higgs are new, heavy particles, we need to thoroughly examine their properties. The $t \rightarrow ch^0$ mode could dominate over $t \rightarrow bW^*$ and allow the top to evade the CDF bound for the region $m_t \lesssim M_W$. The region can be covered readily by LEP–II. For heavier top, the ballpark number is $BR(t \rightarrow ch^0) \sim 1\%$, which cannot be studied at the Tevatron. The expected high $b$–tagging efficiency can be used at the 500 GeV Linear Collider to establish $t \rightarrow ch^0$ at this level. However, 100 fb$^{-1}$ would be needed to have enough statistics to study the decay in more detail. In case $h^0$ is heavier than the top, searching for $h^0 \rightarrow t\bar{c}$, which could well be the dominant mode, should be easy. The discovery of FCNC $t \rightarrow ch^0$ or $h^0 \rightarrow t\bar{c}$ decays would not only be very exciting in itself, it would also rule out the minimal supersymmetric standard model.

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5. References

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