Perspectives of detecting
CKM-suppressed top quark decays at ILC

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Abstract

Top quark decays are of particular interest as a mean to test the standard model (SM) predictions, both for the dominant ($t \to b + W$) and rare decays ($t \to q + W, cV, cV V, c\phi^0, bWZ$). As the latter are highly suppressed, they become an excellent window to probe the predictions of theories beyond the SM. In particular, in this paper, we evaluate the corrections from new physics to the CKM-suppressed SM top quark decay $t \to q + W$ ($q = d, s$), both within the effective lagrangian approach and the MSSM and we discuss the perspectives to probe those predictions at the ILC.

1 Introduction.

After the discovery of the top quark at Fermilab Tevatron Collider [1][2], experimental attention has been turned on the examination of its production mechanisms and decay properties. Within the Standard Model (SM), the top quark production cross section is evaluated with an uncertainty of the order of $\sim 15\%$, while it is assumed to decay to a $W$ boson and a $b$ quark almost $100\%$ of the time. Due to its exceedingly heavy mass, the top quark is expected to be somehow related to new physics, and measuring its properties may then serve as a window for probing physics beyond the SM [3]. It is also considered that the top quark may give some clue to understand the mechanism of electroweak symmetry breaking.

The interactions of quarks and leptons, with gauge bosons, seem to be correctly described by the $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge theory, as plenty of experimental data shows [4]. At tree-level, SM neutral interactions are diagonal, however, flavor changing neutral currents (FCNC) can arise at loop level. The fact that FCNC $B$-meson decays have been already detected, at
rates consistent with the SM [5], represents a great success for the model itself. However, SM predictions for top quark related processes are strongly suppressed, although corresponding experimental bounds are rather weak. At the coming LHC it is important to study rare top quark decays, because about $10^7 \div 10^8$ top pairs will be produced per year. Thus, rare decays with branching ratios ($BR$) of order $10^{-5} \div 10^{-6}$ may be detectable, depending on the signal. The presence of any hint for new top quark physics at LHC [6], would motivate further study to clarify the implications of those effects at the next generation of collider experiments [7].

2 A survey of top decays in the SM and beyond

Because of the structure of the SM, the $W$ boson coupling to fermion pairs ($td;W^\pm$), is proportional to the CKM element $V_{td}$. Thus the decay $t \to b+W$ dominates its $BR$'s. Radiative corrections to this mode have been evaluated in the literature, both in the SM and some extensions, mainly within the minimal SUSY extension of the SM (MSSM). In general, such corrections are at most of order 10%, and therefore difficult to detect at hadron colliders, but may be at the reach of the ILC.

On the other hand, the top decay into the light quarks $t \to W+d(s)$ is suppressed, as they are proportional to $V_{td(s)}$. Furthermore, it is unlikely that these modes could be detected at all at hadron colliders. Probably for this reason, the SM corrections to this mode have not been studied. However, in extensions of the SM, it may be possible to get a large enhancement that could even make it detectable at the ILC, as will be shown in the next section. FCNC top quark decays, such as $t \to c\gamma$, $t \to cg$, $t \to cZ$ and $t \to c\phi$ have been studied, for some time, in the context of both the SM and new physics [8]. In the SM, the branching ratio of FCNC top decays is extremely suppressed, as it is summarized in table 1. The rare top quark decay $t \to c+\gamma$ was calculated first in ref. [9] in the SM and some extensions, the result implied a suppressed $BR$, less than about $10^{-10}$, which was confirmed when subsequent analysis [10] that included the correct top mass value and gave $BR(t \to c+\gamma) = 5 \times 10^{-13}$. The decays $t \to c+Z$ and $t \to c+g$ were also calculated in refs. [10]. The resulting branching ratios turned out to be $BR(t \to c+Z) = 1.3 \times 10^{-13}$ and $BR(t \to c+g) = 5 \times 10^{-11}$. None of them seem detectable at LHC nor at the ILC.

The top-charm coupling with the SM Higgs $\phi^0$ could also be induced at one-loop level [11]. The resulting branching ratio is given by $BR(t \to c+$
\( BR(t \rightarrow sW) \sim 10^{-3} \sim 10^{-3} \times 10^{-3} \)

\( BR(t \rightarrow c\phi^0) \sim 10^{-2} - 10^{-4} \sim 10^{-2} - 10^{-4} \)

\( BR(t \rightarrow c\gamma) < 10^{-6} < 10^{-7} \)

\( BR(t \rightarrow cg) < 10^{-6} < 10^{-7} \)

\( BR(t \rightarrow c\gamma\gamma) < 10^{-16} < 10^{-8} \)

\( BR(t \rightarrow cWW) < 10^{-4} - 10^{-3} < 10^{-4} - 10^{-3} \)

\( BR(t \rightarrow cZZ) < 10^{-5} - 10^{-5} < 10^{-5} - 10^{-5} \)

\( BR(t \rightarrow bWZ) \sim 10^{-4} \sim 10^{-4} \)

Table 1: Branching ratios for some CKM-suppressed and FCNC top quark decays in the SM and beyond, for \( m_t = 173.5 - 178 \) GeV. Decays into a pair of massive gauge bosons include finite width effects of final state unstable particles.

\( \phi^0 = 10^{-15} \), which does not seem detectable neither. The FCNC top decays involving a pair of vector bosons in the final state, \( t \rightarrow cVV \), can also be of interest [12]. Although one could expect such modes to be even more suppressed than the ones with a single vector boson, the appearance of an intermediate scalar resonance, as in the previous case, could enhance the \( BR \). Furthermore, because of the large top quark mass, it also seems possible to allow the tree-level decay \( t \rightarrow b + WZ \), at least close to threshold.

Some typical results for the top decays in the SM are summarized in Table 1. This table also includes, for comparison, the results for top branching ratios from models beyond the SM, in particular from the THDM-III and SUSY, which will be discussed in what follows.

### 3 Detection of top decays at the ILC

The International Linear Collider (ILC) is a proposed new electron-positron collider. Together, with the Large Hadron Collider at CERN (LHC), it would allow physicists to explore energy regions beyond the reach of today’s accelerators. The nature of the ILC’s electron-positron collisions would give it the capability to answer compelling questions that discoveries at the LHC will raise, from the identity of dark matter to the existence of extra dimensions.

In the ILC’s design, two facing linear accelerators, each 20 kilometers long, hurl beams of electrons and positrons toward each other at energy that will be around \( \sqrt{s} = 500 \) GeV. The present phenomenological work have been performed assuming a center of mass energy of \( \sqrt{s} = 500 \) GeV, and an integrated luminosity, assuming two running experiments, taking data at the same time for 4 years (plus the year 0) with a total integrated luminosity.
Heavy quarks, $b$-jets and $c$-jets, are tagged using their well-known unambiguous properties such as their mass and their long lifetimes. Tag light-quark jets is much more difficult but anyhow this is needed in order to get meaningful measurement of the CKM matrix elements. The technique used, in the present work, is the so called Large Flavour Tagging Method (LFTM) \[13\]. Particles with large fraction $x_p = 2p/E_{cm}$, of the momentum, carry information about the primary flavour. Then it is possible to define a class of function $\eta_q(x_p)$ that represent the probability, for a quark of a flavour $q$, to develop into a jet in which $i$ is the particle having the largest $x_p = 2p/E_{cm}$. Tagging Efficiencies are then extracted with almost no reliance on the hadronization model, using a sample of $Z_0$ evaluating single tag and double tag probabilities. Hadronisation symmetries are introduced, in the equation systems, in order to simplify the calculations:

$$\eta_d^{\pi^\pm} = \eta_u^{\pi^\pm}, \quad \eta_s^{K^\pm} = \eta_s^{K^0}, \quad \eta_d^{K^\pm} = \eta_u^{K^\pm}, \quad \eta_d^{\Lambda(\bar{\Lambda})} = \eta_u^{\Lambda(\bar{\Lambda})}$$

We have been looking for dilepton top candidates decays (DIL), not including $\tau$ leptons, with two high-$p_T$ leptons, $M_{\ell^+\ell^-}$ outside the $Z_0$ mass window. Then, the jet-tagging requirements were: one tagged $b$-jet, vetoing the presence of an extra $b$-jet and also vetoing the presence of a tagged $c$-jet. The discrimination of $s$-jets from other light-quark-jets have been achieved using the LFTM.

A preliminary estimation, based on 1 $ab^{-1}$, using the DIL signature, shows that sensitivity up to branching ratios of $10^{-3}$ may be reached in the channel $t \rightarrow sW$ where the Effective Lagrangian Approach predicts branching ratios up to $10^{-2}$, making possible to investigate for physics beyond the Standard Model. Further work, to increase sensitivity, adding $W$+jets analysis and the $\tau$ leptons have to be done.

4 Conclusions and perspectives

Rare decays of the top quark can be interesting probes of new physics. $BR(t \rightarrow s + W) \simeq 1.5 \times 10^{-3}$ is reached in the SM. In the minimal flavor violation scheme, one can get: $BR(t \rightarrow s + W) \simeq 10^{-2}$. In the MSSM, we can get an enhancement of order 50%, which may help to make it detectable at ILC. ILC, assuming a center of mass energy of $\sqrt{s} = 500$ GeV, and a total integrated luminosity, for 4 years, two experiments running, of 1 $ab^{-1}$ will be able to reach sensitivity up to $10^{-3}$. 

4
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