Top Quark Physics

F. Larios

Departmento de Física Aplicada, CINVESTAV-Mérida, AP 73 Cordemex, 97310 Mérida, Yucatán, Mexico

Abstract. We give an overview of the physics of the Top quark, from the experimental discovery to the studies of its properties. We review some of the work done on the Electroweak and Flavor Changing couplings associated with the Top quark in the Standard Model and beyond. We will focus on the specific contribution of phycisits working in México and Mexican physicists working abroad.

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INTRODUCTION

The fact that the Top quark has such a large mass, even close to the Electroweak Symmetry Breaking (EWSB)scale, has given this third family quark an important role in the quest for the mechanism that generates masses for all the other elementary particles known so far. From the theoretical viewpoint, even if the EWSB mechanism is originated just by a Higgs field as the SM predicts, we know that the Top quark is the main source for the higher order corrections to the electroweak observables. On the other hand, it is possible that the Top quark is directly involved in the generation of mass. From the experimental viewpoint, the Top quark is the only quark that decays through the weak interaction before it could ever hadronize. This opens a special window of opportunity to study the effects of any kind of physics beyond the Standard Model (SM).

The Top quark was discovered by the CDF [1] and the DØ [2] collaborations at Fermilab in 1995. Figure 1 depicts the typical production and decay mechanism at the Tevatron collider.

We would like to start by mentioning the active role of Jacobo Konigsberg as a member of the CDF group in the research efforts on the Top quark [3]. On the other hand, for the DØ group, our colleague H. Castilla-Valdez, along with two of his former students R. Hernández-Montoya and A. Sánchez-Hernández, have had a part in this effort as well.

There are two modes for Top quark production: $t\bar{t}$ pairs and single t. Figure 2 depicts the three processes that give rise to a single top event in a hadron collider. So far, single top events have not been identified neither at the tevatron [4], nor at HERA [5]. To end the section of the experimental discovery we mention the role of J.G. Contreras-Nuño and G. Herrera-Corral as members of the H1 group.

As is well known the outstanding feature of the Top quark is its very large mass: $m_t = 173$ GeV [6]. With a width of order 1.5 GeV, the Top quark lives very a very short time, giving no time for hadronization. It decays almost entirely into a b and W^+ pair. As with any process involving quarks, QCD corrections can be very significant.

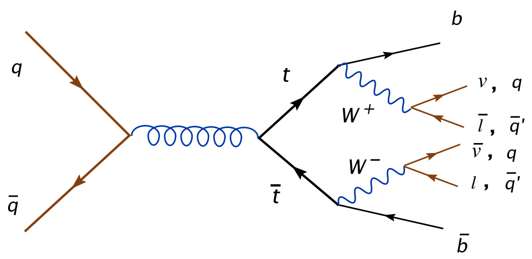

FIGURE 1. One of the processes ($q\bar{q}$ annihilation) that gives rise to $t\bar{t}$ production at the Tevatron. Three distinct decay modes: dilepton, lepton plus jets and hadronic, can identified for the detection of the Top quark.

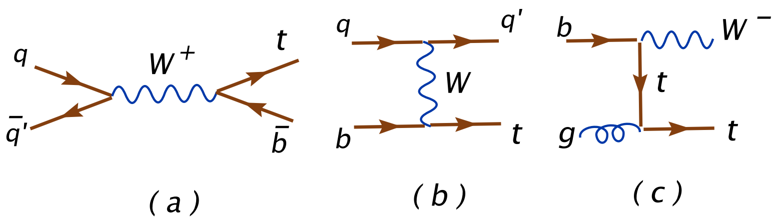

FIGURE 2. The three production modes for single top events in hadron collisions: (a) s-channel, (b) t-channel, and (c) W-associated production.

Their net effect is to reduce the width by about 10% [7]. Another correction comes from the effects due to the finite width of the W boson. In 1989 G. Sánchez-Colón and R. Huerta made a study of the finite W width effects several years before the discovery of the Top quark; however, back then m_t was not thought that could be so heavy, and they assumed $m_W > (m_t - m_b)$ [8]. Recently, G. López-Castro and G. Calderón have made a computation of these effects [9]. The net effect of the W's finite width is to reduce the Top's width about 1%. This small reduction is countered by the also $\sim 1\%$ increase from electroweak corrections.

THE TOP QUARK AND THE PRECISION TEST OF THE SM

Due to its large mass the Top quark plays a major role in the precision tests of the SM [10]. At the one loop level, electroweak corrections of the precision observables of the Z boson are driven by the contributions from the Top quark. Therefore, the LEP and the CLEO data can be used as an indirect measurement of the tbW and ttZ couplings. Figure 3 shows the contributions to the Z and W boson propagators, the Zbb vertex, and the FCNC decay $b \to s\gamma$.

It is possible to parameterize possible deviations from the SM predictions for the tbW and ttZ couplings in terms of only four coefficients $\kappa_{L,R}^{NC}$ and $\kappa_{L,R}^{CC}$ defined as follows [11]:

$$\mathscr{L} = \frac{g}{2c_W}\left(1 - \frac{4s_W^2}{3} + \kappa_L^{NC}\right)\bar{t}_L\gamma^\mu t_L Z_\mu + \frac{g}{2c_W}\left(\frac{-4s_W^2}{3} + \kappa_R^{NC}\right)\bar{t}_R\gamma^\mu t_R Z_\mu$$

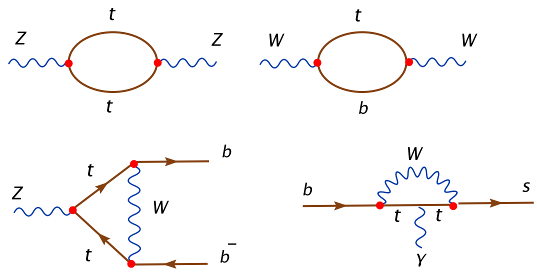

FIGURE 3. The contribution of the ttZ and tbW couplings to the electroweak precision observables and the FCNC decay $b \to s\gamma$.

$$
\begin{aligned}
&+ \frac{g}{\sqrt{2}}\left(1+\kappa_L^{CC}\right)\bar{t}_L\gamma^\mu b_L W_\mu^+ + \frac{g}{\sqrt{2}}\left(1+\kappa_L^{CC\dagger}\right)\bar{b}_L\gamma^\mu t_L W_\mu^- \\
&+ \frac{g}{\sqrt{2}}\kappa_R^{CC}\bar{t}_R\gamma^\mu b_R W_\mu^+ + \frac{g}{\sqrt{2}}\kappa_R^{CC\dagger}\bar{b}_R\gamma^\mu t_R W_\mu^-
\end{aligned} \tag{1}
$$

where t_L denotes a top quark with left-handed chirality, etc. While the ttZ vector and axial-vector couplings are tightly constrained by the LEP data [11], the right handed tbW coupling is severely bounded by the observed $b \to s\gamma$ rate [12] at the 2σ level,

$$
\begin{aligned}
|Re(\kappa_R^{CC})| &\leq 0.4\times 10^{-2} \\
-0.0035 &\leq Re(\kappa_R^{CC}) + 20|\kappa_R^{CC}|^2 \leq 0.0039.
\end{aligned} \tag{2}
$$

On the other hand, LEP/SLC data also constrains the other top-quark couplings included in Eq.(4). Even though these data do not restrict all the anomalous κ terms, they induce the following inequalities

$$
\begin{aligned}
-0.019 &\leq (\kappa_R^{NC}-\kappa_L^{NC}) - (\kappa_R^{NC}-\kappa_L^{NC})^2 + \kappa_L^{CC} + \kappa_L^{CC\ 2} \leq 0.0013 \\
-0.33 &\leq (\kappa_R^{NC}-4\kappa_L^{NC})(1+2\kappa_L^{CC}) \leq 0.1 \\
\kappa_L^{CC} &\sim \kappa_L^{NC}-\kappa_R^{NC}
\end{aligned} \tag{3}
$$

These relations impose in turn strong correlations on the κ couplings so that if only one coupling, κ_L^{CC} for instance, is not zero, the others are forced to be about the same order of magnitude [12].

TOP QUARK PRODUCTION AT PRESENT AND FUTURE COLLIDERS.

Currently, the production of Top quarks has only been observed at the Tevatron machine. In principle, the electrón-protón collider (HERA) runs at an C.M.S. energy of 320 GeV: enough to produce on-shell single Top events. However, the SM amplitude for single Top production in such a collision is very small, and it is not expected that HERA will be able to observe it.

The CDF and DØ groups have been able to measure the $t\bar{t}$ production cross section to about a 20% accuracy. A combination of all the current independent experimental measurements would give $\sigma^{exp}(t\bar{t}) = 7.1 \pm 0.6(stat) \pm 0.8(syst)$ pb, to be compared with the SM prediction $\sigma^{theo}(t\bar{t}) = 6.77 \pm 0.42$ pb. It is expected that with about 2 fb $^{-1}$ of integrated luminosity the error could be reduced to about less than 10% [6].

The production of Top quarks can be divided in two modes: $t\bar{t}$ and single Top, depicted in Figures 1 and 2 respectively. However, it is also possible to produce Tops in pairs of same sign, as we shall see later.

Production of $t\bar{t}$ pairs.

The work done by the Mexican community on $t\bar{t}$ production is focused on the contribution from physics beyond the SM. In 1996 a work was done on the effects of dimension 5 ttZ and tbW couplings on $t\bar{t}$ production [13]. Due to the high energy behavior of the dimension 5 operators[1], it is possible to change significantly the SM prediction for the ZZ and the W^+W^- fusion processes $ZZ \to t\bar{t}$ and $W^+W^- \to t\bar{t}$. Several hundreds or even a few thousand events for every 100 fb $^{-1}$ of luminosity could be generated through these modes at the LHC [13]. A more detailed study on $t\bar{t}$ production was done for the Linear Collider in Ref. [14], where some background effects from initial state radiation were also taken into account. With 200 fb $^{-1}$ of luminosity this collider could be a good probe of the dimension 5 couplings of the Top quark. J. Wudka, et. al. have also analyzed the prospects of Top quark production at this collider in the context of the Linear effective Electroweak Lagrangian [15].

In 1997, J. L. Diaz-Cruz, M. A. Perez and J. J. Toscano considered $t\bar{t}h$ production at the LHC in a model with enhanced ttH couplings [16]. The effects of a strong ttH coupling would also modify the largest mode of Higgs production, which is gluon-gluon fusion. As it is well known, the effective ggH coupling arises at one loop level with the Top quark as the internal fermion line [16]. J. Wudka, et.al. have made an extensive study on Top quark pairs produced at a photon-photon collider, where the use of polarized beams can also distinguish CP violating effects in $tt\gamma$ and tbW couplings [17].

One more interesting mode of Top quark pairs is the same sign tt (instead of $t\bar{t}$) production mode. This mode can appear via a t-channel diagram with the FCNC effective coupling tqV (with $q = uc$ and $V = \gamma Z$) turning the incoming parton quarks into Top quarks. In Ref. [18] it was found that in some models of dynamical Electroweak Symmetry breaking theses couplings could give rise to enough same sign tt pairs to be observed at the LHC.

Production of single Top.

Single Top production is the only process that can probe directly the tbW coupling. It has not been observed at the Tevatron so far, mainly because $t\bar{t}$ production stands as an

[1] Dimension 5 operators arise in the non-Linear Electroweak Lagrangian. There are also many studies based on the Linear version, in which the lowest (higher than 4) dimension for the effective operators is 6.

important background process [6].

As mentioned above, there are three modes of single Top production: s-channel, t-channel and W-associated production (see Fig. 2) [19]. These three modes can be studied separately, and because of their electroweak origin, the produced Top quark has a certain degree of polarization. In the SM, NLO QCD corrections have been calculated that preserve the information of the polarized of the final state particles [20].

The polarizing effect of the SM tbW coupling can also be observed by looking at the polarization state of the decay particles. In particular, CDF and DØ have been able to measure the polarization of the W boson in the decay of the Top. There are three modes in the $t \to bW$ decay, depending on the polarization state of the W boson. Each mode is associated with a fraction, f_0, f_+ or f_-, that corresponds to the longitudinal, right-handed or left-handed polarization, respectively. By definition, we have the constraint $f_0 + f_+ + f_- = 1$. Recent reports by the DØ and CDF collaborations at Fermilab give the following (95% C.L.) results for the longitudinal and right-handed fraction of $t \to bW$ in the $t\bar{t}$ pair events [21]:

$$
\begin{aligned}
f_0 &= 0.91 \pm 0.38\,(\mathrm{CDF})\,, \quad & f_0 &= 0.56\, \pm 0.32\,(\mathrm{D\emptyset})\,, \\
f_+ &\leq 0.18\,(\mathrm{CDF})\,, & f_+ &\leq 0.24\,(\mathrm{D\emptyset})\,.
\end{aligned}
$$

In Ref. [22], it is shown that by using the experimental information of f_0, f_+, σ_t (t-channel single Top) and σ_s (s-channel) we can determine the general tbW vertex that contains four independent coefficients $f^{L,R}_{1,2}$:

$$
\begin{aligned}
\mathscr{L}_{tbW} &= \frac{g}{\sqrt{2}} W^-_\mu\, \bar{b}\,\gamma^\mu \left(f^L_1 P_L + f^R_1 P_R\right) t \\
&- \frac{g}{\sqrt{2} M_W}\, \partial_\nu W^-_\mu\, \bar{b}\,\sigma^{\mu\nu} \left(f^L_2 P_L + f^R_2 P_R\right) t \quad + h.c.\,,
\end{aligned} \tag{4}
$$

In the SM the values of the coefficients are $f^L_1 = V_{tb} \simeq 1$, $f^R_1 = f^L_2 = f^R_2 = 0$. With millions of Top quark events expected at every year of the LHC we should be able to measure these coefficients down to the order of 10^{-2}.

Single Top events could in principle also appear at the electron-proton collider HERA. In this case a large enough FCNC $tq\gamma$ coupling could produce an observable signal. The associated diagram would be t-channel like with the lepton line exchanging a virtual photon with the quark line. It is known that in the low Q region, when the photon gets close to the on-shell condition, the production amplitude grows indefinitely. An infrared divergence has to be avoided by using the non-zero mass of the lepton (electron for HERA). The authors of Ref. [23], calculated the effective $tq\gamma$ (also tqZ) coupling that arises in Topcolor assisted Technicolor theories (TC2) through a strong FC $tc\pi_t$ coupling that appears with the Top-pion condensate formed by the Topcolor interaction. They concluded that the single Top production cross section was high enough to give rise to an observable signal at HERA. With F. Peñuñuri and M.A. Pérez I was able to re-analyze this computation [24]. We found an unfortunate mistake in the numerical integration done in Ref. [23]. The origin of this mistake came from not knowing how to deal with the infrared divergent behavior of the amplitude. Unfortunately, a careful calculation of this process showed that the production cross section of single Top at HERA is very small, even for a model like TC2 where large FCNC Top couplings can arise.

FCNC AND RARE DECAYS OF THE TOP QUARK

In the SM, there are no flavor changing neutral couplings (FCNC) mediated by the Z, γ, g gauge bosons nor the Higgs boson H at tree level because the fermions are rotated from gauge to mass eigenstates by unitary diagonalization matrices. Furthermore, the top-quark FCNC induced by radiative effects are also highly suppressed. The higher order contributions induced by the charged currents are proportional to $(m_i^2 - m_j^2)/M_W^2$, where $m_{i,j}$ are the masses of the quarks circulating in the loop and M_W is the W gauge boson mass. As a consequence, in the SM all top-quark FCNC transitions $t \to qV, qH$, with $V = Z, \gamma, g$, which involve down-type quarks in the loops, are suppressed far below the observable level at existing or upcoming high energy colliders [25].

FCNC and rare Top decay in the SM

In 1990 J.L. Diaz-Cruz, R. Martínez, M.A. Pérez and A. Rosado performed the one loop calculation for the $t \to cV$ transitions. They found that the scale of the respective partial widths is set by the b quark mass [26]:

$$\Gamma(t \to V_i c) \;=\; |V_{bc}|^2 \alpha \alpha_i \, m_t \, (\frac{m_b}{M_W})^4 \, (1 - \frac{m_{V_i}^2}{m_t^2}) \tag{5}$$

where α_i is the respective coupling for each gauge boson V_i. From the above result, it follows the approximated branching ratios $BR(t \to \gamma, Z) \sim 10^{-13}$ and $BR(t \to cg) \sim 10^{-11}$. In contrast, in the $b \to s\gamma$ transitions the leading contribution is proportional to m_t^4/M_W^4 and thus the GIM mechanism induces in this case an enhancement factor. In a similar way, it has been realized that some top-quark FCNC decay modes can be enhanced by several orders of magnitude in scenarios beyond the SM, and some of them falling within the LHC's reach. In this case, the enhancement arises either from a large virtual mass or from the couplings involved in the loop. Top-quark FCNC processes may thus serve as a window for probing effects induced by new physics.

The absence of the vertex Htc at tree-level in the SM can be traced down to the presence of only one Higgs doublet. The process involved in the diagonalization of the fermion masses induces simultaneously diagonal Yukawa couplings for the physical Higgs boson. In models with more than one Higgs doublet, additional conditions have to be imposed to ensure that no FCNC arise at tree level. In particular, a discrete symmetry that makes quarks of same charge to interact with only one of the two (or more) Higgs doublets will, by the Glashow-Weinberg mechanism, cause all the Yukawa couplings involving physical neutral Higgs boson states become diagonal. On the other hand, without any FCNC suppression mechanism these type of models may produce tqH couplings at tree level, which in turn may induce large enhancements of the FCNC tqV by radiative effects [27].

The most general effective Lagrangian describing the FCNC top-quark interactions with a light quark $q' = u, c$, containing terms up to dimension five, can be written as [28]

$$\mathscr{L} \;=\; \bar{t}\{\frac{ie}{2m_t}(\kappa_{tq'\gamma} + i\tilde{\kappa}_{tq'\gamma}\gamma_5)\sigma_{\mu\nu}F^{\mu\nu}$$

$$
\begin{aligned}
&+ \quad \bar{t}\{\frac{ig_s}{2m_t}(\kappa_{tq'g}+i\tilde{\kappa}_{tq'g}\gamma_5)\sigma_{\mu\nu}\frac{\lambda^a}{2}G_a^{\mu\nu} \\
&+ \quad \frac{i}{2m_t}(\kappa_{tq'Z}+i\tilde{\kappa}_{tq'Z}\gamma_5)\sigma_{\mu\nu}Z^{\mu\nu} \\
&+ \quad \frac{g}{2c_w}\gamma_\mu(v_{tq'Z}+a_{tq'Z}\gamma_5)Z^\mu \\
&+ \quad \frac{g}{2\sqrt{2}}(h_{tq'H}+i\tilde{h}_{tq'H}\gamma_5)H\}q'. \qquad (6)
\end{aligned}
$$

where we have assumed also that the top quark and the neutral bosons are on shell or coupled effectively to massless fermions. In terms of these coupling constants, the respective partial widths for FCNC decays are given by [29]

$$
\begin{aligned}
\Gamma(t\to qZ)_\gamma &= \frac{\alpha}{32s_W^2c_W^2}\left(|\kappa_{tqZ}|^2+|\tilde{\kappa}_{tqZ}|^2\right)\frac{m_t^3}{M_Z^2}\left[1-\frac{M_Z^2}{m_t^2}\right]^2\left[1+2\frac{M_Z^2}{m_t^2}\right] \\
\Gamma(t\to qZ)_\sigma &= \frac{\alpha}{16s_W^2c_W^2}\left(|v_{tqZ}|^2+|a_{tqZ}|^2\right)m_t\left[1-\frac{M_Z^2}{m_t^2}\right]^2\left[2+\frac{M_Z^2}{m_t^2}\right] \\
\Gamma(t\to q\gamma) &= \frac{\alpha}{2}\left(|\kappa_{tq\gamma}|^2+|\tilde{\kappa}_{tq\gamma}|^2\right)m_t \\
\Gamma(t\to qg) &= \frac{2\alpha_s}{3}\left(|\kappa_{tqg}|^2+|\tilde{\kappa}_{tqg}|^2\right)m_t \\
\Gamma(t\to qH) &= \frac{\alpha}{32s_W^2}\left(|h_{tqH}|^2+|\tilde{h}_{tqH}|^2\right)m_t\left[1-\frac{M_H^2}{m_t^2}\right]^2 \qquad (7)
\end{aligned}
$$

An update of the original SM calculations [26, 30, 31] for the FCNC top-quark branching ratios gives the following results [29]

$$
\begin{aligned}
BR(t\to q\gamma) &= (4.6^{+1.2}_{-1.0}\pm 0.2\pm 0.4^{+1.6}_{-0.5})\times 10^{-14} \\
BR(t\to qg) &= (4.6^{+1.1}_{-0.9}\pm 0.2\pm 0.4^{+2.1}_{-0.7})\times 10^{-12} \\
BR(t\to qZ) &\approx 1\times 10^{-14} \\
BR(t\to qH) &\approx 3\times 10^{-15} \qquad (8)
\end{aligned}
$$

where the uncertainties shown in the $t\to c\gamma, cg$ branching ratios are associated to the top and bottom quark masses, the CKM matrix elements and the renormalization scale. These updated results are about one order of magnitude smaller than the ones previously obtained [26, 30, 31]. For the decays involving the u quark, the respective BR are a factor $|Vub/Vcb|^2 \sim 0.0079$ smaller than those shown in (8).

The $BR(t\to qZ)$ refers to an on-shell Z boson in the final state. A more realistic analysis considers the subsequent Z decay into a fermion pair. Furthermore, a fermion-antifermion pair can also come from an off-shell photon or gluon. A. Cordero-Cid, J. M. Hernandez, G. Tavares-Velasco and J. J. Toscano, have calculated the rare top quark decay $t\to u(1)\bar{u}(2)u(2)$ in the SM [32]. Their conclusion was that the branching ratio for $t\to u(1)\bar{u}(2)u(2)$ is about the same as the two-body decay $t\to u(1)g$.

FCNC Top decay in models beyond the SM

In 1992, before the discovery of the Top quark, J.L. Diaz-Cruz and G. G. Lopez-Castro analized the possibility of FCNC and CP violation in a Two Higgs doublet model (THDM). The found that the presence of a charged Higgs boson can greatly enhance them in this model [33]. Many years before, in 1983 M.A. Pérez and A. Rosado had already found that contributions from this non-SM Higgs scalar would be important for the decay of a t-meson [34] (then, the Top quark was assumed to be just another heavy quark soon to be observed). In the THDM-III the heavy neutral scalar and pseudoscalar Higgs bosons H and A have non-diagonal couplings to fermions at the tree level. The FCNC decay modes $t \to cV$ and $t \to ch$ proceed at the one-loop level due to the exchange of H, A and $H^{\pm}$. In 1999 J.L. Diaz-Cruz, M.A. Pérez, G. Tavares-Velasco and J.J. Toscano obtained the branching ratios of $t \to cV$ for $V = g, \gamma, Z$ in the context of this model [35]. They found that the respective branching ratios may be enhanced by several orders of magnitude (for reasonable values of the THDM-III parameters) with respect to the SM predictions: $BR(t \to cg) \sim 10^{-4} - 10^{-8}, BR(t \to c\gamma) \sim 10^{-7} - 10^{-11}, BR(t \to cZ) \sim 10^{-6} - 10^{-8}$.

The FCNC decays $t \to cV$ have been studied extensively in the MSSM. The first studies considered one-loop SUSY-QCD and SUSY-EW contributions, which were later generalized in order to include the left-handed (LH) and right-handed (RH) squarks mixings. The SUSY-EW corrections were further generalized and included the neutralino-$q\tilde{q}$ loop, as well as the relevant SUSY mixing angles and diagrams involving a helicity flip in the gluino line. While the first calculations obtained $BR(t \to cV)$ of the order of $10^{-6} - 10^{-8}$, every new study improved these results until the range of values $BR(t \to cg) \sim 10^{-5}$, $BR(t \to c\gamma) \sim 10^{-6}$, $BR(t \to cZ) \sim 10^{-6}$ were reached. However, they are still below the estimated sensitivity at the LHC with an integrated luminosity of 100 fb^{-1}. Similar results were obtained by D. Delepine and S. Khalil in a general SUSY model with a light right-handed top-squark and a large mixing between the first or second and the third generation of up-squarks [36].

On the other hand, while the $t \to cH$ decay is the less favored channel in the SM, it is this FCNC channel which shows the most dramatic enhancements due to new physics effects. In some SUSY extensions its BR can be ten orders of magnitude larger than the SM prediction. This possibility arises not only because in some models the FCNC vertex tcH can be generated at tree level, but also because the GIM suppression does not apply in some loops. In particular, the gluino-mediated FCNC couplings $u_a \tilde{u}_b \tilde{g}$ induces a $BR(t \to ch) \sim 10^{-4}$, where h is the lightest CP-even Higgs boson predicted in the MSSM. The branching fraction for this channel has been found to be as large as $10^{-3} - 10^{-5}$ in a minimal SUSY FCNC scenario in which all the observable FCNC effects come from squark mixings $\tilde{c} - \tilde{t}$ induced by the non-diagonal scalar trilinear interactions [37]. However, it has been pointed out recently that the electroweak precision measurements may impose constraints on this squark mixing; which in turn decrease the MSSM prediction for the FCNC top quark processes [38].

The contribution of an extra neutral gauge boson Z' to the $t \to c\gamma$ decay mode has been studied also in the framework of the TC2 model and the so-called 331 model [39]. Even though the Z' boson predicted in these models couples in a non-universal way to the third generation of fermions, it was found that its contribution to the branching ratio of $t \to c\gamma$ is at most of order of 10^{-8} for $m_{Z'} \sim 500$ GeV [40].

Left-Right (LR) symmetric models are based on the gauge group $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$. Their general aim is to understand the origin of parity violation in low-energy weak interactions. This gauge symmetry allows a seesaw mechanism and predicts naturally neutrino masses and mixing. FCNC top-quark decays have been studied by R. Gaitan, O.G. Miranda and L.G. Cabral-Rosetti in the alternative LR symmetric model. This is a new formulation of LR models with an enlarged fermion sector: it includes vector-like heavy fermions in order to explain the fermionic mass hierarchy. Because of the presence of extra quarks, the CKM mass matrix is not unitary and FCNC may exists at tree level. In particular, there is a top-charm mixing angle which induces the tree level couplings tcZ and tcH. Precision measurements at LEP impose rather weak constraints on this mixing angle, which in turn allows FCNC branching ratios as high as $BR(t \to cH) \sim 10^{-4}$ [41].

In models with extra quarks, the CKM matrix is no longer unitary and the tcZ and tcH couplings may arise at the tree level. When the new quarks are $SU(2)_L$ $Q = 2/3$ singlets, present experimental data allow large branching ratios: $BR(t \to cZ) \sim 1.1 \times 10^{-4}$ and $BR(t \to cH) \sim 4.1 \times 10^{-5}$ [29]. The decay rates for $t \to cg, c\gamma$ are induced at the one-loop level but they receive only moderate enhancements: $BR(t \to cg) \sim 1.5 \times 10^{-7}$ and $BR(t \to c\gamma) \sim 7.5 \times 10^{-9}$. In models with $Q = -1/3$ quark singlets, the respective branching ratios are much smaller since the breaking of the CKM unitarity is very constrained by experimental data [29]. The contributions arising from a sequential fourth generation b' to the FCNC top-quark decays have been also studied [26, 42]. However, the virtual effects induced by a b' heavy quark cannot enhance the respective branching ratios to within the LHC's reach: $BR(t \to cZ) \sim 10^{-6}$, $BR(t \to cH) \sim 10^{-7} - 10^{-6}$, $BR(t \to cg) \sim 10^{-7}$, $BR(t \to c\gamma) \sim 10^{-8}$ [42].

Constraints on FCNC Top quark couplings from experimental data.

The measurement of the inclusive branching ratio for the FCNC process $b \to s\gamma$ has been used to put constraints on the $tc\gamma, tcg$ couplings [43]. These anomalous couplings modify the coefficients of the operators O_7 and O_8 of the effective Hamiltonian for the $b \to s\gamma$ transition. The known branching ratio for $t \to bW$ [44] and the CLEO bound on $b \to s\gamma$ place the limits $|\kappa_g| < 0.9$ and $|\kappa_\gamma| < 0.16$, which can be translated into the bounds $BR(t \to c\gamma) < 2.2 \times 10^{-3}$ and $BR(t \to cg) < 3.4 \times 10^{-2}$ [43].

The FCNC couplings tcZ and tcH have also been constrained by using the electroweak precision observables Γ_Z, R_c, R_b, R_l, A_c and the S/T oblique parameters [45]. The one-loop correction of these couplings to the decay modes $Z \to c\bar{c}$ and $Z \to b\bar{b}$ are shown in Fig. 4. Even though these vertices enter in the Feynman diagrams 3(b)-(d) as a second order perturbation, the known limits on the above precision observables [44] impose significant constraints on the tcH and tcZ couplings [45].

Figures show the 95% C.L. limits on the g_l/g_r and h_l/h_r FCNC top quark vertices and for several values of the intermediate-mass Higgs boson. These limits can be translated into the following bounds for the respective branching ratios: $BR(t \to cZ) < 1.6 \times 10^{-2}$ and $BR(t \to cH) < 0.9 - 29 \times 10^{-4}$ for $116\ GeV < mH < 170\ GeV$ [45]. In particular,

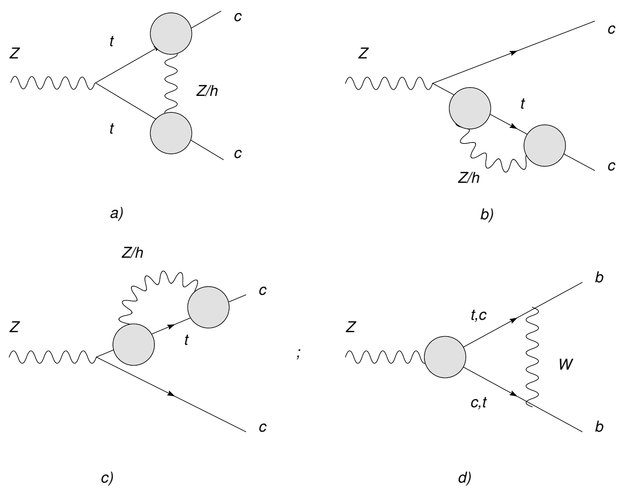

FIGURE 4. Feynman diagrams for the one-loop contribution of the FCNC tcZ/H vertices to the decay mode $Z \to c\bar{c}$

the limit on $Br(t \to cZ)$ is similar to the bound recently reported by the DELPHI Collaboration [47].

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