

Effective approach to top-quark decay and FCNC processes at NLO accuracy

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Abstract. The top quark is expected to be a probe to new physics beyond the standard model. Thanks to the large number of top quarks produced at the Tevatron and the LHC, various properties of the top quark can now be measured accurately. An effective field theory allows us to study the new physics effects in a model-independent way, and to this end accurate theoretical predictions are required. In this talk we will discuss some recent results on top-quark decay processes as well as flavor-changing processes, based on the effective field theory approach.

1. Introduction

Current strategies to search for new physics beyond the standard model (SM) can be broadly divided into two categories. In the first category we look for new resonant states. In the second category, new states are assumed to be heavy, and we look for their indirect effects in the interactions of known particles.

The top quark has been a natural probe to new physics in the first category, due to its large mass and strong coupling to the electroweak symmetry breaking sector. Searches for resonant states through decay processes involving the top quarks have been performed both at the Tevatron and at the LHC. Examples include $t\bar{t}$ resonance searches, top partner production, and so on. Unfortunately, until now no new states have been discovered, and exclusion limits have been placed, up to around several TeV scale.

On the other hand, the top quark physics has entered a precision era, thanks to the large number of top quarks produced at the Tevatron and LHC. Various properties of the top quark have been already measured with high precision, and the upcoming LHC Run-II will continue to increase the precision level. From the theory side, accurate SM predictions are also available. As a result the focus of top quark physics is now moving toward the second category, i.e. to measure accurately the known interactions and the rare processes of SM particles. Examples are measurements on W -helicity fractions in top-quark decay, and searches for processes involving flavor-changing neutral current (FCNC) of the top quark. These are the main topics of this talk.

2. The effective approach

When looking for deviations from the SM interactions, the standard approach is to utilize the effective field theory (EFT) framework, in which deviations from the SM are parameterized by including higher dimensional operators. The approach is valid when the new physics scale, Λ , is higher than the scale of the process. Assuming the full SM gauge symmetries, the leading



new operators involving a top quark arise at dimension six. At this level the Lagrangian can be written as

$$\mathcal{L}_{EFT} = \mathcal{L}_{SM} + \sum_i \frac{C_i}{\Lambda^2} O_i + \text{h.c.} \quad (1)$$

A calculation in the EFT framework consists of three steps:

- (i) Matching calculation. The EFT is matched to the full theory which lives at the high energy scale Λ . This determines the operator coefficients C_i , defined at the matching scale.
- (ii) Renormalization group (RG) evolution. The coefficients will be evolved down to a lower scale E where the actual process takes place. This essentially resums the $\log(\Lambda/E)$ terms.
- (iii) Matrix element calculation, to be performed at scale E .

The procedures are familiar from the RG-improved perturbation theory which plays an important role in flavor physics. Indeed there is a similarity between top quark physics and flavor physics. In flavor physics, the full theory is the SM, possibly with some new physics. The matching is performed at scale $\Lambda = m_W$, where the heavy SM particles are integrated out. The theory is then evolved down to lower scales where the matrix element can be computed either perturbatively or non-perturbatively. In the top quark physics, the full theory is the SM plus new physics, which is to be matched to the EFT at scale $\Lambda = \Lambda_{NP}$, where the new physics lives. The procedure integrates out heavy particles in the new physics, but the heavy particles of the SM remain in the effective theory, leading to 59 dimension-six operators in total for one generation of fermions [1]. We then select the ones that are relevant for top-quark processes and evolve them down to a scale of $\sim m_t$. Cross sections can then be computed in terms of these operator coefficients.

Recently the RG equations for all dimension-six operators have been derived at the one-loop level [2, 3, 4], completing the second step in this picture. There are also new developments in matrix element calculations. In particular, the top-quark decay and several FCNC processes have been computed at NLO in QCD, and the automation of the FCNC processes in the MG5_aMC@NLO framework [5] is now in progress. These will be discussed in the remainder of this talk.

3. Top-quark decay and W -helicity fractions

In this section we will discuss the main decay channel of the top quark, $t \rightarrow bW$, focusing on the W -helicity fractions. For SM couplings and unpolarized top-quark production, the helicity fractions are approximately 70% longitudinal and 30% left-handed. Accurate predictions at NNLO in QCD and NLO in electroweak are available.

In an EFT, dimension-six operators will modify the helicity fractions. First of all, there are operators that directly modify the standard Wtb vertex function. They are

$$\begin{aligned} O_{\varphi Q}^{(3)} &= i\frac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi \right) (\bar{Q} \gamma^\mu \tau^I Q) & O_{tW} &= y_t g_W (\bar{Q} \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I \\ O_{\varphi\varphi} &= i y_t^2 (\tilde{\varphi}^\dagger D_\mu \varphi) (\bar{t} \gamma^\mu b) & O_{bW} &= y_t g_W (\bar{Q} \sigma^{\mu\nu} \tau^I b) \varphi W_{\mu\nu}^I \end{aligned} \quad (2)$$

where Q is the left-handed (t, b) doublet. The QCD corrections to these operators have been computed in Ref. [6]. Deviations from the SM predictions are expected to be dominated by contribution from O_{tW} .

A second possibility comes from the color-dipole operator,

$$O_{tG} = y_t g_s (\bar{Q} \sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A \quad (3)$$

which only contributes at NLO in QCD. This has been computed in Ref. [7]. There is a mixing effect from operator O_{tG} to O_{tW} , given by $\gamma_{C_{tW}, C_{tG}} = 2\alpha_s/3\pi$.

Finally, four-fermion operators such as $O_{lQ}^{(3)} = (\bar{l}\gamma_\mu\tau^I l) (\bar{Q}\gamma^\mu\tau^I Q)$ should also be considered. These operators arise from for example a heavy W' particle exchange, and can directly contribute to the $bl\nu$ final state. Their contributions to the total decay rate are small. Nevertheless we can hope to set some bounds using differential decay rate, since they will affect not only the measured F_+ value (which would be tiny in the SM), but also the $m_{l\nu}$ spectrum.

The helicity fractions are measured both at the Tevatron and at the LHC. Using the results from Ref. [8], one can already set some constraints. For illustration, assuming other operators vanish, the limit on O_{tW} is

$$C_{tW} = -0.11 \pm 1.13 (\Lambda/\text{TeV})^2 \quad (4)$$

at 95% CL. However one should keep in mind that considering only one operator at a time is not natural, in particular due to the operator mixing effects. In principle, four-fermion operators should also be considered, however current strategy to top-quark reconstruction requires that $m_{l\nu}$ is equal to the W mass. This condition does not apply when four-fermion operators are present, so the current limits on the helicity fractions cannot be used to constrain four-fermion operators.

4. Top-quark decay via FCNC

Flavor-changing decay modes such as $t \rightarrow qX$ are suppressed by the Glashow-Iliopoulos-Maiani mechanism, and the SM predictions for the branching ratios are of order $10^{-12} - 10^{-15}$. Any evidence for these decay modes would be a definite signal for new physics. In the EFT framework the decay rates for $t \rightarrow ug$, $t \rightarrow u\gamma$, $t \rightarrow uh$ and $t \rightarrow ull$ are all computed at NLO in QCD [9, 10, 7]. Relevant operators can be found in Appendix A. On the experimental side, branching ratios for $u\gamma$, ull and uh final states have been measured both at the Tevatron and at the LHC. Single top production processes via FCNC couplings are also studied, via $e^+e^- \rightarrow t\bar{q}$ at LEP2, $e^-q \rightarrow e^-t$ at HERA, and $qg \rightarrow t(j)$ at the Tevatron and the LHC. Limits on FCNC couplings obtained from production processes are often converted to limits on branching ratios.

In general, a single process can depend on many operators, and so one measurement can only set bounds on a specific linear combination of operator coefficients. Once we combine all available measurements, a global analysis can be performed to determine the allowed region for all operator coefficients. However, limits obtained by experimental collaborations almost always assume only one FCNC interaction is present at a time. In addition, four-fermion operators are always neglected in both production and decay processes. For these two reasons it is difficult to perform a real global fit based on the EFT framework.

To illustrate the feasibility of such a global approach, here we present an “approximate” global fit for the top quark FCNC sector. We neglect all four-fermion operators, and only consider $t \rightarrow qZ$ [11], $t \rightarrow qh$ [12]¹ and $pp \rightarrow t$ [14] via FCNC couplings involving an up quark. Moreover we interpret the limit from $pp \rightarrow t\gamma$ [15] as a direct bound on the branching ratio of $t \rightarrow q\gamma$, which is much tighter than the current bound measured at the Tevatron. These four measurements suffice to constrain all two-quark FCNC operators. Unfortunately, the published information is not enough for a consistent combination of all four measurements at 95% CL, therefore we only require that all constraints at 95% CL are independently satisfied.

The result of the fit is shown in Figure 1. The blue lines are obtained by setting other coefficients to zero, while the red lines are obtained by allowing other coefficients to float. For some operators the blue and red lines are different, indicating that a correlation is present between the operators. This effect between O_{uB} and O_{uW} can be observed in Figure 2.

The situation can be more complicated if four-fermion operators are included. These operators may contribute to the decay channel $t \rightarrow qll$, which is the actual final state of the

¹ This limit applies for $t \rightarrow ch$, but limit for $t \rightarrow uh$ is expected to be better [13].

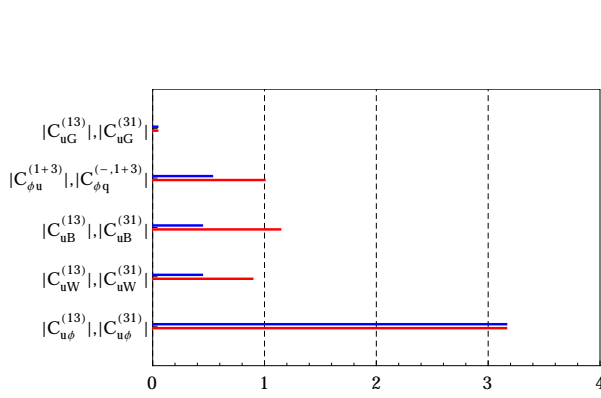


Figure 1. Limits on individual operator coefficients. Blue lines indicate limits obtained by setting other coefficients to zero. Red lines are obtained by allowing other coefficients to float. $\Lambda = 1$ TeV is assumed.

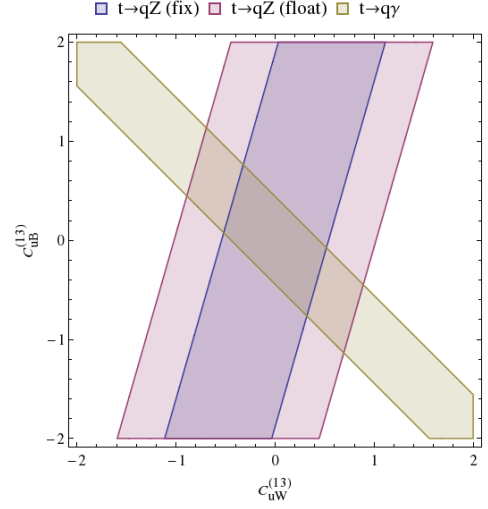


Figure 2. Allowed region in $C_{uW}^{(13)} - C_{uB}^{(13)}$ space, from $t \rightarrow uZ$ and $pp \rightarrow t\gamma$, by fixing other coefficients to zero and by allowing them to float. $\Lambda = 1$ TeV.

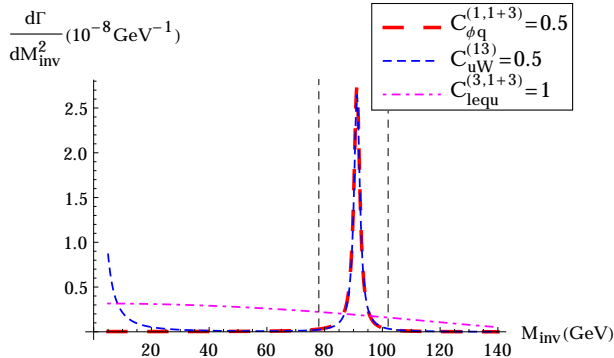


Figure 3. Invariant mass distribution of lepton pairs from FCNC top-quark decay. Contributions from two-fermion operators, $O_{\phi q}^{(1,1+3)}$ and $O_{uW}^{(13)}$, and four-fermion operator $O_{lequ}^{(3,1+3)}$ are compared. $\Lambda=1$ TeV.

$t \rightarrow qZ$ measurements. Consider for example the following operator

$$O_{lequ}^{(3,13)} = (\bar{l}\sigma_{\mu\nu}e)\varepsilon(\bar{q}\sigma^{\mu\nu}t) , \quad (5)$$

its contribution is comparable with typical contributions from two-fermion operators. Therefore constraining four-fermion operator coefficients from $t \rightarrow qZ$ is possible.

The main difference between two- and four-fermion operators is reflected by the invariant mass distribution of the lepton pairs. Two-fermion operators involve a Z boson and show a peak near the Z mass, while four-fermion operators give a more flat spectrum. We illustrate this difference in Figure 3, where the four-fermion operator $O_{lequ}^{(3,1+3)}$ and two additional two-fermion operators $O_{\phi q}^{(1,1+3)}$ and $O_{uW}^{(13)}$ are included. Current strategies to searching for FCNC top-quark decay impose some on-shell cuts on the invariant mass of the two leptons, e.g. $m_{ll} \in [78, 102]$ GeV, to select events with two leptons coming from an on-shell Z boson. These are displayed in Figure 3 as two dashed straight lines. After applying these cuts, the contributions from the three operators are:

$$\Gamma_{\text{on-shell}} = \left(7.0|C_{uW}^{(13)}|^2 + 7.3|C_{\phi q}^{(1,1+3)}|^2 + 0.8|C_{lequ}^{(3,13)}|^2 \right) \times 10^{-5} \text{ GeV} . \quad (6)$$

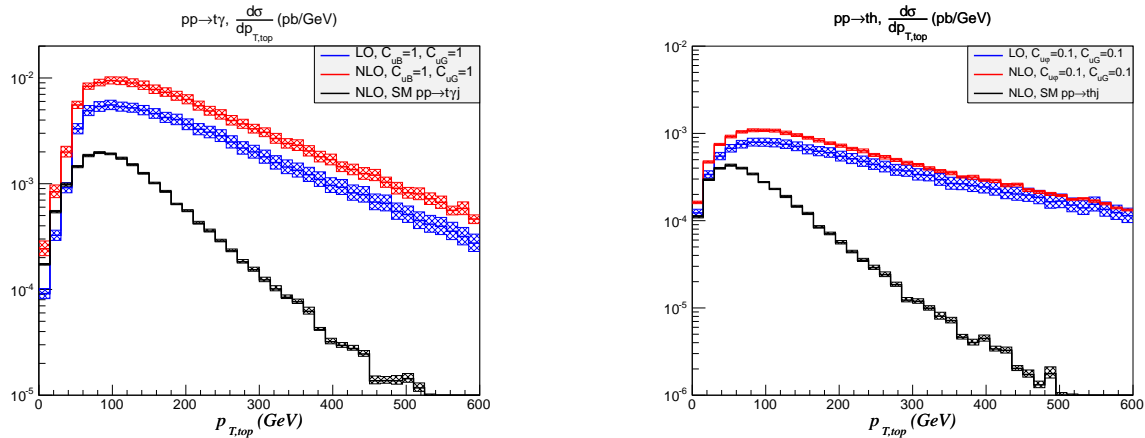


Figure 4. The p_T distribution of the top quark in $pp \rightarrow t\gamma$ (left), and in $pp \rightarrow th$ (right). The SM background is from $t\gamma j$ (left) and thj (right) production.

This implies that even with the on-shell cuts, the four-fermion operator is still not negligible. In fact, the above results will lead to limit on $C_{lequ}^{(3,13)}$ that is only 3 times larger than those of the two-fermion operator coefficients.

On the other hand, looking at the off-shell regions of the spectrum will give us more information. The decay rate in $m_{ll} \in [15, 78] \cup [102, \infty]$ GeV is:

$$\Gamma_{\text{off-shell}} = \left(0.6 |C_{uW}^{(13)}|^2 + 0.4 |C_{\varphi q}^{(1,1+3)}|^2 + 2.7 |C_{lequ}^{(3,13)}|^2 \right) \times 10^{-5} \text{ GeV}. \quad (7)$$

We can see that two-fermion contributions are suppressed while the four-fermion one is enhanced, so by looking at both regions we can constrain two- and four-fermion operators separately. Due to less Drell-Yan background in the off-shell region, one might even get a better sensitivity on four-fermion operators.

5. Single Top Production via FCNC

We now turn to single top production via top-quark FCNC. Recently single top production associated with a photon and with a Z -boson have been searched for at the LHC [15, 16]. Limits are obtained on the FCNC couplings tqg , $tq\gamma$ and tqZ . Single top production associated with a Higgs boson has also been proposed as a probe of the tqg and tqh couplings. These analyses are important consistency checks for the FCNC searches already performed in top-decay processes. In a global fit based on an EFT approach, they can be combined together with the decay processes, to improve the limits on various FCNC couplings.

Theoretical predictions for $t\gamma$, tZ and th production processes have been computed in Refs. [17, 18, 19] at NLO in QCD. The NLO corrections are found to be at $\sim 40\%$ to 80% level. We have implemented the two-quark flavor-changing operators to the MG5_aMC@NLO framework [5], using FeynRules [20] and NLOCT [21]. As a result, processes such as $pp \rightarrow tX$ where $X = j, \gamma, Z, h$ can be computed automatically at NLO in QCD and are matched to parton shower simulation. For illustration, we present in Fig. 4 the p_T distribution of the top in $pp \rightarrow t\gamma$ and in $pp \rightarrow th$ at NLO. Because the calculation is automatic, a rich set of processes can be studied at NLO with parton shower, including single top production in not only pp collision but also e^+e^- collision, and top-quark decay in single top and $t\bar{t}$ production modes. In future four-fermion operators involving the top quark will also be available, allowing for more interesting processes to be studied. All these studies can give useful information about top-quark FCNC couplings.

6. Summary

The top quark physics has entered a precision era. Due to the scale separation between Λ_{NP} and m_t , the EFT approach is a natural tool to study the indirect effects from new physics. In this talk we have discussed theoretical results for top quark processes in the EFT framework. We have focused on top-quark decay and searches for top quark FCNC interactions, and discussed the need for a global analysis for top-quark properties based on an EFT approach. Moreover, NLO predictions are now available for these processes, and in particular, the top-quark FCNC operators are implemented to the MG5_aMC@NLO framework. These results provide information and tools needed to perform a global analysis.

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Appendix A. Top-Quark FCNC Operators

Top FCNC interactions are characterized by the following two-quark operators:

$$\begin{aligned} O_{\varphi q}^{(3,i+3)} &= i \left(\varphi^\dagger \overleftrightarrow{D}_\mu^I \varphi \right) (\bar{q}_i \gamma^\mu \tau^I Q) & O_{\varphi q}^{(1,i+3)} &= i \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) (\bar{q}_i \gamma^\mu Q) & O_{\varphi u}^{(i+3)} &= i \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi \right) (\bar{u}_i \gamma^\mu t) \\ O_{uB}^{(i3)} &= g_Y (\bar{q}_i \sigma^{\mu\nu} t) \tilde{\varphi} B_{\mu\nu} & O_{uW}^{(i3)} &= g_W (\bar{q}_i \sigma^{\mu\nu} \tau^I t) \tilde{\varphi} W_{\mu\nu}^I & O_{uG}^{(i3)} &= g_s (\bar{q}_i \sigma^{\mu\nu} T^A t) \tilde{\varphi} G_{\mu\nu}^A \\ O_{u\varphi}^{(i3)} &= (\varphi^\dagger \varphi) (\bar{q}_i t) \tilde{\varphi} \end{aligned}$$

where the subscript i is the generation of the quark field. Q is the third-generation doublet. For operators with $(i3)$ superscript, a similar set of operators with $(3i)$ flavor structure can be obtained by interchanging $(i3) \leftrightarrow (3i)$, $t \leftrightarrow u_i$ and $Q \leftrightarrow q_i$. We further define $O_{\varphi q}^{(-,i+3)} = (O_{\varphi q}^{(1,1+3)} - O_{\varphi q}^{(3,1+3)})/2$. There are also four-fermion operators involving two quarks and two leptons. A full list can be found elsewhere [7].

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