Top couplings and new physics: theoretical overview and developments

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Abstract. Top-quark physics has entered the precision era. In this talk we discuss the theoretical ingredients required for a global approach to the complete set of top-quark couplings at NLO accuracy. In particular, recent developments on top-quark flavor-changing neutral couplings are shown as an example. Aspects of flavor-conserving sector will also be discussed.

1. Introduction

The top quark and the Higgs boson are the heaviest known fundamental particles. These two particles and their mutual interactions can play crucial roles in many extensions of the standard model (SM). While global analyses of the Higgs interactions based on the effective field theory (EFT) approach are available in literatures, the top quark couplings have been rarely studied with the same strategy. In this talk we will discuss the theoretical framework for a global approach to top quark couplings, in particular with a focus on higher-order QCD corrections and their impacts on the global strategy.

2. Towards a global fit at NLO

The millions of top quarks produced at the Tevatron and the LHC have brought top physics to its precision era. In the past year, progresses have been made in the measurements of various top processes, thanks to the 8 TeV data set at the LHC. The single top production in Wt channel has been observed for the first time [1]. Several measurements and searches on the $t\bar{t}X$ final state have been updated [2, 3, 4, 5], and new constraints on the flavor-changing neutral couplings, $tq\gamma$ and tqh, become available [6, 7, 8].

To extract top-quark couplings from these measurements, the EFT provides a suitable theoretical framework. While EFT has been widely used as a model-independent description of new physics, here we want to emphasize that this approach has the advantage of being consistent at higher orders in perturbative calculation. This is an important feature for top physics, as QCD corrections are in general not negligible for top-quark processes at hadron colliders, in particular when non-SM couplings are involved. Furthermore, in certain processes these couplings are accessible only through a top-quark loop. Therefore a reliable analysis requires predictions within the EFT framework at NLO accuracy.

In an EFT approach, deviations from the SM are described by adding higher-dimensional gauge-invariant operators to the SM Lagrangian. These operators are suppressed by inverse powers of Λ, where Λ is the scale at which new physics lives. The theory can be renormalized

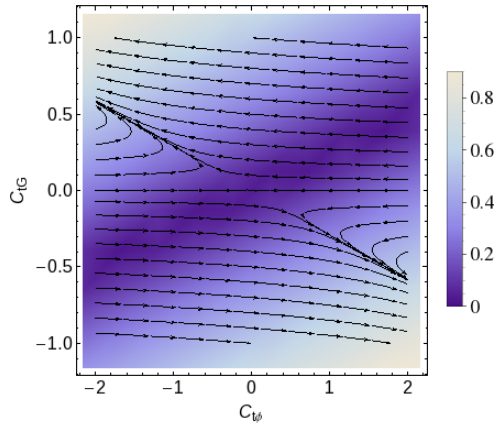

Figure 1. RG evolution of $O_{t\varphi}$ and O_{tG}. The arrows represent the direction of RG flows when the scale increases. The color shows the shift in $C_{t\varphi} - C_{tG}$ space when evolved from m_t to 2 TeV.

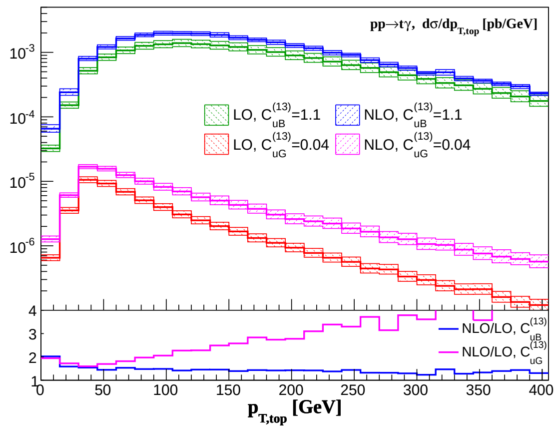

Figure 2. The p_T distribution of top quark in $pp \to t\gamma$ at $\sqrt{s} = 8$ TeV. Photon $p_T > 30$ GeV and $\eta < 2.5$ cuts are imposed. $\Lambda = 1$ TeV. Coefficients are chosen within the current limits.

order by order in $1/\Lambda$, provided that all operators up to a certain order are incorporated. Thus perturbative calculations can be systematically improved, to any desired order of $(\alpha_s/\pi)^m(1/\Lambda)^n$.

It is important to keep in mind that the EFT is a consistent approach only if the complete set of operators are taken into account. In particular, turning on one or several operators at a time may lead to misleading or even basis-dependent conclusions. One example is the two "blind directions" appeared in precision electroweak fit [9]. These directions are transparent only in certain operator basis and can be overlooked if one turns on only one operator at a time. This is one of the reasons why a global analysis can be important.

At NLO, a global strategy becomes even more crucial, as the renormalization group (RG) mixing effects clearly reveals the intrinsic relations among different operators. The evolution of operators are described by a matrix, and mixing effects among different operator coefficients occur whenever the renormalization scale changes. Conceptually, this implies that the very definition of top couplings are obscured at NLO, and the distinction between individual couplings can depend on the scale at which they are probed. This is illustrated in Figure 1, where the RG flows of the operators $O_{t\varphi}$ and O_{tG} are displayed. These two operators give rise to anomalous $t\bar{t}h$ and $t\bar{t}g$ couplings, respectively.

The top EFT has been studied at leading order (LO) for a long time (see, for example, Ref. [10] for more details). At NLO, however, there are still many aspects that require further work. QCD corrections to most dimension-six operators remain to be studied, and for certain processes these include higher-order contaminations from operators not involved at the tree level. In addition, simulation tools that are capable of doing such calculations are desirable in order to have realistic analyses. In the next section we will give a brief summary of some recent progresses made in the flavor-changing neutral current (FCNC) sector of the top quark.

3. Flavor-changing sector

Processes triggered by the FCNC couplings of the top quark are highly suppressed in the SM by the GIM mechanism, thus any signal observed indicates new physics. A wide variety of limits have been set on top-quark FCNC interactions. Currently the best ones on trilinear couplings are from decay processes $t \to ql^+l^-$, $t \to qh$, and production processes $qg \to t$ and $qg \to t\gamma$, all have been searched at the LHC. On the other hand, single top production at LEP2 could provide limits on contact four-fermion interactions.

In an EFT the FCNC couplings involving one top-quark and one light-quark field arise from the following dimension-six operators:

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

where the subscript $i=1,2$ 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 $O_{\varphi q}^{(-,i+3)}$ as $(O_{\varphi q}^{(1,1+3)}-O_{\varphi q}^{(3,1+3)})/2$. In addition, four-fermion operators including two quarks and two leptons are also relevant. A full list can be found in Ref. [11].

It is worth pointing out that the limits obtained by experimental collaborations almost always assume one single FCNC interaction is present at a time. In addition, four-fermion operators are neglected in most cases. These operators could for example describe models where FCNC couplings are mediated by new heavy particles. While they could obviously contribute to $e^+e^-\to tj$, their effects in top decay $t\to qZ\to ql^+l^-$ are not negligible either, even after applying the Z-mass window cuts on the lepton pairs. To have a complete understanding of the current status, one should follow a global approach where all FCNC operators are turned on simultaneously.

Recently, theoretical ingredients required for such a global analysis have been completed at NLO accuracy. In the FCNC sector the relevant mixing effects are those among $O_{uB}^{(i3)}$, $O_{uW}^{(i3)}$, $O_{uG}^{(i3)}$ and $O_{u\varphi}^{(i3)}$, and their $(3i)$ counterparts. NLO predictions for FCNC processes are now available with the operator mixing effects properly taken into account. Various of decay processes have been computed in Refs. [11]. In these processes the $\mathcal{O}(\alpha_s)$ corrections come from not only the standard QCD corrections to dimension-six operators, but also from the operators $O_{uG}^{(i3)}$ and $O_{uG}^{(3i)}$, which affect top decays only at NLO. Contributions from four-fermion operators in three-body decays are also included. On the production side, single top production $qg\to t$ has been computed in Ref. [12]. More recently, the full set of two-fermion FCNC operators, listed in Eq. (1), have been implemented in the MG5_aMC@NLO framework [13], using FeynRules [14] and NLOCT [15]. Details can be found in Ref. [16]. This allows for processes such as $pp\to tX$, with $X=\gamma,Z,h$, to be computed automatically at NLO and matched to parton shower simulation. For illustration we show in Figure 2 the p_T distribution in $pp\to t\gamma$ at 8 TeV center of mass energy. The $e^+e^-\to tj$ process can be studied in the same framework, with the caveat that the four-fermion operators are no yet available. They are planned to be implemented in future, and for the moment analytical results for these operators can be used.

With the above results, a global fit including all processes mentioned in this section can be performed. From the published information it is not clear to us how to combine the 95% CL bounds from different measurements consistently. However, to illustrate the feasibility of this approach, a toy fit is straightforward, by naively combining available limits on branching ratios and cross sections. In Figure 3 we show some results from the toy fit. 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. These information are available from the global fit. The complete analysis is presented in Ref. [17].

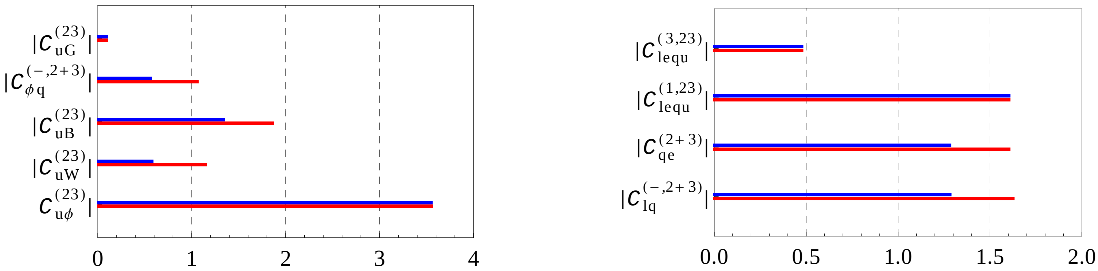

Figure 3. Left: limits on two-fermion operator coefficients. Blue lines indicate limits obtained by setting other coefficients to zero. Red lines are obtained by allowing other coefficients to float. $\Lambda = 1$ TeV is assumed. Right: limits on some four-fermion operators. Their definitions can be found in Ref. [17].

Table 1. Top-quark operators and some of the key processes at the LHC. O_{4f} denotes any four-fermion operator. "L" ("N") represents LO (NLO) contribution. O_G and $O_{\varphi G}$ are included. $O_{\varphi\varphi}$ and O_{bW} are omitted as their leading contributions are suppressed by b mass.

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	$O_{4\mathrm{f}}$	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\tilde{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H,\, H \to \gamma\gamma$	N						N			L

4. Flavor-conserving sector

The non-FCNC sector is more complicated. The top couplings are parameterized by the following operators [18, 19]

$$O_{\varphi Q}^{(3)} = i\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{Q}_i\gamma^\mu\tau^I Q) \quad O_{\varphi Q}^{(1)} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{Q}_i\gamma^\mu Q) \quad O_{\varphi t} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}_i\gamma^\mu t)$$
$$O_{\varphi\varphi} = i\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{t}_i\gamma^\mu b) \quad O_{tB} = g_Y(\bar{Q}_i\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu} \quad O_{tW} = g_W(\bar{Q}_i\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{bW} = g_W(\bar{Q}_i\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu} \quad O_{tG} = g_s(\bar{Q}_i\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu} \quad O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{q}_i t)\tilde{\varphi}$$

Four-fermion operators are not listed here.

Table 1 displays some of the key processes at the LHC, together with the relevant operators in each process. Most two-fermion operators are constrained to some level, thanks to the recent LHC data. However, more aspects need to be studied before a real global fit can be made. In a global approach a complete operator basis should be used, which means that one should include not only four-fermion operators that are often neglected, but also operators with no top-quark field, such as

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho, \qquad O_{\varphi G} = g_s^2\left(\varphi^\dagger\varphi\right) G^A_{\mu\nu}G^{A\mu\nu}\ . \tag{1}$$

They are included in Table 1, and could indeed affect most top processes.

Mixing effects may be important. For instance, a non-vanishing operator O_{tG} at 1 TeV scale can induce an operator $O_{t\varphi}$ at the scale m_t, with $C_{t\varphi}(m_t) \approx 0.45 C_{tG}(1\text{ TeV})$ from the QCD mixing term. Moreover, operators without a top-quark field, such as O_G and $O_{\varphi G}$, can be relevant through mixing effects. In particular the anomalous dimensions $\gamma_{tG,\varphi G}$, $\gamma_{tG,G}$, and $\gamma_{\varphi G,tG}$ are non zero (the last one has been studied in Ref. [20]).

Once the mixing is understood, complete NLO calculation can be carried out. While some operators only give rise to SM-like couplings, others are essentially of higher dimension, and QCD corrections are unknown in most cases, with a few exceptions such as top-decay processes as well as four-fermion operators in $t\bar{t}$ production. From the study of FCNC sector we see that these corrections can be potentially large, and so it is important know their sizes. The feasibility of implementing these operators in the MG5_aMC@NLO framework is being investigated.

5. Summary

With a variety of top processes investigated at the LHC, global analyses based on top EFT are expected to provide a complete understanding of top-quark couplings. However, QCD corrections can be potentially important, and a reliable analysis at NLO accuracy requires further theoretical efforts. We have shown that recent progress completes the theoretical predictions in the top FCNC sector. While the flavor-conserving sector can be more complicated, the feasibility of the same approach is being studied, and automatic NLO calculations involving higher-dimensional top-quark operators can be expected in future.

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