CMS measurements of EFT parameters with top quarks

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Measurements carried out or reinterpreted within the framework of effective field theory (EFT) will constitute a key component of the LHC legacy in the quest towards physics beyond the standard model. Numerous EFT measurements were already published by the CMS Collaboration. In the top quark sector, four distinct approaches to EFT have been identified, each successfully applied in several analyses. We review the pros and cons of each approach, while illustrating them with recent analyses in which they were adopted.

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1 Introduction

The standard model (SM) of particle physics predicts with great accuracy a tremen-
dous number of experimental results covering a wide energy range up to the TeV scale
accessible at the CERN LHC [1]. Still, it does not provide explanations for several
key observations such as the existence of dark matter and energy, or the masses of
neutrinos. More generally, there exists a number of indications that the SM only
corresponds to a low-energy approximation to a more fundamental theory beyond
the standard model (BSM).

Various BSM models postulate the existence of new particles or mechanisms to
address these shortcomings. However the SM does not predict the energy scale at
which new physics may appear, and extensive research efforts notably carried out by
the ATLAS [2] and CMS [3] experiments at the LHC covering a large phase space
region did not yet indicate the presence of new physics.

The large top quark mass of about 173 GeV and its Yukawa coupling to the Higgs
boson close to unity suggest that it may play a special role within the SM, and that
its closer study may shed light on the electroweak symmetry breaking mechanism.
Many BSM theories predict sizeable deviations of the top quark’s couplings with re-
spect to SM predictions. Moreover, most of the canonical top quark processes have
now reached the precision era at the LHC, and their uncertainties are systematics-
dominated. This motivates carrying out an ambitious research program in the top
quark sector in order to reveal new physics effects indirectly through precision mea-

2 Effective field theory

One of the main theoretical frameworks to interpret potential deviations in a model-

independent way is that of effective field theory (EFT). One key assumption of this

approach is that the new physics is characterized by some unknown energy scale Λ

way beyond the energy reach of the LHC. Under this assumption, the SM Lagrangian

is expanded with additional operators of higher mass dimensions ($d > 4$) representing

new interactions between SM fields, whose coupling strengths are described by Wilson

coefficients (WCs). Constraints placed on WCs may then be mapped onto any UV-

complete model. An EFT thus offers a well-motivated and general framework to

maximize the discovery potential of massive BSM states at the LHC and beyond.

For a given basis of operators, i.e. any complete and minimal set of operators at

a given order, there is a large number of operators to consider: for instance there are

already 59 independent operators impacting the top quark at dimension 6, and this

number grows exponentially with mass dimension. Since constraining this huge para-

meter space would require a wealth of data and the combination of a large number
of analyses targeting different final states (which is the ultimate goal), it is natural to
make motivated assumptions regarding the nature of new physics to restrict the con-
sidered phase space. Most LHC EFT analyses up to now have considered dimension-6
operators only, which are in general expected to describe most new physics effects
since higher-order operators are suppressed by powers of $\Lambda$; and operators of dimen-
sion 5 or 7 lead to lepton flavor violation and are only relevant in specific analyses.
Most useful guidelines and prescriptions on relevant assumptions are provided in a
note arising from the LHCTopWG [4], which summarizes the fruitful outcomes of a
collaboration between theorists and experimentalists.

3 Different approaches to EFT

Within the CMS Top group, four different strategies have been identified and em-
ployed so far to constrain EFT operators. They can broadly be classified on a spec-
trum ranging from post-measurement reinterpretations towards direct EFT measure-
ments carried out at the detector level. In the following, we detail each approach
with its pros and cons, and provide recent examples of CMS top quark analyses in
which they were adopted.

3.1 Reinterpretation of an inclusive measurement

A first approach consists in reinterpreting a cross section measurement a posteriori.
Its value can be parameterized with the EFT operators of interest, which makes it
possible to constrain their WCs in a straightforward manner. The main advantages
of this approach are its good scalability and its ease of combination with other mea-
surements obtained with any experiment. It also does not require the generation of
any dedicated Monte-Carlo simulated sample including the impact of EFT operators.
On the other hand, such reinterpretations typically rely on assumptions regarding
new physics, which usually does not only impact the cross section itself, but also
the kinematic distributions of the objects used in an analysis for event selection and
signal extraction.

This approach was adopted to reinterpret the cross section measurement of the
four-top process by CMS [5]. This analysis is particularly challenging since the signal
has an expected SM cross section $\sigma_(SM) = 9.2 \, fb$, 5 orders of magnitude smaller
than that of the main $t\bar{t}$ background. The four-top process is highly sensitive to four-
heavy-quark operators. The signal cross section was parameterized at the generator
level with several EFT operators as:

$$\sigma_{tt\bar{t}t} = \sigma_{tt\bar{t}t}^{SM} + \frac{1}{\Lambda^2} \sum_k C_k \sigma_k^{(1)} + \frac{1}{\Lambda^4} \sum_{j \leq k} C_j C_k \sigma_j^{(2)} , \quad (1)$$
where the linear terms $C_k \sigma_k^{(1)}$ represent the interference terms of the SM and dimension-
6 EFT contributions, while the quadratic terms include two components: the squared contributions from
diagrams containing one EFT operator, and the interference terms for two diagrams both including the insertion of one operator. This parameterization
was used to translate the measured cross section into 95% CL upper limits on each
individual WC, while marginalizing over the other operators.

3.2 Reinterpretation of an unfolded differential measurement

A second approach consists in reinterpreting a differential measurement unfolded at
the generator level. Such reinterpretations may be combined with other results if
bin-to-bin correlation matrices are provided, and require the generation of differential
Monte-Carlo sample including EFT effects at the generator level. Differential
measurements of quantities sensitive to EFT make it possible to also exploit shape
information and typically lead to tighter constraints compared to inclusive ones, but
ignore the effects that new physics may have on the detector acceptance and selection
efficiencies.

This procedure was followed in the CMS measurement of the differential $t\bar{t}$ cross
section as a function of kinematic observables of the top quarks, of its decay products
and of the $t\bar{t}$ system [6]. This analysis targeted the dileptonic opposite-sign final
state. The measurements were unfolded both to the parton and particle levels, in
full and fiducial phase spaces respectively. The angular separation between the two
leptons $\Delta \phi(\ell\ell)$ was simulated at generator level using the RIVET framework and
parameterized with the $O_{tG}$ operator at next-to-leading order (NLO) in QCD. This
operator modifies SM vertices and introduces new coupling structures, thus impacting
both the yield and kinematics of the $t\bar{t}$ process. It is directly related to the top quark
chromomagnetic dipole moment (CMDM), which is predicted to have a small value
within the SM and is modified in several BSM models (2HDM, SUSY, technicolor,
etc.). Limits were set on $O_{tG}$ at the particle level at NLO. The higher accuracy in
QCD was found to enhance the effects of this operator, and to significantly reduce
theoretical scale uncertainties compared to LO predictions.

Using the same data and targeting the same final state, a CMS measurement [7]
of the differential $t\bar{t}$ cross section performed as a function of polarization and spin
correlation observables was used to constrain $O_{tG}$ via a simultaneous $\chi^2$ fit to sev-
eral kinematic observables sensitive to spin correlations. Exploiting these powerful
variables allowed to improve the sensitivity to $O_{tG}$ by about 30% compared to the
previous analysis.
3.3 Hybrid measurement performed at detector level

A third approach dubbed “hybrid measurement” relies on the EFT parameterization of yields or differential distributions at the generator level; this parameterization is then translated to the detector level under SM assumptions to extract the results.

This approach was adopted in a search for new physics targeting the $t\bar{t}$ and $tW$ processes in the dileptonic final state \cite{8}. Limits on six different operators were extracted from a simultaneous fit to counting experiments and neural network discriminants in several categories. This constituted a first important step towards more global fits wherein EFT effects are considered in more than one process.

A CMS measurement of the $t\bar{t}Z$ cross section in $3\ell$ and $4\ell$ final states set limits on several EFT operators using a more involved procedure \cite{9}: first, LO generator level samples were produced on a fine grid over the theory phase space (i.e. both at SM and non-SM points); ratios were computed at different points with respect to the SM prediction to scale the distributions of interest, before applying any event selection; finally, these weights were translated to the detector level and applied to the nominal NLO signal sample to emulate the EFT contributions. The validity of the entire procedure was verified in closure tests. Two-dimensional differential distributions were used to extract limits both within the EFT and anomalous coupling frameworks.

3.4 Direct EFT measurement

Finally the direct measurement approach minimizes the number of SM assumptions to make, and makes it possible to consider EFT effects in all sensitive processes at once. It offers maximal control over correlations and systematic uncertainties. However, it requires the generation of samples including EFT effects up to the detector level.

A recent CMS analysis \cite{10} employed this approach for the first time in the top quark sector to constrain a set of 16 relevant operators. It considered EFT effects in five associated production modes of the top quark with gauge and Higgs bosons ($t\bar{t}Z$, $t\bar{t}W$, $tZq$, $t\bar{t}H$, $tHq$) in multilepton final states. Simulated samples including EFT effects were passed through a full simulation of the CMS detector, and events were categorized based on lepton, jet and $b$ jet multiplicities to enhance the separation between different processes. The postfit yields are shown for different categories in Fig.\cite{1} Both 1D and 2D limits were extracted for each operator, while either setting the other operators to zero or profiling them. This represents an important step towards direct measurements including EFT effects in all relevant processes.
Figure 1: Postfit yields in several multilepton categories from Ref. [10]. The yields of five top quark processes are parameterized with 16 different WCs, which get constrained in a fit to the data.

References

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