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Automating Predictions for Standard Model Effective Field Theory in MADGRAPH5_AMC@NLO

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Next-to-leading order event generation for the Standard Model effective field theory has started to become available in the MADGRAPH5_AMC@NLO framework. In this talk we discuss some of the recent progresses in this direction, with a focus on the top-quark sector.

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[*] Speaker.

1. Introduction

The Standard Model (SM) effective field theory (EFT) at dimension-six [1] is a powerful approach to searching for SM deviations through precision measurements of the SM. By supplementing the SM Lagrangian with a set of higher-dimensional operators, indirect effects of heavy particles, possibly beyond the reach of the LHC, can be consistently accommodated. The program of determining the SM Lagrangian up to dimension-six has been successful at the LHC Run-I [2], and will continue to proceed at Run-II with improved precisions. To this end, accurate predictions from the theory side are needed, not only for the SM contribution but also for the deviations, in order to set the most stringent bounds on new physics scales and also to better characterize the signals and improve the sensitivities. This motivates us to study the higher-order corrections within the SM EFT, and in particular, the next-to-leading order (NLO) QCD corrections are usually the most important ones at the LHC.

Recently, NLO simulation for the SM EFT is becoming available in the MADGRAPH5_AMC@NLO (MG5_AMC) framework [3]. The framework features a fully automatic approach to NLO QCD calculation interfaced with shower via the MC@NLO method [4]. The dimension-six Lagrangian can be implemented with the FEYNRULES package [5], whose output is in the UFO format [6] and can be directly passed to MG5_AMC for event generation. Loop corrections are computed by MADLOOP [7], where the ultraviolet and the R_2 counterterms are required and can be computed by the NLOCT package [8], up to dimension-four. The NLOCT package is currently being developed to also cover the dimension-six counterterms from effective vertices. In the meantime, case studies can be done by considering a certain set of operators and processes, and computing the relevant counterterms separately. Once the NLO UFO model is made, dimension-six contributions to the cross sections and differential distributions can be computed up to NLO in QCD, in a fully automatic way like in the SM. In this talk we summarize some of these studies, with a focus on the top-quark sector.

2. The top-quark sector

We start with the flavor diagonal interactions in the top-quark sector. To probe deviations in the top-quark couplings, a number of dimension-six operators involving two quark fields in the third generation are relevant [9, 10]:

$$\begin{array}{ll}
O_{\varphi Q}^{(3)}=i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu\varphi\right)(\bar{Q}\gamma^\mu\tau^I Q), & O_{\varphi Q}^{(1)}=i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)(\bar{Q}\gamma^\mu Q),\\
O_{\varphi t}=i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}_\mu\varphi\right)(\bar{t}\gamma^\mu t), & O_{tB}=g_Y y_t(\bar{Q}\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu},\\
O_{tW}=g_W y_t(\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}, & O_{tG}=g_s y_t(\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu},\\
O_{t\varphi}=y_t^3(\varphi^\dagger\varphi)(\bar{Q}t)\tilde{\varphi}, & O_{\varphi G}=y_t^2\left(\varphi^\dagger\varphi\right)\left(G^A_{\mu\nu}G^{A\mu\nu}\right),
\end{array}$$

where $g_{s,W,Y}$ are the SM gauge couplings, and y_t is the top Yukawa coupling. Q is the third generation left-handed quark doublet, while t is the right-handed top quark. The last operator $O_{\varphi G}$ does not involve a top quark, but we include it here because it contributes to $t\bar{t}H$ production as well as several top-loop induced processes. Furthermore, it has $\mathscr{O}(\alpha_s)$ mixing terms to $O_{t\varphi}$ and from O_{tG}, and so should not be ignored, in particular if the latter is present. Four-fermion operators, on the

Process	O_{tG}	O_{tB}	O_{tW}	$O_{\varphi Q}^{(3)}$	$O_{\varphi Q}^{(1)}$	$O_{\varphi t}$	$O_{t\varphi}$	$O_{4\mathrm{f}}$	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	a		a	a				a	
$pp \to t\bar{q}$	A		A	A				A	
$pp \to tW$	A		A	A					
$pp \to t\bar{t}$	A							P	
$pp \to t\bar{t}\gamma$	A	A	A					P	
$pp \to t\gamma j$	A	A	A	A				P	
$pp \to t\bar{t}Z$	A	A	A	A	A	A		P	
$pp \to tZj$	A	A	A	A	A	A		P	
$pp \to t\bar{t}W$	A							P	
$e^+e^- \to t\bar{t}$	A	A	A	A	A	A		A	
$pp \to t\bar{t}H$	P						A	P	P
$pp \to tHj$	P		P	P			A	P	P
$gg \to H, Hj$	A						A		A
$gg \to HZ$	A			A	A	A	A		A

Table 1: Top-quark operators and key processes at the LHC, for the flavor-diagonal sector. Contributions which occur at the leading QCD order either at LO, or NLO, or through a top-quark loop, is marked by "a", "A" or "P". "a": result is known analytically; "A": NLO simulation within MG5_aMC is available; "P": NLO simulation is not available currently, but is planned. O_{4f} denotes any four-fermion operator.

other hand, should also be incorporated, but we do not list them because of their huge number. For a discussion on four-fermion operators see [11]. Finally, the operators $O_{\varphi\varphi}$ and O_{bW} are not included as they do not contribution at order Λ^{-2} in the $m_b \to 0$ limit.

Our convention for the normalization of the operators are chosen such that they do not modify the counting of the QCD and electroweak orders comparing with the corresponding SM vertex. It is also consistent with the naive dimension analysis [12], except that $C_{\varphi G}$ is suppressed by a loop factor, $\alpha_s/4\pi$. Under this convention, in Table 1 we mark the current status of all $\mathcal{O}(\Lambda^{-2})$ contributions that exist at the leading QCD order, either at leading order (LO), or at NLO in QCD, or via a top-quark loop, depending on whether they are analytically available, or available with MG5_aMC for event generation. Note, that we did not define the coupling order of the four-fermion operator coefficients. For these operators, in Table 1 we only show contributions that are present at the LO, and correspond to either $\mathcal{O}\left(\frac{C_{4f}}{\Lambda^2 g_s^2}\right)$ or $\mathcal{O}\left(\frac{C_{4f}}{\Lambda^2 g_{W,Y}^2}\right)$ corrections to the SM, if these operators are not defined with any prefactors.

As we can see from Table 1, apart from the decay process which is analytically known [13], the full set of operators that represent deviations in the top-quark couplings to SM gauge bosons can be already simulated at NLO in QCD, for processes that are relevant for their measurements. The chromo-dipole operator has been implemented with $t\bar{t}$ production in Ref. [14]. All the other operators involving the top-quark and the gauge-boson fields have been implemented in recent works, focusing on single top processes [15] and on $t\bar{t}V$ processes and $e^+e^- \to t\bar{t}$ [16]. In these works the corresponding counterterms are computed with the help of the NLOCT package and by using the anomalous dimension matrix for the dipole operators, which is available from Ref. [13]. Some results for single top production (in the leptonic channel) are shown in Figure 1 for illustration, where the interference contributions from $O_{\varphi Q}^{(3)}$ and O_{tW} are compared at LO and NLO. The same approach also covers the loop-induced process initiated by two gluons as well as $t\bar{t}$ production at lepton colliders. Also available is the top-Yukawa operator $O_{t\varphi}$ in $t\bar{t}H$ and tH production, via the Higgs Characterisation (HC) model [17, 18, 19]. The other operators relevant for these two processes are now being studied. Finally, implementation of four-fermion operators is planned. Note that the four-fermion operator that enters the single top production process can be simulated by introducing a heavy W' propagator that mimics the contact interaction, because the QCD corrections to the two fermion currents factorize. Corresponding counterterms can be computed with NLOCT which is publicly available. The similar trick can be used also in $e^+e^- \to t\bar{t}$.

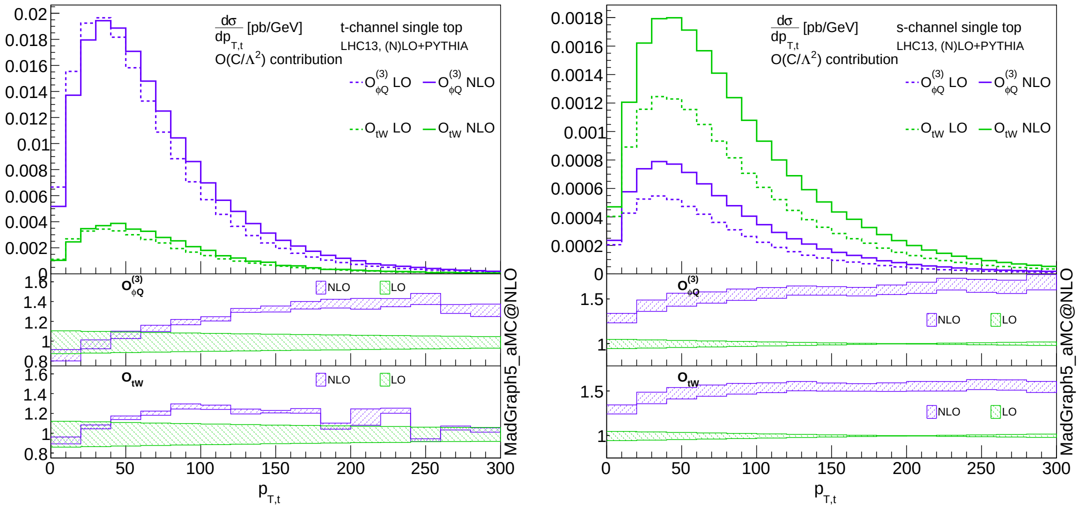

Figure 1: p_T distributions of the top quark, in single top production at the LHC 13 TeV, from the operators $O_{\varphi Q}^{(3)}$ and O_{tW}. Left: t-channel. Right: s-channel. Only the interferences between the SM and the operators are displayed. Anti-top quark is not included. K-factors and scale uncertainties are given in the lower panel.

We now turn to the flavor-changing sector. Deviations in tqB vertex, where B is either a gauge boson or a Higgs boson, are captured by the following operators

$$\begin{aligned}
&O_{\varphi q}^{(3,i+3)} = i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)(\bar{q}_i\gamma^\mu\tau^I Q)\,, && O_{\varphi q}^{(1,i+3)} = i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{q}_i\gamma^\mu Q)\,,\\
&O_{\varphi u}^{(i+3)} = i\frac{y_t^2}{2}\left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)(\bar{u}_i\gamma^\mu t)\,, && O_{uB}^{(i3)} = g_Y y_t(\bar{q}_i\sigma^{\mu\nu}t)\tilde{\varphi}B_{\mu\nu}\,,\\
&O_{uW}^{(i3)} = g_W y_t(\bar{q}_i\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}\,, && O_{uG}^{(i3)} = g_s y_t(\bar{q}_i\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}\,,\\
&O_{u\varphi}^{(i3)} = y_t^3(\varphi^\dagger\varphi)(\bar{q}_i t)\tilde{\varphi}\,,
\end{aligned}$$

where $i = 1, 2$ is the flavor index. 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 $Q \leftrightarrow q_i$. In addition, similar to the flavor-diagonal sector, four-fermion operators could also be relevant for the key processes.

The status of these operators in all the relevant processes are outlined in Table 2, similar to Table 1. The three flavor-changing decay channels are known in Ref. [20, 13]. The single

Process	$O_{\phi q}^{(3)}$	$O_{\phi q}^{(1)}$	$O_{\phi u}^{(1)}$	O_{uW}	O_{uB}	O_{uG}	$O_{u\phi}$	O_{4f}
$t \to qZ^*, q\gamma^* \to ql^+l^-$	a	a	a	a	a	a		a
$t \to q\gamma$				a	a	a		
$t \to qH$						a	a	
$pp \to t$						A		
$pp \to tZ^*, t\gamma^* \to tl^+l^-$	A	A	A	A	A	A		(A)
$pp \to t\gamma$				A	A	A		
$pp \to tH$						A	A	

Table 2: Similar to Table 1 but for the flavor-changing sector, and contributions are at $\mathscr{O}(\Lambda^{-4})$. The flavor indices of operators are omitted.

top production channels are automated with MG5_aMC [21], and the corresponding NLO UFO model is available at the FeynRules repository [22]. The relevant four-fermion operators involve a top quark, a light quark, and two leptons. They are not currently implemented, but are planned to be, and in fact most of them can be easily done by introducing a heavy mediator, with the help of NLOCT, except for $O_{lequ}^{(3)}$ which has a tensor structure. In Ref. [23] we have made use of these results and performed a global fit, for all flavor-changing operators. Even though the fit is based on several simplifications, it provides a proof of principle that a global fitting program can be carried out entirely with NLO accuracy.

3. The Higgs and electroweak sector

In the electroweak sector, operators that do not include any colored field are trivial to add at NLO in QCD, as they do not generate any new dimension-six counterterms. For example, the dimension-six triple gauge-boson operators, the dimension-eight quartic gauge-boson operators, and the operators involving the Higgs boson and the SM weak gauge bosons, are straightforward with the help of NLOCT. As a result, processes such as W-pair production and vector-boson scattering can be simulated at NLO in QCD, with deviations in the triple or the quartic gauge-boson couplings. For illustration, in Figure 2 we show the invariant mass distribution of the W-pair production with the operator O_{WWW} (see, for example, Ref. [24] for its definition), both at LO and NLO. Higgs production processes in vector-boson fusion and in VH associated channel are covered in a similar way, with higher-dimensional interactions between the Higgs and electroweak gauge bosons (see also [25]).

Some Higgs operators involve colored fields. For Higgs measurements the most important ones are $O_{\varphi G}$ and $O_{t\varphi}$. With a slightly different convention, these operators are available in the HC framework, through which all the main Higgs production channels (gluon fusion, weak vector-boson fusion and associated production, and $t\bar{t}H$) [25, 18], as well as the subdominant process, associated production with a single top quark [19], have been studied. The UFO model is available at the FeynRules repository [26]. In addition, the Higgs Effective Lagrangian (HEL), described in Ref. [27], is now being extended to NLO in QCD [28].

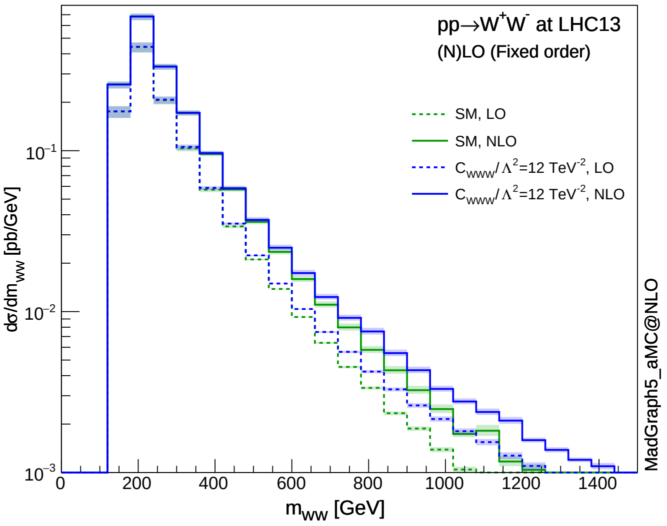

Figure 2: Invariant mass distribution of W-boson pair, at the LHC 13 TeV, in the SM and with the operator O_{WWW}.

4. Summary

NLO simulation for the SM EFT has started to become available with the MG5_aMC framework. Even though the NLO implementation of operators is not fully automated at the moment, in several case by case studies, some UFO models have been made available. With these models, cross sections and differential distributions matched to parton shower can be computed up to NLO in QCD, in a flexible and fully automatic way, just like in the SM. We have briefly discussed several works where such implementations for certain processes and operators are provided. Remarkably, the most important operators in the top quark, the electroweak, and the Higgs sectors are either already available or under investigation. These studies improve the SM predictions at dimension-six, both in accuracy and in precision, and pave the way towards an accurate global fit for SM deviations.

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