PROCEEDINGS OF SCIENCE

# SMEFT calculations for the LHC

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This talk summarizes the status of calculations in the Standard Model Effective Field Theory and gives an overview of the computational techniques that are most commonly employed in order to make predictions for LHC processes in this framework.

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## 1. LHC processes in the SMEFT

The Standard Model Effective Field Theory (SMEFT) is the preferred theoretical framework for indirect searches of new physics at the LHC, see [1] for a review. Its Lagrangian extends the Standard Model (SM) with interaction terms of canonical dimension $d > 4$, built with the SM fields and invariant under the $SU(3) \times SU(2) \times U(1)$ gauge group:

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{d=5}^{\infty} \mathscr{L}_d , \qquad \mathscr{L}_d = \sum_i \frac{C_i^{(d)}}{\Lambda^{d-4}} O_i^{(d)} . \tag{1}$$

At each order the set $\{O_i^{(d)}\}$ forms a complete and non-redundant basis of dimension-$d$ operators, that are accompanied by the Wilson coefficients $C_i^{(d)}$ and suppressed by $(d-4)$ powers of the EFT cutoff scale $\Lambda$. For applications to LHC physics the SMEFT is most often truncated at $d = 6$, that contains the leading lepton- and baryon-number conserving effects. At this order, a generic squared matrix element has the form[1]

$$|\mathcal{A}_{SMEFT}|^2 = |\mathcal{A}_{SM}|^2 + \sum_i \frac{C_i^{(6)}}{\Lambda^2} 2\,\mathrm{Re}(\mathcal{A}_{SM}\mathcal{A}_i^\dagger) + \sum_{i<j} \frac{C_i^{(6)} C_j^{(6)}}{\Lambda^4} 2\,\mathrm{Re}(\mathcal{A}_i \mathcal{A}_j^\dagger) , \tag{2}$$

where $\mathcal{A}_i$ is the amplitude obtained summing all Feynman diagrams containing *one* insertion of the operator $O_i^{(6)}$. Retaining the last term in Eq. (2) is not rigorous from the point of view of the EFT expansion, as a consistent definition of $\mathscr{L}_{SMEFT}$ up to order $\Lambda^{-4}$ would be required. Nonetheless, it is customary to compare global-analysis results obtained with and without their inclusion [4–9], as an assessment *a posteriori* of the validity of the EFT expansion within the sensitivity region.

State-of-the-art SMEFT predictions for LHC processes include corrections up to 1-loop in QCD or in the electroweak (EW) couplings. Higher-order corrections are usually accounted for via overall $K$-factors determined from the SM calculation. Although this talk focuses on the main techniques used for parton-level calculations in the SMEFT, it is worth pointing out that, in principle, SMEFT effects can also enter other ingredients of a realistic prediction. For instance, they can affect the determination of Parton Distribution Functions (PDFs) [10, 11], or induce corrections to the acceptance and efficiency factors employed in the unfolding procedure [12–14], due to SMEFT operators altering the phase space distribution of final-state particles compared to the SM.

More information on the tools mentioned below can be found e.g. in the slides and recordings of a dedicated meeting organized last year by the LHC EFT WG [15].

## 2. Automated predictions

SMEFT predictions for LHC observables are most commonly obtained via Monte Carlo simulations. This option is available for arbitrary processes at LO (tree-level) and at NLO in QCD. The most employed event generator is MadGraph5_aMC@NLO [16, 17], that has some particularly convenient features for SMEFT studies: first of all, it supports input models in the UFO [18] format, and it implements an "interaction orders" syntax that allows the user to specify the desired order in

[1] SMEFT contributions can always be cast into this form by Taylor expanding in the Wilson coefficients. Some extra care is needed for corrections to masses and decay widths, that enter the via the propagators, see e.g. Refs. [2, 3].

arbitrary Lagrangian parameters, both at the amplitude and squared-amplitude levels. In particular, it allows the simulation of the pure interference term between two amplitudes. This simplifies substantially the morphing of the SMEFT signal as a function of the Wilson coefficients.

Further, its reweighting module [19, 20] allows a re-use of simulated samples, by re-evaluating the matrix element at different points in the parameter space while keeping the phase space sampling fixed. It is particularly convenient for SMEFT simulations, as they typically require a large number of evaluations (a quadratic polynomial in $n$ variables contains $n(n+3)/2$ independent terms, plus the SM one) and reweighting is much less computationally expensive than full event generations. Another advantage is that the statistical uncertainties on the original and reweighted samples are fully correlated, and therefore cancel when a ratio, sum or difference of the two is taken.

Finally, it supports the simulation of processes with helicity-polarized states [21].

The most commonly employed UFO models are SMEFTsim [3, 23] and SMEFT@NLO [24]. Both implementations use the Warsaw basis of dimension-6 operators [25] and were validated using the dedicated protocol suggested in [26]. SMEFTsim is designed to enable LO simulations with the full SMEFT Lagrangian, retaining all flavor and CP features. It comes in 10 alternative implementations differing in the flavor symmetry structures and in the choice of EW input quantities. Since version 3.0, it also implements a feature for linearizing propagator (i.e. mass and decay-width) corrections in the Wilson coefficients. SMEFT@NLO is optimized for NLO QCD calculations: it adopts a $U(2)^2 \times U(3)_d$ flavor symmetry in the quark sector that follows the recommendations for top quark analyses [27], combined with a 5-flavor scheme ($m_b = 0$) and with the requirement of CP conservation. Its implementation partially builds upon that of dim6top [27], which automates only LO predictions but includes a larger set of CP- and flavor-violating terms. The HEL UFO [28], that implements an alternative set of operators, has also been often employed for Higgs phenomenology.

Going beyond MadGraph5_aMC@NLO, SMEFT simulations can be performed with many other Monte Carlo event generators, although often with a reduced scope. For instance, Sherpa [29] supports UFO input for tree-level calculations [30] and therefore can be paired e.g. to SMEFTsim. POWHEG BOX [31–33] allows NLO QCD calculations in the SMEFT, but requires a process-by-process implementation. Currently, NLO QCD predictions in SMEFT are available for dilepton, $W$ and EW Higgs production [34–37] and for diboson ($WZ$, $WW$) production [38, 39]. An up-to-date list can be found at the POWHEG BOX homepage [40]. JHUGen [41] is a generator employed for differential studies of Higgs production and decays to $4l$ or $\tau\tau$ final states, including on- and off-shell contributions. It implements tree-level SMEFT effects via an anomalous couplings parameterization that can be mapped to the Warsaw or Higgs bases via the JHUGenLexicon module. A reweighting procedure is also supported. Finally, VBFNLO [42–44] allows simulations of diboson, triboson, Vector Boson Scattering (VBS) and Vector Boson Fusion (VBF) production of $h, Z, W, \gamma$, including NLO QCD and EW corrections in the SM. It implements anomalous triple and quartic gauge couplings that are mapped to SMEFT operators in the HISZ basis [45] for dimension-6 and in the Éboli basis [46] for dimension-8.

## 3. Analytical predictions

An analytical calculation of the matrix element is currently required for SMEFT predictions that include NLO EW corrections, or effects from operators of dimension $d \geq 8$.

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**Beyond tree-level.** The relevance of loop contributions in SMEFT calculation is not limited to a reduction of the uncertainties in the predictions. In fact, they can have a major impact on the observables parameterization in terms of the Wilson coefficients, introducing sensitivity to operators that do not enter the tree level diagrams and even adding discriminating power between otherwise degenerate effects. Their inclusion has visible consequences in global fits and is crucial to ensure a correct interpretation of potential SMEFT signals [47].

Independently of their automation, NLO QCD corrections in SMEFT have been computed for several processes, including Higgs production [48–53] and top quark processes [54–59].

NLO EW corrections pose significantly greater challenges, due to SMEFT effects altering the delicate structure of the EW symmetry breaking sector. Significant progress has been made on this front in the past few years, leading for instance to the generalization of $R_\xi$ gauges, Ward identities and the Background Field Method [60–62]. FeynRules implementations in $R_\xi$ gauge have been made available [63–65], which partially simplifies the task of computing Feynman diagrams. Full NLO EW calculations in the SMEFT have been completed for $\mu \to e\gamma$ [66], 2-body Higgs decays [67–76], $Z, W$ pole observables [77–79] and Drell-Yan [80].

**Beyond dimension-6.** With $d = 6$ SMEFT calculations at such an advanced stage, the interest in incorporating $d = 8$ terms has been recently growing. As a first application, knowledge of these contributions would provide a solid template for estimating uncertainties on $d = 6$ predictions associated to the EFT truncation. Their calculation is also motivated by $d = 8$ being the counterpart to NLO corrections in the double EFT-loop expansion, whose hierarchies are unknown. More in general, a better control of $d = 8$ terms would allow us to study more closely aspects related to the convergence of the EFT series, both in relation to concrete UV scenarios or from the pure EFT point of view, helping for instance to shed light on the long-standing SMEFT-HEFT duality.

Phenomenological studies of dimension-8 operators have been performed in numerous occasions (see e.g. Refs. [37, 81–88]). Complete and non-redundant bases were also constructed [89, 90]. Some of these studies resulted in ad-hoc implementations in Monte Carlo generators. However, no general UFO implementation for $d = 8$ predictions has been produced yet, mainly due to the very large number of invariants to handle (895 for 1 generation, to be compared with 76 at $d = 6$).

Alternative approaches to higher-dimensional contributions were also suggested: for instance, the "geometric SMEFT" [91] provides an all-order parameterization for 2- and 3-point interactions, that allows the calculation of certain processes at arbitrary order in the SMEFT [92–94].

## 4. Outlook

The main near-future challenge for SMEFT calculations concerns the understanding of theory uncertainties, particularly those associated to the EFT truncation, to missing higher loop orders and to the renormalization scale dependence. From the technical point of view, it is reasonable to expect a streamlining of the morphing procedure, with the inclusion of acceptance corrections, and the implementation in NLO Monte Carlo event generations of modules for the Renormalization Group evolution of the Wilson coefficients. In the longer term, the main targets are the streamlining (or automation) of NLO EW and full $O(\Lambda^{-4})$ corrections for arbitrary processes.

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