PROCEEDINGS OF SCIENCE

Impact of NLO contributions and RGE effects on SMEFT global analyses

Riccardo Bartocci[a,*]

[a] *PRISMA+ Cluster of Excellence & Institute of Physics (THEP) & Mainz Institute for Theoretical Physics, Johannes Gutenberg University, D-55099 Mainz, Germany*

E-mail: rbartocc@uni-mainz.de

Global analyses within the Standard Model Effective Field Theory (SMEFT) framework provide a powerful approach to exploring potential directions for new physics. As experimental data continue to grow in both volume and precision, incorporating higher-order contributions becomes increasingly important from a theoretical perspective. These contributions manifest in two critical ways: next-to-leading order (NLO) corrections to observables and the effects of renormalization group evolution (RGE), the latter being essential for a consistent treatment of the large scale separation inherent in combined SMEFT analyses. In this work, we investigate the impact of including NLO corrections and RGE effects in a global SMEFT fit, assuming a $U(3)^5$ flavour symmetry for dimension-six operators. Our analysis yields two significant findings: it places tighter constraints on previously weakly constrained coefficients and uncovers new correlations among coefficients that are uncorrelated at tree level. These results underscore the substantial influence of NLO and RGE effects on the bounds of SMEFT Wilson coefficients.

9th Symposium on Prospects in the Physics of Discrete Symmetries (DISCRETE2024)
2–6 Dec 2024
Ljubljana, Slovenia

*Speaker

ISSN 1824-8039. Published by SISSA Medialab.

PoS(DISCRETE2024)094

1. Introduction

In the absence of direct evidence for new physics (NP), the Standard Model Effective Field Theory (SMEFT)[1, 2] serves as a robust framework for characterizing deviations from Standard Model (SM) predictions. Global analyses within the SMEFT framework are crucial for consolidating experimental constraints on potential NP directions and evaluating their current viability. Such analyses span a wide range of experimental domains, including low-energy processes[3], flavour physics [4, 5], electroweak precision observables (EWPO)[6, 7], and top-quark interactions[8, 9], as well as combined datasets [10–13].

Most global SMEFT fits to LHC data are currently performed at the scale of the observables, often neglecting renormalization group evolution (RGE) effects [14–16] across different energy scales. However, interpreting results in terms of NP models necessitates accounting for RGE effects, which evolve the Wilson coefficients from the NP scale Λ to the observable scale. When measurements conducted at different energy scales are combined into a single global fit, incorporating RGE effects becomes essential. The importance of RGE effects for high-energy LHC and future collider SMEFT analyses has only recently attracted significant attention [17–22].

This proceeding examines the impact of RGE effects on global SMEFT analyses, particularly those incorporating observables measured across a broad energy spectrum, from sub-GeV scales to several TeV. We present an RGE-improved global analysis of all CP-even Wilson coefficients in the Warsaw basis [2], assuming a $U(3)^5$ flavour symmetry at the high scale. This symmetry, rooted in the Minimal Flavour Violation (MFV) framework [23], reduces the number of independent Wilson coefficients to 41.

Finally, we compare these results to those obtained from a global analysis that include next-to-leading order (NLO) contributions.

2. Global analysis setup

2.1 SMEFT assumptions, fit inputs and datatsets

The SMEFT Lagrangian, truncated at dimension six, is given by

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i}{\Lambda^2} Q_i, \tag{1}$$

where C_i denote the Wilson coefficients of the operators Q_i in the Warsaw basis [2] and Λ denotes the NP scale, which we set to $\Lambda = 4$ Tev throughout this work. We truncate all SMEFT predictions at linear order in the Wilson coefficients, neglecting quadratic contributions which are suppressed by Λ^{-4}. We employ the electromagnetic coupling constant, the mass of the Z boson and the Fermi constant $\{\alpha, M_Z, G_F\}$ as our electroweak input parameters. In order to reflect the minimal amount of FCNCs and CP violation observed at the electroweak scale, we make assumptions on the flavour structure of the NP interactions and their CP nature. We consider a $U(3)^5$ symmetry of the SMEFT as initial condition at the high scale. These two assumptions reduce the list of independent Wilson coefficients at dimension six to 41.

Our analysis combines observables measured at a wide range of energy scales, from the sub-GeV level to kinematic distributions at several TeV. Specifically, we include data from EWPO, diboson, Higgs, top, low-energy parity violation experiments (PVE), lepton scattering, flavour, DY as well as dijet+photon production. For a more detailed description of the datasets we refer to [13] and [22].

2.2 Inclusion of RGE and NLO

The energy scale of the observables included in our fit ranges from below 1 GeV, as in the case of PVE, over the mass of the Z boson for EWPO, up to 2.3 TeV for kinematic distributions in DY and $t\bar{t}$ production. To account for the scale dependence of the Wilson coefficients and facilitate the reinterpretation in terms of concrete models, we incorporate RGE effects into our SMEFT predictions. In order to account for RGE effects, we need to assign a scale to each of our observables, for a detailed description of the scale choices we remind the reader to [22].

Concerning NLO predictions we include strong and electroweak corrections to EWPO from [24], SMEFT predictions for top observables as provided by the SMEFit collaboration [25] and we also include the NLO predictions for gluon fusion Higgs production, $t\bar{t}h$ production and the loop-induced decays $h \to gg,\, \gamma\gamma$ [26].

Since NLO predictions are not known for all the observables present in our LO datasets, incorporating RGE effects in global SMEFT fits allows probing the relevance of the lacking NLO corrections consistently.

3. Results

3.1 LO vs NLO results

In Figure 1, we present a comparison of the global fit at LO (blue) with the one including partial NLO SMEFT predictions (orange). The bounds on most operators are only mildly influenced by the inclusion of NLO SMEFT predictions. However, in the four-quark sector the limits on the Wilson coefficients $C_{qd}^{(1)}$, $C_{qu}^{(1)}$, $C_{ud}^{(1)}$ and, to a smaller extent, C_{uu} significantly tighten when improving the SMEFT predictions to NLO precision and are now below $|C|/\Lambda^2 < 10/\text{TeV}^2$. The Wilson coefficients C_{dd} and C'_{dd} remain the only ones exceeding this limit. On the other hand, the bounds on $C_{Hq}^{(1)}$ are weakened by a factor 2.5 through its correlations with four-quark operators in EWPO, in particular with $C_{qq}^{(1)}$ and C_{uu} which are induced through the EWPO SMEFT predictions, weakening the limits on $C_{Hq}^{(1)}$. All 41 Wilson coefficients remain consistent with the SM within 2σ in the NLO fit.

3.2 RGE effects on the global analysis

In Figure 1, we present the results of the LO global fit when the RGE is taken into account (green) and in this section we compare these results to those of the LO analysis. The effects of including RGE effects can be due to diagonal running or mixing. As an example, the limits on most of the Wilson coefficients contributing mainly to Higgs physics do not significantly change after the inclusion of RGE effects. Increases and decreases of the limits in this sector are mostly dominated by diagonal running effects. For the coefficient C_{HG} the diagonal running contribution, $C_{HG}(\Lambda) \approx 0.75\, C_{HG}(m_H)$, dominates the decrease of the bound on this coefficient by around 20%. Relevant effects of non-diagonal running are visible for example in flavour physics. Even if

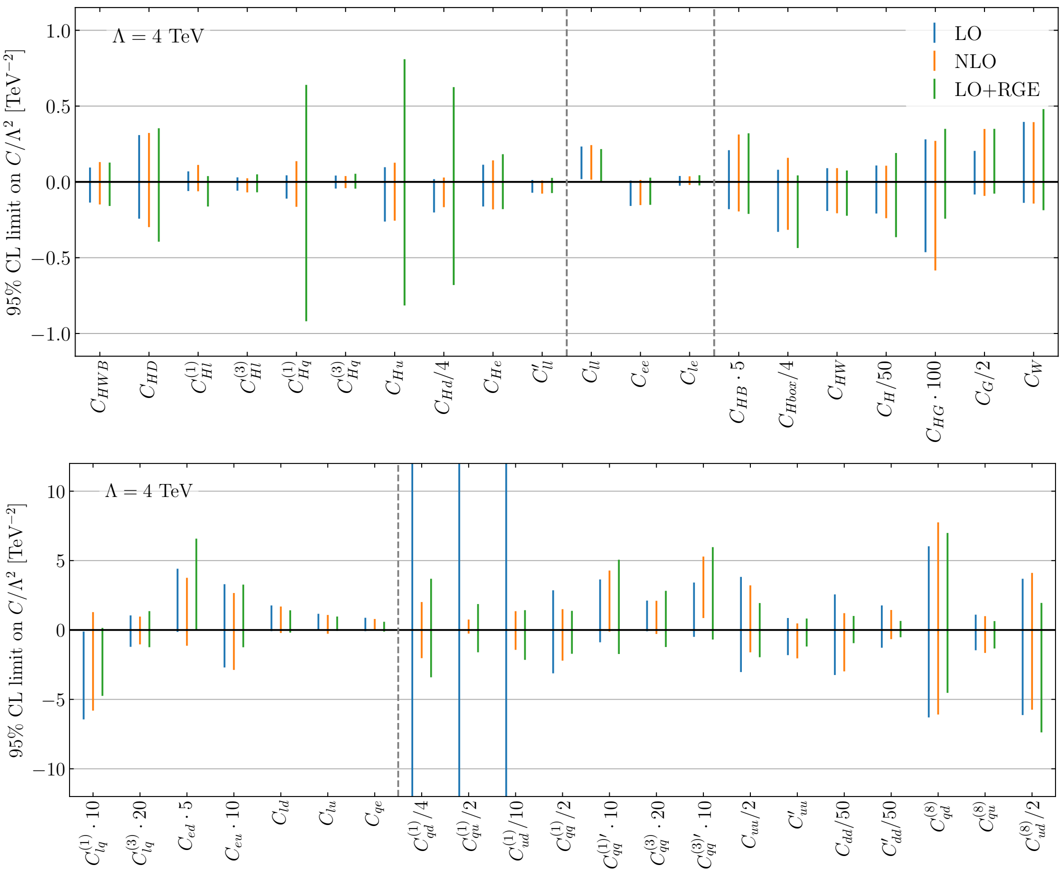

Figure 1: Comparison of the limits on the Wilson coefficients from a global fit purely based on LO predictions (LO), with those including NLO contributions (NLO) and including RGE effects (LO+RGE).

at the high scale the dimension six coefficients are flavour conserving, via RGE and the presence of the SM Yukawa couplings, flavour conserving coefficients can be bounded via flavour violating observables. For details about this and the connected interplay with top physics see [13]. The most relevant mixing effects are observed in the EW sector. The global limits on $C_{Hq}^{(1)}$, C_{Hu} and C_{Hd}, which contribute to modified $Zq\bar{q}(h)$ couplings, increase by factors 10.1, 4.5 and 5.9, respectively. This is the result of significant correlations between the quark-gauge operators and four-quark operators induced by the RG evolution. In the top left panel of Fig. 2, we show the correlations of $C_{Hq}^{(1)}$, C_{Hu} and C_{Hd} with selected four-quark operators after including RGE effects in the fit. As one can see, several correlations are above the 50% level. To highlight how much of these correlations is due to the RGE effects, in the top right panel of Fig. 2, we show the difference between the absolute values between before and after including RGE effects in the fit. The absolute correlations of the operators $C_{Hq}^{(1)}$, C_{Hu}, and C_{Hd} with $C_{ud}^{(1)}$, $C_{qq}^{(1)}$, $C_{qq}^{(1)\prime}$, $C_{qq}^{(3)}$, $C_{qq}^{(3)\prime}$, and C_{uu} all increase by at least 36%. Evidently, the RGE improvement induces strong correlations between the gauge-quark operators and several four-quark operators. In the fit based on partial NLO predictions described in the previous section, we noticed an increase of the limits on $C_{Hq}^{(1)}$ by a factor two when including partial NLO EWPO predictions, while the limits on C_{Hu} and C_{Hd} only marginally changed. This is likely due to the fact that our NLO fit only includes partial NLO corrections. The

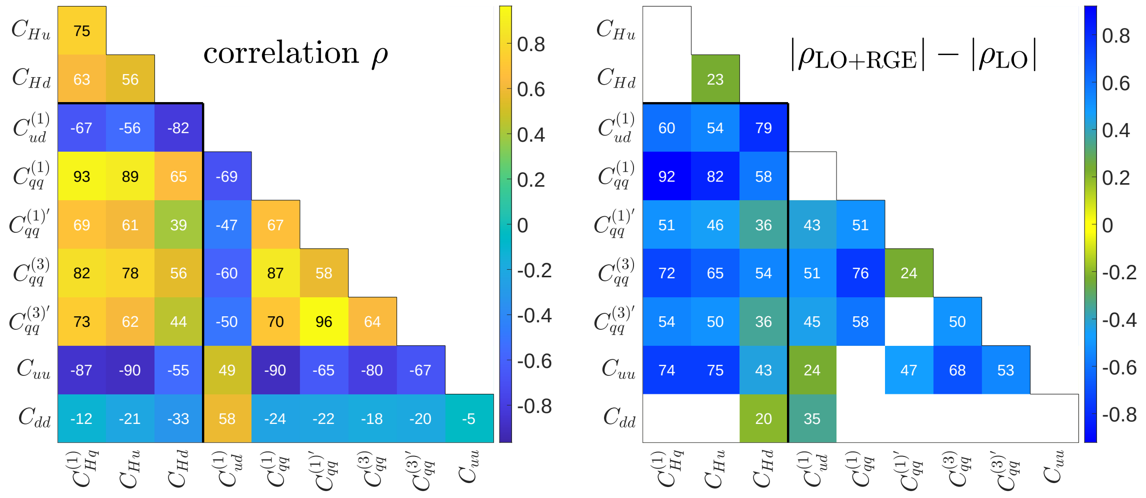

Figure 2: Left: Correlation ρ (in percent) between selected Wilson coefficients in the LO+RGE fit. Right: Difference between the absolute values of the correlations before and after the inclusion of RGE in the fit.

lack of NLO predictions for Vh production leads to four-quark-operator–independent constraints on operators influencing quark-gauge interactions in the partial NLO fit. This highlights the relevance of further NLO SMEFT predictions. The limits on individual four-quark operators significantly improve in the RG improved LO fit. As pointed out above, at LO, the Wilson coefficients $C_{qd}^{(1)}$, $C_{qu}^{(1)}$ and $C_{ud}^{(1)}$ are only constrained by the dijets dataset. Since the corresponding operators do not interfere with the dominant SM diagram as a result of their colour structure, the bounds on these operators from an LO fit are weak, leaving (almost) blind directions in the fit. Through RGE effects, these operators are constrained in EWPO, PVE and DY. The mixing of $C_{qd}^{(1)}$, $C_{qu}^{(1)}$ and $C_{ud}^{(1)}$ generates sizeable contributions to C_{Hu}, C_{Hd} and $C_{qu}^{(1)}$. While the strong crosstalk of these and other four-quark coefficients leads to weaker bounds on the coefficients entering EWPO at LO, as discussed above, bounds on the four-quark coefficients in turn improve.

4. Conclusion and outlook

The inclusion of NLO and RGE effects is a crucial advancement for the precision of global SMEFT analyses and allow for the consistent combination of observables at different energy scales. We find that the limits on most coefficients are only mildly influenced by the inclusion of these loop effects. However, individual Wilson coefficients may also experience a significant decrease or increase of their bounds as a result of correlations and crosstalk between observables induced through these loop effects. The mixing introduces additional constraints on the coefficients from datasets to which they do not contribute at LO, as well as additional correlations between coefficients. The Wilson coefficients corresponding to four-fermion operators are generally improved, as they mix with operators well constrained in precision measurements. On the other hand, limits on operators modifying the $Zq\bar{q}(h)$ coupling, $C_{Hq}^{(1)}$, C_{Hu}, C_{Hd}, are significantly weakened in an RGE improved fit. In a NLO fit we saw that the effects on this operators were only mild, this could be due to the lack of some NLO contributions and the consequent suppression of correlations. However, it could also be that finite terms in NLO SMEFT predictions may tame some of the degeneracies induced by RGE effects (as well as those present already at LO) and further improve the bounds in global fits. Our study also highlights the interconnectedness of (flavour conserving) four-quark interactions with those tested in precision experiments.

Acknowledgments

I am grateful to Anke Biekötter and Tobias Hurth for their invaluable collaboration on this project. I also thank the organizers of DISCRETE 2024 for an amazing conference. This work is supported by the Cluster of Excellence “Precision Physics, Fundamental Interactions, and Structure of Matter" (PRISMA$^+$ EXC 2118/1) funded by the DFG within the German Excellence Strategy.

References

[1] W. Buchmuller and D. Wyler, *Effective Lagrangian Analysis of New Interactions and Flavor Conservation*, *Nucl. Phys. B* **268** (1986) 621–653.

[2] B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, *Dimension-Six Terms in the Standard Model Lagrangian*, *JHEP* **10** (2010) 085, [1008.4884].

[3] A. Falkowski, M. González-Alonso and K. Mimouni, *Compilation of low-energy constraints on 4-fermion operators in the SMEFT*, *JHEP* **08** (2017) 123, [1706.03783].

[4] S. Bruggisser, R. Schäfer, D. van Dyk and S. Westhoff, *The Flavor of UV Physics*, *JHEP* **05** (2021) 257, [2101.07273].

[5] C. Grunwald, G. Hiller, K. Kröninger and L. Nollen, *More synergies from beauty, top, Z and Drell-Yan measurements in SMEFT*, *JHEP* **11** (2023) 110, [2304.12837].

[6] A. Biekötter, T. Corbett and T. Plehn, *The Gauge-Higgs Legacy of the LHC Run II*, *SciPost Phys.* **6** (2019) 064, [1812.07587].

[7] S. Dawson, S. Homiller and S. D. Lane, *Putting standard model EFT fits to work*, *Phys. Rev. D* **102** (2020) 055012, [2007.01296].

[8] A. Buckley, C. Englert, J. Ferrando, D. J. Miller, L. Moore, M. Russell et al., *Constraining top quark effective theory in the LHC Run II era*, *JHEP* **04** (2016) 015, [1512.03360].

[9] I. Brivio, S. Bruggisser, F. Maltoni, R. Moutafis, T. Plehn, E. Vryonidou et al., *O new physics, where art thou? A global search in the top sector*, *JHEP* **02** (2020) 131, [1910.03606].

[10] J. Ellis, M. Madigan, K. Mimasu, V. Sanz and T. You, *Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory*, *JHEP* **04** (2021) 279, [2012.02779].

[11] SMEFiT collaboration, J. J. Ethier, G. Magni, F. Maltoni, L. Mantani, E. R. Nocera, J. Rojo et al., *Combined SMEFT interpretation of Higgs, diboson, and top quark data from the LHC*, *JHEP* **11** (2021) 089, [2105.00006].

[12] F. Garosi, D. Marzocca, A. R. Sánchez and A. Stanzione, *Indirect constraints on top quark operators from a global SMEFT analysis*, *JHEP* **12** (2023) 129, [2310.00047].

[13] R. Bartocci, A. Biekötter and T. Hurth, *A global analysis of the SMEFT under the minimal MFV assumption*, *JHEP* **05** (2024) 074, [2311.04963].

[14] E. E. Jenkins, A. V. Manohar and M. Trott, *Renormalization Group Evolution of the Standard Model Dimension Six Operators I: Formalism and lambda Dependence*, *JHEP* **10** (2013) 087, [1308.2627].

[15] E. E. Jenkins, A. V. Manohar and M. Trott, *Renormalization Group Evolution of the Standard Model Dimension Six Operators II: Yukawa Dependence*, *JHEP* **01** (2014) 035, [1310.4838].

[16] R. Alonso, E. E. Jenkins, A. V. Manohar and M. Trott, *Renormalization Group Evolution of the Standard Model Dimension Six Operators III: Gauge Coupling Dependence and Phenomenology*, *JHEP* **04** (2014) 159, [1312.2014].

[17] M. Battaglia, M. Grazzini, M. Spira and M. Wiesemann, *Sensitivity to BSM effects in the Higgs p_T spectrum within SMEFT*, *JHEP* **11** (2021) 173, [2109.02987].

[18] R. Aoude, F. Maltoni, O. Mattelaer, C. Severi and E. Vryonidou, *Renormalisation group effects on SMEFT interpretations of LHC data*, *JHEP* **09** (2023) 191, [2212.05067].

[19] S. Di Noi and R. Gröber, *Renormalisation group running effects in $pp \to t\bar{t}h$ in the Standard Model Effective Field Theory*, *Eur. Phys. J. C* **84** (2024) 403, [2312.11327].

[20] G. Heinrich and J. Lang, *Renormalisation group effects in SMEFT for di-Higgs production*, 2409.19578.

[21] F. Maltoni, G. Ventura and E. Vryonidou, *Impact of SMEFT renormalisation group running on Higgs production at the LHC*, 2406.06670.

[22] R. Bartocci, A. Biekötter and T. Hurth, *Renormalisation group evolution effects on global SMEFT analyses*, 2412.09674.

[23] G. D'Ambrosio, G. F. Giudice, G. Isidori and A. Strumia, *Minimal flavor violation: An Effective field theory approach*, *Nucl. Phys. B* **645** (2002) 155–187, [hep-ph/0207036].

[24] S. Dawson and P. P. Giardino, *Flavorful electroweak precision observables in the Standard Model effective field theory*, *Phys. Rev. D* **105** (2022) 073006, [2201.09887].

[25] N. P. Hartland, F. Maltoni, E. R. Nocera, J. Rojo, E. Slade, E. Vryonidou et al., *A Monte Carlo global analysis of the Standard Model Effective Field Theory: the top quark sector*, *JHEP* **04** (2019) 100, [1901.05965].

[26] L. Alasfar, J. de Blas and R. Gröber, *Higgs probes of top quark contact interactions and their interplay with the Higgs self-coupling*, *JHEP* **05** (2022) 111, [2202.02333].