smeftFR – Automatising calculations in the SMEFT

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The SM as an EFT

There are two general approaches in the search for physics beyond the Standard Model (SM) of particle physics. One is to search directly for new particles and forces and the other is to look for deviations from the SM predictions in the experimental data. Currently no new particles have been discovered, and the SM predictions are in good agreement with the experimental data, which creates the need of high-precision computations in a UV model independent framework. The use of the Effective Field Theory (EFT) approach seems to fit perfectly in this situation, since we can use EFT to systematically parameterise corrections to the theoretical SM predictions.

The EFT description of the SM, abbreviated as SMEFT, extends the (renormalisable) SM Lagrangian with all independent operators with dimension greater than 4 (effective operators) without introducing any new fields or symmetries. The most general SMEFT Lagrangian can be schematically presented as

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{p=1}^{\infty} \sum_i \frac{c_{p,i}}{\Lambda^p} Q_i^{(4+p)},$$

where Λ is the typical UV scale of the new physics and $c_{p,i}$ are the dimensionless Wilson coefficients multiplying the gauge invariant effective operators $Q_i^{(4+p)}$. For practical computations we neglect the operators with dimension greater than d_{max}, and for most applications it is sufficient to consider the case $d_{max} = 6$.

SMEFT is, by construction, a highly complicated model. While only 1 operator class exists at dimension 5, at dimension 6 there are 59 baryon-number conserving and 4 baryon-number violating independent operator classes. Taking into account fermion generations, flavour structure and Hermitian conjugated operators, there are in total 2499 independent free parameters. Due to the large number and complicated structure of the new terms in the Lagrangian, theoretical calculations of physical processes within the SMEFT can be very challenging — for some examples of analytical computations at NLO in SMEFT see [4, 5] and references therein. Thus, it is important to develop methods and technical tools to automatise such calculations.

Operators in Warsaw basis

The classification of all independent $d \leq 6$ operators in the SMEFT was given in ref. [1] and is referred to as the “Warsaw basis”. In the following table we present all the $d = 6$ operator classes other than the 4-fermion ones in the Warsaw basis:

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\epsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$	$Q_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$i(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

The quantisation and the Feynman rules for the $d = 6$ SMEFT in the Warsaw basis after spontaneous symmetry breaking was presented for the first time in ref. [2], in which the initial version of `smeftFR` was briefly introduced.

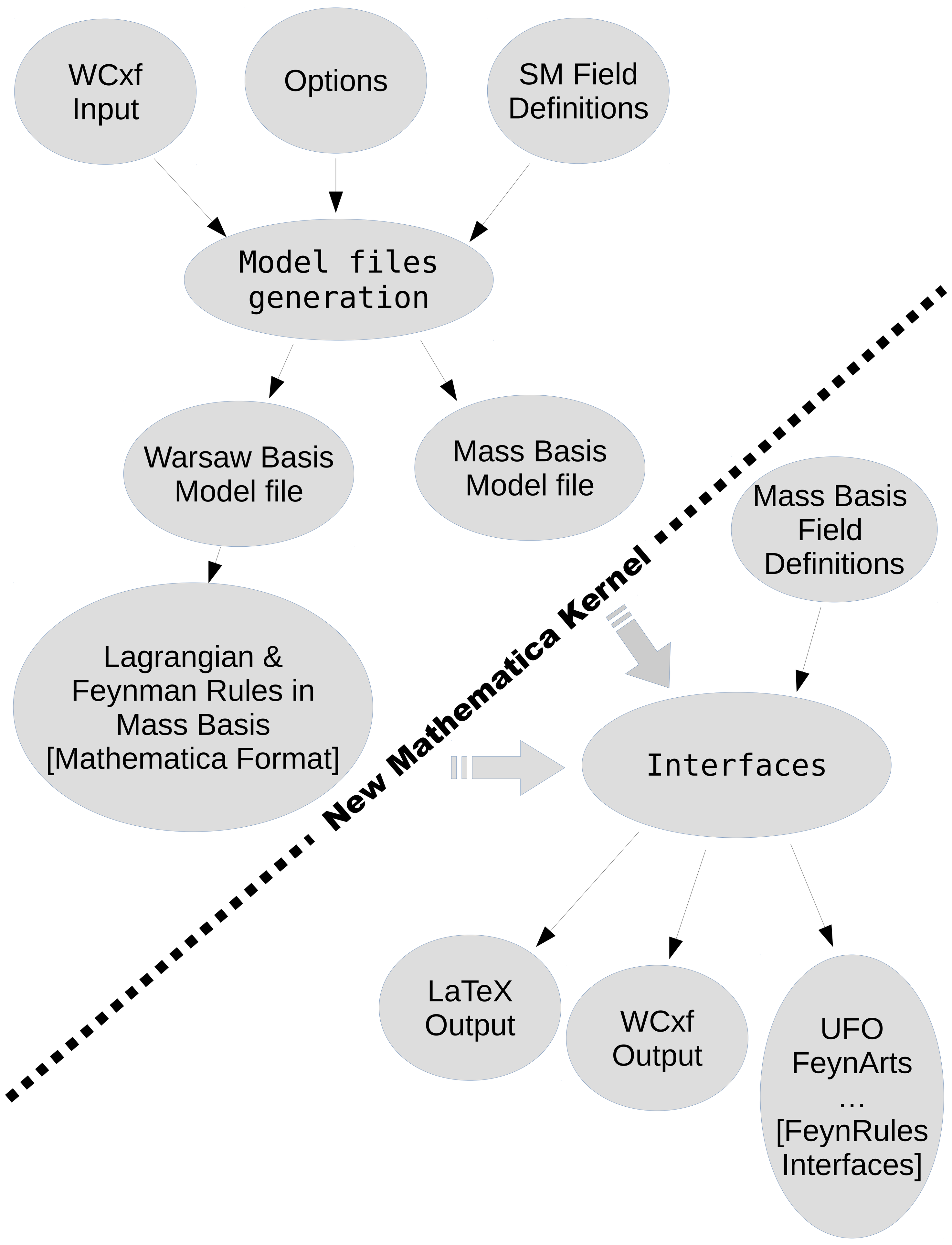
The `smeftFR` package

The package `smeftFR` is a Mathematica package designed to generate the Feynman rules for the SMEFT with operators up to $d = 6$. Feynman rules are generated with the use of `FeynRules` package, directly in the physical (mass eigenstates) basis for all fields. The complete set of interaction vertices can be derived, including all or any chosen subset of SMEFT operators. As an option, the user can also choose the gauge fixing, by choosing between unitary or R_ξ-gauges. The derived Lagrangian in the mass basis can be exported in various formats supported by `FeynRules`, such as `UFO`, `FeynArts`, etc. Initialisation of numerical values of $d = 6$ Wilson coefficients used by `smeftFR` is interfaced to WCxf format. The package also includes a dedicated LaTeX generator, allowing to print the result in human-readable form. Further options allow the user to treat neutrino fields as massless Weyl or (in the case of non-vanishing dimension-5 operator) as massive Majorana fermions.

Feynman rules are calculated first in `FeynRules` format and are expressed in terms of physical SM fields and canonically normalised Goldstone and ghost fields. Expressions for interaction vertices are analytically expanded in powers of inverse Λ, with all terms of dimension higher than 6 consistently truncated. The Feynman rules can be further exported in other formats: `UFO` (importable to Monte Carlo generators like `MadGraph5`, `Sherpa`, `CalcHEP`, `Whizard`), `FeynArts` which generates inputs for loop amplitude calculators like `FeynCalc`, or `FormCalc`, and others output types supported by `FeynRules`. Therefore, the user is provided with many options either for numerical or analytical calculations in the SMEFT.

Code Flowchart

The structure of the `smeftFR` code is summarised in the following figure:



The package `smeftFR` is maintained by prof. Janusz Rosiek and can be downloaded from the address `www.fuw.edu.pl/smeft`

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References

[1] B. Grządkowski, M. Iskrzyński, M. Misiak and J. Rosiek, JHEP **10** (2010) 085

[2] A. Dedes, W. Materkowska, M. Paraskevas, J. Rosiek, and K. Suxho, JHEP **06** (2017) 143

[3] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, Comput. Phys. Commun. **247** (2020), 106931

[4] A. Dedes, M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, JHEP **08** (2018) 103

[5] A. Dedes, K. Suxho and L. Trifyllis, JHEP **06** (2019), 115