SmeftFR – Feynman Rules generator for the SMEFT

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Smeft-Tools
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Based on arXiv:1904.03204, 1704.03888 and references therein

Outline

Motivation

- Effective Field Theories (EFTs) are (mostly) useful when certain terms are forbidden in a Lagrangian.
- The only **known** problem in the Standard Model (SM) of **Electroweak** interactions is that it predicts massless neutrinos.
- Weinberg's $d = 5$ operator leads to Majorana neutrino masses

$$\mathrm{SMEFT}: \frac{C^{\nu\nu}}{\Lambda} \left(\tilde{\varphi}^\dagger \ell_L\right)^T \mathbb{C} \left(\tilde{\varphi}^\dagger \ell_L\right)$$

  One can easily construct a model by completing the portals.
- Could be there is New Physics (NP) for whatever other reason. EFT is then useful to parametrize our ignorance.
- SM is well measured with accuracy less than
  - Gauge sector $\rightarrow 1/200$
  - Fermion sector $\rightarrow 1\%$
  - Higgs sector $\rightarrow 15\%$

Steps towards mass basis up to $1/\Lambda^2$

Step 1: Start out in Warsaw basis with a constant field redefinition of the gauge fields

Step 2: Choose redundant parameters such that gauge field kinetic terms are canonical after Spontaneous Symmetry Breaking

$$\mathcal{L}(W^I_{\mu\nu}, W^I_\mu, ...; g, ...) \to \mathcal{L}(\bar{W}^I_{\mu\nu}, \bar{W}^I_\mu, ...; \bar{g}, ...)$$

We work with the barred parameters and fields.

Step 3: Introduce gauge fixing terms such that after SSB we obtain the familiar SM form

$$\mathcal{L}_{GF} = -\frac{1}{2}\,\mathbf{F}^T\hat{\xi}^{-1}\mathbf{F}, \quad \hat{\xi} = f(\xi_A, \xi_Z, \xi_W, \xi_G)$$

Step 4: Add FP-terms to compensate and restore generalized (BRST) gauge invariance.

Step 5: Diagonalize mass terms to obtain fields and parameters in mass basis

Fields from Warsaw to mass basis

In total the transformations from the "Warsaw gauge" to the "Warsaw mass" basis are :

$$\begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + Z_h^{-1} h + i Z_{G^0}^{-1} G^0) \end{pmatrix} ,$$

$$\begin{pmatrix} B_\mu \\ W^3_\mu \end{pmatrix} = \hat{Z}_{AZ}^{-1} \begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} ,$$

$$W^1_\mu = \frac{1}{\sqrt{2}} (W^+_\mu + W^-_\mu) ,$$

$$W^2_\mu = \frac{i}{\sqrt{2}} (W^+_\mu - W^-_\mu) ,$$

$$G^A_\mu = Z_G^{-1} \, g^A_\mu .$$

Fermion sector

The basis in the fermion sector is not fixed by the structure of gauge interactions allowing for unitary rotations in the flavour space:

$$\psi'_X = U_{\psi_X}\, \psi_X \ , \qquad \psi = \nu, e, u, d \ , \qquad X = L, R \ .$$

ψ_X correspond to real and non-negative eigenvalues of the 3×3 fermion mass matrices:

$$M'_\nu = -v^2 C'^{\nu\nu} \ , \qquad M'_e = \tfrac{v}{\sqrt{2}} \left(\Gamma_e - \tfrac{v^2}{2} C'^{e\varphi} \right),$$
$$M'_u = \tfrac{v}{\sqrt{2}} \left(\Gamma_u - \tfrac{v^2}{2} C'^{u\varphi} \right), \quad M'_d = \tfrac{v}{\sqrt{2}} \left(\Gamma_d - \tfrac{v^2}{2} C'^{d\varphi} \right).$$

The fermion flavour rotations can be adsorbed in redefinitions of Wilson coefficients, leaving CKM ($K = U^\dagger_{u_L}\, U_{d_L}$) and PMNS ($U = U^\dagger_{e_L}\, U_{\nu_L}$) matrices multiplying them.

$$C'^{\nu\nu} \to C^{\nu\nu} \ , \quad C'^{e\varphi} \to C^{e\varphi} \ , \quad \ldots$$

Introducing SmeftFR

- In SMEFT with all $d \leq 6$ operators and no expansion in flavour indices, there are about 120 vertices in unitary gauge and 380 vertices in R_ξ-gauges.
- `SmeftFR` is a code designed to generate the **general** set of Feynman Rules in SMEFT with $d \leq 6$ gauge invariant operators.
- It is based on `Mathematica/FeynRules` language
- Output is given in various formats for further considerations

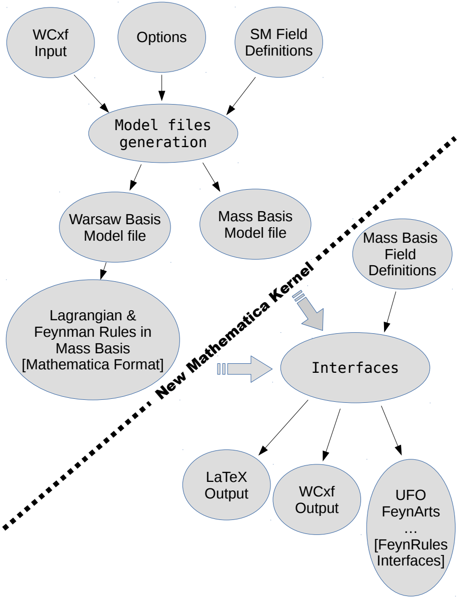
The structure

1. SM Lagrangian + extra operators in Warsaw basis encoded using `FeynRules` syntax
   - `FeynRules` "model files" generated dynamically for user-chosen subset of operators
   - general flavor structure of all Wilson coefficients assumed
   - numerical values of Wilson coefficients (including flavor- and CP-violating ones) are imported from standard files in `WCxf` ("Wilson coefficient exchange format") – could be interfaced to other SMEFT public packages, `Flavio`, `FlavorKit`, `Spheno`, `DSixTools`, `wilson`, `FormFlavor`, `SMEFTSim`, `...`
   - gauge choice user-defined option (unitary or R_ξ-gauges)
   - neutrino masses incorporated in mass basis
2. Derivation of the SMEFT Lagrangian in mass-eigenstate basis, expanded consistently up-to-order $1/\Lambda^2$

The structure

3. Evaluation of Feynman rules in mass basis, available formats:
   - `Mathematica/FeynRules`
   - `Latex/Axodraw` (dedicated generator)
   - `UFO` format $\rightarrow$ "event generators"
   - `FeynArts` $\rightarrow$ "symbolic calculators"
4. various options available
   - neutrino fields treated as massless Weyl or massive Majorana (in the presence of $= 5$ Weinberg operator) spinors
   - correction of `FeynRules` 4-fermion sign issues
   - corrected B-, L- violating 4-fermion vertices and 4-ν vertex
   - ...

SmeftFR code structure



References

Brand new version available since April 2019:

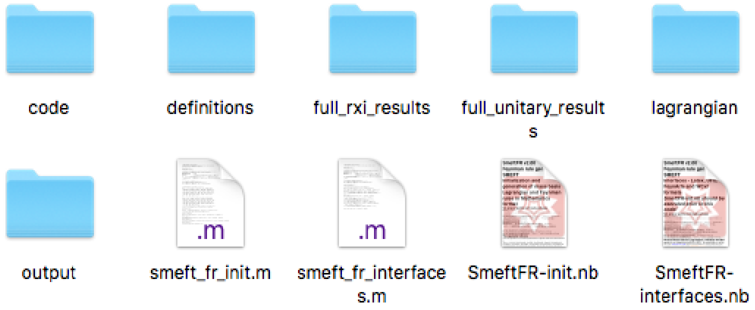
Code :	`SmeftFR v2.0`
URL:	http://www.fuw.edu.pl/smeft
Physics :	`ArXiv:1704.03888`, JHEP 06 (2017) 143.
Manual:	`ArXiv:1904.03204`, submitted to CPC journal
Authors:	A.D, M. Paraskevas, **J. Rosiek**, K. Suxho, L. Trifyllis

SmeftFR Demonstration

We shall go through SmeftFR to create Latex, UFO, and FeynArts files while explaining the structure of SmeftFR

SmeftFR Demonstration

Unpack SmeftFR in FeynRules/Models/SMEFT_2_00 directory.



SmeftFR Demonstration

Open a notebook and set the FeynRules path

```
(*FeynRules and SmeftFR package installation paths-edit if necessary*)
$FeynRulesPath = FileNameJoin[{"/Users", "Dirac", "PROJECTS",
       "EFT-CANONICAL", "PROGRAM", "SYMBOLIC", "FeynRules"}];
SMEFT$MajorVersion = "2";
SMEFT$MinorVersion = "00";
SMEFT$Path = FileNameJoin[{$FeynRulesPath, "Models",
     "SMEFT_" <> SMEFT$MajorVersion <> "_" <> SMEFT$MinorVersion}];

(*Load FeynRules and SMEFT packages*)
Get[FileNameJoin[{$FeynRulesPath, "FeynRules.m"}]];
Get[FileNameJoin[{SMEFT$Path, "code", "smeft_package.m"}]];
```

SmeftFR Demonstration

Provide a list of operators e.g., all those connected to an observable. For example

```
OpList= {"W", "phiD", "phiWB", "phil1", "vv", "ledq"}
```

SmeftFR Demonstration

Initialize Lagrangian, define gauge fixing:

```
SMEFTInitializeModel[Operators -> OpList, Gauge ->
Unitary, MajoranaNeutrino -> True, WCXFInitFile ->
WCXFInput];
```

Calculate FRs in mass basis:

```
SMEFTLoadModel[ ]
```

```
SMEFTFindMassBasis[ ]
```

```
SMEFTFeynmanRules[ ]
```

Now the SMEFT Lagrangian and interaction vertices have been created (in Mathematica form). `FeynRules` model files have been created.

SmeftFR Demonstration

Create the Lagrangian in Mass Basis:

```
SMEFTInitializeMB[ ];
```

The result is stored in `SMEFTMBLagrangian` variable.

SmeftFR Demonstration

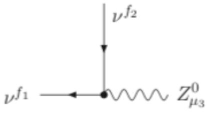
Interface to other programs:

```
SMEFTToLatex[ ];
```

```
WriteUFO[ SMEFTMBLagrangian, "Options" ];
WriteFeynArtsOutput[ SMEFTMBLagrangian, "Options"];
SMEFTToWCxf[ SMEFT_Parameter_File, WCXF_File ];
```

SmeftFR Demonstration

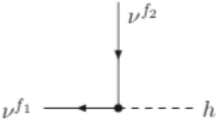
A part of the Latex output for the model assumed in unitary gauge (55 vertices including SM)



$$+\frac{1}{2}i\sqrt{\bar{g}^2+\bar{g}'^2}\delta_{f_1f_2}\gamma^{\mu_3}\gamma^5+\frac{i\bar{g}\bar{g}'v^2}{2\sqrt{\bar{g}^2+\bar{g}'^2}}\delta_{f_1f_2}C^{\varphi WB}\gamma^{\mu_3}\gamma^5$$
$$+\frac{1}{2}iv^2\sqrt{\bar{g}^2+\bar{g}'^2}C^{\varphi l1}_{g_1g_2}\left(U_{g_2f_2}U^*_{g_1f_1}\gamma^{\mu_3}P_L-U_{g_2f_1}U^*_{g_1f_2}\gamma^{\mu_3}P_R\right)$$

SmeftFR Demonstration

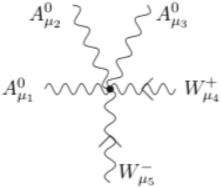
A part of the Latex output for the model assumed in unitary gauge



$$-\frac{2i}{v} m_{\nu_{f_1}} \delta_{f_1 f_2}$$

SmeftFR Demonstration

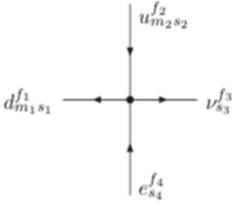
A part of the Latex output for the model assumed in unitary gauge



$$
\begin{aligned}
&+\frac{6i\bar{g}^2\bar{g}'^3}{\left(\bar{g}^2+\bar{g}'^2\right)^{3/2}}C^W\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}\left(-p_3^{\mu_5}\right)-2\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_3}p_1^{\mu_4}\right.\\
&+\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_3}p_2^{\mu_4}+\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_3}p_3^{\mu_4}-\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}p_3^{\mu_5}\\
&+\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_4}p_1^{\mu_3}-\eta_{\mu_1\mu_5}\eta_{\mu_2\mu_4}p_2^{\mu_3}+\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_5}p_1^{\mu_4}\\
&-2\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_5}p_2^{\mu_4}+\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_5}p_3^{\mu_4}-\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_5}p_1^{\mu_3}\\
&+\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_5}p_2^{\mu_3}+2\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}p_3^{\mu_5}+\eta_{\mu_1\mu_5}\eta_{\mu_3\mu_4}p_1^{\mu_2}\\
&-\eta_{\mu_1\mu_5}\eta_{\mu_3\mu_4}p_3^{\mu_2}+\eta_{\mu_2\mu_5}\eta_{\mu_3\mu_4}p_2^{\mu_1}-\eta_{\mu_2\mu_5}\eta_{\mu_3\mu_4}p_3^{\mu_1}\\
&+\left(2\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}-\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}-\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)p_1^{\mu_5}\\
&-\left(\eta_{\mu_1\mu_4}\eta_{\mu_2\mu_3}-2\eta_{\mu_1\mu_3}\eta_{\mu_2\mu_4}+\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_4}\right)p_2^{\mu_5}+\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_5}p_1^{\mu_4}\\
&+\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_5}p_2^{\mu_4}-2\eta_{\mu_1\mu_2}\eta_{\mu_3\mu_5}p_3^{\mu_4}-\eta_{\mu_1\mu_4}\eta_{\mu_3\mu_5}p_1^{\mu_2}\\
&\left.+\eta_{\mu_1\mu_4}\eta_{\mu_3\mu_5}p_3^{\mu_2}-\eta_{\mu_2\mu_4}\eta_{\mu_3\mu_5}p_2^{\mu_1}+\eta_{\mu_2\mu_4}\eta_{\mu_3\mu_5}p_3^{\mu_1}\right)
\end{aligned}
$$

SmeftFR Demonstration

A part of the Latex output for the model assumed in unitary gauge

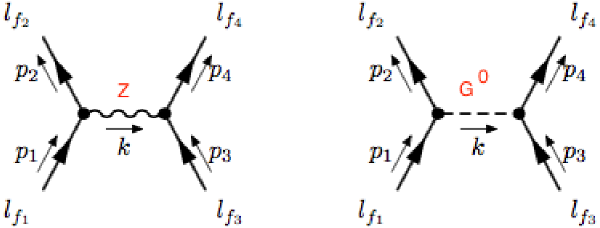


$$+i(P_L)_{s_1 s_2}(P_R)_{s_3 s_4} U^*_{g_1 f_3} K^*_{f_2 g_2} C^{ledq}_{g_1 f_4 f_1 g_2}$$

Tree Level validation

A first check of SmeftFRs is the ξ-independence of tree amplitudes e.g.,

$$\ell_{f_1} + \ell_{f_2} \longrightarrow \ell_{f_3} + \ell_{f_4}$$

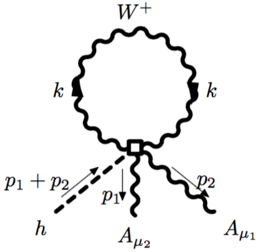


The sum is ξ-independent up to $1/\Lambda^2$ after using explicitly the Z-boson mass expression in SMEFT

More interesting is to check diagrams with neutrino masses kept explicit: ξ-independence is again confirmed up-to $1/\Lambda^2$.

One-Loop Level validation

Highly non-trivial checks involve the ξ-independence of a physical process e.g., $h \to \gamma\gamma$, $h \to Z\gamma$. Seems so far there is no problem.



Only in SMEFT

Interfaces validation

- `WCxf` input and output $\Longrightarrow$ checked
- `Madgraph5_aMC@NLO` $\Longrightarrow$ checked (only for subset of ops)
- `FeynArts` $\Longrightarrow$ checked

Conclusions

- The proliferation of primitive vertices in SMEFT demands computer assistance
- `SmeftFR` is a code for generating Feynman Rules in SMEFT in Warsaw basis so far limited to $d \leq 6$ operators
- `SmeftFR` calculates the FRs in Unitary or R_ξ-gauges
- Output is provided in `Latex`, `UFO` and `FeynArts` outputs
- `SmeftFR` is available at

http://www.fuw.edu.pl/smeft