SmeftFR v3 - a tool for creating and handling vertices in SMEFT to the $\frac{1}{\Lambda^4}$ order

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based on [2302.01353]

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Introducing: SMEFT

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{C_i Q_i}{\Lambda^{d_i - 4}}$$

- Q_i - higher dimensional gauge invariant operators in terms of SM fields
- C_i - Wilson coefficients
- Λ - new physics scale

model independent way of studying BSM phenomena!

Automatising calculations in SMEFT

- SMEFT is a very complicated model
  $\sim$ 60 dimension-6 operators
  $>$ 1000 dimension-8 operators (not counting flavour)
- increasing complexity of addressed problems
- we need a certain degree of automatisation for efficient calculations
- number of publicly available numerical tools designed for calculations in SMEFT:
  `SmeftFR` [1904.03204], [2302.01353]
  `SMEFT@NLO` [2008.11743]
  `SMEFTsim` [1709.06492]
  `Dim6Top` [1802.07237]

SmeftFR v3 - [2302.01353]

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SmeftFR v3 – Feynman rules generator for the Standard Model Effective Field Theory

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SmeftFR available at:

www.fuw.edu.pl/smeft

SmeftFR v3 - main features

1. Mathematica package using FeynRules [1310.1921]
2. consistent calculation of SMEFT vertices up to $\frac{1}{\Lambda^4}$
3. output to LaTeX, FeynArts, UFO, ...
4. improved compatibility & consistent testing of output formats (especially UFO!)
5. predefined input schemes for the EW sector and CKM matrix
6. user can use subset of WCs relevant for a given analysis
7. correction of issues related to B and L violating vertices
8. significant improvement in speed of the code

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SMEFT - going beyond the leading order . . .

. . . in the EFT expansion:

- so far most analyzes & tools concentrated on dim-6 operators $\propto \frac{1}{\Lambda^2}$
- dim-6^2 & dim-8 $\propto \frac{1}{\Lambda^4}$ terms not necessarily negligible
- consistency: simultaneous inclusion of dim-6^2 and dim-8 terms

`SmeftFR` v3: **all dim-6 operators in the Warsaw basis [1008.4884]**
all bosonic dim-8 operators in the basis of [2005.00059]
no dim-8 fermionic operators included - too many! . . .
but if necessary, instructions on program's webpage

SmeftFR v3 - tests and validation

Analytical tests - FeynArts & LaTeX:

- GBET
- various Ward identities

numerical tests - UFO & MG5:

- SmeftFR v3 and SMEFT@NLO, Dim6Top and SMEFTsim at dim-6
- SmeftFR v3 and AnomalousGaugeCoupling [1604.03555] for F^4 dim-8 operators

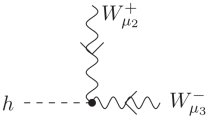
	SMEFT@NLO $\mathcal{O}\left(\Lambda^{-2}\right)$	SmeftFR $\mathcal{O}\left(\Lambda^{-2}\right)$	SmeftFR $\mathcal{O}\left(\Lambda^{-4}\right)$
	$\mu^+\mu^- \to t\bar{t}$		
SM	0.16606 ± 0.00026	0.16608 ± 0.00024	–
C_{uW}^{33}	0.41862 ± 0.00048	0.41816 ± 0.00047	–
$C_{\varphi u}^{33}$	0.16725 ± 0.00027	0.16730 ± 0.00025	–
C_{lu}^{2233}	6.488 ± 0.016	6.491 ± 0.014	–
$C_{\varphi WB}$	0.21923 ± 0.00032	0.21940 ± 0.00030	0.22419 ± 0.00030
$C_{\varphi D}$	0.18759 ± 0.00030	0.18759 ± 0.00027	0.18829 ± 0.00027

for full list see code's webpage

Input schemes in SMEFT

Vertices & observables in mass basis in terms of SM parameters and WCs:

$$\mathcal{O}_{\text{SMEFT}} = \mathcal{O}(g, g', g_s, \lambda, v, m_q, K_{\text{CKM}}, m_l, m_{\nu_l}, U_{\text{PMNS}}, C_i)$$



$$+ \quad \frac{1}{2} i g^2 v \eta_{\mu_2\mu_3} + \frac{1}{2} i g^2 v^3 \eta_{\mu_2\mu_3} C^{\varphi\Box} - \frac{1}{8} i g^2 v^3 \eta_{\mu_2\mu_3} C^{\varphi D}$$
$$+ \quad 4 i v C^{\varphi W} \left(p_2^{\mu_3} p_3^{\mu_2} - p_2 \cdot p_3 \eta_{\mu_2\mu_3}\right)$$

- BUT determination of $g, g', g_s, \ldots$ is affected by the presence of C_i!
- we need to relate them to some relevant input observables $\mathcal{O}_1, \mathcal{O}_2, \ldots$
- and insert those relations into amplitudes + expand again to the desired $\frac{1}{\Lambda}$ order

Input schemes in SMEFT

Example for EW parameters:

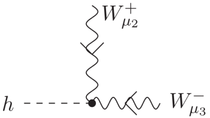
$$(g, g', \lambda, v) \to (G_F, M_H, M_W, M_Z)$$

$$v = \frac{1}{2^{1/4}\sqrt{G_F}}\left(1 - \frac{1}{\Lambda^2}\frac{1}{2\sqrt{2}G_F}\left(C_{ll}^{2112} - C_{\varphi l3}^{11} - C_{\varphi l3}^{22}\right)\right)$$

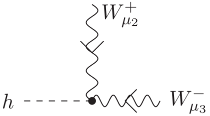
$$\mathcal{O}_{\text{SMEFT}} = \mathcal{O}(g, g', \lambda, v, \ldots, C_i) = \mathcal{O}(G_F, M_H, M_W, M_Z, \ldots, C_i)$$

in principle straightforward but technically complicated & error prone!

Input schemes in SMEFT



$$
\begin{aligned}
&+ \quad \frac{1}{2} i g^2 v \eta_{\mu_2\mu_3} + \frac{1}{2} i g^2 v^3 \eta_{\mu_2\mu_3} C^{\varphi\Box} - \frac{1}{8} i g^2 v^3 \eta_{\mu_2\mu_3} C^{\varphi D} \\
&+ \quad 4 i v C^{\varphi W} \left(p_2^{\mu_3} p_3^{\mu_2} - p_2 \cdot p_3 \eta_{\mu_2\mu_3}\right)
\end{aligned}
$$



$$
\begin{aligned}
&+ \quad i 2^{3/4} \sqrt{G_F} M_W^2 \eta_{\mu_2\mu_3} + \frac{i 2^{3/4} M_W^2}{\sqrt{G_F}} \eta_{\mu_2\mu_3} C^{\varphi\Box} - \frac{i M_W^2}{2^{3/4}\sqrt{G_F}} \eta_{\mu_2\mu_3} C^{\varphi D} \\
&- \quad \frac{i M_W^2}{2^{3/4}\sqrt{G_F}} \eta_{\mu_2\mu_3} C^{ll}_{2112} + \frac{i M_W^2}{2^{3/4}\sqrt{G_F}} \eta_{\mu_2\mu_3} \left(C^{\varphi l3}_{11} + C^{\varphi l3}_{22}\right) \\
&+ \quad \frac{i 2^{7/4}}{\sqrt{G_F}} C^{\varphi W} \left(p_2^{\mu_3} p_3^{\mu_2} - p_2 \cdot p_3 \eta_{\mu_2\mu_3}\right)
\end{aligned}
$$

Input schemes in SmeftFR v3

Predefined input schemes:

- EW sector:
  "smeft" scheme: (g, g', λ, v)
  "GF" scheme: (G_F, M_H, M_W, M_Z)
  "AEM" scheme: $(\alpha_{EM}, M_H, M_W, M_Z)$

- quark sector - based on [1812.08163]:

$$K_{\text{CKM}} \Rightarrow \Gamma\left(B \to \tau\nu_\tau\right), \Gamma\left(K \to \mu\nu_\mu\right)/\Gamma\left(\pi \to \mu\nu_\mu\right), \Delta M_{B_d}, \Delta M_{B_s}$$

user can also define own desired set of input parameters other than those above!
(for details see SmeftFR v3 manual [2302.01353])

SmeftFR v3 by example

Calculations with SmeftFR v3:

1. choose process of interest & relevant set of SMEFT operators
2. use SmeftFR to produce Feynman rules in the FeynRules format
3. export Feynman rules to desired output formats (LaTeX, FeynArts [0012260], UFO [1108.2040], . . .)
4. perform further calculations in SMEFT in FeynArts, FeynCalc [2001.04407], Madgraph [1106.0522], . . .

example:

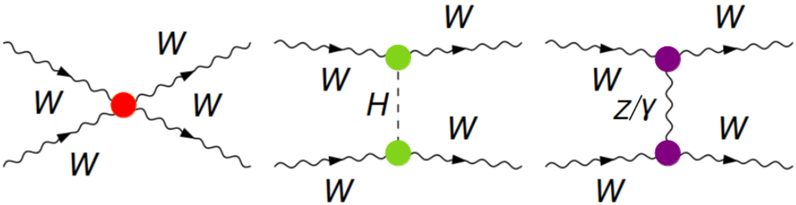
Vector Boson Scattering!

see also [2307.08745]

Calculations with `SmeftFR` v3
step #1: choice of process

Vector Boson Scattering (VBS):

(i) important in understanding EW sector
(ii) potential sensitivity to the BSM



diagrams in Unitary gauge

Calculations with SmeftFR v3
step #2: choice of SMEFT operators

Chosen SMEFT operators modifying VBS processes:

- dimension-6:

X^3		$\varphi^4 D^2$	
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$

- dimension-8:

$\varphi^6 D^2$		$\varphi^4 D^4$	
$Q_{\varphi^6\Box}$	$(\varphi^\dagger\varphi)^2\Box(\varphi^\dagger\varphi)$	$Q_{\varphi^4 D^4}^{(1)}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)$

Calculations with SmeftFR v3
step #3: load packages and operators

Open `SmeftFR-init.nb` notebook provided with `SmeftFR` distribution, then:

i) set proper installation paths of `FeynRules` and `SmeftFR` and load both codes

ii) load chosen set of operators, in our case:

```
In[1]:= OpList6={"phiBox","W"};
        OpList8={"phi6Box","phi4D4n1"};
```

naming: $Q_{\varphi\Box} \to$ "phiBox", $Q^{(1)}_{\varphi^4 D^4} \to$ "phi4D4n1", ...

Calculations with SmeftFR v3
step #4: generation of FeynRules model files

Run the following command with a chosen set of available options (for all possibilities see manual):

```
In[2]:= SMEFTInitializeModel[Operators→OpList,
         Gauge →Rxi,
         ExpansionOrder → 2,
         InputScheme →"GF",
         MaxParticles →4, ...];
```

Calculations with SmeftFR v3
step #5: calculate Feynman rules

(i) Load SMEFT model file & Lagrangian in gauge basis:

```
In[3]:= SMEFTLoadModel[];
```

(ii) find field bilinears and diagonalize mass matrices:

```
In[4]:= SMEFTFindMassBasis[];
```

(iii) evaluate SMEFT Lagrangian and Feynman rules in the mass basis:

```
In[5]:= SMEFTFeynmanRules[];
```

(iv) export and save SMEFT model file, Lagrangian and vertices in mass basis:

```
In[6]:= SMEFTOutput[];
```

Calculations with SmeftFR v3
step #6: print obtained vertices

In default "smeft" scheme

```
In[7]:= SMEFTExpandVertices[Input→"smeft",ExpOrder→2];
        SelectVertices[GaugeHiggsVerticesExp,SelectParticles →{H,W,Wbar}]
```

Out[7]= $\{\{\{\{H,1\},\{W,2\},\{W^{+},3\}\}, \frac{1}{2}\, i\, G_W^2\, vev\, \eta_{\mu_2,\mu_3} + \frac{1}{2}\, i\, C^{\phi Box}\, G_W^2 \frac{1}{\Lambda^2} vev^3 \eta_{\mu_2,\mu_3} + \frac{1}{4}\, i\, (2\, C^{\phi 6Box} + 3\, (C^{\phi Box}))^2 G_W^2 (\frac{1}{\Lambda^2})^2 vev^5\, \eta_{\mu_2,\mu_3}\}\}$

in G_F "user" scheme:

```
In[8]:= SMEFTExpandVertices[Input→"user",ExpOrder→2];
        SelectVertices[GaugeHiggsVerticesExp,SelectParticles →{H,W,Wbar}]
```

Out[8]= $\{\{\{\{H,1\},\{W,2\},\{W^{+},3\}\}, 2\, i\, 2^{1/4}\sqrt{G_F}\, M_W^2 \eta_{\mu_2,\mu_3} + \frac{i\, 2^{3/4}\, C^{\phi Box}\, \frac{1}{\Lambda^2}\, M_W^2 \eta_{\mu_2,\mu_3}}{\sqrt{G_F}} + \frac{i\, (2\, C^{\phi 6Box} + 3\, (C^{\phi Box}))^2\, (\frac{1}{\Lambda^2})^2\, M_W^2 \eta_{\mu_2,\mu_3}}{2^{3/4}\, G_F{}^{3/2}}\}\}$

Calculations with SmeftFR v3
step #7: interfaces - load mass basis lagrangian

To continue with outputs to LaTeX, UFO and FeynArts:

(i) Quit[] Mathematica kernel and open the SmeftFR_interfaces.nb notebook

(ii) load FeynRules and SmeftFR packages

(iii) reload mass basis Lagrangian by executing (may be time consuming!):

```
In[9]:= SMEFTInitializeMB[ Expansion -> "user"];
```

Calculations with SmeftFR v3
step #8: interfaces - FeynArts output

Execute the following command:

```
In[10]:= WriteFeynArtsOutput[SMEFT$MBLagrangian,
         Output →"output/FeynArts/FeynArts"];
```

SmeftFR FA model files can be used for further calculations
e.g. in FeynCalc or FormCalc

example: same sign VBS $W_L^+ W_L^+ \to W_L^+ W_L^+$ process

Calculations with SmeftFR v3

$W_L^+ W_L^+ \to W_L^+ W_L^+$

$$
\begin{aligned}
\mathcal{M}_{W_L^+ W_L^+ \to W_L^+ W_L^+}(s,\theta) \overset{s \gg M_W^2}{=} & -2\sqrt{2} G_F M_H^2 \left[1 - \frac{M_Z^2}{M_H^2}\left(1 - \frac{4}{\sin^2\theta}\right)\right] && \textbf{(SM)} \\
& + \left(2 C_{\varphi\Box} + C_{\varphi D}\right) \frac{s}{\Lambda^2} && \textbf{(dim}-\textbf{6)} \\
& + \big[8 C_{\varphi^6\Box} + 2 C_{\varphi^6 D^2} + 16 (C_{\varphi\Box})^2 + (C_{\varphi D})^2 - 8 C_{\varphi\Box} C_{\varphi D} \\
& - 16 (C^{(1)}_{\varphi^4 D^4} + 2 C^{(2)}_{\varphi^4 D^4} + C^{(3)}_{\varphi^4 D^4}) G_F M_W^2\big] \frac{\sqrt{2}}{8\, G_F \Lambda^2} \frac{s}{\Lambda^2} && \textbf{(dim}-\textbf{8)} \\
& + \left[(3 + \cos 2\theta)(C^{(1)}_{\varphi^4 D^4} + C^{(3)}_{\varphi^4 D^4}) + 8 C^{(2)}_{\varphi^4 D^4}\right] \frac{s^2}{8\Lambda^4}
\end{aligned}
$$

agreement with GBET!

Calculations with SmeftFR v3
step #9: interfaces - UFO output

Execute the following command:

```
In[11]:= SMEFTToUFO[SMEFT$MBLagrangian,Output→"output/UFO"];
```

SmeftFR UFO model files can be used for numerical calculations e.g. in MG5

example: `p p > w+ w+ j j` **process at the LHC**

Simulating VBS process in MG5 with SmeftFR UFO model

	SmeftFR $\mathcal{O}(\Lambda^{-2})$	SmeftFR $\mathcal{O}(\Lambda^{-4})$
`p p > w+ w+ j j QCD=0`		
SM	0.12456 ± 0.00029	
C_W	8.564 ± 0.020	37161 ± 83
$+C_{\varphi\Box}$	0.13387 ± 0.00032	0.20981 ± 0.00059
$-C_{\varphi\Box}$	0.14670 ± 0.00043	0.12511 ± 0.00035
$C_{\varphi 6\Box}$	-	0.12868 ± 0.00031
$C^{(1)}_{\varphi^4 D^4}$	-	10.891 ± 0.024

Table: Simulation results with $\sqrt{s} = 13$ TeV and default SmeftFR v3 (G_F, M_H, M_W, M_Z) EW input scheme. For each run, only one of the Wilson coefficients has non-zero value $\frac{C_i}{\Lambda^2} = \frac{4\pi}{\text{TeV}^2}$ for dim-6 and $\frac{C_i}{\Lambda^4} = \frac{(4\pi)^2}{\text{TeV}^4}$ for dim-8 operators.

Summary

1. SmeftFR v3 is a powerful tool for generating Feynman rules in SMEFT
2. $\frac{1}{\Lambda^4}$ order in the EFT expansion included
3. obtained vertices can be exported to: LaTeX, FeynArts, UFO, ...
4. ...and used for symbolic calculations and numerical simulations e.g. in MG5
5. Feynman rules can be expressed in terms of relevant input observables
6. practical example of VBS process calculation using SmeftFR v3 provided

Thank you!