`SmeftFR` v3 - a tool for creating and handling vertices in SMEFT capabilities and practical examples

Michał Ryczkowski

in collaboration with:
A. Dedes, J. Rosiek, K. Suxho, L. Trifyllis

based on [2302.01353]

HEFT workshop 2023
Manchester, 21.06.2023

FACULTY OF PHYSICS
UNIVERSITY OF WARSAW

Introducing: SMEFT

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

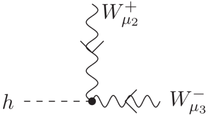
- Q_i - higher dimensional gauge invariant operators in terms of SM fields
- C_i - Wilson coefficients
- Λ - new physics scale

model independent way of studying BSM phenomena!

SMEFT - “standard” parametrization

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

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



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

- 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

Calculations in SMEFT - more precisely

example for EW parameters:

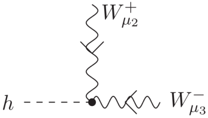
$$(g, g', \lambda, v) \to (G_F, M_H, M_W, M_Z)$$

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

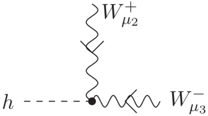
$$\mathcal{O}_{\mathrm{SMEFT}} = \mathcal{O}(g, g', \lambda, v, \ldots, C_i) = \mathcal{O}(G_F, M_H, M_W, M_Z, \ldots, C_i)$$

in principle straightforward but technically complicated & error prone!

Calculations in SMEFT - more precisely



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



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

Automatising calculations in SMEFT

- SMEFT is a very complicated model
- 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]

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

A. Dedes[a], J. Rosiek[b,*], M. Ryczkowski[b], K. Suxho[a], L. Trifyllis[a]

[a]*Department of Physics, University of Ioannina, GR 45110, Ioannina, Greece*
[b]*Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warsaw, Poland*

`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. includes predefined input parameter schemes for the EW sector
4. includes input scheme relating CKM matrix parameters to physical observables
5. user can use subset of WCs relevant for a given analysis
   which greatly simplifies calculations in comparison to the full basis
6. improved compatibility & consistent testing of output formats
   including comparison of `SmeftFR` `UFO` models with other available codes
7. correction of issues related to B and L violating vertices
8. significant improvement in speed of the code

`SmeftFR` v3 - main features

1. `Mathematica` package using `FeynRules` [1310.1921]
2. consistent calculation of SMEFT vertices up to $\frac{1}{\Lambda^4}$
3. includes predefined input parameter schemes for the electroweak sector
4. includes input scheme relating CKM matrix parameters to physical observables
5. user can use subset of WCs relevant for a given analysis
   which greatly simplifies calculations in comparison to the full basis
6. improved compatibility & consistent testing of output formats
   including comparison of `SmeftFR` `UFO` models with other available codes
7. correction of issues related to B and L violating vertices
8. significant improvement in speed of the code

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 - over 4000 types . . .
if necessary contact authors of the code!

Input schemes in `SmeftFR` v3

Predefined input schemes:

- EW sector:

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

$$(g, g', \lambda, v) \rightarrow (\alpha_{EM}, M_H, M_W, M_Z)$$

- quark sector - based on [1812.08163]:

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

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:

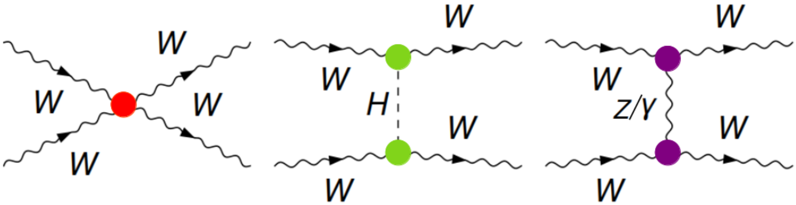
Vector Boson Scattering!

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



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:

1. i) set proper installation paths of `FeynRules` and `SmeftFR` and load both codes
2. ii) load chosen set of operators, in our case:

```
In[1]:= OpList6={"phiBox","W"};
        OpList8={"phi6Box","phi4n1"};
```

naming: $Q_{\varphi\Box} \to$ “`phiBox`”, $Q^{(1)}_{\varphi^4 D^4} \to$ “`phi4n1`”, ...

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,
         WCXFInitFile → WCXFInput,
         InputScheme →"GF",
         RealParameters →True,
         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 running (may be time consuming!):

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

Whole SMEFT mass basis Lagrangian stored in `SMEFT$MBLagrangian` variable

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

Use SMEFT mass basis Lagrangian stored in `SMEFT$MBLagrangian` to produce `FA` model files:

```
In[10]:= WriteFeynArtsOutput[SMEFT$MBLagrangian,
         Output →FileNameJoin[{SMEFT$Path,"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
$W_L^+ W_L^+ \to W_L^+ W_L^+$

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

Agreement with GBET!

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

Use SMEFT mass basis Lagrangian stored in `SMEFT$MBLagrangian` to produce `UFO` model files:

```
In[11]:= SMEFTToUFO[SMEFT$MBLagrangian,Output→FileNameJoin[{SMEFT$Path,
         "output","UFO"}]];
```

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

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. SMEFT if very useful but complicated model
2. we need a certain degree of automatisation
3. `SmeftFR` v3 is a powerful tool for generating Feynman rules in SMEFT
4. NLO order in the EFT expansion included
5. Feynman rules can be expressed in terms of relevant input observables
6. obtained vertices can be exported to other formats: LaTeX, `FeynArts`, `UFO`, ...
7. practical example of VBS process calculation using `SmeftFR` v3 provided

Thank you!

Additional slides

SmeftFR tests and validation

Analytical tests:

- GBET
- various Ward identities

Numerical tests - comparison to various processes with SMEFT@NLO, Dim6Top and SMEFTsim at dim-6 (full list see manual):

	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