The `SmeftFR` code

Handling vertices in SMEFT

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Table of Contents

1. EFT framework
2. `SmeftFR v3`
   - Input parameter schemes
   - $(\text{dim6})^2$ contributions
   - dim8 operators
3. `SmeftFR` by example
4. Conclusions

Table of Contents

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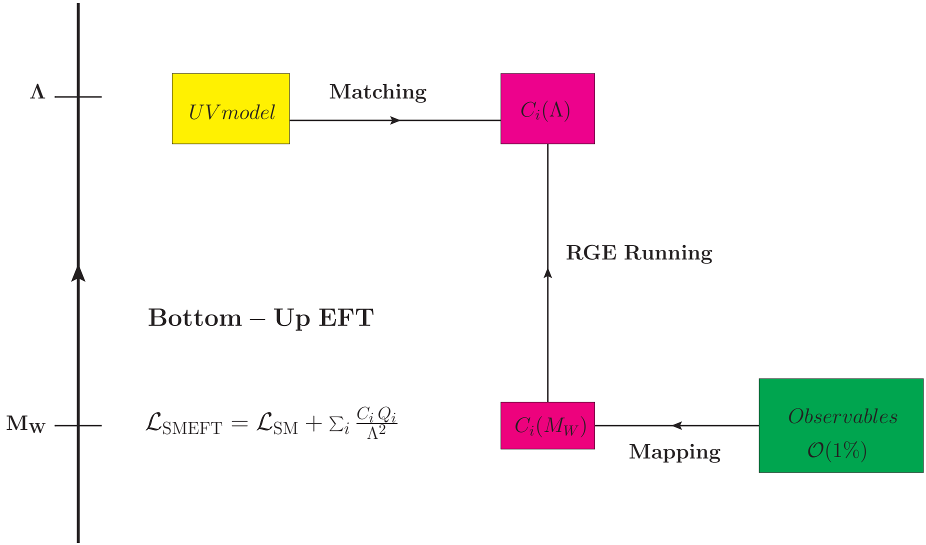
The EFT picture



SMEFT

Symmetries: Lorentz + $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda} C_\nu O_\nu + \frac{1}{\Lambda^2} \sum_i C_i O_i + \frac{1}{\Lambda^3} \sum_i C_i O_i + \dots$$

Not counting flavour we have 60 operators up to dimension-6 and about 1000 for dim8 ones

Renormalization: infinities cancel by the new counterterms δC_i

SMEFT answers questions...

Why the SM is so precise? Because the scale of NP, collectively called Λ, is much higher than every SM particle masses

Neutrino masses require physics beyond SM: they arise from dimension-5 operators. In SMEFT neutrinos are strictly Majorana particles.

Proton decay arises from dimension-6 operators first. Would this discovery come next...?!

Instead of studying a myriad of BSM physics models this SMEFT + experiments may guide us towards a new level of understanding.

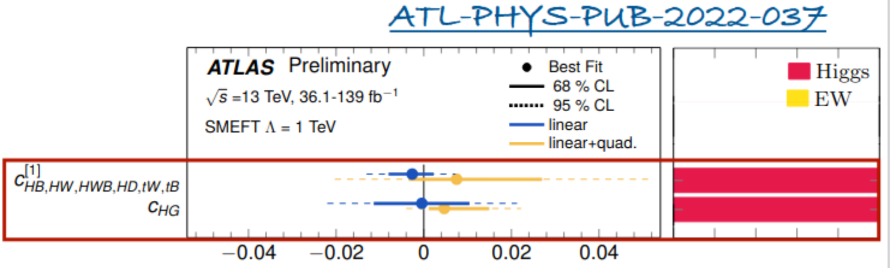
This path may be proven to be useful at the LHC and future colliders

However, the non-redundant (Warsaw) basis contains 2499 d=6 operators!

B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP **10** (2010), 085 [1008.4884]

Recent LHC analyses

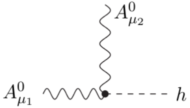
LHC Working groups have started EFT analyses, e.g.



SMEFT Feynman Rules

There are about 400 vertices (in R_ξ-gauges) that have been collected in A. D., W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, JHEP **06** (2017), 143 [1704.03888].

E.g., at $O(1/\Lambda^2)$, the $h\gamma\gamma$ vertex is



$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi WB}\left(p_1^{\mu_2} p_2^{\mu_1} - p_1\cdot p_2 \eta_{\mu_1\mu_2}\right)\\
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1} + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{B}} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}\\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} C^{\varphi\widetilde{W}B} p_1^{\alpha_1} p_2^{\beta_1}\epsilon_{\mu_1\mu_2\alpha_1\beta_1}
\end{aligned}
$$

The code `SmeftFR` produces all of them! A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, Comput. Phys. Commun. **247** (2020), 106931 [arXiv:1904.03204]

Table of Contents

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2 SmeftFR v3
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The code SmeftFR v3

The new version `SmeftFR` is now available[1] goes beyond dim6 operators.

1. input parameter schemes,
2. $(\text{dim6})^2$ operator effects
3. bosonic dim8 operators

`SmeftFR` extracts the full set of Feynman rules in LaTeX or in UFO format or in `FeynArts`.

It can feed various event generators, such as `MadGraph`, which perform amplitude calculations for LHC.

`SmeftFR` download web-page:

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

The program builts on `FeynRules` in *Mathematica*.

[1] A.D., J. Rosiek, M. Ryczkowski, K. Suxho and L. Trifyllis, arXiv 2302.01353

Input parameter schemes in EW and flavour sectors

There are two predefined input schemes in the up-to dim8:

$$\text{“GF”} : \{G_F, m_W, m_Z, m_H\}$$
$$\text{“AEM”} : \{\alpha_{em}, m_W, m_Z, m_H\}$$

SMEFT effects in CKM matrix[2] have been included up-to dim6

As yet, no SMEFT corrections in $\alpha_s(M_Z)$ and/or PMNS matrix

[2] S. Descotes-Genon, A. Falkowski, M. Fedele, M. González-Alonso and J. Virto, JHEP **05** (2019), 172 [arXiv:1812.08163 [hep-ph]].

$(\text{dim6})^2$ contributions in vertices

Canonical kinetic terms after EWSB, e.g., $O_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$

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

where

$$Z_h^{-1} = 1 + C_{\varphi\Box}\left(\frac{v}{\Lambda}\right)^2 + \boxed{\frac{3}{2}\,(C_{\varphi\Box})^2\left(\frac{v}{\Lambda}\right)^4}$$

NDA: $C_{\varphi\Box} \sim g_*^2$ (where g_* the UV-coupling to Higgs)

These $O(\Lambda^{-4})$-terms become important for strongly-coupled UV theories ($g_* \sim 4\pi$) and cutoffs $\Lambda \lesssim g_* v$.

On the other hand for weakly-coupled UV ($g_* \sim g$) these $O(\Lambda^{-4})$ are negligible.

All field normalization parameters are inserted in `SmeftFR` automatically for every dimensionality of operators given

dim8 operators

- We include all bosonic dim8 operators (about 100)
- We use the basis of Ref [3] (apart from two $\varphi^6 D^2$-operators defined differently by us)

Example:

φ^8		$\varphi^6 D^2$		$\varphi^4 D^4$	
Q_{φ^8}	$(\varphi^\dagger\varphi)^4$	$Q_{\varphi^6\Box}$	$(\varphi^\dagger\varphi)^2\Box(\varphi^\dagger\varphi)$	$Q^{(1)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)$
		$Q_{\varphi^6 D^2}$	$(\varphi^\dagger\varphi)(\varphi^\dagger D_\mu\varphi)^*(\varphi^\dagger D^\mu\varphi)$	$Q^{(2)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D_\nu\varphi)(D^\mu\varphi^\dagger D^\nu\varphi)$
				$Q^{(3)}_{\varphi^4 D^4}$	$(D_\mu\varphi^\dagger D^\mu\varphi)(D_\nu\varphi^\dagger D^\nu\varphi)$

- Important for LHC vector-boson scattering processes
- Fermionic dim8 operators can be included in `SmftFR v3` $\rightarrow$ (see tutorial in program's homepage)

[3] C. W. Murphy, JHEP **10** (2020), 174 [arXiv:2005.00059 [hep-ph]].

Table of Contents

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SmeftFR by example

Step 1: Input the operators (gauge basis)

```
In[1]:= OpList6={"phi","phiBox","phiD","phiW","phiWB","phiB","W"};
        OpList8={"phi8","phi6Box","phi6D2","phi4D4n1","phi4D4n2",
        "phi4D4n3"};
```

Step 2: Initialize SMEFT with available options

```
In[2]:= SMEFTInitializeModel[Operators→OpList,
        Gauge→Rxi,
        ExpansionOrder→2,
        WCXFInitFile→WCXFInput,
        InputScheme→"GF",
        CKMInput→"no",
        RealParameters→True,
        MaxParticles→4];
```

Step 3: Read vertices (here $h\gamma\gamma$)

In[3]:=
```
SMEFTExpandVertices[Input→"user",ExpOrder→2];
SelectVertices[GaugeHiggsVerticesExp,SelectParticles→{H,A,A}]
```

Out[3]=

$$
\{\{\{\{A,1\},\{A,2\},\{H,3\}\},\left(\frac{1}{\Lambda^2}\right)^2 \frac{i}{2^{3/4}\, G_F^{3/2}\, M_Z^2\, (M_W^2-M_Z^2)}
\Big(-C^{\phi D} C^{\phi W} M_W^4-8 (C^{\phi W})^2 M_W^4+4 (C^{\phi WB})^2 M_W^4+16 (C^{\phi W})^2 M_W^2 M_Z^2-4 (C^{\phi WB})^2 M_W^2 M_Z^2+C^{\phi D} C^{\phi W} M_Z^4
$$
$$
-8 (C^{\phi W})^2 M_Z^4-C^{\phi D} C^{\phi WB} M_W^3 \sqrt{-M_W^2+M_Z^2}-12 C^{\phi W} C^{\phi WB} M_W^3 \sqrt{-M_W^2+M_Z^2}+12 C^{\phi W} C^{\phi WB} M_W M_Z^2 \sqrt{-M_W^2+M_Z^2}
$$
$$
+8 (C^{\phi B})^2 (M_W^4-M_W^2 M_Z^2)+C^{\phi B} M_W (M_W^2-M_Z^2) (4 C^{\phi Box} M_W+C^{\phi D} M_W-4 C^{\phi WB} \sqrt{-M_W^2+M_Z^2})
$$
$$
-4 C^{\phi Box} (M_W^2-M_Z^2) (C^{\phi W} M_W^2-C^{\phi W} M_Z^2+C^{\phi WB} M_W \sqrt{-M_W^2+M_Z^2})\Big) (p_1^{\mu_2} p_2^{\mu_1}-\eta_{\mu_1,\mu_2} p_1\cdot p_2)
$$
$$
+\frac{1}{\Lambda^2} \frac{2\, i\, 2^{3/4}}{\sqrt{G_F}\, M_Z^2} \left(C^{\phi B} M_W^2-C^{\phi WB} M_W \sqrt{-M_W^2+M_Z^2}+C^{\phi W} (-M_W^2+M_Z^2)\right) (p_1^{\mu_2} p_2^{\mu_1}-\eta_{\mu_1,\mu_2} p_1\cdot p_2)\}\}
$$

SmeftFR by example

Step 3: Read vertices (here *ZZZZ*)

```
In[4]:= SMEFTExpandVertices[Input→"user",ExpOrder→2];
        SelectVertices[GaugeSelfVerticesExp,SelectParticles→{Z,Z,Z,Z}]
```

Out[4]= $\{\{\{\{Z,1\},\{Z,2\},\{Z,3\},\{Z,4\}\},\ 2\,i\,(C^{\phi 4nD41} + C^{\phi 4D4n2} + C^{\phi 4D4n3}) \left(\frac{1}{\Lambda^2}\right)^2 M_Z^4\,(\eta_{\mu_1,\mu_4}\,\eta_{\mu_2,\mu_3} + \eta_{\mu_1,\mu_3}\,\eta_{\mu_2,\mu_4} + \eta_{\mu_1,\mu_2}\,\eta_{\mu_3,\mu_4})\}\}$

This is generated first at dim8 level !

SmeftFR by example

Step 4: Produce UFO files and pass them on to Madgraph

```
In[5]:= SMEFTToUFO[ SMEFT$MBLagrangian, CorrectIO→True ];
```

MG5> generate p p > w+ w- j j (NP<=2 $O(\Lambda^{-4})$) (NP<=1 $O(\Lambda^{-2})$)

	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
$C^{(i)}_{\varphi^4 D^4}$	-	10.891 ± 0.024

For this table we took $C_6 = 4\pi/\mathrm{TeV}^2$ and $C_8 = (4\pi)^2/\mathrm{TeV}^4$

SmeftFR by example

Step 5: Produce `FeynArts/FormCalc` or `FeynCalc` files

```
In[6]:= WriteFeynArtsOutput[SMEFT$MBLagrangian,
        Output→FileNameJoin[{SMEFT$Path,"output","FeynArts","FeynArts"}
```

and calculate matrix elements e.g., longitudinal WW-scattering

$$\mathcal{M}_{W_L^+W_L^+\to W_L^+W_L^+}(s,\theta) = -2\sqrt{2}G_F M_H^2\left[1-\frac{M_Z^2}{M_H^2}\left(1-\frac{4}{\sin^2\theta}\right)\right] \qquad \textbf{(SM)}$$

$$+ \quad (2C_{\varphi\Box}+C_{\varphi D})\frac{s}{\Lambda^2} \qquad \textbf{(dim}-\textbf{6)}$$

$$+ \quad \Big[8C_{\varphi^6\Box}+2C_{\varphi^6D^2}+16(C_{\varphi\Box})^2+(C_{\varphi D})^2-8C_{\varphi\Box}C_{\varphi D}$$

$$- \quad 16(C^{(1)}_{\varphi^4D^4}+2C^{(2)}_{\varphi^4D^4}+C^{(3)}_{\varphi^4D^4})G_F M_W^2\Big]\frac{\sqrt{2}}{8\,G_F\Lambda^2}\frac{s}{\Lambda^2} \qquad \textbf{(dim}-\textbf{6)}^{\mathbf{2}}$$

$$+ \quad \left[(3+\cos 2\theta)(C^{(1)}_{\varphi^4D^4}+C^{(3)}_{\varphi^4D^4})+8C^{(2)}_{\varphi^4D^4}\right]\frac{s^2}{8\Lambda^4} \qquad \textbf{dim}-\textbf{8}\;.$$

Validation of the code

SmeftFR v3 has been validated against other codes

- SmeftSim : for dim6 operator effects
- SMEFT@NLO : for a sample of dim6 operators
- AnomalousGaugeCoupling : with dim8 F^4 operators

Almost perfect agreement found. Find more here

All details can be found in program's homepage

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

and the manual

SmeftFR v3 manual

Maintainer of the code: Janusz Rosiek

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  1. effortless way to handle a plethora of EFT vertices
  2. produces Latex, UFO and FeynArts files
  3. Full dim6 + $(\text{dim6})^2$ + bosonic dim8 operator effects included
  4. Two predefined input schemes + CKM corrections
  5. Baryon number dim6 operators included

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  1. Advances in calculations: STr functional technics
  2. Examples at 1-loop exist: Heavy Leptoquarks, RH neutrinos,...
  3. Near future prospects: From models to observables automatically

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Thank you for your attention