From Operators to Observables: `SmeftFR` as an Engine for SMEFT Phenomenology

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What I would like to convey

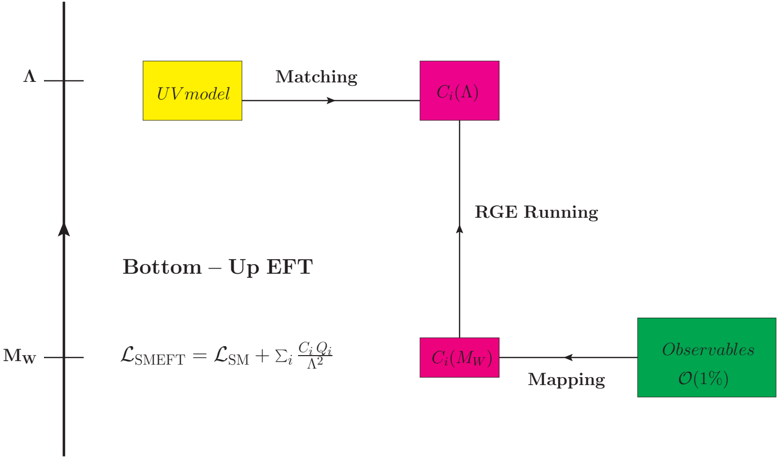
1. Why a mass-basis Feynman-rule engine is useful in realistic SMEFT analyses.
2. What was established in `SmeftFR` v1–v3: dim-6, R_ξ-gauges, input schemes, $1/\Lambda^4$, bosonic dim-8, interfaces.
3. What is new in the current v4 development: fermionic dimension-8, modular operator loading, BLV support, complex-input WCs to UFO, and a dashboard front end.
4. What still needs careful validation before the new sector should be treated as production-ready.

Main message

`SmeftFR` is intended to turn an operator basis into a practical chain

$$\mathcal{L}_{\mathrm{SMEFT}} \longrightarrow \text{mass basis} \longrightarrow \text{vertices} \longrightarrow \text{phenomenology.}$$

The EFT picture



SMEFT Q&A

Why is the SM 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 can arise straight from dimension-5 and higher. In SMEFT neutrinos are strictly Majorana particles.

Proton decay arises from dimension-6 operators first. Maybe next...?

Instead of studying a myriad of BSM models, SMEFT + exp data may guide us towards a certain class of UV-models.

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!

SMEFT: simple principle, difficult bookkeeping

The organising principle is simple:

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda} C^{(5)} Q^{(5)} + \frac{1}{\Lambda^2} \sum_i C_i^{(6)} Q_i^{(6)} + \frac{1}{\Lambda^4} \sum_i C_i^{(8)} Q_i^{(8)} + \cdots .$$

But after EWSB one must consistently handle

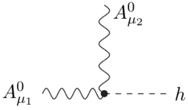
- field and coupling normalisation,
- gauge mixing and Goldstones,
- input-parameter shifts,
- flavour rotations and CKM/PMNS,
- EFT truncation,
- CP-violation,
- Baryon and Lepton number violation,
- export to external tools.

This is exactly the layer where automation becomes valuable.

SMEFT Feynman Rules

There are about 400 vertices (in linear R_ξ-gauges) calculated in Ref [1]

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

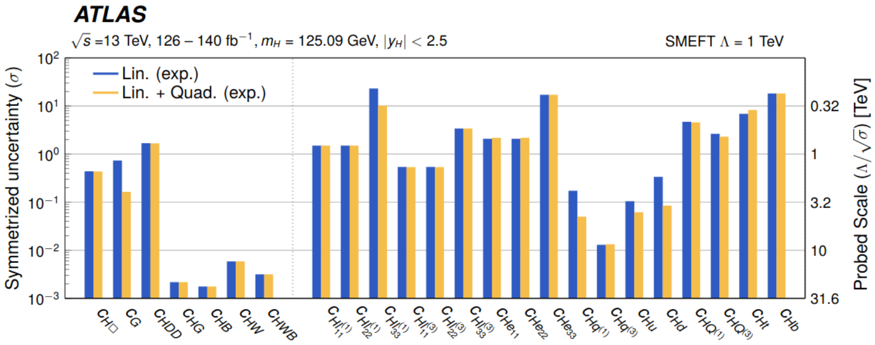


$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi W} (p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta_{\mu_1\mu_2}) \\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} C^{\varphi B} (p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta_{\mu_1\mu_2}) \\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2}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

The `SmeftFR`-code [2, 3] produces all of them!

Recent LHC analyses

LHC Working groups have started EFT analyses, e.g. from Higgs searches,
ATLAS-Summer-2026 (individual bounds)



Bounds obtained: $10^{-3} \lesssim |C_i| \lesssim 10$ for $\Lambda = 1$ TeV

See talks by L. Reina, C. Diez Pardos, K. Mimasu.

Why beyond the linear dimension-6 approximation?

At amplitude level,

$$\mathcal{A} = \mathcal{A}_{\rm SM} + \frac{1}{\Lambda^2}\mathcal{A}_6 + \frac{1}{\Lambda^4}\mathcal{A}_8 + \cdots .$$

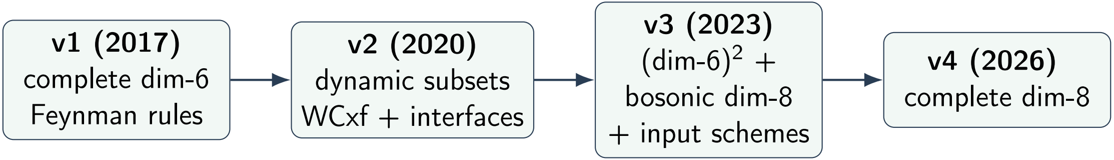
For observables at $\mathcal{O}\left(1/\Lambda^4\right)$:

$$|\mathcal{A}|^2 = |\mathcal{A}_{\rm SM}|^2 + \frac{2}{\Lambda^2}\Re(\mathcal{A}_{\rm SM}\mathcal{A}_6^*) + \frac{1}{\Lambda^4}\left[|\mathcal{A}_6|^2 + 2\Re(\mathcal{A}_{\rm SM}\mathcal{A}_8^*)\right] + \cdots .$$

Implication

A consistent $1/\Lambda^4$ analysis requires both $(d = 6)^2$ effects and genuine dimension-8 contributions.

A short chronology of SmeftFR



- v1: full dim-6 SMEFT Feynman rules, including general R_ξ gauges.
- v2: user options, CPU optimisation, dynamic FeynRules model files, WCxf, UFO/FeynArts.
- v3: complete bosonic dimension-8 sector and consistent expansion through $\mathcal{O}(1/\Lambda^4)$.
- v4: complete fermionic dimension-8 sector, complex WCs for UFO, dashboard (to be released soon)

What the v3 engine provides

- Complete dimension-6 Warsaw basis.
- Complete bosonic dimension-8 sector.
- Physical mass-eigenstate fields.
- Unitary or linear R_ξ gauges.
- Goldstone and ghost interactions.
- EFT truncation to the chosen order.
- Predefined EW input schemes.
- CKM treatment in the SMEFT.
- WCxf input/output.
- Dedicated human-readable LaTeX output.
- UFO and FeynArts interfaces.
- Dynamic operator subsets for speed.

The nontrivial step: Warsaw basis → mass basis

Schematically,

$$\varphi = \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\, Z_{G^+}^{-1} G^+ \\ v + Z_h^{-1} h + i Z_{G^0}^{-1} G^0 \end{pmatrix}, \qquad \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} = Z_{AZ} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix}.$$

The fermions are rotated as ($X = L, R$)

$$\psi'_X = U_{\psi X} \psi_X, \qquad K = U_{uL}^\dagger U_{dL}, \qquad U_{\mathrm{PMNS}} = U_{eL}^\dagger U_{\nu L}.$$

Key feature

The normalisation factors and parameter shifts are generated consistently for the selected operator subset and the requested EFT order.

Example: $(\text{dim6})^2$ 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 e.g.,

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

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 $\Lambda \lesssim g_* v$. They must be kept for gauge invariance to hold even at tree level.

Bosonic dim8 teaks

For dim8 operators we follow Murphy's basis [4] except

$$Q_{\varphi^6}^{(1)} = (\varphi^\dagger\varphi)^2\,(D_\mu\varphi^\dagger D^\mu\varphi)\,, \qquad Q_{\varphi^6}^{(2)} = (\varphi^\dagger\varphi)(\varphi^\dagger\tau^I\varphi)\,(D_\mu\varphi^\dagger\tau^I D^\mu\varphi)$$

$$\Downarrow$$

$$Q_{\varphi^6\Box} = (\varphi^\dagger\varphi)^2\,\Box(\varphi^\dagger\varphi)\,, \qquad Q_{\varphi^6 D^2} = (\varphi^\dagger\varphi)(\varphi^\dagger D_\mu\varphi)^\star(\varphi^\dagger D^\mu\varphi)$$

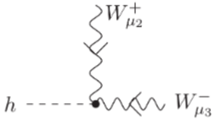
that resemble the Warsaw basis. This change of basis is consistent with the rest of Murphi's basis and it helps to write normalization factors to all orders in EFT. E.g.,

$$Z_h^2 = 1 + \sum_{n=0}\left(\frac{v^2}{2\Lambda^2}\right)^{n+1}\,[C^{\varphi D,n} - 4C^{\varphi\Box,n}]\,,$$

with $Q_{\varphi\Box,n} \equiv (\varphi^\dagger\varphi)^{n+1}\Box(\varphi^\dagger\varphi)$ and $Q_{\varphi D,n} \equiv (\varphi^\dagger\varphi)^n|\varphi^\dagger D_\mu\varphi|^2$.

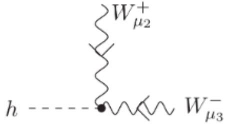
SmeftFR "none" and "smeft" schemes

SmeftFR finds vertices before expansion of field normalizations. E.g.,



$$+\frac{i\bar{g}^2 v}{2Z_h}\eta_{\mu_2\mu_3} + \frac{4iv}{Z_g^2 Z_h}\left(p_2^{\mu_3}p_3^{\mu_2} - p_2\cdot p_3\eta_{\mu_2\mu_3}\right)C^{\varphi W}$$

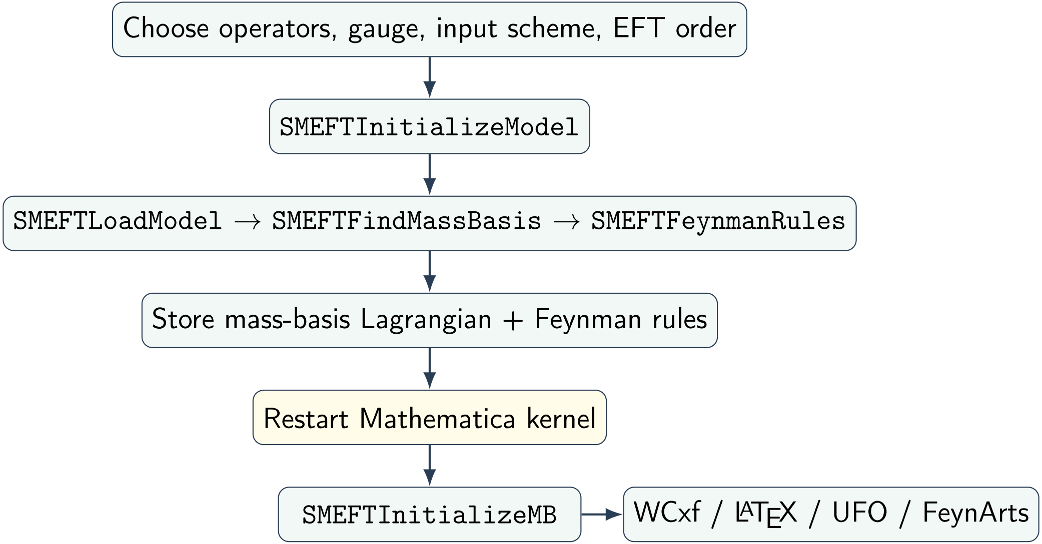
where also $g = Z_g\,\bar{g}$ is the coupling redefinition. At $1/\Lambda^2$ expansion, we arrive in "smeft" scheme



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

All $C's$ in SmeftFR/Latex should be read as $C^{(6)} \to C^{(6)}/\Lambda^2$ and $C^{(8)} \to C^{(8)}/\Lambda^4$.

The two-stage SmeftFR workflow



Input schemes and flavour

Two convenient electroweak schemes used in v3 are, schematically,

$$\{G_F, m_W, m_Z, m_H\}, \qquad \{\alpha_{\rm em}, m_W, m_Z, m_H\}.$$

Why this matters:

- the Wilson coefficients modify relations among Lagrangian parameters and observables;
- different input schemes reshuffle SMEFT corrections, but physical predictions must agree at fixed order;
- flavour-dependent WCs are tensors, and their mass-basis rotations determine where CKM factors appear.
- CKM is corrected by WCs (dim6-implementation from Ref. [7])
- As yet, no SMEFT corrections to PMNS

From analytic rules to phenomenology

Analytic / symbolic

- Mathematica / FeynRules output,
- dedicated LaTeX vertices,
- FeynArts $\to$ FeynCalc/FormCalc.

Monte Carlo

- UFO output,
- MadGraph and other generators,
- operator-subset model files.

`SmeftFR` v3 by example

At $\mathcal{O}(1/\Lambda^4)$, v3 can simultaneously include (dim-6)^2 effects and bosonic dim-8 contributions in processes such as vector-boson scattering.

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];
```

SmeftFR by example

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 I took (an NDA wrong!) $C_6 = 4\pi/\mathrm{TeV}^2$ 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

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

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

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

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

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

Positivity Bounds example

From the previous $W_L W_L$-(forward)scattering we obtain a positivity bound [5]

$$\frac{d^2}{ds^2}\mathcal{M}(W_L W_L \to W_L W_L) = C^{(1)}_{\varphi^4 D^4} + 2\, C^{(2)}_{\varphi^4 D^4} + C^{(3)}_{\varphi^4 D^4} \geq 0\ .$$

This bound is satified trivially when we study other, more restricted, positivity bounds:

$$\begin{aligned} hh \to hh \quad &\Longrightarrow \quad C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4} + C^{(3)}_{\varphi^4 D^4} \geq 0, \\ Z_L h \to Z_L h \quad &\Longrightarrow \quad C^{(2)}_{\varphi^4 D^4} \geq 0, \\ W_L^+ h \to W_L^+ h \quad &\Longrightarrow \quad C^{(1)}_{\varphi^4 D^4} + C^{(2)}_{\varphi^4 D^4} \geq 0. \end{aligned}$$

Input-parameter-scheme independence of these bounds is confirmed.

Validation and distribution of SmeftFR v3

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 and GitHub

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

https://github.com/sakis1234/SmeftFR

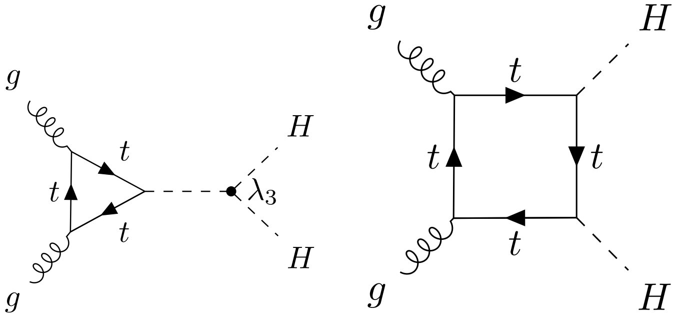
and the manual

SmeftFR v3 manual

Maintainer of the code: Janusz Rosiek

A physics example using `SmeftFR`: Double-Higgs Boson Production

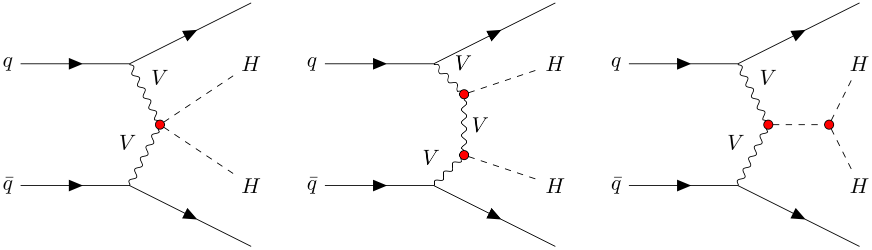
1 Gluon-Fusion (ggF) is the dominant di-Higgs production mechanism



$$\sigma_{SM}^{ggF}(HH) = 31.1 \text{ fb}$$

Double-Higgs Production

2 Vector-Boson-Fusion (VBF) is ten times less sensitive than ggF



$$\sigma_{SM}^{VBF}(HH) = 1.73 \text{ fb}$$

New in VBF:

- the couplings hVV and $hhVV$ (raise with energy in SMEFT)
- characteristic experimental signature

Interpretation in SMEFT

$$\kappa_\lambda = 1 - 0.47\, C_\varphi\ , \qquad \Lambda = 1\ \mathrm{TeV}$$

$$\downarrow \text{(ATLAS (2024))}$$

$$-\frac{13}{\mathrm{TeV}^2} \lesssim \frac{C_\varphi}{\Lambda^2} \lesssim \frac{5}{\mathrm{TeV}^2}$$

$\Rightarrow$ lots of space for NP!

Analogous work with dimension-8 operators: $Q_{\varphi^8} = (\varphi^\dagger \varphi)^4$

$$\kappa_\lambda = 1 - 0.47\, C_\varphi - 0.06\, C_{\varphi^8}$$

Dim-8 effects on κ_λ are $\sim$10 times smaller than dim-6 for equal Cs

Naive Dimensional Analysis (NDA) suggests $C_\varphi \sim g_*^4$ and $C_{\varphi^8} \sim g_*^6$ with $g_* \lesssim 4\pi$ being a generic UV-coupling.

di-Higgs VBF at High-Energies

Examples for dimension-6 derivative operators

$$Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)\,, \quad Q_{\varphi W} = (\varphi^\dagger\varphi)\, W^I_{\mu\nu} W^{I\mu\nu}$$

and dimension-8

$$Q^{(1)}_{\varphi^4 D^4} = (D_\mu\varphi^\dagger D_\nu\varphi)(D^\nu\varphi^\dagger D^\mu\varphi)\,, \quad Q^{(1)}_{W^2\varphi^2 D^2} = (D^\mu\varphi^\dagger D^\nu\varphi) W^I_{\mu\rho} W^{I\rho}_{\nu}$$

Examples of Helicity Amplitudes at HE:

$$\begin{aligned}
\mathcal{M}^{WW\to hh}_{00} &= 2\, C_{\varphi\Box}\left(\frac{s}{\Lambda^2}\right) - \frac{1}{8}\, C^{(1)}_{\varphi^4 D^4}\,(1+\cos^2\theta)\left(\frac{s}{\Lambda^2}\right)^2 + \ldots \\
\mathcal{M}^{WW\to hh}_{\pm\pm} &= 2\, C_{\varphi W}\left(\frac{s}{\Lambda^2}\right) - \frac{1}{4}\, C^{(1)}_{W^2\varphi^2 D^2}\left(\frac{s}{\Lambda^2}\right)^2 + \ldots
\end{aligned}$$

There are simple UV-models (e.g. heavy scalar singlet) where $C_{\varphi\Box}$ is big. VBF can potentially be affected strongly at HE!

A simple UV-Model for di-Higgs

Consider a heavy real-singlet S with mass M.

$$\mathcal{L}_S = \mathcal{L}_{SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}M^2 S^2 - \alpha\, M\, S\varphi^\dagger\varphi - \frac{1}{2}\kappa\,|\varphi|^2 S^2 - \frac{1}{3!}\beta\, M\, S^3 - \frac{1}{4!}\lambda_S\, S^4\ ,$$

By matching the $VVhh$ amplitudes of the UV onto SMEFT at tree level,

$$\lambda_{eff} = \lambda - \alpha^2\ , \quad C_{\varphi\Box} = -\frac{\alpha^2}{2}\ , \quad C_\varphi = -\frac{\alpha^2}{2}\left(\kappa - \frac{\alpha\beta}{3}\right)$$
$$C^{(3)}_{\varphi^4 D^4} = 2\alpha^2\ .$$

Parameter α can be of O(1); WCs can be large.

Calculation/Analysis

- Calculate analytically full $VV \to hh$ amps for dim6 and dim8
  `SmeftFR` $\longrightarrow$ `FeynArts` $\longrightarrow$ `FeynCalc/FormCalc`
- Truncate the amplitude (not the Xsection!) up-to $1/\Lambda^4$ and square
- Take current bounds on dim6 Wilson Coeffs from global fits
- Use "educated NDA" for the dim8 WCs
- Check EFT convergence and unitarity violation bounds
- Calculate $pp \to hhjj$ events vs. di-Higgs invariant mass
  `SmeftFR` $\longrightarrow$ `UFO` $\longrightarrow$ `Madgraph`

Our work does not include any Higgs decays to final states or detector simulations.

$pp \to hhjj$ for C_φ (dim6)

At HL-LHC (14 TeV, 3000 fb^{-1}), similar cuts as in VBS

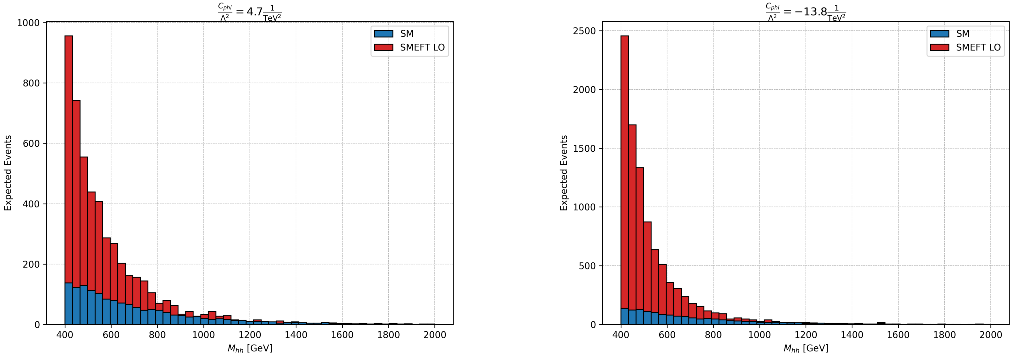
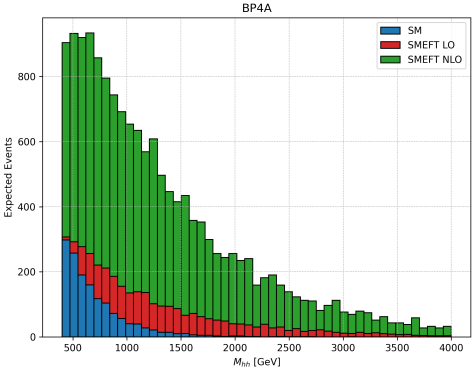


Figure: *Higgs pair invariant mass M_{hh} distribution for C_φ modifying κ_λ.*

A.D., J. Rosiek, M. Ryzckowski, Phys. Rev. D112 (2025) 5, 2506.12917

$pp \to hhjj$ for multiple ops (dim6+dim8)

A benchmark: $C_{\varphi\Box}$, $C_{\varphi^6\Box}$, $C_{\varphi W}$, $C_{W^2\varphi^4}$ (not affecting ggF)



Strong enhancement O(40) mostly due to constructive interference

A.D., J. Rosiek, M. Ryzckowski, Phys. Rev. D112 (2025) 5, 2506.12917

Conclusions to di-Higgs production in SMEFT

Detailed SMEFT analysis of VBF di-Higgs production at (HL)LHC

1. **Non-derivative operators** (C_{φ}, C_{φ^8}):
   - Dominant effect on VBF di-Higgs cross-section [up to $\mathcal{O}(20)$ enhancement].
   - Similar modifications expected in gluon fusion (ggF), likely detectable earlier.
2. **Derivative operators** (e.g., $C_{\varphi\Box}$, $C_{\varphi W}$):
   - Modest enhancements [up to $\mathcal{O}(2-3)$ for dim-6, $\mathcal{O}(1.5)$ for dim-8].
   - Challenging to detect at HL-LHC without multi-WC interference.
3. **Multi-WC scenarios**:
   - Constructive interference can boost cross-section up to $\mathcal{O}(10)$.
   - Most pronounced for high M_{hh} ($\gtrsim 1$ TeV), where energy-dependent terms dominate.

What was missing after v3?

The full dimension-8 basis contains large fermionic sectors in addition to the bosonic operators already implemented in v3.

Current `SmeftFR` v4 [6] development follows the full non-redundant dimension-8 basis operators [4]:

Classes	Field content	Examples
9–17	two fermions	$\psi^2 X^2 H,\ \psi^2 X H^3,\ \psi^2 H^2 D^3, \ldots$
18	four fermions + Higgs	$\psi^4 H^2$
19	four fermions + field strength	$\psi^4 X$
20	four fermions + Higgs + derivative	$\psi^4 H D$
21	four fermions + derivatives	$\psi^4 D^2$

The challenge is not only operator entry: it is mass-basis consistency, flavour, gauge structure, and interfaces.

Why do I bother ?

There is no way to fit ∼40.000 WCs to experimental data. Why then bother?

- A potential new signal at (HL)LHC or elsewhere on a particular observable. Higher precision, questions about convergence, etc.
- Observables that are dimension-6 blind start from dimension-8 onwards.
- Strongly coupled physics at Λ
- Better "unitarization" of $(s/\Lambda^2)^2$ high energy events (if possible).
- "Exotic" processes e.g., electromagnetic interactions of neutrinos
- Baryon and Lepton number violating processes

Scale of the new implementation

The current development log has an automated 1:1 completeness check against Murphy's classes 9–21 [4]:

645 fermionic dimension-8 operators

274 two-fermion + 311 four-fermion, B-conserving + 60 BLV.

Per-class counts implemented in the development tree:

class	9	10	11	12	13	14	15	16	17	18	19	20	21
N	48	11	15	3	12	57	86	24	18	65	169	84	53

Important: implementation completeness is not the same as full runtime/interface validation.

What is already checked – and what is not

Structural checks already performed

- operator names $\leftrightarrow$ files $\leftrightarrow$ WC registration $\leftrightarrow$ `LQ` symbols,
- hermitian-conjugation patterns,
- Lorentz/group-index structures,
- clean parsing / loading of the operator files.
- UFO generation has no confirmed functional failures

Runtime checks still essential

- complicated covariant-derivative structures,
- BLV export through UFO $\rightarrow$ Madgraph
- 69 dim8 CP-violating operators are ignored in FeynRules $\rightarrow$ FeynArts module

A dashboard front end for the SmeftFR workflow

The prototype dashboard exposes the standard workflow without changing the underlying physics code.

Configuration

- FeynRules path / WCxf file,
- gauge and expansion order,
- input scheme, CKM, PMNS,
- operator selection by group/class,
- `MaxParticles`.

Outputs

- Mathematica/FeynRules,
- WCxf,
- LaTeX,
- FeynArts,
- UFO with real/complex flavour parameters.

Validation is part of the physics

Historically, SmeftFR has been tested through

- gauge-parameter independence of physical amplitudes,
- Ward identities, Goldstone boson equivalence theorem
- cancellation of UV divergences in loop calculations,
- comparisons to independent SMEFT implementations,
- MadGraph and FeynArts sample calculations.

For the new fermionic dim-8 sector, a sensible validation ladder is

[operator parse] → [mass-basis] → [Feynman rules] → [UFO/FeynArts] → [amplitude checks]

Where SmeftFR is going

- Complete runtime smoke tests for representative fermionic dim-8 classes.
- Systematic validation of BLV and inclusion of dimension-7 operators too.
- Phenomenology-ready UFO benchmarks for selected dim-8 sectors.

Longer-term goal

A reliable bridge from a very large EFT operator space to analytic amplitudes and collider simulation without sacrificing control over conventions and EFT order.

Backup: key references

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