Higgs and Effective Field Theory
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SOLD

The SMEFT One-Loop Dictionary

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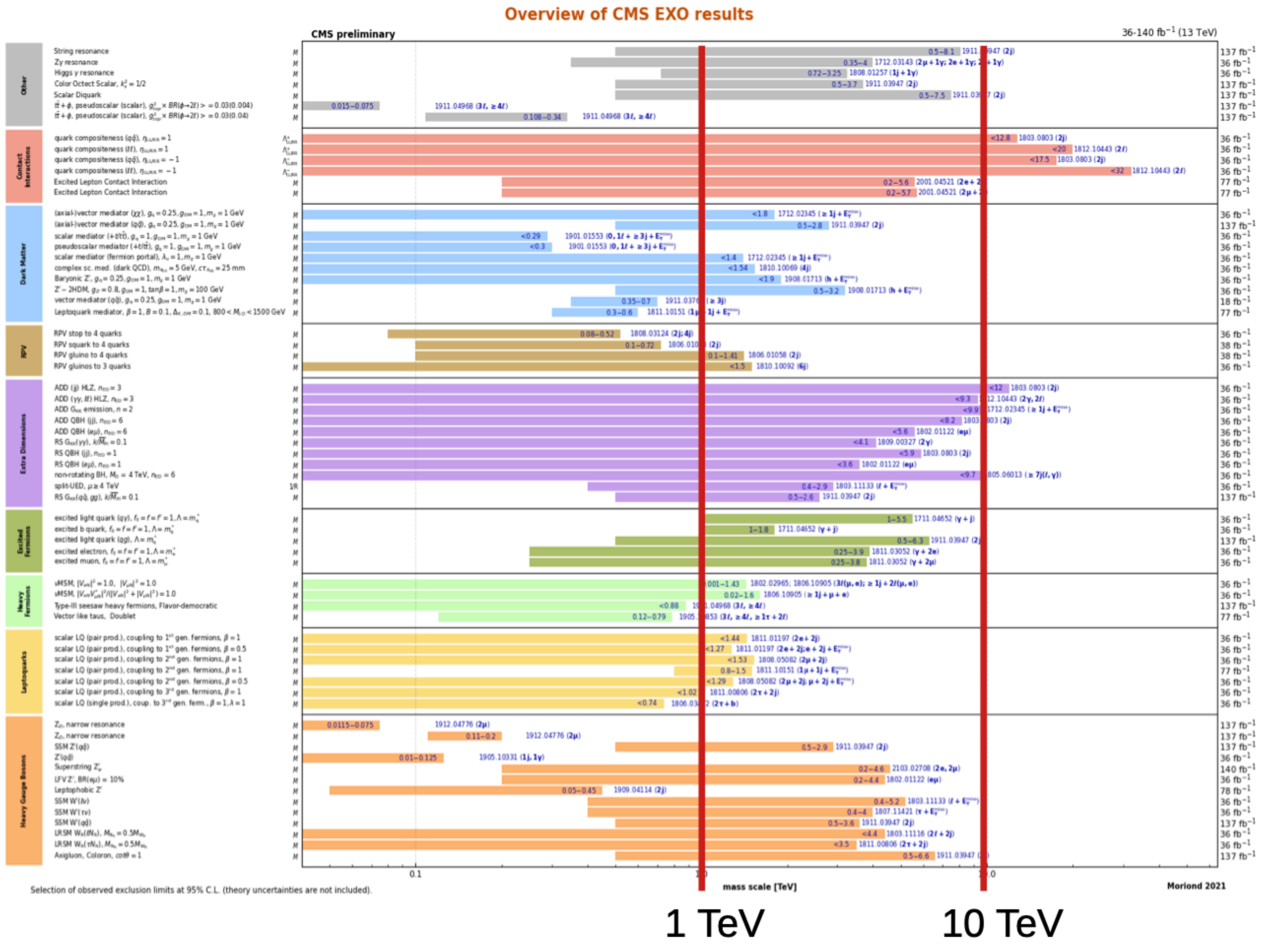
Dictionaries: a new guiding principle

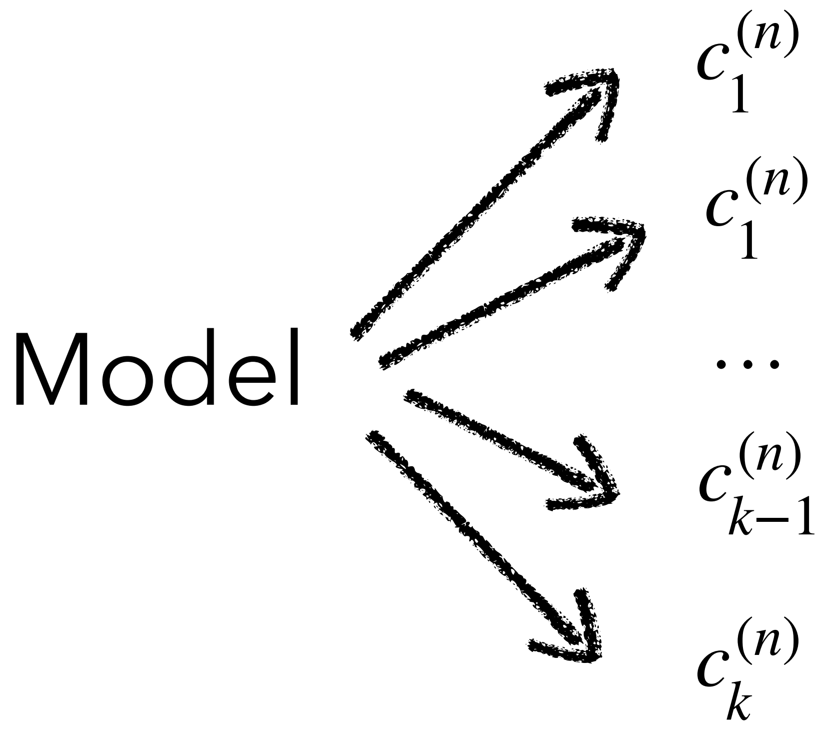
- The increasing limits on the scale of new physics motivate the use of EFTs.

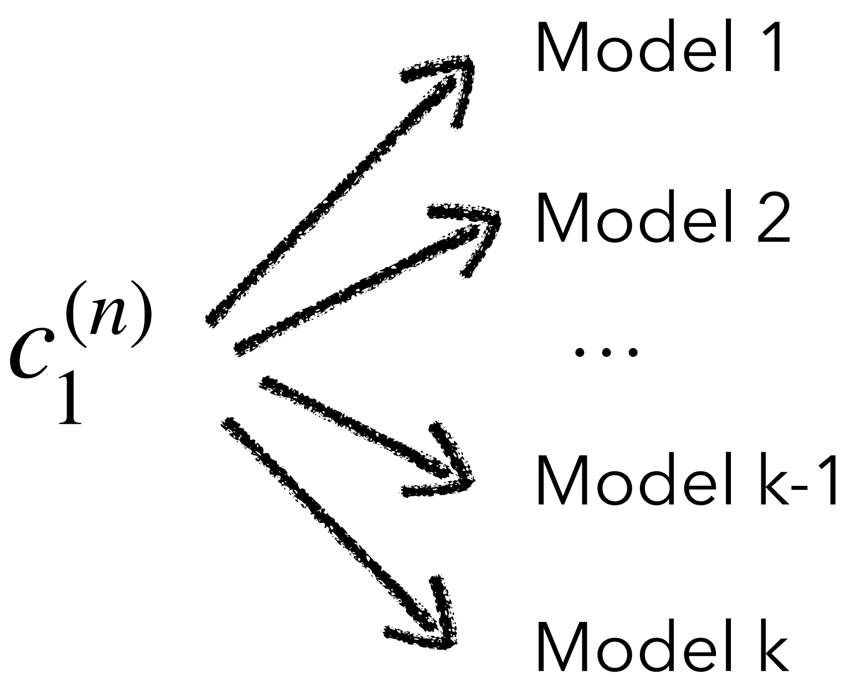
- We need an efficient way of organizing the search for new physics.



Dictionaries: a new guiding principle

- The use of EFTs allows us to classify all observable models of new physics.
- Dictionaries are a mapping between UV extensions and IR effects:





Dictionaries: a new guiding principle

- The use of EFTs allows us to classify all observable models of new physics.
- Dictionaries are a mapping between UV extensions and IR effects:
- The tree level dictionary for the SMEFT at dimension six is already computed.
  [de Blas, Criado, Perez-Victoria, Santiago '18]
- Its extension to one loop is necessary for a realistic analysis.

The One-Loop Dictionary

- SOLD is a Mathematica package encoding the **S**MEFT **O**ne-**L**oop **D**ictionary.

  [G. Guedes, PO, J. Santiago '23]

- The current version includes SMEFT operators whose leading contribution is one loop.

X^3	X^2H^2	$\psi^2 XH + \text{h.c.}$
$\mathcal{O}_{3G} = f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{HG} = G^A_{\mu\nu} G^{A\,\mu\nu} H^\dagger H$	$\mathcal{O}_{uG} = (\bar{q} T^A \sigma^{\mu\nu} u) \widetilde{H} G^A_{\mu\nu}$
$\mathcal{O}_{3\widetilde{G}} = f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{H\widetilde{G}} = \widetilde{G}^A_{\mu\nu} G^{A\,\mu\nu} H^\dagger H$	$\mathcal{O}_{uW} = (\bar{q} \sigma^{\mu\nu} u) \sigma^I \widetilde{H} W^I_{\mu\nu}$
$\mathcal{O}_{3W} = \epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{HW} = W^I_{\mu\nu} W^{I\,\mu\nu} H^\dagger H$	$\mathcal{O}_{uB} = (\bar{q} \sigma^{\mu\nu} u) \widetilde{H} B_{\mu\nu}$
$\mathcal{O}_{3\widetilde{W}} = \epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{H\widetilde{W}} = \widetilde{W}^I_{\mu\nu} W^{I\,\mu\nu} H^\dagger H$	$\mathcal{O}_{dG} = (\bar{q} T^A \sigma^{\mu\nu} d) H G^A_{\mu\nu}$
	$\mathcal{O}_{HB} = B_{\mu\nu} B^{\mu\nu} H^\dagger H$	$\mathcal{O}_{dW} = (\bar{q} \sigma^{\mu\nu} d) \sigma^I H W^I_{\mu\nu}$
	$\mathcal{O}_{H\widetilde{B}} = \widetilde{B}_{\mu\nu} B^{\mu\nu} H^\dagger H$	$\mathcal{O}_{dB} = (\bar{q} \sigma^{\mu\nu} d) H B_{\mu\nu}$
	$\mathcal{O}_{HWB} = W^I_{\mu\nu} B^{\mu\nu} H^\dagger \sigma^I H$	$\mathcal{O}_{eW} = (\bar{\ell} \sigma^{\mu\nu} e) \sigma^I H W^I_{\mu\nu}$
	$\mathcal{O}_{H\widetilde{W}B} = \widetilde{W}^I_{\mu\nu} B^{\mu\nu} H^\dagger \sigma^I H$	$\mathcal{O}_{eB} = (\bar{\ell} \sigma^{\mu\nu} e) H B_{\mu\nu}$

The One-Loop Dictionary

- SOLD is a Mathematica package encoding the **S**MEFT **O**ne-**L**oop **D**ictionary.
  [G. Guedes, PO, J. Santiago '23]

- The current version includes SMEFT operators whose leading contribution is one loop.

- The new version will include the whole SMEFT at dimension six.

Constructing the dictionary

- We consider a generic theory:

$$
\begin{aligned}
\mathcal{L}_{\rm UV} =&\delta_{\Psi_a}\bar{\Psi}_a\Big[\mathrm{i}\not{D} - M_{\Psi_a}\Big]\Psi_a + \delta_{\Phi_a}\Big[|D_\mu\Phi_a|^2 - M^2_{\Phi_a}|\Phi_a|^2\Big] \\
&+ \sum_{\chi=L,R}\Big[Y^\chi_{abc}\overline{\Psi}_a P_\chi \Psi_b \Phi_c + \widetilde{Y}^\chi_{abc}\overline{\Psi}_a P_\chi \Psi_b \Phi^\dagger_c \\
&\qquad + X^\chi_{abc}\overline{\Psi^c}_a P_\chi \Psi_b \Phi_c + \widetilde{X}^\chi_{abc}\overline{\Psi^c}_a P_\chi \Psi_b \Phi^\dagger_c + \mathrm{h.c.}\Big] \\
&+\Big[\kappa_{abc}\Phi_a\Phi_b\Phi_c + \kappa'_{abc}\Phi_a\Phi_b\Phi^\dagger_c + \lambda_{abcd}\Phi_a\Phi_b\Phi_c\Phi_d \\
&+ \lambda'_{abcd}\Phi_a\Phi_b\Phi_c\Phi^\dagger_d + \lambda''_{abcd}\Phi_a\Phi_b\Phi^\dagger_c\Phi^\dagger_d + \mathrm{h.c.}\Big],
\end{aligned}
$$

Φ_a scalar multiplet

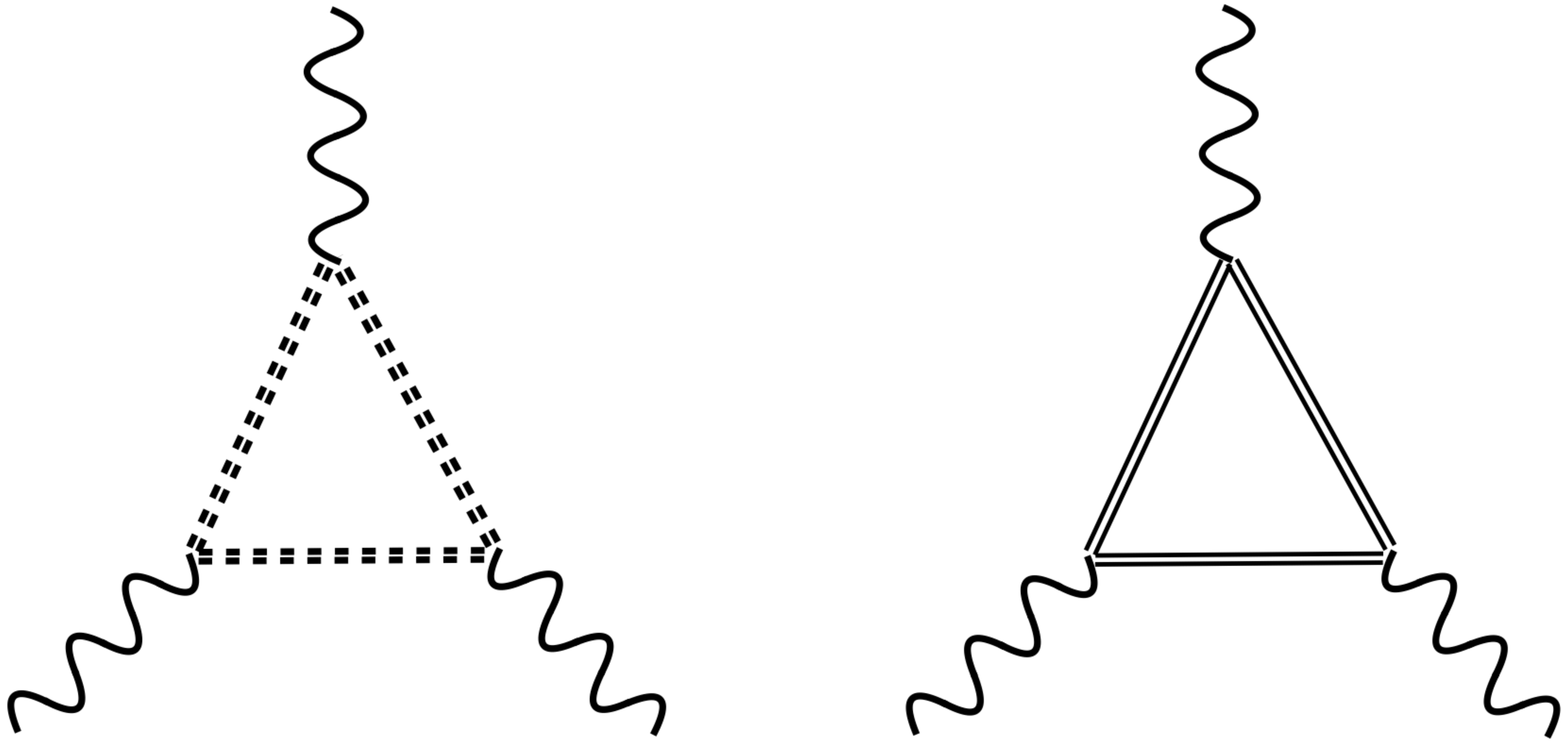
Ψ_a fermion multiplet

$Y_{abc}, X_{abc}, \ldots$ couplings and Clebsch-Gordan tensors

Constructing the dictionary

- We consider a generic theory.
- We use `Matchmakereft` to compute all possible diagrams contributing to a certain operator and extract their hard region.

$$\mathcal{O}_{3V} = \alpha_{3V} f^{ABC} V_{\mu}^{A\nu} V_{\nu}^{B\rho} V_{\rho}^{C\mu}$$



Constructing the dictionary

- We consider a generic theory.
- We use `Matchmakereft` to compute all possible diagrams contributing to a certain operator and extract their hard region.
- We reduce the result to the Warsaw basis and include evanescent contributions.

[J. Fuentes-Martín, M. König et al., '22]

Constructing the dictionary

- We consider a generic theory.
- We use `Matchmakereft` to compute all possible diagrams contributing to a certain operator and extract their hard region.
- With this result we can:
  - → List the representations that contribute.
  - → Fix the representations and compute the result using `GroupMath`.

[Fonseca '20]

Using SOLD

- Installation:

```
In[1]:= Import["https://gitlab.com/jsantiago_ugr/sold/-/raw/main/install.m"];

In[1]:= << SOLD`
        SMEFT One Loop Dictionary loaded
        Version: 1.0.1
        Authors: Guilherme Guedes, Pablo Olgoso, José Santiago
        Reference: arXiv:2303.16965
        Webpage: https://gitlab.com/jsantiago_ugr/sold

        You are currently up to date.

        XXXXXXXXXXXXXXXXXXXXXXXXXXX GroupMath XXXXXXXXXXXXXXXXXXXXXXXXXX
        Version: 1.1.2 (6/May/2020)
        Author: Renato Fonseca
        Reference: 2011.01764 [hep-th]
        Website: renatofonseca.net/groupmath
        Built-in documentation: here
        XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
```

Using SOLD

- Model classification.

In[2]:= `ListModelsWarsaw[alphaOHG]`

Out[2]//MatrixForm=

Field Content	$SU(3)\otimes SU(2)$	$U(1)$
$\{\phi1\}$	$\{\phi1\otimes\overline{\phi1}\supset\mathbf{8}\otimes\mathbf{1},\ \phi1\otimes\overline{\phi1}\supset\mathbf{1}\otimes\mathbf{1}\}$	$\{Y_{\phi1}\}$
$\{\phi1\}$	$\{\phi1\otimes\overline{\phi1}\supset\mathbf{8}\otimes\mathbf{1},\ \phi1\otimes\overline{\phi1}\supset\mathbf{1}\otimes\mathbf{3}\}$	$\{Y_{\phi1}\}$
$\{\psi1\}$	$\{\psi1\to\overline{\mathbf{3}}\otimes\mathbf{1}\}$	$\{Y_{\psi1}\to\frac{1}{3}\}$
$\{\psi1\}$	$\{\psi1\to\overline{\mathbf{3}}\otimes\mathbf{2}\}$	$\{Y_{\psi1}\to-\frac{1}{6}\}$
$\{\psi1\}$	$\{\psi1\to\overline{\mathbf{3}}\otimes\mathbf{2}\}$	$\{Y_{\psi1}\to\frac{5}{6}\}$
$\{\psi1\}$	$\{\psi1\to\overline{\mathbf{3}}\otimes\mathbf{3}\}$	$\{Y_{\psi1}\to\frac{1}{3}\}$
$\{\psi1\}$	$\{\psi1\to\mathbf{3}\otimes\mathbf{1}\}$	$\{Y_{\psi1}\to\frac{2}{3}\}$
$\{\psi1\}$	$\{\psi1\to\mathbf{3}\otimes\mathbf{2}\}$	$\{Y_{\psi1}\to\frac{7}{6}\}$
$\{\psi1\}$	$\{\psi1\to\mathbf{3}\otimes\mathbf{3}\}$	$\{Y_{\psi1}\to\frac{2}{3}\}$
$\{\phi1,\ \phi2\}$	$\{\phi1\to\mathbf{1}\otimes\mathbf{1},\ \phi2\otimes\overline{\phi2}\supset\mathbf{1}\otimes\mathbf{1},\ \phi2\otimes\overline{\phi2}\supset\mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi1}\to0,\ Y_{\phi2}\}$
$\{\phi1,\ \phi2\}$	$\{\phi1\to\mathbf{1}\otimes\mathbf{3},\ \phi2\otimes\overline{\phi2}\supset\mathbf{1}\otimes\mathbf{3},\ \phi2\otimes\overline{\phi2}\supset\mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi1}\to0,\ Y_{\phi2}\}$
$\{\phi1,\ \phi2\}$	$\{\phi1\otimes\overline{\phi1}\supset\mathbf{8}\otimes\mathbf{1},\ \phi2\otimes\overline{\phi2}\supset\mathbf{8}\otimes\mathbf{1},\ \phi1\otimes\overline{\phi2}\supset\mathbf{1}\otimes\mathbf{2}\}$	$\{Y_{\phi2}\to-\frac{1}{2}+Y_{\phi1}\}$
$\{\phi1,\ \psi1\}$	$\{\phi1\to\mathbf{1}\otimes\mathbf{1},\ \psi1\otimes\overline{\psi1}\supset\mathbf{1}\otimes\mathbf{1},\ \psi1\otimes\overline{\psi1}\supset\mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi1}\to0,\ Y_{\psi1}\}$
$\{\phi1,\ \psi1\}$	$\{\phi1\to\mathbf{1}\otimes\mathbf{3},\ \psi1\otimes\overline{\psi1}\supset\mathbf{1}\otimes\mathbf{3},\ \psi1\otimes\overline{\psi1}\supset\mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi1}\to0,\ Y_{\psi1}\}$
$\{\psi1,\ \psi2\}$	$\{\psi1\otimes\overline{\psi1}\supset\mathbf{8}\otimes\mathbf{1},\ \psi2\otimes\overline{\psi2}\supset\mathbf{8}\otimes\mathbf{1},\ \psi1\otimes\overline{\psi2}\supset\mathbf{1}\otimes\mathbf{2}\}$	$\{Y_{\psi2}\to-\frac{1}{2}+Y_{\psi1}\}$

Using SOLD

- Model classification.

In[2]:= `ListModelsWarsaw[alphaOHG]`

Out[2]//MatrixForm=

Field Content	SU(3) ⊗ SU(2)	U(1)
$\{\phi 1\}$	$\{\phi 1\otimes\overline{\phi 1}\supset \mathbf{8}\otimes\mathbf{1},\ \phi 1\otimes\overline{\phi 1}\supset \mathbf{1}\otimes\mathbf{1}\}$	$\{Y_{\phi 1}\}$
$\{\phi 1\}$	$\{\phi 1\otimes\overline{\phi 1}\supset \mathbf{8}\otimes\mathbf{1},\ \phi 1\otimes\overline{\phi 1}\supset \mathbf{1}\otimes\mathbf{3}\}$	$\{Y_{\phi 1}\}$
$\{\psi 1\}$	$\{\psi 1\to \overline{\mathbf{3}}\otimes\mathbf{1}\}$	$\{Y_{\psi 1}\to \frac{1}{3}\}$
$\{\psi 1\}$	$\{\psi 1\to \overline{\mathbf{3}}\otimes\mathbf{2}\}$	$\{Y_{\psi 1}\to -\frac{1}{6}\}$
$\{\psi 1\}$	$\{\psi 1\to \overline{\mathbf{3}}\otimes\mathbf{2}\}$	$\{Y_{\psi 1}\to \frac{5}{6}\}$
$\{\psi 1\}$	$\{\psi 1\to \overline{\mathbf{3}}\otimes\mathbf{3}\}$	$\{Y_{\psi 1}\to \frac{1}{3}\}$
$\{\psi 1\}$	$\{\psi 1\to \mathbf{3}\otimes\mathbf{1}\}$	$\{Y_{\psi 1}\to \frac{2}{3}\}$
$\{\psi 1\}$	$\{\psi 1\to \mathbf{3}\otimes\mathbf{2}\}$	$\{Y_{\psi 1}\to \frac{7}{6}\}$
$\{\psi 1\}$	$\{\psi 1\to \mathbf{3}\otimes\mathbf{3}\}$	$\{Y_{\psi 1}\to \frac{2}{3}\}$
$\{\phi 1,\ \phi 2\}$	$\{\phi 1\to \mathbf{1}\otimes\mathbf{1},\ \phi 2\otimes\overline{\phi 2}\supset \mathbf{1}\otimes\mathbf{1},\ \phi 2\otimes\overline{\phi 2}\supset \mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi 1}\to 0,\ Y_{\phi 2}\}$
$\{\phi 1,\ \phi 2\}$	$\{\phi 1\to \mathbf{1}\otimes\mathbf{3},\ \phi 2\otimes\overline{\phi 2}\supset \mathbf{1}\otimes\mathbf{3},\ \phi 2\otimes\overline{\phi 2}\supset \mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi 1}\to 0,\ Y_{\phi 2}\}$
$\{\phi 1,\ \phi 2\}$	$\{\phi 1\otimes\overline{\phi 1}\supset \mathbf{8}\otimes\mathbf{1},\ \phi 2\otimes\overline{\phi 2}\supset \mathbf{8}\otimes\mathbf{1},\ \phi 1\otimes\overline{\phi 2}\supset \mathbf{1}\otimes\mathbf{2}\}$	$\{Y_{\phi 2}\to -\frac{1}{2}+Y_{\phi 1}\}$
$\{\phi 1,\ \psi 1\}$	$\{\phi 1\to \mathbf{1}\otimes\mathbf{1},\ \psi 1\otimes\overline{\psi 1}\supset \mathbf{1}\otimes\mathbf{1},\ \psi 1\otimes\overline{\psi 1}\supset \mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi 1}\to 0,\ Y_{\psi 1}\}$
$\{\phi 1,\ \psi 1\}$	$\{\phi 1\to \mathbf{1}\otimes\mathbf{3},\ \psi 1\otimes\overline{\psi 1}\supset \mathbf{1}\otimes\mathbf{3},\ \psi 1\otimes\overline{\psi 1}\supset \mathbf{8}\otimes\mathbf{1}\}$	$\{Y_{\phi 1}\to 0,\ Y_{\psi 1}\}$
$\{\psi 1,\ \psi 2\}$	$\{\psi 1\otimes\overline{\psi 1}\supset \mathbf{8}\otimes\mathbf{1},\ \psi 2\otimes\overline{\psi 2}\supset \mathbf{8}\otimes\mathbf{1},\ \psi 1\otimes\overline{\psi 2}\supset \mathbf{1}\otimes\mathbf{2}\}$	$\{Y_{\psi 2}\to -\frac{1}{2}+Y_{\psi 1}\}$

Using SOLD

- Model classification.

In[7]:= $\texttt{ListValidQNs}[\{\psi1\otimes\overline{\psi1} \supset \text{"8"}\otimes\text{"1"},\ \psi2\otimes\overline{\psi2} \supset \text{"8"}\otimes\text{"1"},\ \psi1\otimes\overline{\psi2} \supset \text{"1"}\otimes\text{"2"}\},\ 3,\ 2]$

Out[7]= $\{\{\psi1 \to \mathbf{3}\otimes\mathbf{1}\otimes Y_{\psi1},\ \psi2 \to \mathbf{3}\otimes\mathbf{2}\otimes Y_{\psi2}\},\ \{\psi1 \to \mathbf{3}\otimes\mathbf{2}\otimes Y_{\psi1},\ \psi2 \to \mathbf{3}\otimes\mathbf{1}\otimes Y_{\psi2}\},$
$\{\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{1}\otimes Y_{\psi1},\ \psi2 \to \overline{\mathbf{3}}\otimes\mathbf{2}\otimes Y_{\psi2}\},\ \{\psi1 \to \overline{\mathbf{3}}\otimes\mathbf{2}\otimes Y_{\psi1},\ \psi2 \to \overline{\mathbf{3}}\otimes\mathbf{1}\otimes Y_{\psi2}\}\}$

Using SOLD

- Matching results:

```
In[3]:= Match2Warsaw[alphaOeB[1, 2], {Fa → {1, 2, -1 / 2}}]
```

Out[3]=

$$\frac{\text{g1 L1[Fabar, eR, phi][2]} \times \text{L1[lLbar, eR, phi][1, mif3]} \times \text{L1bar[Fabar, eR, phi][mif3]}}{384\,\text{MFa}^2\,\pi^2}$$

Using SOLD

- Matching results:

```
In[4]:= Match2Warsaw[alphaOeB[1, 2], {Fa → {1, 2, -1/2}}] // NiceOutput
```

Out[4]=

$$\frac{g_1\, y_e{}^{[1,\mathrm{mif3}]}\, \lambda_{\overline{Fa},eR,\phi}{}^{[2]}\, \overline{\lambda}_{\overline{Fa},eR,\phi}{}^{[\mathrm{mif3}]}}{384\,\pi^2\, M_{Fa}^2}$$

Using SOLD

- Generation of Lagrangians:

```
In[4]:= CreateLag[{Fa → {1, 2, -1/2}}]

Out[4]= {Fabar[sp1, ss0].LR[sp1, ff0] × Phi[ss2] λ_{Fā,eR,ϕ}^[ff0] TS11[ss0, ss2], {TS11 → {{1, 0}, {0, 1}}}}
```

Using SOLD

- Interplay with Matchmakereft:

```
In[5]:= GenerateMMEModel[{Fa → {1, 2, -1/2}}, "mymodel"]

In[6]:= CompleteOneLoopMatching[{Fa → {1, 2, -1/2}}, "mymodel"]
```

A pheno example

- Tension in non-leptonic B meson decays alleviated in benchmark point:

  [A. Biswas et al., '23]

$$(C_{dG})_{1,3} \approx -(1.1 + 0.3\mathrm{i}) \times 10^{-5}, \quad (C_{dG})_{2,3} \approx -1 \times 10^{-5}, \quad (C_{dG})_{3,3} \approx 10^{-4},$$

- Check `ListModelsWarsaw` → $\Phi \sim (1,1)_{Y_\Phi}, \quad \Psi_1 \sim (3,2)_{\frac{1}{6}-Y_\Phi}, \quad \Psi_2 \sim (3,1)_{-\frac{1}{3}-Y_\Phi}$

- Check contribution with `Match2Warsaw`.

- Complete analysis with `MatchMakerEFT` in conjunction with other tools (`smelli`, `Match2Fit`…).

Conclusions

- EFTs allow us to construct dictionaries classifying all observable models, even the ones we did not think about.
- The complete dictionary at one loop is essential to perform a comprehensive analysis.
- The ease of use and all its functionalities make SOLD is a powerful tool for model-building.