Higgs Hunting 2025

Results and prospects in the electroweak symmetry breaking sector

Effective Field Theories: Theory overview

José Santiago

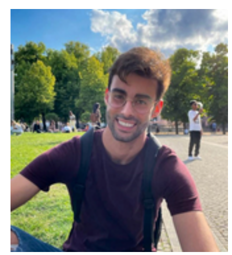
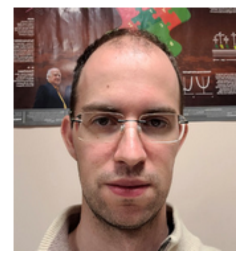
FTAE High Energy Theory

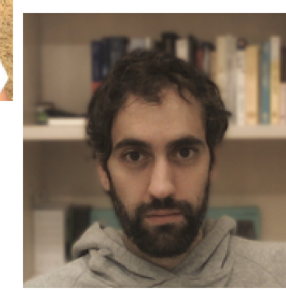
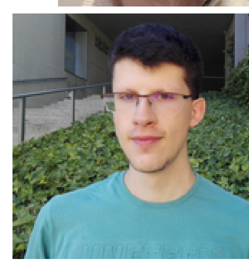
Universidad de Granada

Disclaimer

- 20 minutes is not enough to give a proper overview of the tremendous amount of recent progress in EFTs
- This is going to be a (very) personal view of the status of the field, with a with a particular emphasis on (some of the recent) developments done by members of the group in Granada

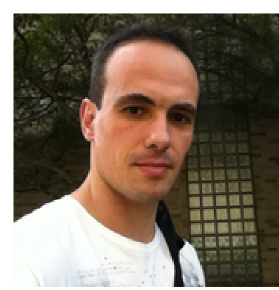


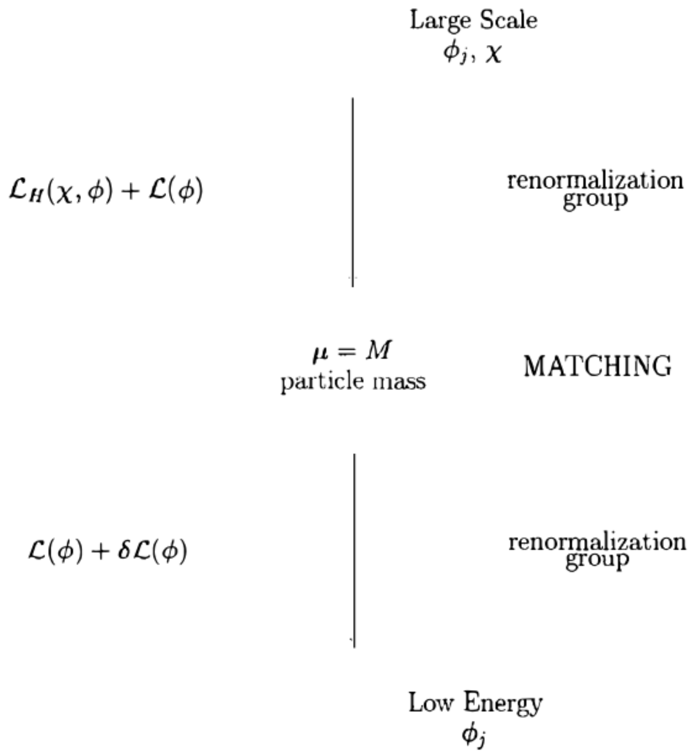





EFTs are essential!

- Effective field theory is an essential tool to study physics across scales



EFTs are essential!

- Effective field theory is an essential tool to study physics across scales.

Annu. Rev. Nucl. Part. Sci. 1993. 43:209–52

EFFECTIVE FIELD THEORY[1]

Howard Georgi

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138

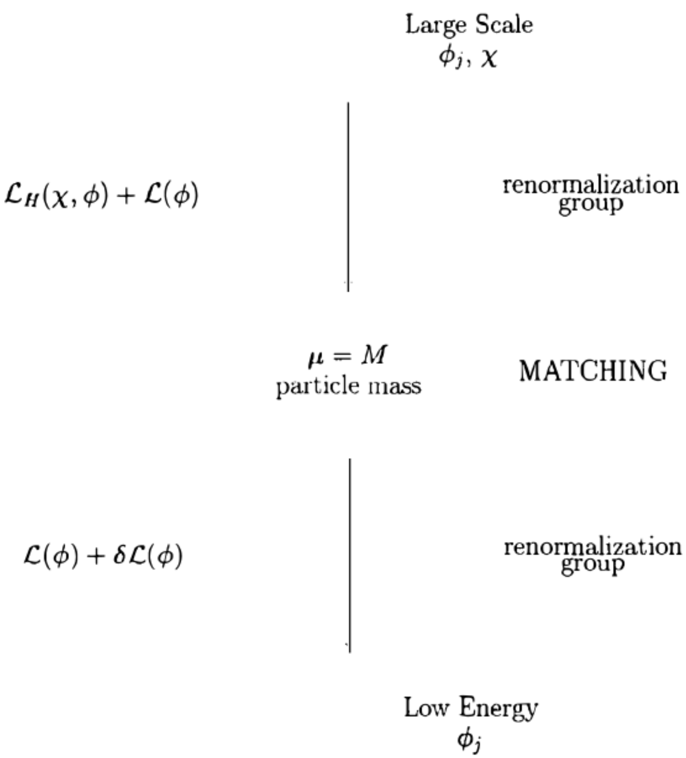
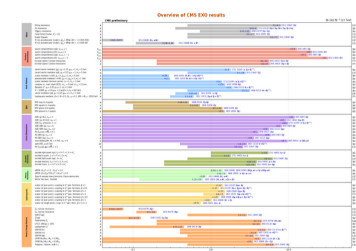


Figure 4 **The general form of a matching calculation.**

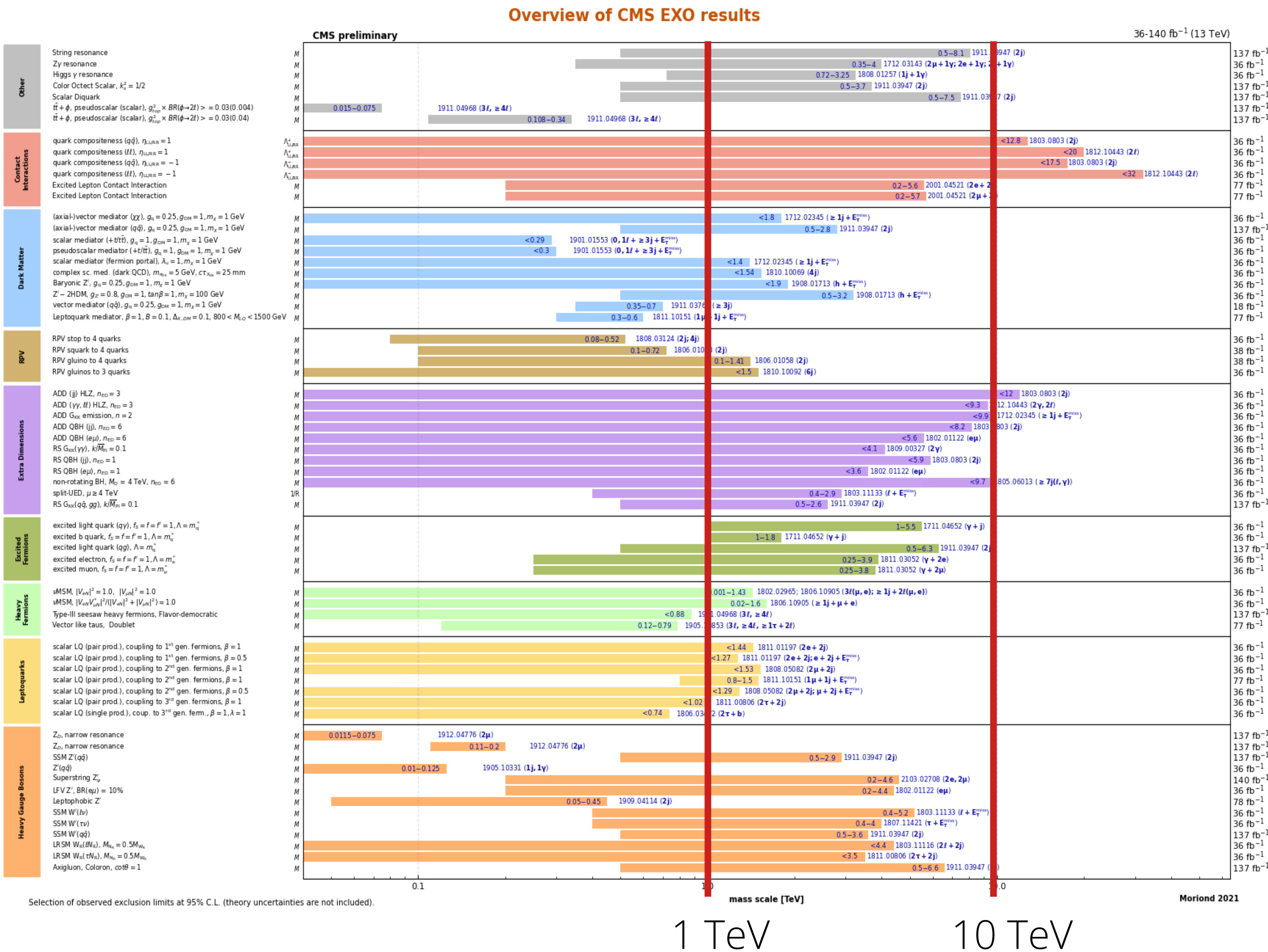
Told you so
(many years ago)

- Why are we so interested now?
  - Experiment:
    - It seems like a mass gap is actually present!



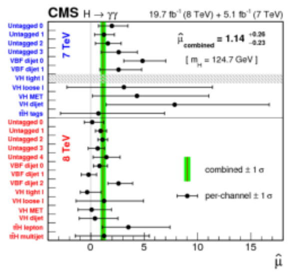
  - Tools:
    - We now have tools that allow us to make calculations that were impossible until recently.

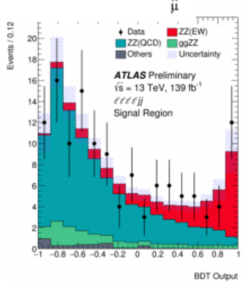
What is experiment telling us?

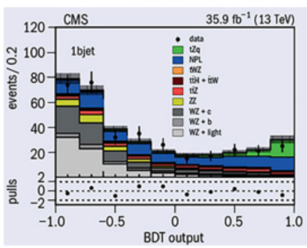


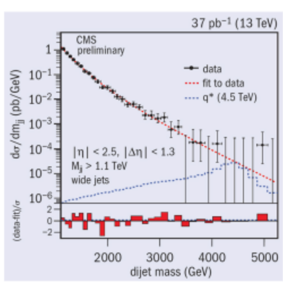
Turning all the stones! NP seems to be relatively heavy.

Connecting theory and experiment

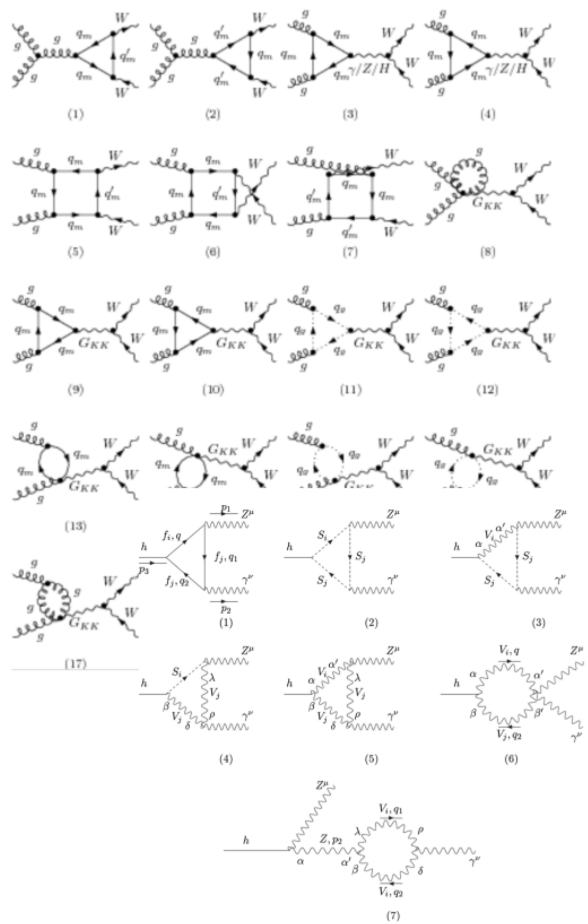


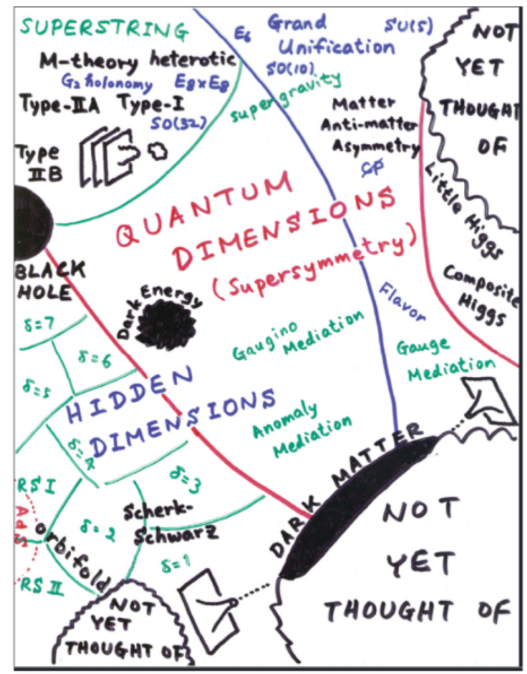






Getting implications of experimental data on new physics models is highly non trivial!

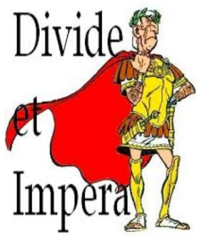




We need a more efficient approach!!

Effective Field Theories!

The effective way beyond the SM



EFTs allow for an efficient two-step comparison between theory and experiment:

Bottom-up: model-independent parametrization of experimental data in the form of global fits.

- Small number of models (EFTs).
- Observables computed just once.

SMEFTsim HEPfit SMEFiT

smelli/smelli
A global likelihood for the Standard Model Effective Field Theory

Top-down: model discrimination (matching).

- Has to be done on a model-by-model basis.
- Can be automated and fully classified.

MEFT

MATCHETE

Bottom-up: global fits

- Global fits allow for a model-independent parametrization of experimental data.

Wilson coefficients

Gauge and Lorent invariant operators

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d>4,i} \frac{c_i^{(d)}}{\Lambda^{d-4}} \mathcal{O}_i^{(d)}$$

Cut-off

- The EFT correctly captures the low-energy effects of arbitrary high-energy physics.
- The higher the mass dimension of an operator the smaller its contribution.

Bottom-up: global fits

- Global fits allow for a model-independent parametrization of experimental data.
- Computer tools fully automate this task.
- HEPfit. Joint fit to SM and BSM parameters (including SMEFT)

Eur. Phys. J. C (2020) 80:456
https://doi.org/10.1140/epjc/s10052-020-7904-z

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

HEPfit: a code for the combination of indirect and direct constraints on high energy physics models

J. de Blas[1,2], D. Chowdhury[3,4], M. Ciuchini[5], A. M. Coutinho[6], O. Eberhardt[7], M. Fedele[8], E. Franco[9], G. Grilli di Cortona[10], V. Miralles[7], S. Mishima[11], A. Paul[12,13,a], A. Peñuelas[7], M. Pierini[14], L. Reina[15], L. Silvestrini[9,16], M. Valli[17], R. Watanabe[5], N. Yokozaki[18]

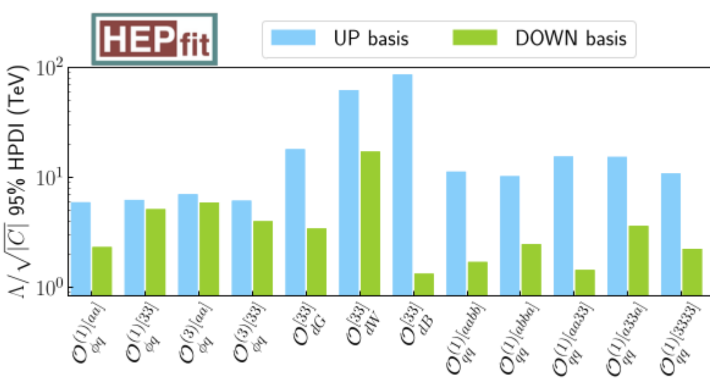
Bottom-up: global fits

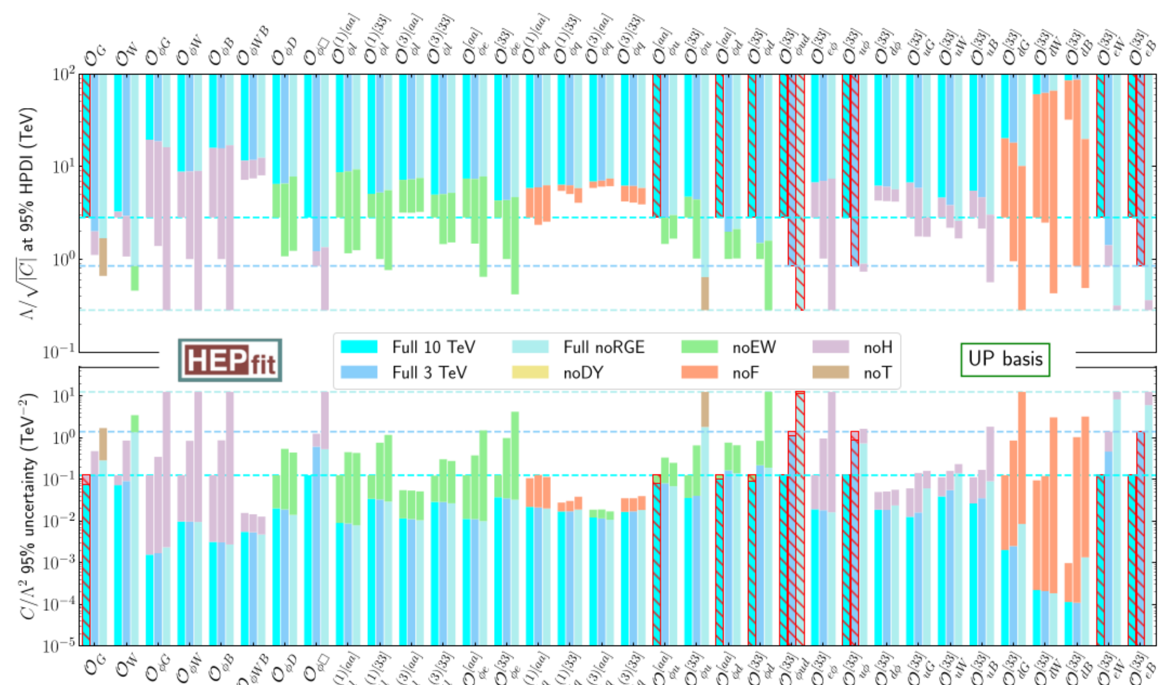
- Global fits allow for a model-independent parametrization of experimental data.
- Computer tools fully automate this task.
- HEPfit. Joint fit to SM and BSM parameters (including SMEFT)

Constraining new physics effective interactions via a global fit of electroweak, Drell-Yan, Higgs, top, and flavour observables

J. de Blas[a] , A. Goncalves[b] , V. Miralles[c] , L. Reina[b] , L. Silvestrini[d] and M. Valli[d]

[a] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain*





Top-down: connecting NP to EFTs

- The top-down approach consists on matching specific NP models to the EFT: computing the EFT Wilson coefficients in terms of the parameters of the NP model.
- We sacrifice model independence in favor of model discrimination (physics) and model completeness.
  - Power counting makes the problem of classifying the models that contribute at a certain order solvable.
  - Computer techniques allow us to automate the matching calculations.
- IR/UV dictionaries tell us all possible models that can contribute to a specific experimental observable at certain order in the EFT expansion: A new, alternative guiding principle beyond naturalness.

Automated matching with MME

SciPost SciPost Phys. 12, 198 (2022)

Matchmakereft: Automated tree-level and one-loop matching

Adrián Carmona[1,2], Achilleas Lazopoulos[2], Pablo Olgoso[1] and José Santiago[1⋆]

1 CAFPE and Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E–18071 Granada, Spain
2 Institute for Theoretical Physics, ETZ Zürich, 8093 Zürich, Switzerland

⋆ jsantiago@ugr.es

Abstract

We introduce `matchmakereft`, a fully automated tool to compute the tree-level and one-loop matching of arbitrary models onto arbitrary effective theories. `Matchmakereft` performs an off-shell matching, using diagrammatic methods and the background field method (BFM) when gauge theories are involved. The large redundancy inherent to the off-shell matching together with explicit gauge invariance offers a significant number of non-trivial checks of the results provided. These results are given in the physical basis but several intermediate results, including the matching in the Green basis before and after canonical normalization, are given for flexibility and the possibility of further cross-checks. As a non-trivial example we provide the complete matching in the Warsaw basis up to one loop of an extension of the Standard Model with a charge −1 vector-like lepton singlet. `Matchmakereft` has been built with generality, flexibility and efficiency in mind. These ingredients allow `matchmakereft` to have many applications beyond the matching between models and effective theories. Some of these applications include the one-loop renormalization of arbitrary theories (including the calculation of the one-loop renormalization group equations for arbitrary theories); the translation between different Green bases for a fixed effective theory or the check of (off-shell) linear independence of the operators in an effective theory. All these applications are performed in a fully automated way by `matchmakereft`.

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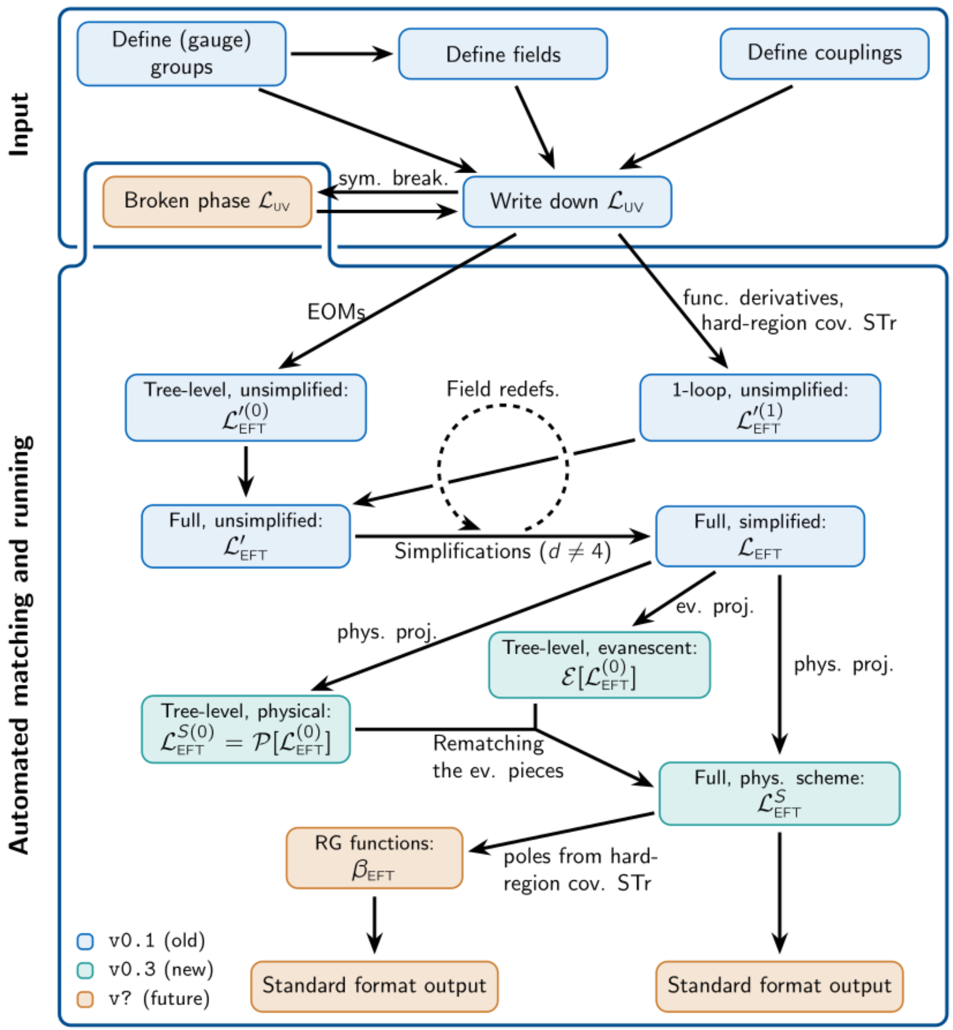
Check for updates

- Off-shell diagrammatic matching.
- Relies on robust tools (qgraf, form, python, mathematica).
- Efficient, flexible, powerful.
- RGE calculation, finite matching, off-shell operator independence, ...
- New developments expected soon:
  - On-shell matching
  - Two-loop calculations

Automated matching with matchete



Fuentes-Martín, König, Pagès, **AET**, Wilsch [2212.04510]

MATCHETE v0.3

- Automatic handling of evanescent contributions
- Extract WCs in user-specified bases (e.g. Warsaw basis)
- Supports flavor indices for heavy fields
- Lots of improvements, optimizations, and fixes

Download v0.3 now!

https://gitlab.com/matchete/matchete

Borrowed from A.E.Thomsen @ HEFT2025

IR/UV dictionaries

- The leading IR/UV dictionary (tree-level, dimension 6 SMEFT) was computed a few years ago. [Blas, Criado, Pérez-Victoria, Santiago '18]
- Complete list of all possible models that contribute to experiment at tree-level and dim 6 (and their contributions).

Granada Dictionary

19 scalars

Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
Name	Ω_1	Ω_2	Ω_4	Υ	Φ			
Irrep	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

13 fermions

Name	N	E	Δ_1	Δ_3	Σ	Σ_1	
Irrep	$(1,1)_0$	$(1,1)_{-1}$	$(1,2)_{-\frac{1}{2}}$	$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Name	U	D	Q_1	Q_5	Q_7	T_1	T_2
Irrep	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

16 vectors

Name	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{G}_1$	$\mathcal{H}$	$\mathcal{L}_1$
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,3)_0$	$(1,3)_1$	$(8,1)_0$	$(8,1)_1$	$(8,3)_0$	$(1,2)_{\frac{1}{2}}$
Name	$\mathcal{L}_3$	$\mathcal{U}_2$	$\mathcal{U}_5$	$\mathcal{Q}_1$	$\mathcal{Q}_5$	$\mathcal{X}$	$\mathcal{Y}_1$	$\mathcal{Y}_5$
Irrep	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Table 3. New vector bosons contributing to the dimension-six SMEFT at tree level.

48 new fields

Towards the next IR/UV dictionaries

- The one-loop, dimension 6 IR/UV dictionary is almost complete (only heavy vectors missing) [Guedes, Olgoso, Santiago Scipost Phys '23] [Guedes, Olgoso '24]

https://gitlab.com/jsantiago_ugr/sold

S SOLD
Project ID: 42493139

32 Commits 1 Branch 1 Tag 69.1 MB Project Storage 1 Release

Smeft **O**ne **L**oop **D**ictionary (**SOLD**)

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

In[1]:= << SOLD`
  SMEFT One Loop Dictionary loaded
  Version: 1.0.1
  Authors: Guilherme Guedes, Pablo Olgoso, José Santiago
  Reference: arXiv:2303.XXXX
  Webpage: https://gitlab.com/jsantiago_ugr/sold

  XXXXXXXXXXXXXXXXXXXXXXXXXXX GroupMath XXXXXXXXXXXXXXXXXXXXXXXXXXX
  Version: 1.1.2 (6/May/2020)
  Author: Renato Fonseca
  Reference: 2011.01764 [hep-th]
  Website: renatofonseca.net/groupmath
  Built-in documentation: here
  XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
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Renormalization of general EFTs

JHEP
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Renormalization of general Effective Field Theories: formalism and renormalization of bosonic operators

Renato M. Fonseca,[a] **Pablo Olgoso**[b,c] **and José Santiago**[a]

[a] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Campus de Fuentenueva, E-18071 Granada, Spain*
[b] *Dipartimento di Fisica e Astronomia, Università di Padova, Via F. Marzolo 8, 35131 Padova, Italy*
[c] *Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Via F. Marzolo 8, 35131 Padova, Italy*

E-mail: renatofonseca@ugr.es, pablo.olgosoruiz@unipd.it, jsantiago@ugr.es

Abstract: We describe the most general local, Lorentz-invariant, effective field theory of scalars, fermions and gauge bosons up to mass dimension 6. We first obtain both a Green and a physical basis for such an effective theory, together with the on-shell reduction of the former to the latter. We then proceed to compute the renormalization group equations for the bosonic operators of this general effective theory at one-loop order.

Keywords: Effective Field Theories, Renormalization and Regularization, SMEFT

ArXiv ePrint: 2501.13185

JHEP07(2025)135

Renormalization of general EFTs

- Matching or RGE calculations have to be repeated on a model-by-model basis. Even with automation this is not very efficient.
- Why not do the calculation once and for all?
  - Write down a generic EFT up to dimension 6 [with Sym2Int].
  - Compute its RGEs [using Matchmakereft].
  - The result is valid for arbitrary EFTs (only the group theory remains to be done).
- The formalism and renormalization of bosonic operators is now finished. [Fonseca, Olgoso, Santiago '25] [Misiak, Nalecz '25] [Aebischer, Bresciani, Selimovic '25]
- We are working on the renormalization of fermionic operators.
- The next step is the calculation of finite matching (of a general UV theory onto the general EFT).

RGEs of general EFTs

[Fonseca, Olgoso, Santiago '25]

- Build the most general EFT using Sym2Int.

$$\mathscr{L}_{d\leq 4} = -\frac{1}{4}(a_{KF})_{AB}F^A_{\mu\nu}F^{B\,\mu\nu} + \frac{1}{2}(a_{K\phi})_{ab}D_\mu\phi_a D^\mu\phi_b + (a_{K\psi})_{ij}\bar{\psi}_i \mathrm{i}\not{D}\psi_j - \frac{1}{2}\left[(m_f)_{ij}\psi_i^T C\psi_j + \text{h.c.}\right]$$
$$-\frac{1}{2}(m_\phi^2)_{ab}\phi_a\phi_b - \frac{1}{2}\left[Y_{ija}\psi_i^T C\psi_j + \text{h.c.}\right]\phi_a - \frac{\kappa_{abc}}{3!}\phi_a\phi_b\phi_c - \frac{\lambda_{abcd}}{4!}\phi_a\phi_b\phi_c\phi_d,$$

$$\mathscr{L}_5^{\text{phys}} = \left[\frac{1}{2}\left(a^{(5)}_{\psi F}\right)_{Aij}\psi_i^T C\sigma^{\mu\nu}\psi_j F^A_{\mu\nu} + \frac{1}{4}\left(a^{(5)}_{\psi\phi^2}\right)_{ijab}\psi_i^T C\psi_j\phi_a\phi_b + \text{h.c.}\right]$$
$$+\frac{1}{2}\left(a^{(5)}_{\phi F}\right)_{ABa}F^{A\,\mu\nu}F^B_{\mu\nu}\phi_a + \frac{1}{2}\left(a^{(5)}_{\phi\widetilde{F}}\right)_{ABa}F^{A\,\mu\nu}\widetilde{F}^B_{\mu\nu}\phi_a + \frac{1}{5!}\left(a^{(5)}_{\phi}\right)_{abcde}\phi_a\phi_b\phi_c\phi_d\phi_e,$$
$$\mathscr{L}_5^{\text{red}} = \frac{1}{2}\left(r^{(5)}_{\phi\Box}\right)_{abc}(D_\mu D^\mu\phi_a)\phi_b\phi_c + \left[\frac{1}{2}\left(r^{(5)}_{\psi}\right)_{ij}(D_\mu\psi_i)^T C D^\mu\psi_j + \left(r^{(5)}_{\psi\phi}\right)_{ija}\bar{\psi}_i\mathrm{i}\not{D}\psi_j\phi_a + \text{h.c.}\right],$$

- Compute its beta functions using MME.

$$\left(\dot{a}^{(5)}_{\phi\widetilde{F}}\right)_{ABa} = -2g^2\theta^C_{ab}\theta^C_{bc}\left(a^{(5)}_{\phi\widetilde{F}}\right)_{ABc} - 2g^2\left\{\left[\frac{11}{6}f^{CDB}f^{CDE} - \frac{1}{12}\theta^B_{bc}\theta^E_{cb} - \frac{1}{3}t^B_{ij}t^E_{ji}\right]\left(a^{(5)}_{\phi\widetilde{F}}\right)_{AEa} + (A\leftrightarrow B)\right\}$$
$$+2\mathrm{i}g\left[\left(a^{(5)}_{\psi F}\right)_{Aij}t^B_{jk}\bar{Y}^a_{ki} - \left[\left(a^{(5)}_{\psi F}\right)_{Aij}\right]^* t^B_{kj}Y^a_{ki} + (A\leftrightarrow B)\right] + \frac{1}{2}\left(a^{(5)}_{\phi\widetilde{F}}\right)_{ABc}\mathrm{Tr}[Y^c\bar{Y}^a + Y^a\bar{Y}^c],$$
$$\left(\dot{a}^{(5)}_{\phi}\right)_{abcde} = \sum_{\text{perm}}\left\{\frac{1}{12}\left(a^{(5)}_{\phi}\right)_{abcfg}\lambda_{defg} - \frac{1}{12}g^2\left(a^{(5)}_{\phi}\right)_{abcdf}\theta^A_{fg}\theta^A_{ge} + \frac{1}{6}g^2\left(a^{(5)}_{\phi}\right)_{abcfg}\theta^A_{df}\theta^A_{eg}\right.$$
$$+\frac{1}{48}\left(a^{(5)}_{\phi}\right)_{abcdf}\mathrm{Tr}[Y^e\bar{Y}^f + Y^f\bar{Y}^e] - \left[\left(a^{(5)}_{\psi\phi^2}\right)_{ijab}\bar{Y}^c_{ik}\bar{Y}^d_{jl}Y^e_{kl} + \left[\left(a^{(5)}_{\psi\phi^2}\right)_{ijab}\right]^*Y^c_{ik}Y^d_{jl}\bar{Y}^e_{kl}\right]$$
$$\left.+\frac{1}{12}\lambda_{fcde}\left[\left(a^{(5)}_{\psi\phi^2}\right)_{ijab}\bar{Y}^f_{ij} + \left[\left(a^{(5)}_{\psi\phi^2}\right)_{ijab}\right]^*Y^f_{ij}\right]\right\}.$$

Other recent progress on EFTs

- Formal developments taking place (and being automated):
  - On-shell matching

    [Chala, López-Miras, Santiago, Vilches Scipost Phys '25]
    [López-Miras, Vilches '25]
  - Automation of EFT calculations beyond one-loop:

    [Fuentes-Martín, Palavric, Thomsen '23]
    [Born, Fuentes-Martín, Kvedaraite, Thomsen '24]
    [Fuentes-Martín, Moreno-Sánchez, Palavric, Thomsen '24]
    [Lazopoulos et al, in progress]
  - Efficient implementation of BMHV scheme for γ^5

    [Olgoso, Vecchi '24]
    [Fuentes-Martín, Moreno-Sánchez in prep.]
  - Geometrical methods in EFTs

    [Alonso, Jenkins, Manohar, Helset, Martin, Pagès, Naterop, Craig, Cohen, Brivio, Davighi, Houtz, West, ...]

Conclusions and outlook

- EFTs have experienced a lot of theoretical progress in the last decade.
- Automation has played a pivotal role in their application to BSM physics.
  - Global fits to all available experimental data now possible and fully automated.
  - RGE and finite matching calculations fully automated at 1-loop (diagrammatic and functional), progress towards 2-loop automation.
  - IR/UV dictionaries now available up to 1-loop order in the SMEFT (almost).
  - Renormalization (and finite matching) of general EFTs.
- The combination of these tools will be crucial to take full advantage of all the experimental information that we will collect in the next decades.

The (effective) future is brilliant, full of tools, interesting physics, many new ideas to develop and plenty of data to analyze!