Progress in the UV—SMEFT connection

LHC EFT Working Group General Meeting #6

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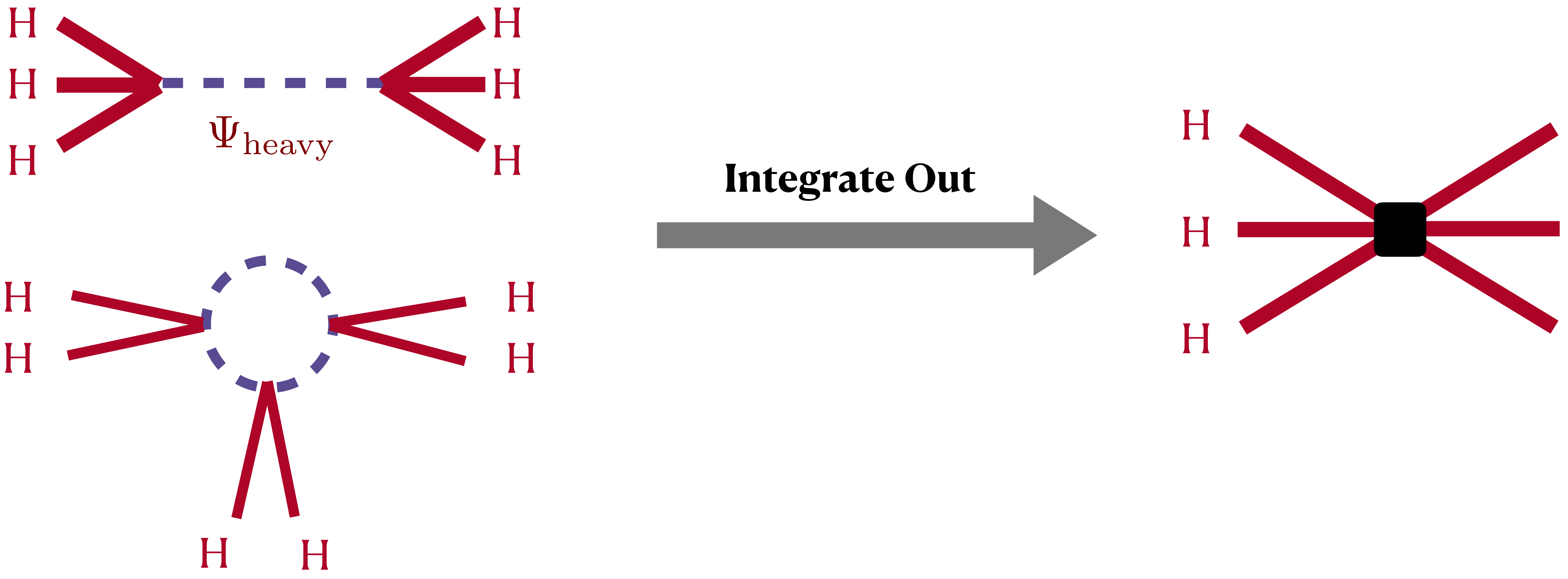
Supratim Das Bakshi | sdb@ugr.es

Departamento de Física Teórica y del Cosmos, UGR
(Granada)

Matching :

- **Comprises of integrating-out heavy fields perturbatively:**



→ **Tree-level**

→ **1-loop-level**

⋮

→ **Higher-loop-level**

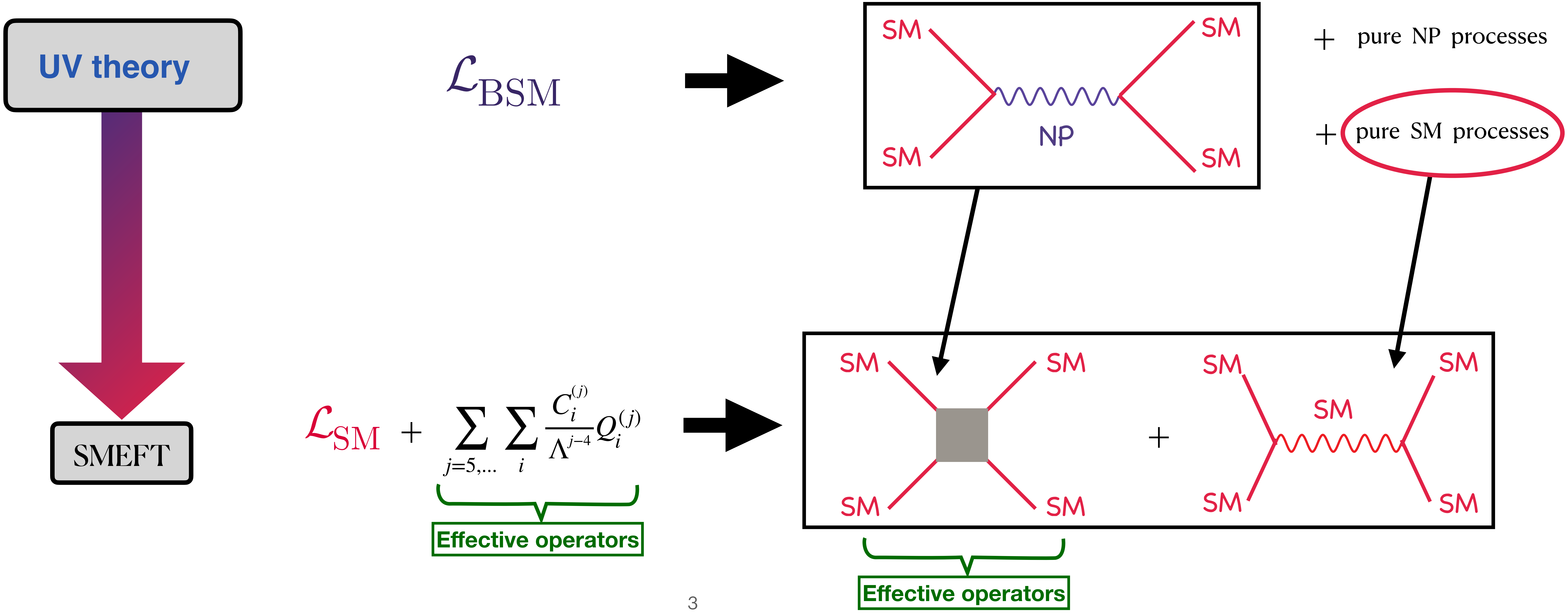
$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_i c_i^{(5)} O_i^{(5)} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^3}\sum_i c_i^{(7)} O_i^{(7)} + \frac{1}{\Lambda^4}\sum_i c_i^{(8)} O_i^{(8)} + \cdots$$

Λ : cut-off scale

Matching :

★ **The Wilson coefficients known in terms of UV model parameters. (Less parameters)**

✤ **The UV complete Lagrangian must be known. (Model specific)**



UV theory

SMEFT

$$\mathcal{L}_{\rm BSM}$$

+ pure NP processes

+ pure SM processes

$$\mathcal{L}_{\rm SM} + \underbrace{\sum_{j=5,\ldots}\sum_{i}\frac{C_i^{(j)}}{\Lambda^{j-4}}Q_i^{(j)}}_{\text{Effective operators}}$$

Effective operators

Diagrammatic methods :

→ **Well-established method to any loop order.**

→ **Matches to an off-shell basis via 1-LPI diagrams.**

→ **The operators of EFT basis and the redundancy relations needs to be predefined.**

Functional methods :

→ **Manifestly gauge invariant formulation.**

→ **Involves computing traces of effective action formula.**

Also see :

Onshell amplitude methods:

arxiv:2308.00035 De Angelis, Durieux **arxiv:2309.10851 Li, Zhou**

Computing Tools talk 2022, Zurich Chala*, Santiago

Functional methods

Action

$$S[\phi, \Phi_c + \eta] \quad = \quad \overbrace{S[\phi, \Phi_c]}^{\text{Tree}} \quad + \quad \eta \cancelto{0}{\frac{\delta S(\phi, \Phi)}{\delta \Phi}} |_{\Phi = \Phi_c} \quad + \quad \frac{\eta^2}{2} \overbrace{\frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}}^{\text{1-Loop}} |_{\Phi = \Phi_c} \quad + \quad \mathcal{O}(\eta^3)$$

Euler-Lagrange equation

Classical configuration

$$\Phi = \Phi_c + \eta$$

Functional methods

Action

$$S[\phi, \Phi_c + \eta] \quad = \quad \overbrace{S[\phi, \Phi_c]}^{\text{Tree}} \quad + \quad \eta \cancelto{0}{\frac{\delta S(\phi, \Phi)}{\delta \Phi}}\Big|_{\Phi = \Phi_c} \quad + \quad \frac{\eta^2}{2} \overbrace{\frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}}^{\text{1-Loop}}\Big|_{\Phi = \Phi_c} \quad + \quad \mathcal{O}(\eta^3)$$

Euler-Lagrange
equation

Classical configuration

$$\Phi = \Phi_c + \eta$$

Summing over η configurations :

$$e^{iS_{\text{eff}}[\phi]} \quad = \int \mathcal{D}\Phi \; e^{iS[\phi, \Phi]} \quad = \int \mathcal{D}\eta \; e^{iS[\phi, \Phi_c + \eta]}$$

$$\Rightarrow S_{\text{eff}}[\phi, \Phi_c] \quad = S[\phi, \Phi_c] + \frac{i}{2} \text{Tr} \log \left(- \frac{\delta^2 S(\phi, \Phi)}{\delta \Phi^2}\Big|_{\Phi = \Phi_c} \right) \qquad \}$$

Dependent only
on light fields

STrEAM, arxiv:2012.07851
Cohen, Lu, Zhang

SuperTracer, arxiv:2012.08506
Fuentes-Martín, König, Pagès, Thomsen, Wilsch

Automated matching packages :

→ **MatchingTools: a Python library for symbolic effective field theory calculations**

Juan C Criado
Comput.Phys.Commun. 227 (2018) 42-50 • e-Print: 1710.06445

→ **CoDEx: Wilson coefficient calculator connecting SMEFT to UV theory**

SDB, Joydeep Chakrabortty, Sunando Kumar Patra
Eur.Phys.J.C 79 (2019) 1, 21 • e-Print: 1808.04403

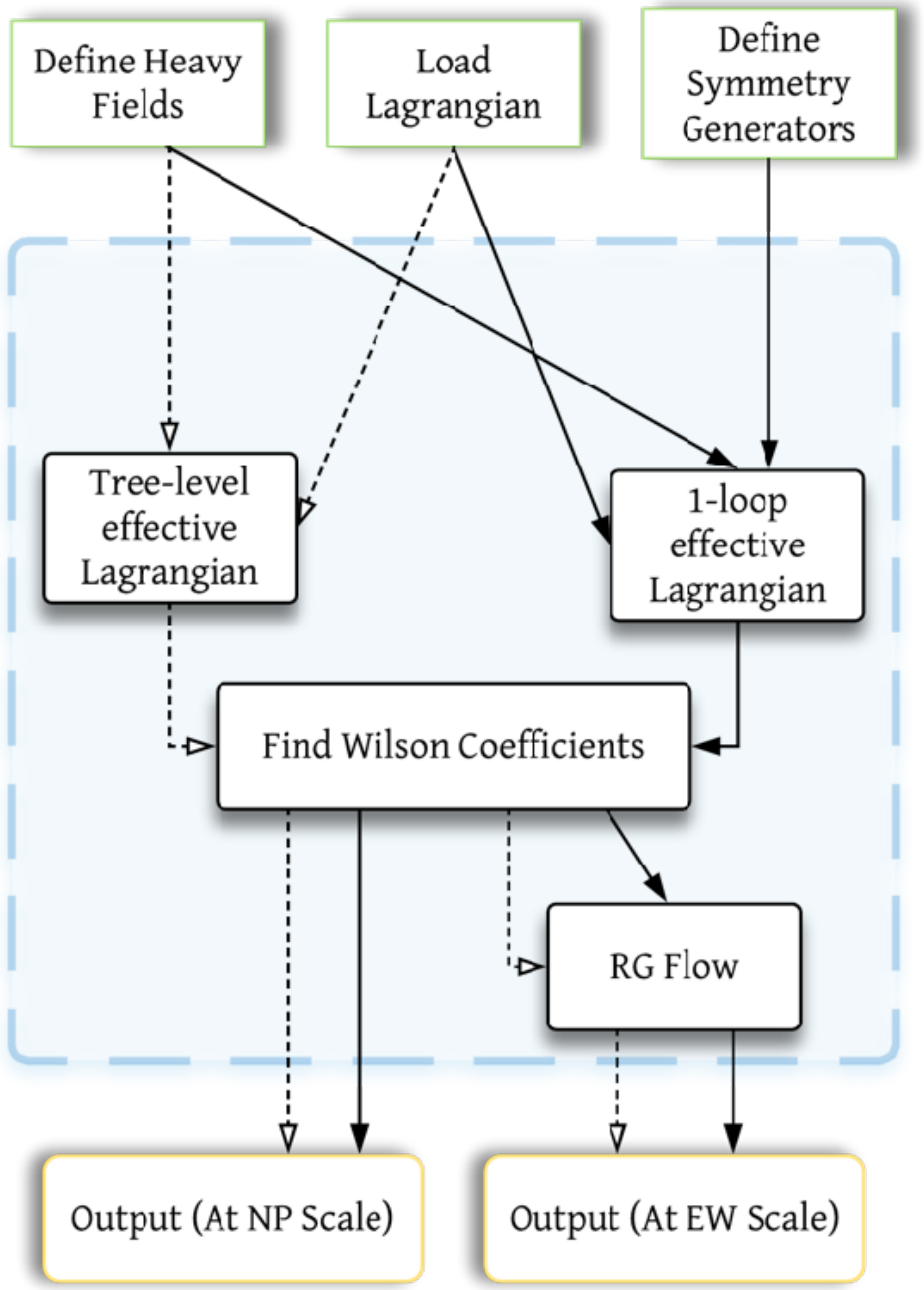
→ **Matchmakereft: automated tree-level and one-loop matching**

Adrian Carmona, Achilleas Lazopoulos, Pablo Olgoso, Jose Santiago
SciPost Phys. 12 (2022) 6 • e-Print: 2112.10787

→ **A Proof of Concept for Matchete: An Automated Tool for Matching Effective Theories**

Javier Fuentes-Martín, Matthias König, Julie Pagès, Anders Eller Thomsen, Felix Wilsch
Eur.Phys.J.C 83 (2023) 7, 662 • e-Print: 2212.04510

CoDEx flowchart



BSM classifications :

EWPO (Leading order)

All scalars

Heavy BSM fields	$SU(3)_C$, $SU(2)_L$, $U(1)_Y$	Q_{HD}	Q_{ll}	Q_{Hu}	Q_{Hd}	Q_{He}	$Q^{(1)}_{Hq}$	$Q^{(1)}_{Hl}$	$Q^{(3)}_{Hl}$	$Q^{(3)}_{Hq}$	Q_{HWB}
$\mathcal{S}$	(1,1,0)	L	✗	✗	✗	✗	✗	✗	✗	✗	L
$\mathcal{S}_2$	(1,1,2)	L	L	L	L	L	L	L	✗	✗	✗
Δ	(1,3,0)	T	L	✗	✗	✗	✗	✗	L	L	L
$\mathcal{H}_2$	$(1,2,-\frac{1}{2})$	L	L	L	L	L	L	L	L	L	L
Δ_1	(1,3,1)	T	T	L	L	L	L	L	L	L	L
Σ	$(1,4,\frac{1}{2})$	L	L	L	L	L	L	L	L	L	L
φ_1	$(3,1,-\frac{1}{3})$	L	L	L	L	L	L	L	✗	✗	✗
φ_2	$(3,1,-\frac{4}{3})$	L	L	L	L	L	L	L	✗	✗	✗

Tree-level (T), 1-loop (L)

* Matching at the heavy field mass

→ **BSMs generate unique sets of SMEFT operators.**
(Double \hline separating the classes)

→ **Same exercise with other observables to break class degeneracy.**

More here:

arxiv:2012.03839

SDB, Chakrabortty, Spannowsky

BSM dictionaries (matching results) :

→ **Catalogue of exhaustive list of single field extension of the SM at Tree-level**

Effective description of general extensions of the Standard Model: the complete tree-level dictionary, **(a.k.a. Granada dictionary)**

J. de Blas, J. C. Criado, M. Perez-Victoria, J. Santiago
JHEP 03 (2018) 109 • e-Print: 1711.10391

→ **Extended to 1-loop order using Matchmakereft.**

Towards the one loop IR/UV dictionary in the SMEFT: one loop generated operators from new scalars and fermions, **(a.k.a. SOLD package)**

G. Guedes, P. Olgoso, J. Santiago
e-Print: 2303.16965

SMEFT Renormalisation Status (2023)!

	d_5	d_5^2	d_6	d_5^3	$d_5 \times d_6$	d_7	d_5^4	$d_5^2 \times d_6$	d_6^2	$d_5 \times d_7$	d_8
$d_{\leq 4}$ (bosonic)			✓						✓		This talk
$d_{\leq 4}$ (fermionic)			✓						X		X
d_5	✓				✓	✓					
d_6 (bosonic)		✓	✓					✓	✓	✓	This talk
d_6 (fermionic)		✓	✓					X	X	X	X
d_7				✓	✓	✓					
d_8 (bosonic)							✓	✓	✓	✓	This talk
d_8 (fermionic)							X	X	X	X	✓

Blank entries vanish; ✓ → known; ✓ → substantially known (not complete); X → nothing, or very little, is known. The contribution discussed in this talk is marked by ▨.

Table compiled from: arxiv:2106.05291, 2205.03301, 2301.07151 . Check these out for Refs.

SMEFT Dim-8 RGEs

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)} O_j^{(8)} + \cdots$$

$\mathcal{L}_5, \mathcal{L}_7 \to$ B/LNV

$\Lambda =$ EFT cut-off scale

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu} \frac{dc_i^{(8)}}{d\tilde{\mu}} = \gamma_{ij} c_j^{(8)} + \gamma'_{ijk} c_j^{(6)} c_k^{(6)}$$

At $\mathcal{O}\left(\frac{1}{\Lambda^4}\right)$, assuming no B/LNV.

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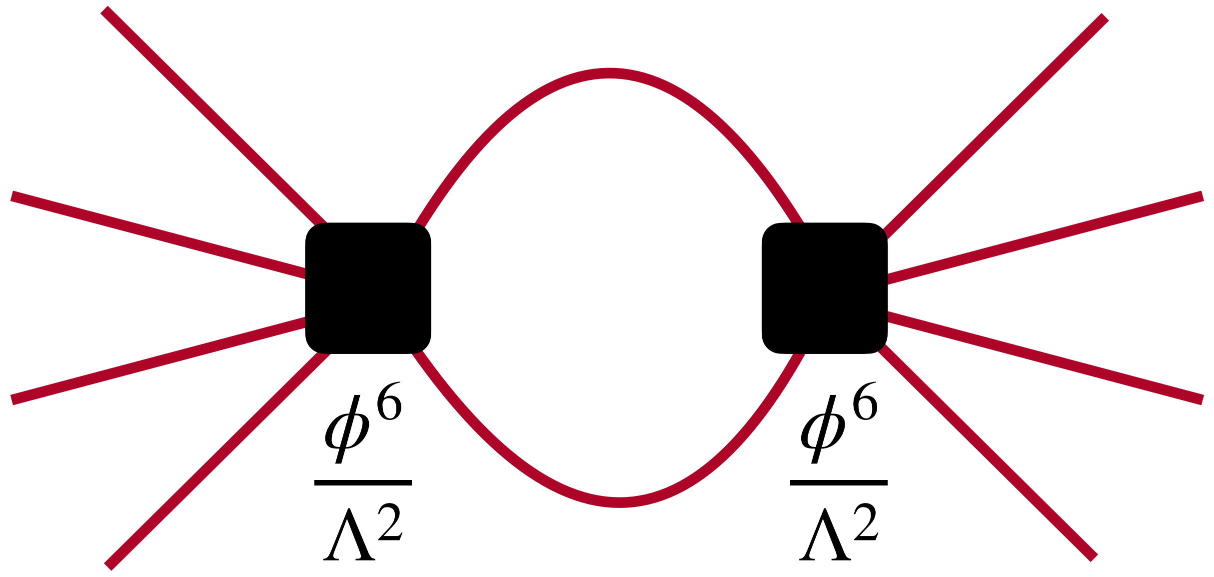
- Two dim-6 operator insertions.

arXiv:2106.05291

Towards the renormalisation of the Standard Model effective field theory to dimension eight: Bosonic interactions I
- M Chala, G Guedes, M Ramos, J Santiago

e.g. :



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$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{1}{\Lambda^2}\sum_i c_i^{(6)} O_i^{(6)} + \frac{1}{\Lambda^4}\sum_j c_j^{(8)} O_j^{(8)} + \cdots$$

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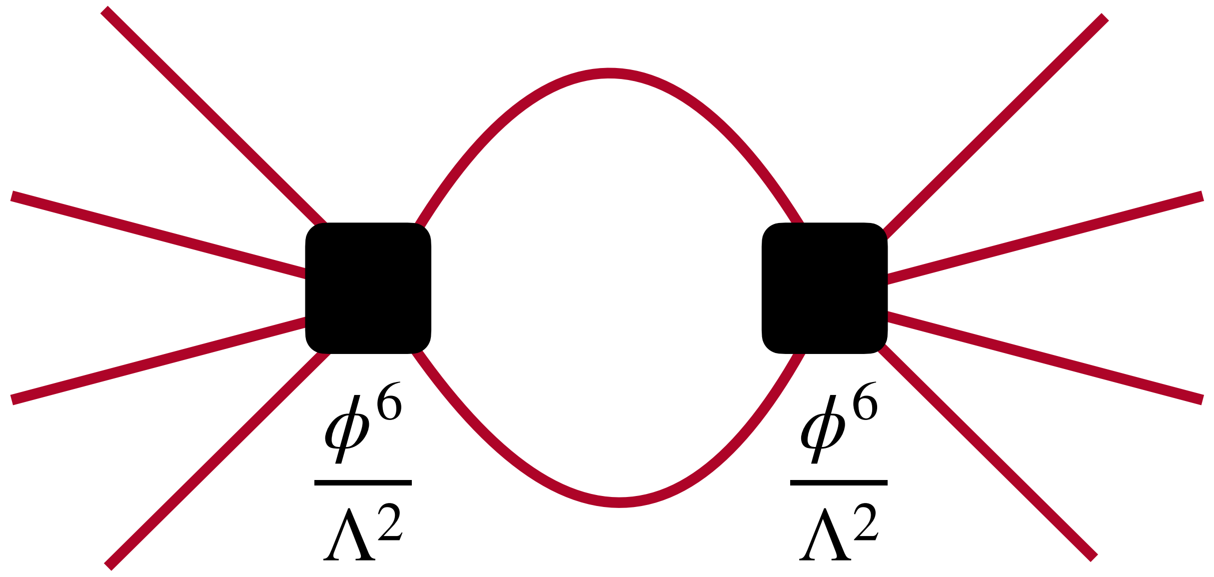


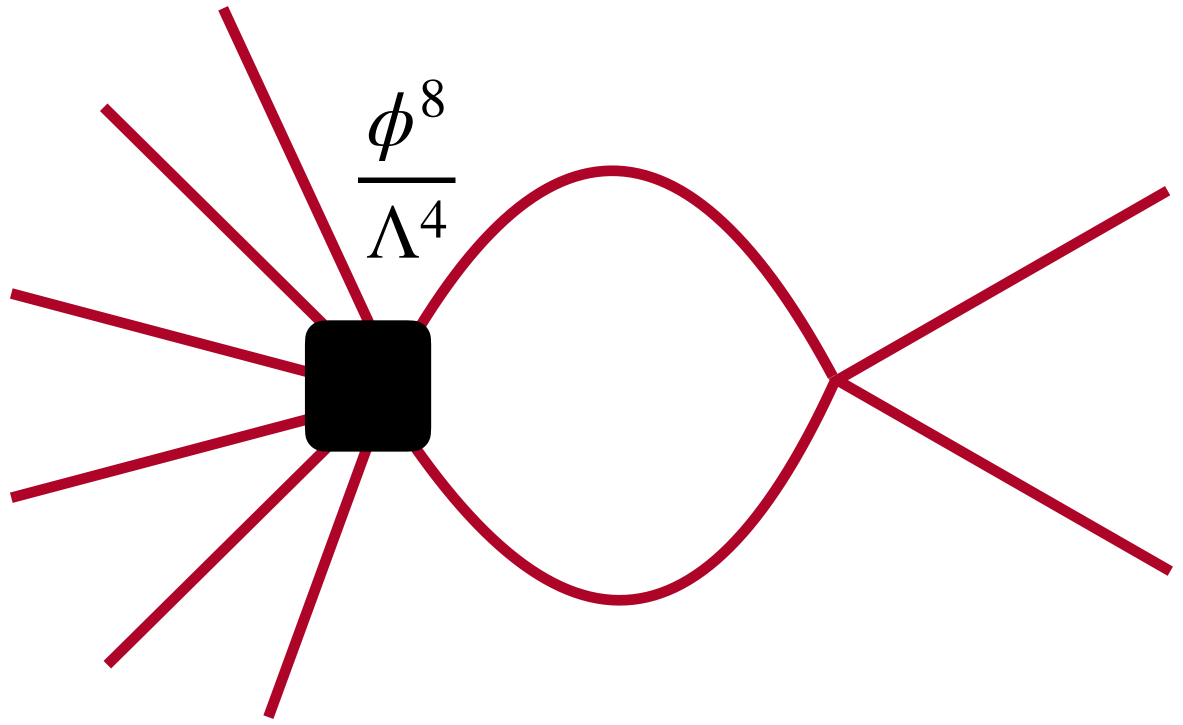
❖ One dim-8 operator insertion.

arXiv:2205.03301

Towards the renormalisation of the Standard Model effective field theory
to dimension eight: Bosonic interactions II

- SDB, M Chala, Á Díaz-Carmona, G Guedes

e.g. :



SMEFT Lagrangian

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu} \frac{dc_i^{(8)}}{d\tilde{\mu}} = \boxed{\gamma_{ij} c_j^{(8)}} + \gamma'_{ijk} c_j^{(6)} c_k^{(6)}$$

- One **tree-level generated** dim-8 operator in one-loop.

arXiv:2001.00017
- Craig, Jiang, Li, Sutherland

Classes of operator that are tree-level generated :

Bosonic : $\{\phi^8, \phi^6 D^2, \phi^4 D^4, X^2 \phi^4, X \phi^4 D^2, X^2 H^2 D^2, X^3 H^2, X^4\}$

Fermionic : $\{\psi^2 X \phi^3,\ \psi^2 \phi^2 D^3,\ \psi^2 \phi^5,\ \psi^2 \phi^4 D,\ \psi^2 X \phi^2 D,\ \psi^2 \phi^3 D^2, \psi^2 X^2 \phi, \psi^2 X^2 D, \psi^2 X \phi D^2\}$

SMEFT Dim-8 **on-shell basis** : arXiv:2005.00059 — C. W. Murphy

SMEFT Dim-8 **Green's/off-shell basis** : arXiv:2112.12724 — M. Chala, Á Díaz-Carmona, G. Guedes

SMEFT Lagrangian

$$\dot{c}_i^{(8)} \equiv 16\pi^2 \tilde{\mu} \frac{dc_i^{(8)}}{d\tilde{\mu}} = \boxed{\gamma_{ij} c_j^{(8)}} + \gamma'_{ijk} c_j^{(6)} c_k^{(6)}$$

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SMEFT Dim-8 **Green's/off-shell basis** : arXiv:2112.12724 — M. Chala, Á Díaz-Carmona, G. Guedes

Divergences to RGEs, some details:

- Compute **1-PI loop diagrams**. Use **FeynRules, FeynARTs,** and **FormCalc** packages.

- Divergences are captured by the operators of **off-shell/Green's basis**.

$$16\pi^2\epsilon\,\mathcal{L}_{\rm DIV} = \tilde{K}_\phi (D_\mu\phi)^\dagger (D^\mu\phi) + \tilde{\mu}^2|\phi|^2 - \tilde{\lambda}|\phi|^4 + \tilde{c}_i^{(6)}\frac{\mathcal{O}_i^{(6)}}{\Lambda^2} + \tilde{c}_j^{(8)}\frac{\mathcal{O}_j^{(8)}}{\Lambda^4}$$

[on RHS we have Green's basis]

arXiv:2112.12724
- M Chala, Á Díaz-Carmona, G Guedes

- **Removing redundant operators** using on-shell relations.

arXiv:2106.05291
- M Chala, G Guedes, M Ramos, J Santiago

- **Cross-checks with MatchMakerEFT**. ✓
  H^8 topologies are computed in MM primarily.

arXiv:2112.10787
- A Carmona, A Lazopoulos, P Olgoso, J Santiago

- **Partial cross-checks** with arXiv:2108.03669 (on-shell amplitude methods). ✓
  and with arXiv:2307.03187 ✓

arXiv:2108.03669
- M A Huber, S De Angelis.

— Assi, Helset, Manohar, Pagès, Shen

Bosonic-bosonic RGE:

Classes of tree-generated bosonic operators

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
$B^2\phi^2 D^2$	g_1^2	0	0	0	0	0	0	0	0
$W^2\phi^2 D^2$	g_2^2	0	0	0	0	0	0	0	0
$WB\phi^2 D^2$	$g_1 g_2$	0	0	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0
$W^2 B\phi^2$	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	g_2^2	0	0	0	0	0	0	0	0
$B\phi^4 D^2$	$g_1 g_2^2$	λ	0	0	0	0	0	0	0
$W\phi^4 D^2$	g_2^3	0	g_2^2	0	0	0	0	0	0
$B^2\phi^4$	$g_1^2 g_2^2$	$g_1\lambda$	$g_1^2 g_2$	λ	0	$g_1 g_2$	0	0	0
$W^2\phi^4$	g_2^4	$g_1 g_2^2$	g_2^3	0	λ	$g_1 g_2$	0	0	0
$WB\phi^4$	$g_1 g_2^3$	$g_2\lambda$	$g_1\lambda$	$g_1 g_2$	$g_1 g_2$	λ	0	0	0
$G^2\phi^4$	0	0	0	0	0	0	g_3^2	0	0
$\phi^6 D^2$	g_2^4	$g_1\lambda$	$g_2\lambda$	0	0	0	0	λ	0
ϕ^8	λ^3	$g_1\lambda^2$	$g_2\lambda^2$	$g_1^2\lambda$	$g_2^2\lambda$	$g_1 g_2\lambda$	0	λ^2	$\boxed{\lambda}$

- **Largest contribution from each operator class is shown.**
- **Loop generated operators that are renormalised by tree-generated operators are in gray.**
- **Violet entries contribute larger than what expected from naive dimensional analysis.**

$$\tilde{\mu}\frac{dc_{\phi^8}}{d\tilde{\mu}} = \frac{1}{16\pi^2}\left(192\lambda - 6(g_1^2 + 3g_2^2) + \ldots\right) c_{\phi^8}$$

Fermionic-bosonic RGE:

Classes of tree-generated fermionic operators

	$\psi^2 B\phi^3$	$\psi^2 W\phi^3$	$\psi^2 G\phi^3$	$\psi^2\phi^2 D^3$	$\psi^2\phi^5$	$\psi^2\phi^4 D$	$\psi^2 B\phi^2 D$	$\psi^2 W\phi^2 D$	$\psi^2 G\phi^2 D$	$\psi^2\phi^3 D^2$
$B^2\phi^2 D^2$	0	0	0	g_1^2	0	0	0	0	0	0
$W^2\phi^2 D^2$	0	0	0	g_2^2	0	0	0	0	0	0
$WB\phi^2 D^2$	0	0	0	$g_1 g_2$	0	0	0	0	0	0
$G^2\phi^2 D^2$	0	0	0	g_3^2	0	0	0	0	0	0
$W^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$W^2 B\phi^2$	0	0	0	0	0	0	0	0	0	0
$G^3\phi^2$	0	0	0	0	0	0	0	0	0	0
$\phi^4 D^4$	0	0	0	$\|y^t\|^2$	0	0	0	0	0	0
$B\phi^4 D^2$	0	0	0	$g_1\|y^t\|^2$	0	0	$\|y^t\|^2$	0	0	$g_1 y^t$
$W\phi^4 D^2$	0	0	0	$g_2\|y^t\|^2$	0	0	0	$\|y^t\|^2$	0	$g_2 y^t$
$B^2\phi^4$	$g_1 y^t$	0	0	$g_1^2\|y^t\|^2$	0	0	$g_1\|y^t\|^2$	0	0	$g_1^2 y^t$
$W^2\phi^4$	0	$g_2 y^t$	0	$g_2^2\|y^t\|^2$	0	g_2^2	0	$g_2\|y^t\|^2$	0	$g_2^2 y^t$
$WB\phi^4$	$g_2 y^t$	$g_1 y^t$	0	$g_1 g_2\|y^t\|^2$	0	$g_1 g_2$	$g_2\|y^t\|^2$	$g_1\|y^t\|^2$	0	$g_1 g_2 y^t$
$G^2\phi^4$	0	0	$g_3 y^t$	0	0	0	0	0	0	0
$\phi^6 D^2$	0	0	0	$g_2^2\|y^t\|^2$	0	$\|y^t\|^2$	$g_1\|y^t\|^2$	$g_2\|y^t\|^2$	0	$\boxed{y^t\|y^t\|^2}$
ϕ^8	0	0	0	$\lambda\|y^t\|^4$	$y^t\|y^t\|^2$	$\lambda\|y^t\|^2$	$g_1\lambda\|y^t\|^2$	$g_2\lambda\|y^t\|^2$	0	$\lambda y^t\|y^t\|^2$

RGEs of Dim-6,4,2

- Dim-8 operators also induce running of dim-6, dim-4, dim-2 operators.

	$\phi^4 D^4$	$B\phi^4 D^2$	$W\phi^4 D^2$	$B^2\phi^4$	$W^2\phi^4$	$WB\phi^4$	$G^2\phi^4$	$\phi^6 D^2$	ϕ^8
ϕ^2	μ^6	0	0	0	0	0	0	0	0
ϕ^4	$\lambda\mu^4$	$g_1\mu^4$	$g_2\mu^4$	0	0	0	0	μ^4	0
$B^2\phi^2$	$g_1^2\mu^2$	$g_1\mu^2$	0	μ^2	0	0	0	0	0
$W^2\phi^2$	$g_2^2\mu^2$	0	$g_2\mu^2$	0	μ^2	0	0	0	0
$WB\phi^2$	$g_1 g_2\mu^2$	$g_2\mu^2$	$g_1\mu^2$	0	0	μ^2	0	0	0
$G^2\phi^2$	0	0	0	0	0	0	μ^2	0	0
$\phi^4 D^2$	$\lambda\mu^2$	$g_1\mu^2$	$g_2\mu^2$	0	0	0	0	μ^2	0
ϕ^6	$\lambda^2\mu^2$	$\lambda g_1\mu^2$	$\lambda g_2\mu^2$	$g_1^2\mu^2$	$g_2^2\mu^2$	$g_1 g_2\mu^2$	0	$\lambda\mu^2$	μ^2

μ^2 is the squared Higgs mass in the SMEFT.

Lower dim. classes renormalised by the bosonic dim-8 operators.
Similar contributions from two-fermionic dim-8 operators are also present.

Summary

- UV models to SMEFT matching via amplitude and functional methods.

- The packages and utilities available for matching.

- BSM classifications, dictionaries, …

- Update on SMEFT renormalization status.

Thanks for your attention!