FTAE High Energy Theory
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AGENCIA ESTATAL DE INVESTIGACIÓN
Junta de Andalucía

The landscape of effective field theories

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(University of Granada)

based on *2110.01624*, *2301.09995*, *2309.10635*, *2309.16611*

Oklahome State High Energy Physics seminar; November 2, 2023

The FTAE group in Granada
(13 senior + 14 junior/postdocs + 18 students)


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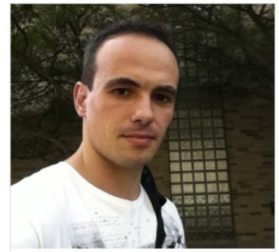
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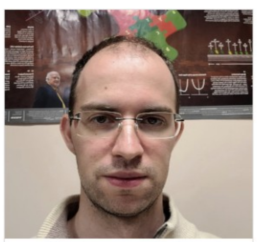
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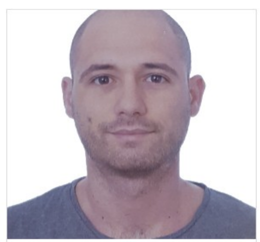
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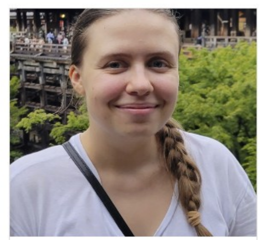
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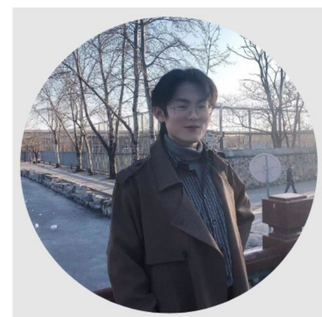

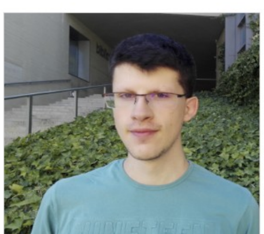
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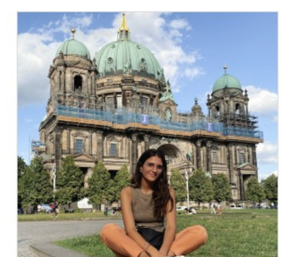
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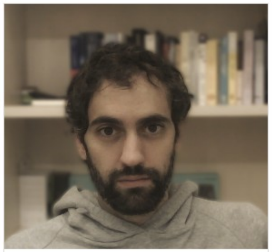
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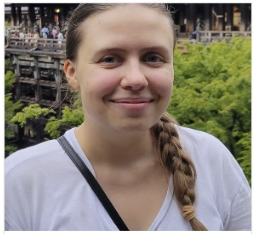
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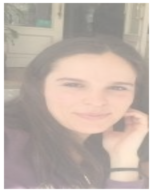


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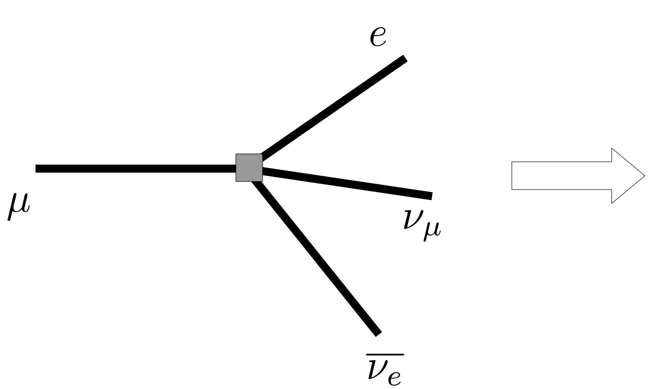
Effective field theories

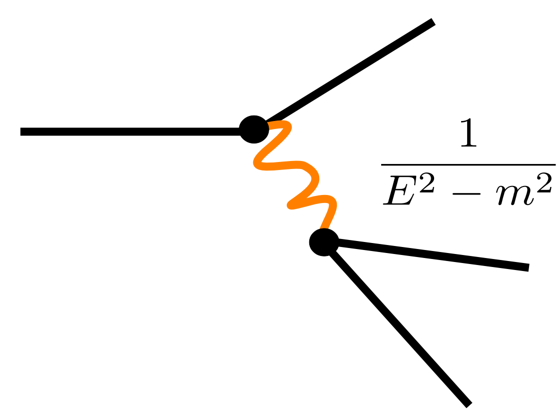
EFTs are QFTs valid only below some given energy. We use them for both practical and technical reasons

They are characterised by the relevant degrees of freedom, symmetries and power counting

Examples are the **SMEFT** (SM+SU(3)xSU(2)xU(1)+1/f expansion) or **CHMs** (h+shift symmetry h→h+c + expansion in derivatives)

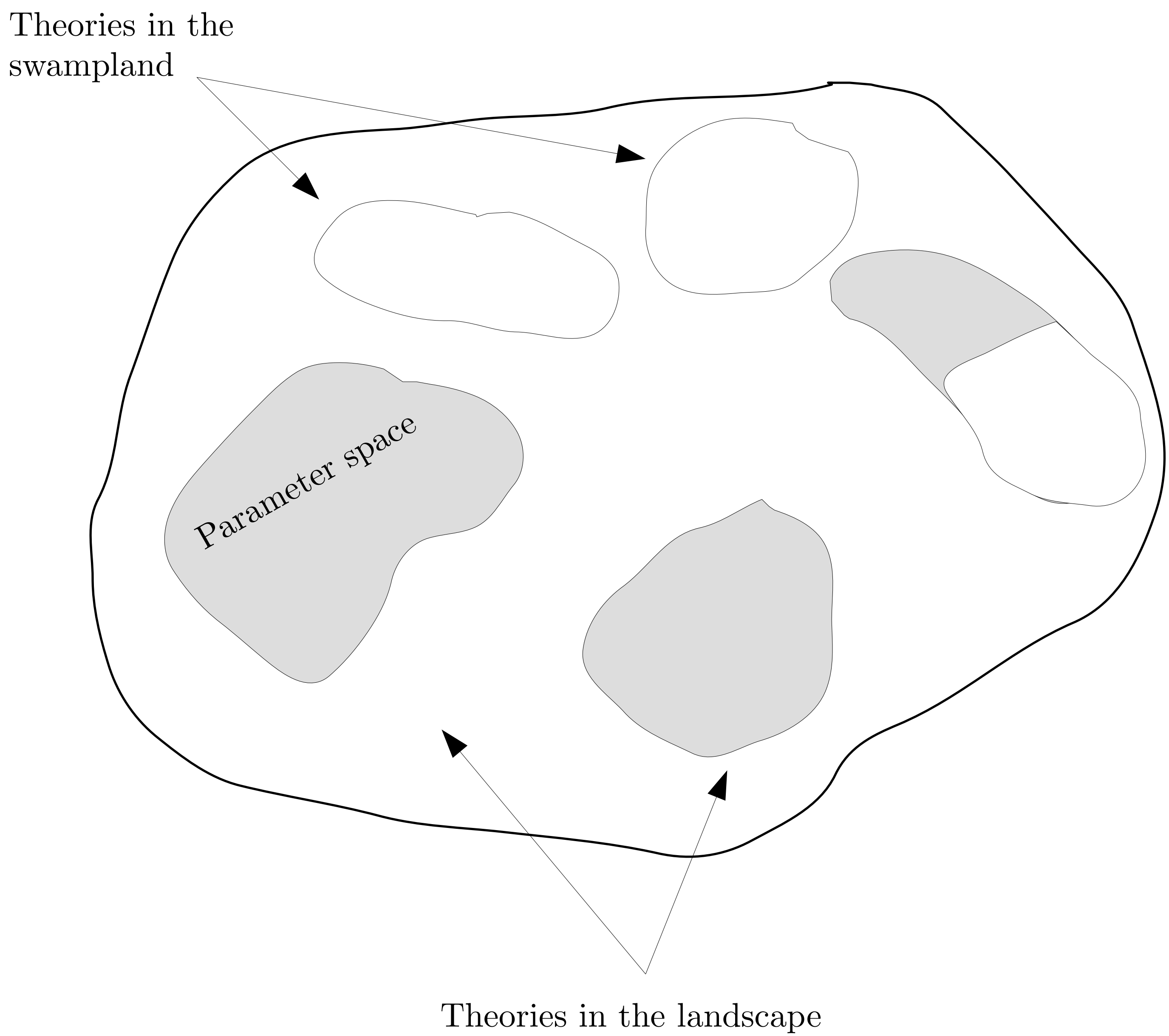


$$\mathcal{A} \sim \frac{E^2}{m^2}$$

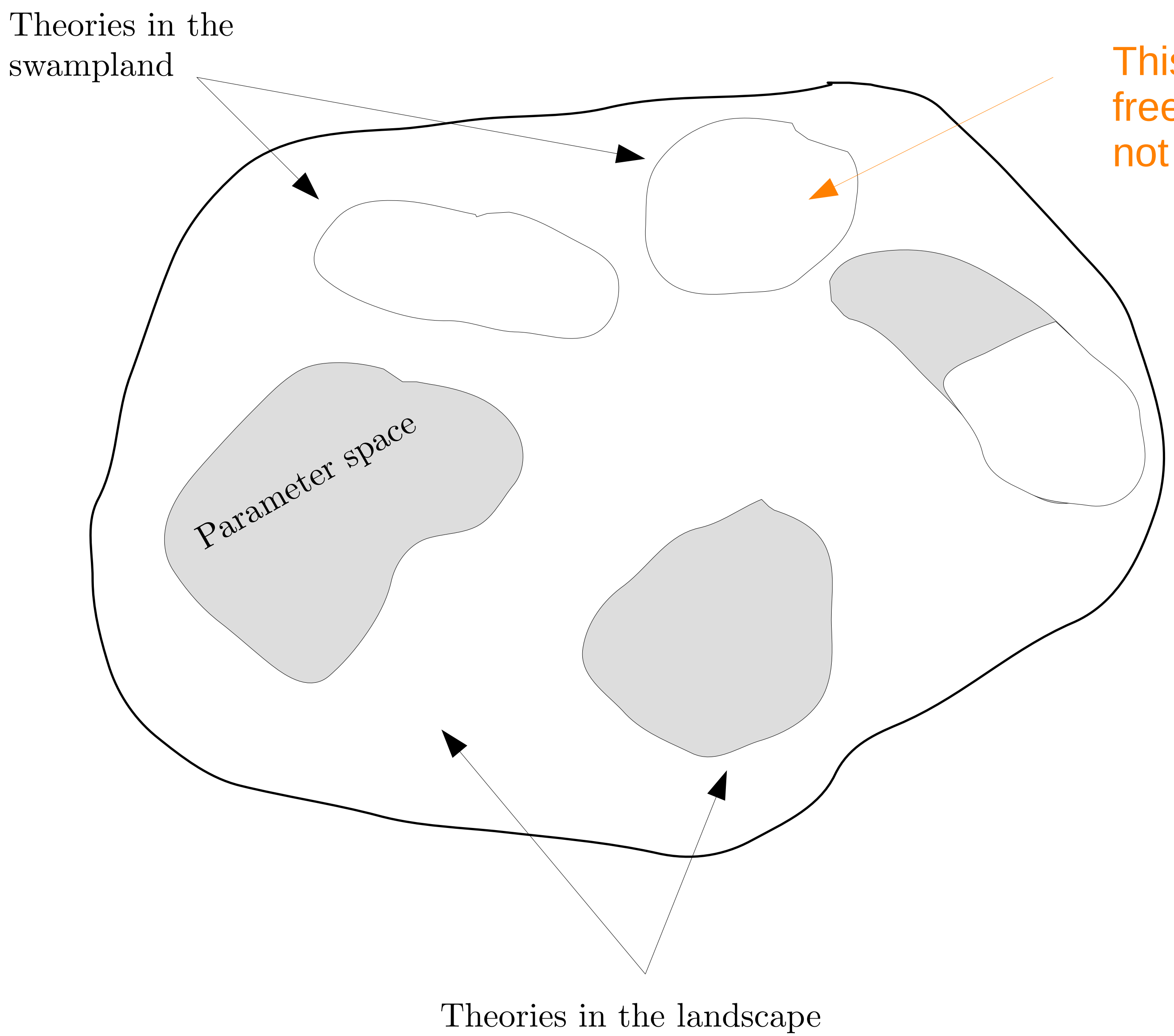


$$\frac{1}{E^2 - m^2} \sim \frac{1}{m^2}$$

The EFT landscape

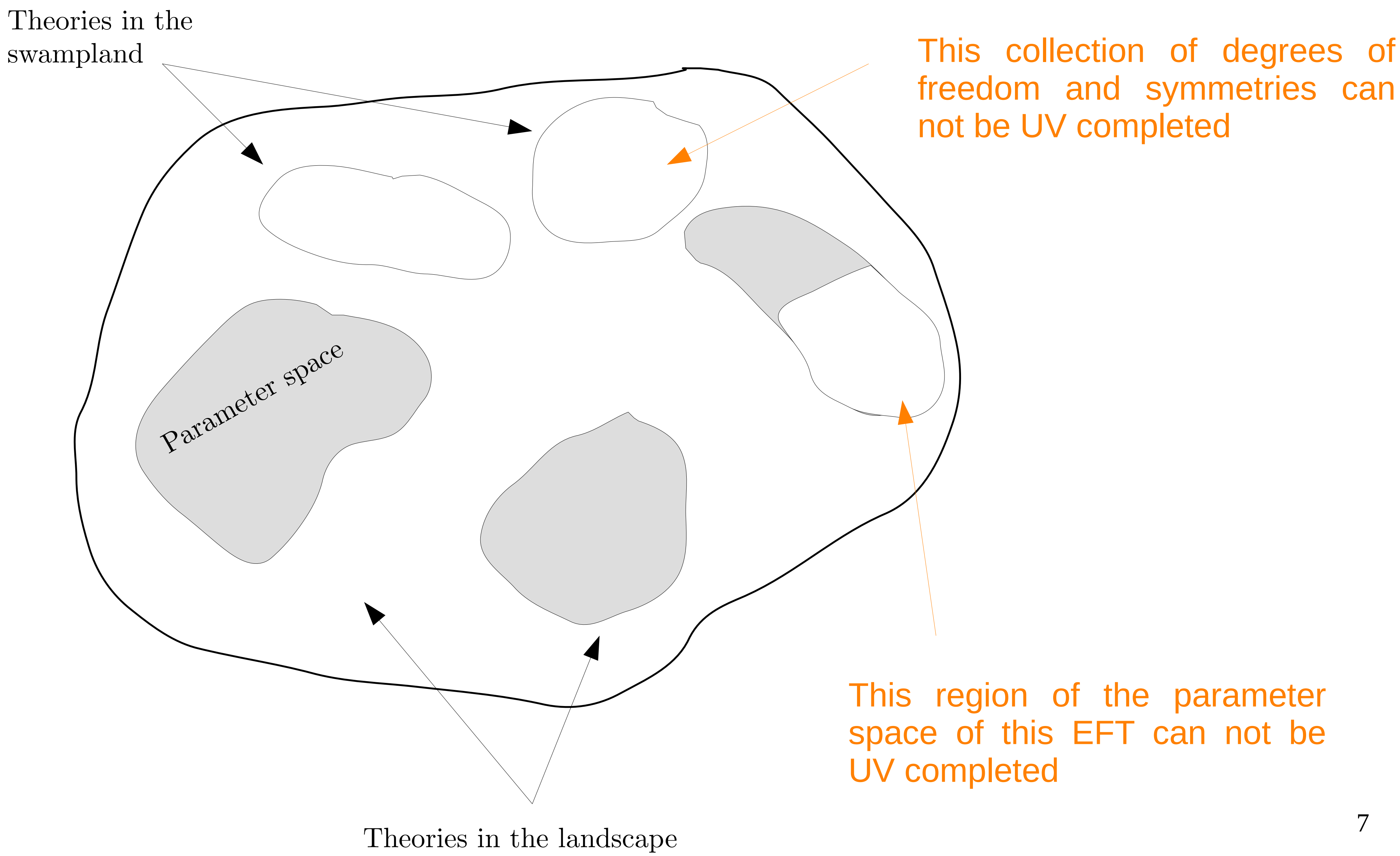


The EFT landscape



This collection of degrees of freedom and symmetries can not be UV completed

The EFT landscape



Examples in CHMs and in the SMEFT

The EFT degrees of freedom in a CHM are (p)NGBs from spontaneous symmetry breaking G→H. They transform in real representations r_H of H

It is impossible to have 8 NGBs transforming in $\mathbf{r}_H=\mathbf{8}$ of H=SO(7)

The EFT degrees of freedom in the SMEFT are the SM particles. The (gauge) symmetries are those of the SM

It is impossible to have $c_{e^4D^2} D_\mu(\bar{e}\gamma^\nu e)D^\mu(\bar{e}\gamma_\nu e)$ with $c_{e^4D^2} \geq 0$

Examples in CHMs and in the SMEFT

There are different ways of unraveling the landscape of EFTs

One is **brute force**: explore all possible UV models (*e.g.* all CHMs with certain maximum number of NGBs) and see how they look in the IR

A different approach is understanding how general properties of the UV (*e.g.* locality and unitarity) manifest in the IR

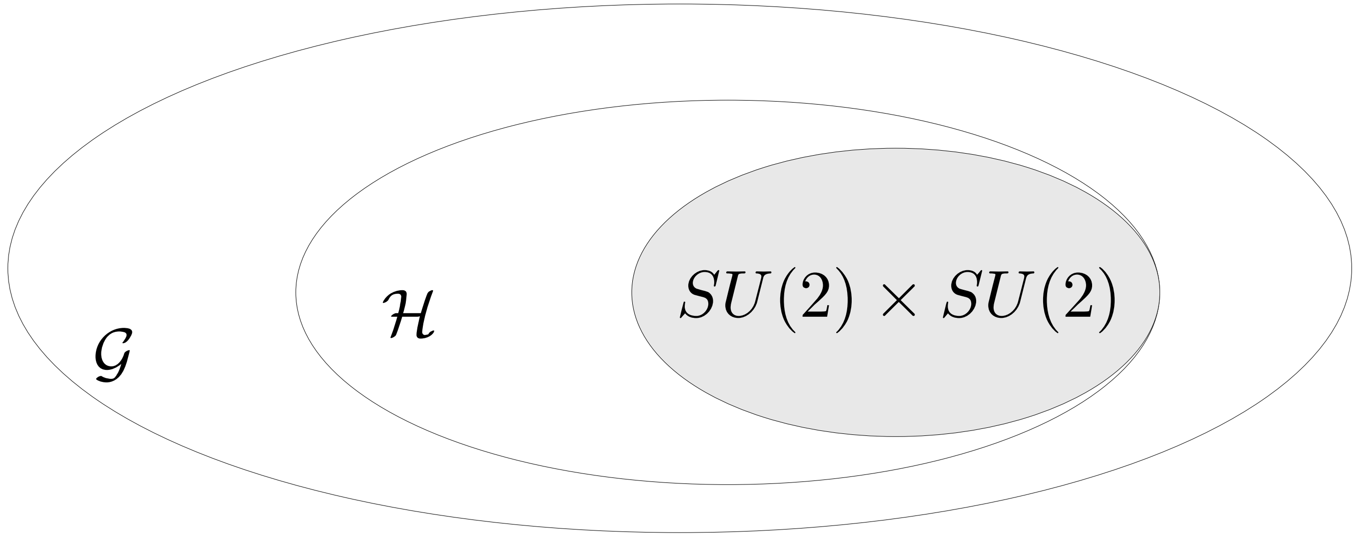
I will mention both, with particular emphasis on the second one

CHMs

Inspired by successful understanding of pion dynamics on the basis of chiral symmetry breaking in **QCD**. The pions are NGBs of

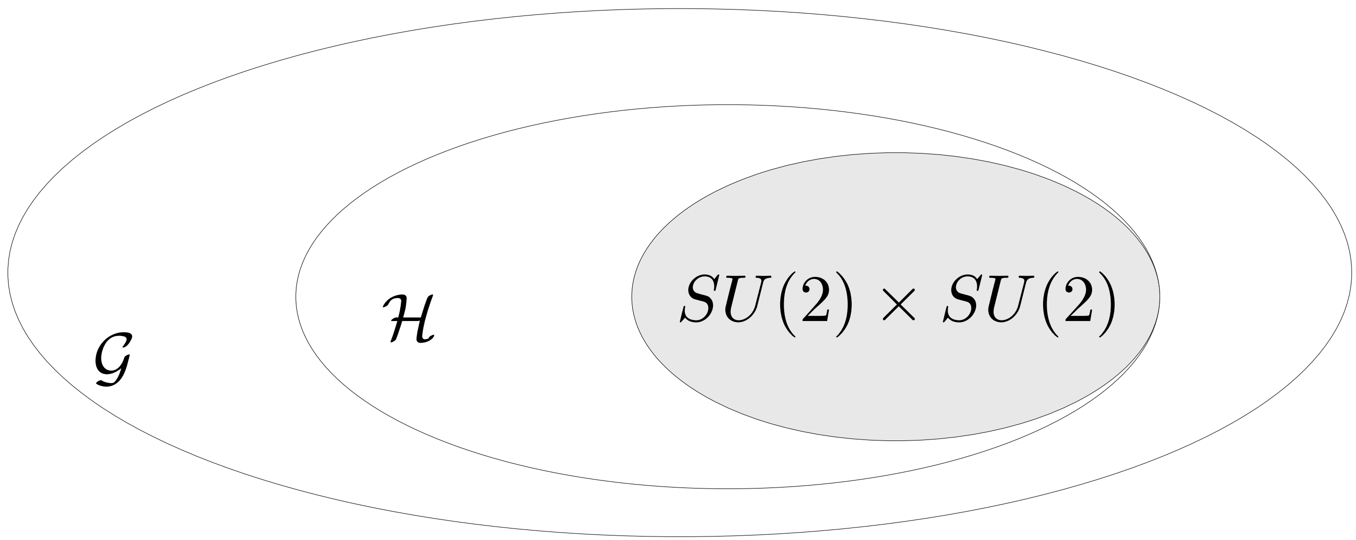
$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R}$$

The four degrees of freedom of the Higgs doublet are assumed to be NGBs of G $\to$ H



CHMs

The four degrees of freedom of the Higgs doublet are assumed to be NGBs of G $\to$ H



We require **no fractional electric charges** among the NGBs

$$\mathrm{Adj}(\mathcal{G}) \to \mathrm{Adj}(\mathcal{H}) + \mathbf{r}_{\mathcal{H}}$$

$$\mathbf{r}_{\mathcal{H}} \to \mathbf{r}_{SU(2)\times SU(2)} = (\mathbf{2},\mathbf{2}) + \cdots \to \mathbf{2}_{\pm\frac{1}{2}} + \cdots$$

Interesting facts about CHMs

The set of all CHMs with m NGBs is finite [non trivial!]

Care must be taken when comparing CHMs. For example, $SU(2)_L x SU(2)_R$ can be broken to SU(2) (left or right) or to $SU(2)_{L+R}$. In the first case, one SU(2) is spectator

$$SU(2)_L \times SU(2)_R \qquad J_{1_L} \; J_{2_L} \; J_{3_L} \qquad J_{1_R} \; J_{2_R} \; J_{3_R}$$

There are many different ways of embedding H into G. For example, p(n)-1 different embeddings of SU(2) into SU(n), where p(1),p(2),...= 1,2,3,5,7, ... $p(n) \sim \exp\sqrt{n}/n$ [Fonseca '15]

Interesting facts about CHMs

Two embeddings of H into G are different if they give rise to different branching rules of all representations (in practice, one only needs to check the fundamental)

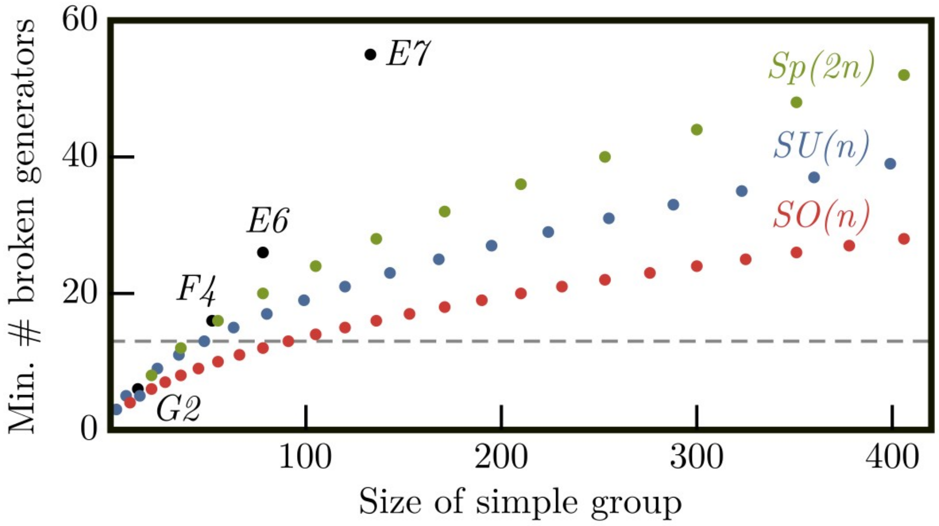
Still, two *a priori* different embeddings could be related by symmetries of G. For example, the embeddings of SU(3) into SU(4) associated to the following branching rules are related

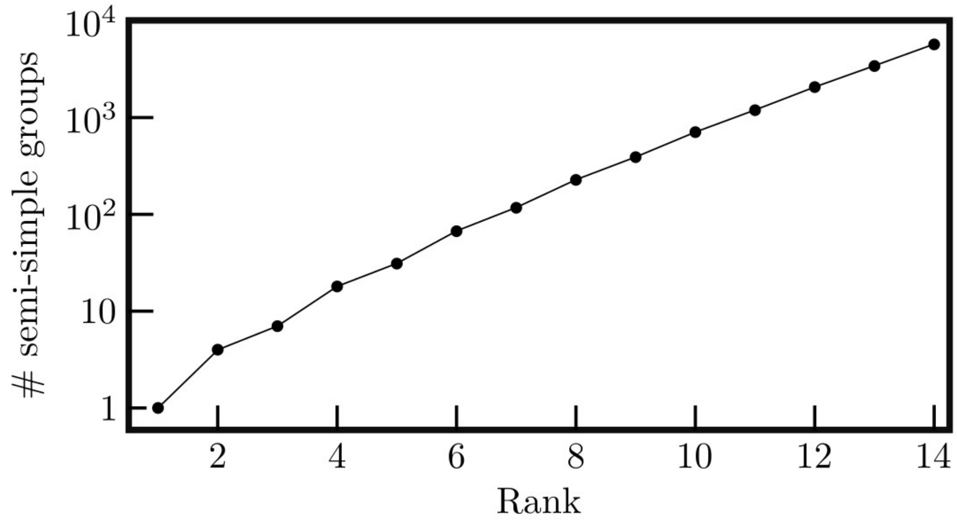
$$\mathbf{4} \to 1 + \mathbf{3} \qquad\qquad \overline{\mathbf{4}} \to 1 + \overline{\mathbf{3}}$$

One needs to take all these caveats into account for obtaining all different CHMs

Interesting facts about CHMs

On top of this, there are **many simple groups** and even more semi-simple ones [use GroupMath; Fonseca '20]





Still, the space of models with at most 13 NGBs can be scanned, and we find **642** of them (if we ignore U(1) factors)

CHMs with at most 8 NGBs

$SU(2)\times SU(2)$ content	$\boldsymbol{r}_{\mathcal{H}}$	$\mathcal{H}$	$\mathcal{G}/\mathcal{H}$
$(\mathbf{2},\mathbf{2})$	$(\mathbf{2},\mathbf{2})$	$SU(2)\times SU(2)$	$SO(5)/SU(2)^2$ [41]
$(\mathbf{2},\mathbf{2})+(1,1)$	$(\mathbf{2},\mathbf{2})+(1,1)$	$SU(2)\times SU(2)$	$SO(5)\times U(1)/SU(2)^2$ [42]
	$\mathbf{5}$	$SO(5)$	$SU(4)/SO(5)$ [38]
$(\mathbf{2},\mathbf{2})+(1,\mathbf{3})$	$(\mathbf{2},\mathbf{2})+(1,\mathbf{3})$	$SU(2)\times SU(2)$	$SU(2)\times SO(5)/SU(2)^2$
	$\mathbf{7}$	G_2	$SO(7)/G_2$ [43]
	$\mathbf{7}$	$SO(7)$	$SO(8)/SO(7)$
	$(1,\mathbf{2},\mathbf{2})+(\mathbf{3},1,1)$	$SU(2)^3$	$SU(2)\times SU(2)\times SO(5)/SU(2)^3$
$2\times(\mathbf{2},\mathbf{2})$	$2\times(\mathbf{2},\mathbf{2})$	$SU(2)\times SU(2)$	$SU(4)/(SU(2)^2\times U(1))$ [39]
	$\mathbf{4}+\bar{\mathbf{4}}$	$SU(4)$	$SU(5)/SU(4)\times U(1)$ [44]
	$\mathbf{8}$	$SO(7)$	–
	$(\mathbf{2},\mathbf{4})$	$SU(2)\times SO(5)$	$Sp(6)/(SU(2)\times SO(5))$ [39]
	$(1,\mathbf{2},\mathbf{2})+(\mathbf{2},1,\mathbf{2})$	$SU(2)^3$	–
	$\mathbf{8}_v$	$SO(8)$	$SO(9)/SO(8)$ [44]
	$(1,\mathbf{2},1,\mathbf{2})+(\mathbf{2},1,\mathbf{2},1)$	$SU(2)^4$	$SO(5)^2/SU(2)^4$
$(\mathbf{2},\mathbf{2})+2\times(1,1)$	$(\mathbf{2},\mathbf{2})+2\times(1,1)$	$SU(2)\times SU(2)$	$SO(5)\times U(1)^2/SU(2)^2$ $SU(2)\times SO(5)/(SU(2)^2\times U(1))$
	$1+\mathbf{5}$	$SO(5)$	$SU(4)\times U(1)/SO(5)$
	$\mathbf{6}$	$SU(4)$	$SO(7)/SU(4)$ [9,12]
$(\mathbf{2},\mathbf{2})+(1,1)+(1,\mathbf{3})$	$1+\mathbf{7}$	G_2	$SO(7)\times U(1)/G_2$
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	$(1,\mathbf{5})+(\mathbf{3},1)$	$SU(2)\times SO(5)$	$SU(2)^2\times SU(4)/(SU(2)\times SO(5))$
	$(1,\mathbf{2},\mathbf{2})+(\mathbf{2},\mathbf{2},1)$	$SU(2)^3$	–
	$(1,1,1)+(1,\mathbf{2},\mathbf{2})+(\mathbf{3},1,1)$	$SU(2)^3$	$SU(2)^2\times SO(5)\times U(1)/SU(2)^3$
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	$(1,1,\mathbf{2},\mathbf{2})+(\mathbf{2},\mathbf{2},1,1)$	$SU(2)^4$	$SO(5)^2/SU(2)^4$
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CHMs with at most 8 NGBs

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	$(1,\mathbf{2},\mathbf{2})+(\mathbf{2},\mathbf{2},1)$	$SU(2)^3$	–
	$(1,1,1)+(1,\mathbf{2},\mathbf{2})+(\mathbf{3},1,1)$	$SU(2)^3$	$SU(2)^2\times SO(5)\times U(1)/SU(2)^3$
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	$2\times 1+\mathbf{5}$	$SO(5)$	$SU(4)\times U(1)^2/SO(5)$ $SU(2)\times SU(4)/(SO(5)\times U(1))$
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	$(1,\mathbf{2},\mathbf{2})+(\mathbf{3},1,1)$	$SU(2)^3$	$SU(2)^2\times SO(5)/SU(2)^3$

Some (brute-force) findings and their explanation

For any (custodial) SM scalar content, there is a CHM; e.g. a Higgs doublet plus a singlet and a triplet [SO(7)/G_2, SO(14)/SO(13), ...]. Easy to understand on the basis of SO(m+1)/SO(m) only

The symmetries in the IR can not be arbitrary, *e.g.*; there is no (composite) 2HDM with symmetry given by 8 of SO(7) (see previous table)

Either 8 NGBs transform in the 8 of SO(8), like in SO(9)/SO(8), or the IR symmetry is smaller

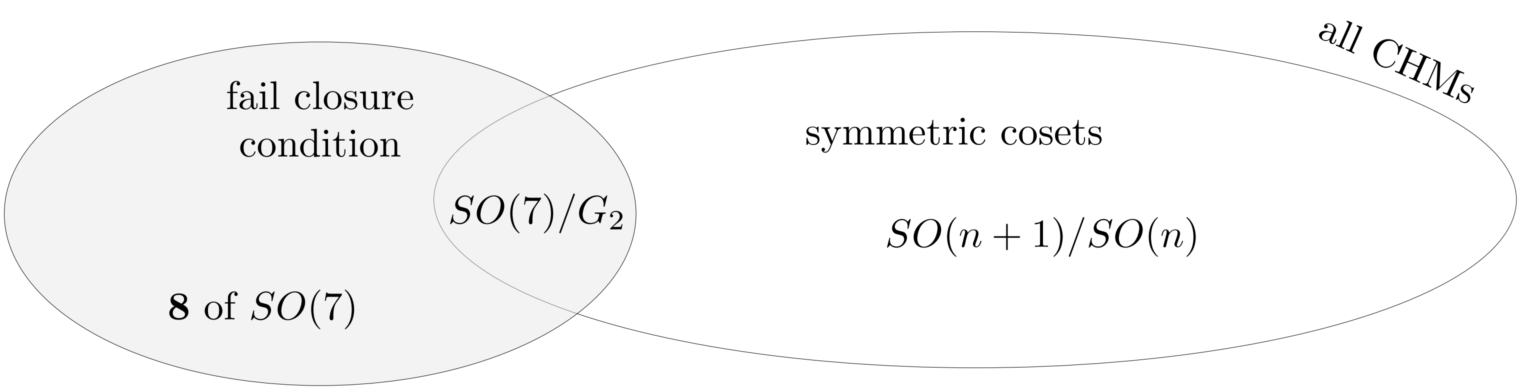
How to understand this from IR information only?

Closure condition

Given a (real) representation R, when can we be sure that there is a CHM such that r_H=R? [see also Low '14'18]

Let T_R be the matrices of the representation R. If the following condition is hold, then there is at least one CHM satisfying r_H=R:

$$\left(T_R^{\widetilde{i}}\right)_{\hat{a}\hat{b}}\left(T_R^{\widetilde{i}}\right)_{\hat{c}\hat{d}}+\left(T_R^{\widetilde{i}}\right)_{\hat{a}\hat{c}}\left(T_R^{\widetilde{i}}\right)_{\hat{d}\hat{b}}+\left(T_R^{\widetilde{i}}\right)_{\hat{a}\hat{d}}\left(T_R^{\widetilde{i}}\right)_{\hat{b}\hat{c}}=0$$



Closure condition

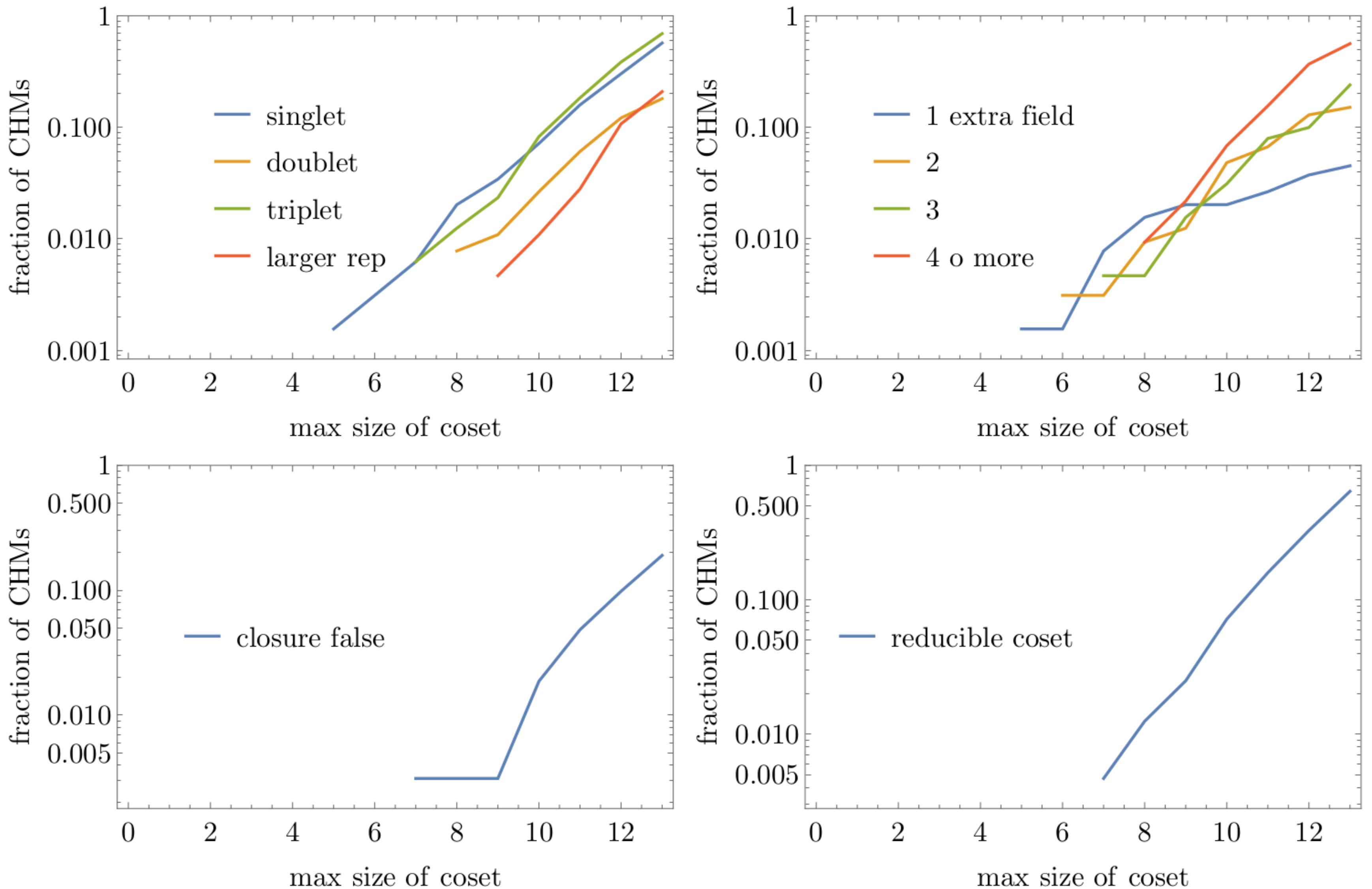
When certain IR scenario fulfills the closure condition, the dynamics of the NGBs can be described using IR information only (no need to know G!)

$$L = \frac{1}{4} f^2 d_\mu^{\hat{a}}\, d^{\mu,\hat{a}}$$

$$d_\mu^{\hat{a}} = \left[\mathcal{F}^{-1} \sin\left(\frac{\mathcal{F}}{f}\right)\right]_{\hat{a}\hat{b}} (\partial_\mu \Pi)_{\hat{b}}$$

It depends on T_R only!

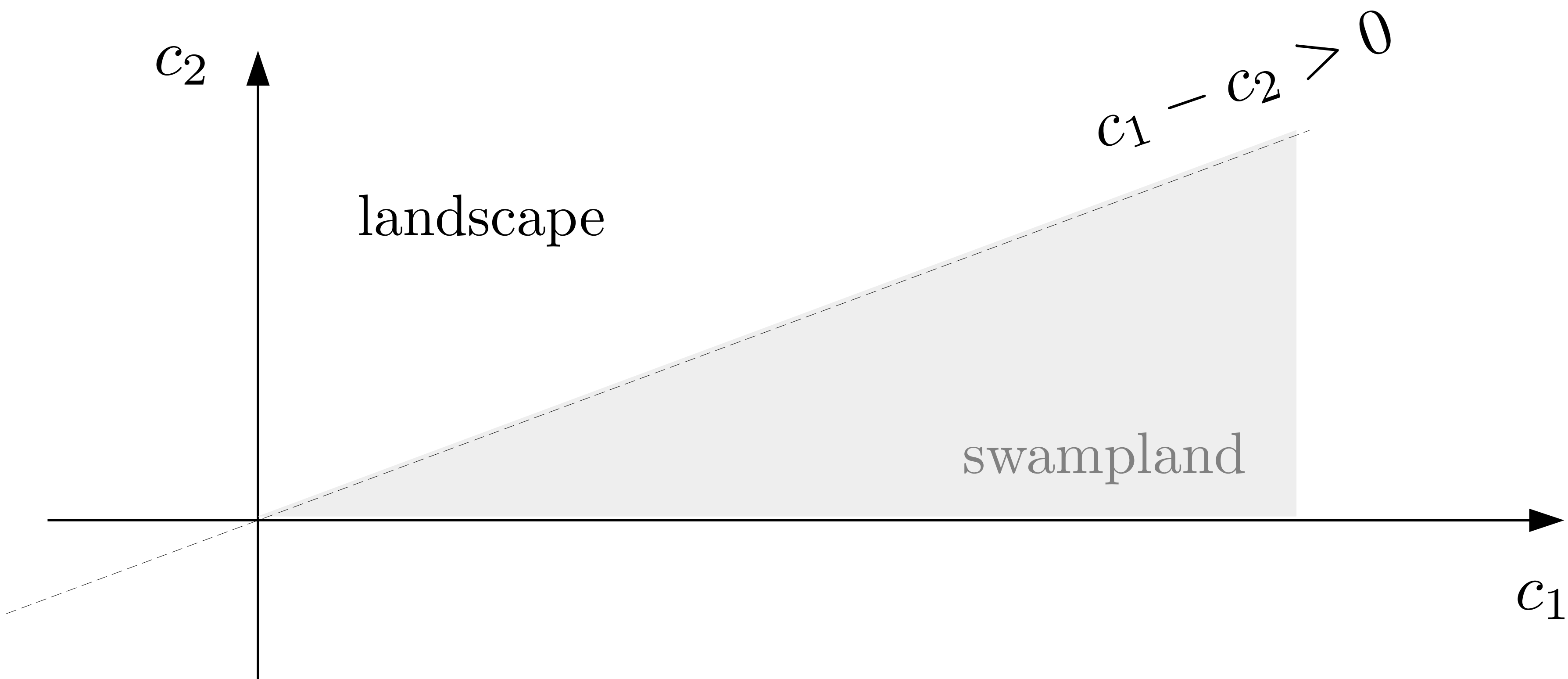
Other aspects of the landscape of CHMs



IR-UV connection in the SMEFT

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)}$$

$$+ \text{ corrections of higher order in } E/\Lambda$$



Brute-force exploration

The set of all UV completions of the SMEFT is infinite. However, if we restrict to those that contribute to the SMEFT at dimension-six at tree level, then it is finite [Blas et al ‘14]

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	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{1}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

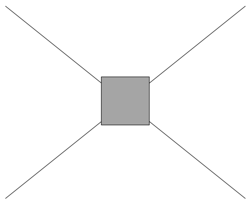
Name	$\mathcal{S}$	$\mathcal{S}_1$	$\mathcal{S}_2$	φ	Ξ	Ξ_1	Θ_1	Θ_3
Irrep	$(1,1)_0$	$(1,1)_1$	$(1,1)_2$	$(1,2)_{\frac{1}{2}}$	$(1,3)_0$	$(1,3)_1$	$(1,4)_{\frac{1}{2}}$	$(1,4)_{\frac{3}{2}}$
Name	ω_1	ω_2	ω_4	Π_1	Π_7	ζ		
Irrep	$(3,1)_{-\frac{1}{3}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{-\frac{4}{3}}$	$(3,2)_{\frac{1}{6}}$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

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	$(1,2)_{-\frac{3}{2}}$	$(3,1)_{\frac{2}{3}}$	$(3,1)_{\frac{5}{3}}$	$(3,2)_{\frac{1}{6}}$	$(3,2)_{-\frac{5}{6}}$	$(3,3)_{\frac{2}{3}}$	$(\bar{6},2)_{\frac{1}{6}}$	$(\bar{6},2)_{-\frac{5}{6}}$

Brute-force exploration

The SMEFT parameter space that results from integrating out the most general Lagrangian involving those fields has been worked out in a series of works [Aguila, Blas, MC, Criado Perez-Victoria, Santiago '01-'14], *e.g.*:

$$(C_{ee})_{ijkl} = \frac{(y_{\mathcal{S}_2})_{rki}(y_{\mathcal{S}_2})^*_{rlj}}{2M^2_{\mathcal{S}_{2r}}} - \frac{(g^e_{\mathcal{B}})_{rkl}(g^e_{\mathcal{B}})_{rij}}{2M^2_{\mathcal{B}_r}}$$

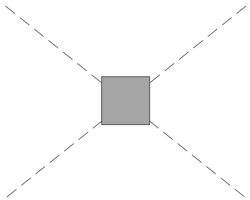


$$(C_{ll})_{ijkl} = \frac{(y_{\mathcal{S}_1})^*_{rjl}(y_{\mathcal{S}_1})_{rik}}{M^2_{\mathcal{S}_{1r}}} + \frac{(y_{\Xi_1})_{rki}(y_{\Xi_1})^*_{rlj}}{M^2_{\Xi_{1r}}} - \frac{(g^l_{\mathcal{B}})_{rkl}(g^l_{\mathcal{B}})_{rij}}{2M^2_{\mathcal{B}_r}} - \frac{(g^l_{\mathcal{W}})_{rkj}(g^l_{\mathcal{W}})_{ril}}{4M^2_{\mathcal{W}_r}} + \frac{(g^l_{\mathcal{W}})_{rkl}(g^l_{\mathcal{W}})_{rij}}{8M^2_{\mathcal{W}_r}},$$

Brute-force exploration

In general, no clear constraints on Wilson coefficients of dimension-six operators (unless the UV consists of only scalars, for example)

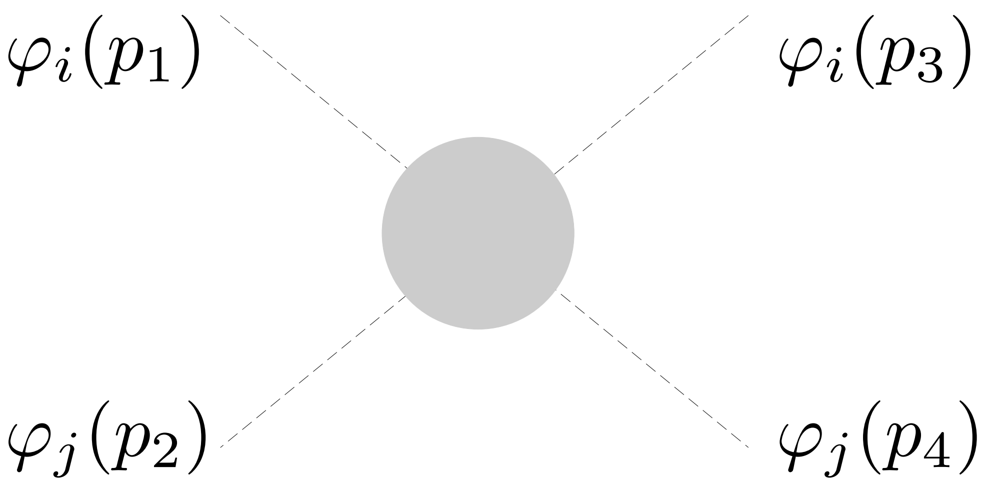
Things are very different at dimension eight:



$$\mathcal{S} \sim (1,1)_0 \longmapsto c^{(1,2,3)}_{H^4D^4} \sim (0,0,1)\,,$$
$$\Xi \sim (1,3)_0 \longmapsto c^{(1,2,3)}_{H^4D^4} \sim (2,0,-1)\,,$$
$$\mathcal{B} \sim (1,1)_0 \longmapsto c^{(1,2,3)}_{H^4D^4} \sim (-1,1,0)\,,$$
$$\mathcal{B}_1 \sim (1,1)_1 \longmapsto c^{(1,2,3)}_{H^4D^4} \sim (1,0,-1)\,,$$
$$\mathcal{W} \sim (1,3)_0 \longmapsto c^{(1,2,3)}_{H^4D^4} \sim (1,1,-2)\,.$$

$$c_2 \geq 0$$
$$c_1 + c_2 \geq 0$$
$$c_1 + c_2 + c_3 \geq 0$$

Positivity bounds



$$s = (p_1 + p_2)^2$$

$$t = (p_1 + p_3)^2$$

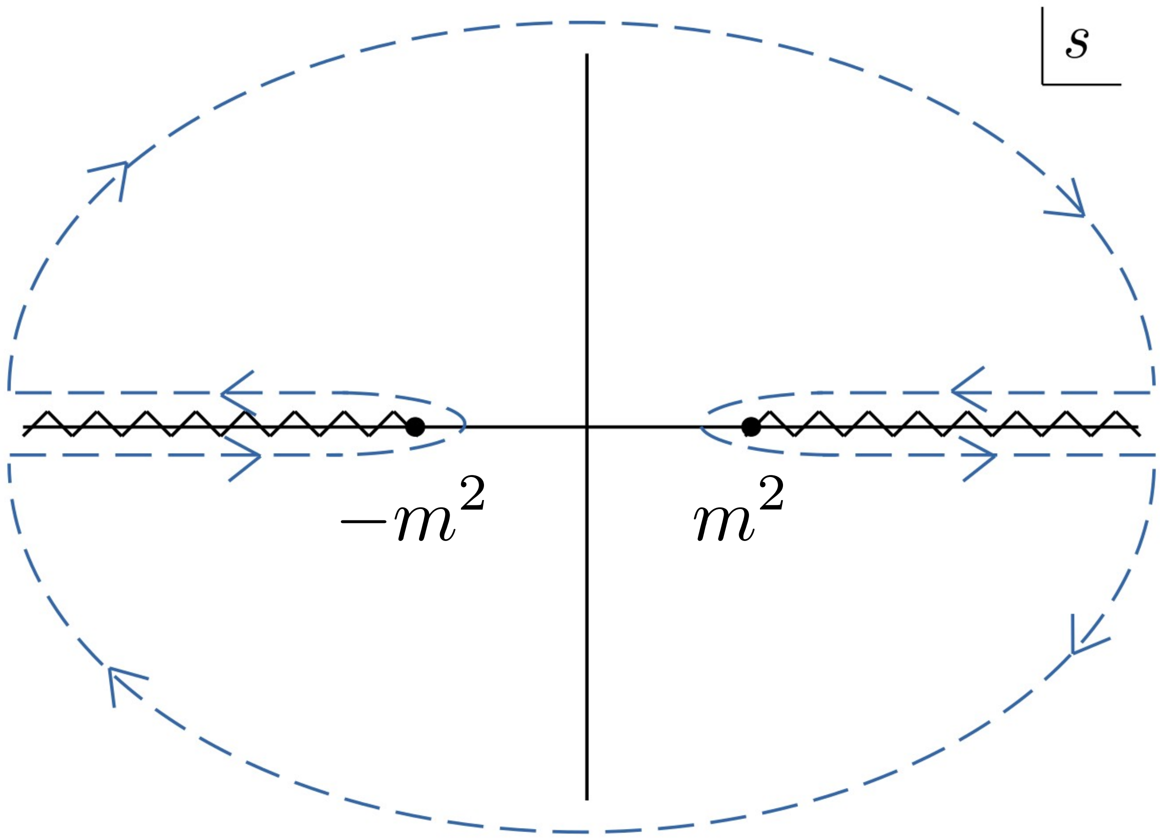
$$u = (p_2 + p_3)^2$$

$$s + t + u = 0$$

$$\mathcal{A}(s) = \mathcal{A}(-s)$$

$$\mathcal{A}(s) = a_0 + a_1 s + a_2 s^2 + \cdots$$

$$\frac{\mathcal{A}(s)}{s^3} \to 0$$

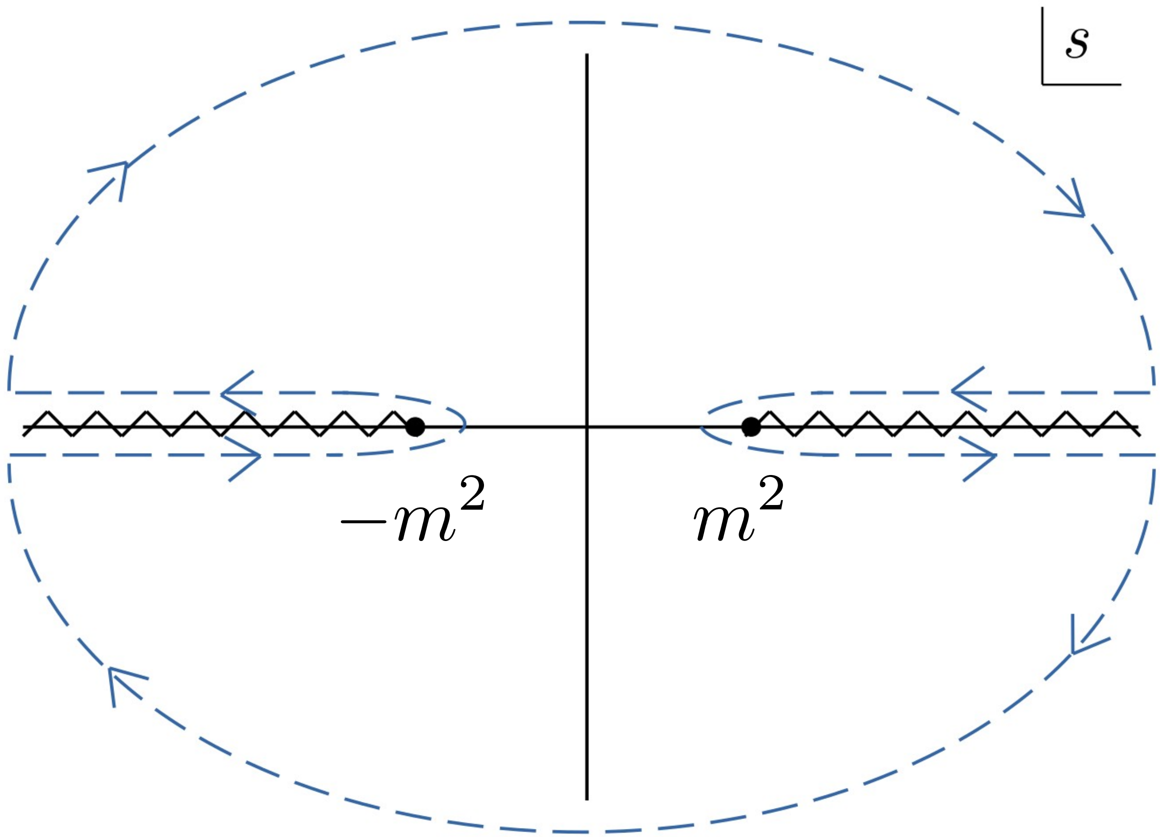


$$\int \frac{\mathcal{A}(s)}{s^3} = 2\int_{m^2}^{\infty} \frac{1}{s^3} \lim_{\epsilon\to 0}[\mathcal{A}(s+i\epsilon) - \mathcal{A}(s-i\epsilon)]$$

$$= 2\int_{m^2}^{\infty} \frac{1}{s^3} \lim_{\epsilon\to 0}[\mathcal{A}(s+i\epsilon) - \mathcal{A}(s+i\epsilon)^*] = 2i\int_{m^2}^{\infty} \frac{\sigma(s)}{s^2}$$

Adams et al '06

$$\frac{\mathcal{A}(s)}{s^3} \to 0$$



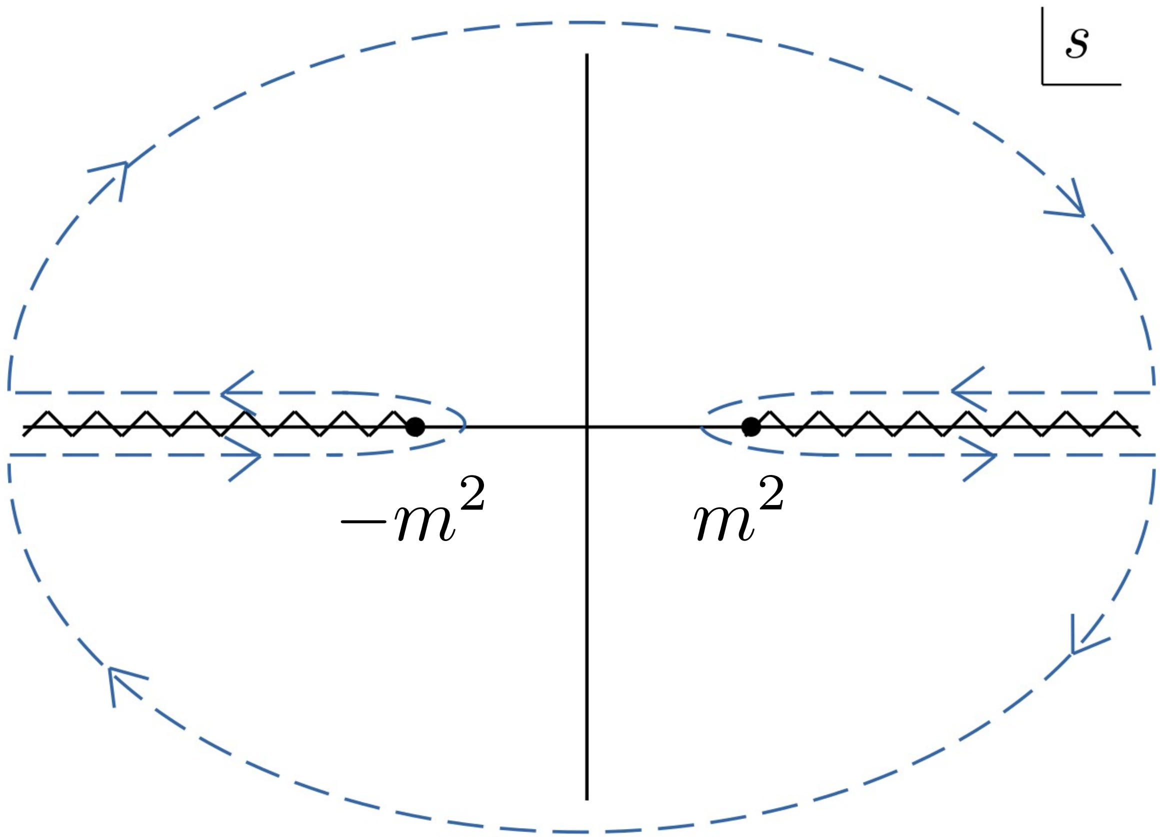
$$2i \int_{m^2}^{\infty} \frac{\sigma(s)}{s^2} = 2\pi i \, \mathrm{Res}[\frac{\mathcal{A}(s)}{s^3}, s = 0] = 2\pi i a_2$$

$$\mathcal{A}(s) = a_0 + a_2 s^2 + \cdots$$

$$\Rightarrow a_2 \geq 0$$

Adams et al '06

$$\frac{\mathcal{A}(s)}{s^3} \to 0$$



Murphy '20

$\mathcal{O}^{(1)}_{H^4D^4}$	$(D_\mu H^\dagger D_\nu H)(D^\nu H^\dagger D^\mu H)$
$\mathcal{O}^{(2)}_{H^4D^4}$	$(D_\mu H^\dagger D_\nu H)(D^\mu H^\dagger D^\nu H)$
$\mathcal{O}^{(3)}_{H^4D^4}$	$(D_\mu H^\dagger D^\mu H)(D^\nu H^\dagger D_\nu H)$

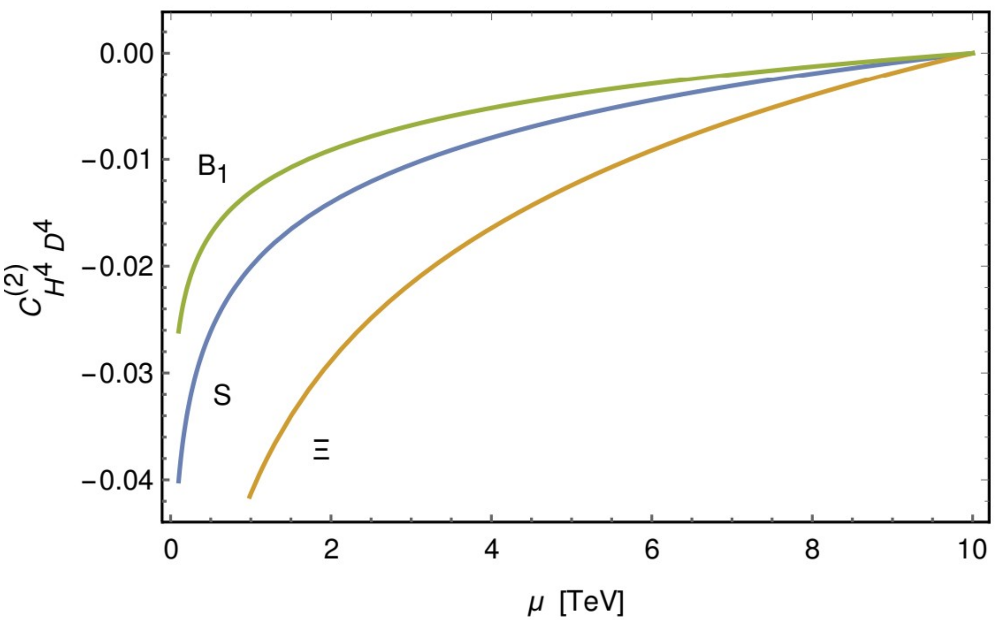
$$\varphi_1\varphi_2 \to \varphi_1\varphi_2 \Rightarrow c^{(2)}_{H^4D^4} \geq 0$$

$$\varphi_1\varphi_3 \to \varphi_1\varphi_3 \Rightarrow c^{(1)}_{H^4D^4} + c^{(2)}_{H^4D^4} \geq 0$$

$$\varphi_1\varphi_1 \to \varphi_1\varphi_1 \Rightarrow c^{(1)}_{H^4D^4} + c^{(2)}_{H^4D^4} + c^{(3)}_{H^4D^4} \geq 0$$

Positivity bounds and running

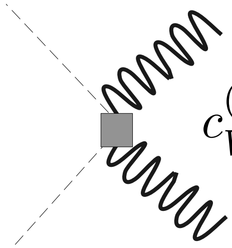
Positivity bounds are not necessarily stable under running



But some are, *e.g.*:

$$\dot{c}^{(1)}_{W^2\phi^2D^2} = +\frac{1}{6}g_2^2\underbrace{(2c^{(1)}_{\phi^4} + 3c^{(2)}_{\phi^4} + c^{(3)}_{\phi^4})}$$

$$\underset{0\leq}{c^{(2)}_{\phi^4}} + \underset{0\leq}{[c^{(1)}_{\phi^4} + c^{(2)}_{\phi^4}]} + \underset{0\leq}{[c^{(1)}_{\phi^4} + c^{(2)}_{\phi^4} + c^{(3)}_{\phi^4}]}$$



$$c^{(1)}_{W^2\phi^2D^2} < 0$$

Positivity bounds and running

Simple rules indicating when positivity bounds are respected by (one-loop) running derived in [MC '23]

This opens the door to constraining the anomalous dimensions of dimension-8 operators themselves, and to **unravel new zeroes**

The logic is schematically as follows. Assume positivity of c_i ($c_i > 0$) is respected in mixing from c_j:

$$\dot{c}_i = \gamma_{ij} c_j$$

$$\dot{c}_i \leq 0$$

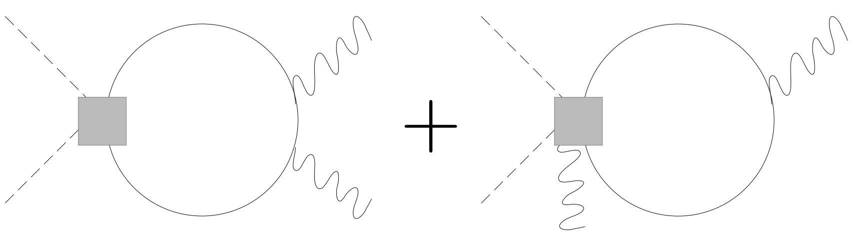
$$\Rightarrow \begin{cases} \gamma_{ij} \leq 0 \ \text{ if } \ c_j \geq 0 \\ \gamma_{ij} = 0 \ \text{ if } \ c_j \ \text{unconstrained} \end{cases}$$

Examples

$$\mathcal{O}^{(1)}_{e^2\phi^2D^3} = i(\bar{e}\gamma^\mu D^\nu e)(D_{(\mu}D_{\nu)}\phi^\dagger\phi) + \text{h.c.}$$

$$\mathcal{O}^{(1)}_{B^2\phi^2D^2} = (D^\mu\phi^\dagger D^\nu\phi)B_{\mu\rho}B^\rho_\nu$$

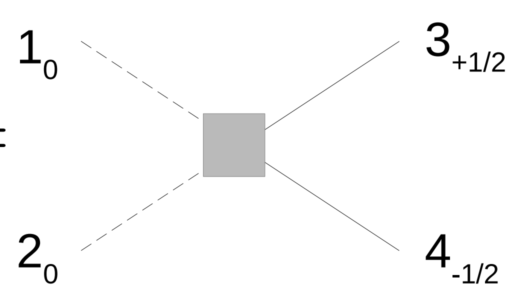
$$\mathcal{O}^{(2)}_{e^2\phi^2D^3} = i(\bar{e}\gamma^\mu D^\nu e)(\phi^\dagger D_{(\mu}D_{\nu)}\phi) + \text{h.c.}$$



$$c^{(1)}_{B^2\phi^2D^2} \leq 0$$

$$+\cdots$$

$$\underbrace{\mathcal{O}^{(1)}_{e^2\phi^2D^3} - \mathcal{O}^{(2)}_{e^2\phi^2D^3}}_{\widetilde{\mathcal{O}}^{(1)}_{e^2\phi^2D^3}} =$$



$$= \langle 43\rangle\langle 41\rangle[43][31]$$

Examples

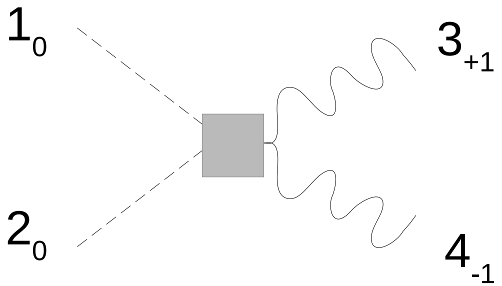
$$\mathcal{O}^{(1)}_{e^2\phi^2D^3} = i(\bar{e}\gamma^\mu D^\nu e)(D_{(\mu}D_{\nu)}\phi^\dagger\phi) + \text{h.c.}$$

$$\mathcal{O}^{(1)}_{B^2\phi^2D^2} = (D^\mu\phi^\dagger D^\nu\phi)B_{\mu\rho}B^\rho_\nu$$

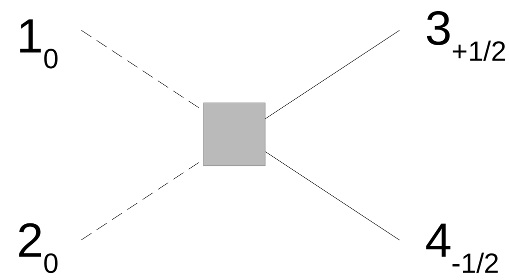
$$\mathcal{O}^{(2)}_{e^2\phi^2D^3} = i(\bar{e}\gamma^\mu D^\nu e)(\phi^\dagger D_{(\mu}D_{\nu)}\phi) + \text{h.c.}$$

$$\dot{c}^{(1)}_{B^2\phi^2D^2} = \#_1\tilde{c}^{(1)}_{e^2\phi^2D^3} + \cdots \Rightarrow \#_1 = 0$$

And this is hard to see even using amplitude methods

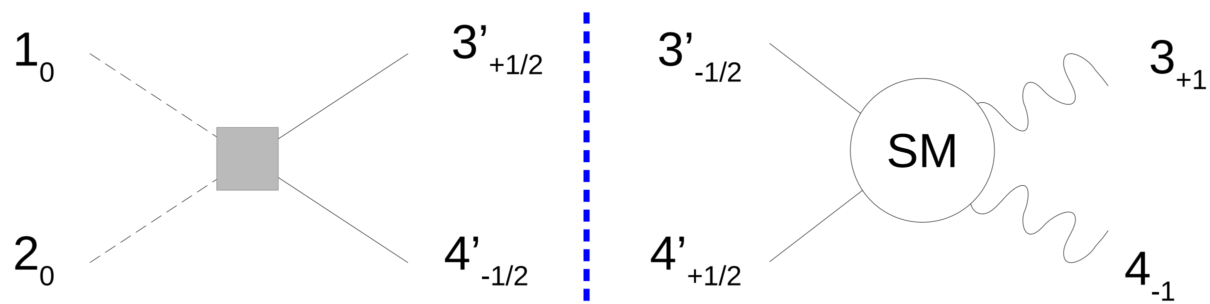


$$= \langle 41\rangle^2[31]^2$$



$$= \langle 43\rangle\langle 41\rangle[43][31]$$

$$\gamma_{\tilde{c}^{(1)}_{e^2\phi^2D^3} \to c^{(1)}_{B^2\phi^2D^2}} \propto$$



$$= \int d\text{LIPS}\langle 4'3'\rangle\langle 4'1\rangle[4'3'][3'1]\frac{\langle 3'4\rangle^2}{\langle 3'3\rangle\langle 34'\rangle}$$

$$= \int_0^{2\pi} d\phi \int_0^{\pi/2} d\theta s_\theta c_\theta \left[\#_1 e^{i\phi} + \cancelto{0}{\#_2 e^{2i\phi}} + \cdots\right]$$

Full electroweak SMEFT (with no flavour)

	$c^{(1)}_{\phi^4 D^4}$	$c^{(2)}_{\phi^4 D^4}$	$c^{(3)}_{\phi^4 D^4}$	$\tilde{c}^{(1)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(1)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(3)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	$c_{e^4 D^2}$	$c^{(1)}_{l^4 D^2}$	$c^{(2)}_{l^4 D^2}$	$c^{(1)}_{l^2 e^2 D^2}$	$c^{(2)}_{l^2 e^2 D^2}$
$c^{(1)}_{B^2\phi^2 D^2}$	+	+	+	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$c^{(1)}_{W^2\phi^2 D^2}$	+	+	+	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	+	+	+	×	×	$\boxed{0}$	−	$\boxed{0}$	−	−	0	0	$\boxed{0}$	−
$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$c_{e^2 B^2 D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	−	0	0	$\boxed{0}$	−
$c_{l^2 B^2 D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	$\boxed{0}$	−
$c_{e^2 W^2 D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	0	0	0	$\boxed{0}$	−
$c^{(1)}_{l^2 W^2 D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	0	0
$c^{(2)}_{l^2 e^2 D^2}$	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	−	−	−	×	×

Full electroweak SMEFT (with no flavour)

	$c^{(1)}_{\phi^4D^4}$	$c^{(2)}_{\phi^4D^4}$	$c^{(3)}_{\phi^4D^4}$	$\tilde{c}^{(1)}_{e^2\phi^2D^3}$	$\tilde{c}^{(2)}_{e^2\phi^2D^3}$	$\tilde{c}^{(1)}_{l^2\phi^2D^3}$	$\tilde{c}^{(2)}_{l^2\phi^2D^3}$	$\tilde{c}^{(3)}_{l^2\phi^2D^3}$	$\tilde{c}^{(4)}_{l^2\phi^2D^3}$	$c_{e^4D^2}$	$c^{(1)}_{l^4D^2}$	$c^{(2)}_{l^4D^2}$	$c^{(1)}_{l^2e^2D^2}$	$c^{(2)}_{l^2e^2D^2}$
$c^{(1)}_{B^2\phi^2D^2}$	$\frac{g^2}{3}$	$\frac{g^2}{2}$	$\frac{g^2}{6}$	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$c^{(1)}_{W^2\phi^2D^2}$	+	+	+	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$\tilde{c}^{(2)}_{e^2\phi^2D^3}$	+	+	+	×	×	$\boxed{0}$	−	$\boxed{0}$	−	−	0	0	$\boxed{0}$	−
$\tilde{c}^{(2)}_{l^2\phi^2D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$\tilde{c}^{(4)}_{l^2\phi^2D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$c_{e^2B^2D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	−	0	0	$\boxed{0}$	−
$c_{l^2B^2D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	$\boxed{0}$	−
$c_{e^2W^2D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	0	0	0	$\boxed{0}$	−
$c^{(1)}_{l^2W^2D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	0	0
$c^{(2)}_{l^2e^2D^2}$	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	−	−	−	×	×

Full electroweak SMEFT (with no flavour)

	$c^{(1)}_{\phi^4 D^4}$	$c^{(2)}_{\phi^4 D^4}$	$c^{(3)}_{\phi^4 D^4}$	$\tilde{c}^{(1)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(1)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(3)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	$c_{e^4 D^2}$	$c^{(1)}_{l^4 D^2}$	$c^{(2)}_{l^4 D^2}$	$c^{(1)}_{l^2 e^2 D^2}$	$c^{(2)}_{l^2 e^2 D^2}$
$c^{(1)}_{B^2\phi^2 D^2}$	$\frac{g^2}{3}$	$\frac{g^2}{2}$	$\frac{g^2}{6}$	$\boxed{0}$	$-$	$\boxed{0}$	$-$	$\boxed{0}$	$-$	0	0	0	0	0
$c^{(1)}_{W^2\phi^2 D^2}$	$+$	$+$	$+$	0	0	$\boxed{0}$	$-$	$\boxed{0}$	$-$	0	0	0	0	0
$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	$+$	$+$	$+$	$\times$	$\times$	$\boxed{0}$	$-\frac{4\lvert Y\rvert^2}{3}$	$\boxed{0}$	$-$	$-$	0	0	$\boxed{0}$	$-$
$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	$+$	$+$	$+$	$\boxed{0}$	$-$	$\times$	$\times$	$\times$	$\times$	0	$-$	$-$	$\boxed{0}$	$-$
$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	$+$	$+$	$+$	$\boxed{0}$	$-$	$\times$	$\times$	$\times$	$\times$	0	$-$	$-$	$\boxed{0}$	$-$
$c_{e^2 B^2 D}$	0	0	0	$\boxed{0}$	$-$	0	0	0	0	$-$	0	0	$\boxed{0}$	$-$
$c_{l^2 B^2 D}$	0	0	0	0	0	$\boxed{0}$	$-$	$\boxed{0}$	$-$	0	$-$	$-$	$\boxed{0}$	$-$
$c_{e^2 W^2 D}$	0	0	0	$\boxed{0}$	$-$	0	0	0	0	0	0	0	$\boxed{0}$	$-$
$c^{(1)}_{l^2 W^2 D}$	0	0	0	0	0	$\boxed{0}$	$-$	$\boxed{0}$	$-$	0	$-$	$-$	0	0
$c^{(2)}_{l^2 e^2 D^2}$	0	0	0	$\boxed{0}$	$-$	$\boxed{0}$	$-$	$\boxed{0}$	$-$	$-$	$-$	$-$	$\times$	$\times$

Full electroweak SMEFT (with no flavour)

	$c^{(1)}_{\phi^4 D^4}$	$c^{(2)}_{\phi^4 D^4}$	$c^{(3)}_{\phi^4 D^4}$	$\tilde{c}^{(1)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	$\tilde{c}^{(1)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(3)}_{l^2\phi^2 D^3}$	$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	$c_{e^4 D^2}$	$c^{(1)}_{l^4 D^2}$	$c^{(2)}_{l^4 D^2}$	$c^{(1)}_{l^2 e^2 D^2}$	$c^{(2)}_{l^2 e^2 D^2}$
$c^{(1)}_{B^2\phi^2 D^2}$	$\frac{g^2}{3}$	$\frac{g^2}{2}$	$\frac{g^2}{6}$	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$c^{(1)}_{W^2\phi^2 D^2}$	+	+	+	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	0	0	0	0
$\tilde{c}^{(2)}_{e^2\phi^2 D^3}$	+	+	+	$g^2 - \lvert Y\rvert^2$	×	$\boxed{0}$	$-\frac{4\lvert Y\rvert^2}{3}$	$\boxed{0}$	−	−	0	0	$\boxed{0}$	−
$\tilde{c}^{(2)}_{l^2\phi^2 D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$\tilde{c}^{(4)}_{l^2\phi^2 D^3}$	+	+	+	$\boxed{0}$	−	×	×	×	×	0	−	−	$\boxed{0}$	−
$c_{e^2 B^2 D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	−	0	0	$\boxed{0}$	−
$c_{l^2 B^2 D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	$\boxed{0}$	−
$c_{e^2 W^2 D}$	0	0	0	$\boxed{0}$	−	0	0	0	0	0	0	0	$\boxed{0}$	−
$c^{(1)}_{l^2 W^2 D}$	0	0	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	0	−	−	0	0
$c^{(2)}_{l^2 e^2 D^2}$	0	0	0	$\boxed{0}$	−	$\boxed{0}$	−	$\boxed{0}$	−	−	−	−	×	×

Extension to full SMEFT [MC, Li '23]
(there are three more tables)

	$\tilde{c}^{(1)}_{l^2\phi^2D^3}$	$\tilde{c}^{(2)}_{l^2\phi^2D^3}$	$\tilde{c}^{(3)}_{l^2\phi^2D^3}$	$\tilde{c}^{(4)}_{l^2\phi^2D^3}$	$\tilde{c}^{(1)}_{e^2\phi^2D^3}$	$\tilde{c}^{(2)}_{e^2\phi^2D^3}$	$\tilde{c}^{(1)}_{q^2\phi^2D^3}$	$\tilde{c}^{(2)}_{q^2\phi^2D^3}$	$\tilde{c}^{(3)}_{q^2\phi^2D^3}$	$\tilde{c}^{(4)}_{q^2\phi^2D^3}$	$\tilde{c}^{(1)}_{u^2\phi^2D^3}$	$\tilde{c}^{(2)}_{u^2\phi^2D^3}$	$\tilde{c}^{(1)}_{d^2\phi^2D^3}$	$\tilde{c}^{(2)}_{d^2\phi^2D^3}$
$\tilde{c}^{(1)}_{l^4D^2}$	×	×	×	×	0	0	0	0	0	0	0	0	0	0
$\tilde{c}^{(2)}_{l^4D^2}$	×	×	×	×	0	0	0	0	0	0	0	0	0	0
$\tilde{c}^{(1)}_{q^4D^2}$	0	0	0	0	0	0	×	×	×	×	0	0	0	0
$\tilde{c}^{(2)}_{q^4D^2}$	0	0	0	0	0	0	×	×	×	×	0	0	0	0
$\tilde{c}^{(3)}_{q^4D^2}$	0	0	0	0	0	0	×	×	×	×	0	0	0	0
$\tilde{c}^{(4)}_{q^4D^2}$	0	0	0	0	0	0	×	×	×	×	0	0	0	0
$\tilde{c}^{(1)}_{l^2q^2D^2}$	–	–	$\boxed{0}$	$\boxed{0}$	0	0	–	–	$\boxed{0}$	$\boxed{0}$	0	0	0	0
$\tilde{c}^{(2)}_{l^2q^2D^2}$	–	–	$\boxed{0}$	$\boxed{0}$	0	0	–	–	$\boxed{0}$	$\boxed{0}$	0	0	0	0
$\tilde{c}_{e^4D^2}$	0	0	0	0	×	×	0	0	0	0	0	0	0	0
$\tilde{c}^{(1)}_{u^4D^2}$	0	0	0	0	0	0	0	0	0	0	×	×	0	0
$\tilde{c}^{(2)}_{u^4D^2}$	0	0	0	0	0	0	0	0	0	0	×	×	0	0
$\tilde{c}^{(1)}_{d^4D^2}$	0	0	0	0	0	0	0	0	0	0	0	0	×	×
$\tilde{c}^{(2)}_{d^4D^2}$	0	0	0	0	0	0	0	0	0	0	0	0	×	×
$\tilde{c}^{(1)}_{e^2u^2D^2}$	0	0	0	0	–	$\boxed{0}$	0	0	0	0	–	$\boxed{0}$	0	0
$\tilde{c}^{(1)}_{e^2d^2D^2}$	0	0	0	0	–	$\boxed{0}$	0	0	0	0	0	0	–	$\boxed{0}$
$\tilde{c}^{(1)}_{u^2d^2D^2}$	0	0	0	0	0	0	0	0	0	0	–	$\boxed{0}$	–	$\boxed{0}$
$\tilde{c}^{(2)}_{u^2d^2D^2}$	0	0	0	0	0	0	0	0	0	0	–	$\boxed{0}$	–	$\boxed{0}$
$\tilde{c}^{(1)}_{l^2e^2D^2}$	–	–	$\boxed{0}$	$\boxed{0}$	–	$\boxed{0}$	0	0	0	0	0	0	0	0
$\tilde{c}^{(1)}_{l^2u^2D^2}$	–	–	$\boxed{0}$	$\boxed{0}$	0	0	0	0	0	0	–	$\boxed{0}$	0	0
$\tilde{c}^{(1)}_{l^2d^2D^2}$	–	–	$\boxed{0}$	$\boxed{0}$	0	0	0	0	0	0	0	0	–	$\boxed{0}$
$\tilde{c}^{(1)}_{q^2e^2D^2}$	0	0	0	0	–	$\boxed{0}$	–	–	$\boxed{0}$	$\boxed{0}$	0	0	0	0
$\tilde{c}^{(1)}_{q^2u^2D^2}$	0	0	0	0	0	0	–	–	$\boxed{0}$	$\boxed{0}$	–	$\boxed{0}$	0	0
$\tilde{c}^{(2)}_{q^2u^2D^2}$	0	0	0	0	0	0	–	–	$\boxed{0}$	$\boxed{0}$	–	$\boxed{0}$	0	0
$\tilde{c}^{(1)}_{q^2d^2D^2}$	0	0	0	0	0	0	–	–	$\boxed{0}$	$\boxed{0}$	0	0	–	$\boxed{0}$
$\tilde{c}^{(2)}_{q^2d^2D^2}$	0	0	0	0	0	0	–	–	$\boxed{0}$	$\boxed{0}$	0	0	–	$\boxed{0}$

A byproduct of this work is that we have worked out positivity bounds not previously derived in the literature

A.1 $\phi^4 D^4$

$$c^{(2)}_{\phi^4 D^4} \geq 0 \,, \quad c^{(2)}_{\phi^4 D^4} + c^{(2)}_{\phi^4 D^4} \geq 0 \,, \quad c^{(1)}_{\phi^4 D^4} + c^{(2)}_{\phi^4 D^4} + c^{(3)}_{\phi^4 D^4} \geq 0 \,. \tag{32}$$

• • •

A.39 $q^2 d^2 D^2$

$$\begin{aligned} 3c^{(1)}_{q^2d^2D^2} - 9c^{(2)}_{q^2d^2D^2} + c^{(3)}_{q^2d^2D^2} - 3c^{(4)}_{q^2d^2D^2} &\geq 0 \,, \\ -3c^{(1)}_{q^2d^2D^2} - 3c^{(2)}_{q^2d^2D^2} - c^{(3)}_{q^2d^2D^2} - c^{(4)}_{q^2d^2D^2} &\geq 0 \,, \\ -6c^{(2)}_{q^2d^2D^2} + c^{(4)}_{q^2d^2D^2} &\geq 0 \,, \end{aligned} \tag{82}$$

$$-3c^{(2)}_{q^2d^2D^2} - c^{(4)}_{q^2d^2D^2} \geq 0 \,, \quad -6c^{(2)}_{q^2d^2D^2} + c^{(4)}_{q^2d^2D^2} \geq 0 \,. \tag{83}$$

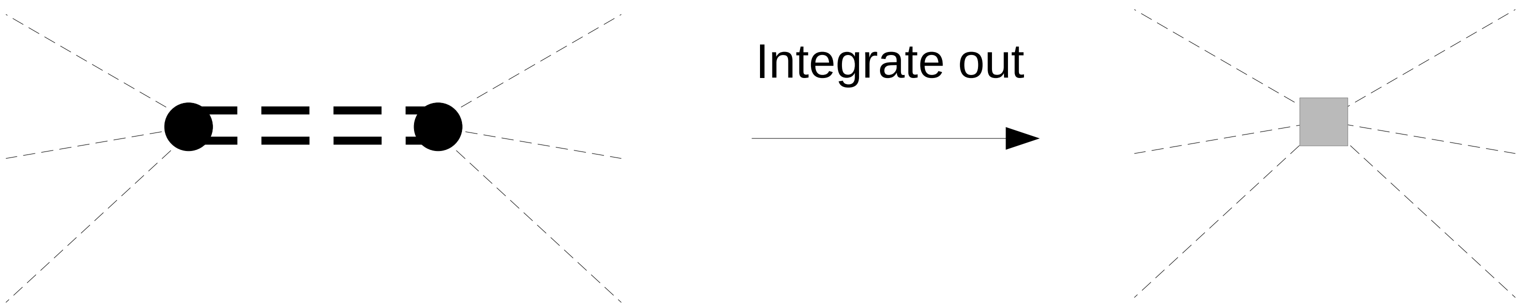
Slowly unraveling the quantum structure of the SMEFT to dimension eight

	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)			✓						✓		✓
$d_{\leq 4}$ (fermionic)			✓						X		X
d_5	✓				✓	✓					
d_6 (bosonic)		✓	✓					✓	✓	✓	✓
d_6 (fermionic)		✓	✓					X	X	X	X
d_7				✓	✓	✓					
d_8 (bosonic)							✓	✓	✓	✓	✓
d_8 (fermionic)							X	X	X	X	✓

MC, Guedes, Ramos, Santiago; 2106.05291
Accettulli Huber, De Angelis; 2108.03669
Bakshi, **MC**, Diaz-Carmona, Guedes; 2205.03301
Helset, Jenkins, Manohar; 2212.03253
Asteriadis, Dawson, Fontes; 2212.03258
Bakshi, Diaz-Carmona; 2301.07151

Besides pure theoretical considerations, anomalous dimensions of dimension-8 operators [Murphy '20; Li, Ren, Shu, Xiao, Yu, Zheng '20] not always phenomenologically irrelevant

Simplest example:



Custodial symmetry violation absent at tree-level dimension-6, one-loop dimension-6 and tree-level dimension-8 [MC, Krause, Nardini '18; Durieux, McCullough, Salvioni '22]

Can’t we just compute all anomalous dimensions in some automated way?

EFT in UV

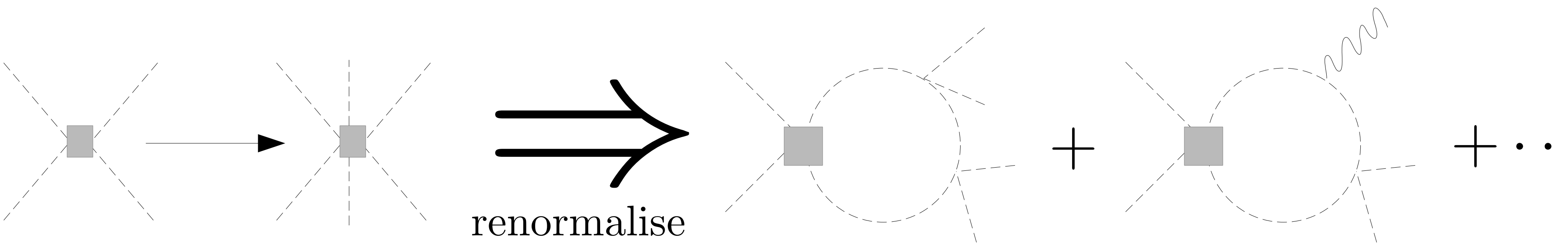
FeynRules
QGRAF
FORM

EFT in IR

Tools like matchmakereft or matchete not yet fully automatic

[Carmona et al ‘ 21; Fuentes-Martin et al ‘22]

Main obstacles: Green’s and physical bases [**MC**, Diaz-Carmona, Guedes ‘21; Ren, Yu ‘22; Fonseca]; field redefinitions [**MC**, Santiago]



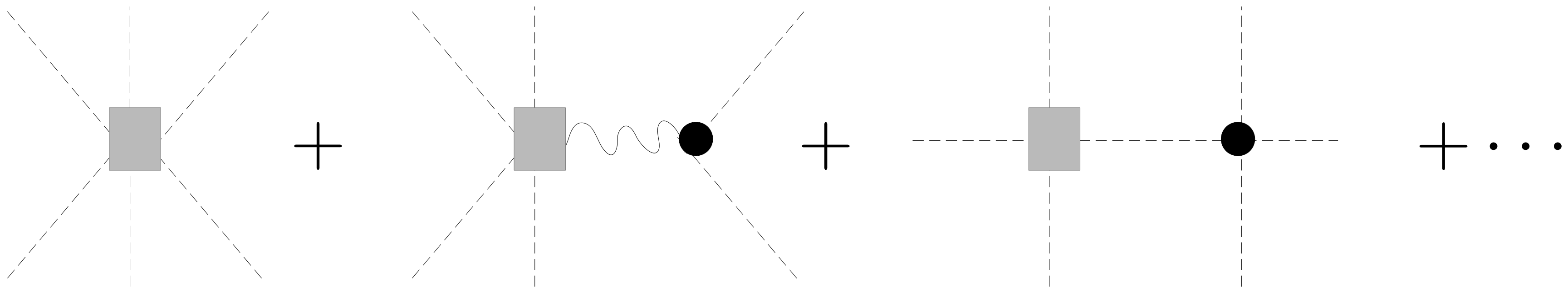
$\phi^4 D^4$ $\phi^6 D^2$ $\phi^6 D^2$ $X\phi^4 D^2$

$$L^{(\mathrm{local})} \sim P(p_i \cdot p_j, p_i \cdot \epsilon_j, \cdots)$$

Require Lagrangian with redundant operators to provide same S-matrix as that without them

Too many constraints on-shell. Solution: go numerics

Compute the amplitudes in different Montecarlo physical phase-space points. Problem reduced to linear algebra



Application to the purely Higgs sector [to appear in SMEFT-Tools 2022 proceedings]:

$$c_{\phi\Box} \to c_{\phi\Box} + \frac{1}{2} r'_{\phi D}\,, \tag{22}$$

$$c_{\phi^6} \to c_{\phi^6} + 2\lambda r'_{\phi D}\,, \tag{23}$$

$$c^{(1)}_{\phi^6 D^2} \to c^{(1)}_{\phi^6 D^2} + 2\lambda\left(2r^{(12)}_{\phi^4 D^4} - 2r^{(4)}_{\phi^4 D^4} - r^{(6)}_{\phi^4 D^4}\right) - 4c_{\phi\Box} r'_{\phi D} - \frac{1}{2} c_{\phi D} r'_{\phi D} - \frac{7}{4} r'^2_{\phi D} + r''^2_{\phi D}\,, \tag{24}$$

$$c^{(2)}_{\phi^6} \to c^{(2)}_{\phi^6} + 2\lambda\left(r^{(12)}_{\phi^4 D^4} - r^{(6)}_{\phi^4 D^4}\right) - c_{\phi D} r'_{\phi D}\,. \tag{25}$$

Outlook

Not all EFTs are the **low-energy limit** of well-behaved UV theories

Within CHMs, there are certain groups of scalars with certain symmetries that never occur. There are **criteria** that allow to discriminate between landscape and swampland using IR information only

In the SMEFT, certain combinations of parameters restricted by positivity bounds. These sometimes stable under running $\rightarrow$ allow to **constrain anomalous dimensions**

Thank you!