Systematic deconstruction of EFT operators

Martin Hirsch

Instituto de Física Corpuscular - CSIC
Universidad Valencia, Spain

http://www.astroparticles.es/

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$\mathcal{I}.$

Introduction

Motivation

Complete list of beyond the standard model discoveries at LHC:

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Complete list of beyond the standard model discoveries at LHC:

⇒ Not a surprise that effective field theory has received
a lot of attention recently ...

Effective field theory

Basic idea of EFT:

New physics exists, but the mass scale involved is $\sqrt{s} \ll \Lambda$:

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM}^{d=4} + \sum_k \frac{C_k}{\Lambda^{d-4}} \mathcal{O}_k$$

⇒ "Integrating out" the heavy resonances "generates" a tower of operators

⇒ d is the dimension of $\mathcal{O}_k$
⇒ Λ is the energy scale of new physics
⇒ C_k the Wilson coefficient, free parameters in SMEFT

⇒ Since suppressed by higher powers of Λ larger d operators become quickly irrelevant phenomenologically

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⇒ At $d = 5$ in SMEFT only one operator: Weinberg operator with 6 complex parameters for 3 generations of leptons

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⇒ At $d = 5$ in SMEFT only one operator: Weinberg operator with 6 complex parameters for 3 generations of leptons

⇒ At $d = 6$ already order $\mathcal{O}(60)$ operators, with 2499 independent parameters

SMEFT @ $d = 5$

Weinberg, 1979:

In SMEFT at $d = 5$ only one operator (structure):

$$\mathcal{O}_{\rm Wbg} = \frac{c_{\alpha\beta}}{\Lambda} \overline{L^c_\alpha} L_\beta H H$$

$\Rightarrow$ $c_{\alpha\beta}$ complex symmetric, 6 complex parameters

$\Rightarrow$ Violates lepton number by two units

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$\Rightarrow$ Violates lepton number by two units

$\Rightarrow$ After EWSB, replace $H \to v_{SM}$

$$\mathcal{O}_{\rm Wbg} \to (m_\nu)_{\alpha\beta} = \frac{c_{\alpha\beta}}{\Lambda} v_{SM}^2$$

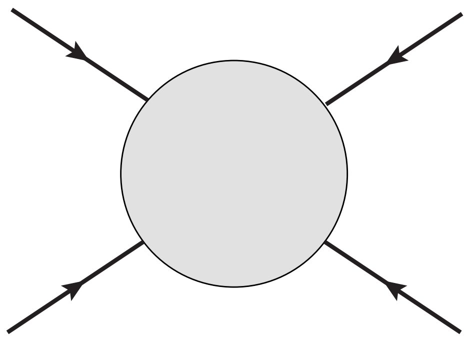
$\Rightarrow$ $\mathcal{O}_{\rm Wbg}$ generates Majorana neutrino masses

$\Rightarrow$ Suppressed by large scale Λ (!!!) - Seesaw mechanism

$\Rightarrow$ For $c_{\alpha\beta} \sim 1$, $\Lambda \sim 10^{(14-15)}$ GeV

Deconstruct $\mathcal{O}_{\rm Wbg}$*: Tree-level*

Consider first only tree-level:



Deconstruct $\mathcal{O}_{\mathrm{Wbg}}$: Tree-level

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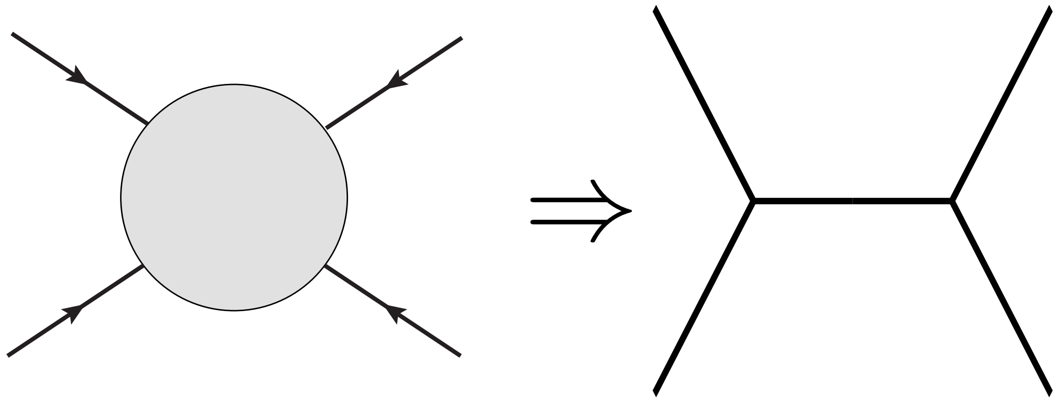

1 - topology with
0 - loops
4 - external legs

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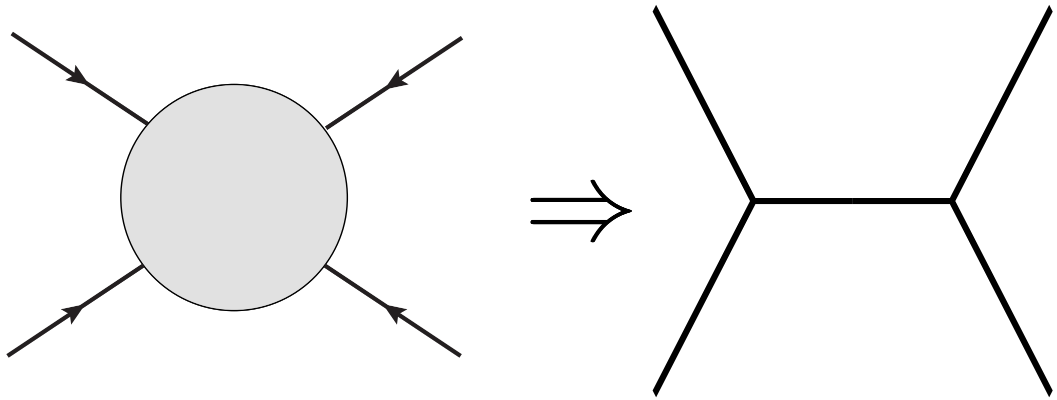

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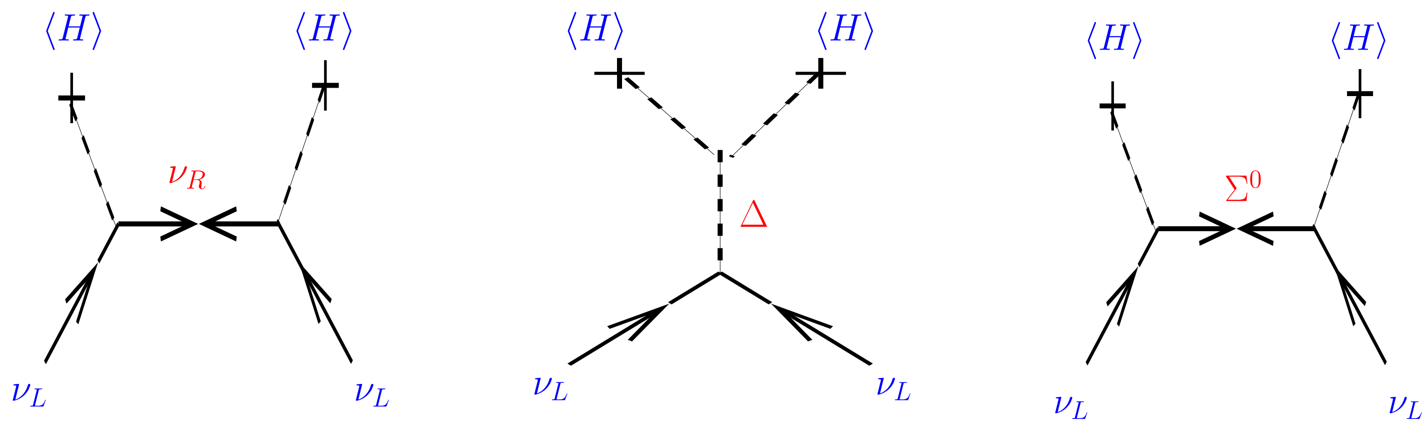
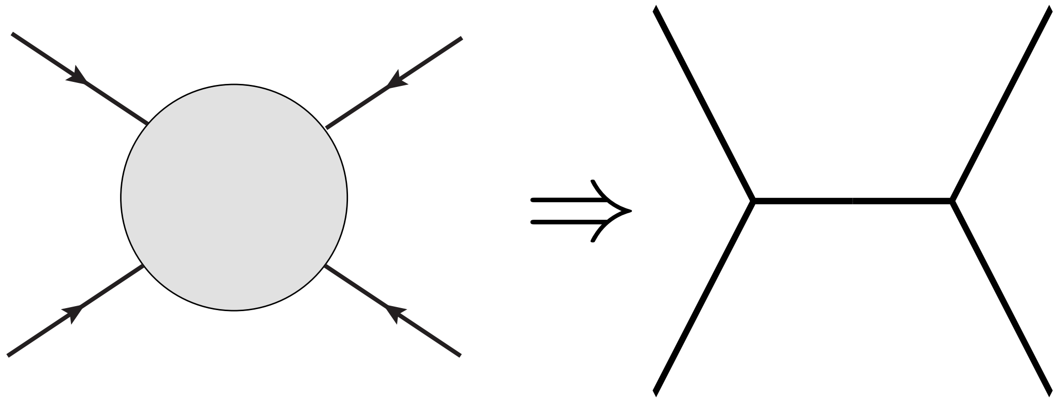
Fixing outside fields yields 3 diagrams:



seesaw type-I　　seesaw type-II　　seesaw type-III

Deconstruct $\mathcal{O}_{\mathrm{Wbg}}$: *Tree-level*

Consider first only tree-level:



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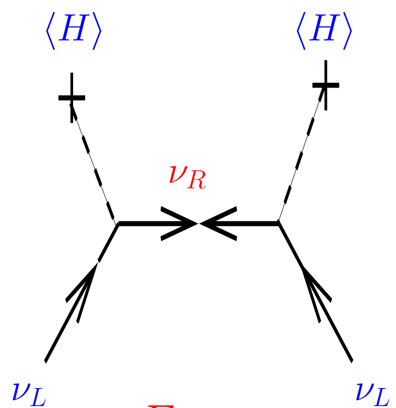
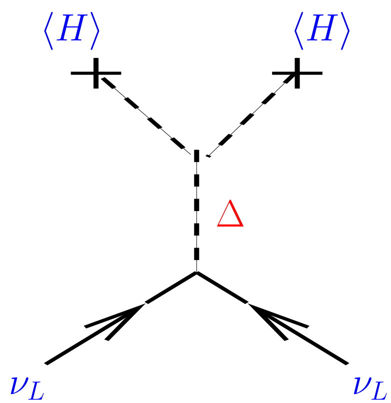


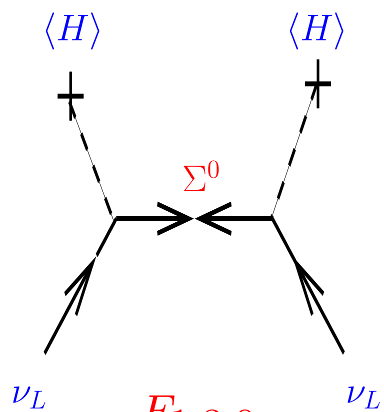
$F_{1,1,0}$

seesaw type-I



$S_{1,3,1}$

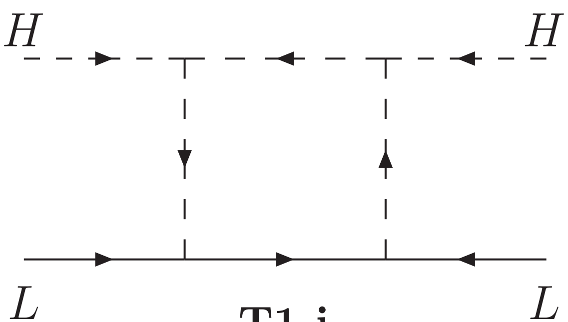
seesaw type-II



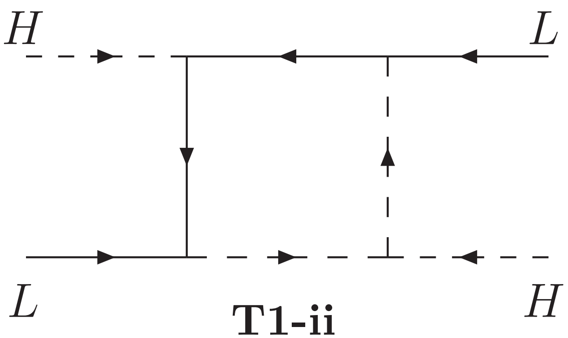
$F_{1,3,0}$

seesaw type-III

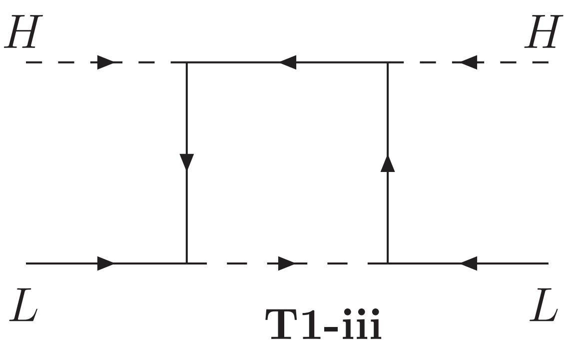
$\mathcal{O}_{\mathrm{Wbg}}$ at 1-loop



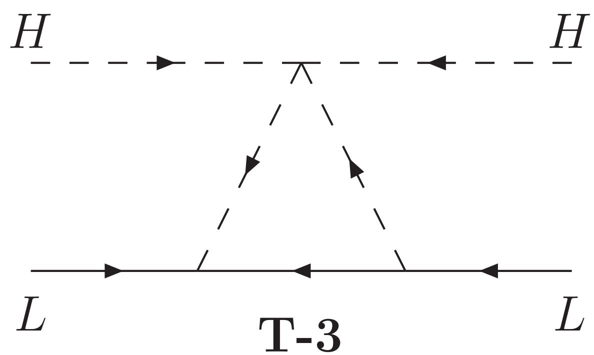
T1-i



T1-ii



T1-iii

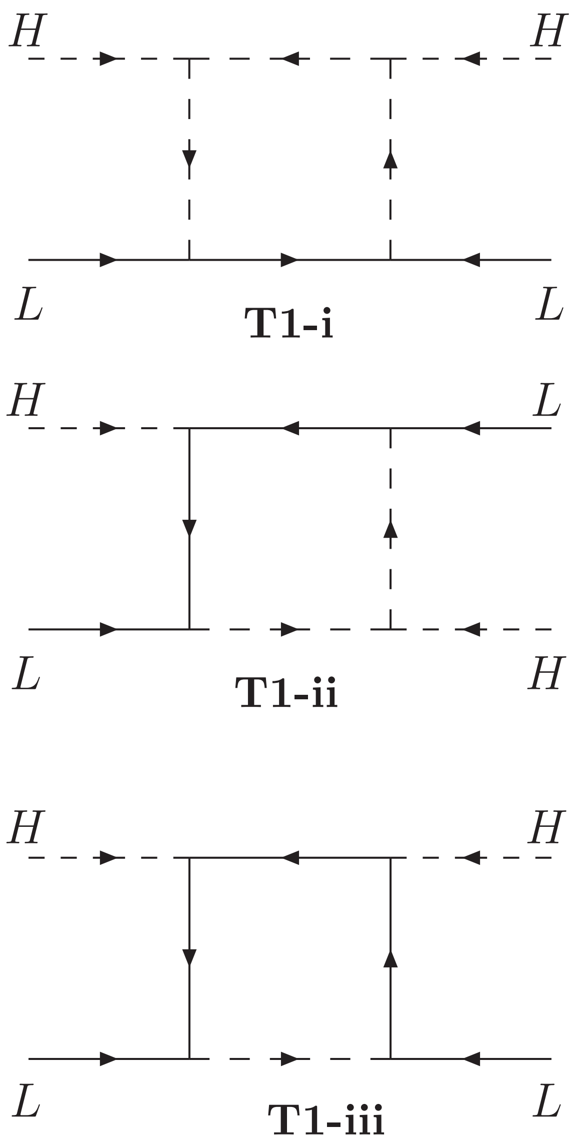


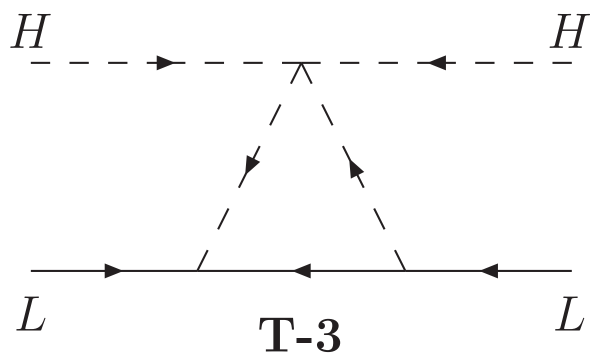
T-3

Only 4 genuine diagrams!

Bonnet et al.; arXiv:1204.5862

$\mathcal{O}_{\rm Wbg}$ at 1-loop





Only 4 genuine diagrams!
Bonnet et al.; arXiv:1204.5862

BUT ... many models!

Arbeláez et al.; arXiv:2205.13063 count:

- 318 models with Dark Matter
- 406 models with "exit" particles

(Considering only scalars & fermions)
(+ similar numbers with vectors)

SMEFT @ $d = 6$

X^3		H^6 and H^4D^2		$\psi^2 H^3$	
$\mathcal{O}_G$	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star \left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2 H^2$		$\psi^2 X H$		$\psi^2 H^2 D$	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p \gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar l_p \tau^I \gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde H\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p \gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p \gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar q_p \tau^I \gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p \sigma^{\mu\nu} T^A d_r) H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p \gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p \gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde W B}$	$H^\dagger \tau^I H\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p \gamma^\mu d_r)$

$(\bar L L)(\bar L L)$		$(\bar R R)(\bar R R)$		$(\bar L L)(\bar R R)$	
$\mathcal{O}_{ll}$	$(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$

$(\bar L R)(\bar R L)$ and $(\bar L R)(\bar L R)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$		

"Warsaw basis"

Grzadkowski et al.; arXiv:1008.4884

Eliminating all redundant ops via: IBP, EOM, Fierz

$\sim \mathcal{O}(60)$ operator structures

In total: 2499 independent parameters

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X^2H^2		ψ^2XH		ψ^2H^2D	
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$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\,\widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
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$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
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$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
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$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$

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$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
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$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
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$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
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$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

"Warsaw basis"

Grzadkowski et al.; arXiv:1008.4884

Eliminating all redundant ops via: IBP, EOM, Fierz

$\sim\mathcal{O}(60)$ operator structures

In total: 2499 independent parameters

Can one automatize model construction?

$\mathcal{II}.$

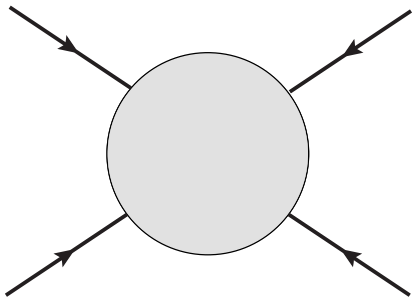
Diagrammatica:
Deconstruction of EFT operators

Four fermion operators:

Cepedello et al.; 2207.13714 & 2301.xxxxx

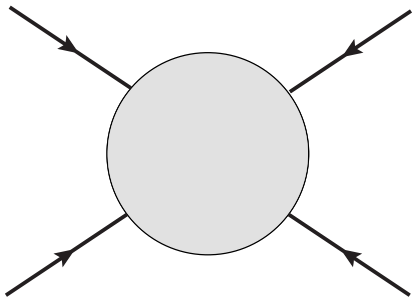
Diagrammatica basics

Consider 4-fermion operator:



Diagrammatica basics

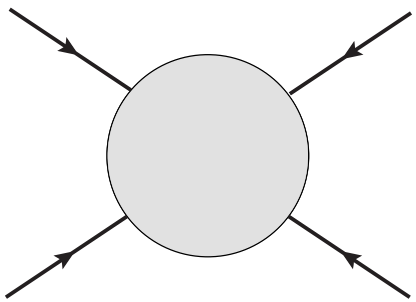
Consider 4-fermion operator:



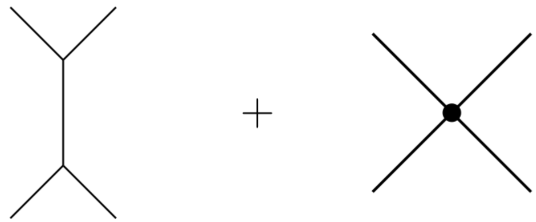
(i) find all topologies

Diagrammatica basics

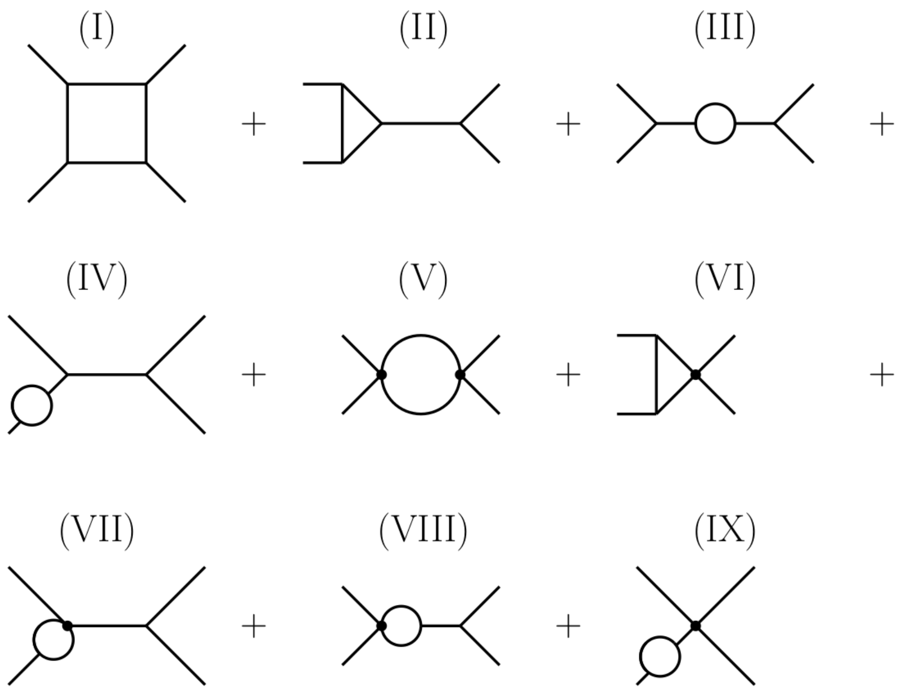
Consider 4-fermion operator:



Tree-level



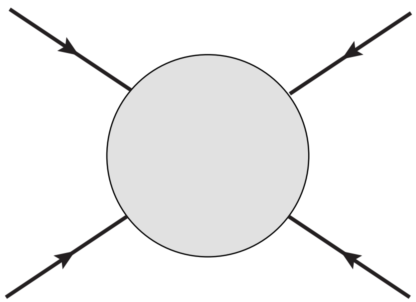
1-loop



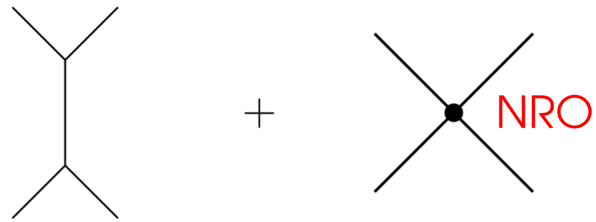
(i) find all topologies

Diagrammatica basics

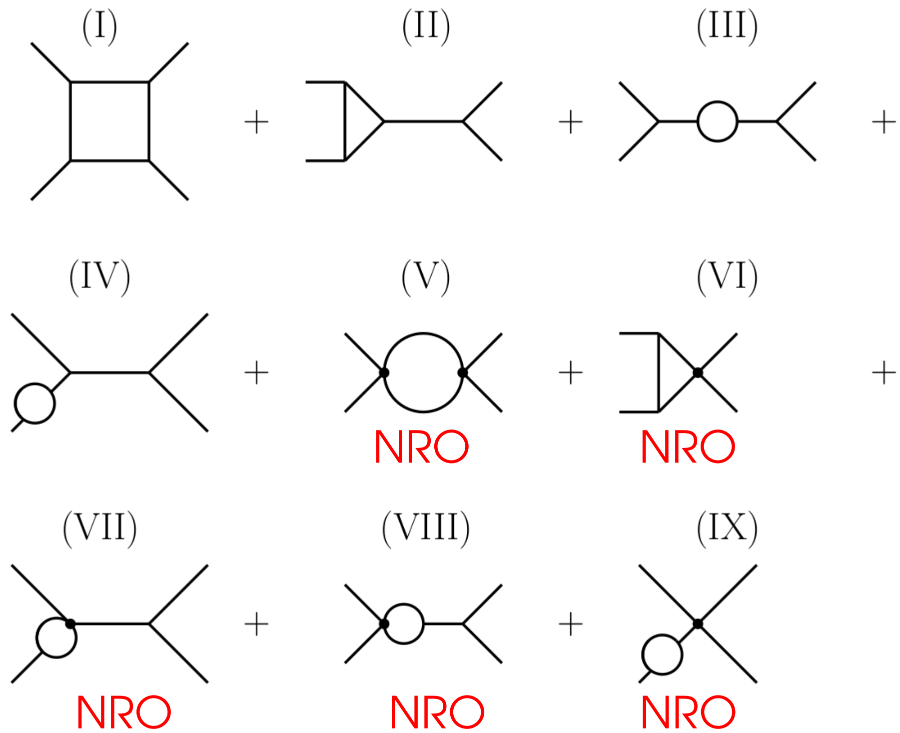
Consider 4-fermion operator:



Tree-level



1-loop

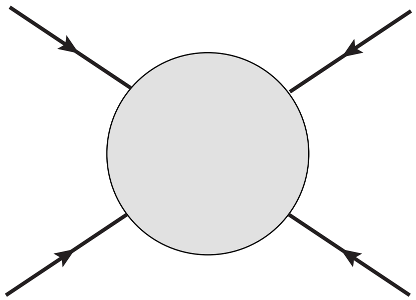


(i) find all topologies

⇒ For a UV complete model consider only renormalizable interactions

Diagrammatica basics

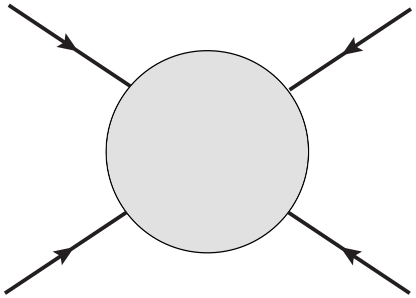
Consider 4-fermion operator:



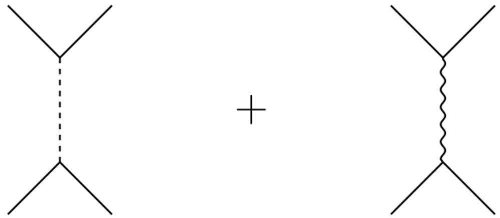
(ii) find all diagrams

Diagrammatica basics

Consider 4-fermion operator:

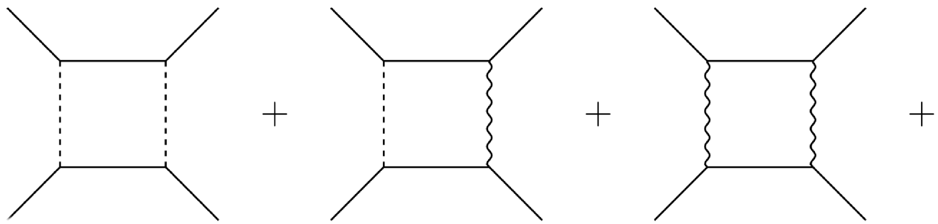


Tree-level



(ii) find all diagrams

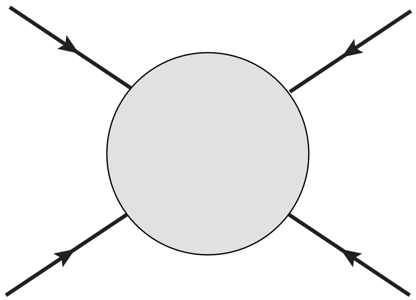
1-loop



$\cdots$ other (non-box) diagrams $\cdots$

Diagrammatica basics

Consider 4-fermion operator:

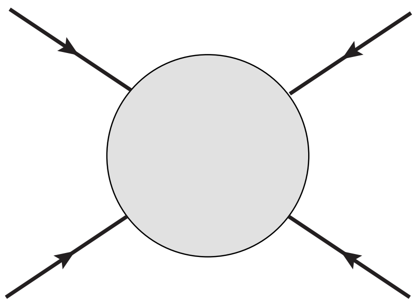


(iii) insert all possible representations

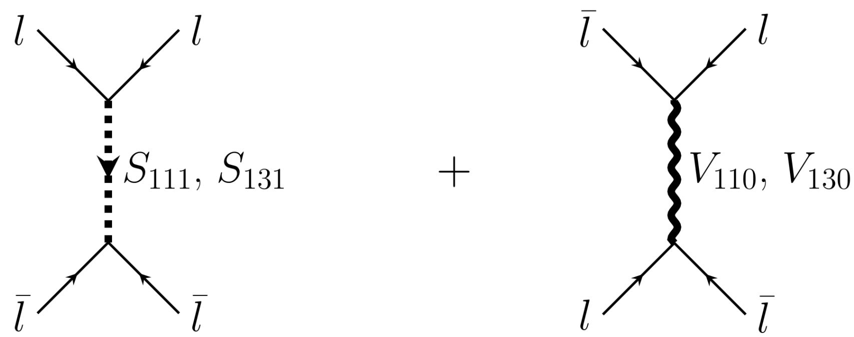
Diagrammatica basics

Consider 4-fermion operator:

$$\mathcal{O}_{ll} = (\overline{l_\alpha}\gamma^\mu l_\beta)(\overline{l_\gamma}\gamma_\mu l_\delta)$$



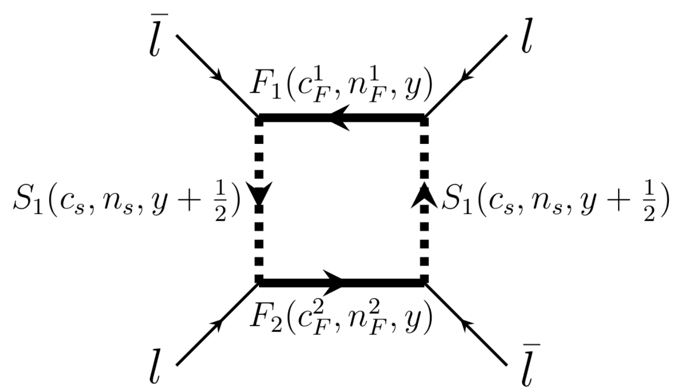
Tree-level



(iii) insert all possible representations

V - vector
S - scalar
F - fermion

1-loop

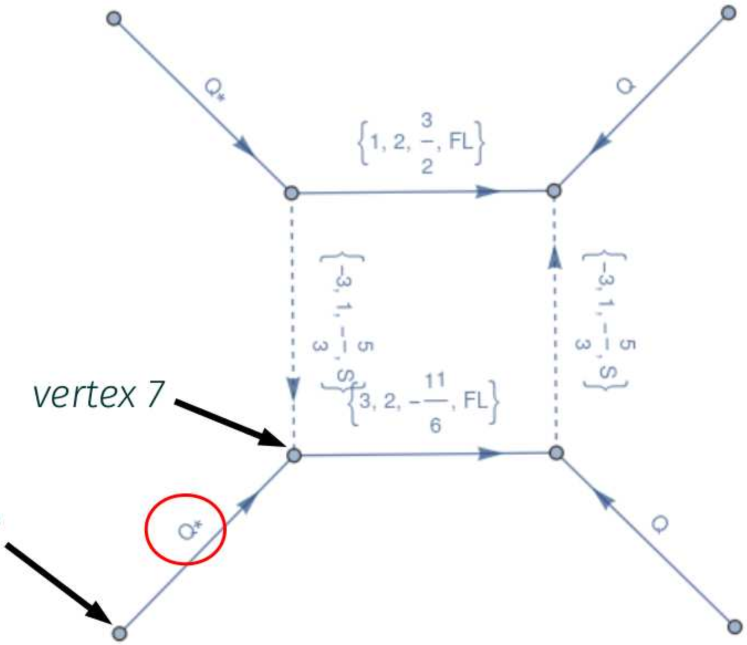


Subscripts:

$SU(3), SU(2)_L, U(1)_Y$

ModGen

All the process can be ***automated*** **via “generalised” adjacency matrices***: the entries are the quantum numbers of the particles in the diagram with every column and row invariant under the symmetries.*



vertex 7 *vertex 2*

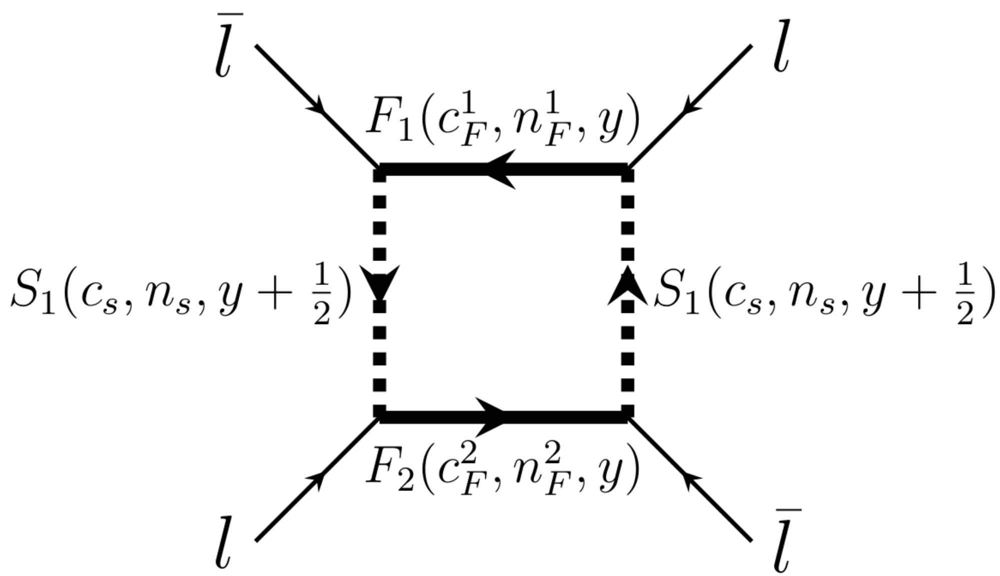
0	0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$
0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0
0	0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0
0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0
0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0	$\{-3, 1, -\frac{5}{3}, S, 0\}$	0	$\{1, 2, \frac{3}{2}, FL, 0\}$
0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0	$\{3, 1, \frac{5}{3}, S, 0\}$	0	$\{3, 2, -\frac{11}{6}, FL, 0\}$	0
0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0	$\{-3, 2, \frac{11}{6}, FR, 0\}$	0	$\{-3, 1, -\frac{5}{3}, S, 0\}$
$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0	$\{1, 2, -\frac{3}{2}, FR, 0\}$	0	$\{3, 1, \frac{5}{3}, S, 0\}$	0

`Mathematica`: Can easily deal with, manipulate and store all necessary info

How many loop models?

Consider a very simple, symmetric example operator: $\mathcal{O}_{ll}$

At 1-loop level consider box diagram:



For $SU(3)$: $\mathbf{c_s} \otimes \mathbf{c_F^i} = \mathbf{1} \oplus \cdots$

For $SU(2)$: $\mathbf{n_s} \otimes \mathbf{n_F^i} = \mathbf{2} \oplus \cdots$

For $U(1)_Y$: $|y| = 0, 1, 2, \cdots$ (for $\mathbf{c_S} = \mathbf{1}$)

$\cdots$

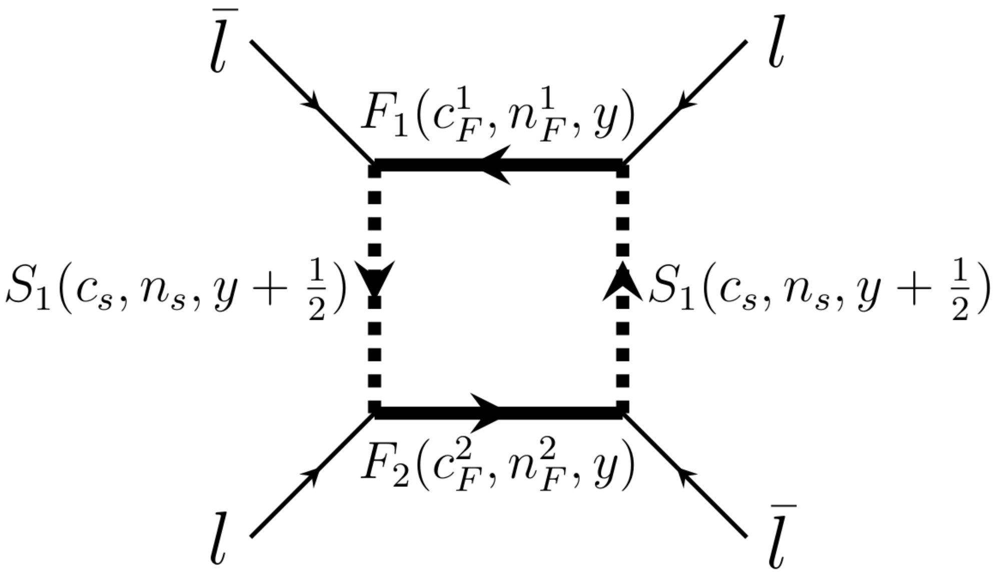
Renato Fonseca
arXiv:2011.01764
GroupMath

How many loop models?

Consider a very simple, symmetric example operator: $\mathcal{O}_{ll}$

At 1-loop level consider box diagram:

Infinite series of models?



For $SU(3)$: $\mathbf{c_s} \otimes \mathbf{c_F^i} = \mathbf{1} \oplus \cdots$

For $SU(2)$: $\mathbf{n_s} \otimes \mathbf{n_F^i} = \mathbf{2} \oplus \cdots$

For $U(1)_Y$: $|y| = 0, 1, 2, \cdots$ (for $\mathbf{c_S} = \mathbf{1}$)

$\cdots$

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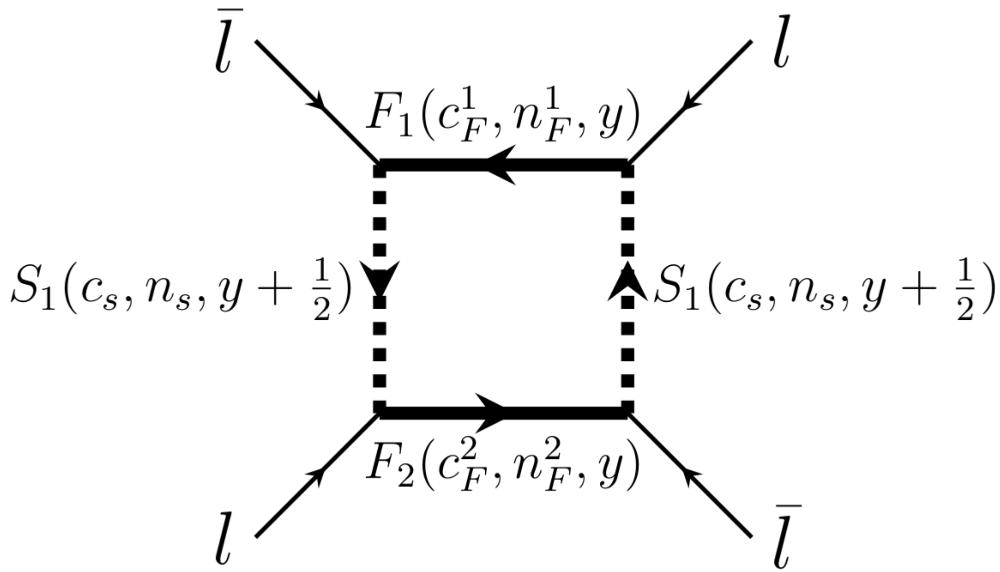

Infinite series of models?

Cutoffs!

(i) Phenomenological constraints

(ii) Theoretical arguments

For $SU(3)$: $\mathbf{c_s} \otimes \mathbf{c_F^i} = \mathbf{1} \oplus \cdots$

For $SU(2)$: $\mathbf{n_s} \otimes \mathbf{n_F^i} = \mathbf{2} \oplus \cdots$

For $U(1)_Y$: $|y| = 0, 1, 2, \cdots$ (for $\mathbf{c_S} = \mathbf{1}$)

$\cdots$

Renato Fonseca
arXiv:2011.01764
GroupMath

$\mathcal{III}.$

1-loop models for 4F operators

Selection criteria

(i) Phenomenological constraint:

(ii) Theoretical arguments:

Selection criteria

(i) Phenomenological constraint:

No stable charged particles

PDG: No stable, charged relics observed in mass range $M \sim (1 - 10^5)$ GeV

(ii) Theoretical arguments:

Selection criteria

(i) Phenomenological constraint:

No stable charged particles

PDG: No stable, charged relics observed in mass range $M \sim (1 - 10^5)$ GeV

(a) "Exit" particles
Any particle with linear coupling to two or more SM fields

J. de Blas et al.
1711.10391
"Granada dictionary"

(b) Dark matter candidate
Any multiplet with neutral state (must be lightest member)

S. Bottaro et al.
2107.09688 & 2205.04486

(ii) Theoretical arguments:

Selection criteria

(i) Phenomenological constraint:

No stable charged particles

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(a) "Exit" particles
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J. de Blas et al. 1711.10391 "Granada dictionary"

(b) Dark matter candidate
Any multiplet with neutral state (must be lightest member)

S. Bottaro et al. 2107.09688 & 2205.04486

(ii) Theoretical arguments:

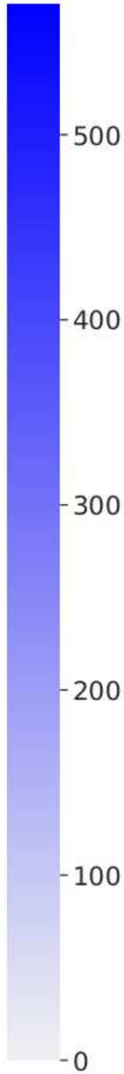
No Landau poles

Adding large multiplets to SM field content one (or more) α_i goes to infinity below M_G

$\cdots$ others $\cdots$

‘Exit’ models: Statistics

	O_{ll}	O_{le}	O_{ee}	O_{lq}	O_{lu}	O_{ld}	O_{lequ}	O_{ledq}	O_{qe}	O_{eu}	O_{ed}	O_{qq}	O_{quqd}	O_{qu}	O_{qd}	O_{uu}	O_{ud}	O_{dd}
O_{ll}	126	8	8	29	18	8	0	0	0	0	0	29	0	0	0	18	4	8
O_{le}	165	165	165	28	25	16	8	3	32	21	21	42	0	9	13	29	8	24
O_{ee}	5	5	38	0	0	0	0	0	9	4	7	9	0	0	3	4	2	7
O_{lq}	571	24	40	571	80	42	9	6	32	10	7	571	20	72	50	104	31	65
O_{lu}	236	18	26	50	236	44	7	0	5	22	6	70	0	52	8	236	58	62
O_{ld}	238	20	28	58	68	238	1	6	16	0	24	78	0	11	58	86	74	238
O_{lequ}	261	181	261	193	193	30	261	16	196	187	49	261	16	194	40	261	53	63
O_{ledq}	299	201	299	233	62	224	33	299	231	61	225	299	36	72	222	101	77	299
O_{qe}	37	27	271	30	8	8	8	6	271	39	56	271	15	43	53	51	20	67
O_{eu}	16	10	139	7	12	0	7	0	32	139	38	43	0	28	6	139	42	45
O_{ed}	16	12	141	6	0	12	0	5	35	34	141	45	0	0	33	42	38	141
O_{qq}	72	0	38	72	0	0	0	0	38	1	1	418	20	58	58	58	20	58
O_{quqd}	43	10	45	39	19	26	10	10	41	35	28	311	311	311	311	311	250	311
O_{qu}	74	10	91	54	56	8	12	0	77	75	24	548	64	548	132	548	144	160
O_{qd}	80	10	79	64	12	60	0	6	65	0	64	507	52	139	507	167	151	507
O_{uu}	12	0	18	0	12	0	0	0	0	18	8	29	0	29	0	105	30	30
O_{ud}	27	0	46	2	20	16	1	0	10	41	39	72	12	56	56	259	259	259
O_{dd}	10	0	17	1	0	10	0	0	9	1	17	29	0	0	29	32	32	95



‘Overlap matrix’:

Excluding ‘exits’ that generate 4F at tree $SU(3) \leq \mathbf{3}$, $SU(2) \leq \mathbf{4}$

How to read:

On the diagonal: number of models for $\mathcal{O}_{ii}$ Max: 571

Entry i, j (row, column): number of models for $\mathcal{O}_i$ generating also $\mathcal{O}_j$

Entry is zero: Not generated for SM: $\forall g_i, Y_i \to 0$

‘Exit’ models: Statistics

	O_{ll}	O_{le}	O_{ee}	O_{lq}	O_{lu}	O_{ld}	O_{lequ}	O_{ledq}	O_{qe}	O_{eu}	O_{ed}	O_{qq}	O_{quqd}	O_{qu}	O_{qd}	O_{uu}	O_{ud}	O_{dd}
O_{ll}	11	1	1	2	2	0	0	0	0	0	0	2	0	0	0	2	0	0
O_{le}	28	28	28	2	6	0	2	0	2	6	4	4	0	2	1	8	2	4
O_{ee}	1	1	18	0	0	0	0	0	2	4	4	2	0	0	0	4	2	4
O_{lq}	19	1	3	19	2	0	2	1	2	2	1	19	1	1	1	3	1	1
O_{lu}	26	3	7	2	26	3	3	0	2	6	2	3	0	2	1	26	6	6
O_{ld}	23	3	7	4	9	23	0	2	3	0	6	5	0	1	3	12	10	23
O_{lequ}	21	14	21	15	15	2	21	2	14	17	5	21	2	15	3	21	6	6
O_{ledq}	22	15	22	17	6	16	5	22	16	7	17	22	5	5	15	10	8	22
O_{qe}	5	3	30	4	3	3	3	2	30	6	6	30	4	5	4	7	5	7
O_{eu}	5	3	40	3	4	0	3	0	4	40	12	5	0	3	0	40	12	13
O_{ed}	1	1	35	1	0	0	0	1	2	13	35	3	0	0	1	15	13	35
O_{qq}	2	0	2	2	0	0	0	0	2	0	0	10	1	1	1	1	1	1
O_{quqd}	0	0	4	0	0	0	0	0	3	4	2	10	10	10	10	10	9	10
O_{qu}	6	3	14	4	5	1	4	0	11	12	4	29	6	29	8	29	11	11
O_{qd}	2	1	8	2	1	0	0	0	5	0	6	20	4	6	20	9	9	20
O_{uu}	2	0	7	0	2	0	0	0	0	7	3	1	0	1	0	18	7	7
O_{ud}	2	0	14	0	2	0	0	0	0	13	11	1	1	1	1	32	32	32
O_{dd}	0	0	4	0	0	0	0	0	0	1	4	1	0	0	1	7	7	12

‘Overlap matrix’:

Excluding ‘exits’ that generate 4F at tree $SU(3) \leq \mathbf{3}$, $SU(2) \leq \mathbf{2}$

How to read:

On the diagonal: number of models for $\mathcal{O}_{ii}$
Max: 40

Entry i, j (row, column): number of models for $\mathcal{O}_i$ generating also $\mathcal{O}_j$

Entry is zero: Not generated for SM: $\forall g_i, Y_i \to 0$

Dark matter models

	$\mathcal{O}_{ll}$	$\mathcal{O}_{le}$	$\mathcal{O}_{ee}$	$\mathcal{O}_{lq}$	$\mathcal{O}_{lu}$	$\mathcal{O}_{ld}$	$\mathcal{O}_{lequ}$	$\mathcal{O}_{ledq}$	$\mathcal{O}_{qe}$	$\mathcal{O}_{eu}$	$\mathcal{O}_{ed}$	$\mathcal{O}_{qq}$	$\mathcal{O}_{quqd}$	$\mathcal{O}_{qu}$	$\mathcal{O}_{qd}$	$\mathcal{O}_{uu}$	$\mathcal{O}_{ud}$	$\mathcal{O}_{dd}$
$\mathcal{O}_{ll}$	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\mathcal{O}_{le}$	28	28	28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\mathcal{O}_{ee}$	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
$\mathcal{O}_{lq}$	72	0	0	72	0	0	0	0	0	0	0	72	0	0	0	0	0	0
$\mathcal{O}_{lu}$	28	0	0	0	28	8	0	0	0	0	0	0	0	0	0	28	8	8
$\mathcal{O}_{ld}$	28	0	0	8	8	28	0	0	0	0	0	8	0	4	8	8	8	28
$\mathcal{O}_{lequ}$	48	32	48	32	32	8	48	12	36	32	12	48	12	36	16	48	16	16
$\mathcal{O}_{ledq}$	48	32	48	32	8	36	8	48	32	12	32	48	8	16	36	16	12	48
$\mathcal{O}_{qe}$	0	0	28	0	0	0	0	0	28	8	0	28	0	8	0	8	0	0
$\mathcal{O}_{eu}$	0	0	14	0	0	0	0	0	0	14	4	0	0	0	0	14	4	4
$\mathcal{O}_{ed}$	0	0	14	0	0	0	0	0	0	0	14	0	0	0	0	0	0	14
$\mathcal{O}_{qq}$	10	0	0	10	0	0	0	0	0	0	0	36	0	0	0	0	0	0
$\mathcal{O}_{quqd}$	8	4	4	8	4	4	4	4	4	4	4	48	48	48	48	48	48	48
$\mathcal{O}_{qu}$	0	0	8	0	0	0	0	0	8	8	0	56	16	56	16	56	16	16
$\mathcal{O}_{qd}$	8	0	0	8	0	8	0	0	0	0	0	56	16	16	56	16	16	56
$\mathcal{O}_{uu}$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
$\mathcal{O}_{ud}$	0	0	4	0	0	0	0	0	0	4	4	0	0	0	0	28	28	28
$\mathcal{O}_{dd}$	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	8

Colour scale: 0, 10, 20, 30, 40, 50, 60, 70

'Overlap matrix':

Dark matter candidate:

$S_{1,3,0}$ or $F_{1,3,0}$

How to read:

On the diagonal:
number of models for $\mathcal{O}_{ii}$
Max: 72

Entry i, j (row, column):
number of models for $\mathcal{O}_i$
generating also $\mathcal{O}_j$

Entry is zero:
Not generated for
SM: $\forall g_i, Y_i \to 0$

$\mathcal{IV}.$

A minimal example model: Phenomenology

Toy model

Lagrangian:

$$\mathcal{L} = -\lambda_E \overline{\mathbf{E}} L H^\dagger - \lambda_U \overline{\mathbf{U}} Q H + \text{h.c.} - m_E \overline{\mathbf{E}}\mathbf{E} - m_U \overline{\mathbf{U}}\mathbf{U}$$

$\mathbf{E} = F_{1,1,-1}$ and $\mathbf{U} = F_{3,1,2/3}$ - vector-like fermions

Toy model

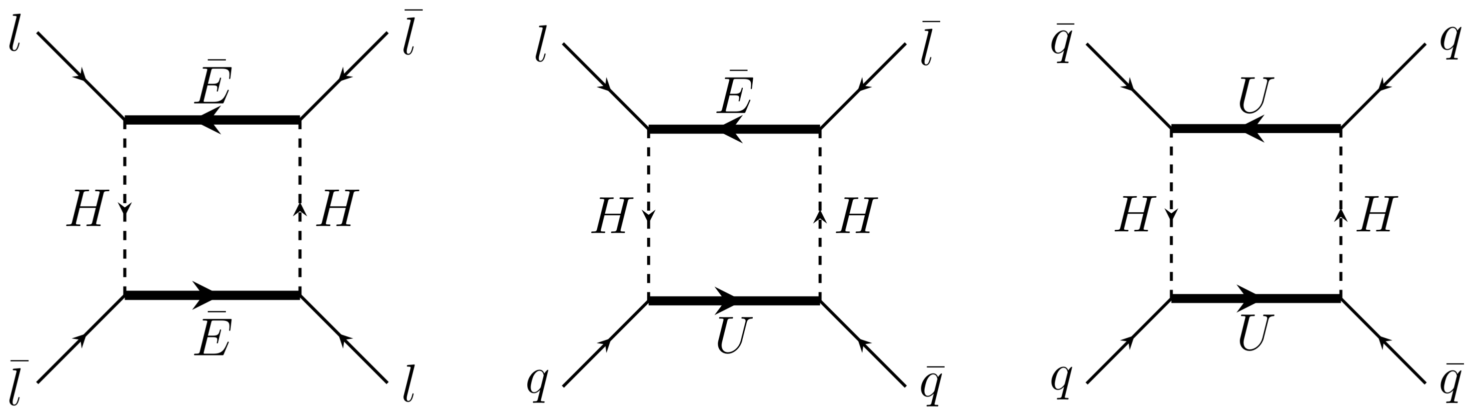
Lagrangian:

$$\mathcal{L} = -\lambda_E \overline{\mathbf{E}} L H^\dagger - \lambda_U \overline{\mathbf{U}} Q H + \text{h.c.} - m_E \overline{\mathbf{E}}\mathbf{E} - m_U \overline{\mathbf{U}}\mathbf{U}$$

$\mathbf{E} = F_{1,1,-1}$ and $\mathbf{U} = F_{3,1,2/3}$ - vector-like fermions

Matching:

O_{ll} O_{lq} O_{qq}



In the limit:
$\lambda_E = \lambda_U$ &
$m_E = m_U = \Lambda$
and $g_i^{SM} \to 0$

$$c_{ll} = -c_{lq}^{(1)} = c_{lq}^{(3)} = 2\, c_{qq}^{(1)} = 2\, c_{qq}^{(3)}$$

(No other 4F operator!)

Toy model

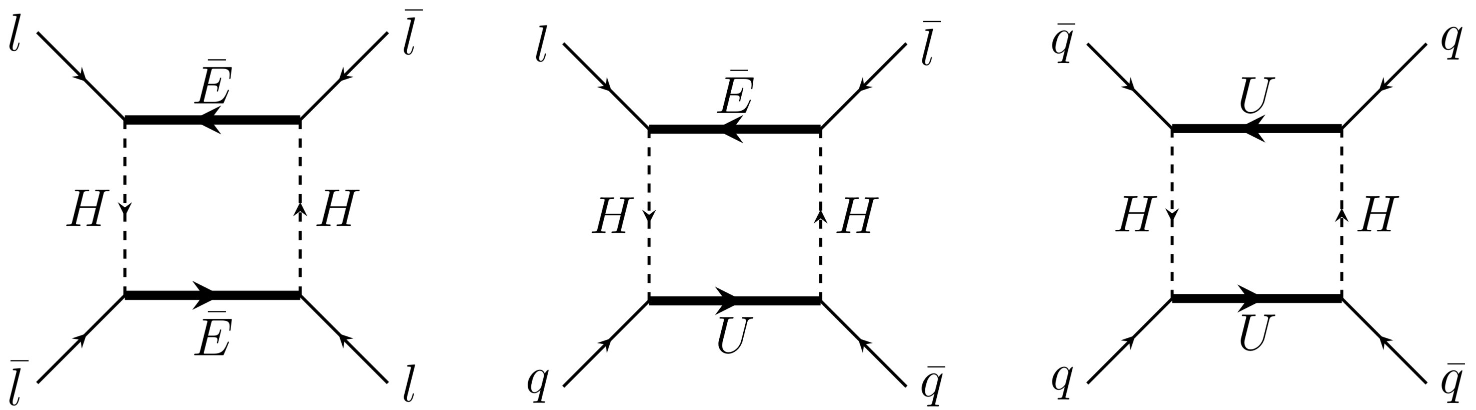
Lagrangian:

$$\mathcal{L} = -\lambda_E \overline{\mathbf{E}} L H^\dagger - \lambda_U \overline{\mathbf{U}} Q H + \text{h.c.} - m_E \overline{\mathbf{E}}\mathbf{E} - m_U \overline{\mathbf{U}}\mathbf{U}$$

$\mathbf{E} = F_{1,1,-1}$ and $\mathbf{U} = F_{3,1,2/3}$ - vector-like fermions

Matching:

O_{ll} $\quad$ O_{lq} $\quad$ O_{qq}



In the limit:
$\lambda_E = \lambda_U$ &
$m_E = m_U = \Lambda$
and $g_i^{SM} \to 0$

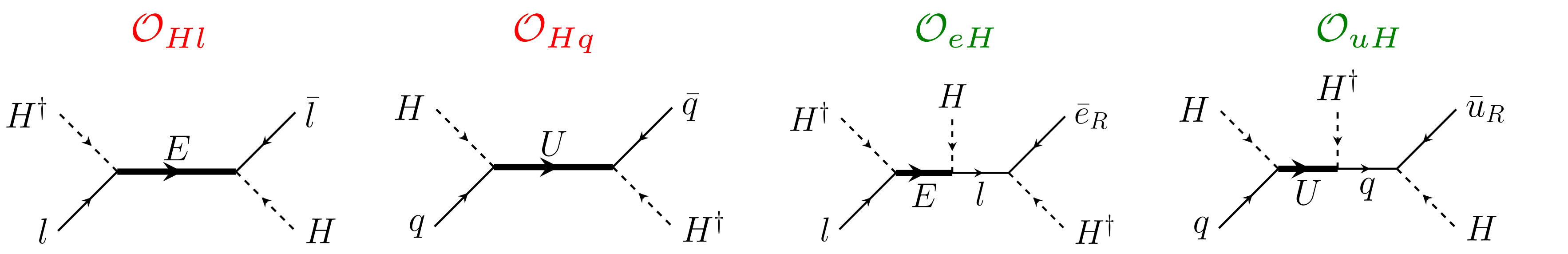
$$c_{ll} = -c_{lq}^{(1)} = c_{lq}^{(3)} = 2\,c_{qq}^{(1)} = 2\,c_{qq}^{(3)}$$

(No other 4F operator!)

Exact matching done using MatchmakerEFT
Carmona et al.
arXiv:2112.10787

Higgs-fermion operators

In the 'exit' class of models, unavoidably:



Operator	General expression
$c^{(1)}_{\phi l}$	$-\frac{1}{4}\frac{\lvert\lambda_E\rvert^2}{m_E^2}$
$c^{(3)}_{\phi l}$	$-\frac{1}{4}\frac{\lvert\lambda_E\rvert^2}{m_E^2}$
$c^{(1)}_{\phi q}$	$\frac{1}{4}\frac{\lvert\lambda_U\rvert^2}{m_U^2}$
$c^{(3)}_{\phi q}$	$-\frac{1}{4}\frac{\lvert\lambda_U\rvert^2}{m_U^2}$
$c_{e\phi}$	$\frac{1}{2}\frac{\lvert\lambda_E\rvert^2}{m_E^2}y_e$
$c_{u\phi}$	$\frac{1}{2}\frac{\lvert\lambda_U\rvert^2}{m_U^2}y_u$

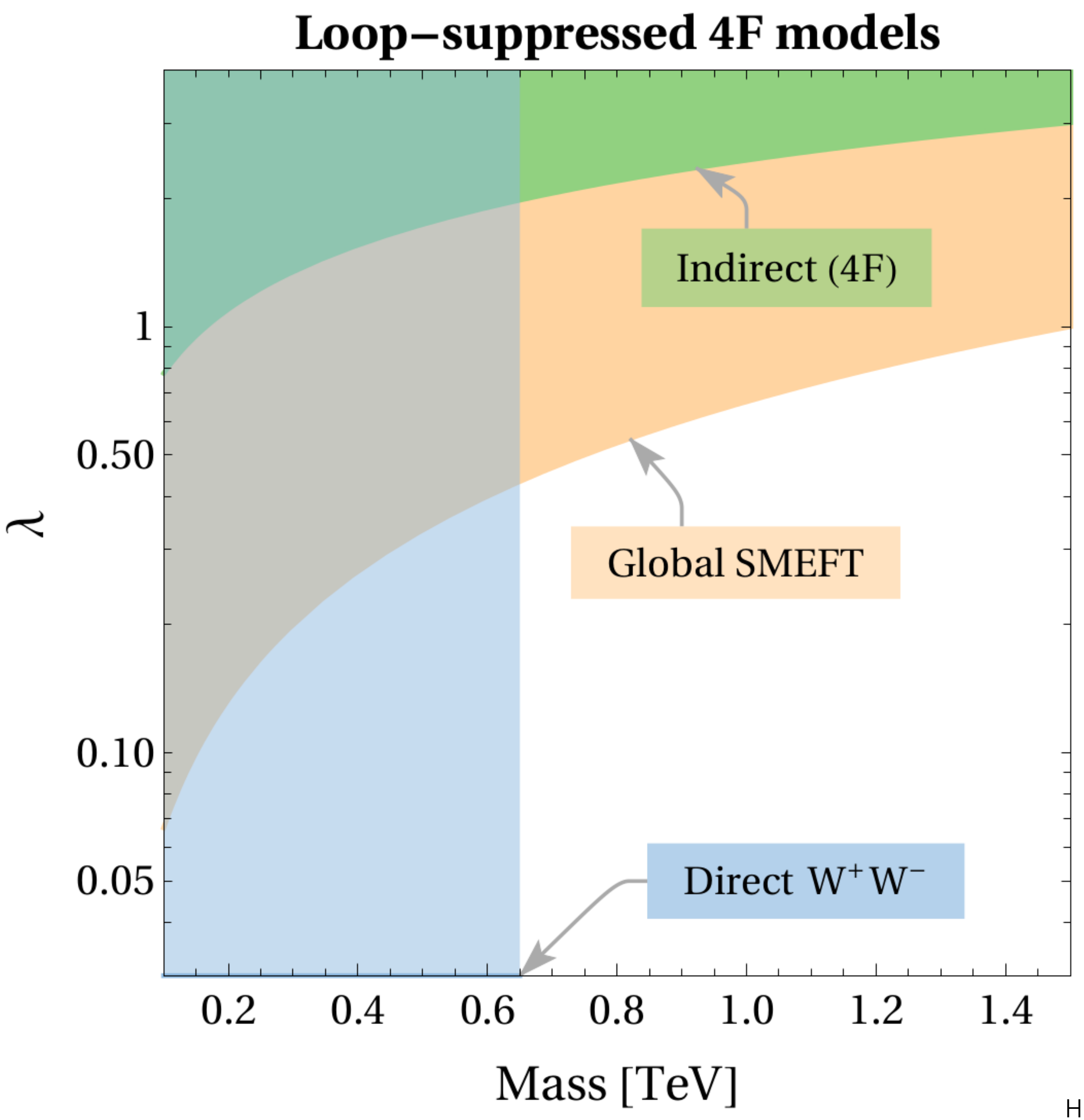
Tree-level generated operators:

$\mathcal{O}_{Hx}$ and $\mathcal{O}_{xH}$

stringent constraints from $\mathcal{O}_{Hx}$

$\Leftarrow$ $\mathcal{O}_{xH}$ SM Yukawa suppressed

Summary: 1-loop exits



⇐ Low energy 4F Ops: $m_{EU} \geq 0.17|\lambda_{EU}|^2$ TeV

⇐ Global SM fit ($\mathcal{O}_{Hx}^{\rm Tree}$): $m_{EU} \geq 1.5|\lambda_{EU}|$ TeV

LHC direct probes more stringent at smaller couplings

⇐ Reinterpretation of $WW + 2j$ search ATLAS (Note: Not optimal search strategy)

Conclusions

⇒ Effective field theory has gained a lot of attention

⇒ What types of UV models are possible? How many are there?

⇒ Different UV models contribute to different operators
Exclude some (or identify!) model from measured operators (if any)?

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$\Rightarrow$ Effective field theory has gained a lot of attention

$\Rightarrow$ What types of UV models are possible? How many are there?

$\Rightarrow$ Different UV models contribute to different operators
Exclude some (or identify!) model from measured operators (if any)?

$\Rightarrow$ Automatization of finding UV models is possible!

$\Rightarrow$ Discussed here 4-fermion operators at 1-loop level

$\Rightarrow$ Applicable in principle to any operator ...

$\Rightarrow$ Not included yet: Vectors

$\Rightarrow$ Not tested yet $d > 6$ or more than 1-loop