Mapping the SMEFT to discoverable models for 4-fermion operators

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Effective Field Theories

- Full theory with Lagrangian $\mathcal{L}$, energy scale Λ
- Describe the low-energy ($E \ll \Lambda$) dynamics independently of details of high-energy ($E \gg \Lambda$) interactions
- Take into account states with mass $m \ll \Lambda$, "integrate out" heavier modes $M \gg \Lambda$
  $\rightarrow$ Replace non-local heavy–particle exchanges by a series of local interactions among the light particles:

$$\mathcal{L}_{EFT} = \sum_i c_i \mathcal{O}_i \quad \text{with} \quad c_i \propto \frac{1}{\Lambda^{d_i - 4}}$$

- Irrelevant operators with $d_i > 4$ are suppressed by powers of Λ

Top-down vs. bottom-up

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- What if we do not know the full theory?
  $\rightarrow$ **Bottom-up** EFT: Build a tower of UV completions starting from an EFT at low energies

SMEFT

- Bottom-up EFT in practice: Take a well-known theory (e.g. the SM) as EFT and match a priori unknown UV theories to the EFT

  $\rightarrow$ Obtain constraints through matching conditions

  $\rightarrow$ Starting from SM as EFT $\Rightarrow$ **SMEFT**

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \delta\mathcal{L}^{d\leq 4} + c_5\mathcal{O}_5 + \sum_i c_{6i}\mathcal{O}_{6i} + \sum_i c_{8i}\mathcal{O}_{8i} + \dots$$

- e.g. 4-fermion operators

$$\mathcal{L}^{d=6} \supset c_{4F}(\bar{F}F)(\bar{F}F)$$

4-fermion operators

- Focus on 4-fermion operators due to their good experimental constraints
- Match Wilson coefficients c_{4F} to a UV theory
- **Idea of this project**: Study (minimal) extensions of the SM (UV models) that can open up a particular 4-fermion operator
- Use constraints on the Wilson coefficient of the operator (e.g. from global fits) to derive bounds on the masses and the couplings of the model
- Generically:

$$c_{4F} < YY \quad \Rightarrow \quad \Lambda_{NP} > XX \text{ Tev}$$

What characterises good UV models for 4F operators?

1. **No charged DM**
   $\Rightarrow$ **Need exit particle in the model**

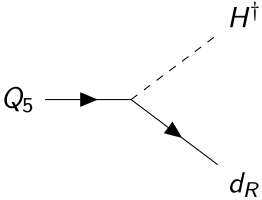
2. Interplay between direct and indirect search
   $\Rightarrow$ Look for models that contribute to the operator only at 1-loop level and to no other 4-fermion operator at tree-level

3. Only gauge vectors

4. No SM particles in the loop (Yukawa suppressed)

Exit particles

- Exit particle: A BSM particle that can decay at tree-level into two SM particles



$Q_5 = \{3, 2, -\frac{5}{6}, F\}$ decays
into $d_R = \{3, 1, -\frac{1}{3}, F\}$ and
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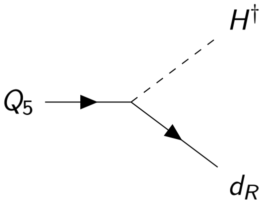

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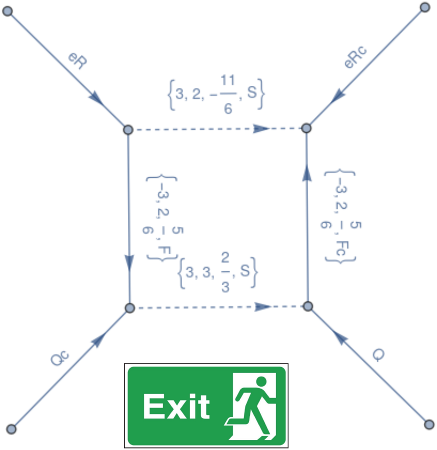

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- Loop without exits: Lightest particle would have to be stable
  $\Rightarrow$ DM problems unless neutral

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Interplay Direct vs. Indirect Search

- For $M \gg \sqrt{s}$: only indirect search possible
- For $M \sim \sqrt{s}$: also direct search possible
- interplay direct vs. indirect search $\rightarrow$ want M as small as possible

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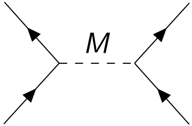
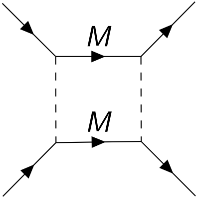


At tree-level: $c_{4F} \propto \frac{1}{M^2}$



At 1-loop: $c_{4F} \propto \frac{1}{16\pi^2} \frac{1}{M^2}$

- Applying constraints on c_{4F}: $M_{tree} \geq \Lambda$ but $M_{1-loop} \geq \frac{1}{4\pi}\Lambda$
- If allowed, tree-level will give dominant contribution to c_{4F}
  $\Rightarrow$ want models that contribute only at 1-loop but not at tree-level

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What can the *ModelGenerator* do for us?

It gives us ALL models that can open up a certain operator at tree-level or 1-loop

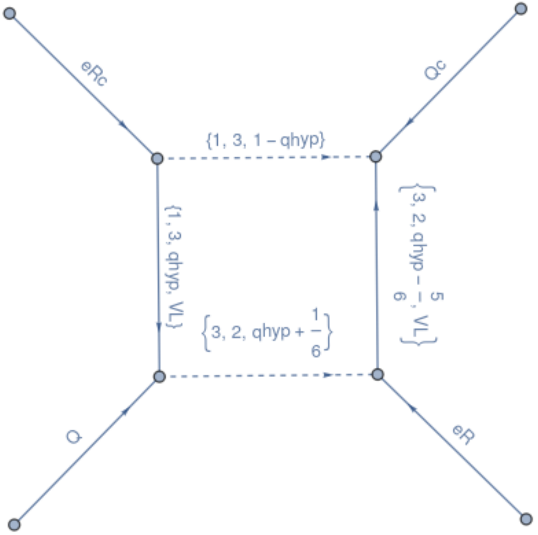
- we can specify the maximal representations (maxSU3, maxSU2, maxHyp)
- automatically contracts $SU(3)$ and $SU(2)$ representations
- variable value of the hypercharge inside the loops
- we DO NOT have to specify any UV model before

$\rightarrow$ easy to compare which of the models contain an exit/have only exits that do not contribute at tree-level and select the viable models

$\rightarrow$ Systematic approach to classify these interesting models

Example $\bar{Q}.Q.\bar{e}_R.e_R$

- In the Warsaw basis: 18 non-B-violating 4-fermion operators
- Decide for $\bar{Q}.Q.\bar{e}_R.e_R$: well constrained and not too simplistic (contains coloured particles and doublets)
- Generate all models for this operator at 1-loop with variable hypercharge, e.g.



$\bar{Q}.Q.\bar{e}_R.e_R$ - The Q_5 model

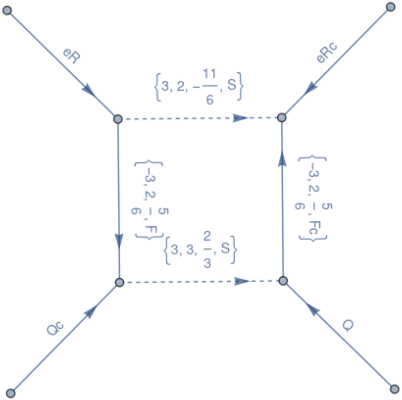
- Check which of the general models give rise to models with exits
- Number of models with only non-tree-level-opening exits:
  - $\rightarrow$ For $(maxSU3, maxSU2) = (8, 6)$: 251
  - $\rightarrow$ For $(maxSU3, maxSU2) = (3, 2)$: 23

Settle for one particular model:
The Q_5 model

$$Q_5 = \left(3, 2, -\frac{5}{6}, F\right),$$

$$S_{3,2,-\frac{11}{6}} = \left(3, 2, -\frac{11}{6}, S\right),$$

$$S_{3,3,\frac{2}{3}} = \left(3, 3, \frac{2}{3}, S\right)$$



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Deriving mass limits for the particles in the UV model

- Constraints on the Wilson coefficients of the operator e.g. by global fits (compare [Falkowski 2017, 1706.03783])
- Calculate the diagram and use the matching condition:

$$c_{4F} = \frac{1}{16\pi^2}\frac{2g^4}{6M^2},$$

assuming all couplings and masses in the loop are equal.

- Invert this relation to get a lower bound on the mass from the constraints on c_{4F}

$$M \geq \frac{1}{4\pi}\frac{g^2}{\sqrt{3c_{4F}^{max}}}$$

Summary

- SMEFT provides a suitable framework to explore minimal extensions of the SM
- 4-fermion operators: constraints on Wilson coefficient used to derive mass limits for UV models
- Criteria for viable UV models (exits, no tree-level contributions) make it hard to find all models by hand
- The *ModelGenerator* implements a systematic approach to classify these interesting models

Outlook

- Pheno for Q_5 model, obtain solid mass limits
- Study model overlap between operators (models that open up more than one 4-fermion operator)
- Include SM particles in the loop
- Compare with *matchmakereft*
- Include models that give rise to neutral DM