Mapping the SMEFT to UV models for 4F operators

with Ricardo Cepedello, Martin Hirsch and Veronica Sanz

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arxiv:2302.03485

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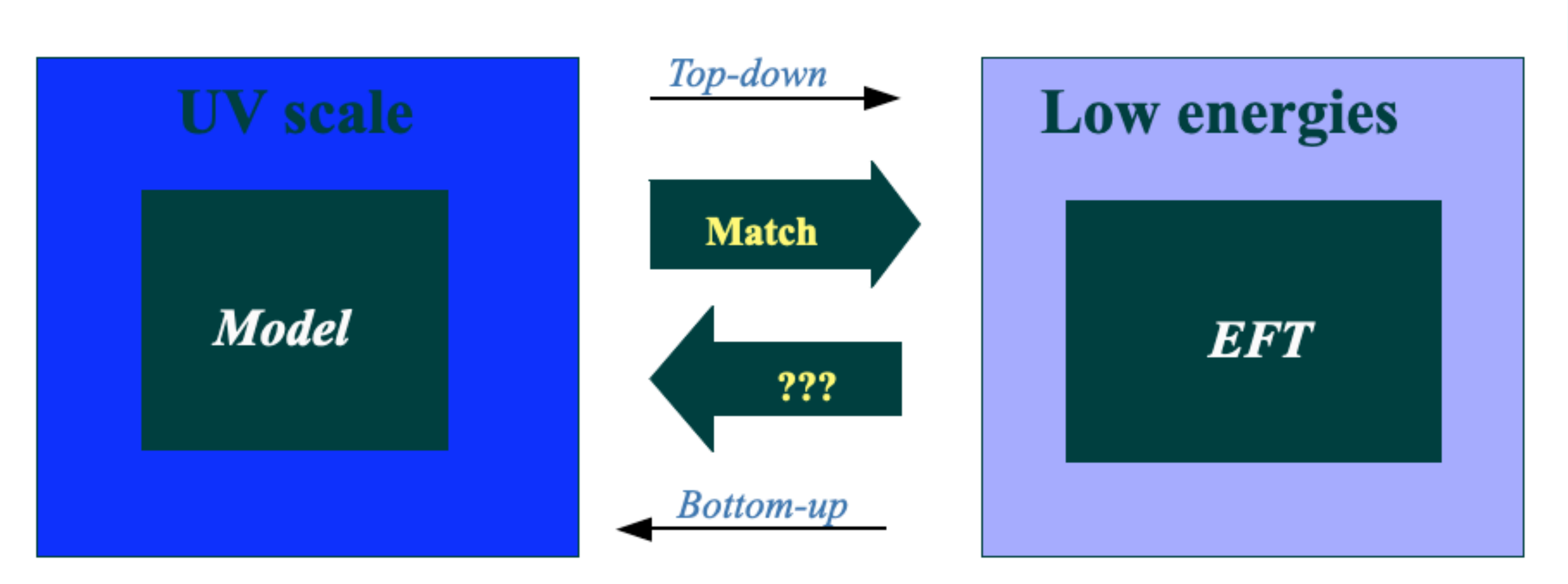
1. Standard Model Effective Field Theory

Top-down vs bottom-up EFT

Top-down EFT: We know the full theory and want to calculate its effects to a low energy EFT

→ e.g. matching the MSSM to SM, probe it at the LHC, …

→ matching well understood and easy to automise



What if we do *NOT* know the full theory?

→ ***Bottom-up*** EFT: Build a tower of UV completions starting from an EFT at low energies

SMEFT

- Bottom-up EFT, starting from SM at EW scale → ***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:

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

- Plethora of UV models the SMEFT can be matched to
- We can do global SMEFT fits, but it remains difficult and tedious to systematically list and classify possible UV completions

→ *need a tool that implements a systematic approach to classify these interesting UV models*

→ *diagrammatic method*

2. Motivation

→ What class of UV models?

→ Why 4F operators?

Motivation - what class of UV models?

Identify classes of UV models which

1. Contribute to precise low-energy measurements

AND

A. Could be discovered at the LHC (exit case)
B. Can explain the DM relic abundance from CMB determination (DM case)

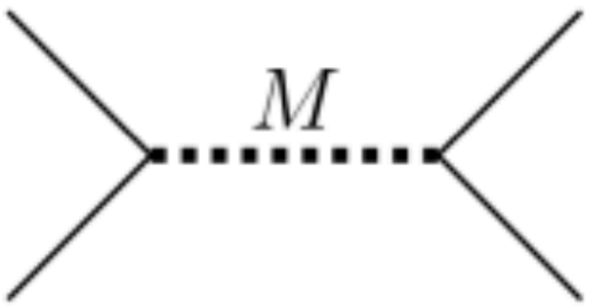
➡ *Scenarios where information from low-energy precision measurements, collider searches and CMB measurements would be complementary*

- Map (parts of the) SMEFT to these UV models
- The tightest SMEFT bounds come from operators involving four fermions (4F) → we focus on 4F operators with *no flavour violation*, *no chirality violation* *and no B-violation*

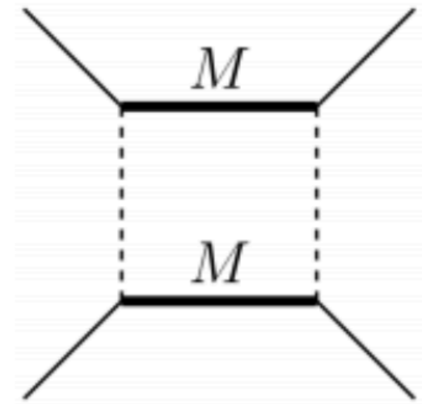
4F operators: tree-level vs. 1-loop

*New resonances producing 4F operators at **tree-level** are constrained to mass regions of the order of $m >$ (coupling)$^2 \times$(multi-TeV)*

*In scenarios where 4F are **loop-induced** at leading order the constraints would be reduced by a factor of order $1/16\pi^2$*



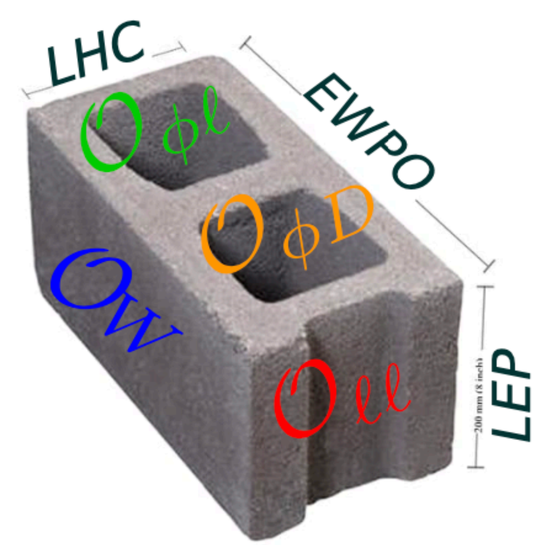
$$c_{4F}^{tree} \propto \frac{1}{M^2}$$



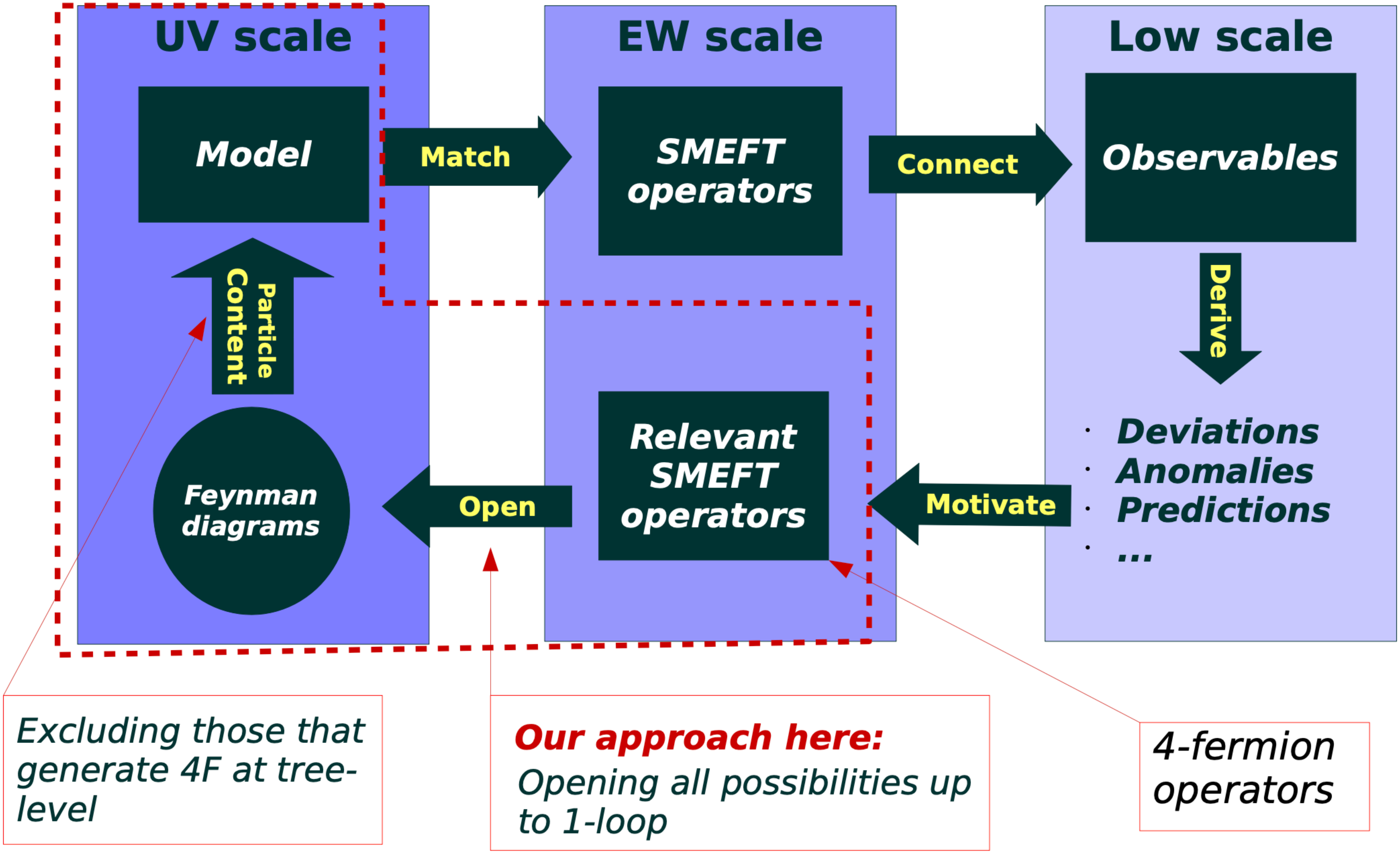
$$c_{4F}^{1l} \propto \frac{1}{16\pi^2}\frac{1}{M^2}$$

*The new resonances, appearing only at 1-loop, could be much lighter, directly **accessible at colliders***

In this class of scenarios, there is an interplay between low-energy precision measurements and collider searches



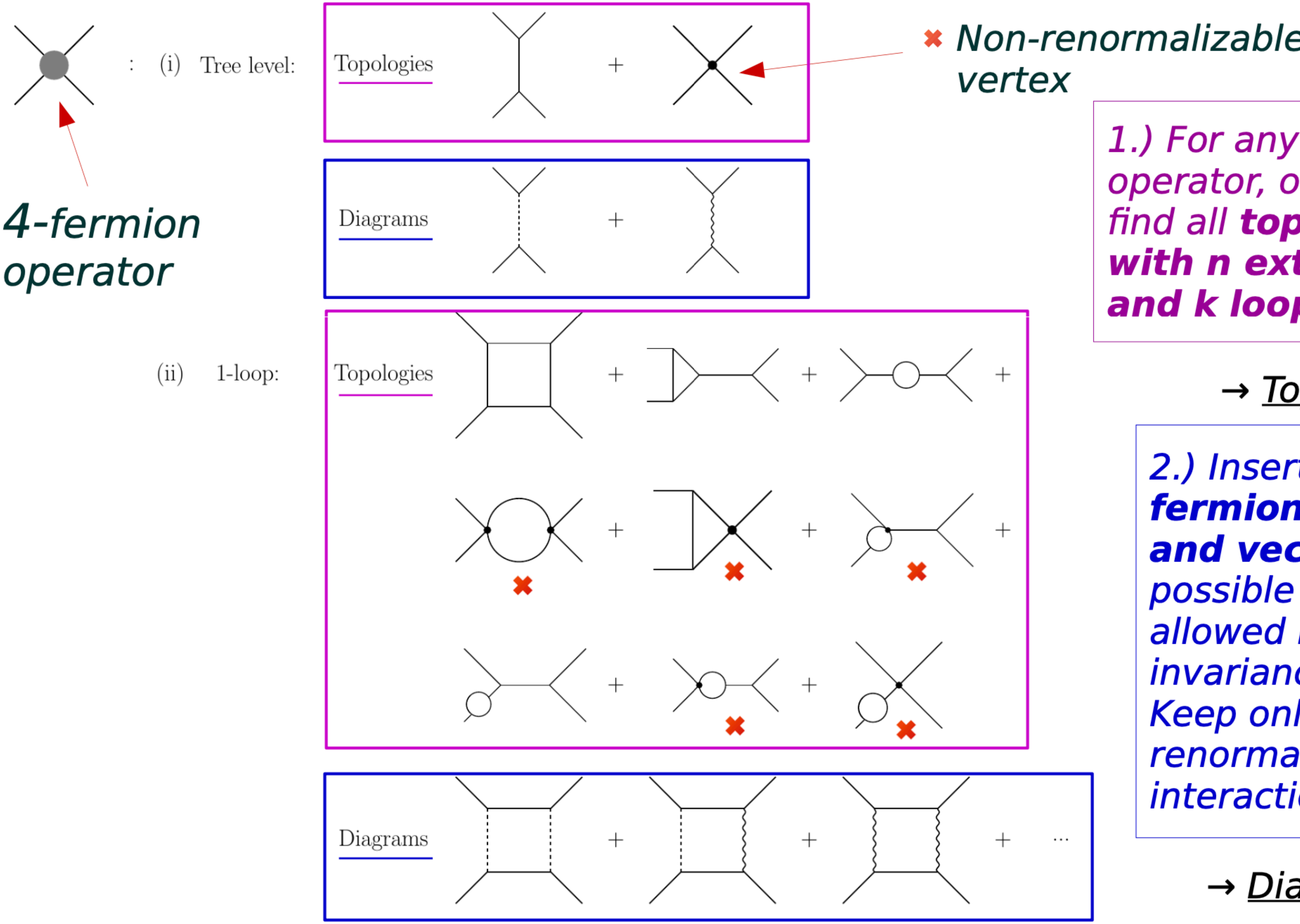
Method



UV scale
Model
Particle Content
Feynman diagrams
Match
EW scale
SMEFT operators
Relevant SMEFT operators
Open
Connect
Low scale
Observables
Derive
Deviations
Anomalies
Predictions
...
Motivate
Excluding those that generate 4F at tree-level
Our approach here:
Opening all possibilities up to 1-loop
4-fermion operators

3. “*Mapping*” - The diagrammatic method

From operators to models



*1.) For any given operator, one can first find all **topologies with n external legs and k loops***

→ *Topologies*

*2.) Insert **fermions, scalars and vectors** in all possible ways allowed by Lorentz invariance. Keep only renormalisable interactions.*

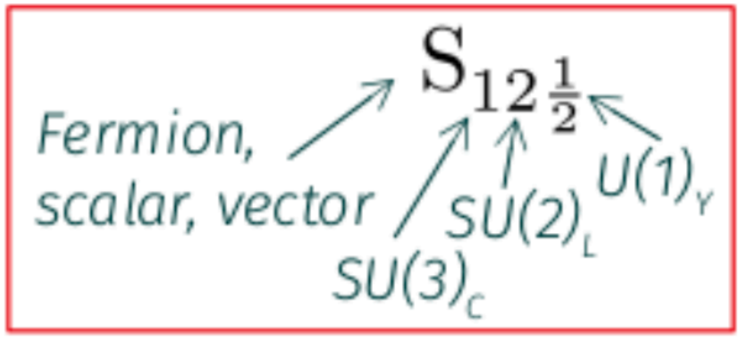
→ *Diagrams*

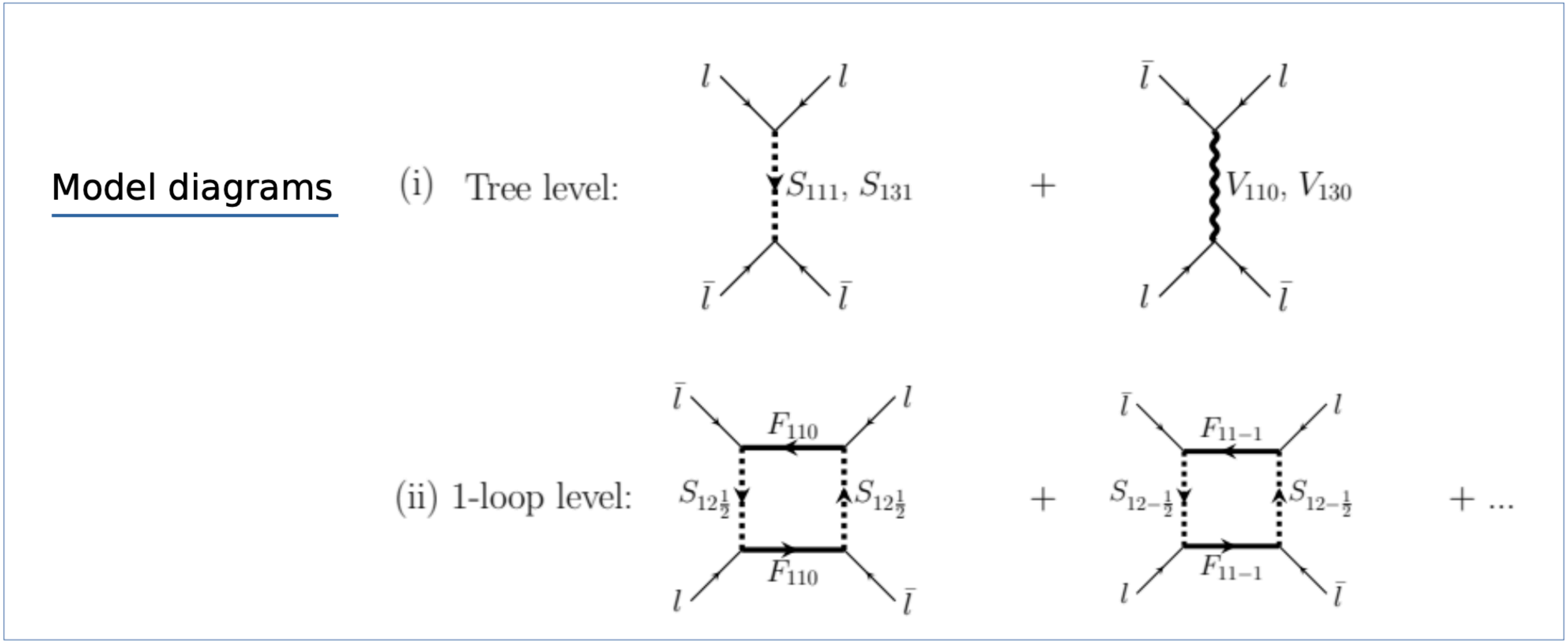
From operators to models

*3.) Insert **all possible representations** for scalars, fermions and vectors (i.e. specific particles)*

→ *Model diagrams*

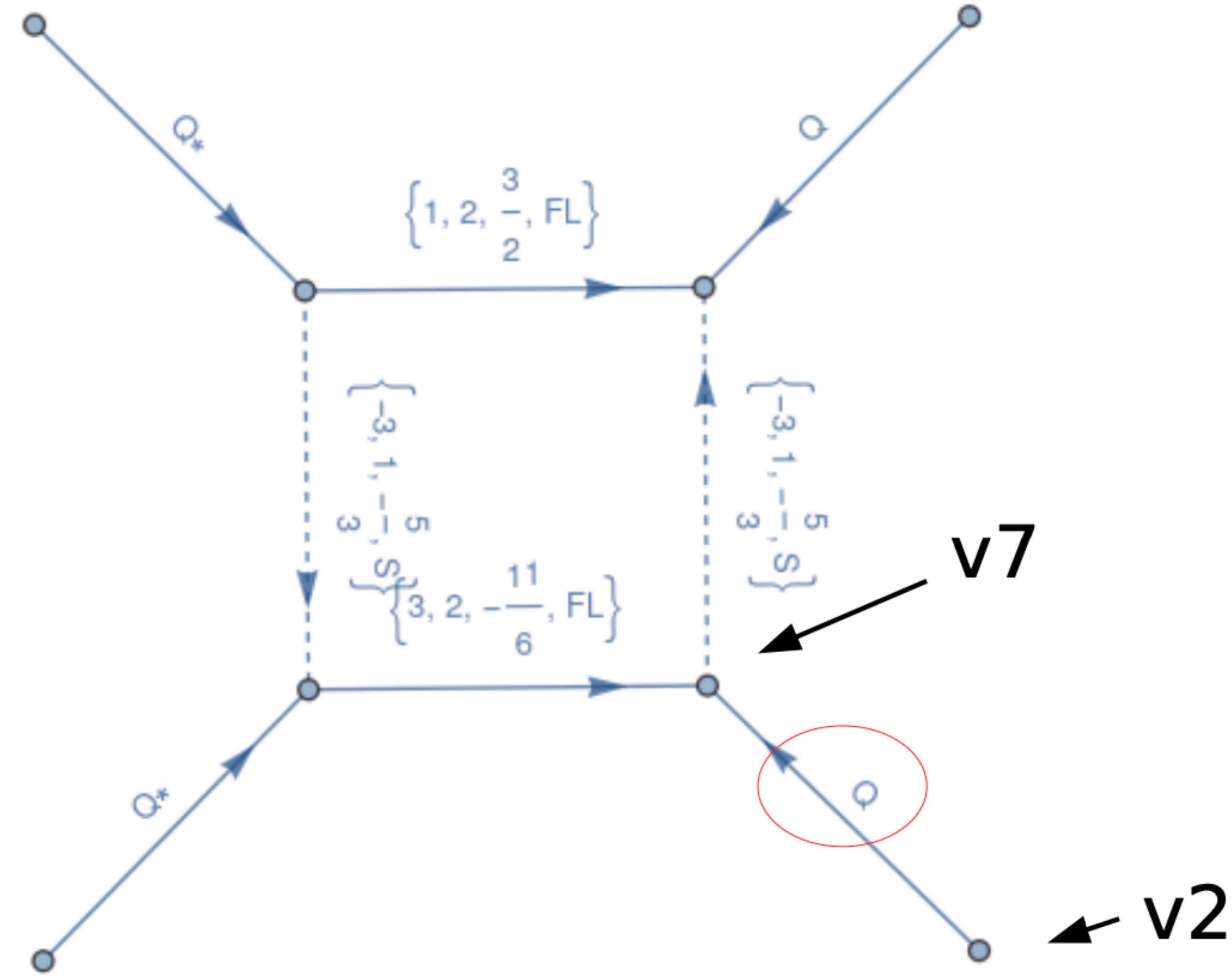
Notation:





From operators to models

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

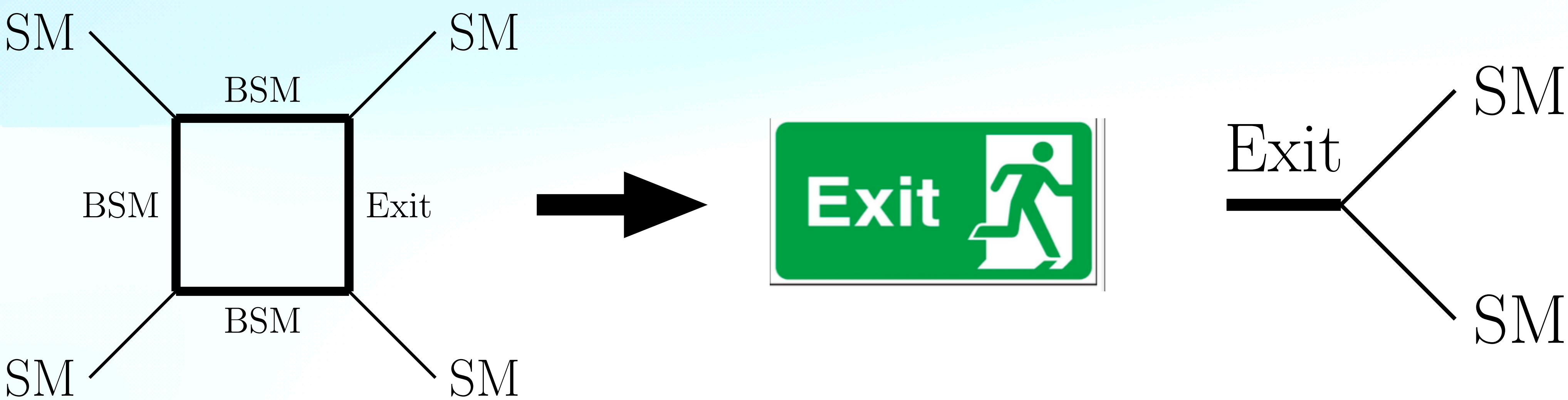
0	0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$
0	0	0	0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0
0	0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0
0	0	0	0	$\{-3, 2, -\frac{1}{6}, FR, 1\}$	0	0	0
0	0	0	$\{3, 2, \frac{1}{6}, FL, 1\}$	0	$\{-3, 1, -\frac{5}{3}, S, 0\}$	0	$\{1, 2, \frac{3}{2}, FL, 0\}$
0	0	$\{3, 2,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

Choices for LHC testable UV models

1. **Exclude** all models of a 1-loop generated 4F operator whose particle content produce any other 4F operator at **tree-level**

2. Must avoid **stable charged relics**

   a) models with **exits** (BSM particles that can decay at tree-level into SM particles): [arxiv: 2207.13714]



   b) models with electrically neutral **DM candidates**: [arxiv:2302.03485]

3. **No internal vectors** in the loop

4. **No SM Yukawa couplings** in the loop (suppressed)

4. Example UV models

Patterns and minimal models

Classify three types of scenarios

- **Lepton-specific**: strong low energy limits
- **Quark-specific**: interesting at the LHC
- **Generic or hybrid**

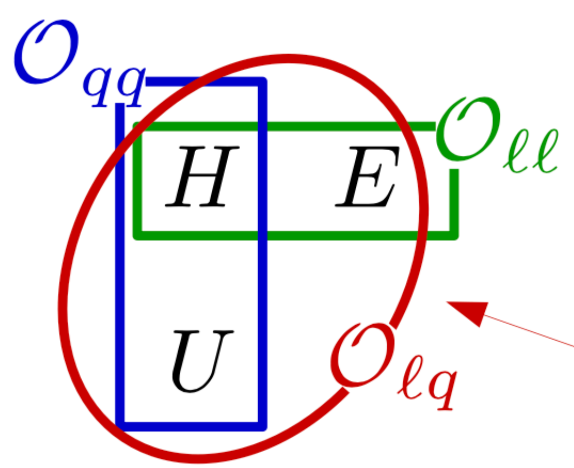
Minimal models:

- **Lepton-/Quark-**specific: 1 BSM fermion + 1 SM Higgs
- **Hybrid** models: at least 2 BSM particles

Toy example

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

SM



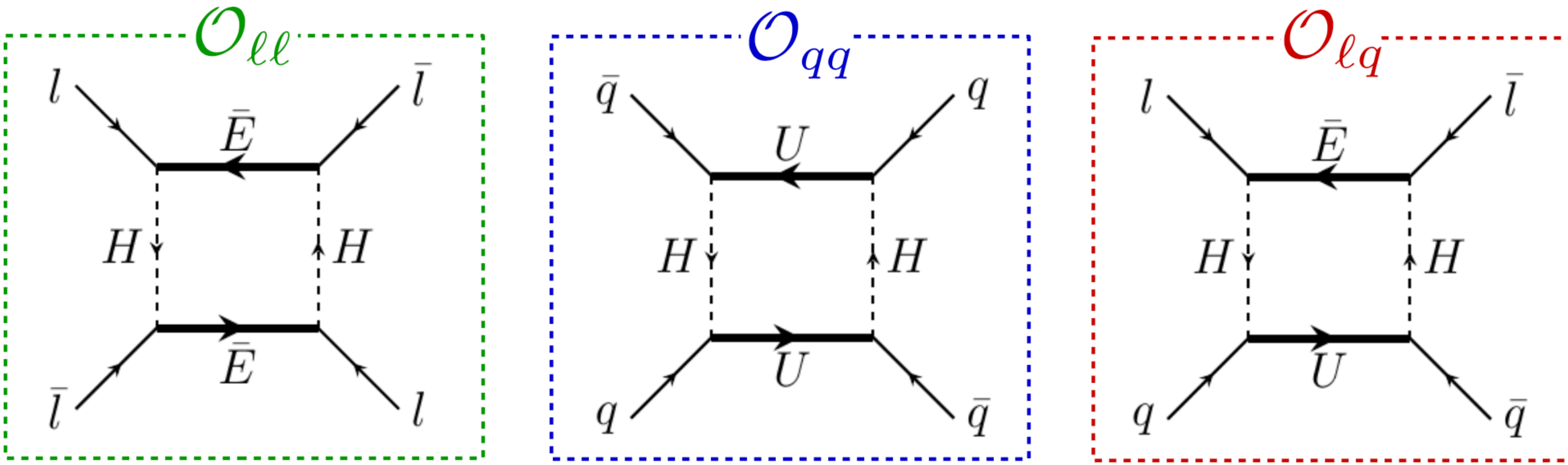
Vector-like
$E = (1, 1, -1)$

Vector-like
$U = (3, 1, 2/3)$

1-loop boxes contribution to a 4F operator generated by each set of fields

EU model

Matching



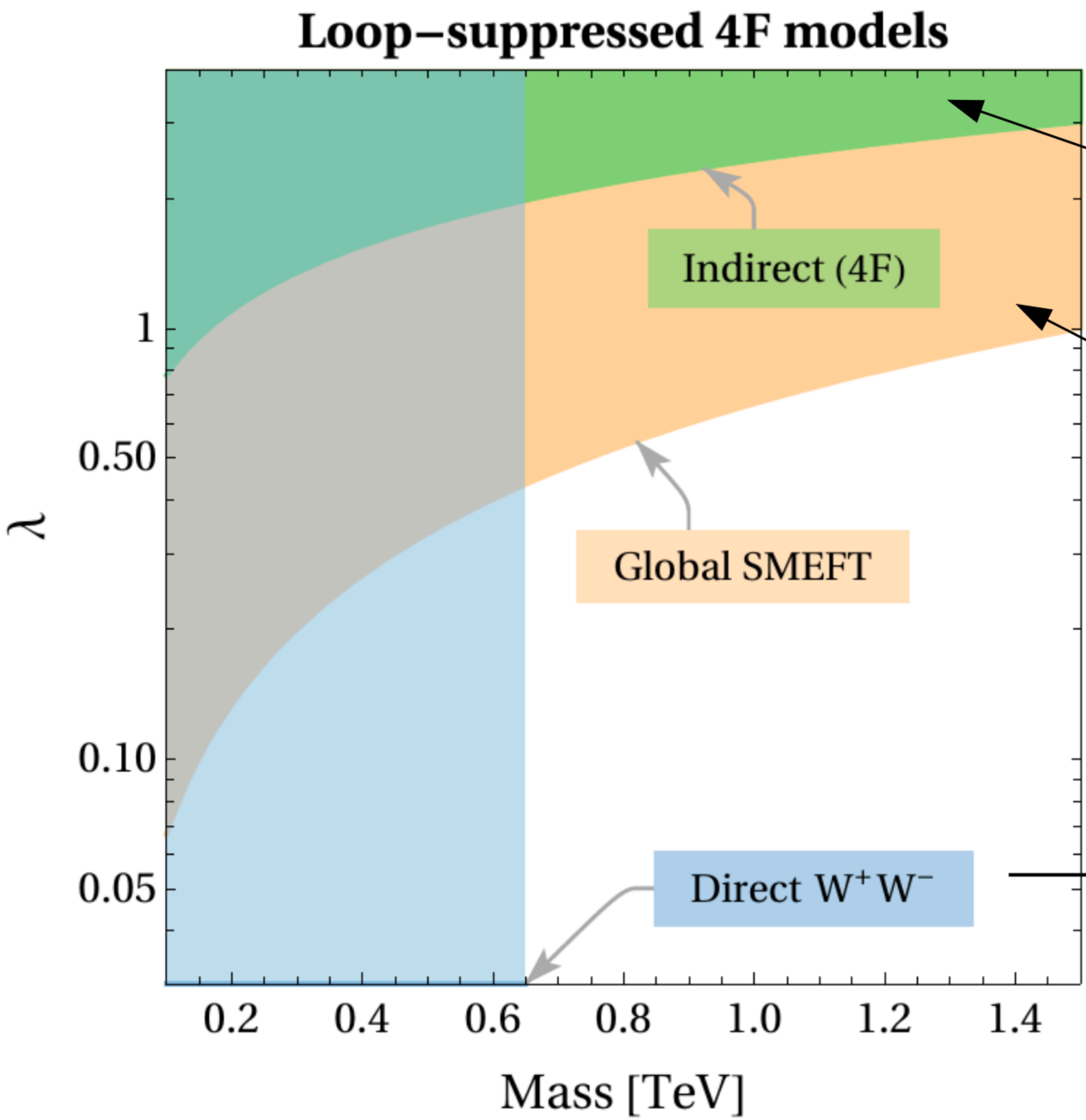
Operator	General expression
c_{ll}	$-\frac{1}{8}\frac{1}{16\pi^2}\frac{\lvert\lambda_E\rvert^4}{m_E^2}$
$c_{lq}^{(1)}$	$\frac{1}{8}\frac{1}{16\pi^2}\frac{\lvert\lambda_E\rvert^2\lvert\lambda_U\rvert^2\log\left(\frac{m_E^2}{m_U^2}\right)}{m_E^2-m_U^2}$
$c_{lq}^{(3)}$	$-\frac{1}{8}\frac{1}{16\pi^2}\frac{\lvert\lambda_E\rvert^2\lvert\lambda_U\rvert^2\log\left(\frac{m_E^2}{m_U^2}\right)}{m_E^2-m_U^2}$
$c_{qq}^{(1)}$	$-\frac{1}{16}\frac{1}{16\pi^2}\frac{\lvert\lambda_U\rvert^4}{m_U^2}$
$c_{qq}^{(3)}$	$-\frac{1}{16}\frac{1}{16\pi^2}\frac{\lvert\lambda_U\rvert^4}{m_U^2}$

Matching of the boxes (for SM Yukawa = 0), with MatchMakerEFT *[Carmona et al 2022]*

Limit of equal masses and couplings:

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

Interplay direct vs. indirect search



4F constraints at low energies
$m_{EU} > 0.17\,|\lambda_{EU}|^2$ TeV

Global SMEFT fits
$m_{EU} > |\lambda_{EU}| 1.5$ TeV

Direct search
$m_{EU} > 650$ GeV

Summary

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- We have focused on identifying UV scenarios leading to ***loop-suppressed 4F operators***

- We presented a ***diagrammatic approach*** to classify the topologies, diagrams and models leading to loop-suppressed 4F operators

- We classified the 4F operators as
  - ***lepton-specific*** ***(strong low energy limits)***
  - ***quark- specific*** ***(interesting at colliders)***

  or mixed operators to connect with phenomenology

- We found an interesting complementarity between constraints from indirect low-energy constraints and direct searches at the LHC for exits and an interplay between the CMB DM relic abundance for DM models

- Outlook: dim-8!


Thank you!
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