UNIVERSIDAD DE GRANADA

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Plan de Recuperación, Transformación y Resiliencia

AGENCIA ESTATAL DE INVESTIGACIÓN

Mapping the SMEFT onto BSM models

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Universidad de Granada

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Works

"Mapping the SMEFT to discoverable models"
JHEP 09 (2022) 229 || arXiv: 2207.13714

work with ***Fabian Esser, Veronica Sanz, Martin Hirsch***

"SMEFT goes dark: Dark Matter models for four-fermion operators"
JHEP 09 (2023) 081 || arXiv: 2302.03485

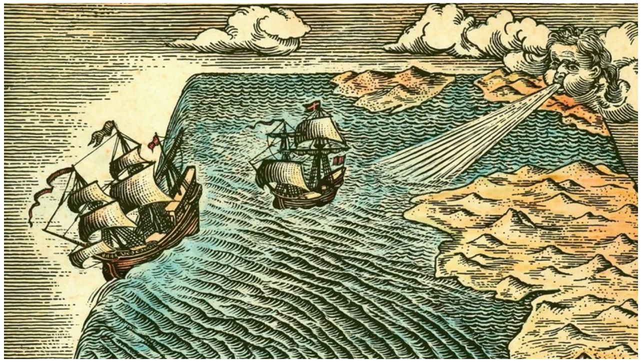
Special guests:

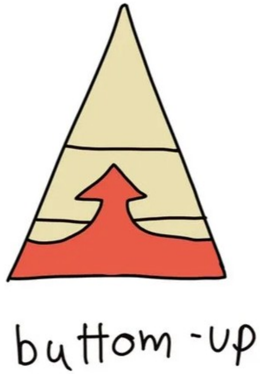
"Neutrino masses, flavor anomalies, and muon g-2 from dark loops"
with ***Pablo Escribano*** *and* ***Avelino Vicente****. PRD 107 (2023) 3, 035034 || arXiv: 2302.03485*

"Tree-level UV completions for NR-SMEFT d=6 and d=7 operators"
with ***Rebeca Beltrán*** *and* ***Martin Hirsch****. JHEP 08 (2023) 166 || arXiv: 2306.12578*

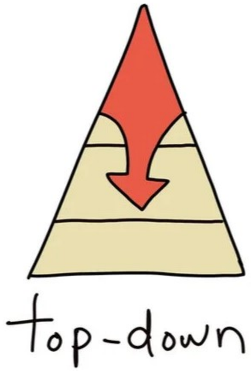
Warm-up – SMEFT

The Effective path to physics beyond the SM:





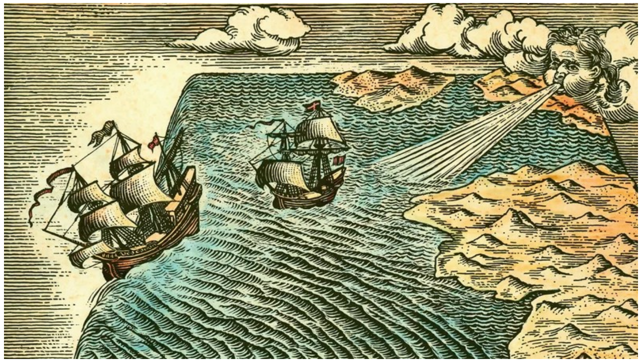
- *Model-independent (global fits)*
- *Build basis of operators without making any connection to a UV complete theory*
- *Wilson coefficients entirely unspecified*

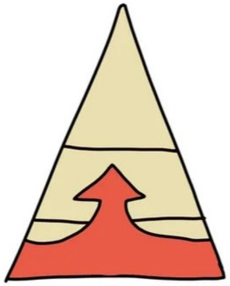


- *Matching: calculate its effects to a low energy EFT*
- *Has to be done on a model-by-model basis*
- *Wilson coefficients defined by variables of full theory*

Warm-up – SMEFT

The Effective path to physics beyond the SM:





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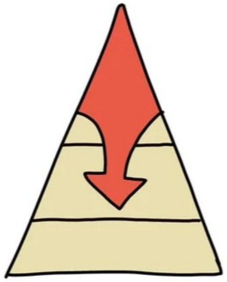

Can be automated and classified

The model generator

Ideally . . .

A code that can give us all models that can contribute to a specific experimental observable at certain order in the EFT expansion

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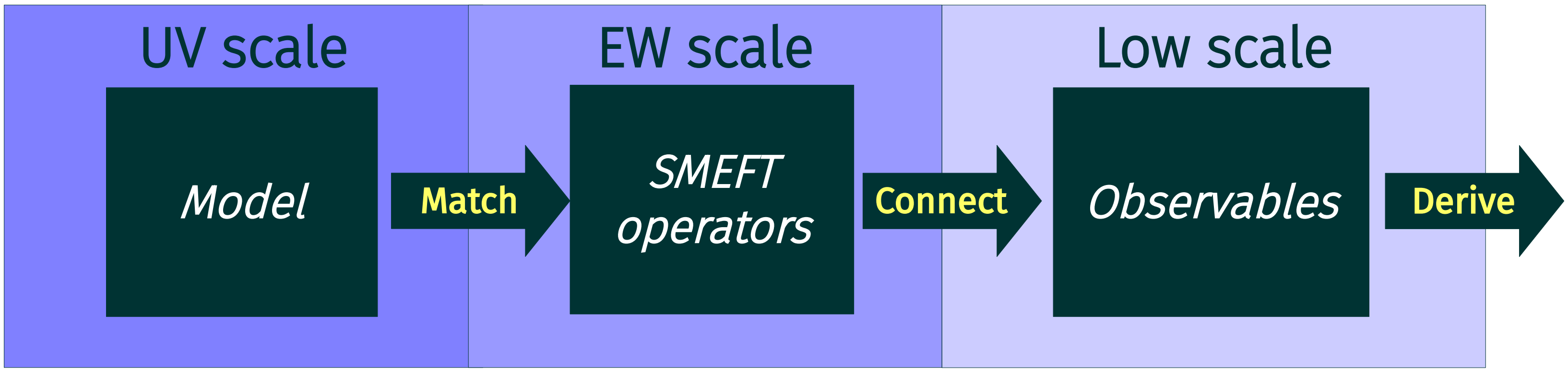
We need to map your EFT (or a part of it) to UV models

Automate this approach to point towards:

- Model discrimination
- Classification of models
- UV dictionaries
- Find new BSM models
- Look for patterns in the SMEFT

. . .

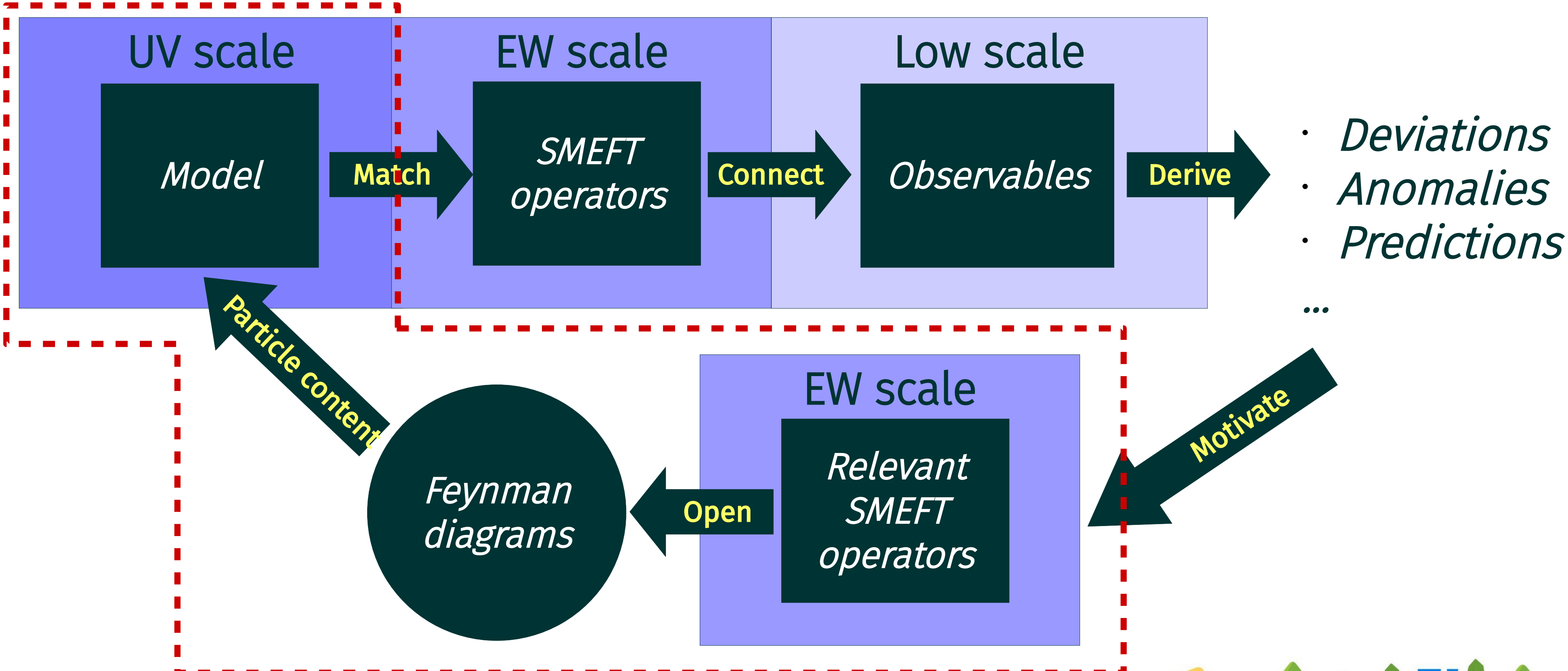
Method



- *Deviations*
- *Anomalies*
- *Predictions*

...

Method

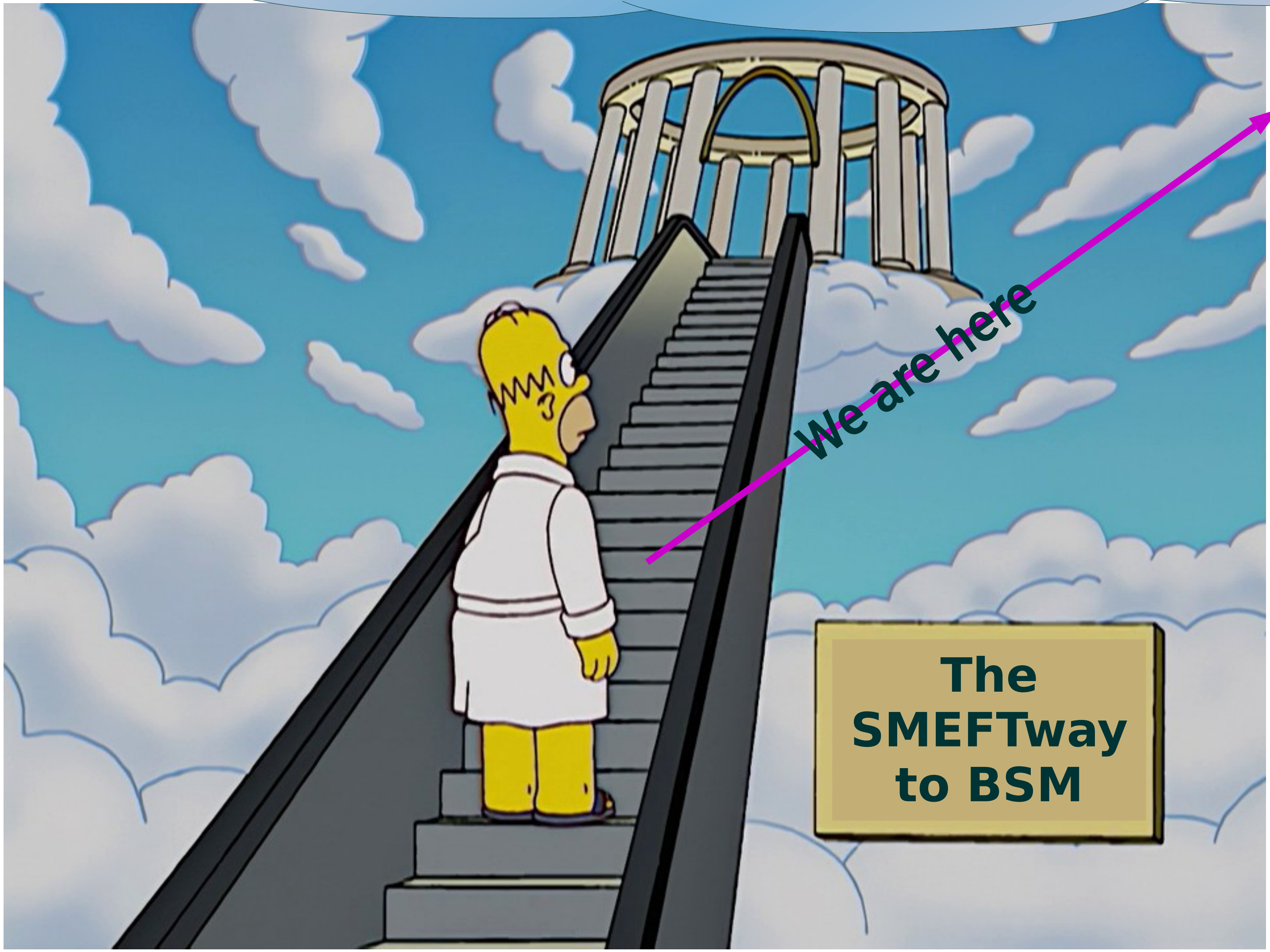


Our approach here:

[Similar approaches in Banerjee et al 2020; Das Bakshi et al 2021; Naskar et al 2022]

Motivation

A code that can give us all models that can contribute to a specific experimental observable at certain order in the EFT expansion



- *Right now... it works!!*
- *Though needs work to make it more "usable" and lacks some pheno input/options too.*
- *Not public... yet!*

A model-building example

"Neutrino masses, flavor anomalies, and muon g-2 from dark loops"
with Pablo Escribano and Avelino Vicente

PRD 107 (2023) 3, 035034 // arXiv: 2302.03485

A BSM example

Neutrino masses and mixings at one-loop

Flavor anomalies in the $b \to sll$ at one-loop

Muon (g-2) anomaly

Viable dark matter candidate

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→ Weinberg op.

Flavor anomalies in the b→sll at one-loop

↓

Olq, Oqe, Olu, ...

Muon (g-2) anomaly

→ EMD op. with a 1LPI diagram
(nice connection at the level of topologies)

Viable dark matter candidate

A model to fit them all

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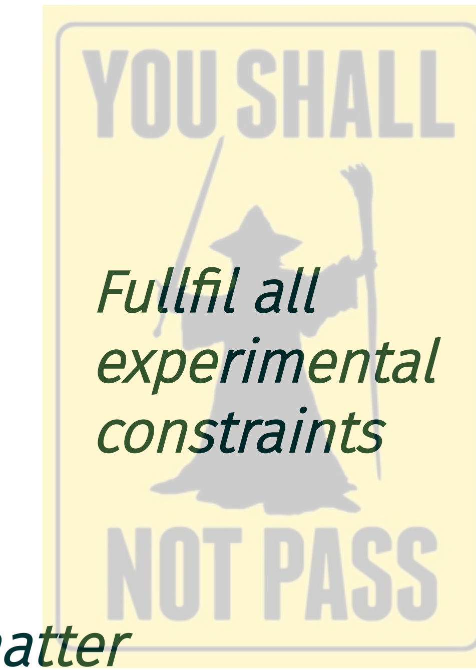


Fullfil all experimental constraints

Muon (g-2) anomaly

→ EMD op. with a 1LPI diagram
(nice connection at the level of topologies)

Viable dark matter candidate

[Some works on 1-loop b→sll and some of the other anomalies:
Da Huang et al 2020; Arcadi et al 2021; Becker et al 2021;
Freitas et al 2022; Capucha et al 2022]

The (one?) model

PRD 107 (2023) 3, 035034
arXiv: 2302.03485

	gen	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$\mathbb{Z}_2$
η	2*	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$-$
S	1	$\mathbf{3}$	$\mathbf{2}$	$1/6$	$-$
ϕ	1	$\mathbf{1}$	$\mathbf{1}$	-1	$-$
N	1*	$\mathbf{1}$	$\mathbf{1}$	0	$-$

← *Dark Matter!*

← *Scalar Leptoquark* $S = \begin{pmatrix} S_{2/3} & S_{-1/3} \end{pmatrix}$

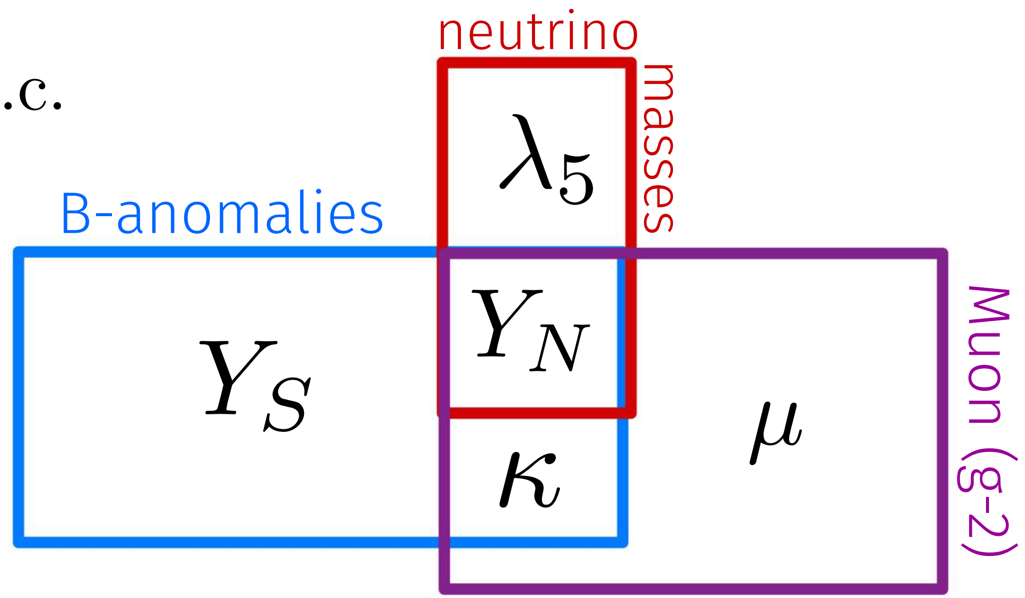
* *One massless neutrino*

[Scenario of Arnan et al 2017]

$$-\mathcal{L}_{\rm NP} = Y_N\, \overline{N}\, \ell_L\, \eta + Y_S\, \overline{q}_L\, S\, N + \kappa\, \overline{N^c}\, e_R\, \phi^\dagger + \frac{1}{2} M_N\, \overline{N^c}\, N + \text{h.c.}$$

$$\mathcal{V}_{\rm NP} \supset \frac{\lambda_5}{2} \left(H^\dagger \eta\right)^2 + \mu\, H\, \eta\, \phi + \text{h.c.}$$

*Of course, there are new couplings, but **linked** through the observables*

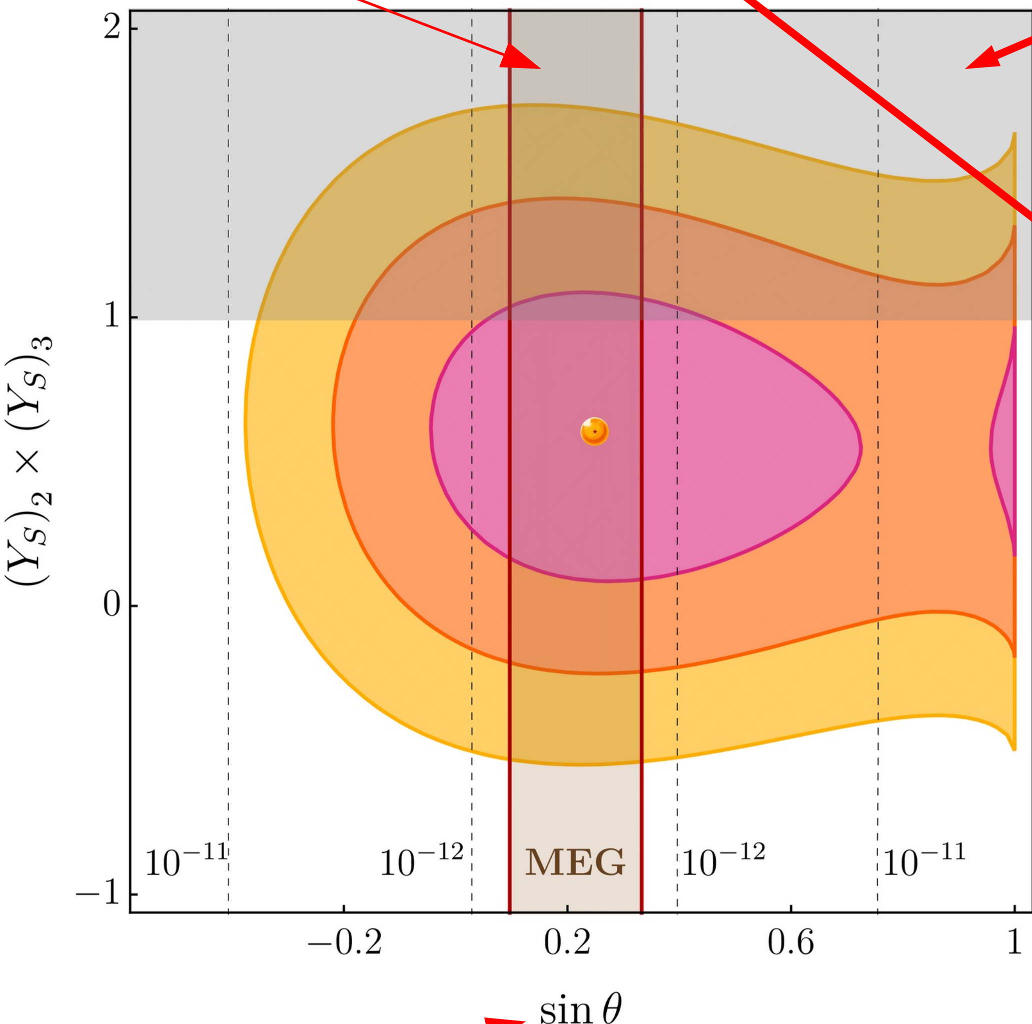


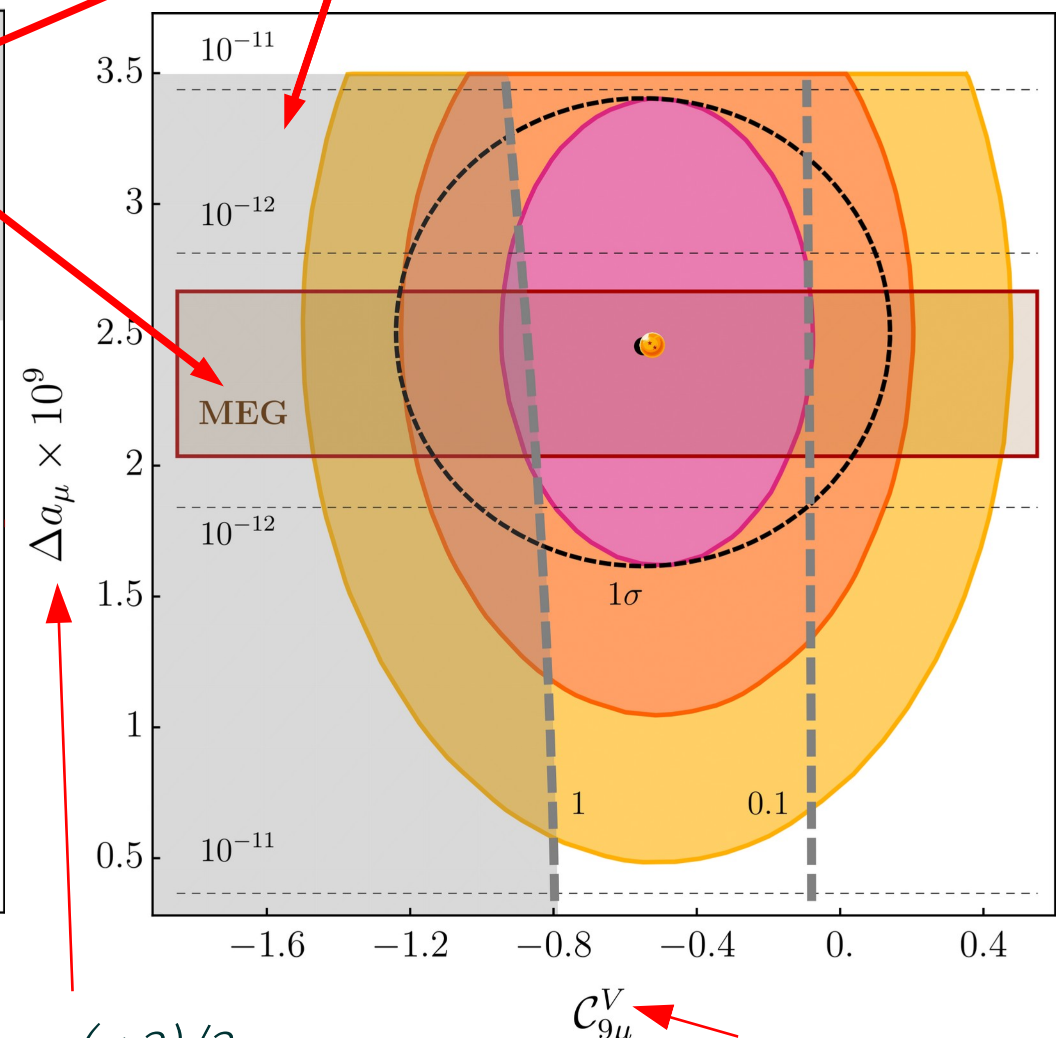
Results

PRD 107 (2023) 3, 035034
arXiv: 2302.03485

$\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$

$\mathrm{BR}(b \to s\gamma) = (3.49 \pm 0.19) \times 10^{-4}$





Only free parameter in ***Y**$_N$*

(R matrix angle)

Muon (g-2)/2

Coefficient of
$(\bar{s}\gamma_\nu P_L b)(\bar{\mu}\gamma^\nu \mu)$

Another (longer) example:
Patterns in the SMEFT

"Mapping the SMEFT to discoverable models"
*with **Fabian Esser, Martin Hirsch** and **Veronica Sanz***
JHEP 09 (2022) 229 // arXiv: 2207.13714

Motivation

Identify classes of UV models which could be discovered at the LHC, despite contributing to precise low-energy measurements

↓

We need to map the SMEFT (or a part of it) to UV mode

Motivation

Identify classes of UV models which could be discovered at the LHC, despite contributing to precise low-energy measurements

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Automate this approach to point towards:

- *Model discrimination*
- *Classification of models*
- *UV dictionaries*
- *Find new BSM models*

Look for patterns in the SMEFT

Scenarios where information from low-energy precision measurements and collider searches would be complementary

Motivation

Identify classes of UV models which could be discovered at the LHC, despite contributing to precise low-energy measurements

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The tightest SMEFT bounds come from operators involving four fermions (4F)

[Falkowski et al 2017]

Find new BSM models

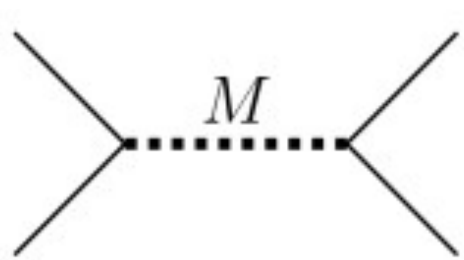
Look for patterns in the SMEFT

Scenarios where information from low-energy precision measurements and collider searches would be complementary

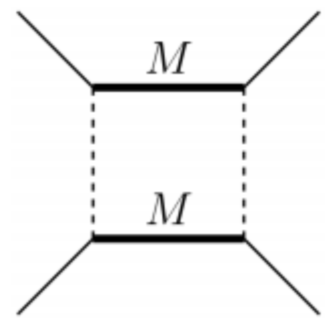
Motivation

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

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



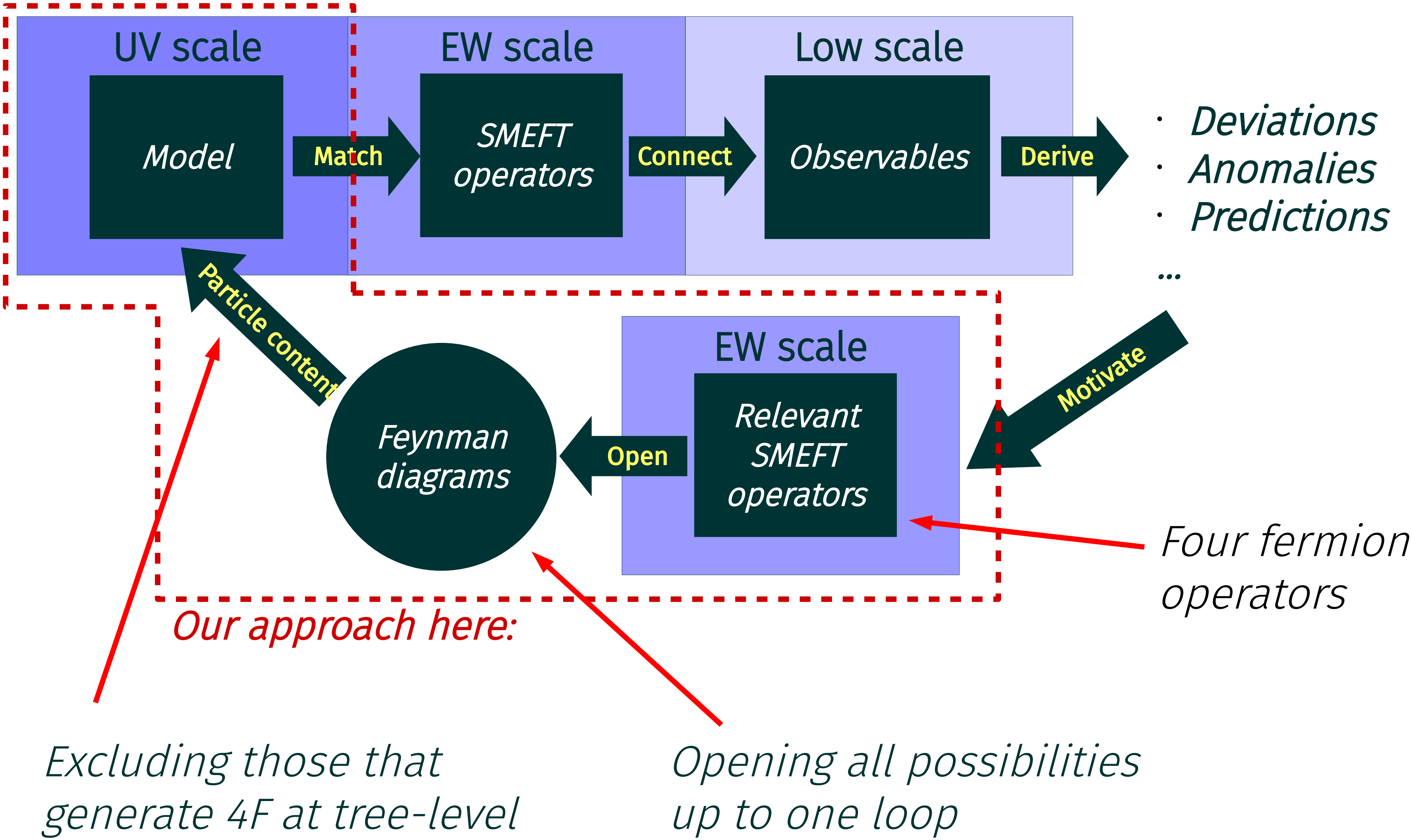
$$c_{4F}^{tree} \propto \frac{1}{M^2}$$



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

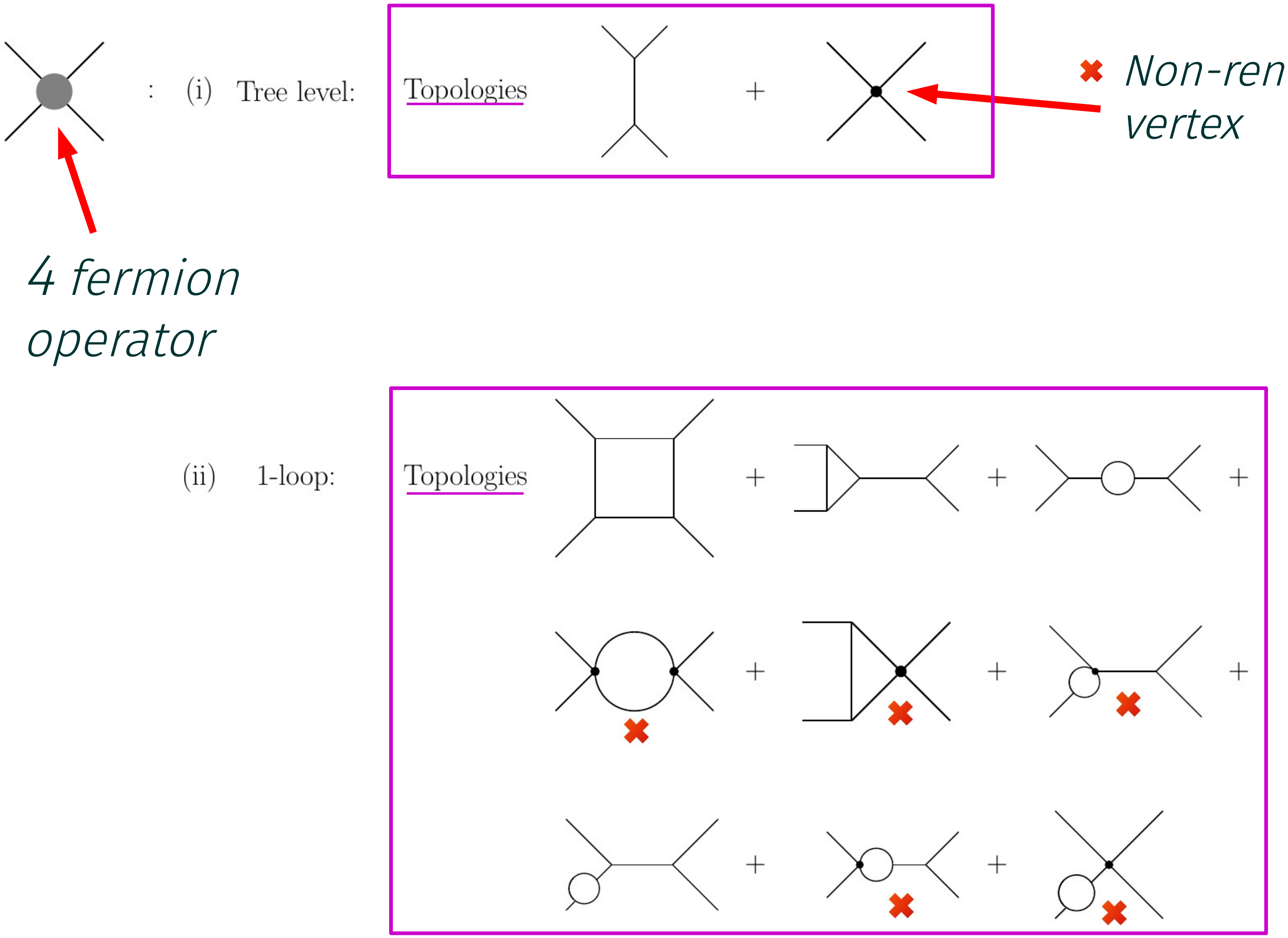
*The new resonances, appearing only at 1-loop, could be much lighter, directly **accessible at colliders***

Method



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

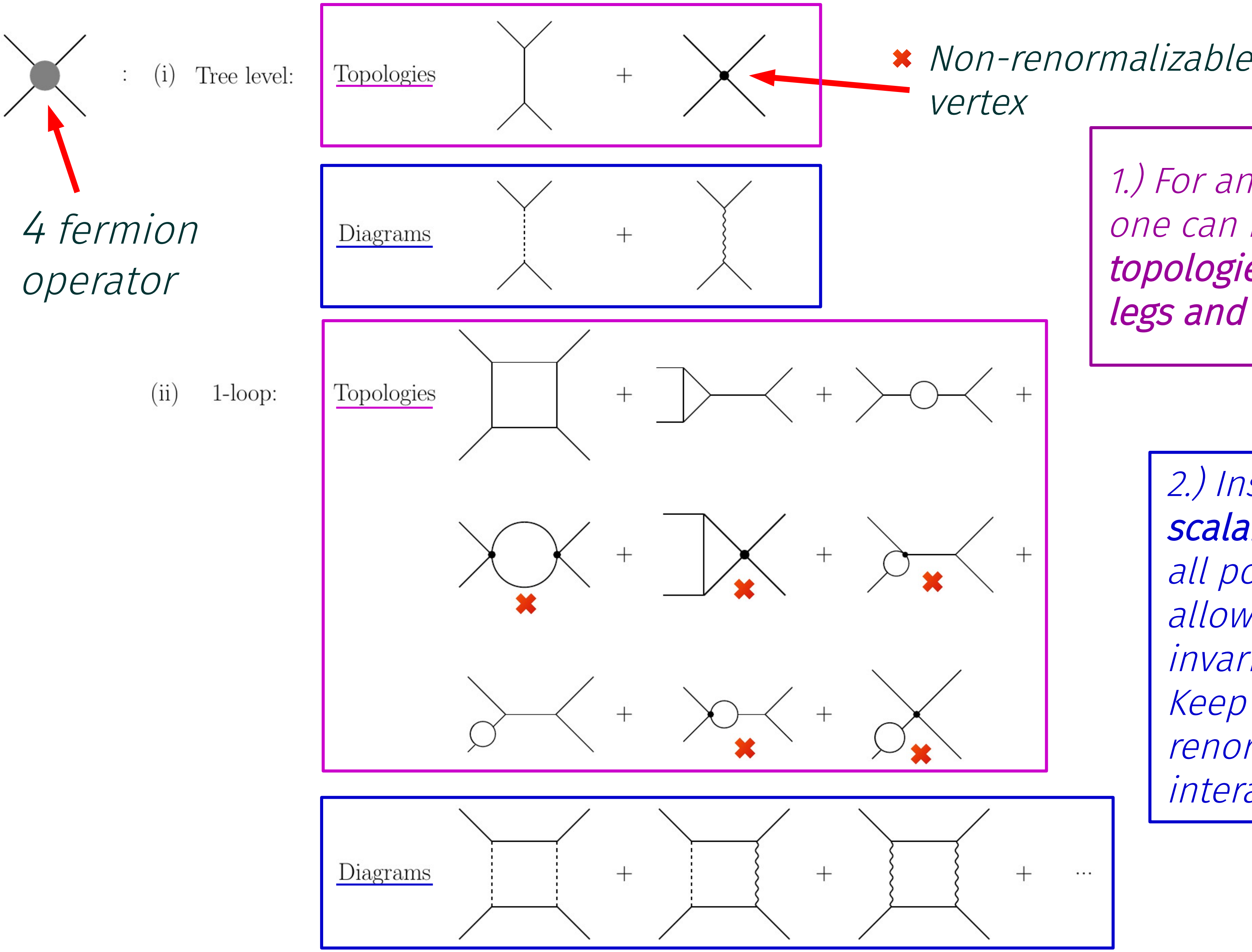
From operators to models "diagrammatically"



✖ Non-renormalizable vertex

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

From operators to models “diagrammatically”



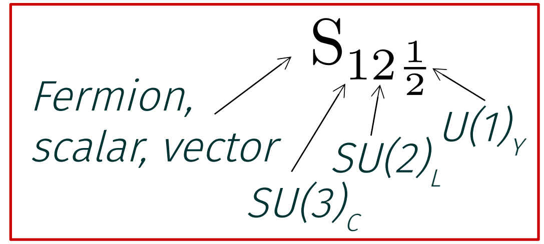
1.) For any given operator, one can first find all ***topologies with n external legs and k loops***

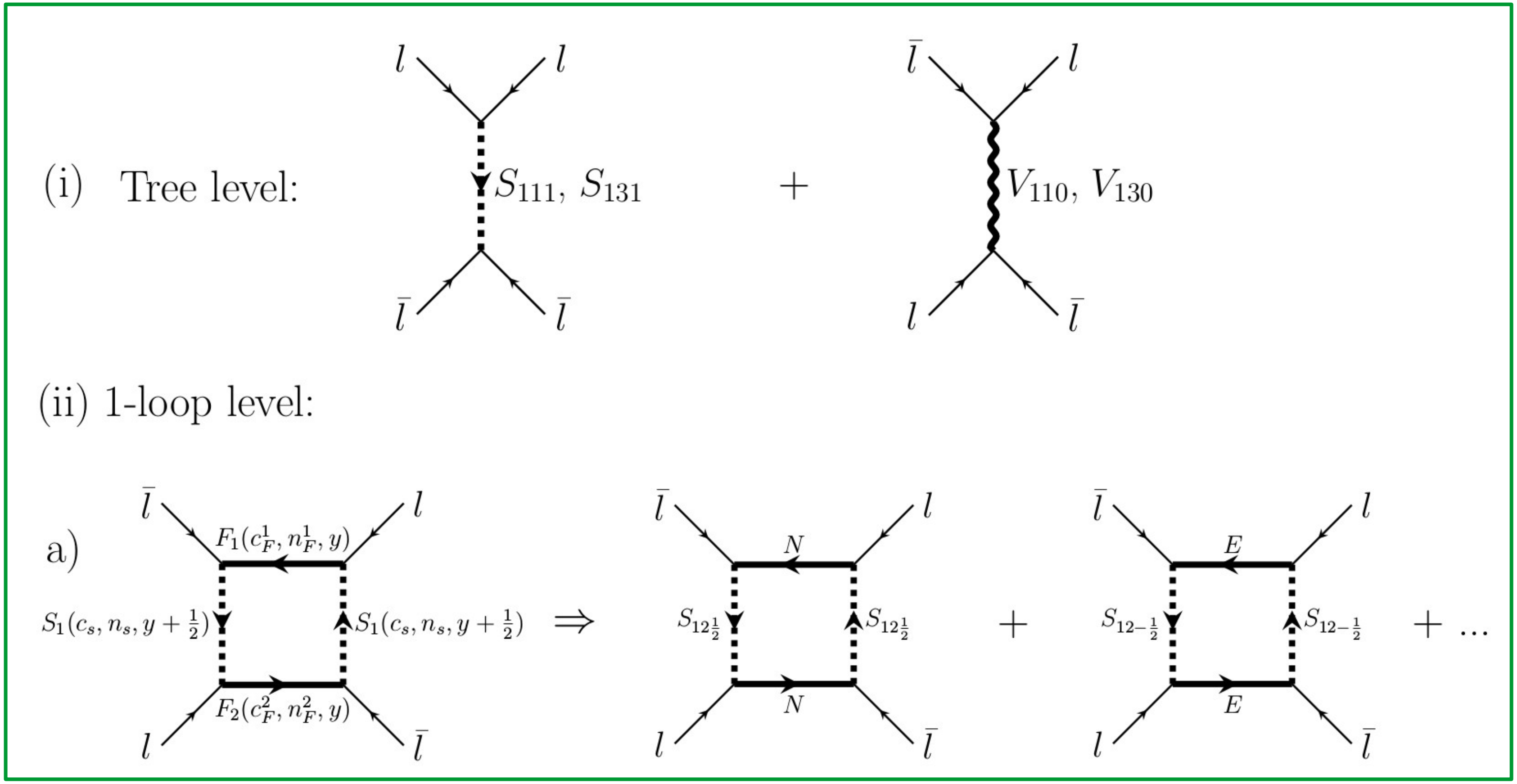
2.) Insert ***fermions, scalars and vectors*** *in all possible ways allowed by Lorentz invariance.*
Keep only renormalisable interactions.

From operators to models "diagrammatically"

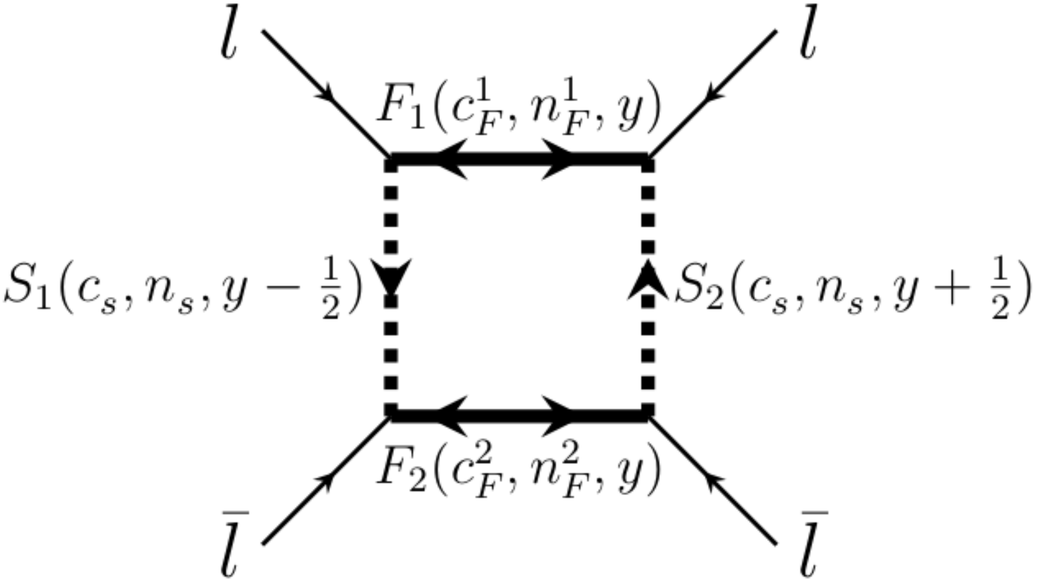
3.) Insert ***all possible representations*** *for scalars, fermions and vectors (i.e. specific particles)*

Notation:





Let's consider a very simple symmetric example: 1-loop box Oll



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 $\mathbf{c_S} = \mathbf{1}$)

$\cdots$

How many 1-loop models are there?

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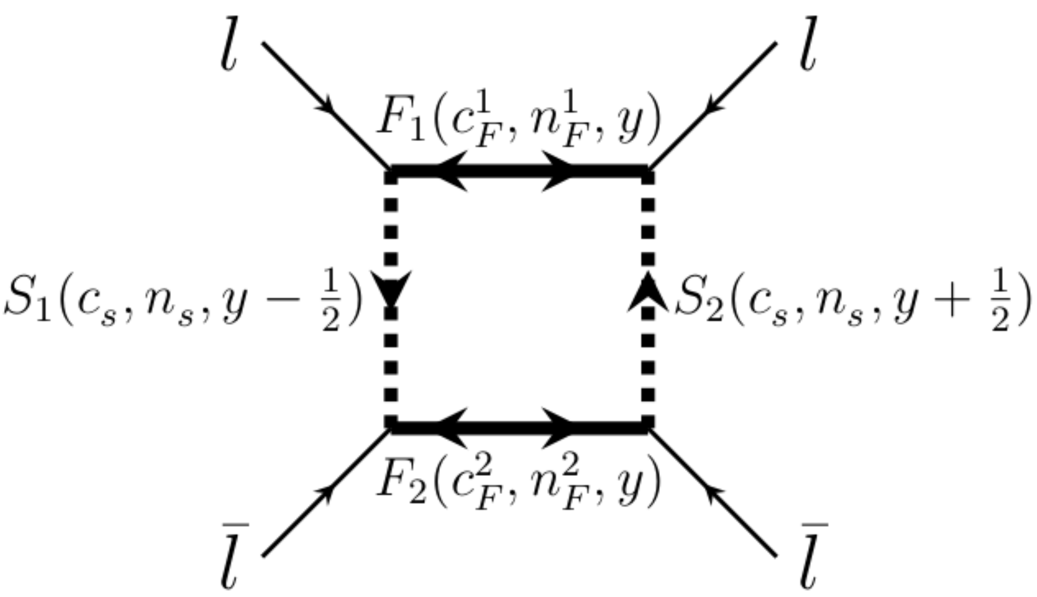

Are there an infinite series of models !?

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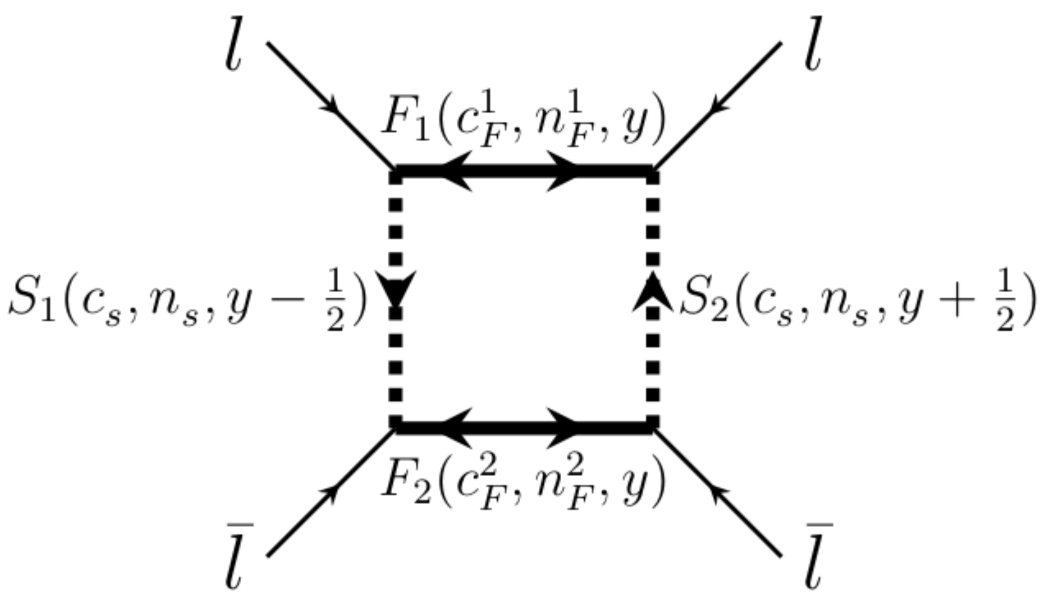

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$\cdots$

Are there an infinite series of models !?

No! Cutoffs!!

· Phenomenological constraints

· Theoretical arguments

· Motivation

Selection criteria

Phenomenological contraints:

i.e. BSM particle that can decay to SM particles only.

- *Avoid models with stable charged relics*
  - *Models with "**exits**" in the loop*
  - *Models with **dark matter** candidate in the loop*

[Bottaro et al 2021+2022]

*Equiv. to the list of particles that can generate the d = 6 SMEFT at tree-level. **Granada dictionary!!** [de Blas et al 2018]*

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[de Blas et al 2018]

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Motivation:

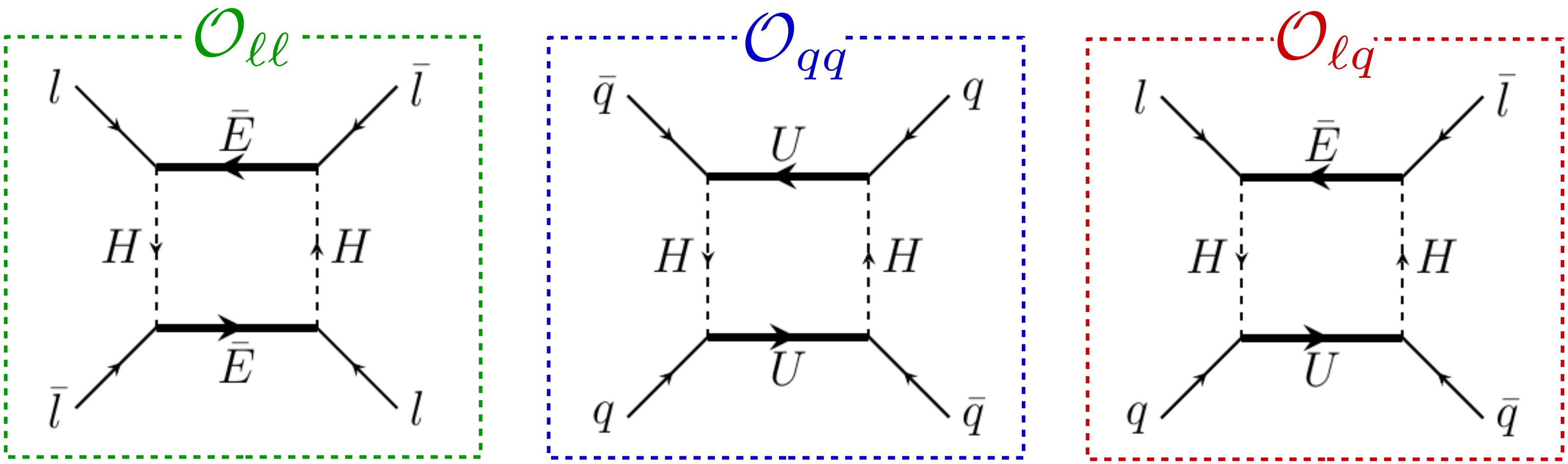
- *Exclude all models of a one-loop generated 4F operator whose particle content produces any other 4F operator at tree-level*
  - *directly accessible at the LHC*

“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

- *Warsaw basis:* ***25 baryon conserving 4F operator*** *structures at d=6 (no flavour indices)*
- *For simplicity, here only models up to colour triplets, SU(2) doublets and hypercharge 4.* *(numbers saturate at maxSU3=8, maxSU2=6 and maxY=5)*
- ***Usage:*** *for example, the third row states that 18 models open O_{ee} out of which 1 open up Oll , 1 open Ole , 2 Oqe , …*
- *Many zeroes appear. Gives some information on the underlying UV 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 to the boxes in the limit of $\lambda_{SM}\to 0$

- *No other 4F operators are generated*
- *Only contributions come from the 1-loop boxes*

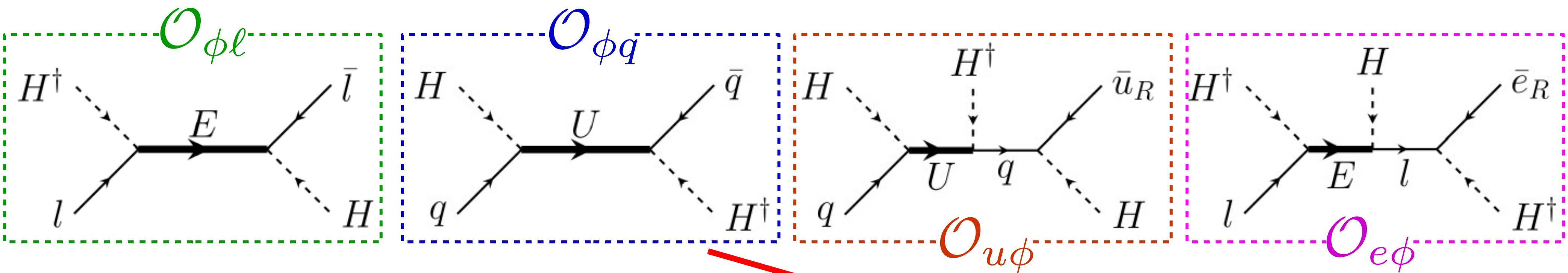
Complete matching done with ***MatchMakerEFT*** *[Carmona et al 2022]*

Equal mass and couplings limit

$$\text{EU model pattern: } c_{ll} = -c_{lq}^{(1)} = c_{lq}^{(3)} = 2\,c_{qq}^{(1)} = 2\,c_{qq}^{(3)}$$

Matching

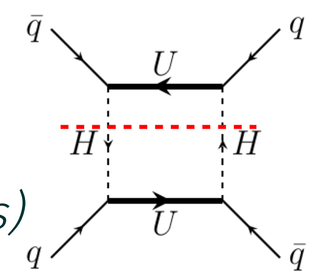
*Unavoidable contributions to **Higgs-fermion couplings**:*



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

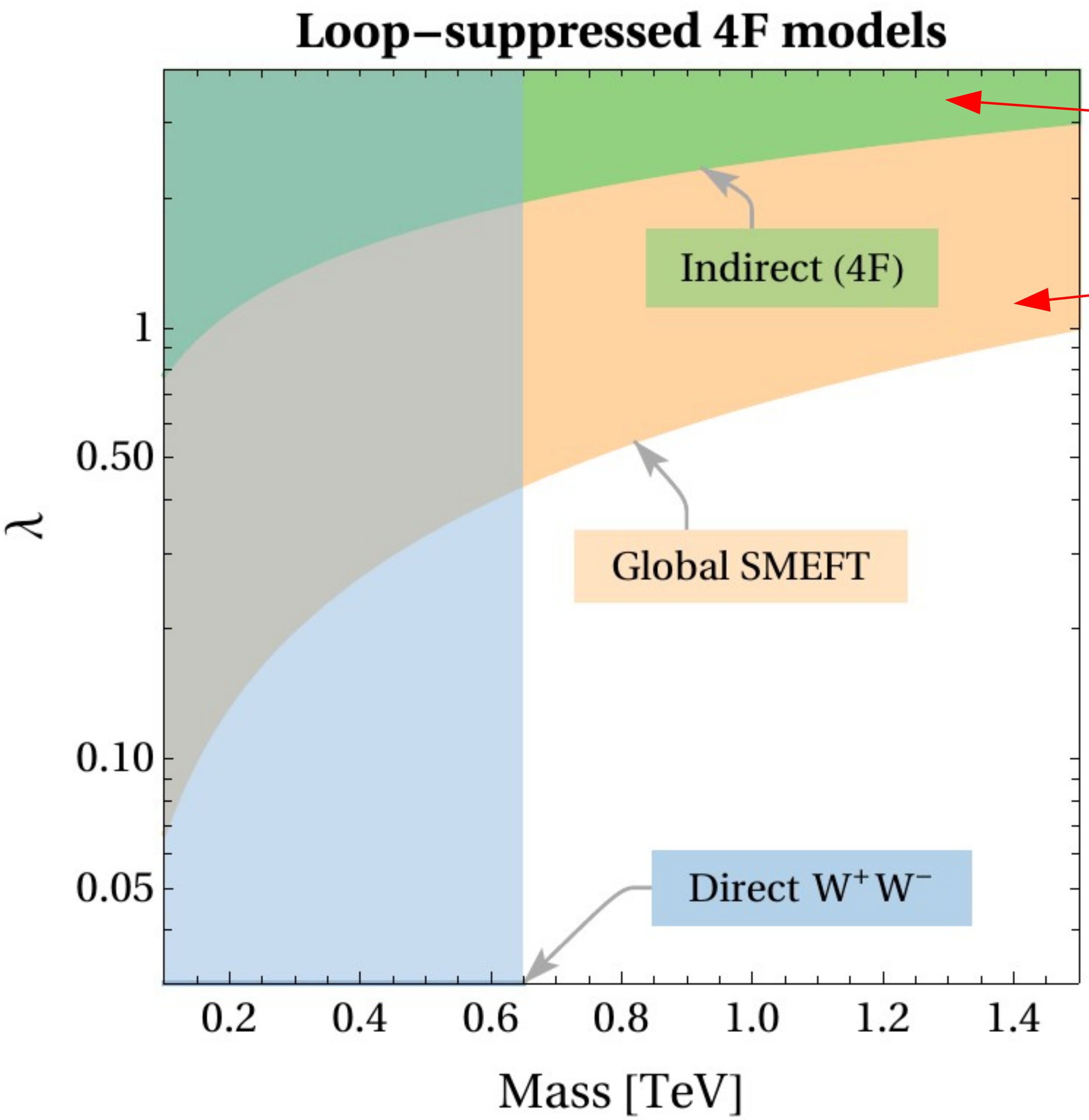
SM Yukawa suppressed (except top-quark)

They come from "cutting" the boxes, e.g. (similar for the LL boxes)



Produced at tree-level
→ stringent indirect limits for this model

Direct / Indirect interplay



4F constraints at low energies:

$$m_{EU} > 0.17\,|\lambda_{EU}|^2 \text{ TeV}$$

Global SMEFT fits

$$m_{EU} > |\lambda_{EU}| 1.5 \text{ TeV}$$

LHC direct probes provide a better handle on scenarios with relatively small coupling

DM 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}	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O_{le}	14	14	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O_{ee}	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
O_{lq}	26	0	0	26	0	0	0	0	0	0	0	26	0	0	0	0	0	0
O_{lu}	14	0	0	0	14	4	0	0	0	0	0	0	0	0	0	14	4	4
O_{ld}	14	0	0	4	4	14	0	0	0	0	0	4	0	2	4	4	4	14
O_{lequ}	24	16	24	16	16	4	24	6	18	16	6	24	6	18	8	24	8	8
O_{ledq}	24	16	24	16	4	18	4	24	16	6	16	24	4	8	18	8	6	24
O_{qe}	0	0	14	0	0	0	0	0	14	4	0	14	0	4	0	4	0	0
O_{eu}	0	0	14	0	0	0	0	0	0	14	4	0	0	0	0	14	4	4
O_{ed}	0	0	14	0	0	0	0	0	0	0	14	0	0	0	0	0	0	14
O_{qq}	4	0	0	4	0	0	0	0	0	0	0	14	0	0	0	0	0	0
O_{quqd}	4	2	2	4	2	2	2	2	2	2	2	24	24	24	24	24	24	24
O_{qu}	0	0	4	0	0	0	0	0	4	4	0	28	8	28	8	28	8	8
O_{qd}	4	0	0	4	0	4	0	0	0	0	0	28	8	8	28	8	8	28
O_{uu}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0
O_{ud}	0	0	4	0	0	0	0	0	0	4	4	0	0	0	0	28	28	28
O_{dd}	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	8

Colour scale: 0, 5, 10, 15, 20, 25

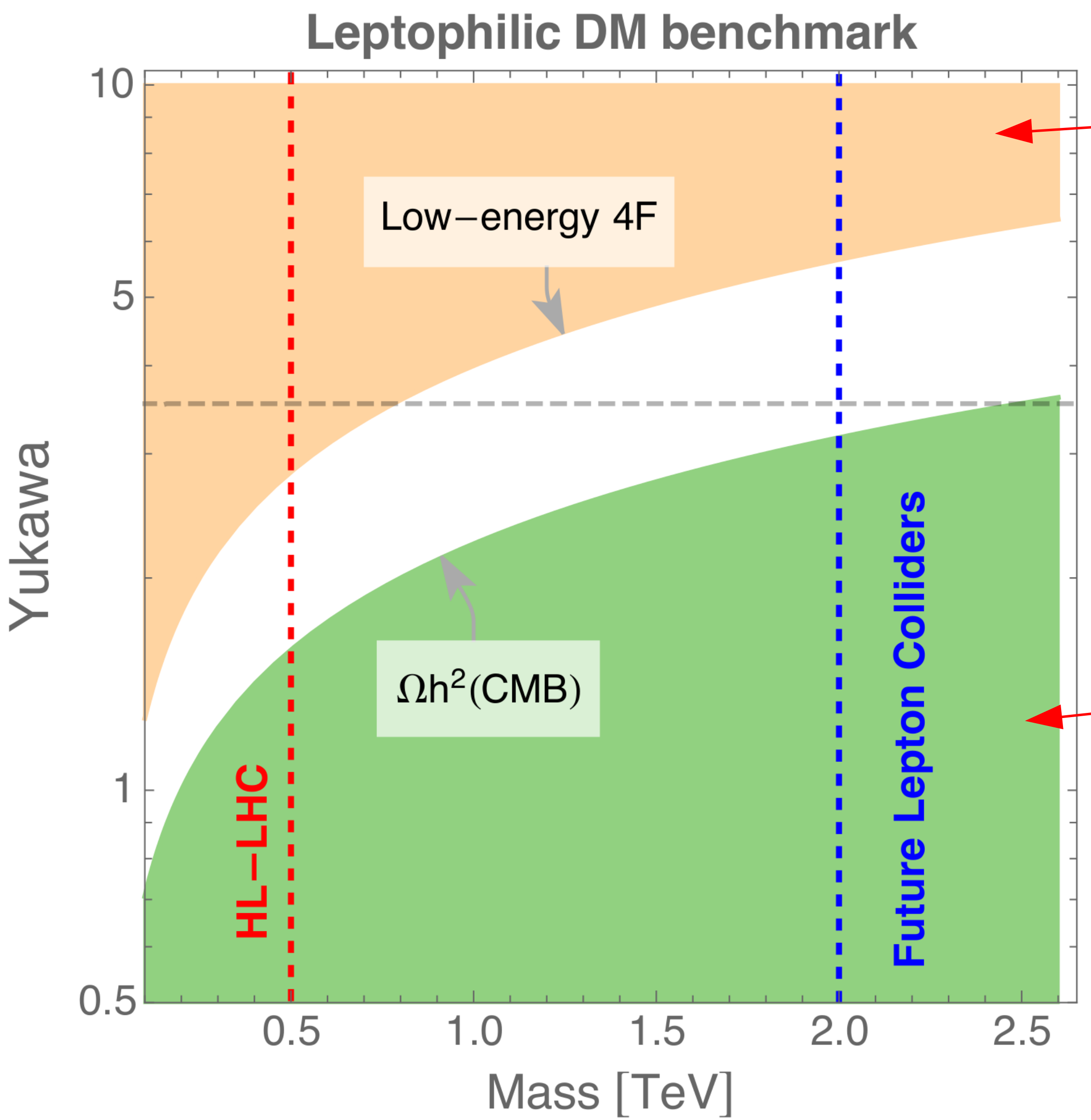
Warsaw basis:

B-conserving 4F operators

Many zeros due to the symmetry stabilizing the dark matter candidate.

For example, any model generating Oll, Oee or Ouu and containing a stable DM, don't generate any other 4F operator.

Interplay with DM



4F constraints at low energies:

$$m_F > 0.1|Y|^2 \text{ TeV}$$

(generous) perturbative limit:

$$|Y| < \sqrt{4\pi}$$

DM relic density:

$$m_F \lesssim 0.2|Y|^2 \text{ TeV}$$

Summary

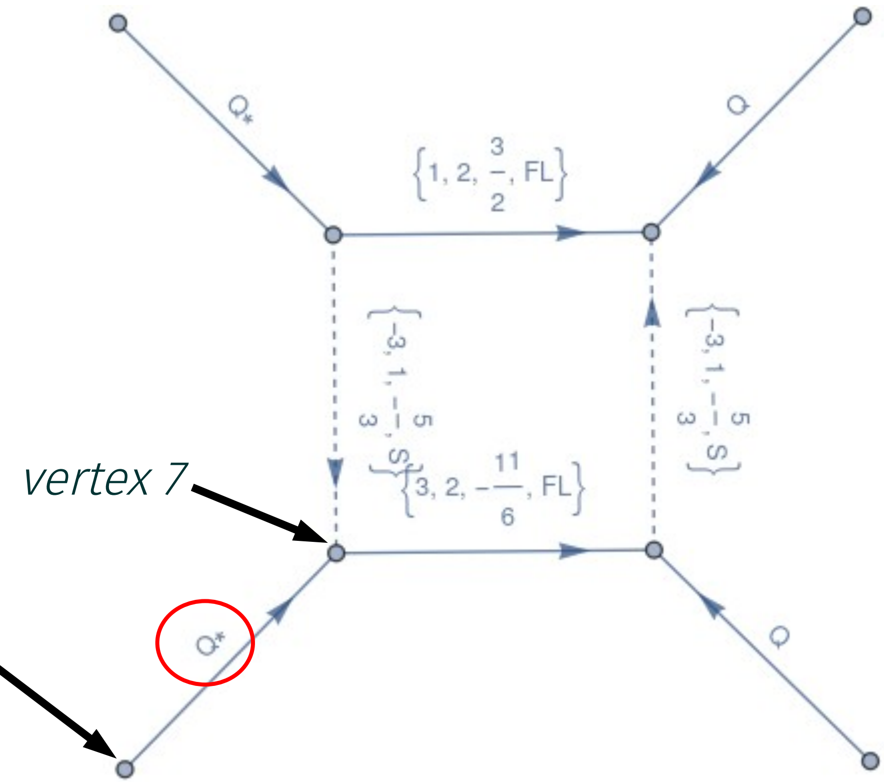
- The method is general and currently implemented in Mathematica (modulo bugs + some subtleties to be solved) ...
- Different UV models contribute to different operators. Exclude some (or identify!) model from measured operators (if any?)
  → Automation of finding UV models is possible!
- The code is very flexible and modular. You can ask for any particle content you may like and no need to go all the way to operator level, you can ask only for topologies, diagrams, ... whatever you may need.
- It is not limited to SMEFT, can be done for any operators. We have already generate dictionaries for NR-SMEFT, but also possible for DM-SMEFT and other EFTs, as well as going to more loops and dimensions.
- Discussed here 4-fermion operators at 1-loop level.

Thank you!!

Backup

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

Motivation

*The tightest SMEFT bounds come from operators involving **four fermions (4F)***

[Falkowski et al 2017]

Precise low-energy measurements:
- neutrino scattering
- e^+e^- colliders
- atomic parity violation
- hadron decays
- ...

For example:

$(ee)(qq)$

	$[c^{(3)}_{\ell q}]_{1111}$	$[c_{\ell q}]_{1111}$	$[c_{\ell u}]_{1111}$	$[c_{\ell d}]_{1111}$	$[c_{eq}]_{1111}$	$[c_{eu}]_{1111}$	$[c_{ed}]_{1111}$
CHARM	-80 ± 180	700 ± 1800	370 ± 880	-700 ± 1800	x	x	x
APV	27 ± 19	$\mathbf{1.6 \pm 1.1}$	$\mathbf{3.4 \pm 2.3}$	$\mathbf{3.0 \pm 2.0}$	$\mathbf{-1.6 \pm 1.1}$	$\mathbf{-3.4 \pm 2.3}$	$\mathbf{-3.0 \pm 2.0}$
QWEAK	7.0 ± 12	-2.3 ± 4.0	-3.5 ± 6.0	-7 ± 12	2.3 ± 4.0	3.5 ± 6.0	7 ± 12
PVDIS	-8 ± 12	24 ± 35	38 ± 48	-77 ± 96	-77 ± 96	-12 ± 17	24 ± 35
SAMPLE	-8 ± 45	x	-17 ± 90	17 ± 90	x	-17 ± 90	17 ± 90
$d_j \to u \ell \nu$	$\mathbf{0.38 \pm 0.28}$	x	x	x	x	x	x
LEP-2	3.5 ± 2.2	-42 ± 28	-21 ± 14	42 ± 28	-18 ± 11	-9.0 ± 5.7	18 ± 11

$\times 10^{-3}$

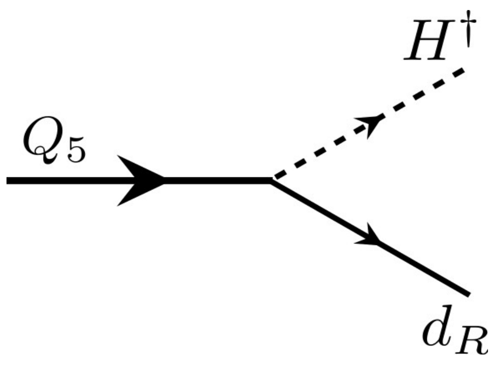
*We focus on **4F operators** with no flavour violation, no chirality violation and no B-violation.*

Exit: *BSM particle that can appear linearly in a Lagrangian term with SM fields, i.e. BSM particle that can decay to SM particles only.*

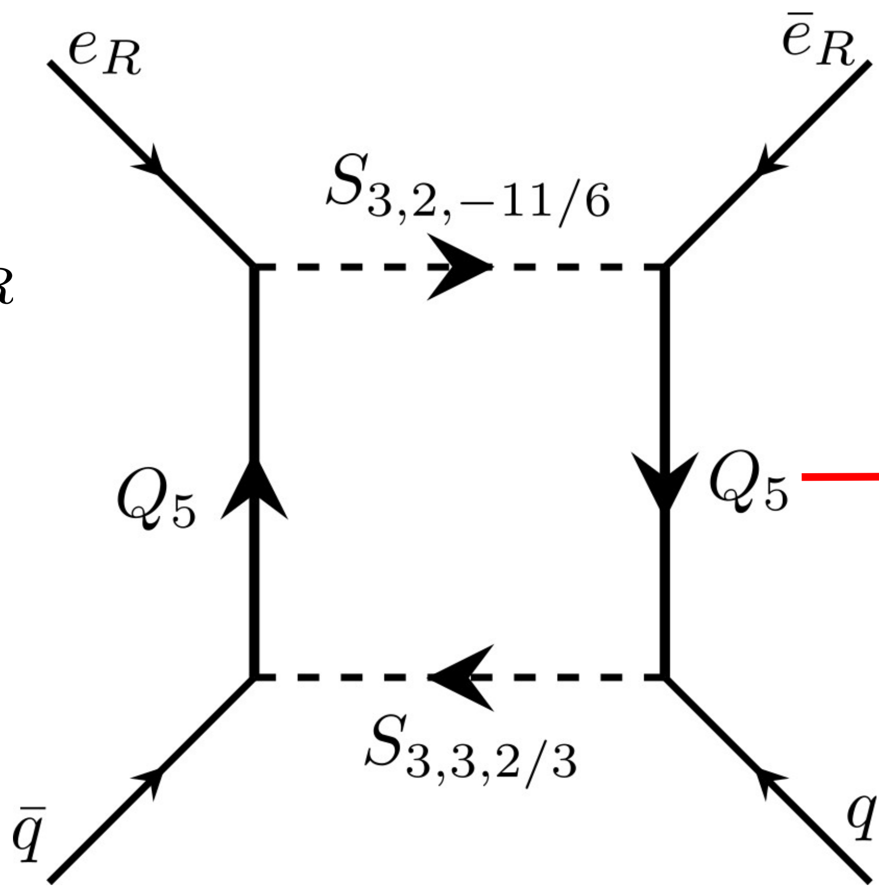
For example:

$$Q_5 = F_{3,2,-5/6}$$

$$\mathcal{L}_{Q_5} \supset \lambda_{Q_5} H Q_5 \bar{d}_R$$

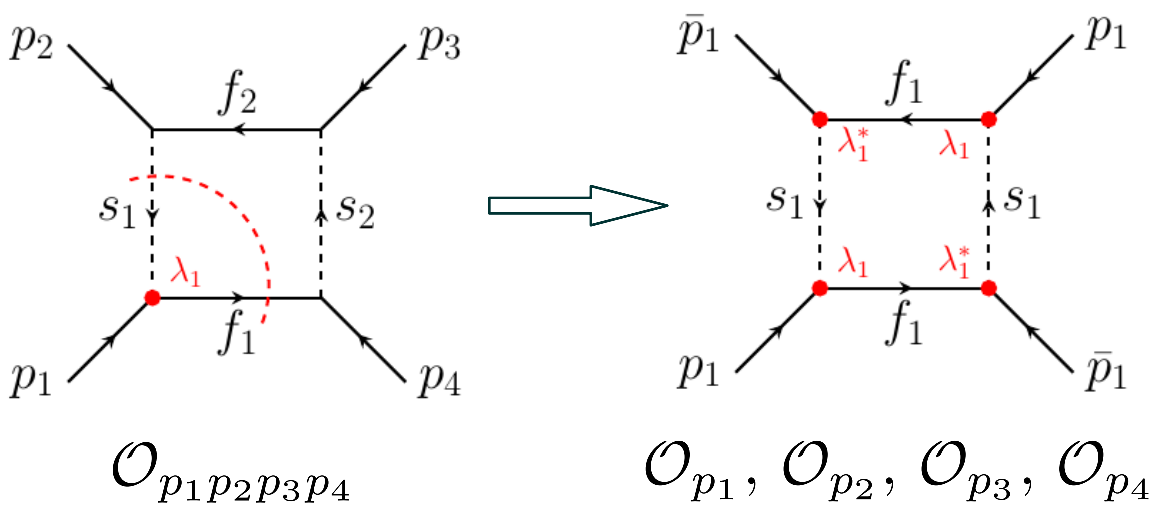


✓ *Decays at tree-level into SM particles*



Equivalent to the list of particles that can generate the d = 6 SMEFT at tree-level. Granada dictionary!! *[de Blas et al 2018]*

Patterns in SMEFT 4F operators



Starting from a 1-loop realization of an operator, ceratin other operators may be unavoidable

Important consequences for observables,
e.g. 1-loop contributions to B-anomalies → strong constrains from neutral mesons mixings
[RC, Escribano, Vicente 2022]

We can classify three types of scenarios:

- *Lepton-specific: exclusively producing 4F involving leptons* ($O_{LL} \to O_{ll}, O_{ee}, O_{le}$)
- *Quark-specific: constrained to affecting hadronic observables* ($O_{QQ} \to O_{qq}, O_{uu}, O_{qd}, O_{quqd}, \ldots$)
- *Generic or hybrid: which contribute to the three types of 4F operators* ($O_{LL}, O_{QQ}, O_{LQ} \to O_{lq}, O_{lequ}, \ldots$)

New fields in the 4F operators

There is a finite set of new BSM particles that appear in the UV completions, with exotic charges and decay channels

Scalars:

Name	Π_5	Π_{11}	Π_{13}	ω_5	ϕ_3
Irrep	$(3,2,-\frac{5}{6})$	$(3,2,-\frac{11}{6})$	$(3,2,\frac{13}{6})$	$(3,1,\frac{5}{3})$	$(1,2,\frac{3}{2})$

**Here only fields up to colour triplets and SU(2) doublets as an example*

Fermions:

Name	Q_{11}	Q_{13}	Q_{17}	X_4	X_5	X_7	Δ_5	N_2
Irrep	$(3,2,-\frac{11}{6})$	$(3,2,\frac{13}{6})$	$(3,2,-\frac{17}{6})$	$(3,1,-\frac{4}{3})$	$(3,1,\frac{5}{3})$	$(3,1,-\frac{7}{3})$	$(1,2,\frac{5}{2})$	$(1,1,2)$

They decay always through an "exit" particle

- *Scalars decay via boson + 2 jets or boson + lepton + jet*
- *Fermions decay through the scalars with an extra jet, i.e. boson + 3 jets or boson + lepton + 2 jets*

*Minimal scenarios**

**(models that include as few non-SM particles as possible)*

Lepton- and quark-specific *scenarios:*
one BSM fermion + SM Higgs in the box diagram

Hybrid *scenarios: at least two BSM fermions*

Minimal scenarios*

*(models that include as few non-SM particles as possible)

Lepton- and quark-specific *scenarios:*

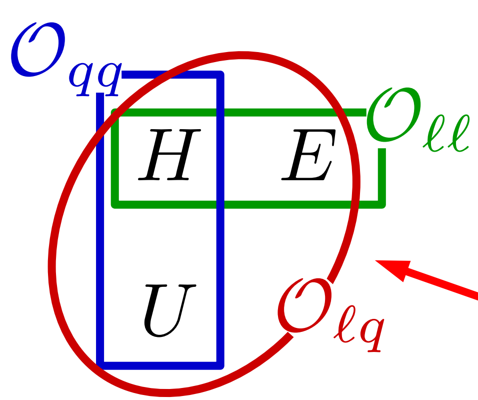
one BSM fermion + SM Higgs in the box diagram

Hybrid *scenarios: at least two BSM fermions*

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*

Complete list of UV models

	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

Colour scale: 0, 100, 200, 300, 400, 500

Warsaw basis:

***B-conserving 4F operators** at d=6*

→ no flavour indices

→ group by external particles

Diagonal:
Models up to **colour octets, SU(2) sextets** and **hypercharge 5** (complete set for exits)

Models for O_{uu} that open up other 4F operators

Exits for loop-induced 4F operator

Scalar exits:

Name	$\mathcal{S}$	Ξ	Θ_1	Θ_3
Irrep	$(1,1,0)$	$(1,3,0)$	$(1,4,\frac{1}{2})$	$(1,4,\frac{3}{2})$

Only ones that don't decay to SM fermions

Equivalent to the list of particles that can generate the d = 6 SMEFT at tree-level.

BUT: exclude (scalar) exits that contribute to 4F at tree-level!

Tree-level dim 6 UV dictionary [de Blas et al 2018]

Fermionic exits:

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

*All fermion exits decay via **boson + jet** or **boson + lepton***

Decay channels for exits

Fermions:

name	representation	decays
N	$(1,1,0)$	$N \to l + H$
E	$(1,1,-1)$	$E \to l + H^\dagger$
Δ_1	$(1,2,-\frac{1}{2})$	$\Delta_1 \to e_R + H$
Δ_3	$(1,2,-\frac{3}{2})$	$\Delta_3 \to e_R + H^\dagger$
Σ	$(1,3,0)$	$\Sigma \to l + H$
Σ_1	$(1,3,-1)$	$\Sigma_1 \to l + H^\dagger$
U	$(3,1,\frac{2}{3})$	$U \to q + H$
D	$(3,1,-\frac{1}{3})$	$D \to q + H^\dagger$
Q_1	$(3,2,\frac{1}{6})$	$Q_1 \to u_R + H^\dagger$, $Q_1 \to d_R + H$
Q_5	$(3,2,-\frac{5}{6})$	$Q_5 \to d_R + H^\dagger$
Q_7	$(3,2,\frac{7}{6})$	$Q_7 \to u_R + H$
T_1	$(3,3,-\frac{1}{3})$	$T_1 \to q + H$
T_3	$(3,3,\frac{2}{3})$	$T_3 \to q + H^\dagger$

Scalars:

name	representation	decays
$\mathcal{S}$	$(1,1,0)$	$S \to H + H^\dagger$
Ξ	$(1,3,0)$	$\Xi \to H + H^\dagger$
Θ_1	$(1,4,\frac{1}{2})$	$\Theta_1 \to H + H + H^\dagger$
Θ_3	$(1,4,\frac{3}{2})$	$\Theta_3 \to H + H + H$

Naming from the tree-level dictionary [de Blas et al 2018]

Decay channels for non-exits

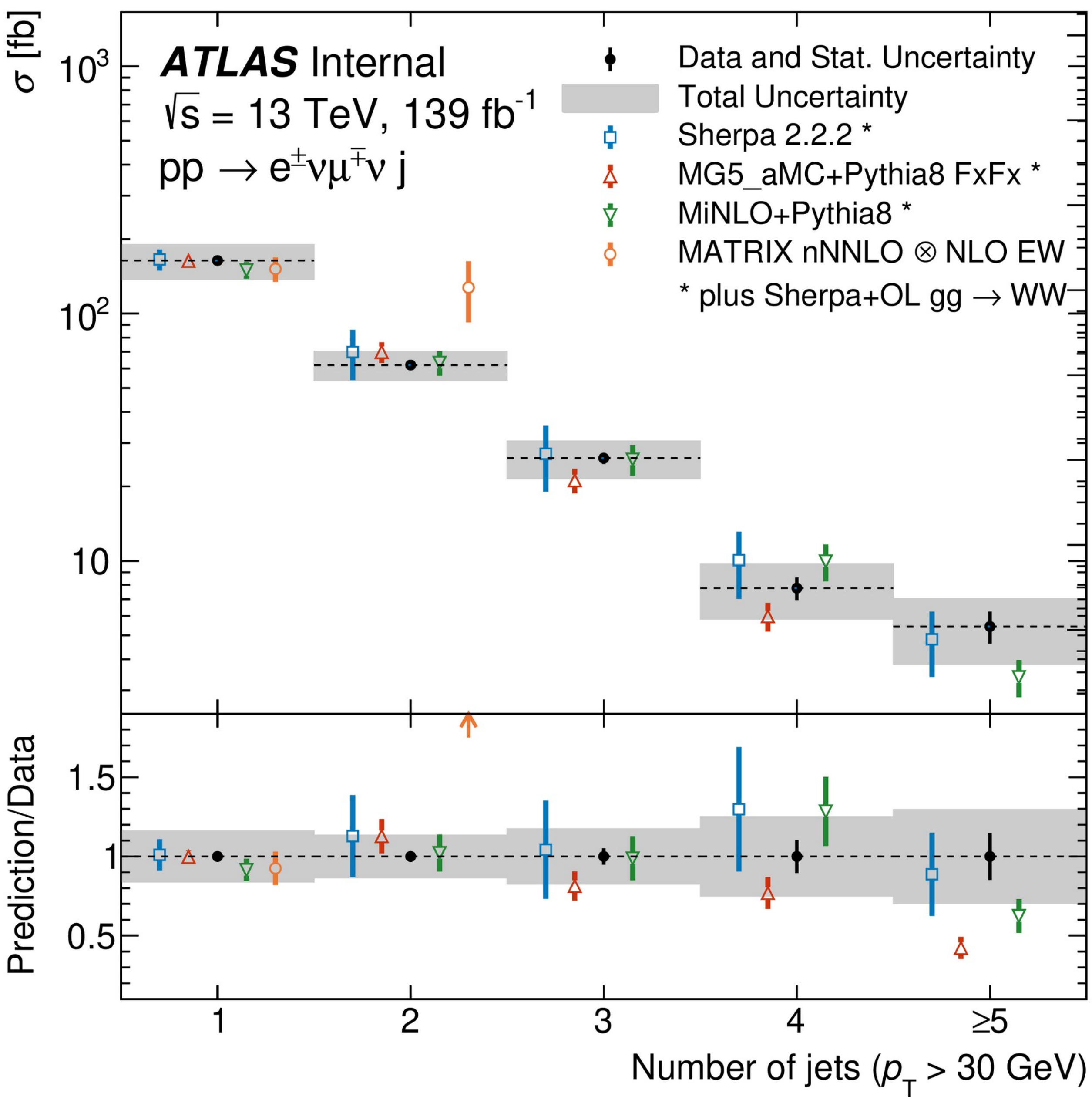
Fermions:

name	representation	decays
Q_{11}	$(3, 2, -\frac{11}{6})$	$Q_{11} \to \phi_3^\dagger + d_R$ $Q_{11} \to \omega_5^\dagger + \bar{q}$ $Q_{11} \to \Pi_{13}^\dagger + \bar{d}_R$
Q_{13}	$(3, 2, \frac{13}{6})$	$Q_{13} \to \phi_3 + u_R$ $Q_{13} \to \Pi_{11}^\dagger + \bar{d}_R$
Q_{17}	$(3, 2, -\frac{17}{6})$	$Q_{17} \to \Pi_{13}^\dagger + \bar{u}_R$
X_4	$(3, 1, -\frac{4}{3})$	$X_4 \to \phi_3^\dagger + q$ $X_4 \to \omega_5^\dagger + \bar{d}_R$
X_5	$(3, 1, \frac{5}{3})$	$X_5 \to \phi_3 + q$ $X_5 \to \Pi_{11}^\dagger + \bar{q}$
X_7	$(3, 1, -\frac{7}{3})$	$X_7 \to \omega_5^\dagger + \bar{u}_R$ $X_7 \to \Pi_{13}^\dagger + \bar{q}$
Δ_5	$(1, 2, \frac{5}{2})$	$\Delta_5 \to \Pi_{11}^\dagger + u_R$ $\Delta_5 \to \Pi_{13} + \bar{d}_R$
N_2	$(1, 1, 2)$	$N_2 \to \omega_5 + \bar{d}_R$ $N_2 \to \Pi_{11}^\dagger + q$ $N_2 \to \Pi_{13} + \bar{q}$

Scalars:

name	representation	decays
Π_5	$(3, 2, -\frac{5}{6})$	$\Pi_5 \to E + q$ $\Pi_5 \to \bar{U} + \bar{q}$ $\Pi_5 \to \Delta_1 + d_R$ $\Pi_5 \to \Delta_3 + u_R$ $\Pi_5 \to \bar{Q}_1 + \bar{u}_R$ $\Pi_5 \to \bar{Q}_7 + \bar{d}_R$
Π_{11}	$(3, 2, -\frac{11}{6})$	$\Pi_{11} \to \Delta_3 + d_R$ $\Pi_{11} \to \bar{Q}_7 + \bar{u}_R$
Π_{13}	$(3, 2, \frac{13}{6})$	$\Pi_{13} \to \bar{\Delta}_3 + u_R$
ω_5	$(3, 1, \frac{5}{3})$	$\omega_5 \to \bar{E} + u_R$ $\omega_5 \to \bar{\Delta}_3 + q$
ϕ_3	$(1, 2, \frac{3}{2})$	$\phi_3 \to \bar{Q}_5 + u_R$ $\phi_3 \to Q_7 + \bar{d}_R$

Sources for direct LHC searches



https://www.hepdata.net/record/ins1852328

Indirect searches

1) Low-energy measurements: **Constraints on LL and LQ** operators are particularly strong [Falkowski, Mimouni 2016; Carpentier, Davidson 2010; de Blas et al 2013]

⇩

precision measurements at e^+e^-, neutrino scattering, APV, …

For our particular example*:

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

*In general, every UV completion generates only a subset of Wilson coeffs.

Global analysis: [Falkowski et al 2017]

$$\chi^2(\bar{c}_{ll}) = 26.8 + 198.4\,\bar{c}_{ll} + 1.42 \times 10^6\,\bar{c}_{ll}^2$$

$$c_{ll}^{EU} \in [-2.9, 2.7] \times 10^{-2}\ \text{TeV}^{-2}$$
$$m_{EU} > 0.17\,|\lambda_{EU}|^2\ \text{TeV}$$

2) Global SMEFT fits: using **low-energy data** and **LHC precision** measurements, marginalise over SMEFT contributions

→ In our case, applies mainly to the tree-level contribution of operators with fermions and Higgses

Most stringent limit is the 2σ bound:

$$c_{\phi q}^{(3)} \in [-0.11, +0.012]\ \text{TeV}^{-2}$$

[Ellis et al 2018]

Which translates to:

$$m_{EU} > |\lambda_{EU}| 1.5\ \text{TeV}$$

All masses and couplings equal m_{EU} and λ_{EU}

Direct searches

*New **colour charged** fields produced more copiously at the LHC*

U	$(3, 1, \frac{2}{3})$	$U \to q + H$
D	$(3, 1, -\frac{1}{3})$	$D \to q + H^\dagger$
Q_1	$(3, 2, \frac{1}{6})$	$Q_1 \to u_R + H^\dagger$, $Q_1 \to d_R + H$

Our example model

***Main LHC channel** to look for the resonance of the U particle:*
***Diboson production** with two energetic jets: one boson and one jet reconstruct the resonance*

$$pp \to h\,h + 2\,j$$
$$W^\pm\,(Z,\gamma) + 2\,j$$
$$W^+\,W^- + 2\,j$$
$$(Z,\gamma)\,(Z,\gamma) + 2\,j$$

*Current most sensitive channel is the SM **W^+W^- in the two-jet channel**:*
2σ cross-section limit of 65 fb
→ mass limit ~ 650 GeV

[ATLAS: link1, link2, link3]

Possible DM candidates

- *Some symmetry (explicit or accidental) stabilising the DM contained in the loop realization of the four-fermion operator.*

- *Odd SU(2) multiplet with zero hypercharge: (1, n, 0) with n=1, 3, ..., 13*

- *Even SU(2) multiplet with non-zero hypercharge are in principle excluded, unless they fall within the inelastic dark matter class.*

  → Always granted for scalars with quantum numbers (1, 2n, ½)
  **For example, the inert doublet Higgs*

  → For fermions and Y=1 (triplet+quintuplets), mass spliting only via non-renormalisable operators

- *As the SM goes only up to SU(2) doublets, the number of models saturates at triplets.*

Overlap with Fermion-higgs operators

4F operators

Fermion-Higgs ops. (H^3F^2 or H^2F^2D)

	#mdls	O_{eH}	O_{uH}	O_{dH}	O_{Hl}	O_{He}	O_{Hq}	O_{Hu}	O_{Hd}	O_{Hud}
O_{ll}	8	0	0	0	0	0	0	0	0	0
O_{le}	14	10	0	0	10	10	0	0	0	0
O_{ee}	4	0	0	0	0	0	0	0	0	0
O_{lq}	28	0	0	0	0	0	0	0	0	0
O_{lu}	14	0	0	0	0	0	0	0	0	0
O_{ld}	14	0	0	0	0	0	0	0	0	0
O_{lequ}	24	16	16	6	16	16	16	16	6	4
O_{ledq}	24	16	4	16	16	16	16	6	16	4
O_{qe}	14	0	0	0	0	0	0	0	0	0
O_{eu}	14	0	0	0	0	0	0	0	0	0
O_{ed}	14	0	0	0	0	0	0	0	0	0
O_{qq}	16	0	0	0	0	0	0	0	0	0
O_{quqd}	24	2	20	20	4	2	20	20	20	6
O_{qu}	28	0	16	6	0	2	16	16	6	4
O_{qd}	28	0	6	16	2	0	16	6	16	4
O_{uu}	8	0	0	0	0	0	0	0	0	0
O_{ud}	28	0	0	0	0	0	0	0	0	0
O_{dd}	8	0	0	0	0	0	0	0	0	0

Fermion-Higgs operators are generated also at 1-loop due to the symmetry.

But they are still an important constraint to consider.

Differently from before, only some models generate these operator.

Backup – A model to fit them all

Dark loops

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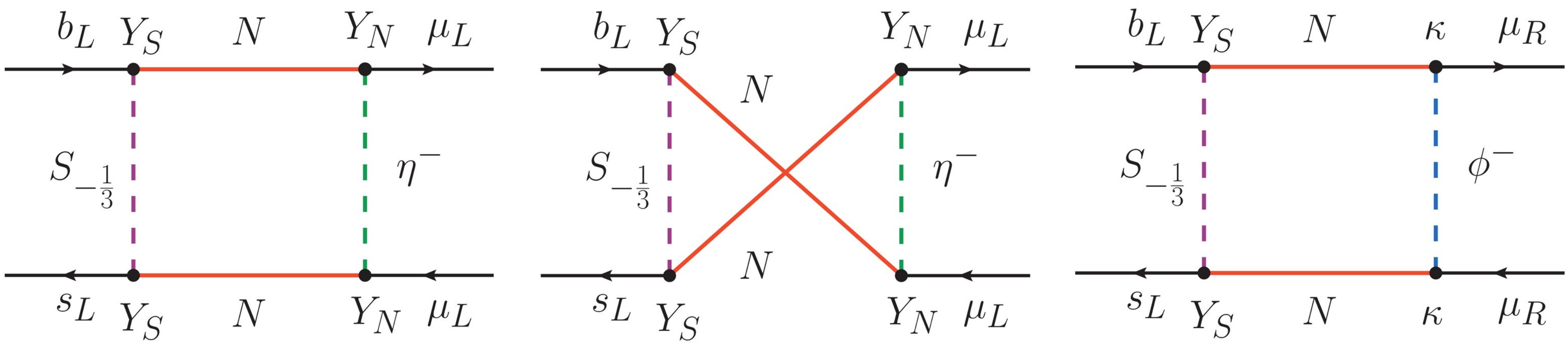
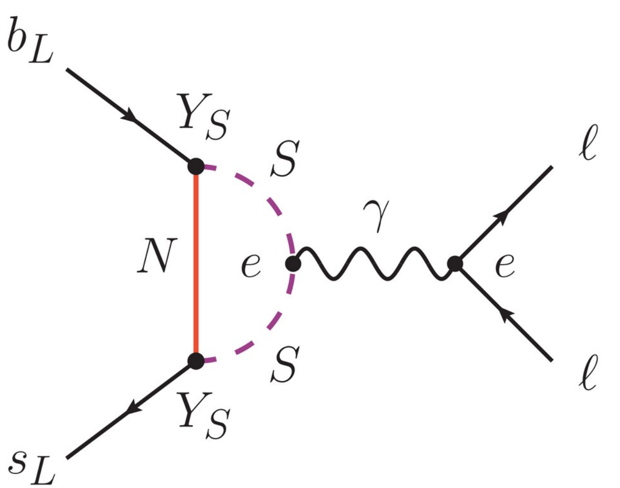
arXiv: 2302.03485

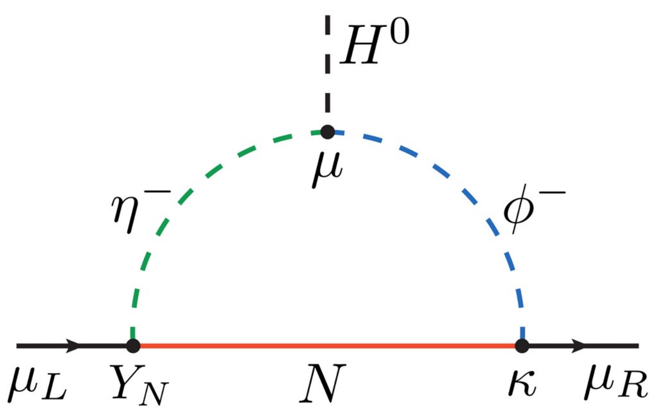
Flavor non-universal $b \to s\ell\ell$



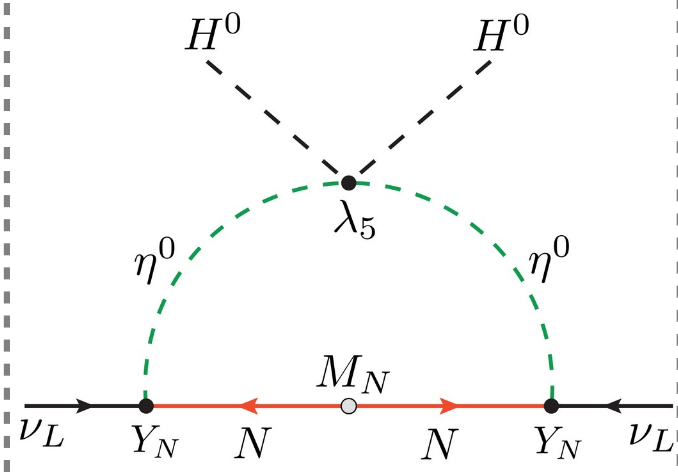
Flavor universal $b \to s\ell\ell$



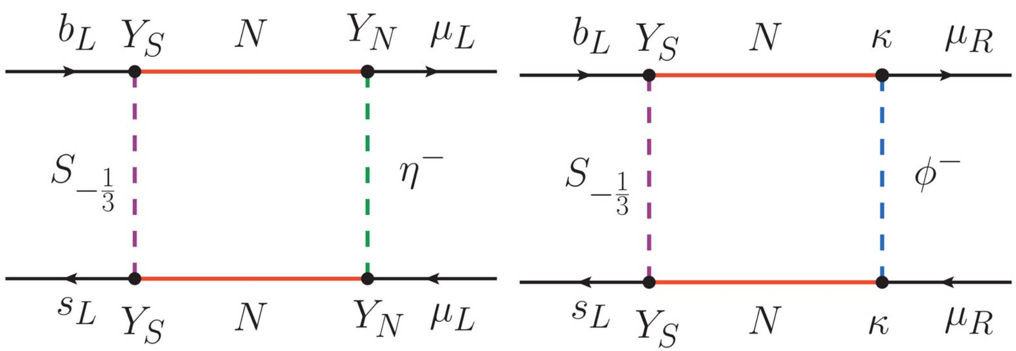
Muon (g-2)



Neutrino masses



Box contributions to LFUV C_9 and C_{10}



+ crossings

***Problem** with 1-loop boxes: unavoidable large B_s mixing*

***Solution**: the Majorana nature of the N singlets can be used to suppress the mixing in the limit of (nearly) degenerate NP masses with the crossed diags.* [Arnan et al 2019]

Always the combination: $(Y_S)_2 \times (Y_S)_3$

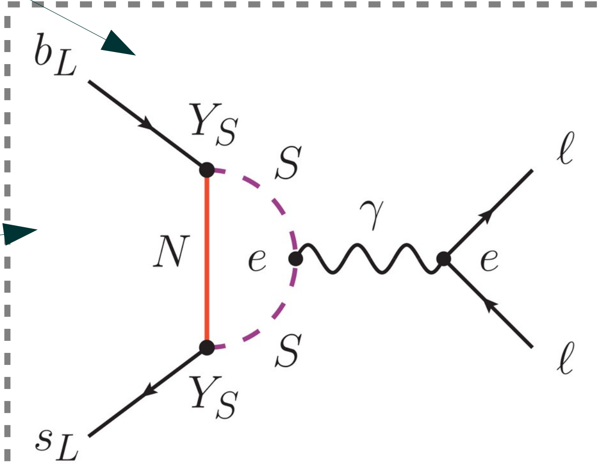
$$\mathcal{O}_9 = \frac{\alpha_{EM}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \mu)$$

$$\mathcal{O}_{10} = \frac{\alpha_{EM}}{4\pi}(\bar{s}\gamma_\mu P_L b)(\bar{\mu}\gamma^\mu \gamma_5 \mu)$$

***Problem**: contribution to the magnetic operators O_7 and O_8 i.e. $b \to s\gamma$*

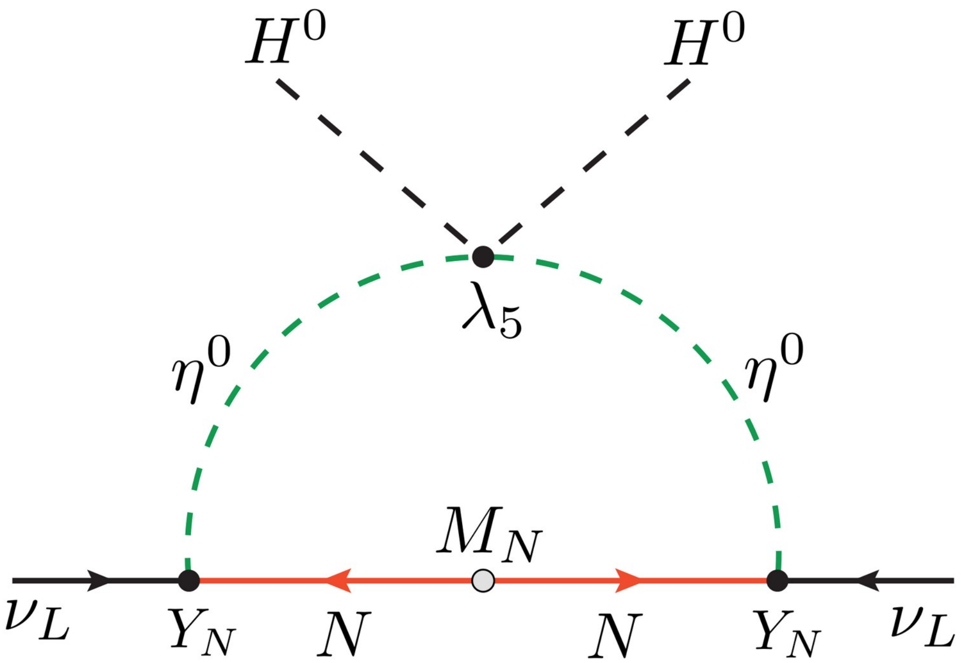
$\Rightarrow (Y_S)_2 \times (Y_S)_3$ *will have an upper bound*

Universal penguin



Neutrino masses

Tree-level *forbidden by the Z_2 symmetry* → ***naturally light masses*** *via one-loop suppression*



(Scotogenic mechanism)

[Ma 2006]

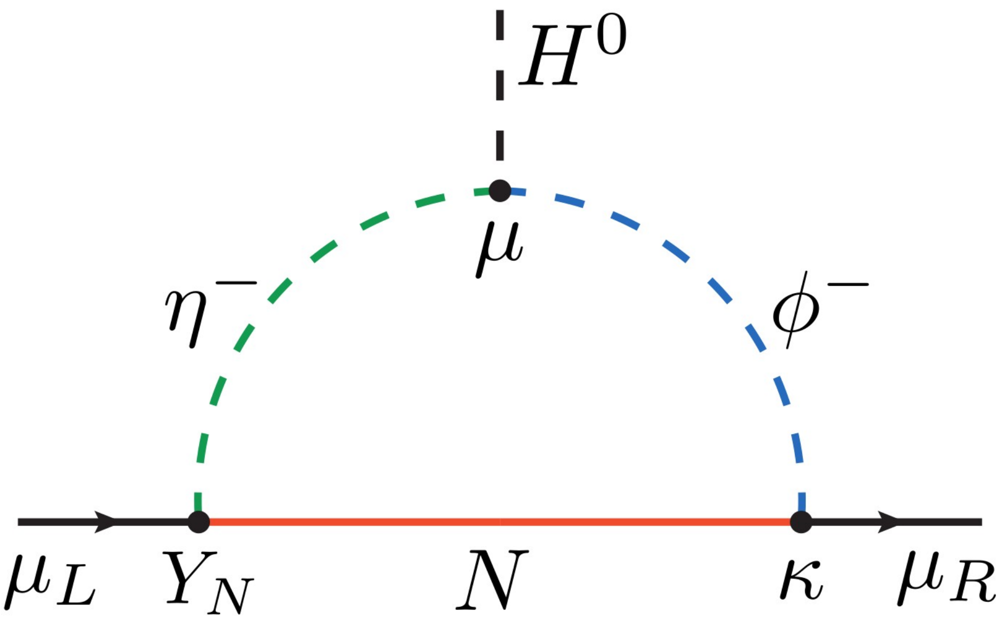
unusual number of generations:

$$n_N = 1 \qquad n_\eta = 2$$

Only two light neutrino masses

$$(m_\nu)_{\alpha\beta} \approx \frac{1}{32\pi^2} v^2 \sum_{a,b} (Y_N)_{\alpha a} (Y_N)_{\beta b}\, \lambda_5^{ab} \frac{M_N}{m_b^2 - M_N^2} \left[\frac{m_b^2}{m_a^2 - m_b^2} \log \frac{m_a^2}{m_b^2} - \frac{M_N^2}{m_a^2 - M_N^2} \log \frac{m_a^2}{M_N^2} \right]$$

The anomalous magnetic moment



EM dipole moment operator:

$$c_R^{\alpha\beta}\overline{\ell_\alpha}\sigma_{\mu\nu}P_R\ell_\beta F^{\mu\nu}$$

Diagonal: (g-2)
Off-diagonal: cLFV

[see e.g. Crivellin et al 2018]

- *N couples to left and right-handed leptons:* ***dominant contribution proportional to M_N***
- *Contributes also to charged lepton flavor violating processes like $\mu \to e\gamma$*
- ***Y_N*** *fits neutrino oscillation data and* ***κ*** *participates in C_9 and C_{10} boxes*

Dark matter

The lightest particle odd under Z_2 is stable → ***dark matter candidate***

***Fermionic dark matter**: singlet* N

- *Pure singlet: produced only via Yukawa Y_N*
- *Underproduced unless Y_N is large*
- *Potential problems with lepton flavor violation*

[Vicente, Yaguna 2015]

***Scalar dark matter**: doublet* η_a

- *Similar to the well-studied Inert Doublet Model*
- *Interacts also via gauge*
- *Relic density: mass around 500-600 GeV*

[for example,
Honorez et al 2007;
Honorez, Yaguna 2010;
Aurelio Diaz et al 2016]

Analysis

- *We aim to accommodate* ***all the anomalies*** *while being consistent with* ***neutrino oscillation data***
- *We built a χ^2-function the Wilson coeff. and the muon (g-2)*
- *m_η = 550 GeV (DM), the rest close to 1 TeV and nearly degenerate (B_s mixing)*

Global fit (scenario 5)

$$\mathcal{C}_{9\mu}^{V} = -0.55^{+0.44}_{-0.47}\,,$$
$$\mathcal{C}_{10\mu}^{V} = 0.49^{+0.35}_{-0.41}\,,$$
$$\mathcal{C}_{9}^{U} = \mathcal{C}_{10}^{U} = -0.35^{+0.42}_{-0.38}\,,$$

[Algueró et al 2022]

Experimental constraints

- *Charged lepton flavor violation: very stringent bounds on $\mu \to e\gamma$*
- *B_s mixing inevitable at 1-loop and very constraining*
- *$b \to s\gamma$ yield strong constraints on the coefficients of dipole operators*
- *$B \to K^{(*)}\nu\nu$ unavoidable if a contribution to $R_{K(*)}$ exists:* $R_K^{\nu\bar{\nu}} < 3.9,\ R_{K^*}^{\nu\bar{\nu}} < 2.7$

Neutrino fit

Neutrino oscillation data from global fit (link)

[de Salas et al 2021]

Apply ***Casas-Ibarra parametrization*** *to get the Yukawa Y_N in terms of the oscillation data:*

[Casas, Ibarra 2001]

$$Y_N^T = V\, D_{\sqrt{\Sigma}}\, R\, D_{\sqrt{m_\nu}}\, U^\dagger_{\rm PMNS}$$

Defined by:

$$m_\nu = Y_N \cdot \Sigma \cdot Y_N$$

and diagionalized by V

(D_X) Diagonal form of the matrix X

Complex orthogonal matrix

$$R = \begin{pmatrix} 0 & \cos\theta & -\sin\theta \\ 0 & \sin\theta & \cos\theta \end{pmatrix}$$

Parameters

To prove that our model can accommodate the anomalies and simplify the analysis, we fixed several parameters before minimizing the χ^2-function.

- m_η = 550 GeV (DM), the rest close to 1 TeV and nearly degenerate (B_S mixing)
- The 2x2 λ_5 is taken diagonal, i.e. $\lambda_5 = \lambda_5^0 \cdot$ Identity, with $\lambda_5^0 = 2 \times 10^{-10}$
- $\mu_1 = -\mu_2 = -1.0$ TeV
- $\kappa_1 = 0$, $\kappa_2 = 0.04$

The smallness of λ_5 is technically natural and protected against radiative corrections since in the limit $\lambda_5 \to 0$ lepton number is restored. ['t Hooft 1979]

The minimum of the χ^2-function was found for:

$$(Y_S)_2 \times (Y_S)_3 = 0.6\,, \quad \sin\theta = 0.25$$

Conclusions

- ✓ *Novel model that accommodates the existing deviations in* ***b → sll*** *and the* ***muon g-2****, induces* ***neutrino masses*** *and provides a* ***dark matter*** *candidate*

- ✓ *The dark sector participates in the observables of interest at the 1-loop level (****dark loops****)*

- ✓ *We get a minimum of* $\chi^2_{\min} = 1.52$ *a considerable* ***improvement*** *with respect to the SM* $(\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\min} = 21.23)$

- ✓ *BSM fields may be produced at* ***colliders****, but decay always via missing energy. For example,* $S \to j\, N \to j\, \ell\, \not{E}_T$ *where the jet can be 2nd or 3rd gen quark*