Mapping the SMEFT one-loop structure of linear SM extensions

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[arXiv: 24XX.XXXXX]

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“Theory space of particle physics models”

$$H \sim (\mathbf{1}, \mathbf{2}, \tfrac{1}{2}), \quad Q \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}), \quad \bar{u} \sim (\bar{\mathbf{3}}, \mathbf{1}, -\tfrac{2}{3}), \quad \bar{d} \sim (\bar{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}), \quad L \sim (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}), \quad \bar{e} \sim (\mathbf{1}, \mathbf{1}, 1)$$

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{p,q} c_{pq}^{(5)} (L_p L_q) HH + \sum_{i=1}^{2499} \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{d=6} + \cdots$$

Bottom–up approach

UV/IR dictionary

Top–down approach

$$H \sim (\mathbf{1}, \mathbf{2}, \tfrac{1}{2}), \quad Q \sim (\mathbf{3}, \mathbf{2}, \tfrac{1}{6}), \quad \bar{u} \sim (\bar{\mathbf{3}}, \mathbf{1}, -\tfrac{2}{3}), \quad \bar{d} \sim (\bar{\mathbf{3}}, \mathbf{1}, \tfrac{1}{3}), \quad L \sim (\mathbf{1}, \mathbf{2}, -\tfrac{1}{2}), \quad \bar{e} \sim (\mathbf{1}, \mathbf{1}, 1)$$

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{p,q} c^{(5)}_{pq} (L_p L_q) H H + \sum_{i=1}^{2499} \frac{c_i^{(6)}}{\Lambda^2} \mathscr{O}_i^{d=6} + \cdots$$

Linear SM extensions

Granada dictionary: de Blas, Criado, Pérez-Victoria, Santiago arXiv:1711.10391
MatchingTools: Criado arXiv:1710.06445

- Patterns of minimal tree-level deviation from the SM can be understood in terms of linear SM extensions

$$\mathscr{L}_{\text{int}} \sim \text{SM} \cdot \text{SM} \cdot X + \text{SM} \cdot \text{SM} \cdot \text{SM} \cdot X + \cdots$$

- 48 exotic multiplets **generating $d = 6$ operators at tree level**
- Catalogued in the Granada dictionary
- Fermions are vector-like or Majorana

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	$(6,1)_{\frac{1}{3}}$	$(6,1)_{-\frac{2}{3}}$	$(6,1)_{\frac{4}{3}}$	$(6,3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$

Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

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

Table 2. New vector-like fermions contributing to the dimension-six SMEFT at tree level.

Tree-level UV/IR dictionary

Granada dictionary: de Blas, Criado, Pérez-Victoria, Santiago arXiv:1711.10391
MatchingTools: Criado arXiv:1710.06445

Top−down

UV | IR

Fields	Operators
$\mathcal{S}$	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{\phi B}$, $\mathcal{O}_{\phi\tilde{B}}$, $\mathcal{O}_{\phi W}$, $\mathcal{O}_{\phi\tilde{W}}$, $\mathcal{O}_{\phi G}$, $\mathcal{O}_{\phi\tilde{G}}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
$\mathcal{S}_1$	$\mathcal{O}_{ll}$
$\mathcal{S}_2$	$\mathcal{O}_{ee}$
φ	$\mathcal{O}_{le}$, $\mathcal{O}^{(1)}_{qu}$, $\mathcal{O}^{(8)}_{qu}$, $\mathcal{O}^{(1)}_{qd}$, $\mathcal{O}^{(8)}_{qd}$, $\mathcal{O}_{ledq}$, $\mathcal{O}^{(1)}_{quqd}$, $\mathcal{O}^{(1)}_{lequ}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
Ξ	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{\phi WB}$, $\mathcal{O}_{\phi W\tilde{B}}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
Ξ_1	$\mathcal{O}_{\phi 4}$, $\mathcal{O}_{5}$, $\mathcal{O}_{ll}$, $\mathcal{O}_{\phi}$, $\mathcal{O}_{\phi D}$, $\mathcal{O}_{\phi\Box}$, $\mathcal{O}_{e\phi}$, $\mathcal{O}_{d\phi}$, $\mathcal{O}_{u\phi}$
Θ_1	$\mathcal{O}_{\phi}$
Θ_3	$\mathcal{O}_{\phi}$
ω_1	$\mathcal{O}^{(1)}_{qq}$, $\mathcal{O}^{(3)}_{qq}$, $\mathcal{O}^{(1)}_{lq}$, $\mathcal{O}^{(3)}_{lq}$, $\mathcal{O}_{eu}$, $\mathcal{O}^{(1)}_{ud}$, $\mathcal{O}^{(8)}_{ud}$, $\mathcal{O}^{(1)}_{quqd}$, … $\mathcal{O}^{(1)}_{lequ}$, $\mathcal{O}^{(3)}_{lequ}$, $\mathcal{O}_{duq}$, $\mathcal{O}_{qqu}$, $\mathcal{O}_{qqq}$, $\mathcal{O}_{duu}$
ω_2	$\mathcal{O}_{dd}$
ω_4	$\mathcal{O}_{uu}$, $\mathcal{O}_{ed}$, $\mathcal{O}_{duu}$
Π_1	$\mathcal{O}_{ld}$
Π_7	$\mathcal{O}_{lu}$, $\mathcal{O}_{qe}$, $\mathcal{O}^{(1)}_{lequ}$, $\mathcal{O}^{(3)}_{lequ}$
ζ	$\mathcal{O}^{(1)}_{qq}$, $\mathcal{O}^{(3)}_{qq}$, $\mathcal{O}^{(1)}_{lq}$, $\mathcal{O}^{(3)}_{lq}$, $\mathcal{O}_{qqq}$
Ω_1	$\mathcal{O}^{(1)}_{qq}$, $\mathcal{O}^{(3)}_{qq}$, $\mathcal{O}^{(1)}_{ud}$, $\mathcal{O}^{(8)}_{ud}$, $\mathcal{O}^{(1)}_{quqd}$, $\mathcal{O}^{(8)}_{quqd}$
Ω_2	$\mathcal{O}_{dd}$
Ω_4	$\mathcal{O}_{uu}$
Υ	$\mathcal{O}^{(1)}_{qq}$, $\mathcal{O}^{(3)}_{qq}$
Φ	$\mathcal{O}^{(1)}_{qu}$, $\mathcal{O}^{(8)}_{qu}$, $\mathcal{O}^{(1)}_{qd}$, $\mathcal{O}^{(8)}_{qd}$, $\mathcal{O}^{(8)}_{quqd}$

Table 7. Operators generated by the heavy scalar fields int…

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				$2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
					Φ			
				$3)_{\frac{1}{3}}$	$(8,2)_{\frac{1}{2}}$			

…to the dimension-six SMEFT at tree level.

Δ_3	Σ	Σ_1	
$(1,2)_{-\frac{3}{2}}$	$(1,3)_0$	$(1,3)_{-1}$	
Q_5	Q_7	T_1	T_2
$(3,2)_{-\frac{5}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$	$(3,3)_{\frac{2}{3}}$

…ng to the dimension-six SMEFT at tree level.

28 pages…

IR | UV

D.3 Four-fermion Operators

D.3.1 $(\bar{L}L)(\bar{L}L)$

$$(C_{ll})_{ijkl} = \frac{(y_{\mathcal{S}_1})^*_{rjl}(y_{\mathcal{S}_1})_{rik}}{M^2_{\mathcal{S}_{1r}}} + \frac{(y_{\Xi_1})_{rki}(y_{\Xi_1})^*_{rlj}}{M^2_{\Xi_{1r}}} - \frac{(g^l_{\mathcal{B}})_{rkl}(g^l_{\mathcal{B}})_{rij}}{2M^2_{\mathcal{B}_r}} - \frac{(g^l_{\mathcal{W}})_{rkj}(g^l_{\mathcal{W}})_{ril}}{4M^2_{\mathcal{W}_r}} + \frac{(g^l_{\mathcal{W}})_{rkl}(g^l_{\mathcal{W}})_{rij}}{8M^2_{\mathcal{W}_r}}, \quad \text{(D.11)}$$

$$\left(C^{(1)}_{qq}\right)_{ijkl} = \frac{(y^{qq}_{\omega_1})_{rik}(y^{qq}_{\omega_1})^*_{rlj}}{2M^2_{\omega_{1r}}} + \frac{3(y^{qq}_{\zeta})_{rki}(y^{qq}_{\zeta})^*_{rlj}}{2M^2_{\zeta_r}} + \frac{(y^{qq}_{\Omega_1})^*_{rik}(y^{qq}_{\Omega_1})_{rjl}}{4M^2_{\Omega_{1r}}} + \frac{3(y_{\Upsilon})_{rlj}(y_{\Upsilon})^*_{rki}}{4M^2_{\Upsilon_r}} - \frac{(g^q_{\mathcal{B}})_{rkl}(g^q_{\mathcal{B}})_{rij}}{2M^2_{\mathcal{B}_r}} - \frac{(g^q_{\mathcal{G}})_{rkj}(g^q_{\mathcal{G}})_{ril}}{8M^2_{\mathcal{G}_r}} + \frac{(g^q_{\mathcal{G}})_{rkl}(g^q_{\mathcal{G}})_{rij}}{12M^2_{\mathcal{G}_r}} - \frac{3(g_{\mathcal{H}})_{rkj}(g_{\mathcal{H}})_{ril}}{32M^2_{\mathcal{H}_r}}, \quad \text{(D.12)}$$

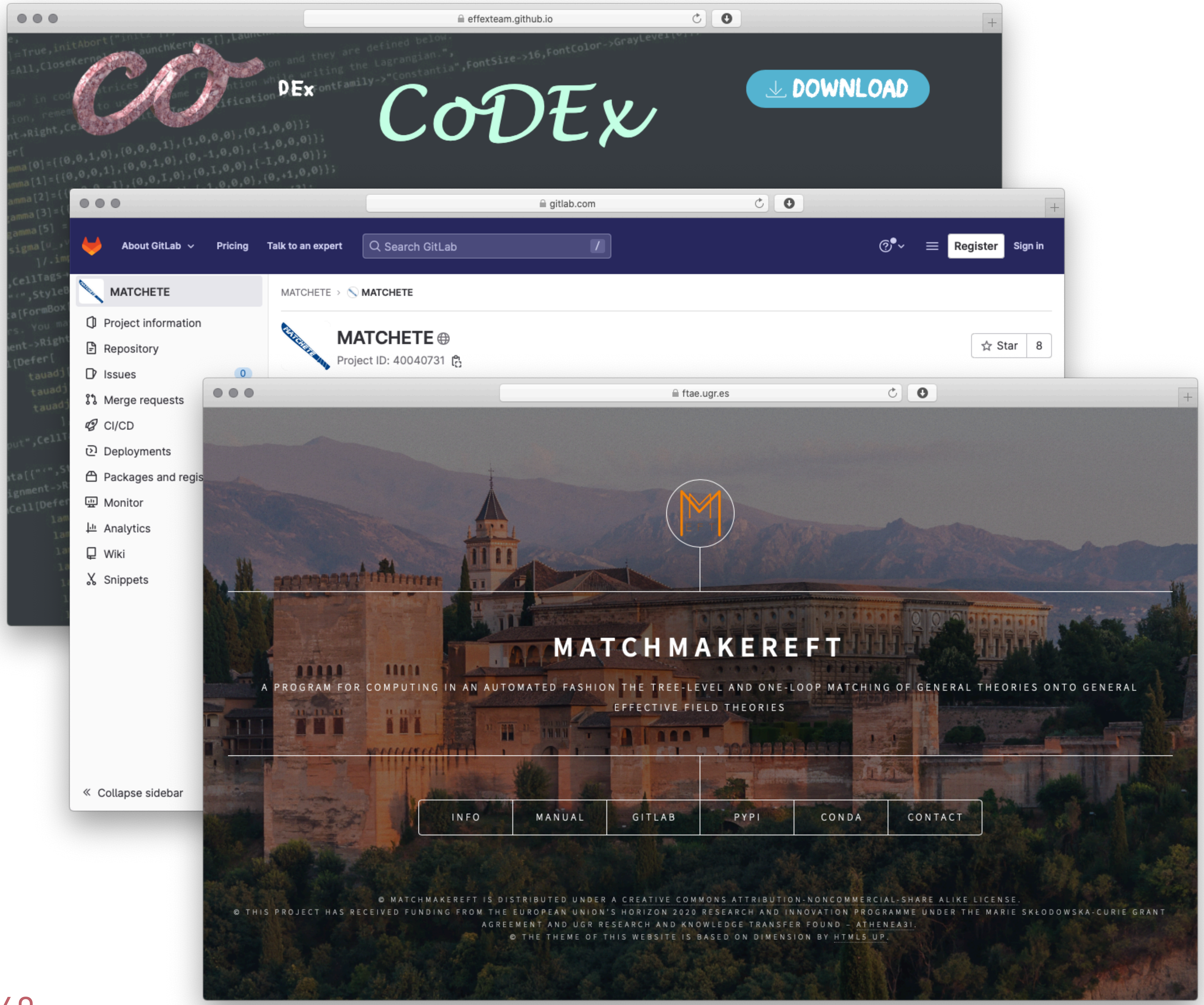
$$\left(C^{(3)}_{qq}\right)_{ijkl} = -\frac{(y^{qq}_{\omega_1})_{rki}(y^{qq}_{\omega_1})^*_{rjl}}{2M^2_{\omega_{1r}}} - \frac{(y^{qq}_{\zeta})_{rki}(y^{qq}_{\zeta})^*_{rjl}}{2M^2_{\zeta_r}} + \frac{(y^{qq}_{\Omega_1})^*_{rik}(y^{qq}_{\Omega_1})_{rlj}}{4M^2_{\Omega_{1r}}} + \frac{(y_{\Upsilon})^*_{rki}(y_{\Upsilon})_{rjl}}{4M^2_{\Upsilon_r}} - \frac{(g^q_{\mathcal{W}})_{rkl}(g^q_{\mathcal{W}})_{rij}}{8M^2_{\mathcal{W}_r}} - \frac{(g^q_{\mathcal{G}})_{rkj}(g^q_{\mathcal{G}})_{ril}}{8M^2_{\mathcal{G}_r}} + \frac{(g_{\mathcal{H}})_{rkl}(g_{\mathcal{H}})_{rij}}{48M^2_{\mathcal{H}_r}} + \frac{(g_{\mathcal{H}})_{rkj}(g_{\mathcal{H}})_{ril}}{32M^2_{\mathcal{H}_r}}, \quad \text{(D.13)}$$

Bottom−up

One-loop tools

Impressive recent progress in automating one-loop matching:

- CoDeX implements UOLEA results
- MatchMakerEFT implements diagrammatic matching
- Matchete uses functional techniques (built upon SuperTracer)



CoDeX: Bakshi Chakrabortty, Patra arXiv:1808.04403
UOLEA results: Drozd, Ellis, Quevillon, You arXiv:1512.03003
Ellis, Quevillon, You, Zhang arXiv:1604.02445
Ellis, Quevillon, Vuong, You, Zhang arXiv:2006.16260
Larue, Quevillon arXiv:2303.10203
MatchMakerEFT: Carmona, Lazopoulos, Olgoso, Santiago arXiv:2112.10787
SOLD: Guedes, Olgoso, Santiago arXiv:2303.16965
Matchete & SuperTracer: Fuentes-Martín, Koenig, Pagès, Thomsen, Wilsch arXiv:2212.04510, arXiv:2012.08506

Going past tree level

Bonnet, Hirsch, Ota, Winter arXiv:1204.5862
Aristizabal Sierra, Degee, Dorame, Hirsch arXiv:1411.7038
Cepedello, Fonseca, Hirsch arXiv:1807.00629

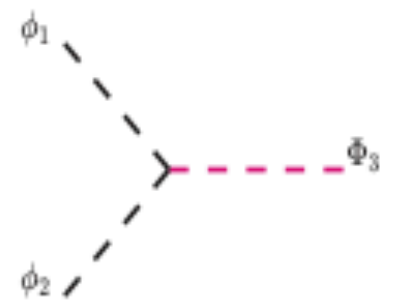
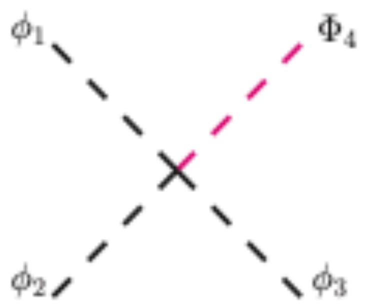
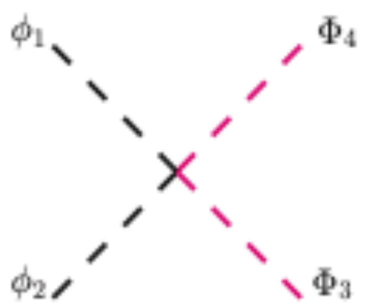
Bakshi, Chakrabortty, Prakash, Rahaman, Spannowsky arXiv:2103.11593
Naskar, Prakash, Rahaman arXiv:2205.00910

- Loop-level completions of dimension-5 Weinberg operator known up to three loops, for dimension-7 analogue up to one

  Cepedello, Esser, Hirsch, Sanz arXiv:2207.13714
- Methods extended to general loop-level studies of *e.g.* four-fermion operators
- Diagram-topology analysis of one-loop contributions to all dimension-6 and dimension-8 operators
- SOLD provides complete one-loop dictionary for subset of operators at dimension 6. Mathematica package for results

  Guedes, Olgoso, Santiago arXiv:2303.16965

E.g. Scalar interactions allowed @ one-loop and dimension 6

Vertex	S. No.	Light fields	Heavy field(s)
	V1-(i)	$\phi_1=\phi_2=H_{(1,2,\frac{1}{2})}$ or $H^\dagger_{(1,2,-\frac{1}{2})}$	$\Phi_3\in\{(1,3,\pm1),\ (1,1,\pm1)\}$
	V1-(ii)	$\phi_1=H,\ \ \phi_2=H^\dagger$	$\Phi_3\in\{(1,3,0),\ (1,1,0)\}$
	V2	$\phi_1=H$ or $H^\dagger$	$\Phi_2\in(R_{C_2},R_{L_2},Y_2)$, $\Phi_3\in(R_{C_3},R_{L_3},Y_3)$ with $R_{C_2}\otimes R_{C_3}\equiv 1$, $R_{L_2}\otimes R_{L_3}\equiv 2$ and $Y_2+Y_3=\pm\frac{1}{2}$.
	V3-(i)	$\phi_1=\phi_2=\phi_3=H$ or $H^\dagger$	$\Phi_4\in\{(1,4,\pm\frac{3}{2}),\ (1,2,\pm\frac{3}{2})\}$
	V3-(ii)	$\phi_1=\phi_2=H,\ \ \phi_3=H^\dagger$	$\Phi_4\in\{(1,4,\pm\frac{1}{2}),\ (1,2,\pm\frac{1}{2})\}$
	V4-(i)	$\phi_1=H,\ \ \phi_2=H^\dagger$	$\Phi_3\in(\{1,R_C\},\{1,R_L\},\{0,Y\}),\ \ \Phi_4=\Phi_3^\dagger$
	V4-(ii)	$\phi_1=\phi_2=H$ or $H^\dagger$	$\Phi_3\in(R_{C_3},R_{L_3},Y_3)$, $\Phi_4\in(R_{C_4},R_{L_4},Y_4)$ with $R_{C_3}\otimes R_{C_4}\equiv 1$, $R_{L_3}\otimes R_{L_4}\equiv 1$ or 3 and $Y_3+Y_4=\pm1$.

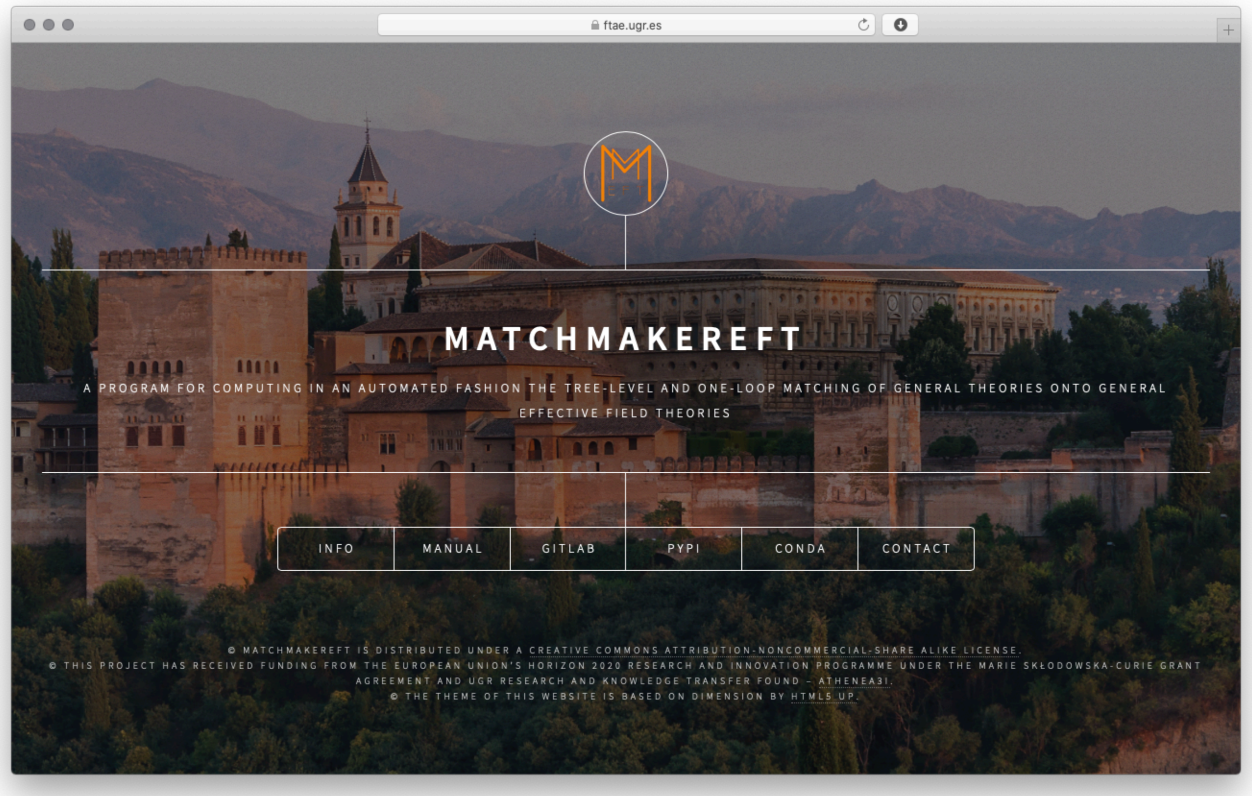
Results in terms of exotic quantum numbers

Our approach: overview

Linear SM extensions are a physically motivated subset of toy models that parametrise tree-level deviation from the SM

Primary aim: Use these tools to extend results for the **linear SM extensions** to the **one-loop level**

Extend Lagrangian sufficient to generate dimension-6 operators at one loop



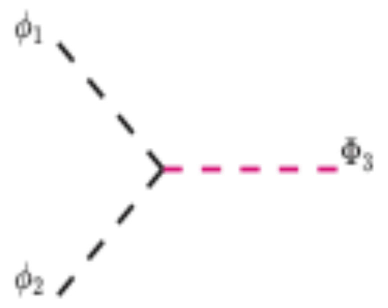
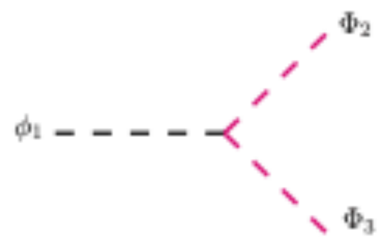
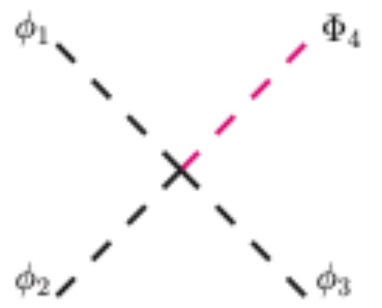
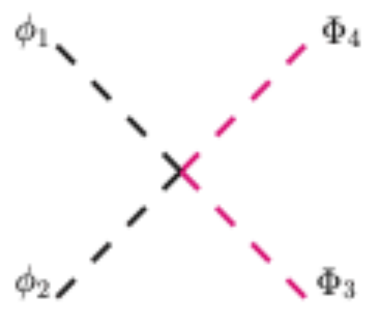
`MatchMakerParser:` Parses Mathematica to Python, writes classes for each multiplet

Lagrangian

- Similar assumptions to tree-level dictionary: limit ourselves to scalars and vector-like and Majorana fermions. **Our Lagrangian matches the conventions of the tree-level dictionary**
- We don't consider mixed terms
- For one-loop matching, only need to alter scalar interactions

$$\Delta\mathscr{L} = \sum_S \hat{\lambda}_S (H^\dagger H)(S^\dagger S) + \hat{\lambda}'_\varphi (H^\dagger \varphi)(\varphi^\dagger H) + \sum_{i\in\{1,3\}} \hat{\lambda}'_{\Theta_i} (\Theta_i^\dagger T_{\mathbf{4}}^a \Theta_i)(H^\dagger \sigma^a H)$$
$$+ \sum_{i\in\{1,7\}} \hat{\lambda}'_{\Pi_i} (\Pi_i^\dagger H)(H^\dagger \Pi_i) + \hat{\lambda}'_\Phi \mathrm{Tr}[(\mathbf{\Phi}^\dagger \cdot \boldsymbol{\lambda} H)(H^\dagger \mathbf{\Phi} \cdot \boldsymbol{\lambda})]$$
$$+ \sum_{S\in\{\zeta,\Upsilon\}} \hat{\lambda}'_S f_{abc} (S^{a\dagger} S^b)(H^\dagger \sigma^c H)$$
$$+ \left\{ \hat{\lambda}''_{\Theta_1} \frac{8}{3\sqrt{5}} (\Theta_1^I \epsilon_{IJ} [T_{\mathbf{4}}^a]^J{}_K \Theta_1^K)(H^\dagger \sigma^a \tilde{H}) + \hat{\lambda}''_\Phi \mathrm{Tr}[(H^\dagger \mathbf{\Phi} \cdot \boldsymbol{\lambda})(H^\dagger \mathbf{\Phi} \cdot \boldsymbol{\lambda})] + \mathrm{h.c.} \right\}$$

Bakshi, Chakrabortty, Prakash, Rahaman, Spannowsky
arXiv:2103.11593

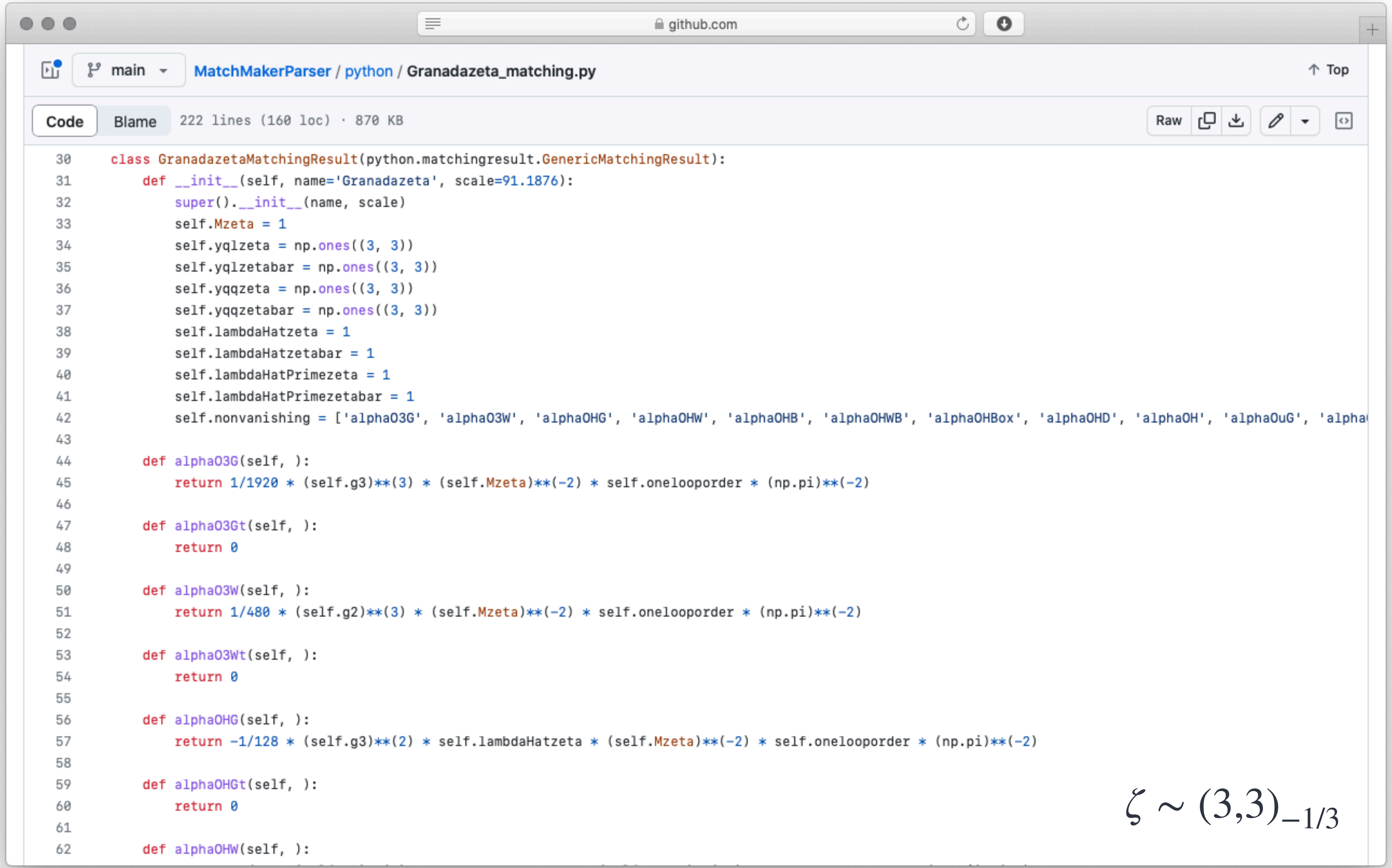
Vertex	S. No.	Light fields	Heavy field(s)
	V1-(i)	$\phi_1 = \phi_2 = H_{(1,2,\frac{1}{2})}$ or $H^\dagger_{(1,2,-\frac{1}{2})}$	$\Phi_3 \in \{(1,3,\pm1),\ (1,1,\pm1)\}$
	V1-(ii)	$\phi_1 = H,\ \ \phi_2 = H^\dagger$	$\Phi_3 \in \{(1,3,0),\ (1,1,0)\}$
	V2	$\phi_1 = H$ or $H^\dagger$	$\Phi_2 \in (R_{C_2}, R_{L_2}, Y_2)$, $\Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$ with $R_{C_2} \otimes R_{C_3} \equiv 1$, $R_{L_2} \otimes R_{L_3} \equiv 2$ and $Y_2 + Y_3 = \pm\frac{1}{2}$.
	V3-(i)	$\phi_1 = \phi_2 = \phi_3 = H$ or $H^\dagger$	$\Phi_4 \in \{(1,4,\pm\frac{3}{2}),\ (1,2,\pm\frac{3}{2})\}$
	V3-(ii)	$\phi_1 = \phi_2 = H,\ \ \phi_3 = H^\dagger$	$\Phi_4 \in \{(1,4,\pm\frac{1}{2}),\ (1,2,\pm\frac{1}{2})\}$
	V4-(i)	$\phi_1 = H,\ \ \phi_2 = H^\dagger$	$\Phi_3 \in (\{1, R_C\}, \{1, R_L\}, \{0, Y\})$, $\Phi_4 = \Phi_3^{\dagger *}$
	V4-(ii)	$\phi_1 = \phi_2 = H$ or $H^\dagger$	$\Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$, $\Phi_4 \in (R_{C_4}, R_{L_4}, Y_4)$ with $R_{C_3} \otimes R_{C_4} \equiv 1$, $R_{L_3} \otimes R_{L_4} \equiv 1$ or 3 and $Y_3 + Y_4 = \pm 1$.

Reading the Lagrangian and parsing the output: MatchMakerParser

- Written a lightweight wrapper around FeynRules to encode Lagrangians with less boilerplate code and more consistency checks

- A simple implementation of missing PythonForm to parse results from MatchMaker

- Outputs are Python classes with coefficients as methods.


github.com
main
MatchMakerParser / python / Granadazeta_matching.py
Top
Code
Blame
222 lines (160 loc) · 870 KB
Raw

```python
class GranadazetaMatchingResult(python.matchingresult.GenericMatchingResult):
    def __init__(self, name='Granadazeta', scale=91.1876):
        super().__init__(name, scale)
        self.Mzeta = 1
        self.yqlzeta = np.ones((3, 3))
        self.yqlzetabar = np.ones((3, 3))
        self.yqqzeta = np.ones((3, 3))
        self.yqqzetabar = np.ones((3, 3))
        self.lambdaHatzeta = 1
        self.lambdaHatzetabar = 1
        self.lambdaHatPrimezeta = 1
        self.lambdaHatPrimezetabar = 1
        self.nonvanishing = ['alphaO3G', 'alphaO3W', 'alphaOHG', 'alphaOHW', 'alphaOHB', 'alphaOHWB', 'alphaOHBox', 'alphaOHD', 'alphaOH', 'alphaOuG', 'alpha

    def alphaO3G(self, ):
        return 1/1920 * (self.g3)**(3) * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaO3Gt(self, ):
        return 0

    def alphaO3W(self, ):
        return 1/480 * (self.g2)**(3) * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaO3Wt(self, ):
        return 0

    def alphaOHG(self, ):
        return -1/128 * (self.g3)**(2) * self.lambdaHatzeta * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaOHGt(self, ):
        return 0

    def alphaOHW(self, ):
```

$$\zeta \sim (3,3)_{-1/3}$$

Reading the Lagrangian and parsing th

```
In [10]: from python.Granadazeta_matching import GranadazetaMatchingResult

In [11]: zeta_matching = GranadazetaMatchingResult(scale=1e3)

In [12]: zeta_matching.alphaOHD()
Out[12]: -0.0063515302515737395

In [13]:
```

- Written a lightweight wrapper around FeynRules to encode Lagrangians with less boilerplate code and more consistency checks

- A simple implementation of missing PythonForm to parse results from MatchMaker

- Outputs are Python classes with coefficients as methods.

main · MatchMakerParser /

Code · Blame · 222 lines (160 loc)

```
class GranadazetaMatchingResu
    def __init__(self, name='
        super().__init__(name, scale)
        self.Mzeta = 1
        self.yqlzeta = np.ones((3, 3))
        self.yqlzetabar = np.ones((3, 3))
        self.yqqzeta = np.ones((3, 3))
        self.yqqzetabar = np.ones((3, 3))
        self.lambdaHatzeta = 1
        self.lambdaHatzetabar = 1
        self.lambdaHatPrimezeta = 1
        self.lambdaHatPrimezetabar = 1
        self.nonvanishing = ['alphaO3G', 'alphaO3W', 'alphaOHG', 'alphaOHW', 'alphaOHB', 'alphaOHWB', 'alphaOHBox', 'alphaOHD', 'alphaOH', 'alphaOuG', 'alpha

    def alphaO3G(self, ):
        return 1/1920 * (self.g3)**(3) * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaO3Gt(self, ):
        return 0

    def alphaO3W(self, ):
        return 1/480 * (self.g2)**(3) * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaO3Wt(self, ):
        return 0

    def alphaOHG(self, ):
        return -1/128 * (self.g3)**(2) * self.lambdaHatzeta * (self.Mzeta)**(-2) * self.onelooporder * (np.pi)**(-2)

    def alphaOHGt(self, ):
        return 0

    def alphaOHW(self, ):
```

$\zeta \sim (3,3)_{-1/3}$

Connection to Python ecosystem

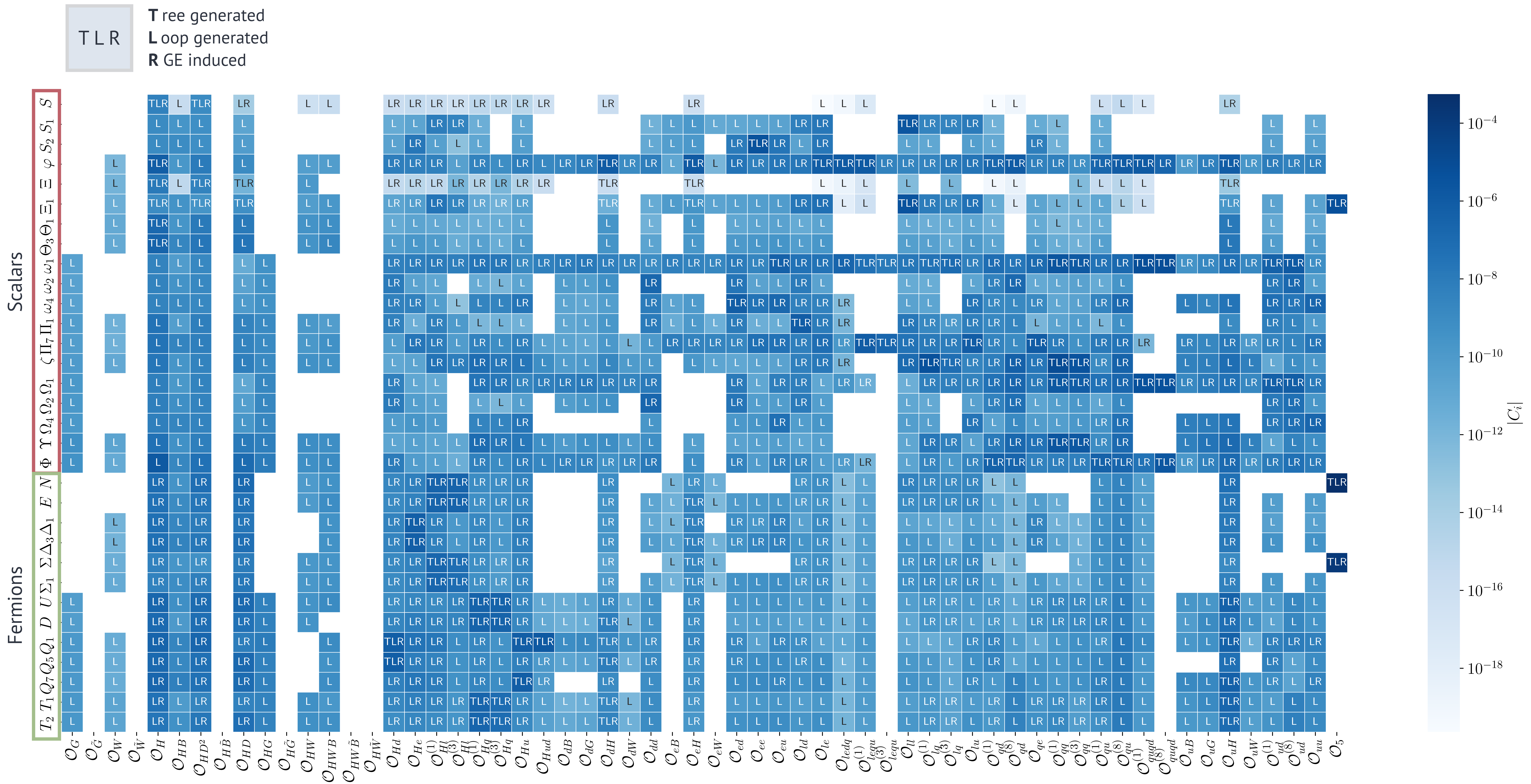
Wilson: Aebischer, Kumar, Straub arXiv:1804.05033
flavio: Straub arXiv:1810.08132

MatchingDB: Criado gitlab.com/jccriado/matchingdb

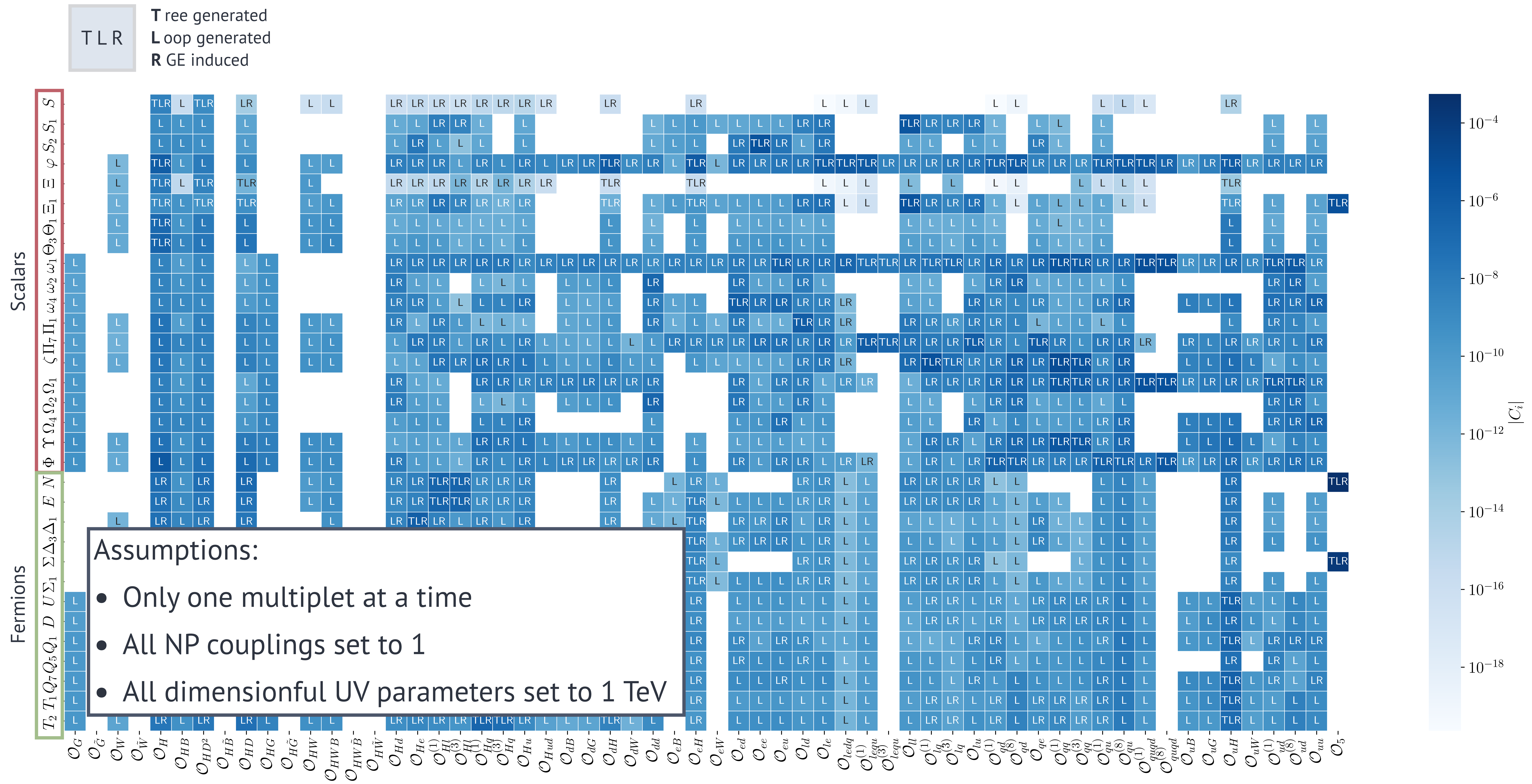
- Plans to put one-loop dictionary on PyPI for easy use with other tools
- Limited searching and querying ability, looking into other export options

$\zeta \sim (3,3)_{-1/3}$

```
import wilson
import flavio

from oneloopdict import ZetaMatching

SCALE = 1e3

# Get coefficients
zeta_matching = ZetaMatching(scale=SCALE)
coefficients = zeta_matching.coefficient_dictionary

# Calculate!
zeta_wilson = wilson.Wilson(coefficients, scale=SCALE, eft="SMEFT", basis="Warsaw")
prediction = flavio.np_prediction("a_mu", zeta_wilson)
~
~
```



T L R
T ree generated
L oop generated
R GE induced
Scalars
S S_1 S_2 φ Ξ Ξ_1 Θ_1 Θ_3 ω_1 ω_2 ω_4 Π_1 Π_7 ζ Ω_1 Ω_2 Ω_4 Υ Φ
Fermions
N E Δ_1 Δ_3 Σ Σ_1 U D Q_1 Q_5 Q_7 T_1 T_2
$\mathcal{O}_G$ $\mathcal{O}_{\tilde{G}}$ $\mathcal{O}_W$ $\mathcal{O}_{\tilde{W}}$ $\mathcal{O}_H$ $\mathcal{O}_{HB}$ $\mathcal{O}_{HD^2}$ $\mathcal{O}_{H\tilde{B}}$ $\mathcal{O}_{HD}$ $\mathcal{O}_{HG}$ $\mathcal{O}_{H\tilde{G}}$ $\mathcal{O}_{HW}$ $\mathcal{O}_{HWB}$ $\mathcal{O}_{HW\tilde{B}}$ $\mathcal{O}_{H\tilde{W}}$ $\mathcal{O}_{Hd}$ $\mathcal{O}_{He}$ $\mathcal{O}_{Hl}^{(1)}$ $\mathcal{O}_{Hl}^{(3)}$ $\mathcal{O}_{Hq}^{(1)}$ $\mathcal{O}_{Hq}^{(3)}$ $\mathcal{O}_{Hu}$ $\mathcal{O}_{Hud}$ $\mathcal{O}_{dB}$ $\mathcal{O}_{dG}$ $\mathcal{O}_{dH}$ $\mathcal{O}_{dW}$ $\mathcal{O}_{dd}$ $\mathcal{O}_{eB}$ $\mathcal{O}_{eH}$ $\mathcal{O}_{eW}$ $\mathcal{O}_{ed}$ $\mathcal{O}_{ee}$ $\mathcal{O}_{eu}$ $\mathcal{O}_{ld}$ $\mathcal{O}_{le}$ $\mathcal{O}_{ledq}$ $\mathcal{O}_{lequ}^{(1)}$ $\mathcal{O}_{lequ}^{(3)}$ $\mathcal{O}_{ll}$ $\mathcal{O}_{lq}^{(1)}$ $\mathcal{O}_{lq}^{(3)}$ $\mathcal{O}_{lu}$ $\mathcal{O}_{qd}^{(1)}$ $\mathcal{O}_{qd}^{(8)}$ $\mathcal{O}_{qe}$ $\mathcal{O}_{qq}^{(1)}$ $\mathcal{O}_{qq}^{(3)}$ $\mathcal{O}_{qu}^{(1)}$ $\mathcal{O}_{qu}^{(8)}$ $\mathcal{O}_{quqd}^{(1)}$ $\mathcal{O}_{quqd}^{(8)}$ $\mathcal{O}_{uB}$ $\mathcal{O}_{uG}$ $\mathcal{O}_{uH}$ $\mathcal{O}_{uW}$ $\mathcal{O}_{ud}^{(1)}$ $\mathcal{O}_{ud}^{(8)}$ $\mathcal{O}_{uu}$ $\mathcal{O}_5$
10^{-4} 10^{-6} 10^{-8} 10^{-10} 10^{-12} 10^{-14} 10^{-16} 10^{-18}
$|C_i|$

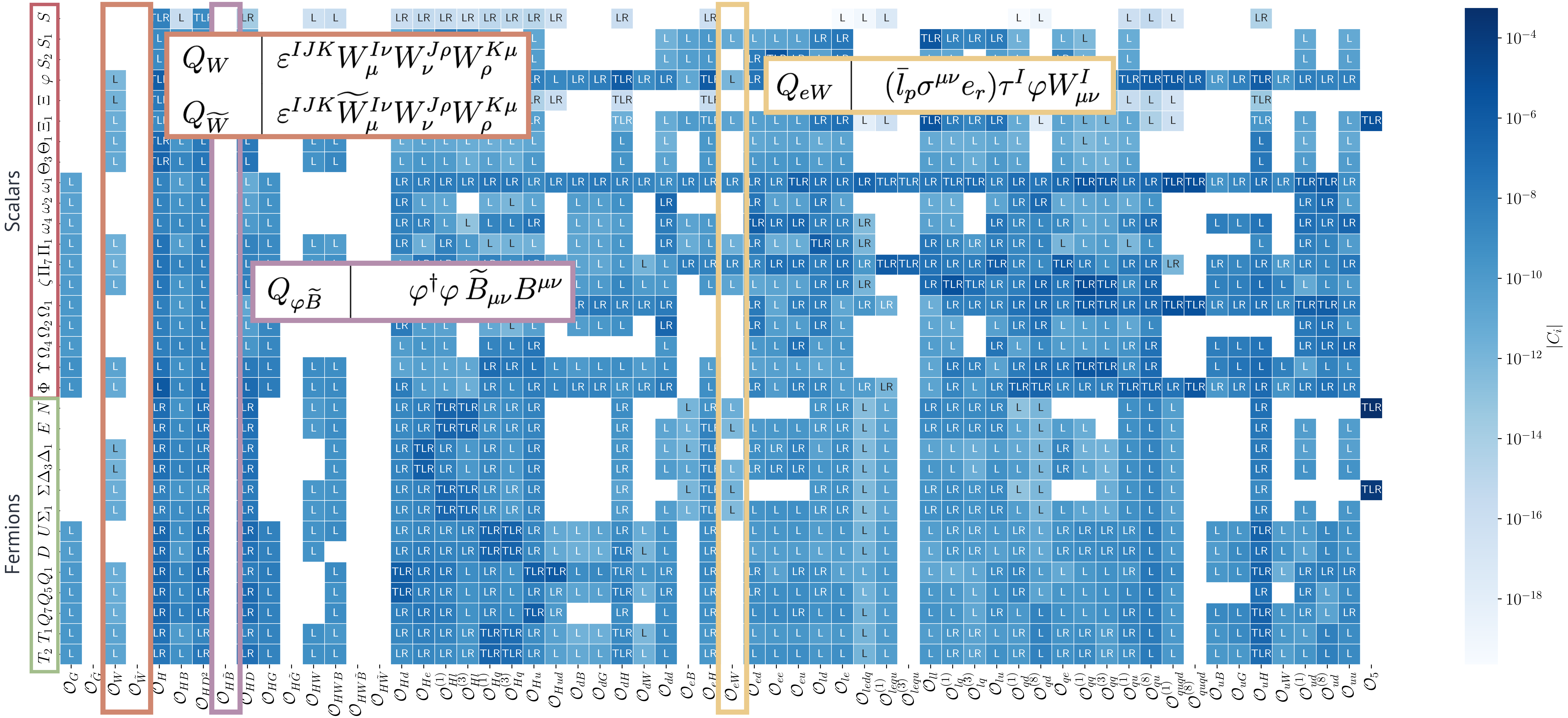


Assumptions:

- Only one multiplet at a time
- All NP couplings set to 1
- All dimensionful UV parameters set to 1 TeV

T L R

T ree generated
L oop generated
R GE induced



Ellis, Quevillon, Vuong, You, Zhang arXiv:2006.16260

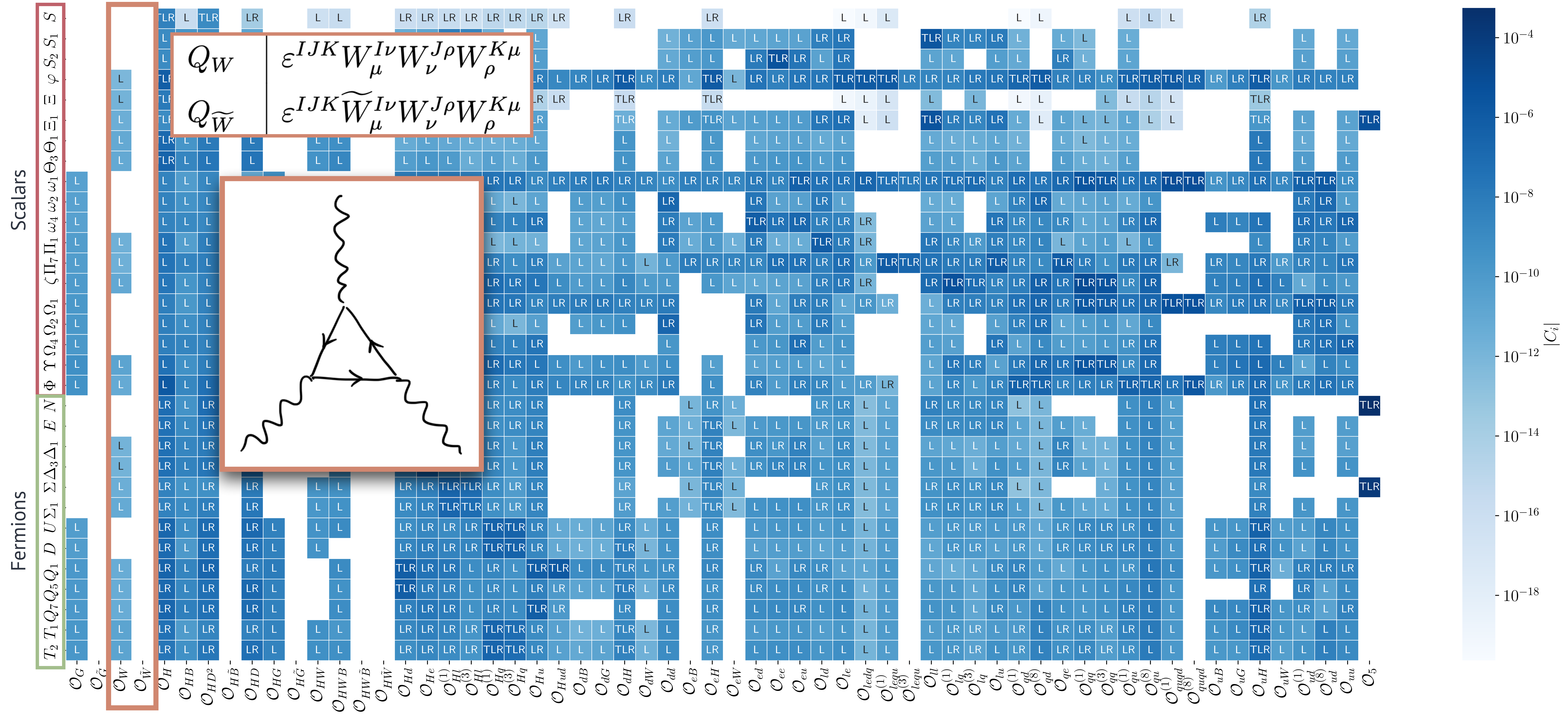
TLR

T ree generated
L oop generated
R GE induced

CP-odd triple-gauge operators not generated at one loop:
Clear already from UOLEA

$$Q_W \quad \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

$$Q_{\widetilde{W}} \quad \varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$$

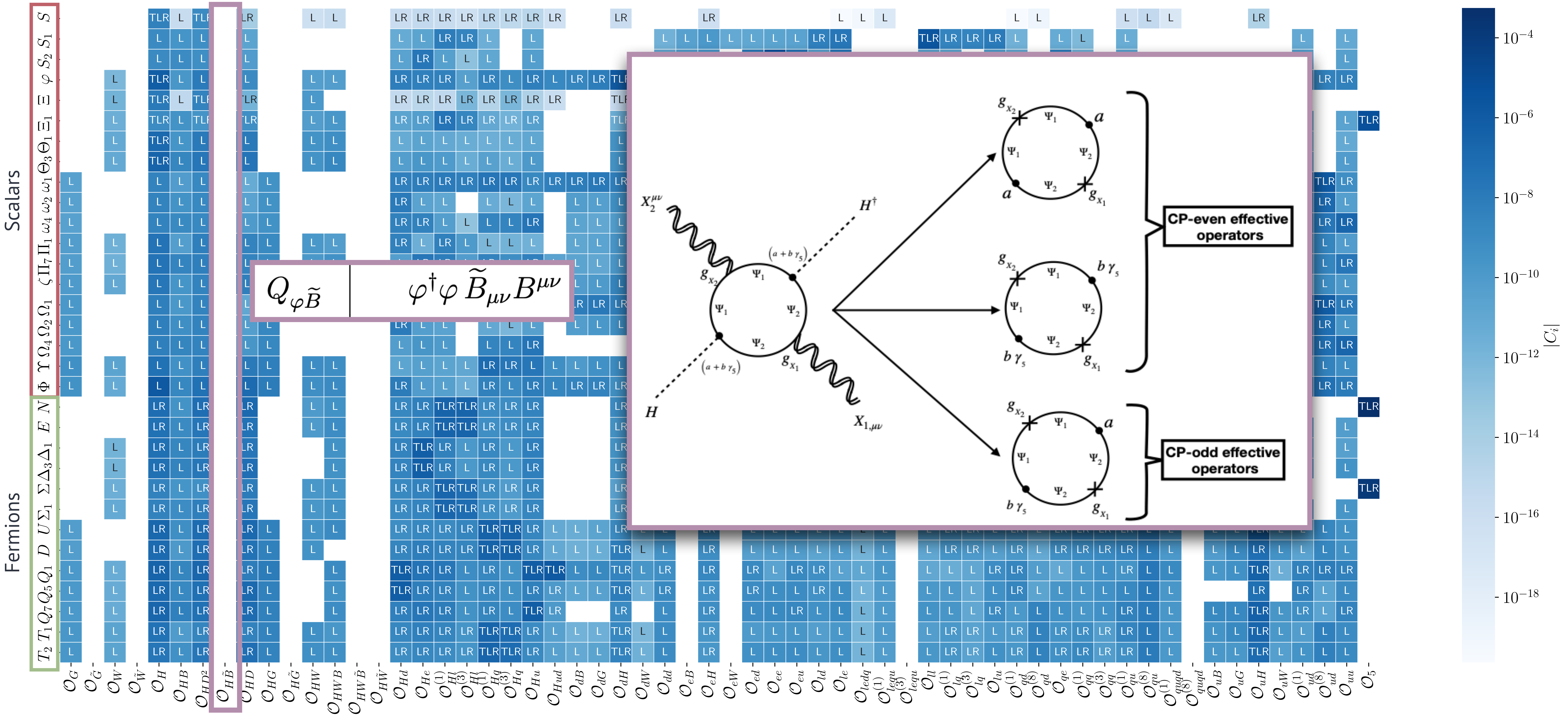


TLR

T ree generated
L oop generated
R GE induced

Bakshi, Chakrabortty, Englert, Spannowsky, Stylianou arXiv:2103.15861

Other CP-odd bosonic operators can be generated at one loop, require **two** exotic multiplets



$$Q_{\varphi\widetilde{B}} \quad \varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$$

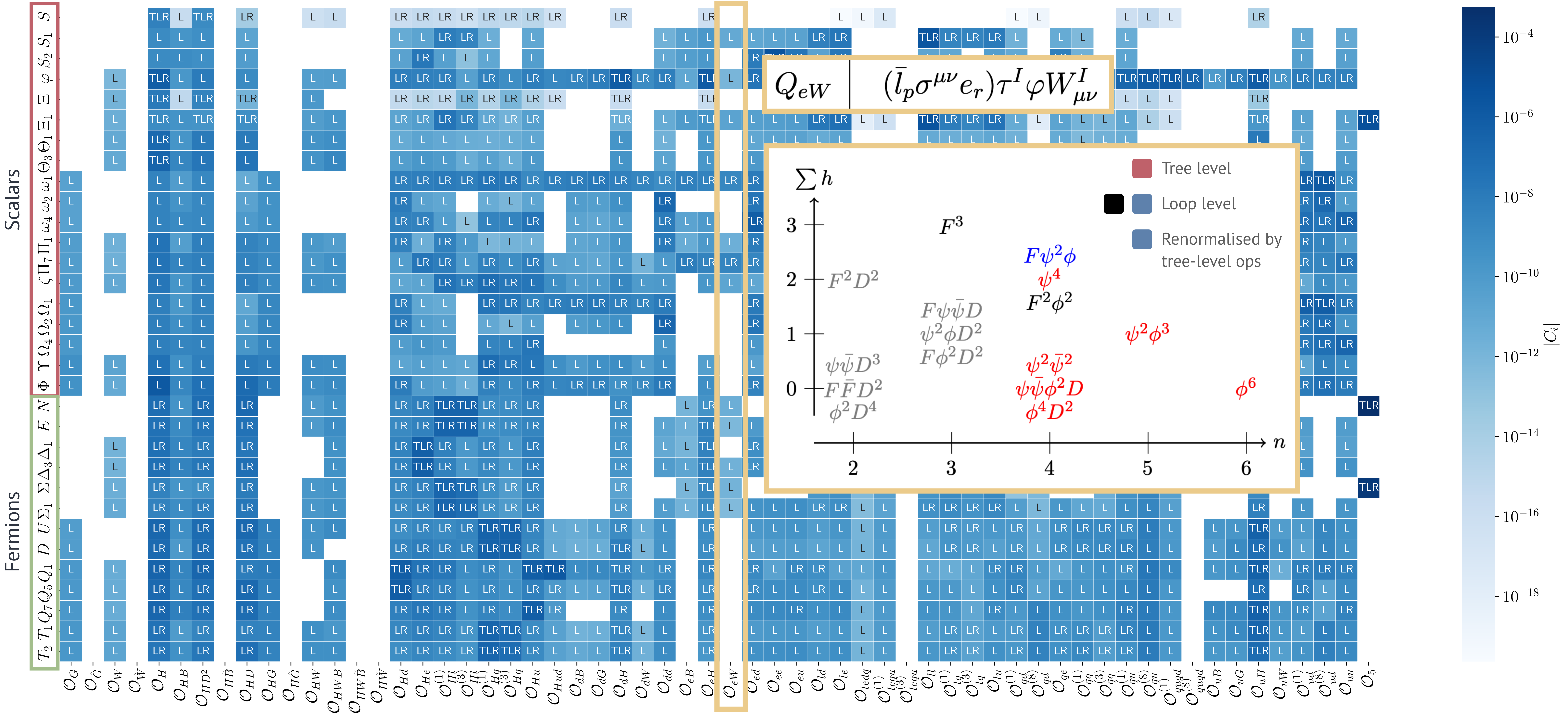
T L R

T ree generated
L oop generated
R GE induced

Craig, Jiang, Li, Sutherland arXiv:2001.00017

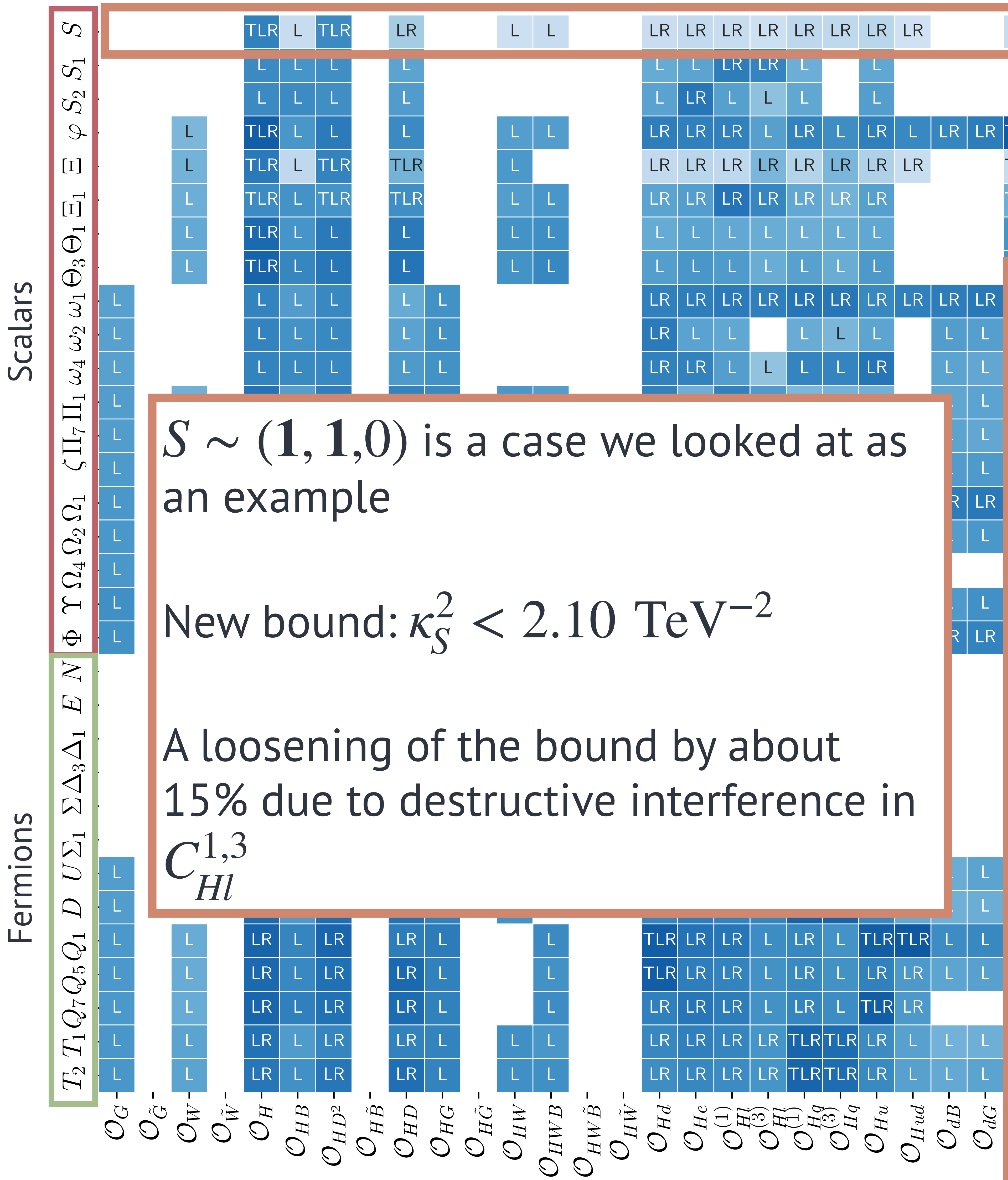
Operators of the form $F\psi^2\phi^2$ are renormalised by four-fermion operators

Q_{eW} $\quad (\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$



TLR
T ree generated
L oop generated
R GE induced

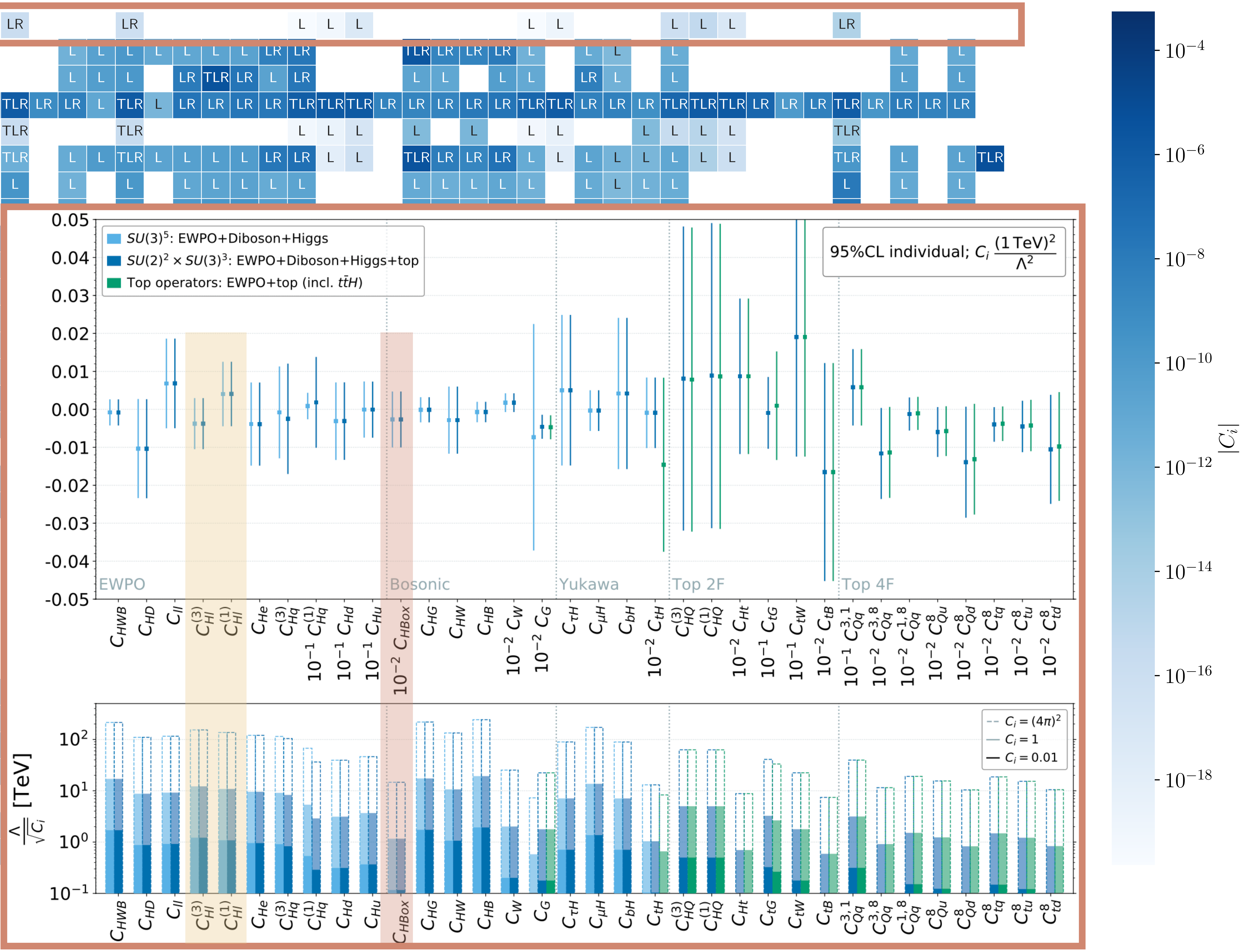
FitMaker: Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779



$S \sim (\mathbf{1}, \mathbf{1}, 0)$ is a case we looked at as an example

New bound: $\kappa_S^2 < 2.10\ \mathrm{TeV}^{-2}$

A loosening of the bound by about 15% due to destructive interference in $C_{Hl}^{1,3}$



Conclusions and outlook

- Computational tools are essential for the publishing and querying of UV/IR dictionaries going forward
- We use MatchMakerEFT and our MatchMakerParser to present our UV/IR dictionary for the linear SM extensions at one loop
- Useful tool for phenomenological analyses and general studies

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$$

$$\mathcal{O}_{HB} = H^\dagger H B_{\mu\nu} B$$

$$\mathcal{O}_{HD} = (H^\dagger D$$

¡Muchas gracias!

$$\mathcal{O}_{HG} = H^\dagger H G^A_{\mu\nu} G^{A\mu\nu}$$

Backup

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int \mathcal{L}\,dt = (3.2 - 139)\ \text{fb}^{-1}$ $\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int \mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1 – 4 j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WW \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV η_{LL}^-		1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV η_{LL}^-		CERN-EP-2020-066
	CI $tttt$	≥1 e, μ	≥1 b, ≥1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t} \rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	1 – 4 j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(LQ_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(LQ_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3} \vert T_{5/3} \to Wt + X$	2(SS)/≥3 e, μ	≥1 b, ≥1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, ≥ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e, μ, 2 γ	≥ 1 b, ≥ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q \rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g \rvert = 1g_D$, spin 1/2	1905.10130

$\sqrt{s}$ = 8 TeV | $\sqrt{s}$ = 13 TeV partial data | $\sqrt{s}$ = 13 TeV full data

10^{-1} 1 10 Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

See talk by Patricia Conde Muíño

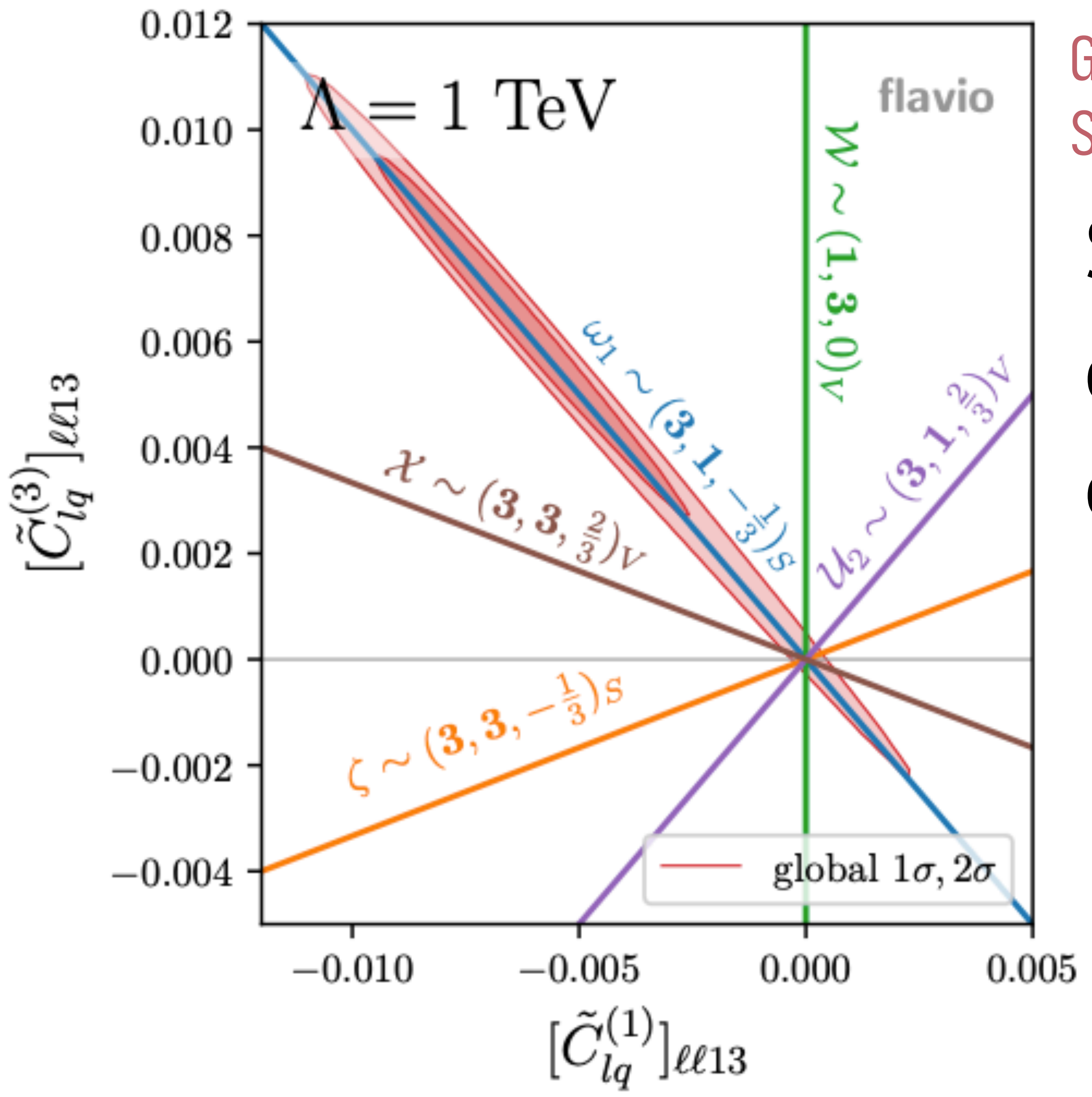
Linear SM extensions are useful

- Linear SM extensions are a physically motivated subset of toy models

Herrero-Garcia, Schmidt arXiv:1903.10552

- Can be used to organise complex UV models

- Can motivate directions in the space of WCs



Greljo, Salko, Smolkovic, Stangl arXiv:2306.09401

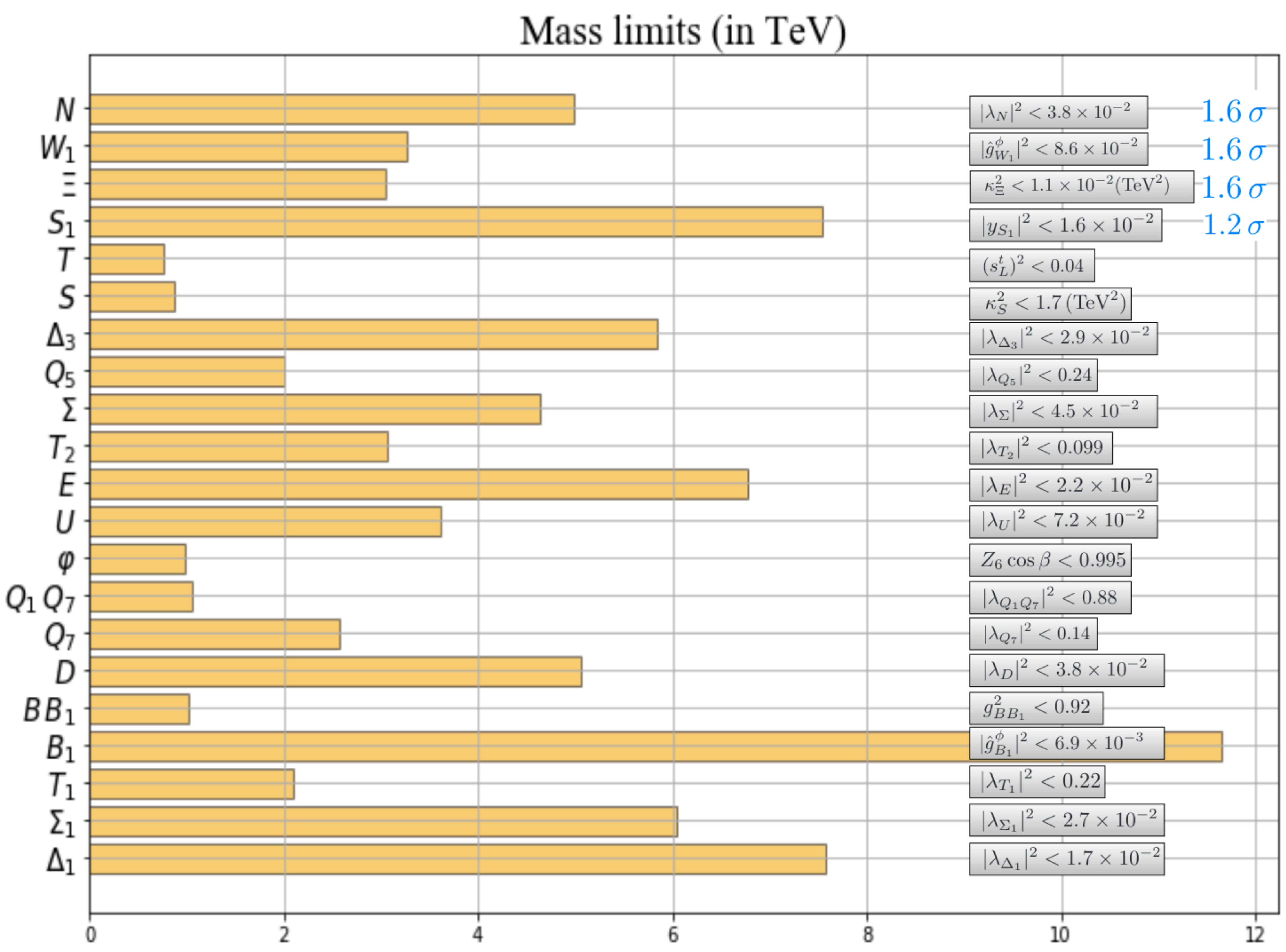
Study of tension in exclusive V_{ub} extraction

Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						$-\frac{3}{2}$	$-y_\tau$	$-y_t$	$-y_b$
$\{Q_1, Q_7\}$								y_t	
Model	C_{Hq}^3	C_{Hq}^1	$(C_{Hq}^3)_{33}$	$(C_{Hq}^1)_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t \frac{M_T^2}{v^2}$		

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

FitMaker group: Fit to top, Higgs, diboson and EW data

Linear SM extensions are useful



Model	C_{HD}	C_{ll}	C^3_{Hl}	C^1_{Hl}	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						$-\frac{1}{2}$			
S_1		1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						$-\frac{3}{2}$	$-\ y_\tau$	$-\ y_t$	$-\ y_b$
$\{Q_1, Q_7\}$								y_t	

Model	C^3_{Hq}	C^1_{Hq}	$(C^3_{Hq})_{33}$	$(C^1_{Hq})_{33}$	C_{Hu}	C_{Hd}	C_{tH}	C_{bH}	
U	$-\frac{1}{4}$	$\frac{1}{4}$	$-\frac{1}{4}$	$\frac{1}{4}$			$\frac{y_t}{2}$		
D	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$	$-\frac{1}{4}$				$\frac{y_b}{2}$	
Q_5						$-\frac{1}{2}$		$\frac{y_b}{2}$	
Q_7					$\frac{1}{2}$		$\frac{y_t}{2}$		
T_1	$-\frac{1}{16}$	$-\frac{3}{16}$	$-\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_t}{4}$	$\frac{y_b}{8}$	
T_2	$-\frac{1}{16}$	$\frac{3}{16}$	$-\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_t}{8}$	$\frac{y_b}{4}$	
T			$-\frac{1}{2}\frac{M_T^2}{v^2}$	$\frac{1}{2}\frac{M_T^2}{v^2}$			$y_t\frac{M_T^2}{v^2}$		

Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779

FitMaker group: Fit to top, Higgs, diboson and EW data

Linear SM extensions are complicated

de Blas, Criado, Pérez-Victoria, Santiago arXiv:1711.10391
MatchingTools: Criado arXiv:1710.06445

Exotic fermion interactions

$$
\begin{aligned}
-\mathcal{L}^{(4)}_{\text{leptons}} = {} & (\lambda_N)_{ri}\bar{N}_{Rr}\tilde{\phi}^\dagger l_{Li} + (\lambda_E)_{ri}\bar{E}_{Rr}\phi^\dagger l_{Li} \\
& + (\lambda_{\Delta_1})_{ri}\bar{\Delta}_{1Lr}\phi e_{Ri} + (\lambda_{\Delta_3})_{ri}\bar{\Delta}_{3Lr}\tilde{\phi} e_{Ri} \\
& + \frac{1}{2}(\lambda_\Sigma)_{ri}\bar{\Sigma}^a_{Rr}\tilde{\phi}^\dagger\sigma^a l_{Li} + \frac{1}{2}(\lambda_{\Sigma_1})_{ri}\bar{\Sigma}^a_{1Rr}\phi^\dagger\sigma^a l_{Li} \\
& + (\lambda_{N\Delta_1})_{rs}\bar{N}^c_{Rr}\phi^\dagger\Delta_{1Rs} + (\lambda_{E\Delta_1})_{rs}\bar{E}_{Lr}\phi^\dagger\Delta_{1Rs} \\
& + (\lambda_{E\Delta_3})_{rs}\bar{E}_{Lr}\tilde{\phi}^\dagger\Delta_{3Rs} + \frac{1}{2}(\lambda_{\Sigma\Delta_1})_{rs}\bar{\Sigma}^{ca}_{Rr}\tilde{\phi}^\dagger\sigma^a\Delta_{1Rs}
\end{aligned}
$$

$-\mathcal{L}_{\text{q}}^{(4)}$ …

Dimension-5 scalar interactions

$$
\begin{aligned}
-\mathcal{L}^{(5)}_{\mathcal{S}} = \frac{1}{f}\Big[& (\tilde{k}^\phi_{\mathcal{S}})_r\mathcal{S}_r D_\mu\phi^\dagger D^\mu\phi + (\tilde{\lambda}_{\mathcal{S}})_r\mathcal{S}_r|\phi|^4 \\
& + (\tilde{k}^B_{\mathcal{S}})_r\mathcal{S}_r B_{\mu\nu}B^{\mu\nu} + (\tilde{k}^W_{\mathcal{S}})_r\mathcal{S}_r W^a_{\mu\nu}W^{a\,\mu\nu} + (\tilde{k}^G_{\mathcal{S}})_r\mathcal{S}_r G^A_{\mu\nu}G \ldots \\
& + (\tilde{k}^{\tilde{B}}_{\mathcal{S}})_r\mathcal{S}_r B_{\mu\nu}\tilde{B}^{\mu\nu} + (\tilde{k}^{\tilde{W}}_{\mathcal{S}})_r\mathcal{S}_r W^a_{\mu\nu}\tilde{W}^{a\,\mu\nu} + (\tilde{k}^{\tilde{G}}_{\mathcal{S}})_r\mathcal{S}_r G^A_{\mu\nu}\tilde{G} \ldots \\
& + \Big\{(\tilde{y}^e_{\mathcal{S}})_{rij}\mathcal{S}_r\bar{e}_{Ri}\phi^\dagger l_{Lj} + (\tilde{y}^d_{\mathcal{S}})_{rij}\mathcal{S}_r\bar{d}_{Ri}\phi^\dagger q_{Lj} + (\tilde{y}^u_{\mathcal{S}})_{rij}\mathcal{S}_r\bar{u}_{Ri} \ldots \\
& + (\tilde{k}^\phi_\Xi)_r\Xi^a_r D_\mu\phi^\dagger\sigma^a D^\mu\phi + (\tilde{\lambda}_\Xi)_r\Xi^a_r|\phi|^2\phi^\dagger\sigma^a\phi \\
& + (\tilde{k}^{WB}_\Xi)_r\Xi^a_r W^a_{\mu\nu}B^{\mu\nu} + (\tilde{k}^{W\tilde{B}}_\Xi)_r\Xi^a_r W^a_{\mu\nu}\tilde{B}^{\mu\nu} \\
& + \Big\{(\tilde{y}^e_\Xi)_{rij}\Xi^a_r\bar{e}_{Ri}\phi^\dagger\sigma^a l_{Lj} + (\tilde{y}^d_\Xi)_{rij}\Xi^a_r\bar{d}_{Ri}\phi^\dagger\sigma^a q_{Lj} + (\tilde{y}^u_\Xi)_{rij} \ldots \\
& + \Big\{(\tilde{k}_{\Xi_1})_r\Xi^{a\dagger}_{1r}D_\mu\tilde{\phi}^\dagger\sigma^a D^\mu\phi + (\tilde{\lambda}_{\Xi_1})_r\Xi^{a\dagger}_{1r}|\phi|^2\tilde{\phi}^\dagger\sigma^a\phi + (\tilde{y}^e_{\Xi_1})_r \ldots \\
& + (\tilde{y}^d_{\Xi_1})_{rij}\Xi^{a\dagger}_{1r}\bar{d}_{Ri}\tilde{\phi}^\dagger\sigma^a q_{Lj} + (\tilde{y}^u_{\Xi_1})_{rij}\Xi^{a\dagger}_{1r}\bar{q}_{Li}\sigma^a\phi u_{Rj} + \text{h.c.} \ldots
\end{aligned}
$$

Scalar-vector mixed interactions

$$
\begin{aligned}
-\mathcal{L}_{\text{SV}} = {} & (\delta_{\mathcal{BS}})_{rs}\mathcal{B}_{r\mu}D^\mu\mathcal{S}_s + (\delta_{\mathcal{W}\Xi})_{rs}\mathcal{W}_{r,\mu}D^\mu\Xi_s \\
& + \Big\{(\delta_{\mathcal{L}^1\varphi})_{rs}\mathcal{L}^{1\dagger}_{1r\mu}D^\mu\varphi_s + (\delta_{\mathcal{W}^1\Xi_1})_{rs}\mathcal{W}^{1\dagger}_{1r\mu}D^\mu\Xi_{1s} + \text{h.c.}\Big\} \\
& + (\varepsilon_{\mathcal{S}\mathcal{L}_1})_{rst}\mathcal{S}_r\mathcal{L}^\dagger_{1s\mu}\mathcal{L}^\mu_{1t} + (\varepsilon_{\Xi\mathcal{L}_1})_{rst}\Xi^a_r\mathcal{L}^\dagger_{1s\mu}\sigma^a\mathcal{L}^\mu_{1t} \\
& + \Big\{(\varepsilon_{\Xi_1\mathcal{L}_1})_{rst}\Xi^a_{1i}\mathcal{L}^\dagger_{1s\mu}\sigma^a\tilde{\mathcal{L}}^\mu_{1t} + \text{h.c.}\Big\} \\
& + \Big\{(g_{\mathcal{S}\mathcal{L}_1})_{rs}\phi^\dagger\left(D_\mu\mathcal{S}_r\right)\mathcal{L}^\mu_{1s} + (g'_{\mathcal{S}\mathcal{L}_1})_{rs}\left(D_\mu\phi\right)^\dagger\mathcal{S}_r\mathcal{L}^\mu_{1s} \\
& \quad + (g_{\Xi\mathcal{L}_1})_{rs}\phi^\dagger\sigma^a\left(D_\mu\Xi^a_r\right)\mathcal{L}^\mu_{1s} + (g'_{\Xi\mathcal{L}_1})_{rs}\left(D_\mu\phi\right)^\dagger\sigma^a\Xi^a_r\mathcal{L}^\mu_{1s} \\
& \quad + (g_{\Xi_1\mathcal{L}_1})_{rs}\tilde{\phi}^\dagger\sigma^a\left(D_\mu\Xi^a_{1r}\right)^\dagger\mathcal{L}^\mu_{1s} + (g'_{\Xi_1\mathcal{L}_1})_{rs}\left(D_\mu\tilde{\phi}\right)^\dagger\sigma^a\Xi^{a\dagger}_{1r}\mathcal{L}^\mu_{1s} + \text{h.c.}\Big\},
\end{aligned}
$$

7 pages…

- Lagrangian contains terms up to dimension 5 **sufficient to generate dimension-6 operators at tree level**
- Also includes "mixed" terms with multiple exotic multiplets

Going past dimension 6

JG, Volkas arXiv:2009.13537
https://github.com/johngarg/neutrinomass
Completions database: https://zenodo.org/record/4054618

- Tree-level completions of operators of odd mass dimension written down up to dimension 11
  - Database of 500,000 Lagrangians ⇒ Requires computational tools!
  - Matching onto any specific basis still needs to be done by hand

github.com

12772	16179461	8614953467442367	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1

There are many search results. Let's make a more specific query.

In [20]:

```
# Extend the query to look at the models with fewer than 5 fields that need to be at less than 7000 TeV
df[
    (df["democratic_num"] % df.exotics["S,01,0,1/3,-1"] == 0) &
    (df["democratic_num"] % df.exotics["S,00,0,1,0"] == 0) &
    (df["scale"] < 7000) &
    (df["n_fields"] < 5)
]
```

Out[20]:

	democratic_num	stringent_num	op	dim	scale	symbolic_scale	topology	n_fields	n_scalars	n_fermions	min_loops	max_loo
8387	3379507	30579275025083	10	9	5967.42299748072	loop**2*v**2*yd*ye/Λ	0s6f_1	3	3	0	2	
12771	12372529	1378968263787181	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1	2	
12772	16179461	8614953467442367	63d	11	37.9148278684193	loop**2*loopv2*v**2*yd*ye/Λ	2s6f_4	4	3	1	2	

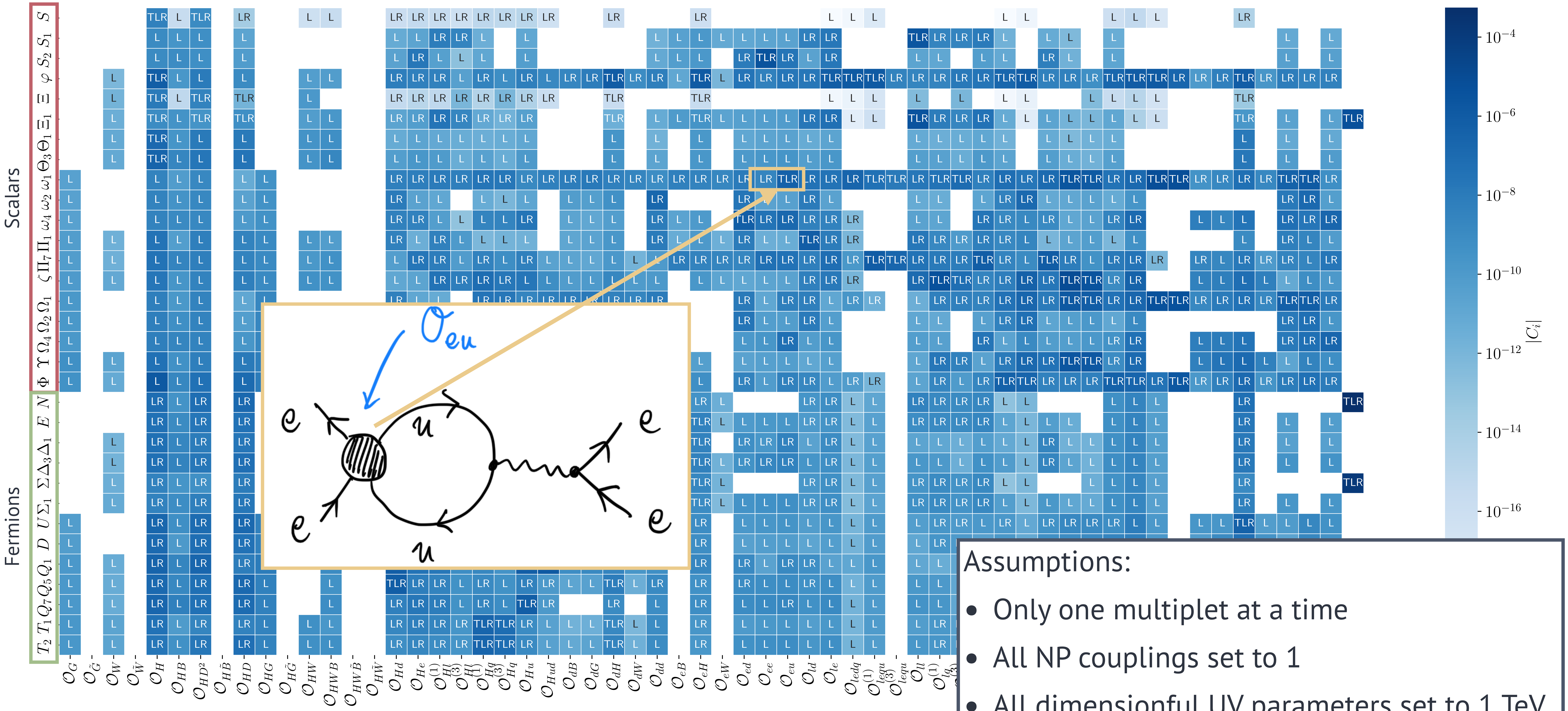
Symbolic matching estimates

TLR — **T** ree generated, **L** oop generated, **R** GE induced

L — Heavy loop

L R — Heavy-light loop

Craig, Jiang, Li, Sutherland arXiv:2001.00017



Assumptions:

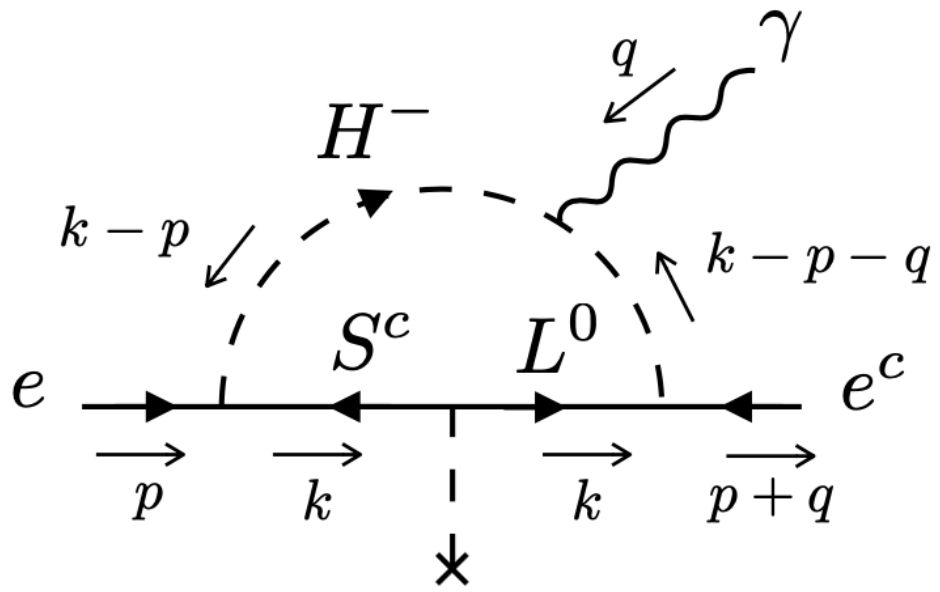
- Only one multiplet at a time
- All NP couplings set to 1
- All dimensionful UV parameters set to 1 TeV

Investigation of *magic* zeros

Arkani-Hamed, Harigaya arXiv:2106.01373
Craig, Garcia Garcia, Vainshtein, Zhang arXiv:2112.05770

- Magic zero: a quantity suppressed without an *apparent* symmetry explanation
- E.g. Vanishing dipole coefficient $H^\dagger \ell \sigma^{\mu\nu} e^c F_{\mu\nu}$ in model with two vector-like Dirac fermions: $S \sim (1,1)_0$ and $L \sim (1,2)_{1/2}$

$$\mathscr{L} \supset -m_L L^0 L^{c0} - m_S S S^c - \boxed{Y_V' H^0 L^0 S^c} + Y_L H^+ e S^c - Y_R H^- L^0 e^c + \mathrm{h.c.}$$



$$\sim \quad \tau_L \equiv \frac{e}{32\pi^2} \cdot \frac{v}{\sqrt{2}} \cdot \frac{Y_L Y_R Y_V'^*}{|m_L|^2 - |m_S|^2} \xrightarrow{\mathscr{P}'} -\tau_L$$

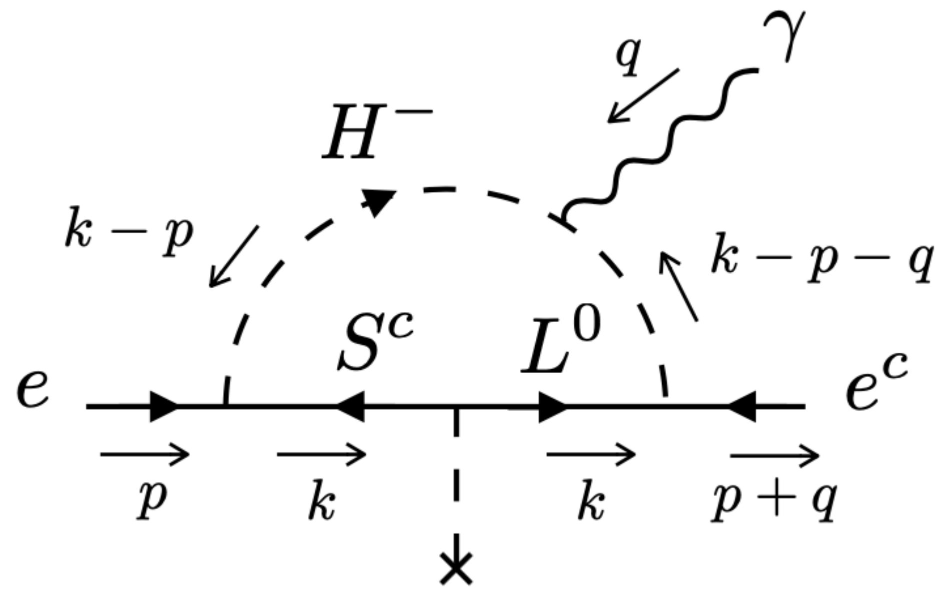
- Generalised parity symmetry $\mathscr{P}'$: $L^0 \leftrightarrow S^{c\dagger}$, $L^{c0} \leftrightarrow S^\dagger$, $m_L \leftrightarrow m_S^*$, $Y_V' \leftrightarrow Y_V'^*$, $Y_L \leftrightarrow Y_R^*$
- But dipole operator even under parity!

Investigation of *magic* zeros

Arkani-Hamed, Harigaya arXiv:2106.01373
Craig, Garcia Garcia, Vainshtein, Zhang arXiv:2112.05770

```
In[3]:= alphaOeB[1, 1] /. MatchingResult

Out[3]=            1
        ─────────────────────────
        384 MDelta1^2 MN^2 π^2
        g1 onelooporder (4 MN^2 lambdaDelta1[1] × lambdaDelta1bar[mif3] × yl[1, mif3] -
          3 iCPV^2 MN^2 lambdaDelta1[1] × lambdaDelta1bar[mif3] × yl[1, mif3] +
          MDelta1^2 lambdaN[mif3] × lambdaNbar[1] × yl[mif3, 1])

In[4]:= alphaOeB[1, 1] /. MatchingResult /. yl[x_, y_] :> 0

Out[4]= 0
```

- Magic zero: a quant
- E.g. Vanishing dipol : $S \sim (1,1)_0$ and $L \sim (1,2)_{1/2}$



$$\sim \quad \tau_L \equiv \frac{e}{32\pi^2} \cdot \frac{v}{\sqrt{2}} \cdot \frac{Y_L Y_R Y_V'^*}{|m_L|^2 - |m_S|^2} \xrightarrow{\mathscr{P}'} -\tau_L$$

- Generalised parity symmetry $\mathscr{P}'$: $L^0 \leftrightarrow S^{c\dagger}$, $L^{c0} \leftrightarrow S^\dagger$, $m_L \leftrightarrow m_S^*$, $Y_V' \leftrightarrow Y_V'^*$, $Y_L \leftrightarrow Y_R^*$
- But dipole operator even under parity!