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

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

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

$\mathcal{O}_{ll} = (\bar{l}_p \gamma$

$\mathcal{O}^{(1)}_{lq} =$

Mapping the one-loop structure of the linear SM extensions

John Gargalionis, Jérémie Quevillon, Pham Ngoc Hoa Vuong, Tevong You

[arXiv: 24XX.XXXXX]

"Theory space of particle physics models"

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

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{d \leq 4} + \sum_{p,q} \frac{c_{pq}^{(5)}}{\Lambda} (L_p L_q) H H + \sum_{i=1}^{2499} \frac{c_i^{(6)}}{\Lambda^2} \mathscr{O}_i^{d=6} + \cdots$$

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

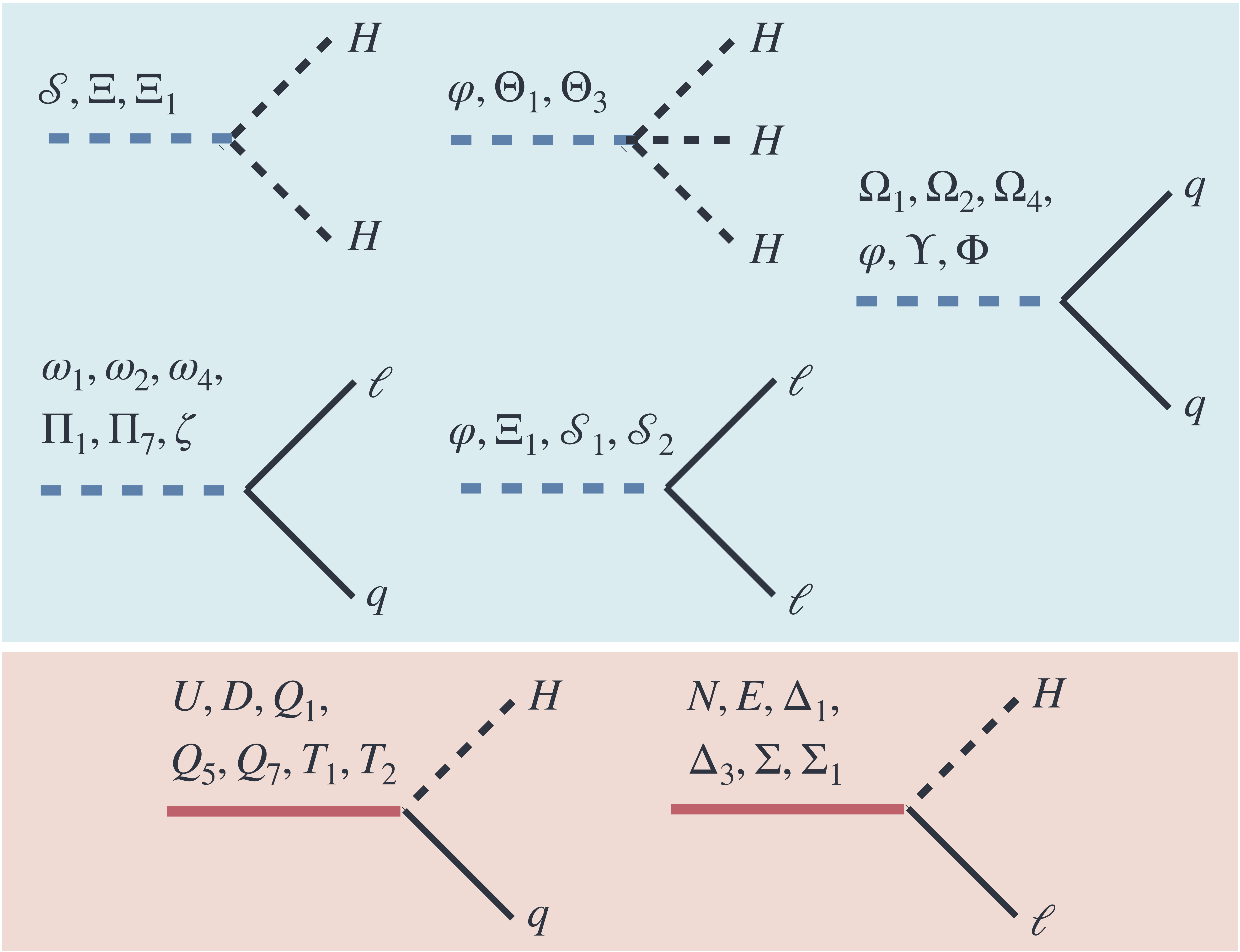
- Patterns of minimal tree-level deviation from the SM can be understood in terms of linear SM extensions

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

- 48 exotic multiplets generating $d = 6$ operators at tree level, we leave out vector bosons

- Fermions enter as vector-like or Majorana

- Represent a non-trivial cross section of exotics search programme at the LHC



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- Represent a non-trivial cross section of exotics search programme at the LHC

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

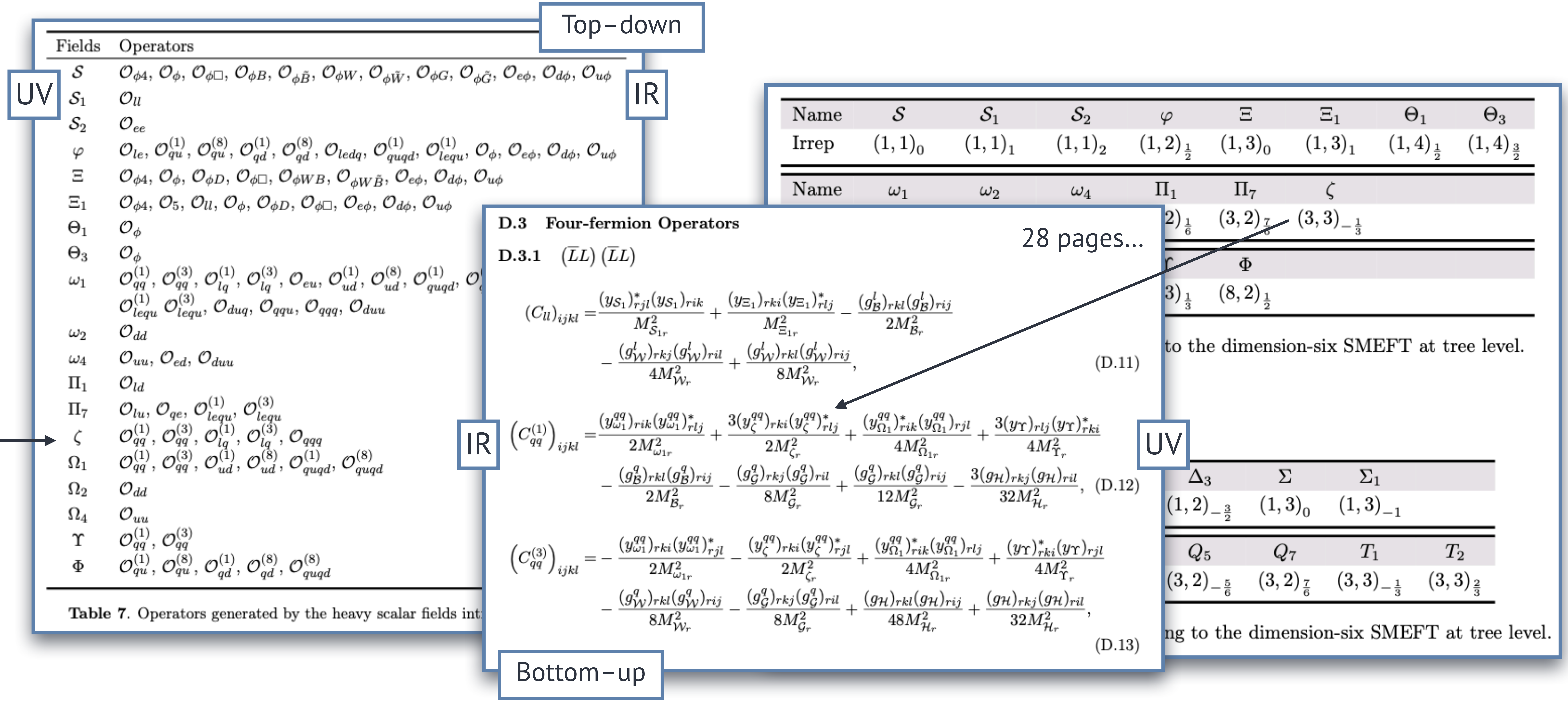
Table 1. New scalar bosons contributing to the dimension-six SMEFT at tree level.

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



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	$\mathcal{O}^{(1)}_{qq}$, $\mathcal{O}^{(3)}_{qq}$, $\mathcal{O}^{(1)}_{lq}$, $\mathcal{O}^{(3)}_{lq}$, $\mathcal{O}_{eu}$, $\mathcal{O}^{(1)}_{ud}$, $\mathcal{O}^{(8)}_{ud}$, $\mathcal{O}^{(1)}_{quqd}$, $\mathcal{O}$ … $\mathcal{O}^{(1)}_{lequ}$, $\mathcal{O}^{(3)}_{lequ}$, $\mathcal{O}_{duq}$, $\mathcal{O}_{qqu}$, $\mathcal{O}_{qqq}$, $\mathcal{O}_{duu}$
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		
				$2)_{\frac{1}{6}}$	$(3,2)_{\frac{7}{6}}$	$(3,3)_{-\frac{1}{3}}$		
					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.

D.3 Four-fermion Operators

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

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

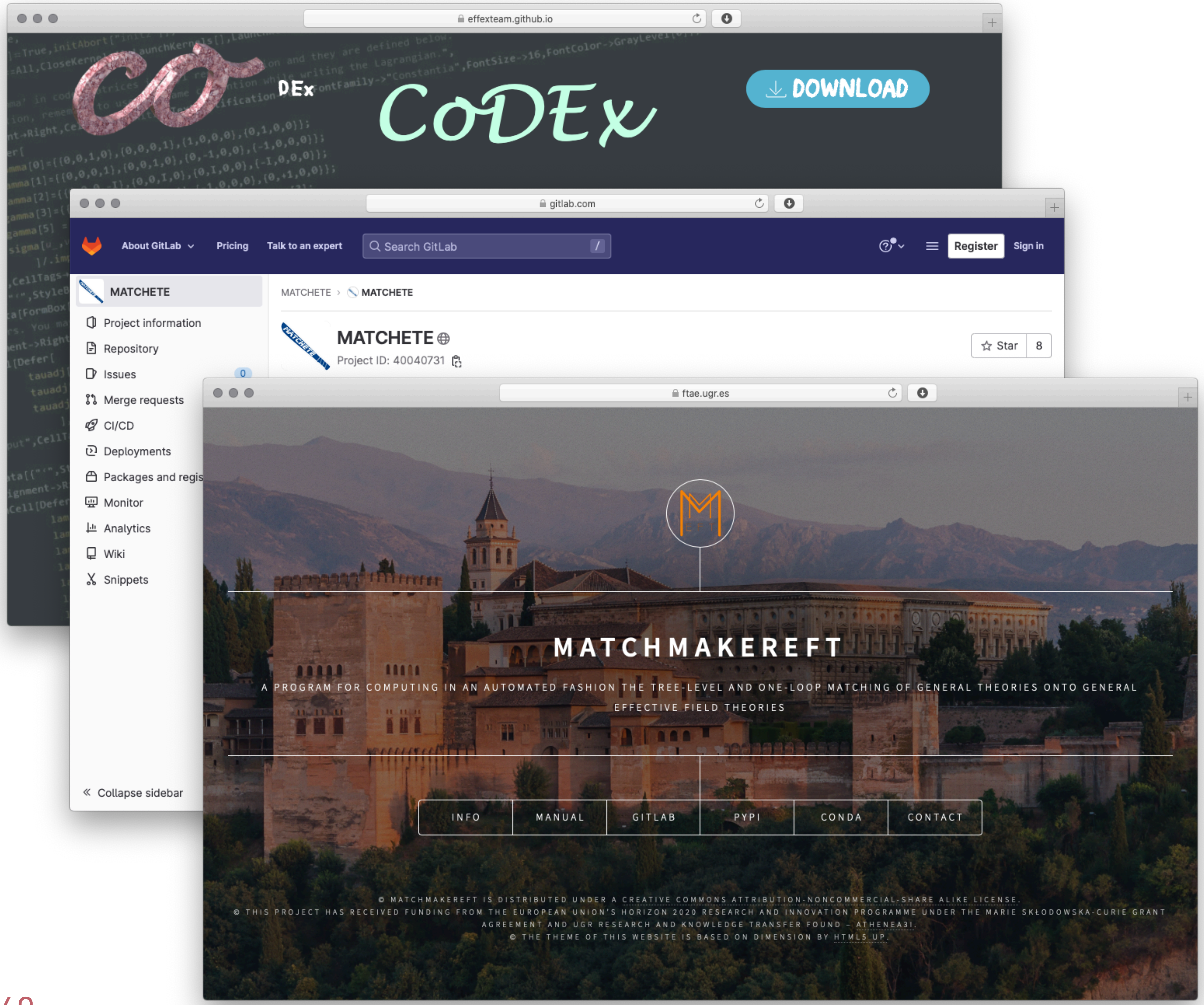
$$\left(C^{(1)}_{qq}\right)_{ijkl} = \frac{(y^{qq}_{\omega_1})_{rik}(y^{qq}_{\omega_1})^*_{rlj}}{2M^2_{\omega_{1r}}} + \frac{3(y^{qq}_{\zeta})_{rki}(y^{qq}_{\zeta})^*_{rlj}}{2M^2_{\zeta_r}} + \frac{(y^{qq}_{\Omega_1})^*_{rik}(y^{qq}_{\Omega_1})_{rjl}}{4M^2_{\Omega_{1r}}} + \frac{3(y_{\Upsilon})_{rlj}(y_{\Upsilon})^*_{rki}}{4M^2_{\Upsilon_r}}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

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

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)



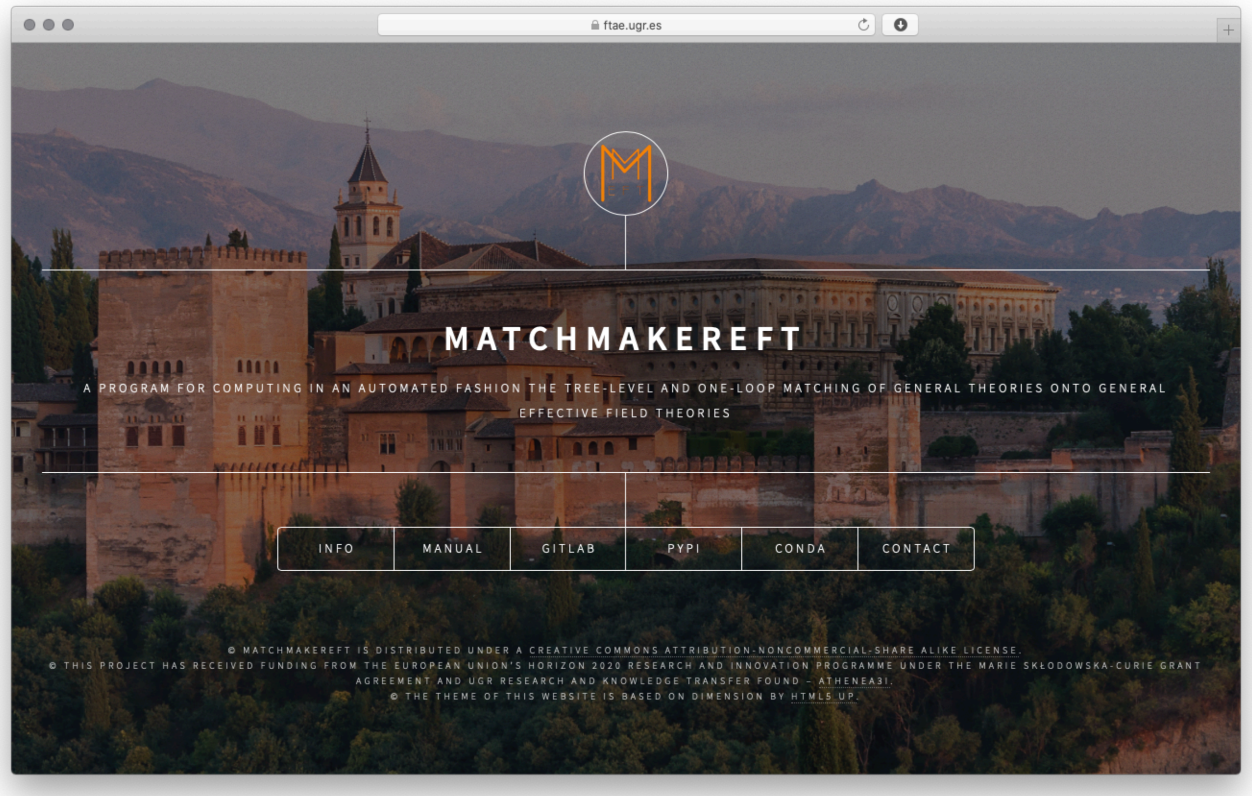
CoDeX: Bakshi Chakrabortty, Patra arXiv:1808.04403
UOLEA results: Drozd, Ellis, Quevillon, You arXiv:1512.03003
Ellis, Quevillon, You, Zhang arXiv:1604.02445
Ellis, Quevillon, Vuong, You, Zhang arXiv:2006.16260
Larue, Quevillon arXiv:2303.10203
MatchMakerEFT: Carmona, Lazopoulos, Olgoso, Santiago arXiv:2112.10787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

A one-loop dictionary for the linear SM extensions

Main 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



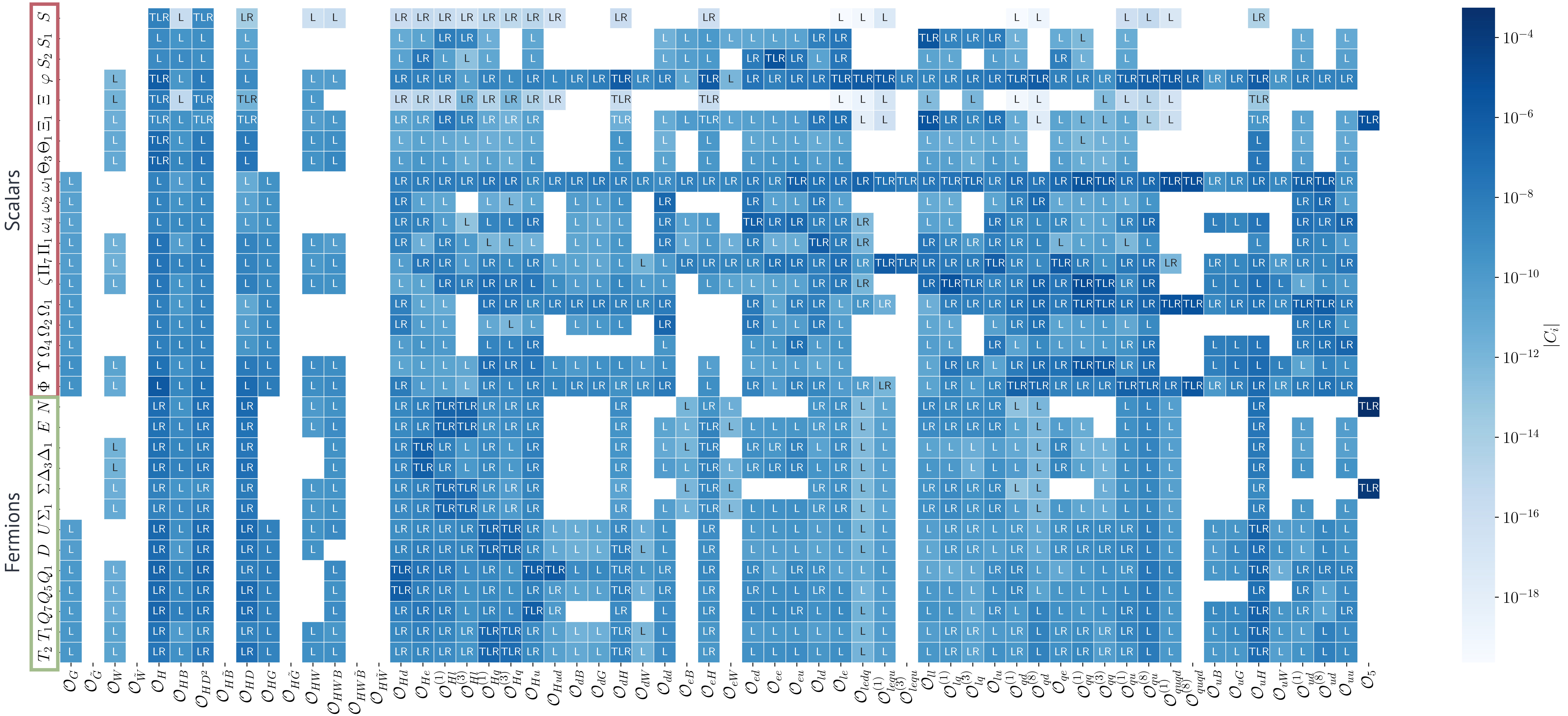
`MatchMakerParser:` Parses Mathematica to Python, writes classes for each multiplet

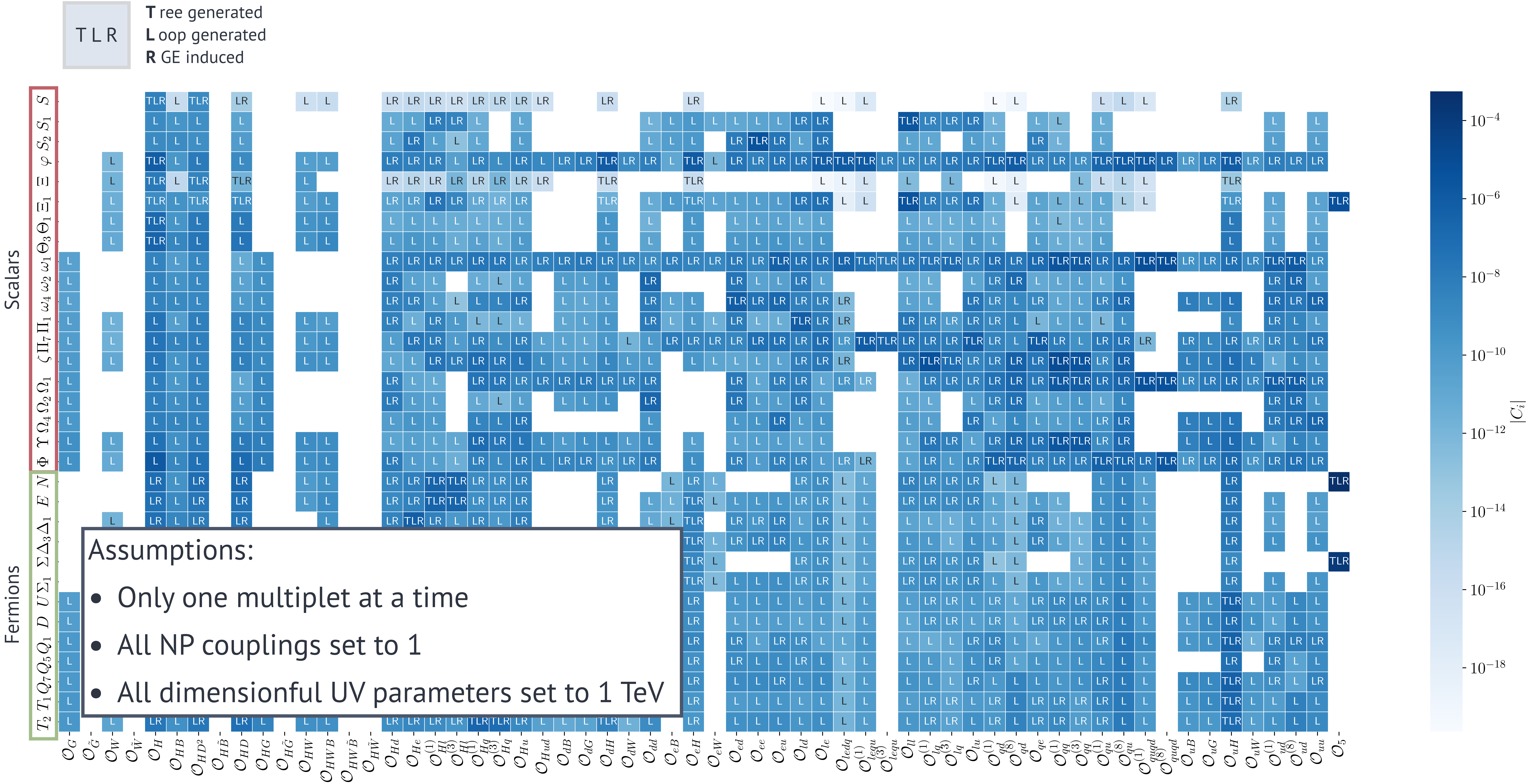
TLR

T ree generated

L oop generated

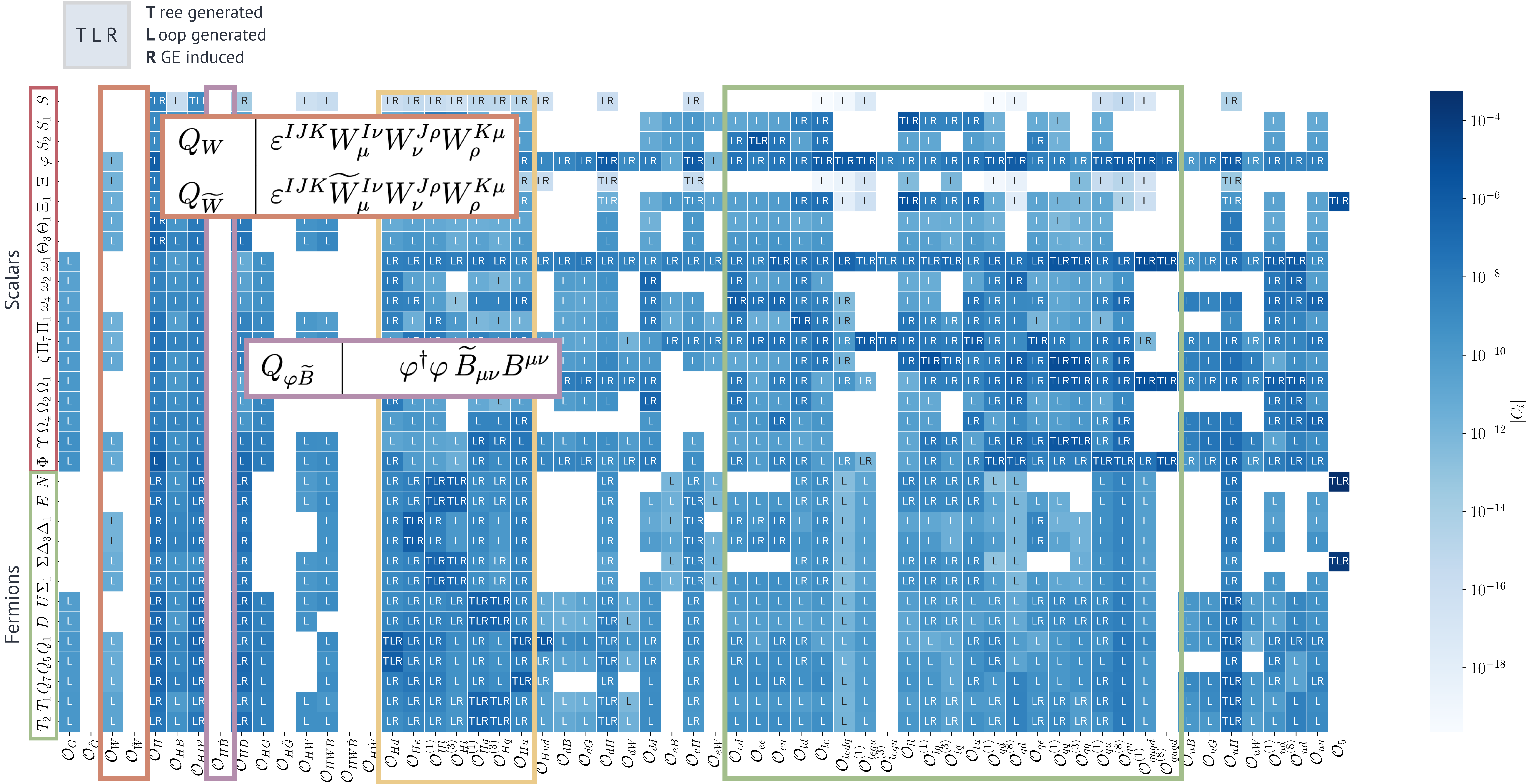
R GE induced





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
Scalars
Fermions
Q_W | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$ | $\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\varphi\widetilde{B}}$ | $\varphi^\dagger \varphi \, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
$|C_i|$

TLR

T ree generated
L oop generated
R GE induced

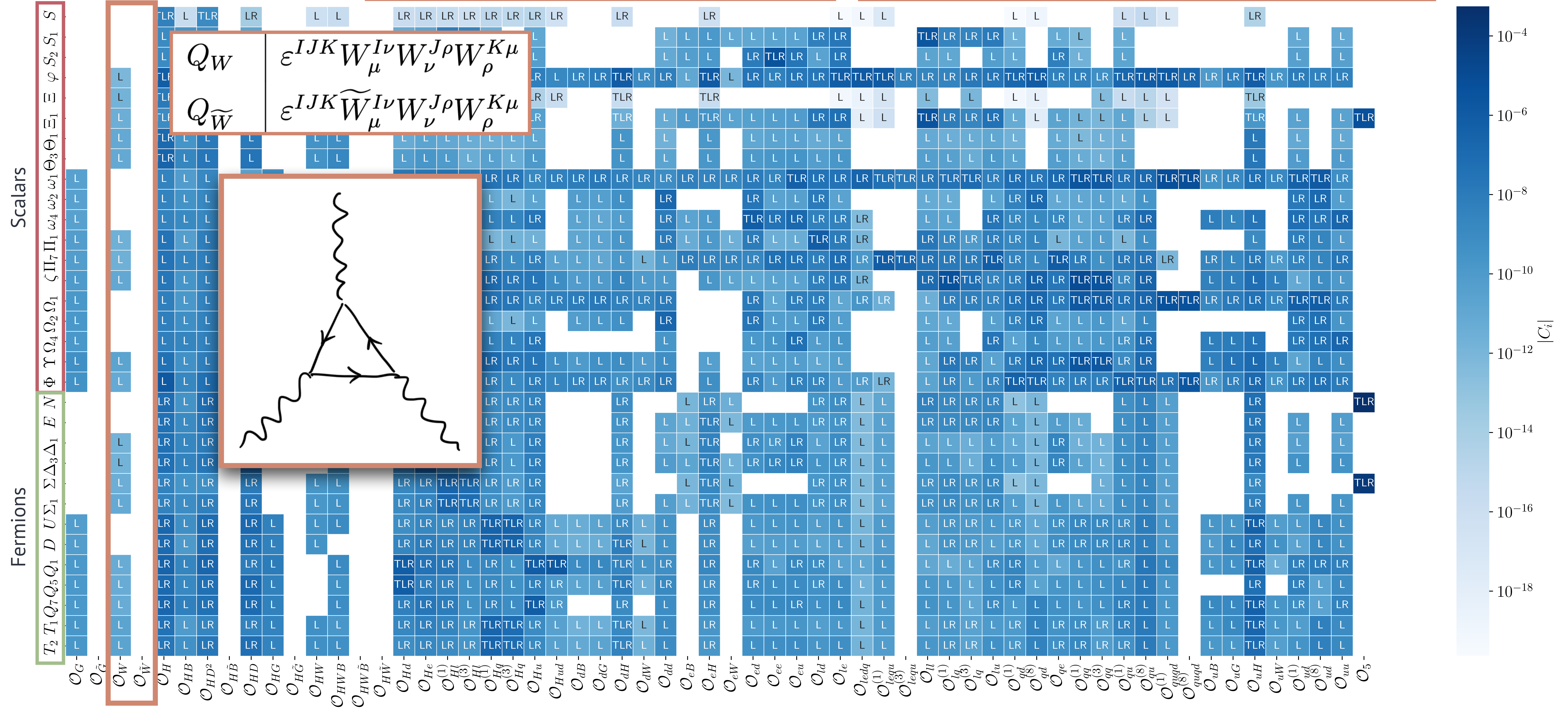
Arzt, Einhorn, Wodka, '95

CP-even triple-gauge operators not generated at tree-level

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

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

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

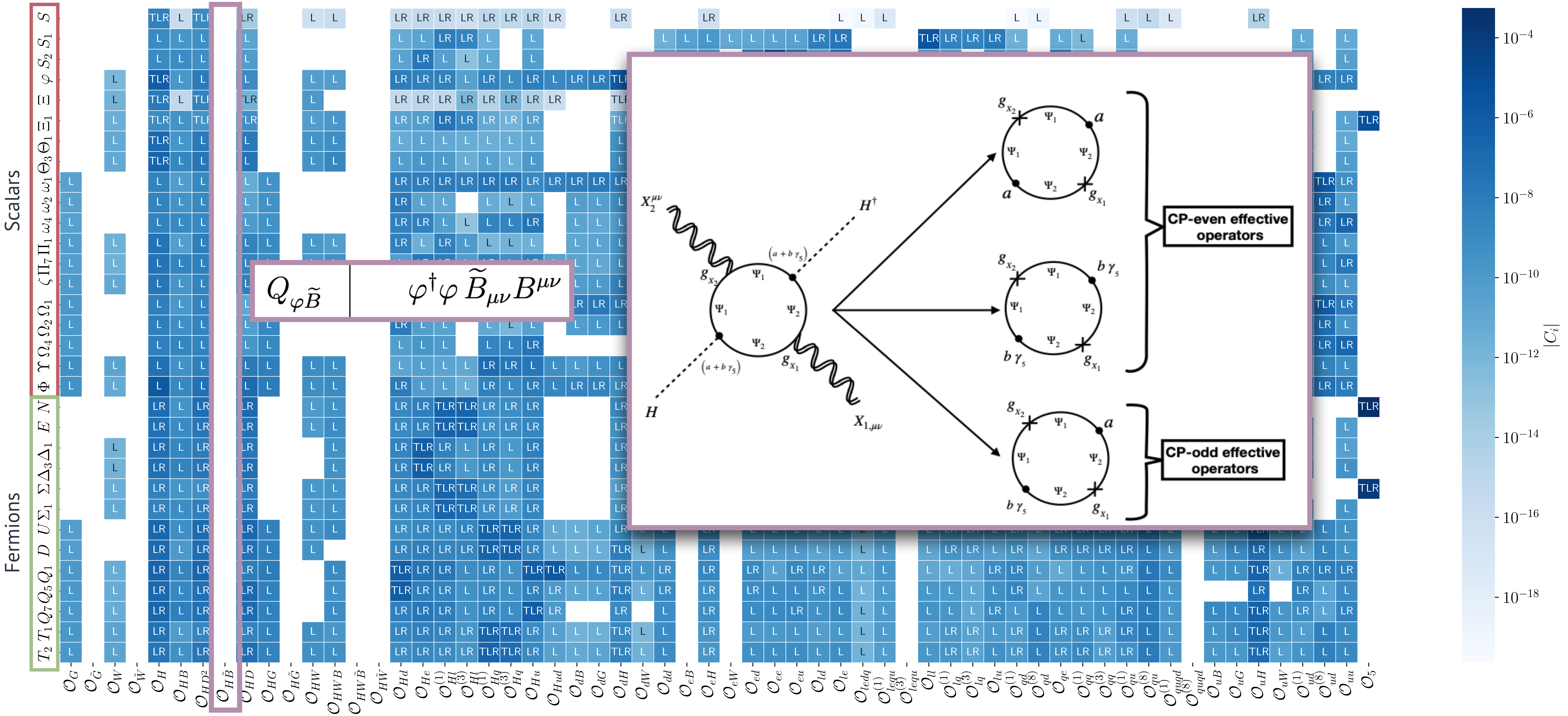


Bakshi, Chakrabortty, Englert, Spannowsky, Stylianou arXiv:2103.15861

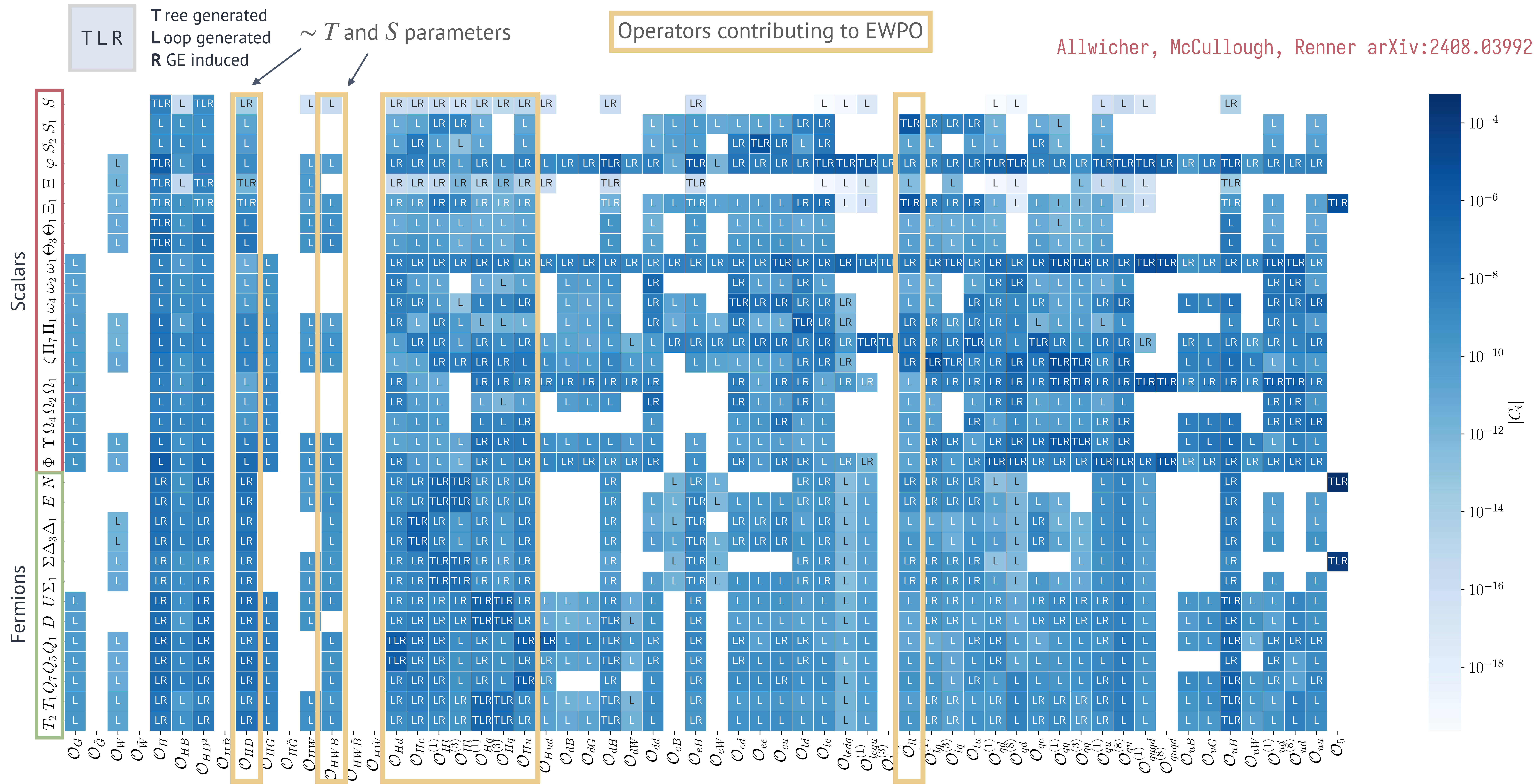
TLR

T ree generated
L oop generated
R GE induced

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



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


TLR
T ree generated
L oop generated
R GE induced
$\sim T$ and S parameters
Operators contributing to EWPO
Allwicher, McCullough, Renner arXiv:2408.03992
Scalars
Fermions
$|C_i|$

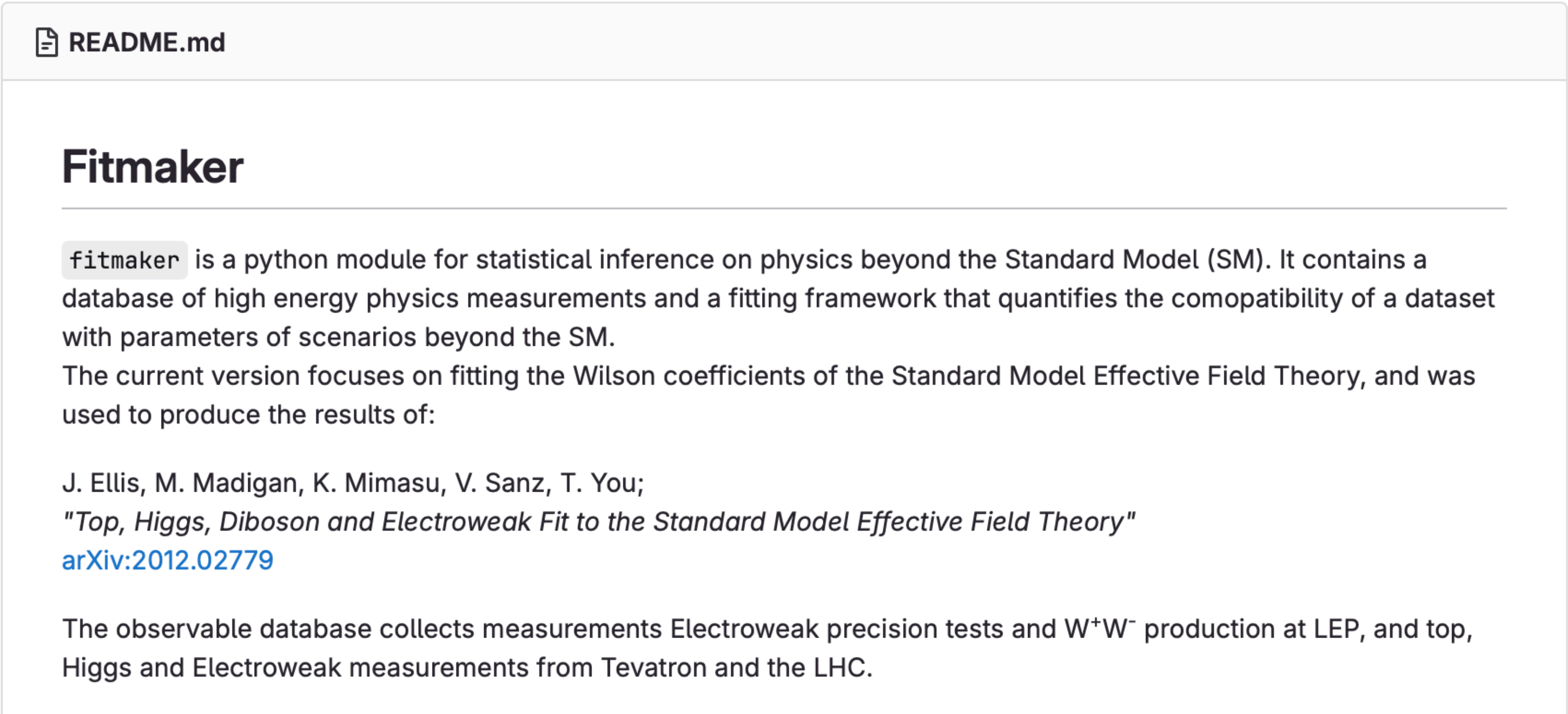
Ellis, Madigan, Mimasu, Sanz, You arXiv:2012.02779
https://gitlab.com/kenmimasu/fitrepo

Allwicher, McCullough, Renner arXiv:2408.03992

Tera-Z sensitivity to linear SM extensions

All of the linear SM extensions contribute at loop level to EWPO and can be probed at a Tera-Z run

UV models and matching data from MME and MatchMakerParser



README.md

Fitmaker

`fitmaker` is a python module for statistical inference on physics beyond the Standard Model (SM). It contains a database of high energy physics measurements and a fitting framework that quantifies the comopatibility of a dataset with parameters of scenarios beyond the SM.
The current version focuses on fitting the Wilson coefficients of the Standard Model Effective Field Theory, and was used to produce the results of:

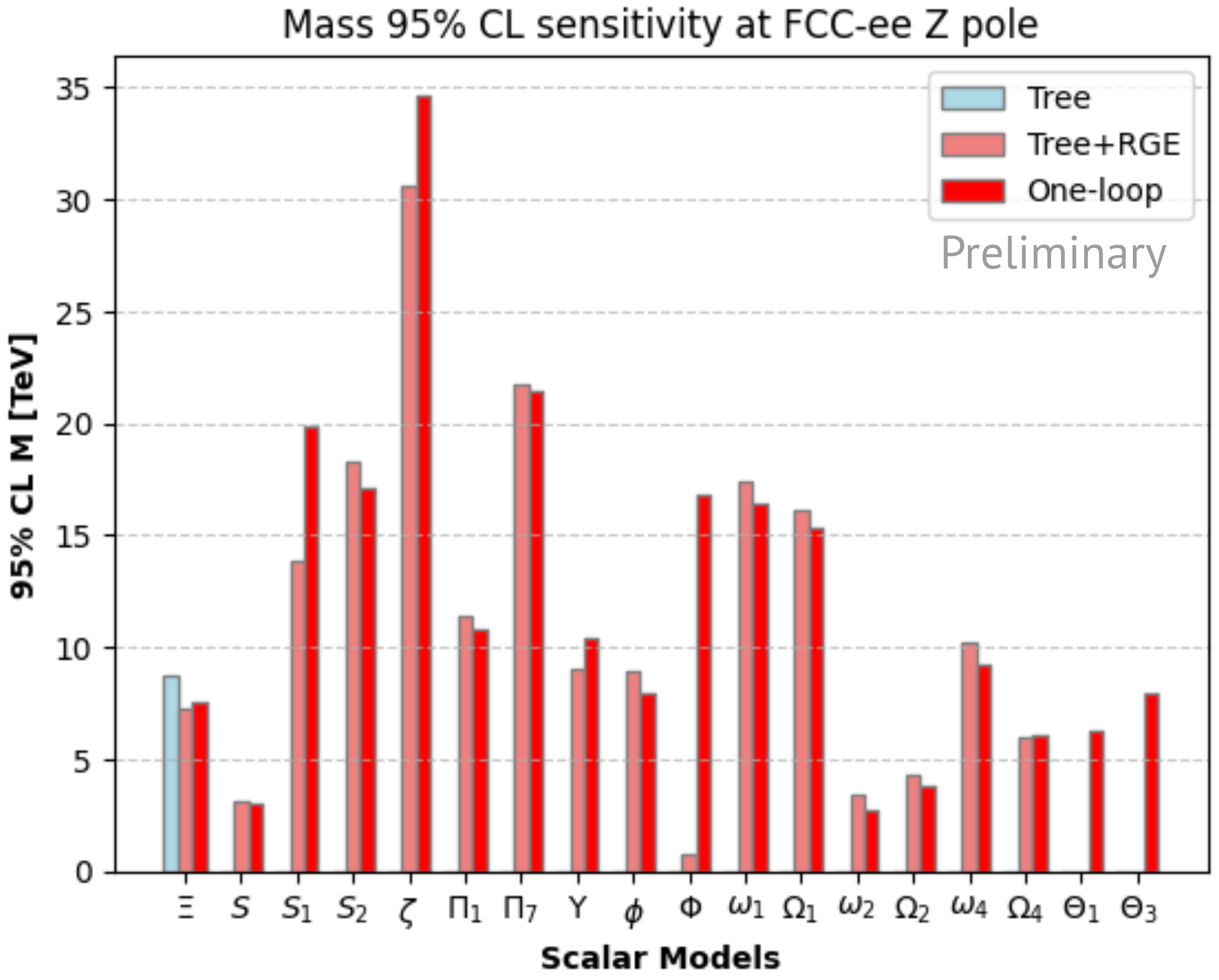
J. Ellis, M. Madigan, K. Mimasu, V. Sanz, T. You;
"Top, Higgs, Diboson and Electroweak Fit to the Standard Model Effective Field Theory"
arXiv:2012.02779

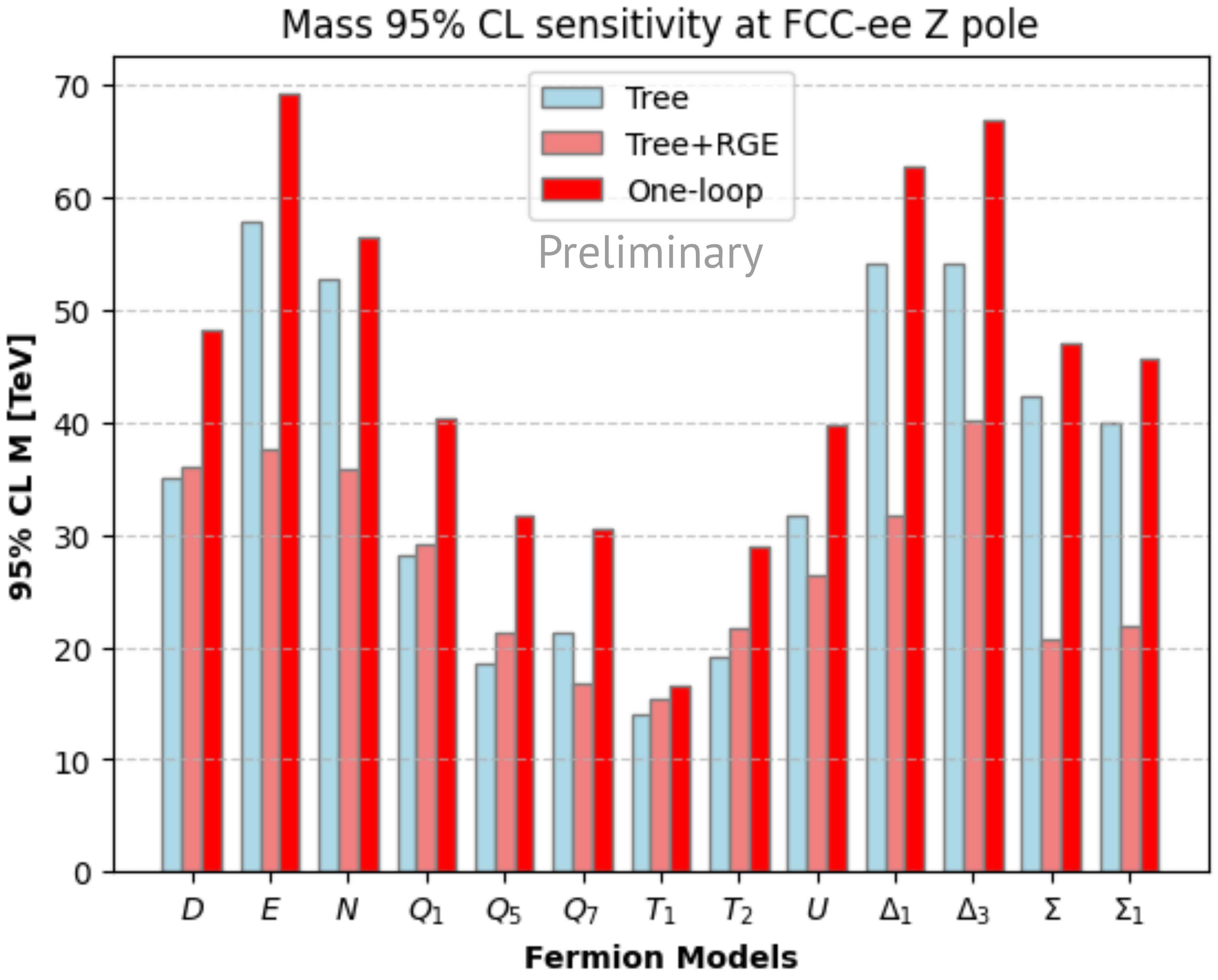
The observable database collects measurements Electroweak precision tests and W^+W^- production at LEP, and top, Higgs and Electroweak measurements from Tevatron and the LHC.

Projected bounds on linear SM extensions at one loop

Tera-Z sensitivity to linear SM extensions

FCC-ee sensitivities:
arXiv:2203.06520 (Snowmass 2021)





Conclusions and outlook

- The linear SM extensions are a useful framework for thinking about UV physics
- 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
- Our results strengthen the case for the potential of a Tera-Z run to constrain a wide range of new-physics models

Merci beaucoup!

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

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

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

$$\mathcal{O}_{ll} = (\bar{l}_p \gamma$$

$$\mathcal{O}^{(1)}_{lq} =$$

Backup

Linear SM extensions are complicated

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

Exotic fermion interactions

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

Dimension-5 scalar interactions

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

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...

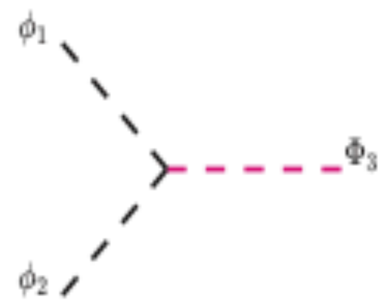
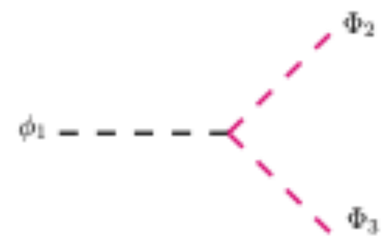
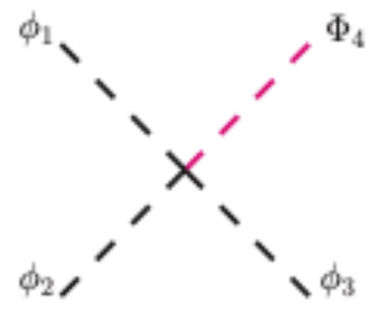
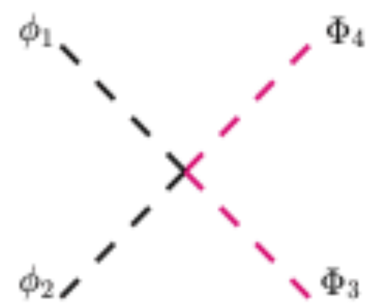
- Lagrangian contains terms up to dimension 5 **sufficient to generate dimension-6 operators at tree level**
- Also includes "mixed" terms with multiple exotic multiplets

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

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

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

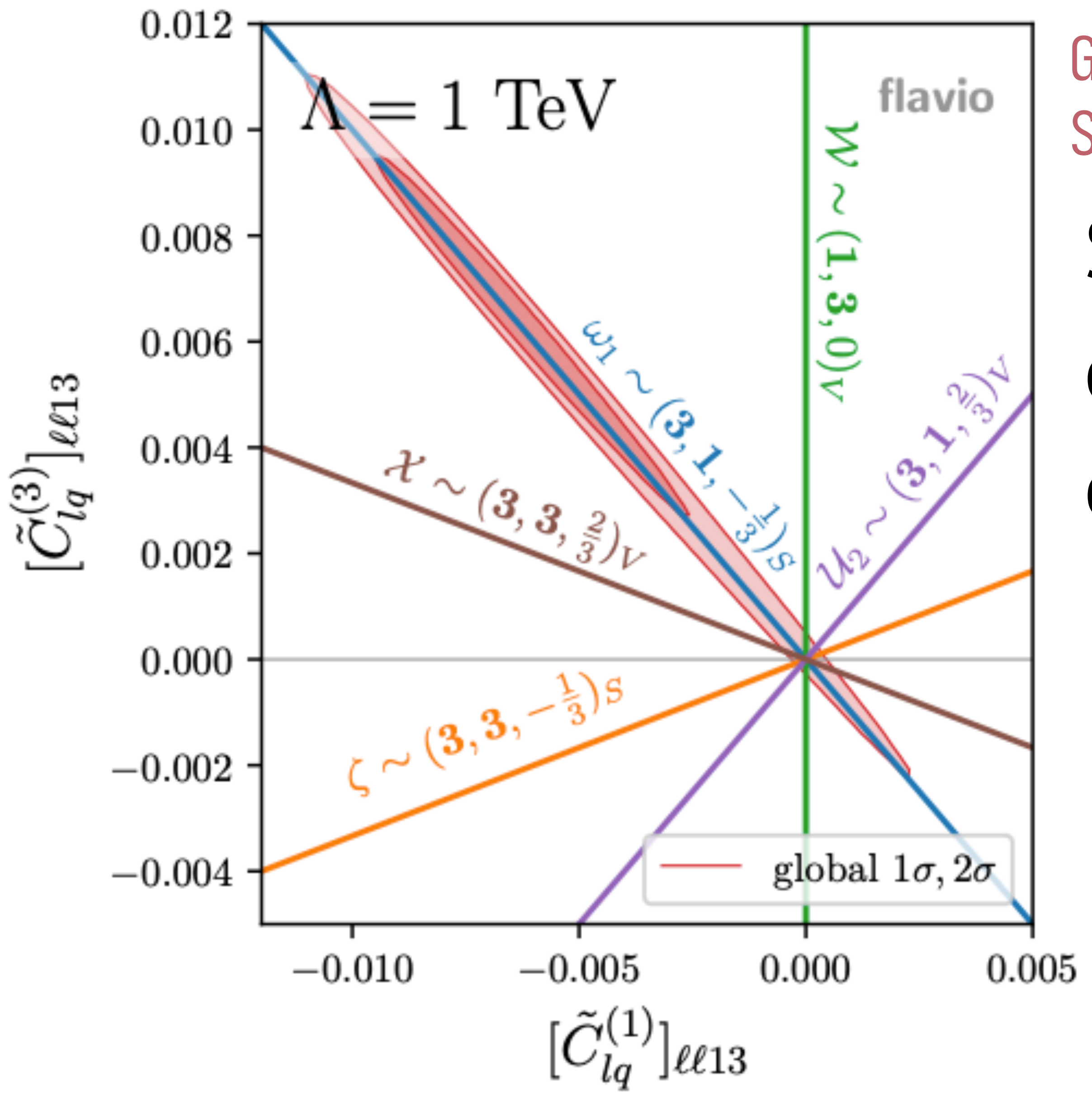
Vertex	S. No.	Light fields	Heavy field(s)
	V1-(i)	$\phi_1 = \phi_2 = H_{(1,2,\frac{1}{2})}$ or $H^\dagger_{(1,2,-\frac{1}{2})}$	$\Phi_3 \in \{(1,3,\pm1),\ (1,1,\pm1)\}$
	V1-(ii)	$\phi_1 = H,\ \ \phi_2 = H^\dagger$	$\Phi_3 \in \{(1,3,0),\ (1,1,0)\}$
	V2	$\phi_1 = H$ or $H^\dagger$	$\Phi_2 \in (R_{C_2}, R_{L_2}, Y_2)$, $\Phi_3 \in (R_{C_3}, R_{L_3}, Y_3)$ 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 $Y_3 + Y_4 = \pm 1$.

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

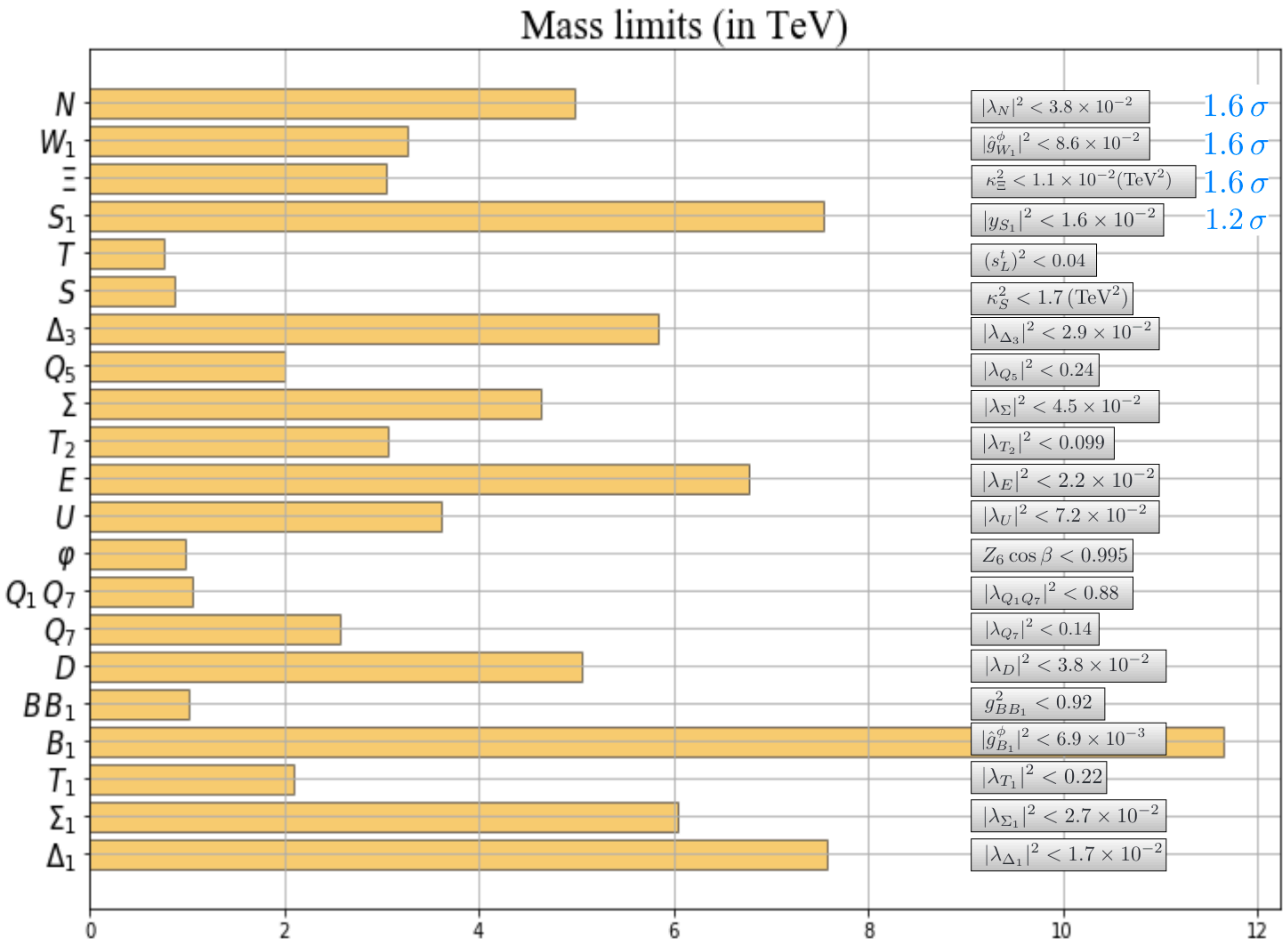
Study of tension in exclusive V_{ub} extraction

Model	C_{HD}	C_{ll}	C^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 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

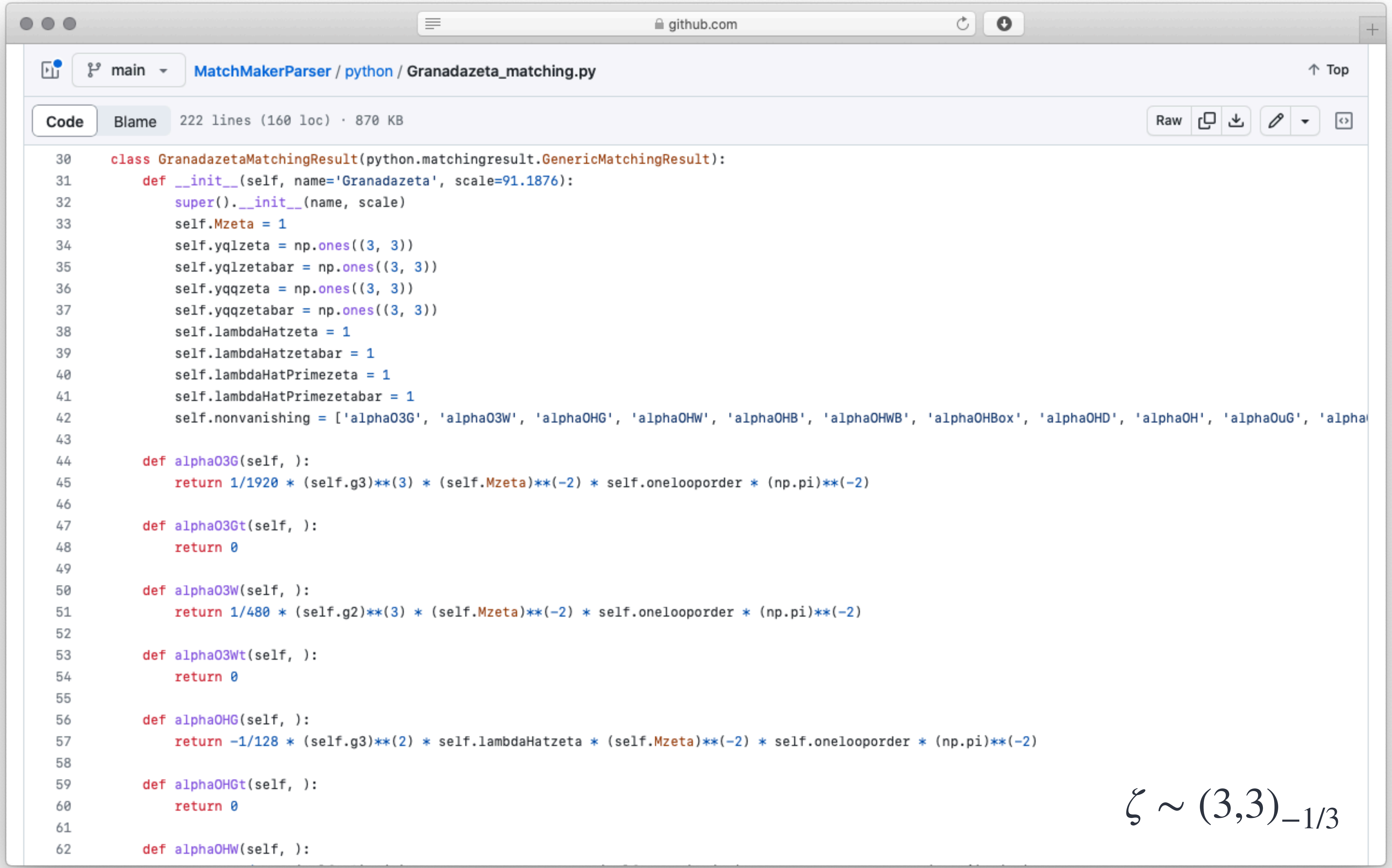
FitMaker group: Fit to top, Higgs, diboson and EW data

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.




```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

- 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.

```
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]:
```

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.oneloop order * (np.pi)**(-2)

    def alphaO3Gt(self, ):
        return 0

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

    def alphaO3Wt(self, ):
        return 0

    def alphaOHG(self, ):
        return -1/128 * (self.g3)**(2) * self.lambdaHatzeta * (self.Mzeta)**(-2) * self.oneloop order * (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

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

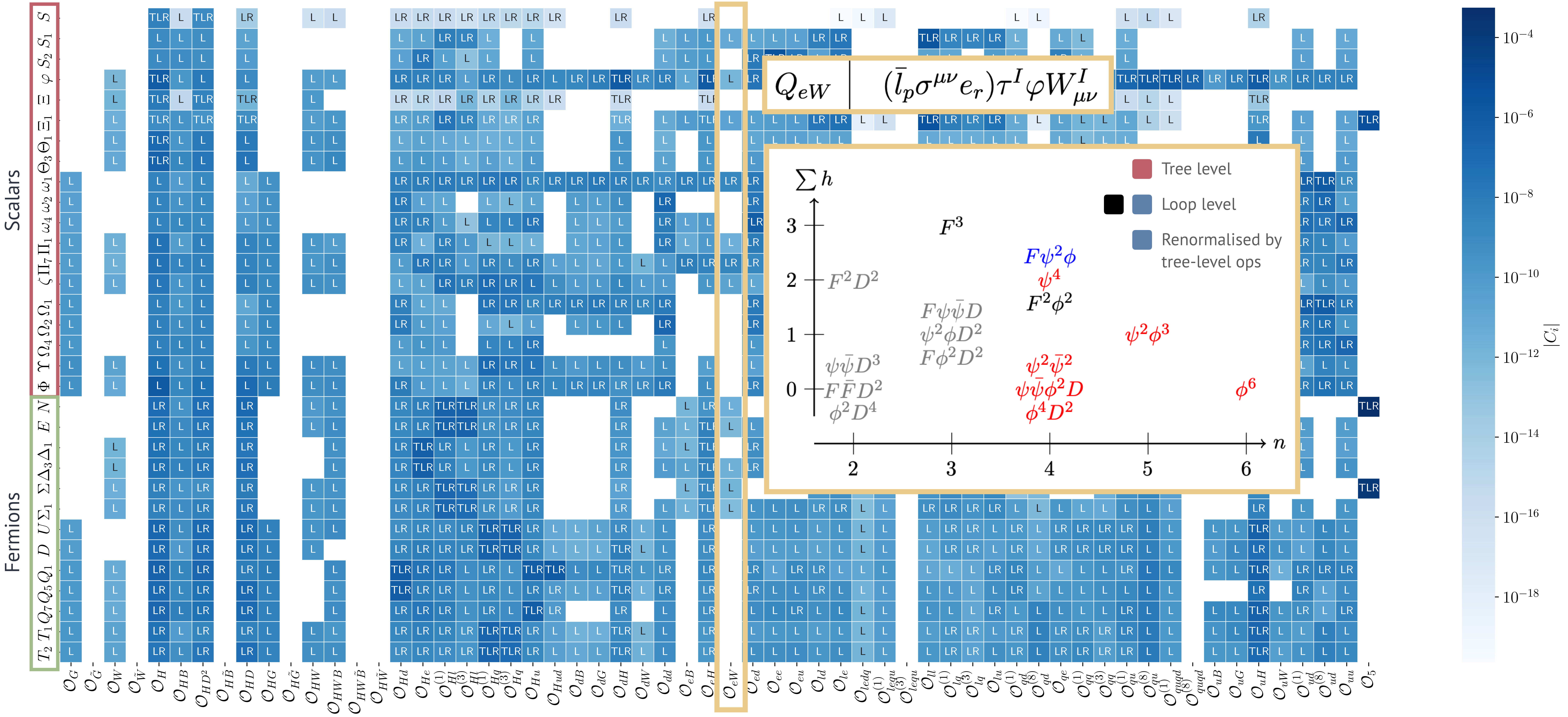
```
import wilson
import flavio

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)
~
~
```

TLR

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



EWPO

LHC EFT WG 2022: Castro et al. arXiv:2211.08353

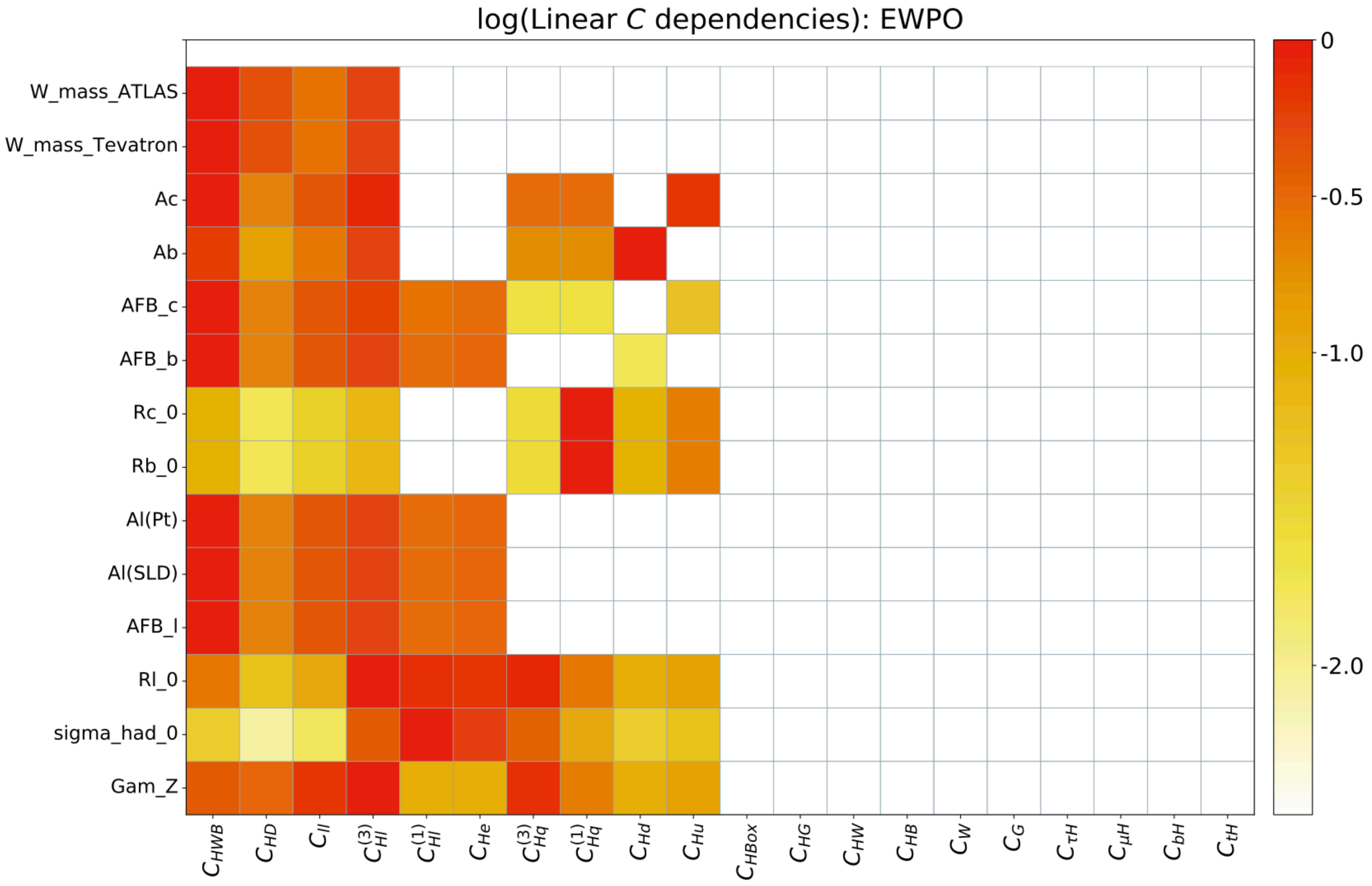
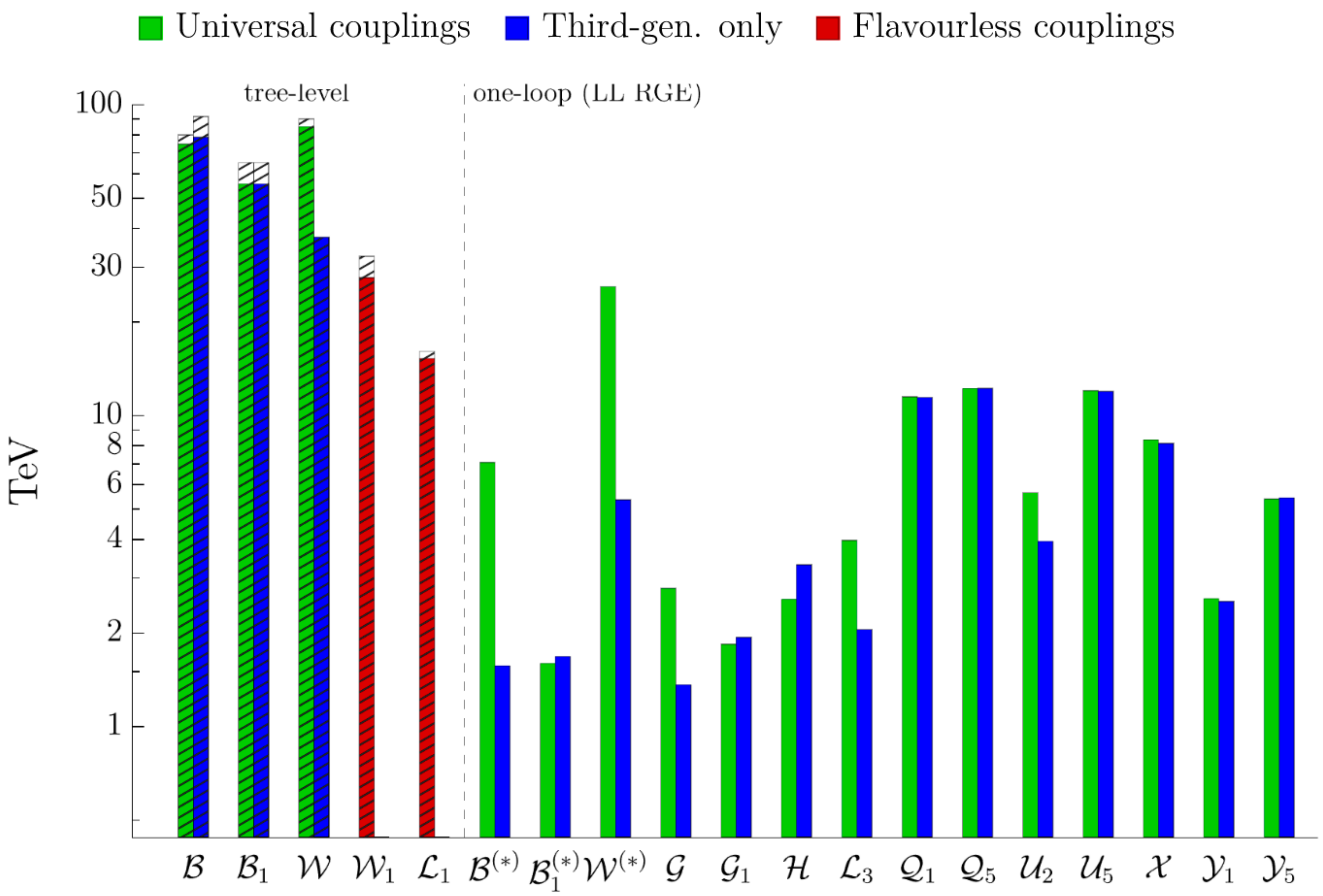


Fig. 7: Logarithm of normalised linear dependences for electroweak measurements. The entries are normalised by dividing each one by the largest operator dependence of a given measurement, $a^X_{\max}$, such that the colour map depicts $\log(a^X_i/a^X_{\max})$.

Limits on vectors

Allwicher, McCullough, Renner arXiv:2408.03992

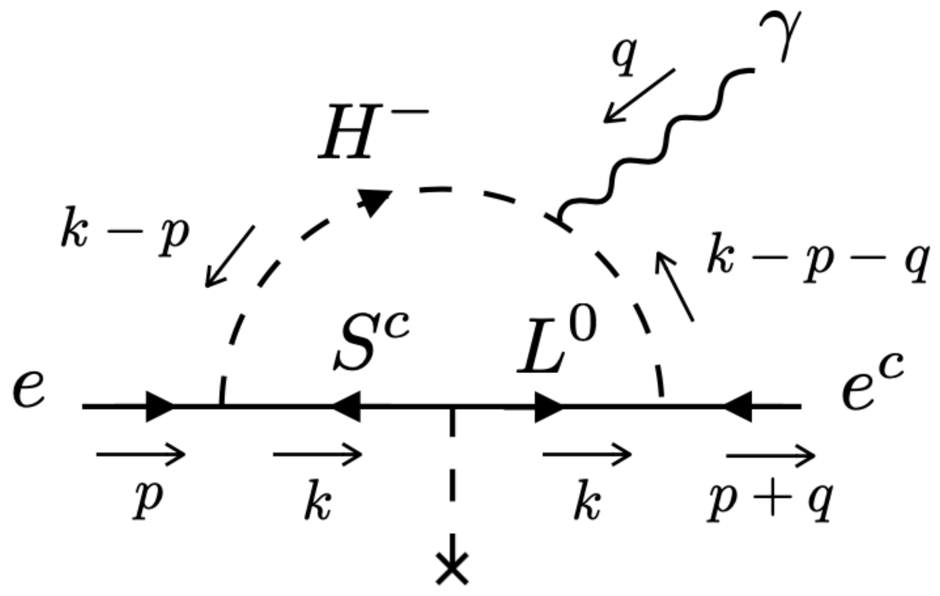


Investigation of *magic* zeros

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 $L \sim (1,2)_{1/2}$

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



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

- 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
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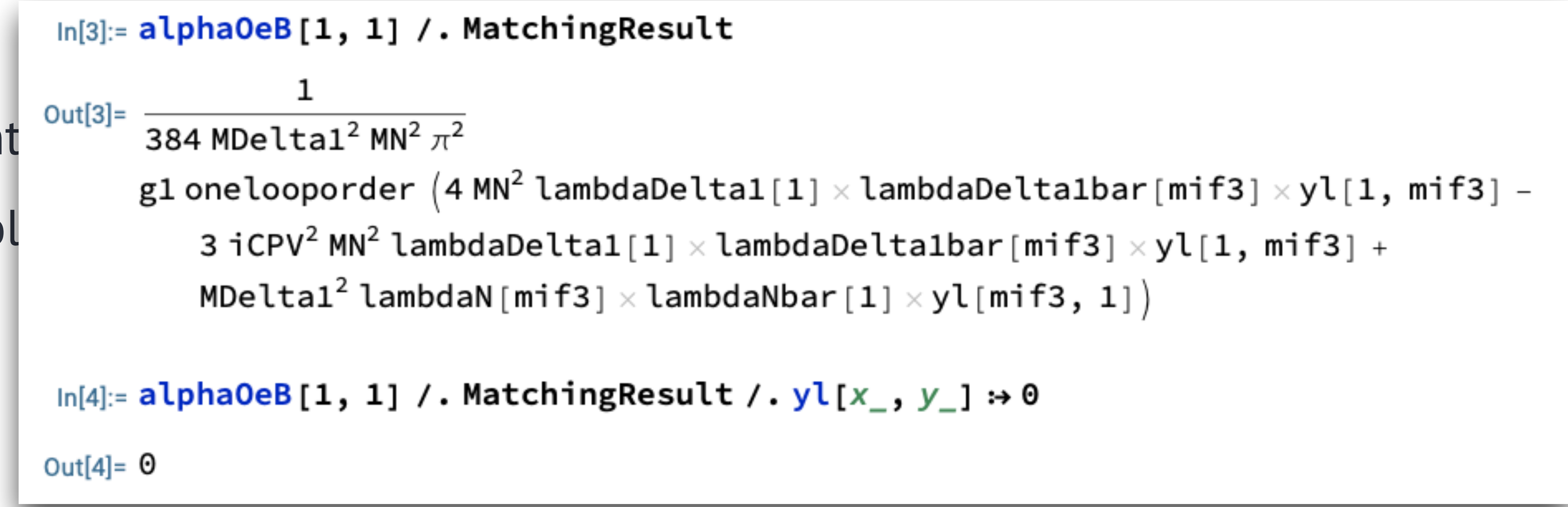


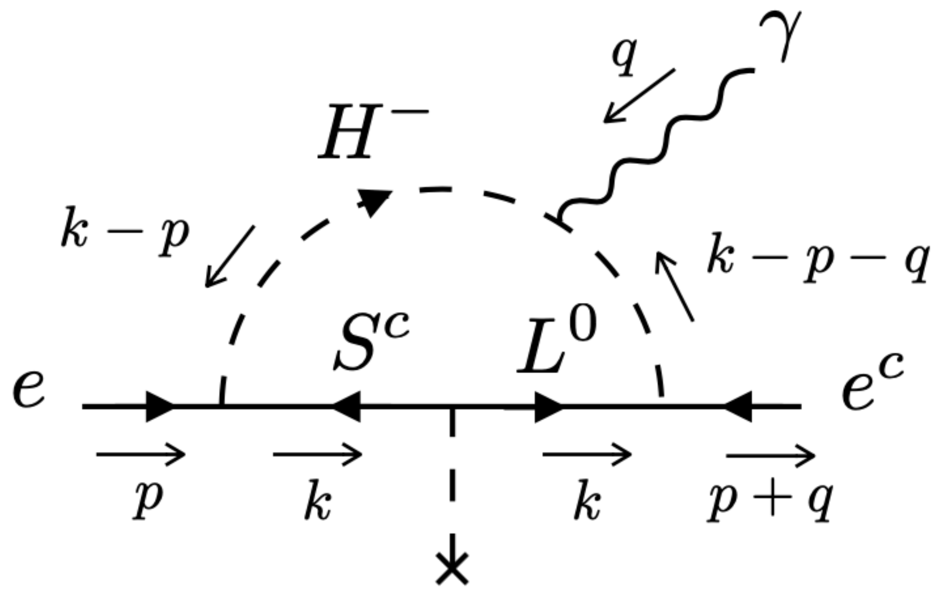
```
In[3]:= alphaOeB[1, 1] /. MatchingResult

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 $L \sim (1,2)_{1/2}$



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

- 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!