Effective Field Theory for Everything

Bottom-Up and Top-Down examples

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Table of Contents

Table of Contents

Weinberg's Theorem

"If one writes down the most general possible Lagrangian, including all terms consistent with assumed symmetry principles, and then calculates matrix elements with this Lagrangian to any given order of perturbation theory, the result will simply be the most general possible S-matrix consistent with perturbative unitarity, analyticity, cluster decomposition, and the assumed symmetry properties."

S. Weinberg, *Phenomenological Lagrangians*, Physica A **96**, 327 (1979).

"In this sense, non-renormalizable theories are just as renormalizable as renormalizable theories, as long as we include all possible terms in the Lagrangian."

S. Weinberg, *The Quantum Theory of Fields*, **Vol. I: Foundations**, Cambridge Univ.Press.

$\lambda\varphi^4$-EFT

Symmetries: Lorentz invariance + discrete $\varphi \to -\varphi$

$$\mathcal{L}_{\lambda\varphi^4-\mathrm{EFT}} = -\frac{1}{2}\varphi(\Box + m^2)\varphi - \frac{\lambda}{4!}\varphi^4 \qquad \mathcal{D} = 4$$

$$+ \frac{C^{\Box^2}}{\Lambda^2}\varphi\Box^2\varphi + \frac{C^{\varphi\Box}}{\Lambda^2}\varphi^2\Box\varphi^2 + \frac{C^{\varphi}}{\Lambda^2}\varphi^6 \qquad \mathcal{D} = 6$$

$$+ \mathcal{O}(\frac{1}{\Lambda^8}) \qquad \mathcal{D} = 8 \quad + \dots$$

If new physics, beyond $\lambda\varphi^4$, enters at scale $\Lambda \gg m$ then this is a $\lambda\varphi^4$-**Effective Field Theory**. Amplitudes will grow at most like

$$\mathcal{A} \sim \left(\frac{p}{\Lambda}\right)^{\mathcal{D}-4} , \qquad p \ll \Lambda$$

The $\lambda\varphi^4$-EFT Lagrangian for S-matrix

S-matrix scattering amplitudes i.e., $\varphi\varphi \to \varphi\varphi$ are independent from field redefinitions:

$$\varphi \to \varphi + \frac{1}{\Lambda^2}(\alpha\varphi^3 + \beta\Box\varphi)$$

Choose parameters α, β such that to remove redundant operators from the previous Lagrangian and left with (3-2=)1 dimension-6 operators, i.e.,

$$\mathcal{L}_{\lambda\varphi^4-\mathrm{EFT}} = -\frac{1}{2}\varphi(\Box + m^2)\varphi - \frac{\lambda}{4!}\varphi^4 \qquad \mathcal{D} = 4$$

$$+ \frac{C^{\varphi}}{\Lambda^2}\varphi^6 \qquad \mathcal{D} = 6$$

$$+ \mathcal{O}(\frac{1}{\Lambda^8}) \qquad \mathcal{D} = 8 \qquad + \dots$$

If $\Lambda \gg m$ the $\mathcal{D} = 4$ (renormalizable) part is the dominant one with NP corrections expected at $1/\Lambda^2$. Experiments may be sensitive enough to see these corrections!

SMEFT

Symmetries: Lorentz $+$ $SU(3)_c \times SU(2)_L \times U(1)_Y$ gauge invariance

$$\boxed{\mathcal{L}_{\rm SMEFT} \;=\; \mathcal{L}_{\rm SM} + \frac{1}{\Lambda} C_\nu O_\nu + \frac{1}{\Lambda^2} \sum_i C_i O_i + \frac{1}{\Lambda^3} \sum_i C_i O_i + \ldots}$$

Not counting flavour we have 60 operators up to dimension-6

Renormalization: infinities cancel by the new counterterms δC_i

SMEFT answers questions...

Why the SM is so precise? Because the scale of NP, collectively called Λ, is much higher than every SM particle masses

Neutrino masses require physics beyond SM: they arise from dimension-5 operators. In SMEFT neutrinos are strictly Majorana particles.

Proton decay arises from dimension-6 operators first. Would this discovery come next...?!

Instead of studying a myriad of BSM physics models this SMEFT + experiments may guide us towards a new level of understanding.

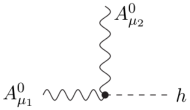
This path may be proven to be useful at the LHC and future colliders

However, the non-redundant (Warsaw) basis contains 2499 d=6 operators!

B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, JHEP **10** (2010), 085 [1008.4884]

There are about 400 vertices (in R_ξ-gauges) that have been collected in A. D., W. Materkowska, M. Paraskevas, J. Rosiek and K. Suxho, JHEP **06** (2017), 143 [1704.03888].

E.g., at d=6, $h \to \gamma\gamma$ vertex



$$
\begin{aligned}
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi W}} (p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta_{\mu_1\mu_2}) \\
&+\frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi B}} (p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta_{\mu_1\mu_2}) \\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi WB}} (p_1^{\mu_2} p_2^{\mu_1} - p_1 \cdot p_2 \eta_{\mu_1\mu_2}) \\
&+\frac{4i\bar{g}'^2 v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi\widetilde{W}}} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1} + \frac{4i\bar{g}^2 v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi\widetilde{B}}} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1} \\
&-\frac{4i\bar{g}\bar{g}' v}{\bar{g}^2+\bar{g}'^2} \boxed{C^{\varphi\widetilde{W}B}} p_1^{\alpha_1} p_2^{\beta_1} \epsilon_{\mu_1\mu_2\alpha_1\beta_1}
\end{aligned}
$$

The code `SmeftFR` produces all of them! A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, Comput. Phys. Commun. **247** (2020), 106931 [arXiv:1904.03204]

The code SmeftFR v3.00

Our group[1] is currently updating SmeftFR to consinstently account for

- input parameter schemes,
- $(\text{dim6})^2$ operator effects
- bosonic dim8 operators

SmeftFR extracts the full set of Feynman rules in LaTeX or in UFO format or in FeynArts.

It can feed various event generators, such as MadGraph, which perform amplitude calculations for LHC.

SmeftFR download web-page:

http://www.fuw.edu.pl/smeft

The program builts on FeynRules in *Mathematica*.

[1] A.D., J. Rosiek, M. Ryczkowski, K. Suxho and L. Trifyllis, to appear soon

The EFT picture

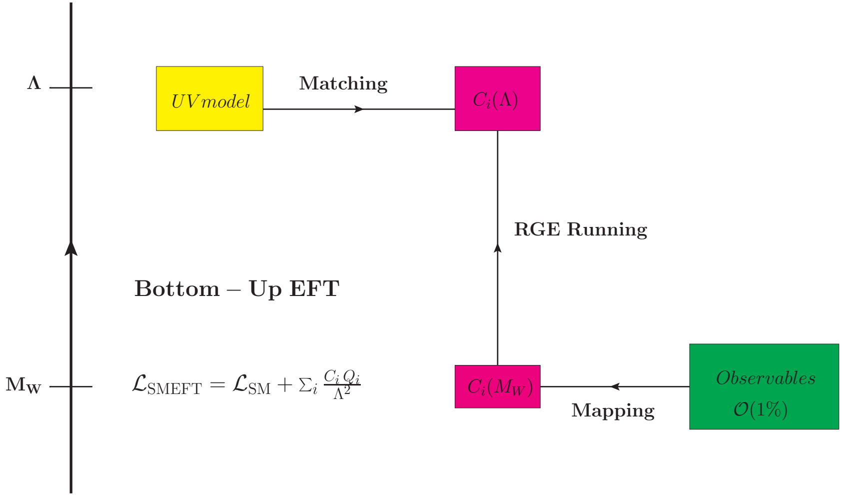


Table of Contents

The decay $h \to \gamma\gamma$ in SMEFT

$$\mathcal{R}_{h\to\gamma\gamma} = \frac{\Gamma(\mathrm{SM\ EFT}, h \to \gamma\gamma)}{\Gamma(\mathrm{SM}, h \to \gamma\gamma)} = 1 + \delta\mathcal{R}_{h\to\gamma\gamma}$$

$$\text{ATLAS:} \qquad \mathcal{R}_{h\to\gamma\gamma} = 0.99^{+0.15}_{-0.14}\,,$$
$$\text{CMS:} \qquad \mathcal{R}_{h\to\gamma\gamma} = 1.18^{+0.17}_{-0.14}\,.$$

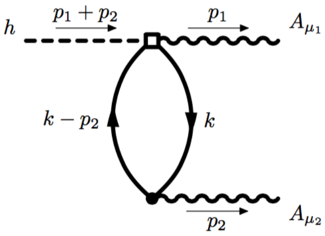
Let's remember this $\delta\mathcal{R}_{h\to\gamma\gamma}$ ∼15% available from LHC data!

Operators participating in $\mathcal{R}_{h\to\gamma\gamma}$ at 1-loop

$Q_W = \varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{e\varphi} = (\varphi^\dagger\varphi)(\bar{l}'_p e'_r \varphi)$
$Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p u'_r \widetilde{\varphi})$
$Q_{\varphi D} = \left(\varphi^\dagger D^\mu\varphi\right)^* \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi} = (\varphi^\dagger\varphi)(\bar{q}'_p d'_r \varphi)$
$Q_{\varphi B} = \varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	$Q_{ll} = (\bar{l}'_p\gamma_\mu l'_r)(\bar{l}'_s\gamma^\mu l'_t)$
$Q_{\varphi W} = \varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$	$Q_{\varphi l}^{(3)} = (\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar{l}'_p\tau^I\gamma^\mu l'_r)$
$Q_{\varphi WB} = \varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$	
$Q_{eB} = (\bar{l}'_p\sigma^{\mu\nu}e'_r)\varphi B_{\mu\nu}$	$Q_{eW} = (\bar{l}'_p\sigma^{\mu\nu}e'_r)\tau^I\varphi W^I_{\mu\nu}$
$Q_{uB} = (\bar{q}'_p\sigma^{\mu\nu}u'_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{uW} = (\bar{q}'_p\sigma^{\mu\nu}u'_r)\tau^I\widetilde{\varphi}\, W^I_{\mu\nu}$
$Q_{dB} = (\bar{q}'_p\sigma^{\mu\nu}d'_r)\varphi\, B_{\mu\nu}$	$Q_{dW} = (\bar{q}'_p\sigma^{\mu\nu}d'_r)\tau^I\varphi\, W^I_{\mu\nu}$

CP-violating operators **do not** contribute at $1/\Lambda^2$ and at 1-loop. There are **17 operators** (not including flavour and H.c.)

SMEFT Graphity: an example



Only in SMEFT

Renormalization

We worked[2] at 1-loop and up to $1/\Lambda^2$ in EFT expansion

1. We regularize integrals with DR
2. We use a simple renormalization framework[3] with $\overline{\mathrm{MS}}$ in Wilson coefficients
3. We establish a ξ-independent and renormalization scale invariant $h \to \gamma\gamma$ amplitude using the β-functions of Refs[4]
4. All infinities absorbed by SMEFT parameters' counterterms
5. A closed expression for the amplitude that respects the Ward-Identities

[2] A. D., M. Paraskevas, J. Rosiek, K. Suxho and L. Trifyllis, JHEP **08** (2018), 103 [arXiv:1805.00302]

[3] A. Sirlin, Phys. Rev. D**22**, 1980

[4] R. Alonso, E. E. Jenkins, A. V. Manohar and M. Trott, arXiv:1308.2627, arXiv:1310.4838, arXiv:1312.2014

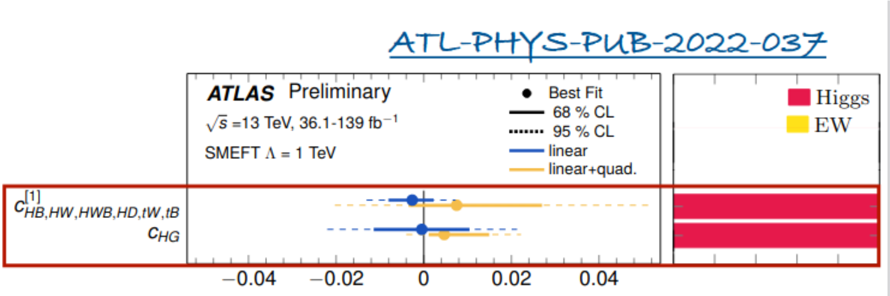
Results for $\mathcal{R}_{h\to\gamma\gamma}$

$$\begin{aligned}
\delta\mathcal{R}_{h\to\gamma\gamma} = & -\left[48.04 - 1.07\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi B}(\mu)}{\Lambda^2} \\
& -\left[14.29 - 0.12\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi W}(\mu)}{\Lambda^2} \\
& +\left[26.17 - 0.52\log\frac{\mu^2}{M_W^2}\right]\frac{C^{\varphi WB}(\mu)}{\Lambda^2} \\
& +\left[2.11 - 0.84\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uB}_{33}(\mu)}{\Lambda^2} \\
& +\left[1.13 - 0.45\log\frac{\mu^2}{M_W^2}\right]\frac{C^{uW}_{33}(\mu)}{\Lambda^2} \\
& \ldots
\end{aligned}$$

Λ is in TeV units and μ is the renormalization scale parameter

This is a renormalization scale invariant result

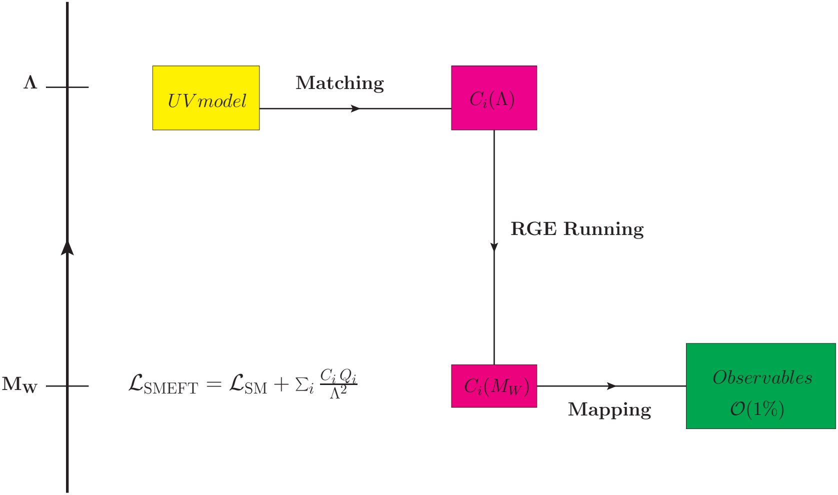
LHC Working groups have started EFT analyses, e.g.



See talk by E. Vryonidou

Table of Contents

The top-down EFT picture



Brief History of Matching to EFT

- Heavy fields are integrated out from a *known* UV-theory
  Appelquist and Carazzone, PRD (1975)
- Last five years, an old **functional matching** technique [Gaillard, NPB (1986)] has seen a renewed interest Henning, Lu and Murayama, JHEP (2016,2018)
- SuperTrace functional technique [Cohen, Lu, Zhang, 2011.02484] establishes a clean way to display gauge covariant diagrams for matching. Automated tools exist [`STream`, 2012.07851; `SuperTracer`, 2012.08506]. *It is this approach we followed in our work.*
- Example: One-loop effective action after decoupling all scalar Leptoquarks [A. D. and K. Mantzaropoulos, JHEP **11** (2021), 166 [arXiv:2108.10055]
- About to become all automated!
  Matchete, 2212.04510; Matchmakereft, 2112.10787; CoDEx 1808.04403; Wilson, 1804.05033

The STr functional matching procedure

The Basic formula for functional matching:

$$\Gamma_{\mathrm{EFT}}[\phi] \;=\; \Gamma_{\mathrm{L,UV}}[\phi]$$

where ϕ denotes light-fields.

The STr functional matching procedure

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- **Tree-level:** $\mathcal{L}^{(\mathrm{tree})}_{\mathrm{EFT}}[\phi] \;=\; \mathcal{L}_{\mathrm{UV}}[S,\phi]\Big|_{S=S_c[\phi]}$ with S being heavy-fields.

The STr functional matching procedure

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- **Tree-level:** $\mathcal{L}_{\rm EFT}^{\rm (tree)}[\phi] \;=\; \mathcal{L}_{\rm UV}[S,\phi]\Big|_{S=S_c[\phi]}$ with S being heavy-fields.
- **One-loop:**

$$\Gamma_{\rm L,UV}[\phi]\Big|_{\rm hard} \;=\; \frac{i}{2}{\rm STr}\log \mathbf{K}\Big|_{\rm hard} \;-\; \frac{i}{2}\sum_{n=1}^{\infty}\frac{1}{n}{\rm STr}[(K^{-1}X)^n]\Big|_{\rm hard}$$

The STr functional matching procedure

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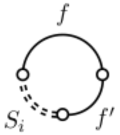
- **Tree-level:** $\mathcal{L}^{(\mathrm{tree})}_{\mathrm{EFT}}[\phi] \;=\; \mathcal{L}_{\mathrm{UV}}[S,\phi]\Big|_{S=S_c[\phi]}$ with S being heavy-fields.
- **One-loop:**

$$\Gamma_{\mathrm{L,UV}}[\phi]\Big|_{\mathrm{hard}} \;=\; \frac{i}{2}\mathrm{STr}\log \mathbf{K}\Big|_{\mathrm{hard}} \;-\; \frac{i}{2}\sum_{n=1}^{\infty}\frac{1}{n}\mathrm{STr}[(K^{-1}X)^n]\Big|_{\mathrm{hard}}$$

The expansion in $(K^{-1}X)$ can be graphed (STr diagrams), e.g., $n = 3$



Two heavy LQs: $S_1 + \tilde{S}_2$

Lets consider two (out of five), heavy LQs with masses M_1 and $\tilde{M}_2$:

Field/Group	SU(3)	SU(2)	U(1)
S_1	$\bar{3}$	1	$\frac{1}{3}$
$\tilde{S}_2$	3	2	$\frac{1}{6}$

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$\tilde{S}_2$	3	2	$\frac{1}{6}$

New Interactions with Quarks and Leptons:

$$\begin{aligned}
\mathcal{L}_{\text{S-f}} = &\left[\left(\lambda^{1\text{L}}_{pr}\right) \bar{q}^c_{pi} \cdot \epsilon \cdot \ell_r + \left(\lambda^{1\text{R}}_{pr}\right) \bar{u}^c_i \, e_r\right] S_{1i} + \text{h.c.} \\
&+ (\lambda^{\not{B}L}_{pr}) \, S_{1i} \, \epsilon^{ijk} \, \bar{q}_{pj} \cdot \epsilon \cdot q^c_{rk} + (\lambda^{\not{B}R}_{pr}) \, S_{1i} \, \epsilon^{ijk} \bar{d}_{pj} \, u^c_{rk} + \text{h.c.} \\
&+ (\tilde{\lambda}_{pr}) \, \bar{d}_{pi} \tilde{S}^T_{2i} \cdot \epsilon \cdot \ell_r + \text{h.c.} \, ,
\end{aligned}$$

Two heavy LQs: $S_1 + \tilde{S}_2$

Lets consider two (out of five), heavy LQs with masses M_1 and $\tilde{M}_2$:

Field/Group	SU(3)	SU(2)	U(1)
S_1	$\bar{3}$	1	$\frac{1}{3}$
$\tilde{S}_2$	3	2	$\frac{1}{6}$

New Interactions with the Higgs:

$$\mathcal{L}_{\text{S-H}} = -\left(M_1^2 + \lambda_{H1}|H|^2\right)|S_1|^2 - \left(\tilde{M}_2^2 + \tilde{\lambda}_{H2}|H|^2\right)|\tilde{S}_2|^2 + \lambda_{\tilde{2}\tilde{2}}\left(\tilde{S}_{2i}^\dagger \cdot H\right)\left(H^\dagger \cdot \tilde{S}_{2i}\right)$$
$$- A_{\tilde{2}1}\left(\tilde{S}_{2i}^\dagger \cdot H\right) S_{1i}^\dagger + \frac{1}{3}\lambda_3 \epsilon^{ijk}\left(\tilde{S}_{2i}^T \cdot \epsilon \cdot \tilde{S}_{2j}\right)\left(H^\dagger \cdot \tilde{S}_{2k}\right) + \text{h.c.} \qquad (3.3)$$

Two heavy LQs: $S_1 + \tilde{S}_2$

Lets consider two (out of five), heavy LQs with masses M_1 and $\tilde{M}_2$:

Field/Group	SU(3)	SU(2)	U(1)
S_1	$\bar{3}$	1	$\frac{1}{3}$
$\tilde{S}_2$	3	2	$\frac{1}{6}$

New Self-Interactions:

$$-\mathcal{L}_{\mathrm{S}} = \frac{c_1}{2}\,(S_1^\dagger S_1)^2 + \frac{\tilde{c}_2}{2}\,(\tilde{S}_2^\dagger \cdot \tilde{S}_2)^2 + c_{1\tilde{2}}^{(1)}\,(S_1^\dagger S_1)(\tilde{S}_2^\dagger \cdot \tilde{S}_2) + c_{1\tilde{2}}^{(2)}\,(\tilde{S}_{2\alpha}^\dagger S_1)(S_1^\dagger \tilde{S}_{2\alpha})$$
$$+\, c_{\tilde{2}}^{(8)}(\tilde{S}_{2i}^\dagger \cdot \tilde{S}_{2j})\,(\tilde{S}_{2j}^\dagger \cdot \tilde{S}_{2i}) + \left[A' S_{1i}^\dagger\, \epsilon^{ijk} \left(\tilde{S}_{2j}^T \cdot \epsilon \cdot \tilde{S}_{2k}\right) + \mathrm{h.c.}\right]\ .$$

Tree-level ($S_1 + \tilde{S}_2$ model)

There are 12 baryon number conserving operators (semileptonic + four-quark)

$$\left[G_{\ell q}^{(1)}\right]_{prst}^{(0)} = \frac{(\lambda_{sp}^{1\mathrm{L}})^*(\lambda_{tr}^{1\mathrm{L}})}{4M_1^2}\,, \qquad \left[G_{\ell q}^{(3)}\right]_{prst}^{(0)} = -\frac{(\lambda_{sp}^{1\mathrm{L}})^*(\lambda_{tr}^{1\mathrm{L}})}{4M_1^2}\,,$$

$$\left[G_{lequ}^{(1)}\right]_{prst}^{(0)} = \frac{(\lambda_{sp}^{1\mathrm{L}})^*(\lambda_{tr}^{1\mathrm{R}})}{2M_1^2}\,, \qquad \left[G_{\ell equ}^{(3)}\right]_{prst}^{(0)} = -\frac{(\lambda_{sp}^{1\mathrm{L}})^*(\lambda_{tr}^{1\mathrm{R}})}{8M_1^2}\,,$$

$$[G_{eu}]_{prst}^{(0)} = \frac{(\lambda_{sp}^{1\mathrm{R}})^*(\lambda_{tr}^{1\mathrm{R}})}{2M_1^2}\,, \qquad [G_{\ell d}]_{prst}^{(0)} = -\frac{(\tilde{\lambda}_{tp})^*(\tilde{\lambda}_{sr})}{2\tilde{M}_2^2}\,,$$

$$\left[G_{qq}^{(1)}\right]_{prst}^{(0)} = \frac{(\lambda_{rt}^{\not{B}L})^*(\lambda_{sp}^{\not{B}L})}{2M_1^2}\,, \qquad \left[G_{qq}^{(3)}\right]_{prst}^{(0)} = -\frac{(\lambda_{rt}^{\not{B}L})^*(\lambda_{sp}^{\not{B}L})}{2M_1^2}\,,$$

$$\left[G_{ud}^{(1)}\right]_{prst}^{(0)} = \frac{(\lambda_{tr}^{\not{B}R})^*(\lambda_{sp}^{\not{B}R})}{3M_1^2}\,, \qquad \left[G_{ud}^{(8)}\right]_{prst}^{(0)} = -\frac{(\lambda_{tr}^{\not{B}R})^*(\lambda_{sp}^{\not{B}R})}{M_1^2}\,,$$

$$\left[G_{quqd}^{(1)}\right]_{prst}^{(0)} = \frac{4}{3}\frac{(\lambda_{ts}^{\not{B}R})^*(\lambda_{pr}^{\not{B}L})}{M_1^2}\,, \qquad \left[G_{quqd}^{(8)}\right]_{prst}^{(0)} = -4\frac{(\lambda_{ts}^{\not{B}R})^*(\lambda_{pr}^{\not{B}L})}{M_1^2}\,,$$

Tree-level ($S_1 + \tilde{S}_2$ model)

and (all) 4 baryon number violating operators

$$[G_{qqq}]^{(0)}_{prst} = -2\frac{(\lambda^{\not B L}_{pr})^*(\lambda^{1L}_{st})}{M_1^2}\,, \qquad [G_{qqu}]^{(0)}_{prst} = \frac{(\lambda^{\not B L}_{pr})^*(\lambda^{1R}_{st})}{M_1^2}\,,$$

$$[G_{duq}]^{(0)}_{prst} = \frac{(\lambda^{\not B R}_{pr})^*(\lambda^{1L}_{st})}{M_1^2}\,, \qquad [G_{duu}]^{(0)}_{prst} = \frac{(\lambda^{\not B R}_{pr})^*(\lambda^{1R}_{st})}{M_1^2}\,.$$

usually not discussed or killed by extra (ad-hoc?) discrete symmetries.

One-loop ($S_1 + \tilde{S}_2$ model)

Renormalizable operators: e.g corrections to the Higgs mass, $\delta m^2/16\pi^2$

$$(\delta m^2) = N_c \Big[\lambda_{H1} M_1^2 (1 + L_1) + (2\tilde{\lambda}_{H2} - \lambda_{\tilde{2}\tilde{2}})\tilde{M}_2^2(1 + L_2) + |A_{\tilde{2}1}|^2 \left(1 + \frac{M_1^2 \log \mu^2/M_1^2 - \tilde{M}_2^2 \log \mu^2/\tilde{M}_2^2}{\Delta_{12}^2}\right)\Big] .$$

where

$$L_i = \log \frac{\mu^2}{M_i^2} \ , \quad \Delta_{12}^2 = M_1^2 - \tilde{M}_2^2 \ ,$$

and μ is the renormalization scale.

One-loop ($S_1 + \tilde{S}_2$ model)

Renormalizable operators: e.g corrections to the Higgs mass, $\delta m^2/16\pi^2$

$$(\delta m^2) = N_c \left[\lambda_{H1} M_1^2 (1 + L_1) + (2\tilde{\lambda}_{H2} - \lambda_{\tilde{2}\tilde{2}}) \tilde{M}_2^2 (1 + L_2) \right. \\ \left. + |A_{\tilde{2}1}|^2 \left(1 + \frac{M_1^2 \log \mu^2/M_1^2 - \tilde{M}_2^2 \log \mu^2/\tilde{M}_2^2}{\Delta_{12}^2}\right)\right] \, .$$

Possible solutions:

1. LQ masses $M_1, \tilde{M}_2$ of the order of the TeV scale and $O(1)$ couplings
2. LQ masses at a high scale ($>> m_w$) but Higgs sector couplings tiny

One-loop ($S_1 + \tilde{S}_2$ model): Neutrino masses

Neutrino operator is radiatively induced: $\mathcal{L}_{\rm EFT} \supset \frac{G_{\nu\nu}}{16\pi^2}\mathcal{O}_{\nu\nu}$

$$[G_{\nu\nu}]^{(1)}_{pr} = N_c\, A_{\tilde{2}1} \left((\lambda^{1\rm L})^T y_D \tilde{\lambda} \right)_{pr} \frac{\log M_1^2/\tilde{M}_2^2}{M_1^2 - \tilde{M}_2^2} \,.$$

$\mathcal{O}_{\nu\nu}$	$\epsilon^{\alpha\beta}\epsilon^{\alpha_1\beta_1} H^\alpha H^{\alpha_1}\, \bar{\ell}^c_{p\beta}\, \ell_{r\beta_1}$

Physical neutrino masses:

$$m_\nu \;=\; -\frac{\sqrt{2}}{16\pi^2}\frac{v A_{\tilde{2}1}}{M_1^2 - \tilde{M}_2^2} \left[U^T_{\rm MNS}\, (\hat{\lambda}^{1L})^T\, K_{\rm CKM}\, m_d \hat{\tilde{\lambda}}\, U_{\rm MNS} \right] \log\left(\frac{M_1^2}{\tilde{M}_2^2} \right)$$

One-loop ($S_1 + \tilde{S}_2$ model): $(g-2)_\ell$

A recent 4.2σ anomaly $\Delta\alpha_\mu = (251 \pm 59) \times 10^{-11}$ [BNL collab., 2104.03281] has re-warmed up all BSM physics enthusiasts around the globe.

Two $d = 6$ operators are responsible in SMEFT,

$\mathcal{O}_{eW}$	$(\bar{\ell}\sigma^{\mu\nu}e)\sigma^I H W^I_{\mu\nu}$
$\mathcal{O}_{eB}$	$(\bar{\ell}\sigma^{\mu\nu}e)HB_{\mu\nu}$

$$[C_{eB}]^{(1)}(\mu) = \frac{g' N_c}{16\pi^2}\left\{\frac{5}{24}\left[\log\left(\frac{\mu^2}{M_1^2}\right) + \frac{19}{10}\right]\frac{Y_{1U}^{1L}}{M_1^2} - \frac{1}{24}\frac{y_E \cdot \Lambda_e}{M_1^2} - \frac{1}{48}\frac{\tilde{\Lambda}_\ell \cdot y_E}{\tilde{M}_2^2}\right\}$$

$$[C_{eW}]^{(1)}(\mu) = \frac{g N_c}{16\pi^2}\left\{-\frac{1}{8}\left[\log\left(\frac{\mu^2}{M_1^2}\right) + \frac{3}{2}\right]\frac{Y_{1U}^{1L}}{M_1^2} + \frac{1}{24}\frac{\Lambda_\ell \cdot y_E}{M_1^2} - \frac{1}{48}\frac{\tilde{\Lambda}_\ell \cdot y_E}{\tilde{M}_2^2}\right\}$$

$$\Downarrow$$

One-loop ($S_1 + \tilde{S}_2$ model): $(g-2)_\ell$

$$\Delta a_\ell^{(S_1+\tilde{S}_2)} = \sum_{q=u,c,t} \frac{m_\ell}{4\pi^2} \frac{m_q}{M_1^2} \left[\log\left(\frac{m_t^2}{M_1^2}\right) + \frac{7}{4} \right] \Re e(\hat{\lambda}_{q\ell}^{1L*} \hat{\lambda}_{q\ell}^{1R})$$

$$- \frac{m_\ell^2}{32\pi^2 M_1^2} \left(\hat{\lambda}_{q\ell}^{1L*} \hat{\lambda}_{q\ell}^{1L} + \hat{\lambda}_{q\ell}^{1R*} \hat{\lambda}_{q\ell}^{1R} \right) ,$$

in agreement with fixed order calculations, e.g. Bauer and Neubert, PRL (2016)

A chiral enhancement of $O(m_t/m_\mu)$ can solve the anomaly for a TeV S_1-mass and $O(1)$ couplings.

However, the same covariant diagram results in large contributions to the muon mass as well.

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Thank you for your attention