Scalar Leptoquark Matching onto SMEFT

A functional approach

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Table of Contents

Table of Contents

History of Matching to EFT - I

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- Last decade, an old **functional matching** technique [Gaillard, NPB (1986), Cheyette NPB (1988), L-H Chan, PRL (1986)] has seen a renewed interest Henning, Lu and Murayama, JHEP (2016,2018)

History of Matching to EFT - II

- First Universal results for the One-Loop Effective Action (UOLEA) [Drozd, J. Ellis, Quevillon, You, JHEP (2016); S. Ellis, Quevillon, You, Zhang, PLB (2016); JHEP (2017)] did not account for mixed statistics and open covariant derivatives.

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- SuperTrace functional technique [Cohen, Lu, Zhang, 2011.02484] establishes a cleaner way to display covariant diagrams for matching. Automated tools exist [`STream`, 2012.07851; `SuperTracer`, 2012.08506]. *It is this approach we follow in our work.*

  Advances on this topic include: Finn, Karamitsos, Pilaftsis, EPJC (2021)

The STr functional matching procedure

The Basic formula for functional matching:

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

where ϕ denotes light-fields.

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- **One-loop:**

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

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

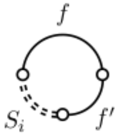

Table of Contents

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- LQs' decoupling produce 54/60 operators in Warsaw basis (all but bosonic CP-violating ones)
- This is the first study of functional matching with multiple heavy-field decoupling.
- Support the usefulness of STr functional matching over other methods

Steps for functional matching

1. Find the tree level EFT, $\mathcal{L}_{\rm EFT}^{(\rm tree)}[\phi]$

   For LQs only four fermion interactions appear at tree level

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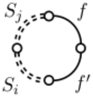
3. Enumerate UOLEA-terms (19) and STr diagrams (15) up-to $d = 6$
   e.g.,



$$= \quad -\frac{i}{2}\,\mathrm{STr}\left[\frac{1}{P^2 - M_i^2} U_{S_i S_j} \frac{1}{P^2 - M_j^2} U_{S_j f} \frac{1}{\not{P}} U_{f f'} \frac{1}{\not{P}} U_{f' S_i}\right]\Bigg|_{\mathrm{hard}}$$

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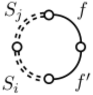

$$= -\frac{i}{2}\,\mathrm{STr}\left[\frac{1}{P^2 - M_i^2} U_{S_i S_j} \frac{1}{P^2 - M_j^2} U_{S_j f} \frac{1}{\not{P}} U_{f f'} \frac{1}{\not{P}} U_{f' S_i}\right]\Bigg|_{\text{hard}}$$

$$= \frac{i}{2}\,\frac{\log M_i^2 / M_j^2}{M_i^2 - M_j^2}\,\mathrm{tr}\{U_{S_i S_j} U_{S_j f} U_{f f'} U_{f' S_i}\}$$

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The effective Lagrangian is the sum: $\mathcal{L}^{(\text{tree})}_{\text{EFT}}[\phi] + \mathcal{L}^{(1-\text{loop})}_{\text{EFT}}[\phi]$

Table of Contents

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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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.} \, ,
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New Interactions with the Higgs:

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

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New Self-Interactions:

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

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

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

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

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

$$\left[G_{eu}\right]_{prst}^{(0)} = \frac{(\lambda_{sp}^{1\mathrm{R}})^*(\lambda_{tr}^{1\mathrm{R}})}{2M_1^2} ,$$

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

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

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

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

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

$$\left[G_{\ell d}\right]_{prst}^{(0)} = -\frac{(\tilde{\lambda}_{tp})^*(\tilde{\lambda}_{sr})}{2\tilde{M}_2^2} ,$$

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

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

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

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.

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

Only four-fermion operators → suitable for explaining possible anomalies in meson decays

Bauer and Neubert, PRL (2016); A. Crivellin, C. Greub, D. Müller and F. Saturnino, JHEP (2021); A. Angelescu, D. Bečirević, D.A. Faroughy, F. Jaffredo and O. Sumensari, 2103.12504.

Also talks by Steve King, S. Trifinopoulos, N. Mahmoudi and J. Kumar earlier in this workshop.

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.

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Perturbation theory instability is evident. The Higgs field is part of the light fields so it should be of the order of EW scale. Otherwise EFT does not make sense!

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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
3. Choose a renorm scale μ such that $L_1 = L_2 = -1$: Then $\delta m^2 = 0$!
4. Supersymmetrize the LQ-model

or combinations of the above four cases...

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

Non-Renormalizable operators: $\mathcal{L}_{\rm EFT} \supset G_{\ell d}\mathcal{O}_{\ell d}$

$$[G_{\ell d}]_{prst} \propto -\frac{\tilde{\lambda}^*_{tp}\tilde{\lambda}_{sr}}{2\tilde{M}_2^2}\left(1+\frac{1}{16\pi^2}\frac{M_1^2}{\tilde{M}_2^2}(N_c c^{(1)}_{1\tilde{2}} + c^{(2)}_{1\tilde{2}})(1+L_1)\right) .$$

$\mathcal{O}_{\ell d}$	$(\bar{\ell}\gamma^\mu\ell)(\bar{d}\gamma_\mu d)$

Perturbative instability for large hierarchy of M_1 and $\tilde{M}_2$.

This tunning is not usually quoted in the literature. Same solutions as before may be admitted. No problem when masses are close to each other.

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

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

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

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

Physical neutrino masses: (in mass basis of 1704.03888) $(m_\nu/16\pi^2)$

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

See also, Mahanta, PRD (2000); Dorsner, PRD (2012); A. Crivellin, C. Greub, D. Müller and F. Saturnino, 2010.06593; Zhang, 2105.08670

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 (Warsaw basis),

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

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

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

$$\Downarrow$$

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

To leading-log approximation, just set $\mu = m_t$

OR

From $\mu = M_1$ run down to m_t with RGEs Jenkins, Manohar, Trott, 1310.4838

$$\Downarrow$$

and plug it into

$$\Delta a^\ell \ = \ \frac{4 m_\ell v}{\sqrt{2}} \left[\frac{1}{g'} \Re e[\mathcal{C}_{eB}] \ - \ \frac{1}{g} \Re e[\mathcal{C}_{eW}] \right]_{\ell\ell}$$

see A.D., Materkowska, Paraskevas, Suxho, Rosiek, 1704.03888

$$\Downarrow$$

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

$$\Delta a_\ell^{(S_1+\tilde{S}_2)} = \sum_{q=u,c,t} \frac{m_\ell}{4\pi^2} \frac{m_q}{M_1^2} \left[\log\left(\frac{m_t^2}{M_1^2}\right) + \frac{7}{4}\right] \Re e(\hat{\lambda}_{q\ell}^{1L*} \hat{\lambda}_{q\ell}^{1R})$$
$$- \frac{m_\ell^2}{32\pi^2 M_1^2} \left(\hat{\lambda}_{q\ell}^{1L*} \hat{\lambda}_{q\ell}^{1L} + \hat{\lambda}_{q\ell}^{1R*} \hat{\lambda}_{q\ell}^{1R}\right) + \frac{m_\ell^2}{32\pi^2 \tilde{M}_2^2} \hat{\tilde{\lambda}}_{q\ell}^{*} \hat{\tilde{\lambda}}_{q\ell}$$

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. See talk by M. Tammaro in this workshop

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

Table of Contents

Conclusions

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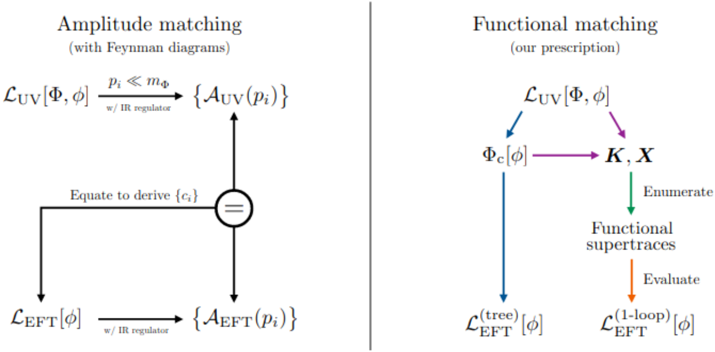
Thank you for your attention

Backup: Feynman diagrammatic vs. functional matching

Figure taken from Cohen, Lu, Zhang, 2011.02484



Advantages of functional approach: a systematic approach, no EFT basis needed, no guess of effective operators, no calculating twice amplitudes.