R_ξ gauges in the SMEFT

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based on JHEP 1902 (2019) 051 by MM, M. Paraskevas, J. Rosiek, K. Suxho and B. Zglinicki

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After perturbative decoupling of heavy particles with masses $\sim \Lambda$, the EFT Lagrangian takes the form:

$$\mathcal{L} \;=\; \mathcal{L}^{(4)} \;+\; \sum_{k=1}^{\infty} \frac{1}{\Lambda^k} \sum_i C_i^{(k+4)} Q_i^{(k+4)}$$

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Notation: $F^a_{\mu\nu} = \partial_\mu A^a_\mu - \partial_\nu A^a_\mu - f^{abc} A^b_\mu A^c_\nu$, $\quad D_\mu \Phi = (\partial_\mu + i A^a_\mu T^a)\Phi$, $\quad (D_\rho F_{\mu\nu})^a = \partial_\rho F^a_{\mu\nu} - f^{abc} A^b_\rho F^c_{\mu\nu}$.

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Claim: Out of all $\Phi^n F^m D^k$, only Φ^n, $\Phi^n D^2$ and $\Phi^n F^2$ matter for the bilinear terms after the EOM reduction (actually, field redefinitions - see J. C. Criado, M. Perez-Victoria, arXiv:1811.09413).

Examples: Before the reduction, e.g., $(D_\mu\Phi)^T(D^\mu\Phi)F^a_{\nu\rho}F^{a\,\nu\rho}$ does not matter but, e.g., $(\Phi^T\Phi)(\Phi^T D^\mu D^\nu D_\mu D_\nu \Phi)$ may matter.

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In the following, F may stand for $\tilde{F}$, too.

Step-by-step EOM reduction (starting from the lowest dimension, and highest number of derivatives at a given dimension):

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At this point, no operators with second or higher derivatives of Φ need to be considered any longer.

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   Bianchi identity: $D_{[\mu} F_{\nu\rho]} = 0$, EOM: $D_{[\mu} \tilde{F}_{\nu\rho]} = \boxed{HL}$

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5. Skip $\Phi^n F \tilde{F}$ (total derivative after $\Phi \to v$).

$\square$

The sum of all the $\Phi^n D^2$ and $\Phi^n F^2$ terms can be written as:

$$\mathcal{L}_{h,g} = \frac{1}{2}(D_\mu \Phi)_i \; K_{ij}[\Phi] \; (D^\mu \Phi)_j - \frac{1}{4} F^a_{\mu\nu} \; J^{ab}[\Phi] \; F^{b\,\mu\nu}$$

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The bilinear terms are selected by setting

$K_{ij}[\Phi] \to K_{ij}[v] \equiv K_{ij}$ and $J^{ab}[\Phi] \to J^{ab}[v] \equiv J^{ab}$.

Then $\mathcal{L}_{h,g} = \frac{1}{2}(D_\mu \Phi)^T K \, (D^\mu \Phi) - \frac{1}{4} A^T_{\mu\nu} \, J \, A^{\mu\nu} + \text{(interactions)}$ with $A^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu$.

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The “unwanted” tree-level mixing:

$$\mathcal{L}_{A\varphi} = -i \left(\partial^\mu A^a_\mu\right) \left[\varphi^T K T^a v\right]$$

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Now, we can specify the R_ξ gauge-fixing term as:

$\mathcal{L}_{GF} = -\frac{1}{2\xi} \mathcal{G}^a J^{ab} \mathcal{G}^b$ with $\mathcal{G}^a = \partial^\mu A^a_\mu - i\xi (J^{-1})^{ab} \left[\varphi^T K T^b v \right]$.

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The kinetic terms are rendered canonical via: $\tilde{\varphi}_i = (K^{\frac{1}{2}})_{ij}\varphi_j$, $\tilde{A}^a_\mu = (J^{\frac{1}{2}})^{ab}A^b_\mu$,

which brings the bilinear terms to the familiar form:

$$\mathcal{L}_{\text{kin,mass}} = -\tfrac{1}{4}\tilde{A}^T_{\mu\nu}\tilde{A}^{\mu\nu} + \tfrac{1}{2}\tilde{A}^T_\mu(M^T M)\tilde{A}^\mu + \tfrac{1}{2}(\partial_\mu\tilde{\varphi})^T(\partial^\mu\tilde{\varphi}) - \tfrac{1}{2\xi}(\partial^\mu\tilde{A}_\mu)^T(\partial^\nu\tilde{A}_\nu) - \tfrac{\xi}{2}\tilde{\varphi}^T(MM^T)\tilde{\varphi},$$

with $M_j{}^b \equiv [K^{\frac{1}{2}}(iT^a)v]_j\,(J^{-\frac{1}{2}})^{ab}$ (real matrix).

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Singular Value Decomposition: $M = U^T\Sigma V,$ $\Sigma_{ij} = 0$ when $i \neq j,$ U, V – orthogonal matrices.

$$\Rightarrow \qquad MM^T = U^T(\Sigma\Sigma^T)U \quad \text{and} \quad M^TM = V^T(\Sigma^T\Sigma)V.$$

Mass eigenstates: $\phi_i = U_{ij}\tilde{\varphi}_j,$ $W^a_\mu = V^{ab}\tilde{A}^b_\mu.$

Diagonal mass matrices: $m^2_\phi = \Sigma\Sigma^T = \begin{bmatrix} D & \\ & 0 \end{bmatrix}_{m\times m}$ $m^2_W = \Sigma^T\Sigma = \begin{bmatrix} D & \\ & 0 \end{bmatrix}_{n\times n}$

The bilinear terms in the mass eigenbasis take the standard form:

$$\mathcal{L}_{\text{kin,mass}} = -\frac{1}{4}W^T_{\mu\nu}W^{\mu\nu} + \frac{1}{2}W^T_\mu m^2_W W^\mu + \frac{1}{2}(\partial_\mu\phi)^T(\partial^\mu\phi) - \frac{1}{2\xi}(\partial^\mu W_\mu)^T(\partial^\nu W_\nu) - \frac{\xi}{2}\phi^T m^2_\phi\phi.$$

Ghost sector and BRST

Infinitesimal gauge transformations in the initial basis:

$$\delta\varphi = -i\alpha^a T^a\,(\varphi + v), \qquad \delta A^a_\mu = \partial_\mu \alpha^a - f^{abc} A^b_\mu \alpha^c.$$

The corresponding BRST variations:

$$\delta_{\mathrm{BRST}}\varphi = -i\epsilon N^a T^a\,(\varphi + v)\,, \qquad \delta_{\mathrm{BRST}} A^a_\mu = \epsilon\left(\partial_\mu N^a - f^{abc} A^b_\mu N^c\right).$$

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Gauge-fixing functional: $\mathcal{G}^a = \partial^\mu A^a_\mu - i\xi (J^{-1})^{ac}\left[\varphi^T K T^c v\right].$

Its BRST variation: $\delta_{\text{BRST}}\mathcal{G}^a = \epsilon M^{ab}_F N^b.$

Introducing the ghost term: $\mathcal{L}_{GF} + \mathcal{L}_{FP} \;=\; -\frac{1}{2\xi}\,\mathcal{G}^a J^{ab}\mathcal{G}^b \;+\; \bar{N}^a J^{ab} M^{bc}_F N^d.$

Explicitly: $\mathcal{L}_{FP} = J^{ab}\bar{N}^a \Box N^b + \xi\bar{N}^a[v^T T^a K T^b v]N^b + \bar{N}^a\,\overleftarrow{\partial}^\mu J^{ab} f^{bcd} A^c_\mu N^d + \xi\bar{N}^a[v^T T^a K T^b \varphi]N^b.$

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Introducing the ghost term: $\mathcal{L}_{GF} + \mathcal{L}_{FP} \;=\; -\frac{1}{2\xi}\mathcal{G}^a J^{ab} \mathcal{G}^b \;+\; \bar{N}^a J^{ab} M_F^{bc} N^d.$

Explicitly: $\mathcal{L}_{FP} = J^{ab}\bar{N}^a \Box N^b + \xi \bar{N}^a [v^T T^a K T^b v] N^b + \bar{N}^a \overleftarrow{\partial}^\mu J^{ab} f^{bcd} A_\mu^c N^d + \xi \bar{N}^a [v^T T^a K T^b \varphi] N^b.$

BRST variations of the ghosts: $\delta_{\text{BRST}} N^a = \frac{\epsilon}{2} f^{abc} N^b N^c, \qquad \delta_{\text{BRST}} \bar{N}^a = \frac{\epsilon}{\xi}\mathcal{G}^a.$

$$\Rightarrow \quad \delta_{\text{BRST}}\left(M_F^{ab} N^b\right) = 0 \quad \Rightarrow \quad \delta_{\text{BRST}}\left(\mathcal{L}_{GF} + \mathcal{L}_{FP}\right) = 0.$$

Ghost sector and BRST

Infinitesimal gauge transformations in the initial basis:

$$\delta\varphi = -i\alpha^a T^a(\varphi + v), \qquad \delta A^a_\mu = \partial_\mu \alpha^a - f^{abc} A^b_\mu \alpha^c.$$

The corresponding BRST variations:

$$\delta_{\text{BRST}}\varphi = -i\epsilon N^a T^a(\varphi + v), \qquad \delta_{\text{BRST}} A^a_\mu = \epsilon\left(\partial_\mu N^a - f^{abc} A^b_\mu N^c\right).$$

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Mass eigenstates: $\eta = V J^{\frac{1}{2}} N, \qquad \bar{\eta} = V J^{\frac{1}{2}} \bar{N}.$

The ghost bilinear terms in the mass eigenbasis take the standard form:

$$\mathcal{L}_{FP} = \bar{\eta}^T \Box \eta + \xi\, \bar{\eta}^T m_W^2 \eta + \text{(interactions)}.$$

Expressing N complex fields in terms of $2N$ real fields:

$$\Phi = \mathcal{U} \begin{pmatrix} H \\ H^\star \end{pmatrix}, \qquad \mathcal{U} = \frac{S}{\sqrt{2}} \begin{pmatrix} 1_{N\times N} & 1_{N\times N} \\ -i1_{N\times N} & i1_{N\times N} \end{pmatrix}, \qquad S \text{ – arbitrary orthogonal matrix.}$$

$$D_\mu H = \left(\partial_\mu + iA^a_\mu C^a\right) H \quad \Rightarrow \quad D_\mu \Phi = \left(\partial_\mu + iA^a_\mu T^a\right) \Phi \quad \text{with} \quad T^a = iS \begin{pmatrix} \mathrm{Im}\, C^a & \mathrm{Re}\, C^a \\ -\mathrm{Re}\, C^a & \mathrm{Im}\, C^a \end{pmatrix} S^T.$$

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Choose $S = \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 1 & 0 & 0 \end{pmatrix}$, then $H = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$, $A^a_\mu = (W^1_\mu, W^2_\mu, W^3_\mu, B_\mu)^a$ and

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Matrices in the kinetic terms:

$$J = \begin{pmatrix} 1+J_+ & 0 & 0 & 0 \\ 0 & 1+J_+ & 0 & 0 \\ 0 & 0 & 1+J_1 & J_3 \\ 0 & 0 & J_3 & 1+J_2 \end{pmatrix} \equiv \begin{pmatrix} J_C & 0_{2\times 2} \\ 0_{2\times 2} & J_N \end{pmatrix}$$

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At the dimension-six level in the Warsaw basis:

$$J_+ = J_1 = -\frac{2v^2}{\Lambda^2}C^{\varphi W}, \quad J_2 = -\frac{2v^2}{\Lambda^2}C^{\varphi B}, \quad J_3 = \frac{v^2}{\Lambda^2}C^{\varphi WB},$$

$$K_+ = K_3 = 0, \quad K_1 = \frac{v^2}{2\Lambda^2}C^{\varphi D}, \quad K_2 = \frac{v^2}{2\Lambda^2}(C^{\varphi D} - 4C^{\varphi\Box}).$$

$Q_{\varphi W} = \varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$ $\quad Q_{\varphi D} = (\varphi^\dagger D^\mu\varphi)^\star(\varphi^\dagger D_\mu\varphi)$

$Q_{\varphi B} = \varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$ $\quad Q_{\varphi\Box} = (\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$

$Q_{\varphi WB} = \varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$

$\Rightarrow$ same results as in arXiv:1704.0388.

Summary

- **We considered R_ξ gauge fixing in EFTs arising after decoupling of heavy ($M \sim \Lambda$) particles, assuming that scalar VEVs ($\langle \Phi \rangle \ll \Lambda$) give masses to some of the gauge bosons via the Higgs mechanism.**

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- Specifying the gauge-fixing and ghost terms, as well as the BRST variations proceeds along the same lines as in a renormalizable theory with non-canonical kinetic terms.

- Standard relations between the masses of gauge bosons, would-be Goldstone bosons and ghosts remain valid. However, their interactions are affected by the presence of higher-dimensional operators.

BACKUP SLIDE

Square roots in neutral sector:

$$J_N^{1/2} = \frac{1}{\sqrt{J_1'+J_2'}} \begin{pmatrix} J_1' & J_3 \\ J_3 & J_2' \end{pmatrix}, \qquad J_N^{-1/2} = \frac{1}{\sqrt{(J_1'+J_2')\,\det J_N}} \begin{pmatrix} J_2' & -J_3 \\ -J_3 & J_1' \end{pmatrix}, \quad \text{where } J_i' = 1 + J_i + \sqrt{\det J_N}.$$

SVD matrices in this sector:

$$U_N = \begin{pmatrix} \cos\omega & \sin\omega \\ -\sin\omega & \cos\omega \end{pmatrix}, \qquad V_N = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \qquad \text{with} \begin{cases} \omega = \arctan(K_3/K_1'), \\ \theta = \arctan[(g'J_1' + gJ_3)/(gJ_2' + g'J_3)]. \end{cases}$$

In the limit $\Lambda \to \infty$, we have $\omega \to 0$ and $\theta \to \theta_W \equiv \arctan(g'/g)$.