SMEFT vs HEFT interplay: status and prospects

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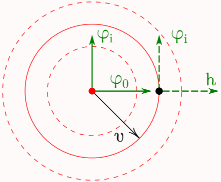
SMEFT

Higgs doublet:

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix}\varphi_2 + i\varphi_1 \\ \varphi_0 - i\varphi_3\end{pmatrix} = \frac{v+h}{\sqrt{2}}\,\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$



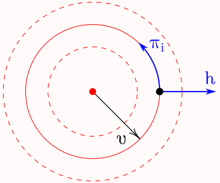
HEFT (EWχL)

Goldstone chiral field:

$$\mathbf{U} = \exp\left(\frac{i\vec{\sigma}\cdot\vec{\pi}}{v}\right)$$

Physical Higgs singlet:

$$h$$



HEFT Lagrangian

LO

Feruglio 9301281, Grinstein,Trott 0704.1505, Buchalla,Catà 1203.6510, Alonso+ 1212.3305, IB+ 1311.1823,1604.06801, Buchalla+ 1307.5017,1511.00988. . .

$$
\begin{aligned}
\mathscr{L}_0 = & -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} - \frac{1}{4}W^I_{\mu\nu}W^{I\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} \\
& + \frac{1}{2}\partial_\mu h \partial^\mu h - \lambda v^4 \mathcal{V}(h) - \frac{v^2}{4}\mathrm{Tr}\left(\mathbf{V}_\mu \mathbf{V}^\mu\right)\mathcal{F}_C(h) + c_T \frac{v^2}{4}\mathrm{Tr}\left(\mathbf{T}\mathbf{V}_\mu\right)^2 \mathcal{F}_T(h) \\
& + i\overline{Q}_L \not{D} Q_L + i\overline{Q}_R \not{D} Q_R + i\overline{L}_L \not{D} L_L + i\overline{L}_R \not{D} L_R \\
& - \frac{v}{\sqrt{2}}\left(\overline{Q}_L \mathbf{U} \mathcal{Y}_Q(h) Q_R + \mathrm{h.c.}\right) - \frac{v}{\sqrt{2}}\left(\overline{L}_L \mathbf{U} \mathcal{Y}_L(h) L_R + \mathrm{h.c.}\right)
\end{aligned}
$$

where

$\mathbf{V}_\mu = (D_\mu \mathbf{U})\mathbf{U}^\dagger \xrightarrow{\text{unit. gauge}} W^\pm_\mu, Z_\mu$

$\mathbf{T} = \mathbf{U}\sigma^3\mathbf{U}^\dagger \to$ custodial break

$\mathcal{Y}_Q(h) = \mathrm{diag}(Y_u\,\mathcal{F}_u(h), Y_d\,\mathcal{F}_d(h))\,,$

$\mathcal{F}_i(h), \mathcal{V}(h)$ all of the form $1 + a_i \frac{h}{v} + b_i \frac{h^2}{v^2} + \dots$

HEFT Lagrangian

NLO

Buchalla,Catà,Krause 1307.5017, IB+ 1604.06801, Sun,Xiao,Yu 2210.14939

Class	Example	# for 3 (1) gen, $B-L$ cons
$D^4\mathbf{U}h$	$\langle\mathbf{V}_\mu\mathbf{V}^\mu\rangle^2\mathcal{F}(h)$	15
$X^2\mathbf{U}h$	$B_{\mu\nu}\langle\mathbf{T}W^{\mu\nu}\rangle\mathcal{F}(h)$	10
$D^2X\mathbf{U}h$	$\mathrm{Tr}\,W_{\mu\nu}[\mathbf{V}^\mu,\mathbf{V}^\nu]\rangle\mathcal{F}(h)$	8
X^3h	$\varepsilon^{IJK}W_\nu^{I\mu}W_\rho^{J\nu}W_\mu^{K\rho}$	6
$D\psi^2\mathbf{U}h$	$(\bar{Q}_L\gamma^\mu\mathbf{V}_\mu Q_L)\mathcal{F}(h)$	117 (13)
$D^2\psi^2\mathbf{U}h$	$(\bar{Q}_L\mathbf{U}Q_R)\langle\mathbf{V}_\mu\mathbf{V}^\mu\rangle\mathcal{F}(h)$	540 (60)
$X\psi^2\mathbf{U}h$	$(\bar{Q}_L\sigma^{\mu\nu}\mathbf{U}Q_R)B_{\mu\nu}\mathcal{F}(h)$	198 (22)
$\psi^4\mathbf{U}h$	$(\bar{Q}_L\mathbf{U}Q_R)^2\mathcal{F}(h)$	6813 (90)

Hilbert series counting: Gráf,Henning,Lu,Melia,Murayama 2211.06725, Alonso,Ur Rahaman 2412.09463

NNLO basis (10^6+ parameters): Sun,Wang,Yu 2211.11598

SMEFT vs HEFT

- are the two EFTs physically **different or equivalent**?
- in choosing one or the other, are we making different **assumptions on the UV**?
- do they give different **phenomenologies**, i.e. point to different signals to search for?
- can one of them be **“ruled out”**?

☞ can take order-by-order or all-orders approach

all-orders helps understanding fundamental differences, order-by-order necessary for pheno eventually

SMEFT vs HEFT: order-by-order comparisons

(a) interactions that are **correlated in SMEFT** and **decorrelated in HEFT**

(b) interactions that appear at **a lower order in HEFT** compared to SMEFT

Examples

SMEFT vs HEFT: order-by-order comparisons

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(b) interactions that appear at **a lower order in HEFT** compared to SMEFT

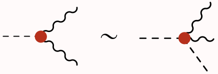
Examples

$$D_\mu H^\dagger D^\mu H \left[1 + \frac{c_6}{\Lambda^2}(H^\dagger H)\right]$$

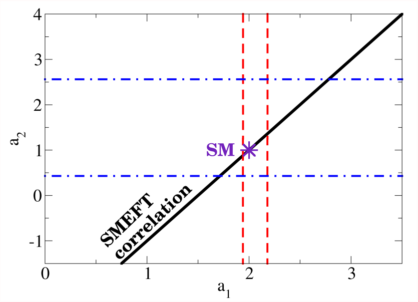
vs

$$v^2\langle \mathbf{V}_\mu \mathbf{V}^\mu \rangle \left[1 + a_1 \frac{h}{v} + a_2 \frac{h^2}{v^2} + \ldots\right]$$

👉 dim-6 SMEFT correlates



Gomez-Ambrosio+ 2204.01763, 2207.09848, 2311.04280
see also: Bhardwaj+ 2407.14608, Anisha+ 2402.06746,2407.20706



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(b) interactions that appear at **a lower order in HEFT** compared to SMEFT

Examples

Éboli,Gonzalez-Garcia,Martines 2112.11468. also: IB+ 1311.1823,1604.06801
related study: Isidori,(Manohar),Trott 1305.0663,1307.4051

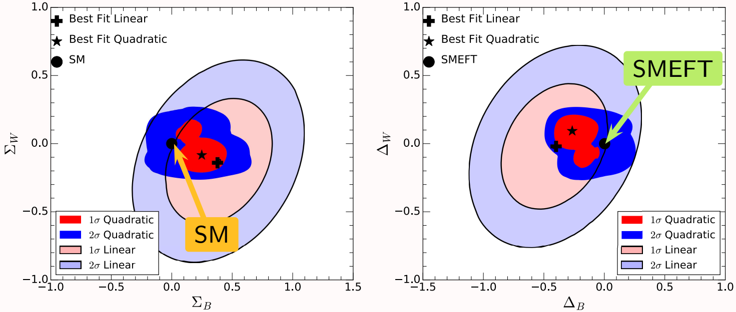
$$\frac{c_{BH}}{\Lambda^2} D_\mu H^\dagger B_{\mu\nu} D^\mu H$$

vs

$$c_2\, B_{\mu\nu} \langle \mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu]\rangle \mathcal{F}(h) +$$
$$c_4\, B_{\mu\nu} \langle \mathbf{T}\mathbf{V}^\mu \rangle \partial^\nu \mathcal{F}(h)$$

$$\Sigma_B \sim 2c_2 + c_4, \quad \Delta_B \sim 2c_2 - c_4$$

c_2 enters VVV, c_4 enters VVH



SMEFT vs HEFT: order-by-order comparisons

(a) interactions that are **correlated in SMEFT** and **decorrelated in HEFT**

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Examples

$$\frac{1}{\Lambda^8}(H^\dagger \overleftrightarrow{D}_\mu H)^4$$

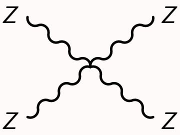
vs

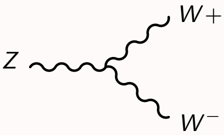
$$\langle \mathbf{T}\mathbf{V}_\mu \rangle^4 \mathcal{F}(h)$$

$$\frac{1}{\Lambda^4}(H^\dagger W_{\mu\nu} H)(D^\mu H^\dagger D^\nu H)$$

vs

$$\langle \mathbf{T} W_{\mu\nu} \rangle \langle \mathbf{T}[\mathbf{V}^\mu, \mathbf{V}^\nu] \rangle \mathcal{F}(h)$$





+ others

SMEFT vs HEFT: order-by-order comparisons

(a) interactions that are **correlated in SMEFT** and **decorrelated in HEFT**

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Examples

IB+ 1604.06801

$$\frac{1}{\Lambda^4} i(\bar{Q}_L \tilde{H} \sigma^{\mu\nu} u_R + \bar{Q}_L H \sigma^{\mu\nu} d_R)(H^\dagger W_{\mu\nu} H)$$

vs

$$i\bar{Q}_L \sigma^{\mu\nu}\{W_{\mu\nu}, \mathbf{T}\}\mathbf{U} Q_R \mathcal{F}(h)$$

$$\frac{1}{\Lambda^4}(\bar{Q}_L \tilde{H} u_R)^2 - \frac{1}{\Lambda^4}(\bar{Q}_L H d_R)^2$$

vs

$$(\bar{Q}_L \mathbf{U} Q_R)(\bar{Q}_L \mathbf{T}\mathbf{U} Q_R)\mathcal{F}(h)$$

custodial-breaking and chirality-flipping fermionic operators also lowered in order!

SMEFT vs HEFT: order-by-order comparisons

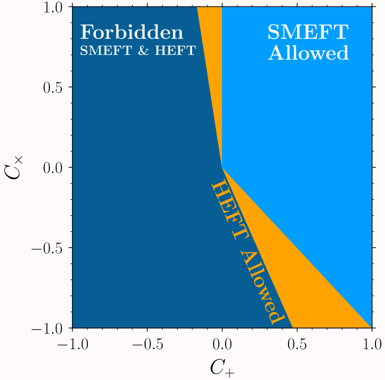
(c) Positivity constraints

Remmen,Rodd 2412.07827
also: Chakraborty+ 2412.14155

$$\mathcal{O}_+ = (\partial_\mu H^\dagger \partial_\nu H)(\partial^\mu H^\dagger \partial^\nu H) \quad \text{sym. } \mu \leftrightarrow \nu$$
$$\mathcal{O}_\times = (\partial_\mu H^\dagger \partial^\mu H)^2$$

$$\mathcal{O}_1^h = (\partial_\mu h)^4$$
$$\mathcal{O}_1^{h\pi} = (\partial_\nu h)^2 (\partial_\mu \vec{\pi} \cdot \partial^\mu \pi)$$
$$\mathcal{O}_2^{h\pi} = (\partial_\mu h \partial_\nu h)(\partial^\mu \vec{\pi} \cdot \partial^\nu \pi)$$
$$\mathcal{O}_1^\pi = (\partial_\mu \vec{\pi} \cdot \partial^\mu \pi)^2$$
$$\mathcal{O}_2^\pi = (\partial_\mu \vec{\pi} \cdot \partial_\nu \pi)^2$$

$$4\mathcal{O}_+ = \mathcal{O}_1^h + 2\mathcal{O}_2^{h\pi} + \mathcal{O}_2^\pi$$
$$4\mathcal{O}_\times = \mathcal{O}_1^h + 2\mathcal{O}_1^{h\pi} + \mathcal{O}_1^\pi$$



projecting HEFT positivity bounds onto SMEFT plane
gives a broader allowed region

HEFT power counting

a source of recurring confusion for the order-by-order perspective!

- what is the criterion for sorting operators in $\mathscr{L}_{\rm HEFT}$?
  chiral dimension? primary dimension? derivatives?... Gavela+ 1601.07551, Buchalla+, 1312.5624,1603.03062

- what is the HEFT order of a diagram ? does **squaring** amount to a suppression?
  how does it depend on the number of insertions and operator order? on the number of loops?...

- what is the final expansion one obtains for the observable predictions?
  what does HEFT expand on, in the end of the day?

trying to identify valid counting rules by starting from the bottom (observables): IB,Gröber,Schmid w.i.p

$$\sigma \sim p^{-2}(4\pi)^3 \left(\frac{p}{\Lambda}\right)^{\alpha_\Lambda^p} \left(\frac{4\pi v}{\Lambda}\right)^{N_v} \left(\frac{g}{4\pi}\right)^{N_g} \left(\frac{y}{4\pi}\right)^{N_y} \dots$$

HEFT power counting

preliminary result:

IB,Gröber,Schmid w.i.p

(A): **v** is the suppression scale for scalars in $(h/v), (\pi^I/v)$

☞ can have a dual expansion in $\frac{p}{\Lambda} \sim \frac{g, g', y, \sqrt{\lambda}}{4\pi}$ and in $\frac{g_s}{4\pi}$

Op. class	$\mathbf{N_\chi - N_{g_s}}$
1	-2
d, ψ^2	-1
$d^2, d\psi^2, \psi^4, y\psi^2$	0
$d^3, d^2\psi^2, d\psi^4, \psi^6$	1
$d^4, d^3\psi^2, d^2\psi^4, d\psi^6, \psi^8$	2
	...

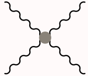
$d = D_\mu, \partial_\mu, B_{\mu\nu}, W_{\mu\nu}, \mathbf{V}_\mu$

arbitrary nr of scalars allowed

arbitrary nr of $G_{\mu\nu}$, color-D_μ allowed

$$N_{\text{HEFT}}(\mathcal{M}) = n - 2 + 2L + \sum_{i \in \text{vertices}} (N_{\chi,i} - N_{g_s,i})$$

2



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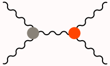

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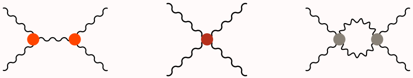

HEFT power counting

preliminary result: IB,Gröber,Schmid w.i.p

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- can have a dual expansion in $\frac{p}{\Lambda} \sim \frac{g, g', y, \sqrt{\lambda}}{4\pi}$ and in $\frac{g_s}{4\pi}$

(B): **f** $> v$ is the suppression scale for scalars in $(h/v), (\pi^I/f)$

- can have a dual expansion in $\frac{p}{\Lambda} \sim \frac{v}{f} = \sqrt{\xi}$ and in $\frac{g_s}{4\pi}$
- similar to the SMEFT expansion
- no univocal model-independent way to introduce ξ in $\mathscr{L}_{\rm HEFT}$

SMEFT – HEFT mapping

it is possible to convert between the two theories with

$$H = \frac{v+h}{\sqrt{2}}\mathbf{U}\begin{pmatrix}0\\1\end{pmatrix}$$

$$\mathbf{U} = \frac{\begin{pmatrix}\tilde{H} & H\end{pmatrix}}{\sqrt{H^\dagger H}}\,, \qquad h = \sqrt{2H^\dagger H} - v$$

SMEFT $\rightarrow$ HEFT is always possible

SMEFT $\leftarrow$ HEFT is possible
iff EFT analytical at $H^\dagger H = 0$

Falkowski,Rattazzi 1902.05936

- all HEFT operators can be expressed in a SMEFT-like form, always valid at $H^\dagger H = v^2/2$
- $\mathcal{F}(h) \sim \sum_n^\infty (H^\dagger H)^n/\Lambda^{2n}$
- all HEFT effects have a SMEFT-equivalent at high enough dim.
  - ☞ unclear if operator bases across orders can be mapped 1-to-1
- if analytical at $H^\dagger H = 0$, $H \leftrightarrow \mathbf{U}, h$ conversion is an **unphysical field redefinition**

SMEFT vs HEFT: geometrical interpretation

let us consider only the 4 scalar fields : they can be seen as coordinates on 4D manifold

Alonso,Jenkins,Manohar 1511.00724,1605.03602. lectures: Alonso 2307.14301

SMEFT ∼ **cartesian** coord.

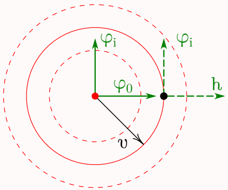
HEFT ∼ **polar** coord.

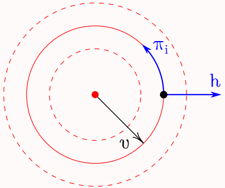
$(\mathbb{R}^4)$ $$\vec{\phi} = \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}$$

$$\vec{\phi} = (v+h)\exp\left[\frac{2\pi^i t_i}{v}\right]\begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$(SU(2))$ $$H = \frac{1}{\sqrt{2}}\begin{pmatrix} \phi_2 + i\phi_1 \\ \phi_4 - i\phi_3 \end{pmatrix}$$

$$\mathbf{U} = \exp\left[\frac{\pi^i \sigma_i}{v}\right]$$





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SMEFT ∼ **cartesian** coord.

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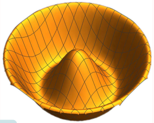
HEFT ∼ **polar** coord.

$$\vec{\phi} = (v + h) \exp\left[\frac{2\pi^i t_i}{v}\right] \begin{pmatrix} 0 \\ 0 \\ 0 \\ 1 \end{pmatrix}$$

$$\mathbf{U} = \exp\left[\frac{\pi^i \sigma_i}{v}\right]$$



- field redefinition ↔ change of coordinates
- physics can be associated to geometry of the field space, independent of coordinates

Physics – Geometry connection

The kinetic term corresponds to a metric in field space

$$\mathscr{L} = \frac{1}{2}\partial_\mu\phi^i\partial^\mu\phi^j g_{ij}(\phi) + \dots$$

it captures **all operators with 2 derivatives**, up to arbitrary dimensions. e.g.

$$\begin{aligned}
\partial_\mu H^\dagger\partial^\mu H\,(H^\dagger H)^n &= \frac{1}{2}\partial_\mu\vec\phi\cdot\partial^\mu\vec\phi\;\frac{|\vec\phi|^{2n}}{2^n} &\to\quad g_{ij} = \delta_{ij}\,\frac{|\vec\phi|^{2n}}{2^n}\\
H^\dagger H\,\square\,(H^\dagger H) &= -(\vec\phi\cdot\partial_\mu\vec\phi)^2 &\to\quad g_{ij} = -2\phi_i\phi_j\\
(iH^\dagger\partial_\mu H - i\partial_\mu H^\dagger H)^2 &= 4(\partial_\mu\vec\phi\;t_{3R}\;\vec\phi)^2 &\to\quad g_{ij} = 8(t_{3R}\phi)_i(t_{3R}\phi)_j
\end{aligned}$$

scattering amplitudes are proportional to the Riemann curvature invariants at the vacuum

$$\mathcal{A}(\phi_i\phi_j\to\phi_k\phi_l) = R_{ijkl}s_{ik} + R_{ikjl}s_{ij}$$

gauge sector and fermions can also be included in the formalism

Cheung,Helset,Parra-Martinez 2111.03045,2202.06972
Helset,Jenkins,Manohar 2210.08000
Assi+ 2307.03187, 2504.18537
Cohen,Lu,Sutherland 2312.06748

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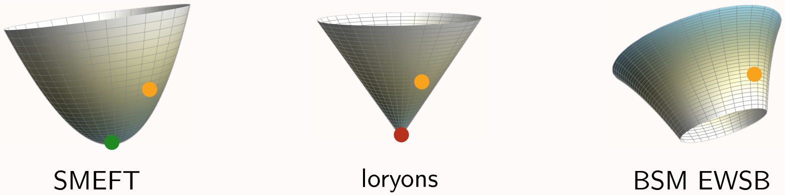
- allows to identify **UV completions that can only be matched onto HEFT**:
  - with BSM sources of EWSB
  - with decoupled particles whose mass came mostly from Higgs mechanism (loryons)

Banta+ 2110.02967, Crawford,Sutherland 2409.18177



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- can be employed in **matching** Li+ 2411.04173

...

Limitations of the geometric approach

it does not provide (yet) an algorithm to discriminate SMEFT/HEFT phenomenologically

- SMEFT/HEFT discriminant is at $H^\dagger H = 0$ but all experiments are at the vacuum $H^\dagger H = v^2/2$

  even for loryons, we can still do "standard" pheno, no new exotic signatures

  a way to target phenomenology at $H^\dagger H = 0$ is through **cosmological** signatures Alonso+ 2312.00881

- **limited to 2 derivatives**: all-orders in field insertions but not in ∂

  alternative approaches proposed: functional geometry Cheung+ 2202.06972, Cohen+ 2410.21378
  Lagrange spaces Craig+ 2305.09722
  jet bundle geometry Craig,Lee 2307.15742, Aliminawi,IB,Davighi 2308.00017

~~Jet~~ Fibre bundle geometry

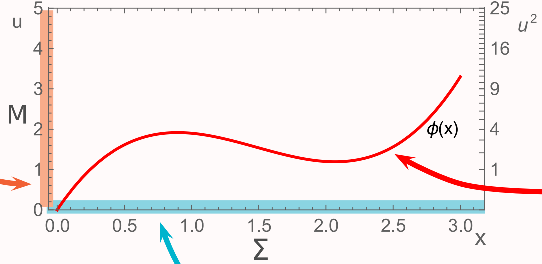
key point: keep ϕ dependence on x manifest $\rightarrow$ be able to describe $\partial_\mu \phi(x)$ Alminawi,IB,Davighi 2308.00017

rather than a coordinate on a manifold, $\phi(x)$ is a section of a fibre bundle

field config. space M

w/ coord u^i

$\equiv$ **fibre**



field $\phi^i(x) : \Sigma \rightarrow M$

$\equiv$ **section** of E over Σ

$\neq u^i$

Minkowski spacetime Σ

w/ coord x^μ , metric η

$\equiv$ **base space**

Fibre bundle: from geometry to amplitudes

fibre bundle formalism allows to write

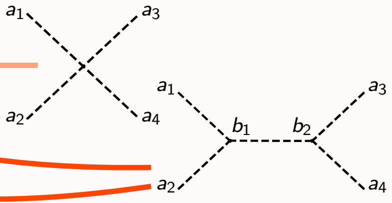
Alminawi,IB,Davighi 2308.00017 + w.i.p

$$\mathscr{L} = \underbrace{\frac{1}{2}\eta^{\rho\sigma} g_{\rho\sigma}(\phi)}_{\equiv -V(\phi)} + \underbrace{\frac{1}{2} g_{ij}(\phi)\partial_\rho \phi^i \partial^\rho \phi^j}_{\text{same as usual geometry}}$$

geo interpretation of scalar potential! ☺

leading to scattering amplitudes such as:

$$i\mathcal{M}_{a_1 a_2 a_3 a_4} = -\frac{1}{12}\nabla_{a_1}\nabla_{a_3} R^{\mu}{}_{a_2 \mu a_4} + 2R^{\mu}{}_{a_1 \nu a_2} R^{\nu}{}_{a_3 \mu a_4} - R_{a_1 a_3 a_4 a_2} s_{a_1 a_2}$$
$$-\frac{3}{4}(\nabla_{a_2} R^{\mu}{}_{b_1 \nu a_1})(\nabla_{a_4} R^{\nu}{}_{b_2 \mu a_3})\Delta^{b_1 b_2}(s_{a_1 a_2})$$
$$+ (\dots) + \text{perms}_{1234}$$



$$\Delta^{ij}(s) = \left[s\, g_{ij} + \frac{1}{2} R^{\nu}{}_{i\nu j} \right]^{-1}$$

jet bundles generalize this adding new metric entries → op. with $\partial^{\geq 4}$

Summary

- SMEFT and HEFT are the main candidates to capture physical effects of decoupled new physics. they differ in the fields choice for the scalar sector and in the power counting.

$$\text{HEFT} \supseteq \text{SMEFT} \supseteq \text{SM}$$

  HEFT could be relevant for BSM theories with large mixings or that are not very decoupled.

- order-by-order phenomenological comparisons highlight phenomenological differences

  ☞ can be refined (e.g. making power countng more rigorous) and streamlined/automated

- geometrical methods proved successful to address a deeper, all-orders comparison

  ☞ being developed further, especially towards **higher derivatives**

  ☞ phenomenological implications still to be fully explored

- matching to UV models explored in a few cases, also left questions to be clarified