FALSIFICATION OF SMEFT THROUGH HIGGS MEASUREMENTS

Exposing the correlations of SMEFT parameters

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Dubrovnik, Friday 3rd June, 2022

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Outline

- Introduction and motivation.
- *SMEFT* $\subset$ *HEFT*: an overview.
- Correlations of HEFT parameters when assuming SMEFT's validity. **Explicit computation.**
- Measurements: $W_L W_L \to n \times h$ to discern between SMEFT and pure-HEFT.

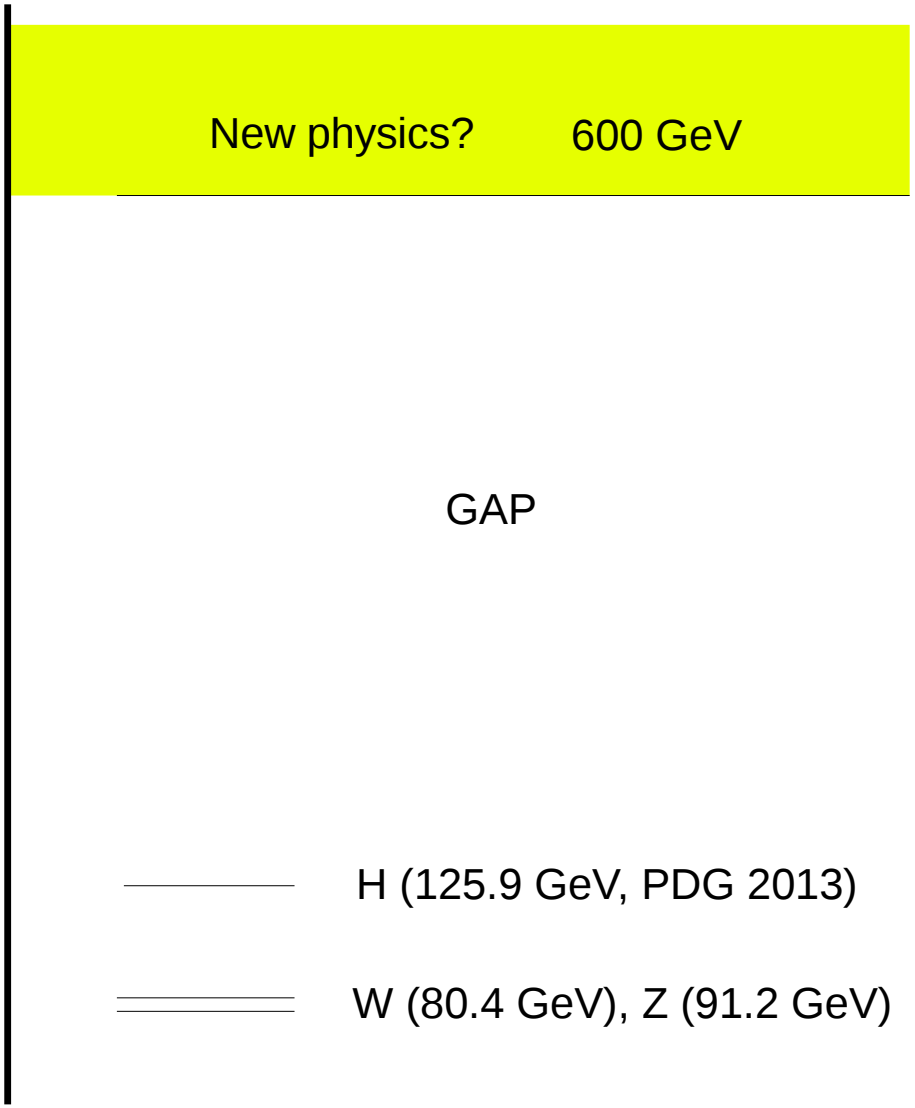
Based on *"The flair of Higgsflare"*
`https://arxiv.org/abs/2204.01763`.

Effective Field Theory scenario

Mass Gap to any new physics $\Longrightarrow$ EFT

Falsifying the SM:

- Discover new particles, or
- Discover new forces



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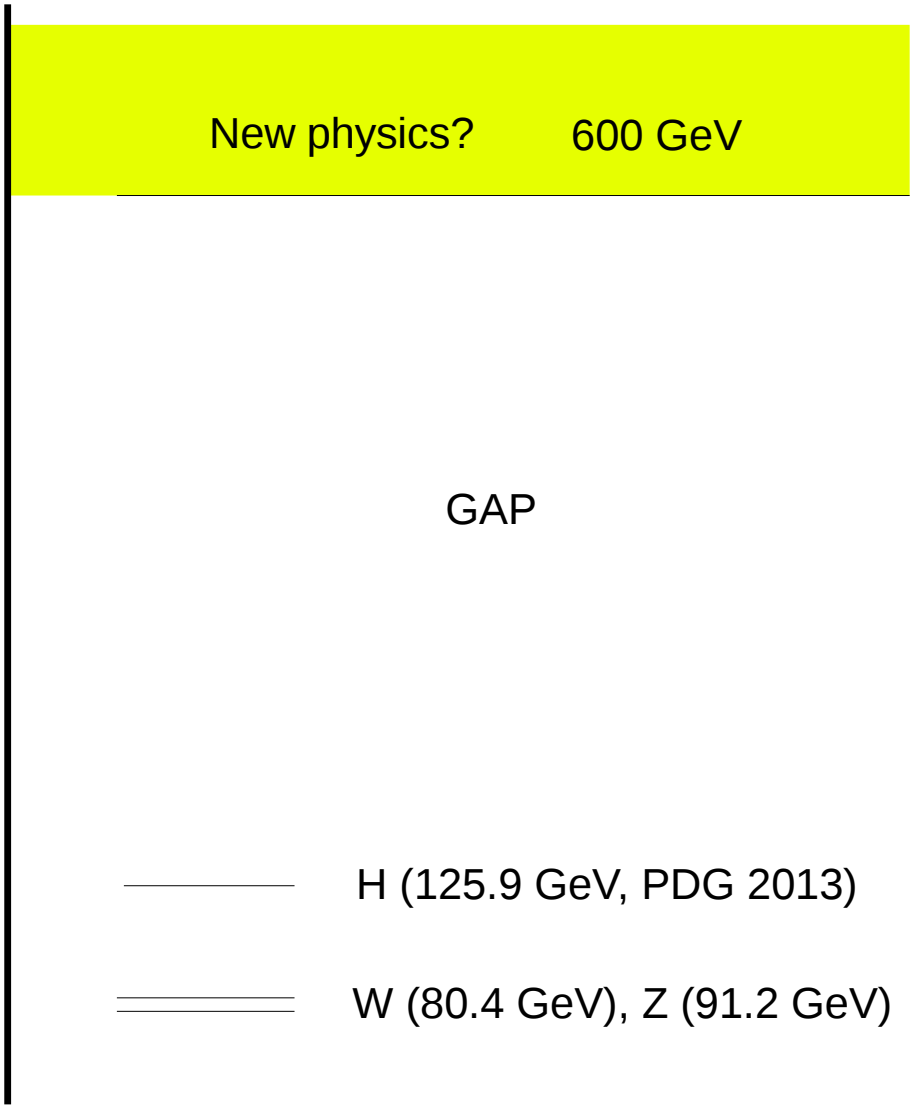

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One of the most uncharted and promising sectors in SM

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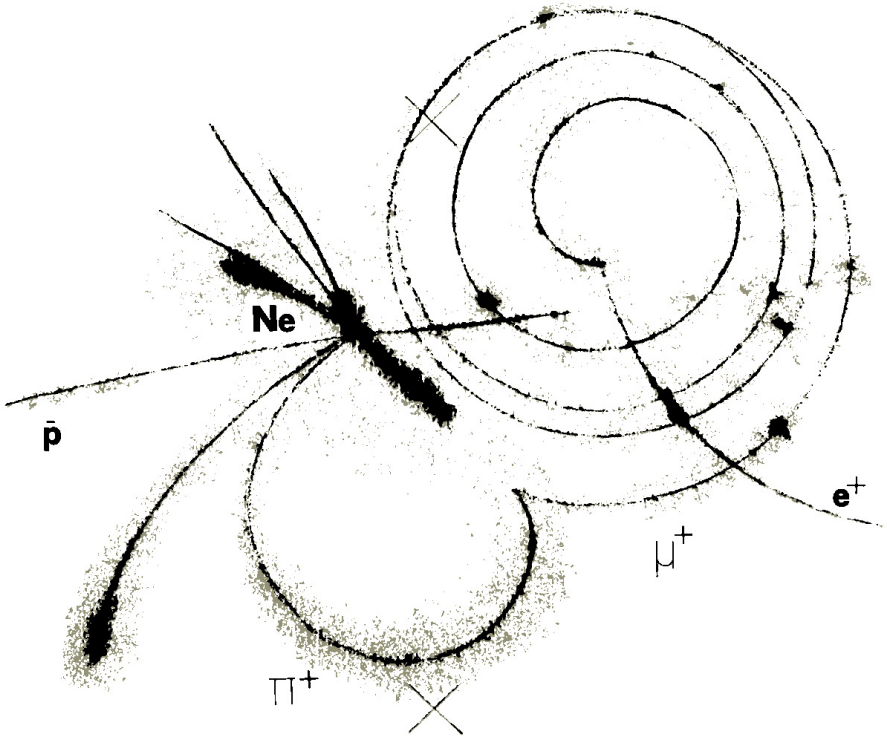
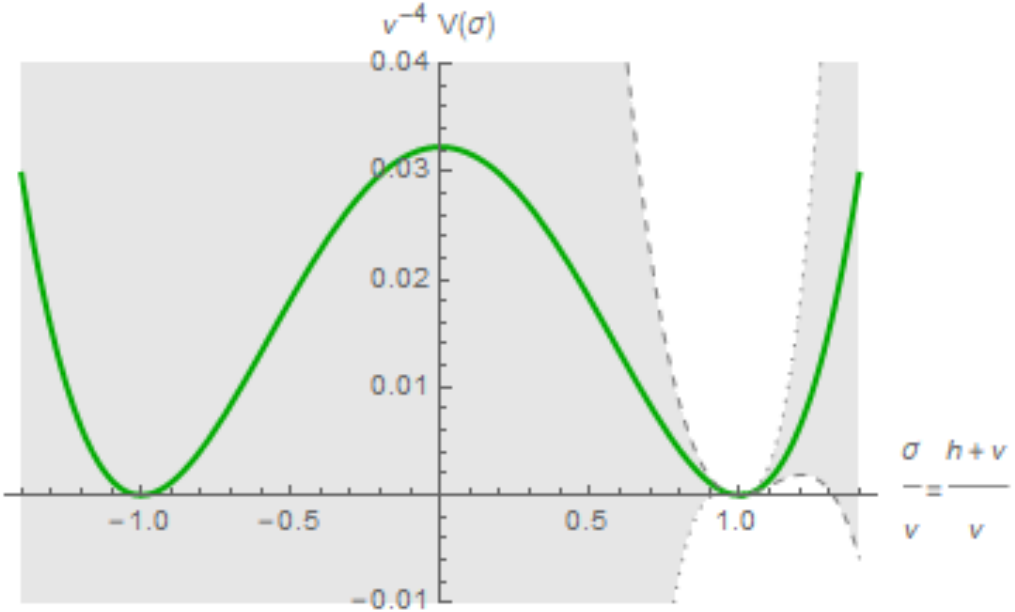
Could EW Goldstone bosons (ω_is) resemble a π (pion)?



The Electroweak Sector

One of the most uncharted and promising sectors in SM

- Nature of Higgs boson and EW gauge bosons? Composite or not?
- Measurable: Higgs self interaction and its coupling to electroweak gauge bosons.



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"Two" EW EFT candidates

- Standard Model Effective Field Theory (SMEFT)

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- Higgs Effective Field Theory (HEFT):

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- Higgs Effective Field Theory (HEFT):
  Chiral Lagrangian

$$\mathcal{L}_{\rm HEFT} = \frac{1}{2}\partial_\mu h \partial^\mu h - V(h) + \frac{1}{2}\mathcal{F}(h)\partial_\mu \omega^i \partial^\mu \omega^j \left(\delta_{ij} + \frac{\omega^i \omega^j}{v^2 - \omega^2}\right) \ .$$

Flare function
(coupling any number of h to ww)

The Electroweak Sector Extensions

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What is their relation?

SMEFT

- ω_a and h fit in a left-$SU(2)$ doublet
- Higgs always in the combination: $(h+v)$
- Higher symmetry
- Natural when h is a fundamental field
- ET usually based in a cutoff Λ expansion: $O(d)/\Lambda^{d-4}$ (d = operator dimension: 4,6,8 ...)

$$\mathcal{O}_H = (H^\dagger H)^3\,, \qquad \mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)\,,$$
$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,.$$

HEFT

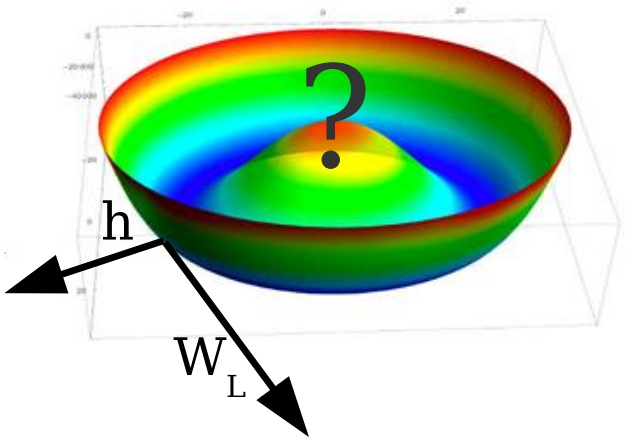
- h is a $SU(2)$ singlet and ω_a are coordinates on a coset: $SU(2)_L \times SU(2)_R / SU(2)_V \simeq SU(2) \simeq S3$
- Lesser symmetry; more independent higher-dimension effective operators but less model dependent
- Derivative expansion
- ECLh with $\mathcal{F}(h)$ insertions
- Typical for composite models of the SBS (h as a GB) (Strongly interacting and consistent with the presence of the GAP)

Dobado and Espriu, Prog.Part.Nucl.Phys. 115 (2020) 103813

$$SMEFT \subset HEFT$$

Geometric distinction HEFT/SMEFT

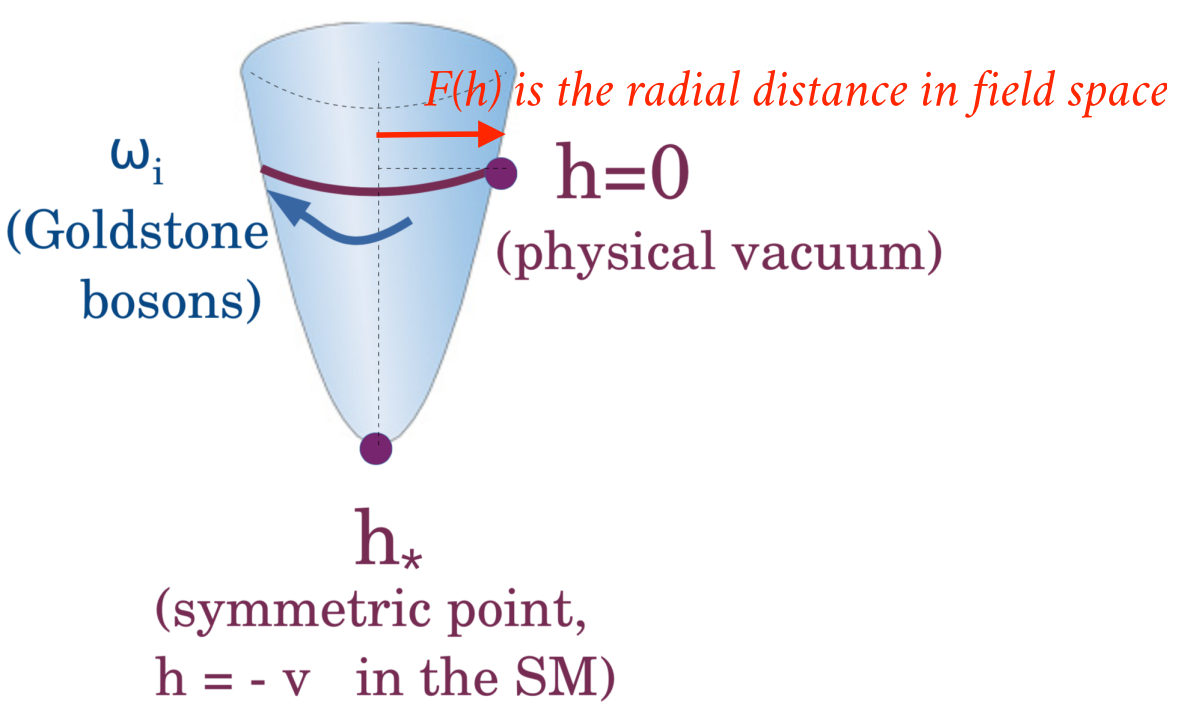
- Several works have provided field-redefinition invariant criteria to distinguish SMEFT from HEFT:
  - R. Alonso, E. E. Jenkins, and A. V. Manohar,
    "A Geometric Formulation of Higgs Effective Field Theory: Measuring the Curvature of Scalar Field Space," Phys. Lett. B754 (2016) 335–342, arXiv:1511.00724 [hep-ph].
    "Sigma Models with Negative Curvature," Phys.Lett.B756,358(2016),arXiv:1602.00706 [hep-ph].
    "Geometry of the Scalar Sector," JHEP 08 (2016) 101, arXiv:1605.03602 [hep-ph]."
    (Cohen et al., 2021, p. 95)
  - T. Cohen, N. Craig, X. Lu, and D. Sutherland:
    "Is SMEFT Enough?", JHEP 03, 237, arXiv:2008.08597 [hep-ph].
    "Unitarity Violation and the Geometry of Higgs EFTs",
    (2021), arXiv:2108.03240 [hep- ph].



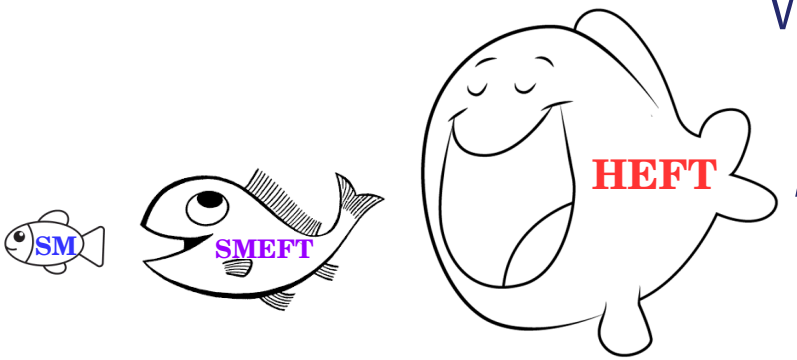
Geometric distinction HEFT/SMEFT

In a nutshell, SMEFT is valid provided:

- $\exists h_* \in \mathbb{R}$ where $\mathcal{F}(h_*) = 0$, and
- Because of the need for $\mathcal{L}_{\mathrm{SMEFT}}$ analyticity, $\mathcal{F}$ is analytic between our vacuum $h = 0$ and h_*, particularly around h_*. Moreover its odd derivatives vanish at symmetric point.
- Similar criteria for the potential $V(h)$.



Always possible to write a SMEFT as a HEFT



Writing SMEFT in HEFT form:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ (v + h_{\mathrm{SMEFT}}) + i\phi_3 \end{pmatrix} \quad \textit{SU(2) doublet}$$

$$\phi = (\phi_1, \phi_2, \phi_3, h + v) \quad \textit{O(4) fund. rep.}$$

Change to polar-like coordinates:

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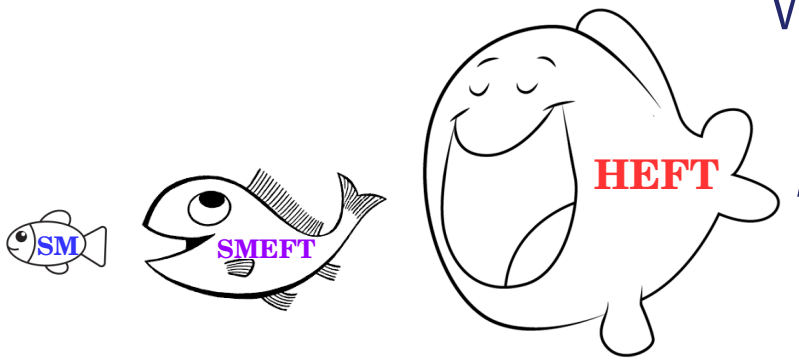

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$$\phi = (\phi_1, \phi_2, \phi_3, h + v)$$

Change to polar-like coordinates:

$$\phi = (1 + h/v)\boldsymbol{n} \quad \text{with } \boldsymbol{n} = (\omega_1, \omega_2, \omega_3, \sqrt{v^2 - \omega_1^2 - \omega_2^2 + \omega_3^2})$$

Generic SMEFT operators

$$\mathcal{L}_{\rm SMEFT} = A(|H|^2)|\partial H|^2 + \frac{1}{2}B(|H|^2)(\partial(|H|^2))^2 - V(|H|^2) + \mathcal{O}(\partial^4)$$

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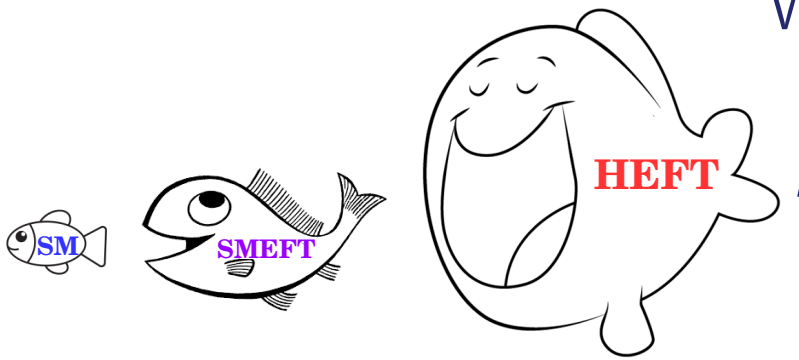

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In polar coordinates

$$\mathcal{L}_{\rm polar-SMEFT} = \frac{1}{2}(v+h)^2 A(h)(\partial_\mu \boldsymbol{n} \cdot \partial^\mu \boldsymbol{n}) + \frac{1}{2}\Big(A(h) + (v+h)^2 B(h)\Big)(\partial h)^2$$

Always possible to write a SMEFT as a HEFT

$$\mathcal{L}_{\text{polar}-\text{SMEFT}} = \frac{1}{2}(v+h)^2 A(h)(\partial_\mu \boldsymbol{n}\cdot\partial^\mu \boldsymbol{n}) + \frac{1}{2}\Big(A(h)+(v+h)^2 B(h)\Big)(\partial h)^2$$

$$L_{\text{LO HEFT}} = \frac{1}{2}\mathcal{F}(h)\partial_\mu \omega^i \partial^\mu \omega^j \left(\delta_{ij} + \frac{\omega^i \omega^j}{v^2 - \boldsymbol{\omega}^2}\right) + \frac{1}{2}\partial_\mu h \partial^\mu h$$

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Identification

Field redefinition

$$L_{\text{LO HEFT}} = \frac{1}{2}\mathcal{F}(h)\partial_\mu \omega^i \partial^\mu \omega^j \left(\delta_{ij} + \frac{\omega^i \omega^j}{v^2 - \boldsymbol{\omega}^2}\right) + \frac{1}{2}\partial_\mu h \partial^\mu h$$

Identify the Flare function and canonicalize higgs kinetic term and :

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Identify the Flare function and canonicalize higgs kinetic term and :

$$\mathcal{F}(h_{\text{HEFT}}) = \left(1 + \frac{h_{\text{SMEFT}}(h_{\text{HEFT}})}{v}\right)^2 A(h_{\text{SMEFT}})$$

$$\boxed{dh_{\text{HEFT}} = \sqrt{A(h_{\text{SMEFT}}) + (v + h_{\text{SMEFT}})^2 B(h_{\text{SMEFT}})}\; dh_{\text{SMEFT}}}$$

Always possible to find a HEFT from a given SMEFT

From HEFT to SMEFT

From HEFT to SMEFT one has to solve

$$h_{\mathrm{HEFT}} = \mathcal{F}^{-1}\left((1 + h_{\mathrm{SMEFT}}/v)^2\right)$$

and in order to have an analytic Lagrangian:

$$\mathcal{L}_{\mathrm{SMEFT}} = \underbrace{|\partial H|^2}_{=\mathcal{L}_{\mathrm{SM}}} + \underbrace{\frac{1}{2}\left[\frac{8|H|^2}{v^2}\left((\mathcal{F}^{-1})'\left(2|H|^2/v^2\right)\right)^2 - 1\right]\frac{(\partial|H|^2)^2}{2|H|^2}}_{=\Delta\mathcal{L}_{\mathrm{BSM}}} .$$

Possible non-analyticity

$\Rightarrow$ Provides conditions on the derivatives of the flare function $\mathcal{F}(h)$.

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⇒ Provides conditions on the derivatives of the flare function $\mathcal{F}(h)$.
⇒ Correlation of HEFT parameters by assuming an analytic SMEFT.

High energy measurements

At high energies (TeV region) only (D=6) derivative operators are relevant:

$$\mathcal{O}_H = (H^\dagger H)^3 \,, \qquad \mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H) \,,$$

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Subleading

$$\mathcal{O}_H = (H^\dagger H)^3\,, \qquad \mathcal{O}_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)\,,$$

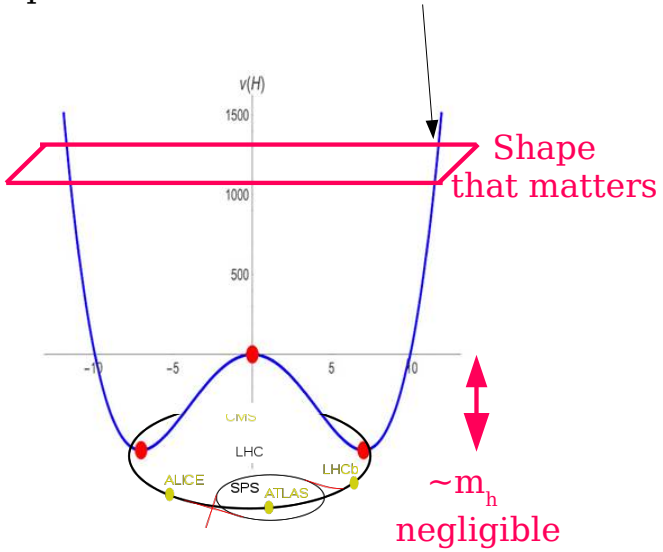
Custodial-violating

$$\mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H)\,.$$

$A(H)$ can be set to 1

Relevant Operator

TeV parton-level collisions sit here



$\Rightarrow$ Cleaner measurement of the Flare function $\mathcal{F}$ at high energies.

SMEFT to HEFT relevant at High energies

Relevant SMEFT at the TeV scale:

$$\mathcal{L}_{\mathrm{SMEFT}} = |\partial H|^2 + \frac{c_{H\Box}}{\Lambda^2}(H^\dagger H)\Box(H^\dagger H)$$

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To polar-like coordinates:

$$\mathcal{L}_{\mathrm{SMEFT}} = \frac{1}{2}\left(1 - 2(v+h)^2\frac{c_{H\Box}}{\Lambda^2}\right)(\partial_\mu h)^2 + \frac{1}{2}(v+h)^2(\partial_\mu \boldsymbol{n}\cdot\partial^\mu \boldsymbol{n})\ .$$

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Canonical Higgs kinetic term by solving:

$$h_{\rm HEFT} = \int_0^h \sqrt{1-(v+t)^2\frac{2c_{H\Box}}{\Lambda^2}}\,dt$$

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Yields:

$$h = h_{\mathrm{HEFT}} + \frac{1}{3}\Big(\frac{c_{H\Box}}{\Lambda^2}\Big)(h_{\mathrm{HEFT}}^3 + 3h_{\mathrm{HEFT}}^2 v + 3h_{\mathrm{HEFT}}v^2) + \mathcal{O}\Big(\frac{c_{H\Box}^2}{\Lambda^4}\Big)\ .$$

Correlations on the Flare function coefficients

The HEFT function coupling Higgses to the GB kinetic term becomes correlated:

Correlated coefficients

$$\mathcal{F}(h_{\rm HEFT}) = 1 + \left(\frac{h_{\rm HEFT}}{v}\right)\left(2 + 2\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h_{\rm HEFT}}{v}\right)^2\left(1 + 4\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h_{\rm HEFT}}{v}\right)^3\left(8\frac{c_{H\Box}v^2}{3\Lambda^2}\right) + \left(\frac{h_{\rm HEFT}}{v}\right)^4\left(2\frac{c_{H\Box}v^2}{3\Lambda^2}\right).$$

Whereas in a general HEFT:

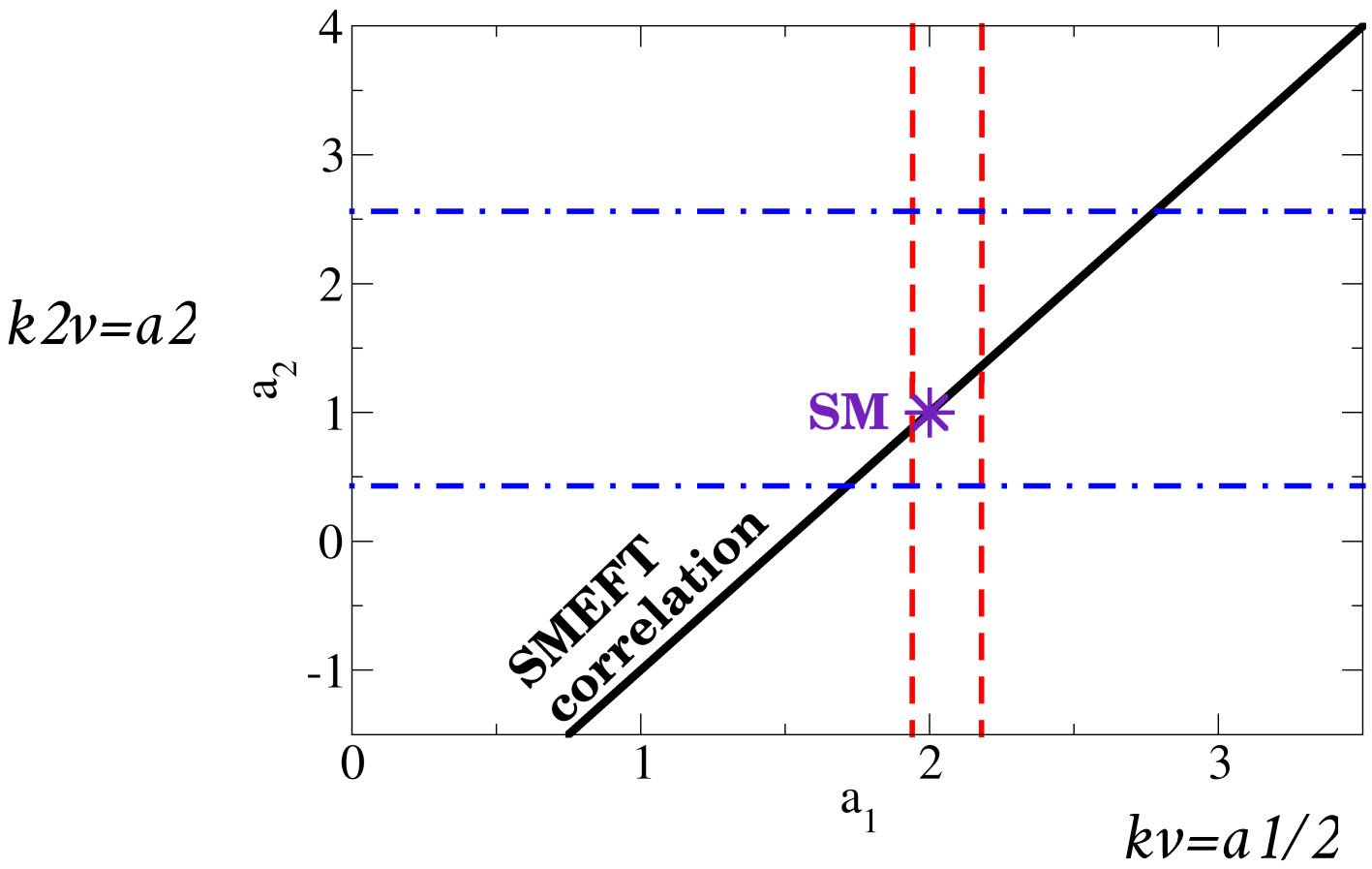
Uncorrelated coefficients

$$\mathcal{F}(h_{\rm HEFT}) = 1 + \sum_{n=1}^{\infty} a_n \left(\frac{h_{\rm HEFT}}{v}\right)^n.$$

SMEFT assumption ⇒ HEFT parameters correlation

Correlations among HEFT parameters due to SMEFT structure:

(Bands from single Higgs production at ATLAS (ATLAS-CONF-2020-027) and Higgs Pair production at CMS https://arxiv.org/abs/2202.09617)



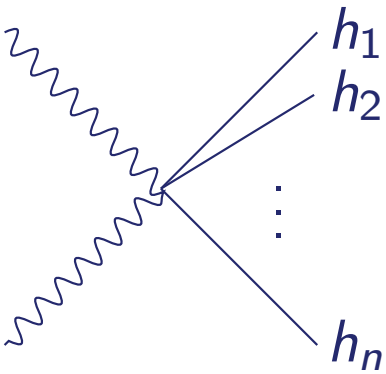
Measurements

High energy measurements

In this region the potential is subleading. The flare function $\mathcal{F}$ encodes relevant physics (it accompanies the GB kinetic term)

$$\mathcal{F}(h_{\mathrm{HEFT}}) = 1 + \sum_{n=1}^{\infty} a_n \left(\frac{h_{\mathrm{HEFT}}}{v}\right)^n .$$

At high energies (Equivalence Theorem) $\omega \simeq W_L$
$\Rightarrow \omega\omega \to n \times h$ can falsify SMEFT.



$$= -\frac{n!\, a_n}{2v^n}\, s$$

Measure $\mathcal{F}$ expansion in multiHiggs final states

$$T_{\omega\omega\to h} = -\frac{a_1 s}{2v}$$

$$T_{\omega\omega\to hh} = \frac{s}{v^2}\left(\frac{a_1^2}{4} - a_2\right),$$

Linear in the highest parameter

$$\begin{aligned}
T_{\omega\omega\to hhh} &= -\frac{s}{8v^3}\Bigg(a_1^3\Big[4f_1 f_3^2\left(\frac{z_{23}(f_1 z_{23}-1)}{f_3(z_3-2f_1 z_{23})+f_2 z_2}+\frac{z_{13}(f_1 z_{13}-1)}{f_1(z_1-2f_3 z_{13})+f_3 z_3}\right)+\\
&+2f_3\left(f_1\left(\frac{z_{23}-2f_2 z_{23}}{-2f_1 f_3 z_{23}+f_2 z_2+f_3 z_3}+\frac{z_{13}-2f_1 z_{13}}{-2f_1 f_3 z_{13}+f_1 z_1+f_3 z_3}+z_{13}+z_{23}\right)+3(z_3-2)\right)+\\
&+\frac{2f_1 f_2 z_{12}(2f_1(f_2 z_{12}-1)-2f_2+1)}{f_1(z_1-2f_2 z_{12})+f_2 z_2}+2f_1(f_2 z_{12}+3z_1-6)+6f_2 z_2-12f_2+9\Big]+\\
&+4a_1 a_2\Big[\frac{f_1^2\left(2z_1(-2f_2 z_{12}+f_3(z_{13}+z_{23})-3)-4f_2 z_{12}(f_3(z_{13}+z_{23})-2)+3z_1^2\right)}{2f_1 f_2 z_{12}-f_1 z_1-f_2 z_2}+\\
&+\frac{2f_1 f_2(-2f_2 z_{12}(z_2+1)+z_2(f_3(z_{13}+z_{23})+3z_1-3)+z_{12})+3f_2^2 z_2^2}{2f_1 f_2 z_{12}-f_1 z_1-f_2 z_2}+6(f_2+f_3-1)-\\
&-\frac{2f_1 f_3 z_{23}(2f_3(f_1 z_{23}-1)-2f_2+1)}{f_3(z_3-2f_1 z_{23})+f_2 z_2}-\frac{2f_1 f_3 z_{13}(2f_1(f_3 z_{13}-1)-2f_3+1)}{f_1(z_1-2f_3 z_{13})+f_3 z_3}-3f_3 z_3\Big]+24a_3\Bigg).
\end{aligned}$$

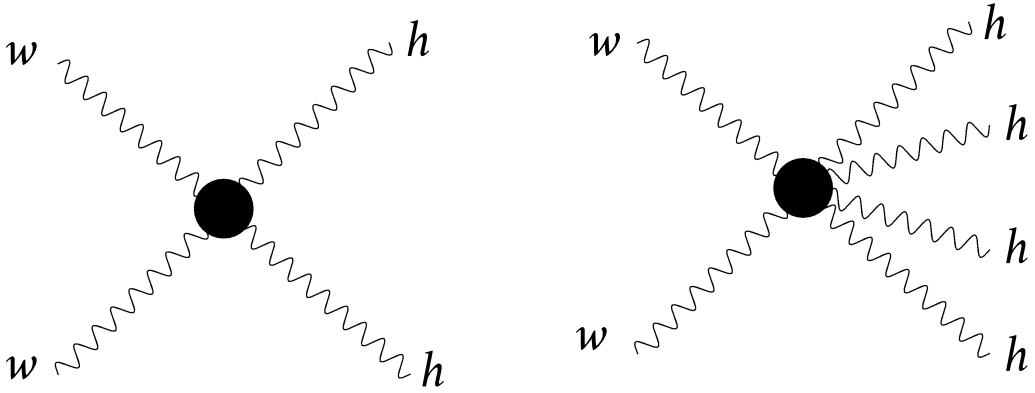
($f_i \equiv ||\vec{p}_i||/\sqrt{s}$; $z_i(\omega_1, h_i) \equiv 2\sin^2(\theta_i/2)$; $z_{ij}(h_i, h_j) \equiv 2\sin^2(\theta_{ij}/2)$) We provide all tree level amplitudes.

SMEFT Cross Sections

At the TeV-scale, linear-dimension-6 SMEFT predicts:

$$\boxed{\frac{\sigma(\omega\omega \to nh)}{\sigma(\omega\omega \to mh)} = \text{ independent of } \; c_{H\Box}} \; .$$

$\Rightarrow$ Violation of this would shed doubts on SMEFT validity.



Conclusions

- SMEFT is a special case of HEFT.
- SMEFT is falsifiable studying correlations induced in HEFT parameters.
- TeV-scale measurements of $W_L W_L \to n \times H$ are needed to assess if SMEFT is applicable.