# 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* ⊂ *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.

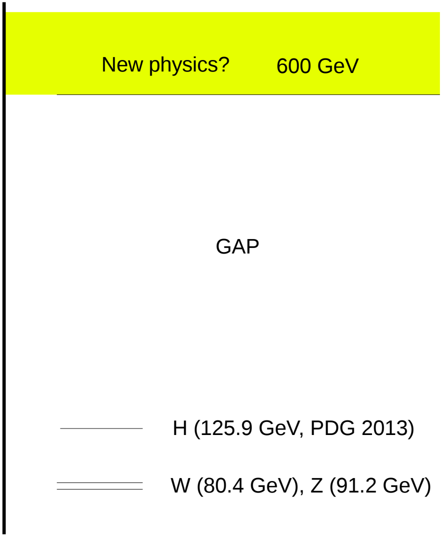
**Based on *"The flair of Higgsflare"***
https://arxiv.org/abs/2204.01763.

# 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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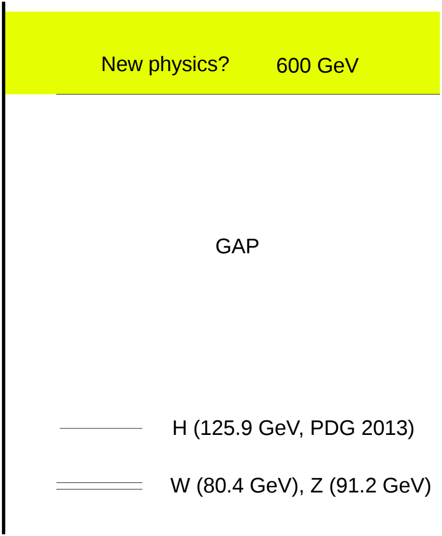

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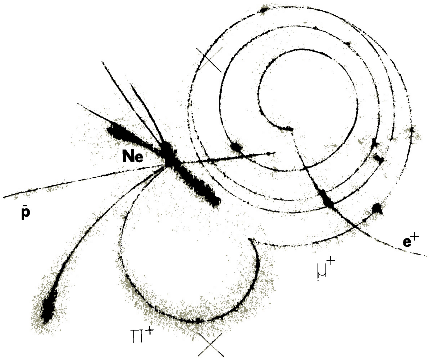
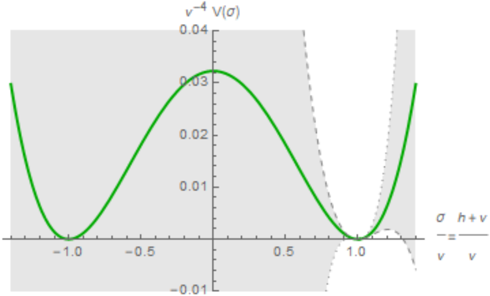
Could EW Goldstone bosons ($\omega_i$s) resemble a $\pi$ (pion)?



# 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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- Higgs Effective Field Theory (HEFT):
  Chiral Lagrangian

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

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What is their relation?

# SMEFT

- $\omega_a$ 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 $\Lambda$ 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

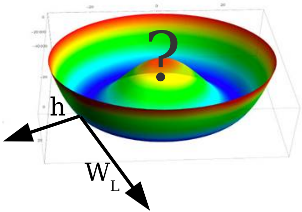
- $h$ is a $SU(2)$ singlet and $\omega_a$ are coordinates on a coset: $SU(2)_L \times SU(2)_R/SU(2)_V \simeq SU(2) \simeq S3$
- Lesser symmetry; more independent higher-dimension effective operators but less model dependent
- Derivative expansion
- ECLh with $\mathcal{F}(h)$ insertions
- Typical for 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

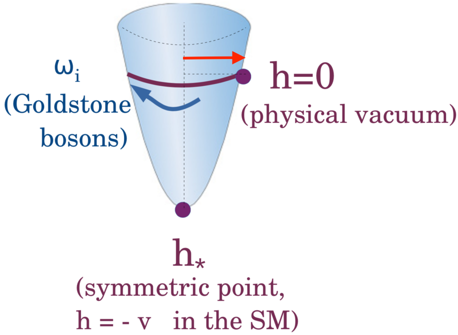
- Several works have provided field-redefinition invariant criteria to distinguish SMEFT from HEFT:
  - R. Alonso, E. E. Jenkins, and A. V. Manohar,
    "A Geometric Formulation of Higgs Effective Field Theory: Measuring the Curvature of Scalar Field Space," Phys. Lett. B754 (2016) 335–342, arXiv:1511.00724 [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].



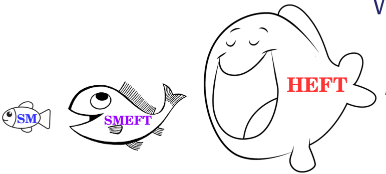
# Geometric distinction HEFT/SMEFT

In a nutshell, SMEFT is valid provided:

- $\exists h_* \in \mathbb{R}$ where $\mathcal{F}(h_*) = 0$, and
- Because of the need for $\mathcal{L}_{\rm SMEFT}$ 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:

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

$$\phi = (\phi_1, \phi_2, \phi_3, h + v)$$ *O(4) fund. rep.*

Change to polar-like coordinates:

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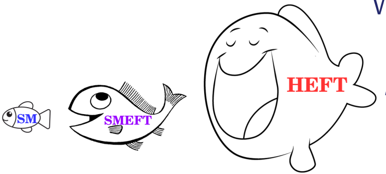


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Change to polar-like coordinates:

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

*Generic SMEFT operators*

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

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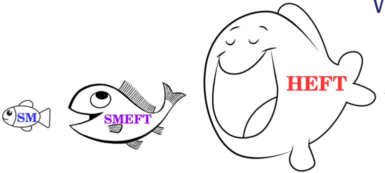


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↓

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

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

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Identify the Flare function and canonicalize higgs kinetic term and :

# Always possible to write a SMEFT as a HEFT

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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

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

and in order to have an analytic Lagrangian:

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

*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

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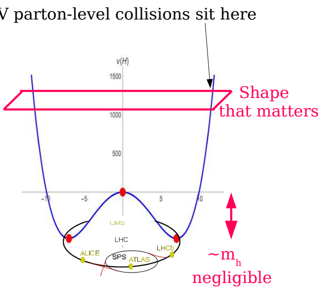
Custodial-violating

$A(H)$ can be set to 1

Relevant Ope




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

# SMEFT to HEFT relevant at High energies

Relevant SMEFT at the TeV scale:

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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:

$$h = h_{\rm HEFT} + \frac{1}{3}\left(\frac{c_{H\Box}}{\Lambda^2}\right)(h^3_{\rm HEFT} + 3h^2_{\rm HEFT}v + 3h_{\rm HEFT}v^2) + \mathcal{O}\left(\frac{c^2_{H\Box}}{\Lambda^4}\right) \, .$$

# Correlations on the Flare function coefficients

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

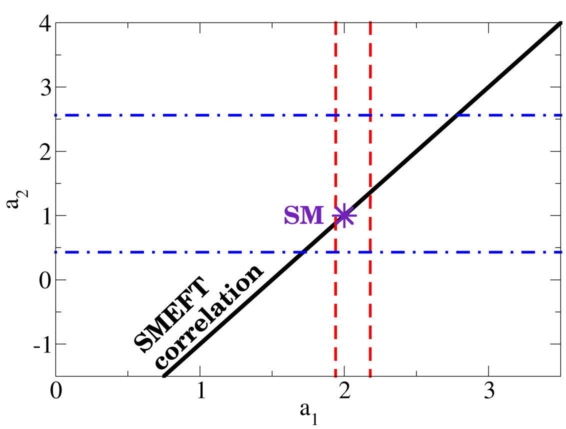
$$\mathcal{F}(h_{\rm HEFT}) =$$
$$1 + \left(\frac{h_{\rm HEFT}}{v}\right)\left(2 + 2\frac{c_{H\Box}v^2}{\Lambda^2}\right) + \left(\frac{h_{\rm HEFT}}{v}\right)^2\left(1 + 4\frac{c_{H\Box}v^2}{\Lambda^2}\right) +$$
$$+ \left(\frac{h_{\rm HEFT}}{v}\right)^3\left(8\frac{c_{H\Box}v^2}{3\Lambda^2}\right)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

Whereas in a general HEFT:

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

# 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`)



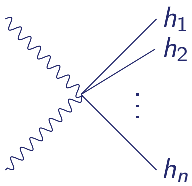
# Measurements

## High energy measurements

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

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

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

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

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

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

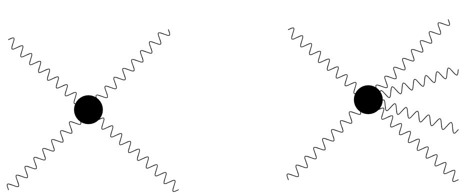
($f_i \equiv ||\vec{p}_i||/\sqrt{s}$; $z_i(\omega_1, h_i) \equiv 2\sin^2(\theta_i/2)$; $z_{ij}(h_i, h_j) \equiv 2\sin^2(\theta_{ij}/2)$) We provide all tree level amplitudes.

# 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.