SMEFT is falsifiable through multi-Higgs measurements (even in the absence of new light particles)

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Based on 2207.09848

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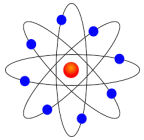
XVth Quark Confinement and the Hadron Spectrum Conference

And the Higgs was found...

- Explained the size of the atom and of all beautiful things

$$\frac{1}{\lambda_e v_{\text{Higgs}}} \propto \frac{1}{m_e} \propto a_{\text{Bohr}}$$



Bohr radius
gives us scale

This talk is about the EW-SBS sector of particle physics

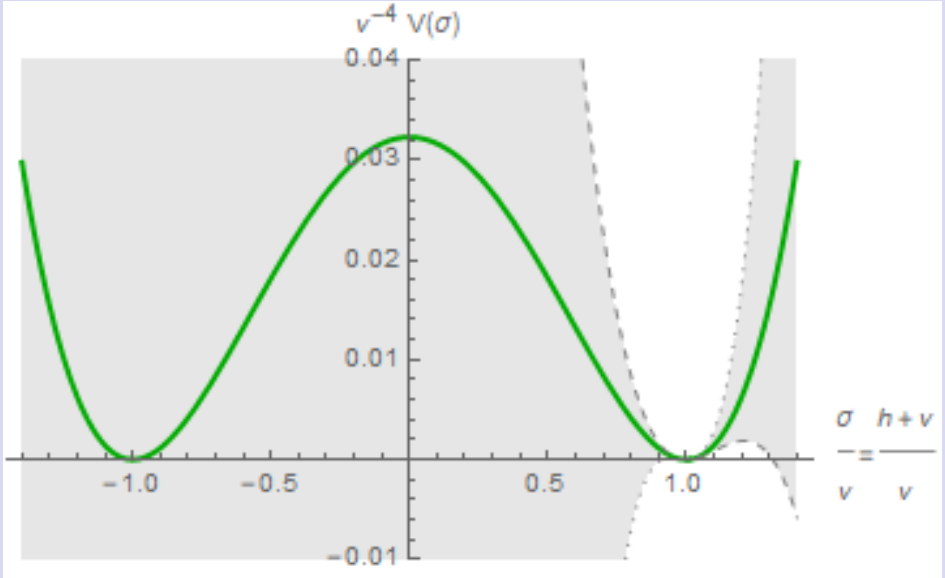
$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ (v + h) + i\omega_3 \end{pmatrix}$$

$H \to h,\ W_L \sim \omega,\ Z_L \sim z$ (Equivalence Theorem)

$$\mathcal{L}_{SM} = (D_\mu H)^\dagger D^\mu H - \underbrace{\lambda (H^\dagger H)^2 - \mu^2 H^\dagger H}_{V(H)}$$

Higgs self-couplings and couplings to Goldstone bosons

Status of Higgs potential

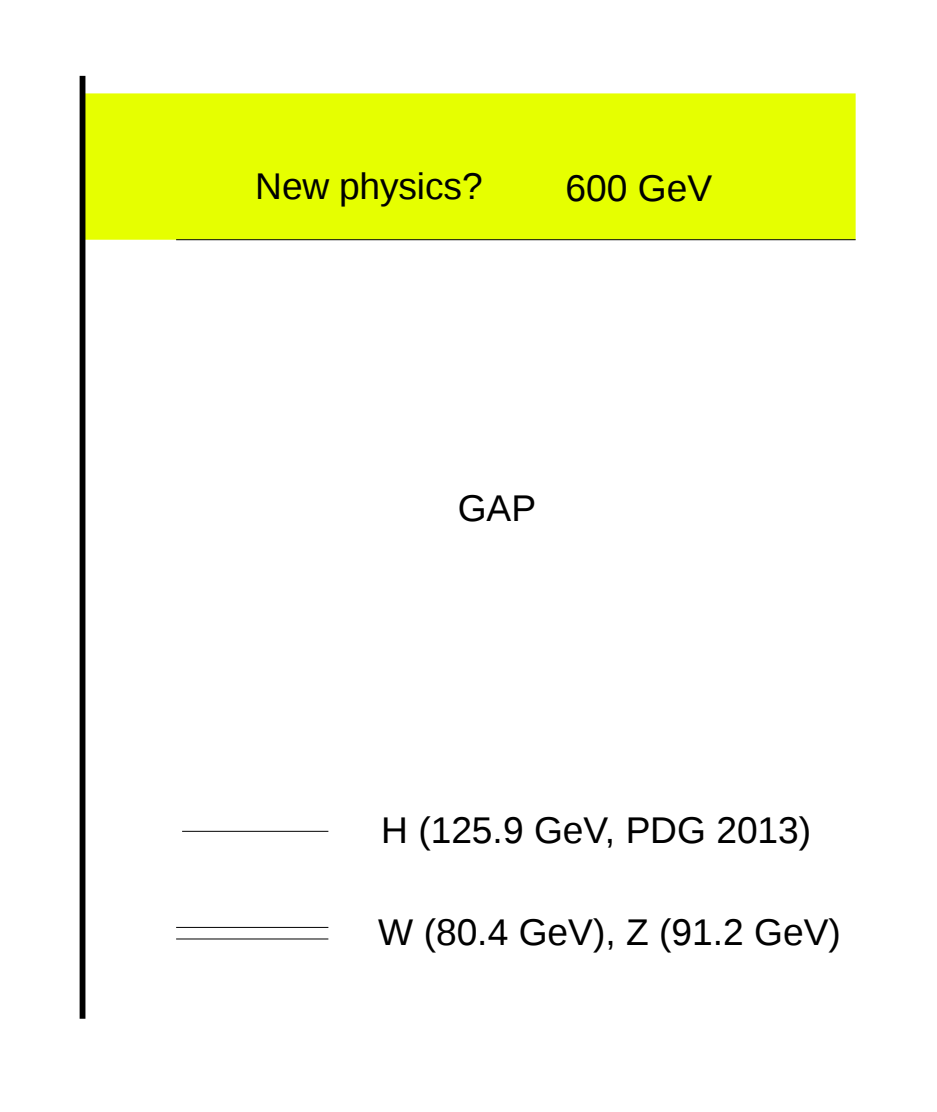


(taken from J.J.Sanz-Cillero)

Mass Gap to any new physics $\Longrightarrow$ EFT

Falsifying the SM:

- Discover new particles, or
- Discover new forces



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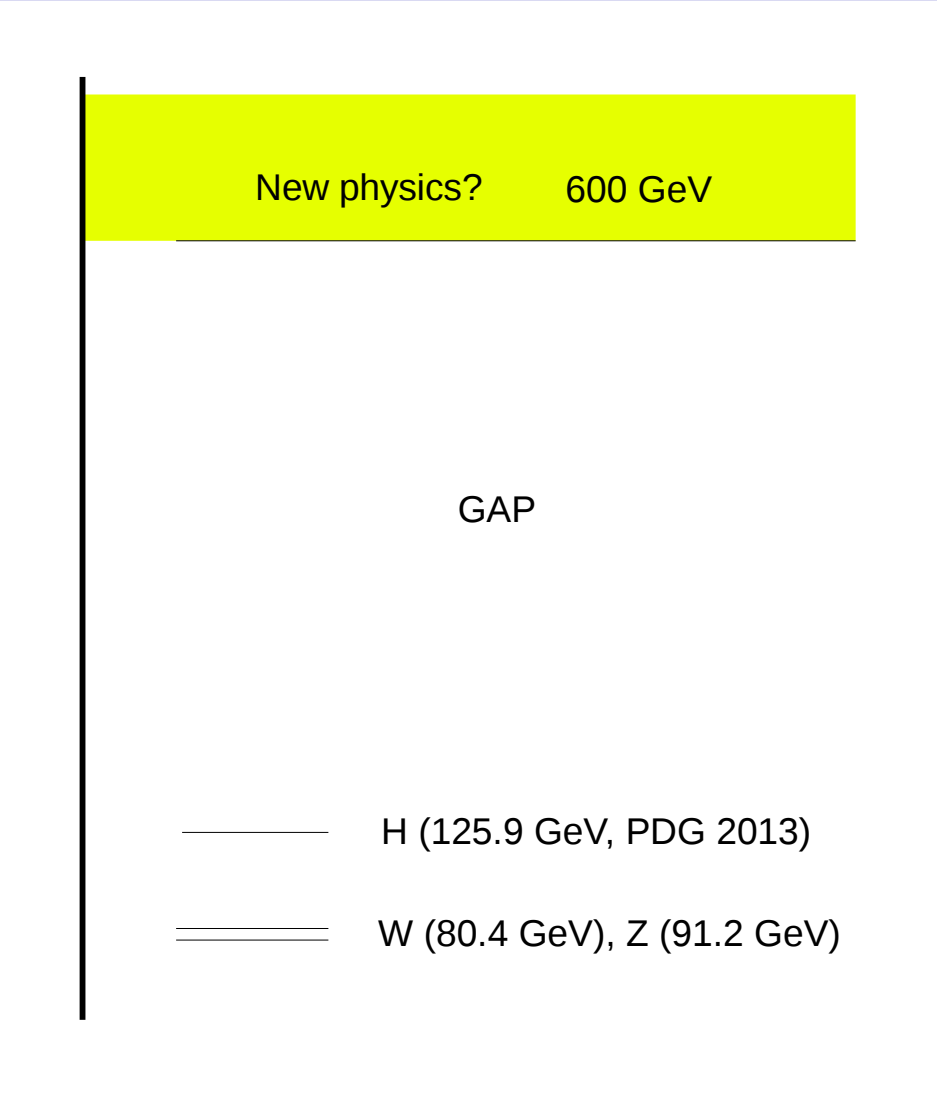
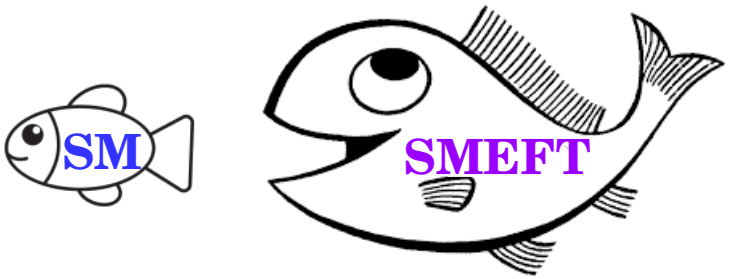


Two formulations, SMEFT & HEFT

SMEFT extension



$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ (v+h) + i\omega_3 \end{pmatrix}$$

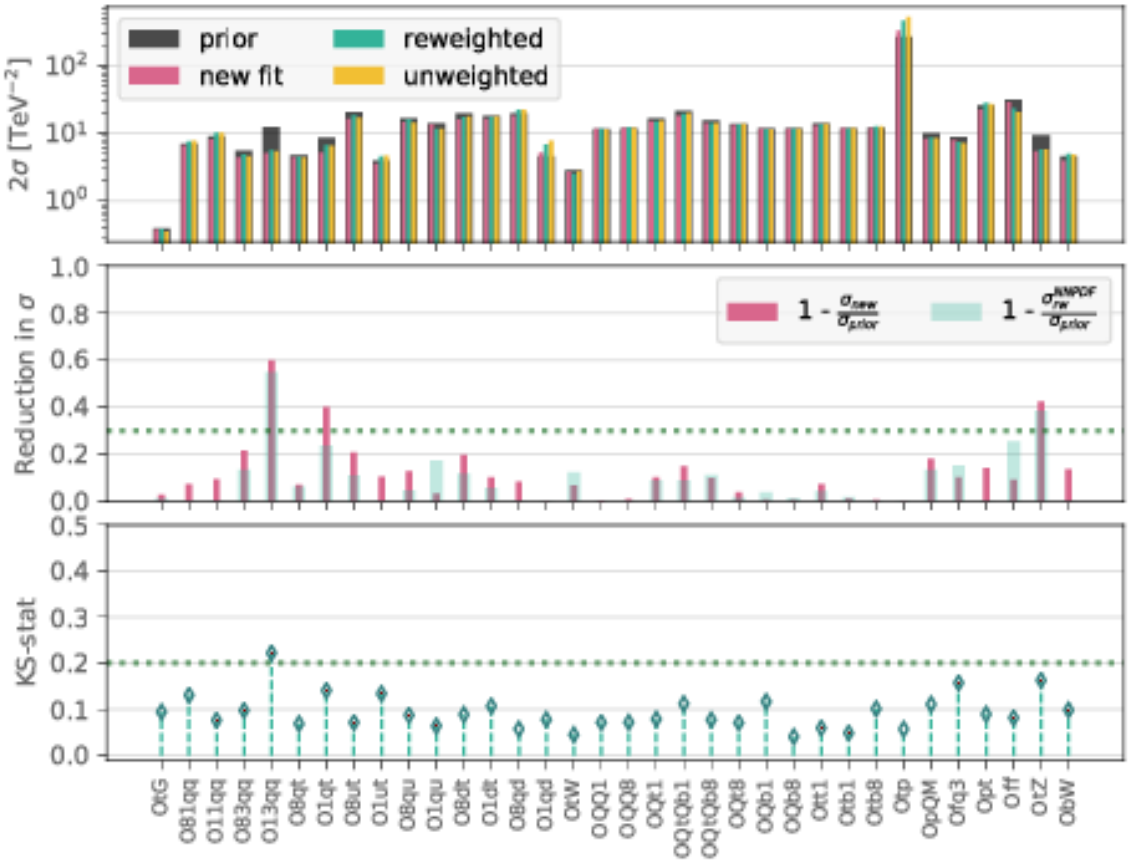
$$\mathcal{L}_{\rm SMEFT} = |\partial H|^2 - V(|H|^2) + \frac{1}{2} B(|H|^2)(\partial(|H|^2))^2 + \ldots$$

Linear representation: (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 ...)

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

Efforts to constrain SMEFT coefficients ongoing



Beek, Nocera, Rojo, Slade, SciPost Phys. **7** (2019) 5, 070

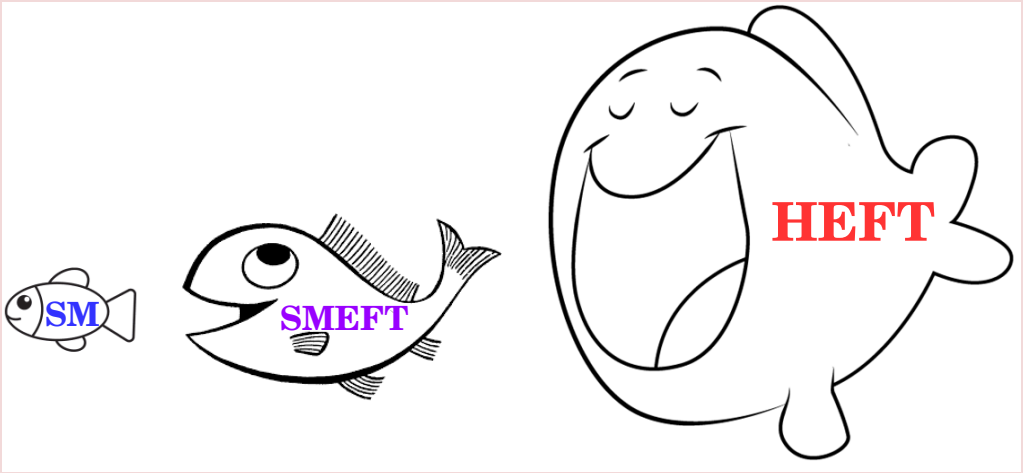
Strategy 1: "No stone left unturned", constrain them all.

Minimization suited for Artificial Intelligence

Falsifying a theory

- SM falsified by a nonzero SMEFT Wilson coefficient
- But after that, how do you falsify SMEFT itself?

HEFT extension



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

Non-linear representation: (HEFT)

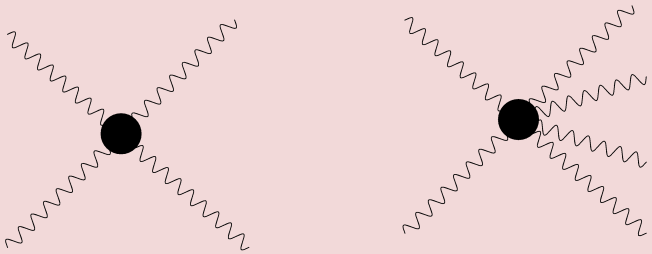
- h is a $SU(2)$ singlet and ω_a are coordinates on a coset: $SU(2)_L \times SU(2)_R / SU(2)_V \simeq SU(2) \simeq S3$
- Lesser symmetry; more independent higher-dimension effective operators but less model dependent
- Derivative expansion
- ECLh with $\mathcal{F}(h)$ insertions
- Typical for composite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

Cosmetic SMEFT-HEFT difference: Counting organization

- SMEFT by canonical dimension (independently of $N_{\rm loops}$)
- HEFT by number of derivatives (independently of $N_{\rm particles}$)

Example 1



(same order in HEFT, but not in SMEFT)

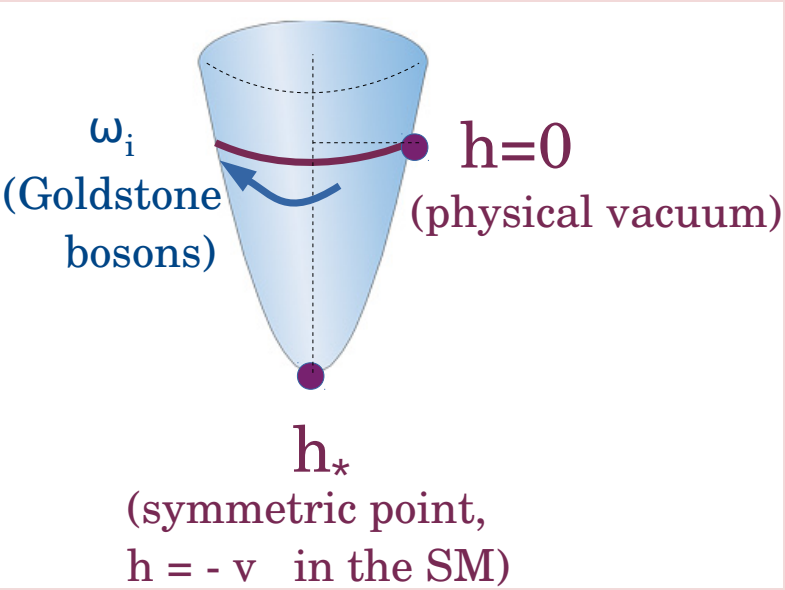
Example 2

$W_L W_L \partial^4 W_L W_L$

- NLO in HEFT (consider immediately after the SM $W_L \partial^2 W_L$)
- Dim. 8 In SMEFT (consider after Dim. 6 operators worked out)

When SMEFT exists

- But change coordinates like Cartesian to Spherical ones
- Use coordinate-independent approach (San Diego)

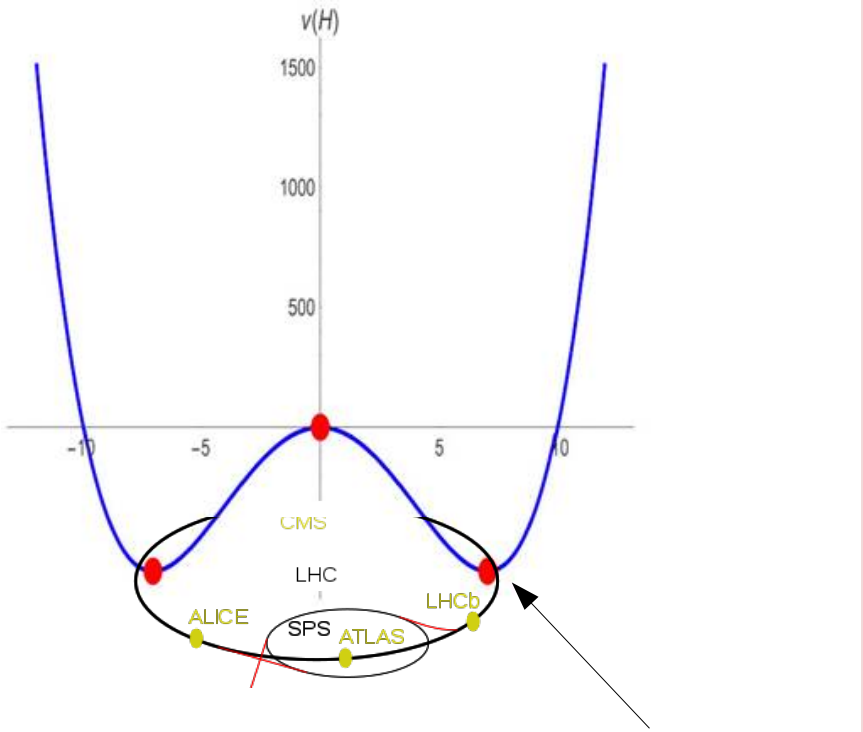


$$\mathcal{F}(h) = 1 + \sum_{n=1}^{\infty} a_n \left(\frac{h}{v}\right)^n$$

gives the radial "scale"

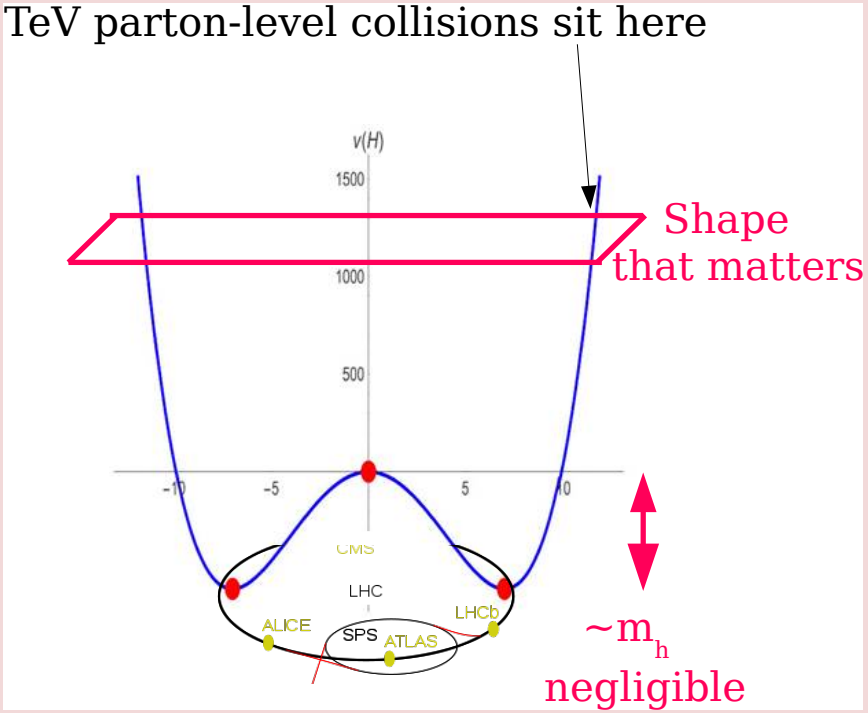
(think of $a(t)$ in a FRW cosmology)

Beyond the Higgs potential: flare function $\mathcal{F}$



The LHC sits here

If there is new physics



$$m_h \sim m_W \sim m_Z \ll \sqrt{s}$$

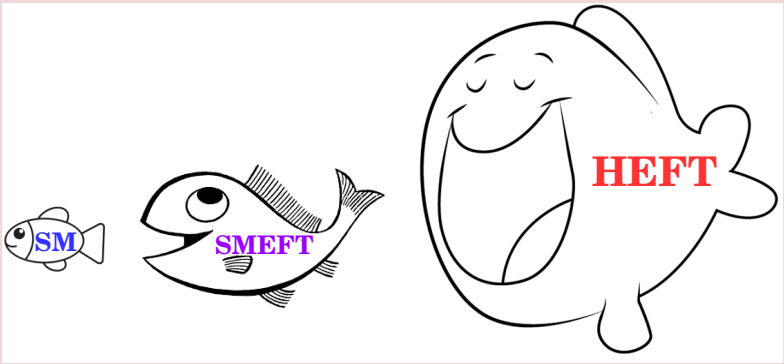
$$\Longrightarrow \quad V(h)_{\mathrm{SM-like}} \ll \sqrt{s}$$

$\mathcal{F}(h)$ multiplying Goldstone kinetic term wins at high E

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}\boxed{\left(1+2a\frac{h}{v}+b\left(\frac{h}{v}\right)^2\right)}\partial_\mu\omega^a\partial^\mu\omega^b\left(\delta_{ab}+\frac{\omega^a\omega^b}{v^2}\right)\\
&+ \frac{4a_4}{v^4}\partial_\mu\omega^a\partial_\nu\omega^a\partial^\mu\omega^b\partial^\nu\omega^b+\frac{4a_5}{v^4}\partial_\mu\omega^a\partial^\mu\omega^a\partial_\nu\omega^b\partial^\nu\omega^b\\
&+ \frac{1}{2}\partial_\mu h\partial^\mu h+\frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2\\
&+ \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^a\partial^\nu\omega^a+\frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^a\partial_\nu\omega^a.
\end{aligned}
$$

R. L. Delgado, A. Dobado and FJLE, PRD **91**, 075017 2015

Zero of $\mathcal{F}$ without geometry



Writing SMEFT in HEFT form:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ (v + h_{\rm SMEFT}) + i\omega_3 \end{pmatrix}$$

$$\frac{1}{2} B(|H|^2)(\partial(|H|^2))^2 \to$$

$$\frac{v^2}{4} \mathcal{F}(h_{\rm HEFT}) \langle D_\mu U^\dagger D^\mu U \rangle + \frac{1}{2}(\partial h_{\rm HEFT})^2$$

$$\boxed{dh_{\rm HEFT} = \sqrt{1 + (v + h_{\rm SMEFT})^2 B(h_{\rm SMEFT})}\; dh_{\rm SMEFT}}$$

Always possible to find a HEFT corresponding to a given SMEFT

Zero of $\mathcal{F}$ without geometry

Inverse not guaranteed, so HEFT more general ($\mathcal{F} := F^2$):

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

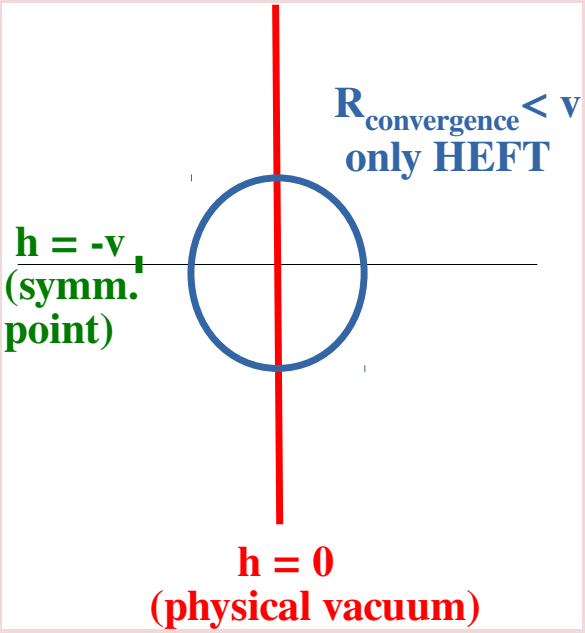
$$\begin{aligned} |H|^2 &= \frac{(v+h)^2}{2}\,, \\ (\partial|H|^2)^2 &= (v+h)^2\,(\partial h)^2 = 2|H|^2\,(\partial h)^2\,. \end{aligned}$$

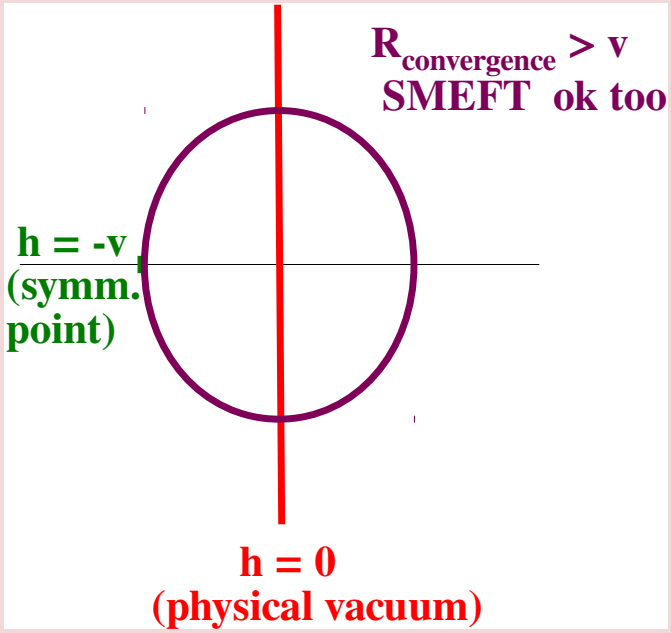
$$\mathcal{L}_{\rm SMEFT} = \underbrace{|\partial H|^2}_{=\mathcal{L}_{SM}} + \underbrace{\frac{1}{2}\left[\left(\frac{1}{v}(F^{-1})'[\sqrt{2|H|^2/v^2}]\right)^2 - 1\right]\frac{(\partial|H|^2)^2}{2|H|^2}}_{=\Delta\mathcal{L}_{BSM}}\,.$$

To guarantee the SMEFT expansion:

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum_{n=5}^{\infty} \sum_{i} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}(H)$$

Convergence of $\mathcal{F}(h)$ expansion in h field space





Problem: for now we have only the first one or two terms

San Diego criterion: symmetric point under custodial group

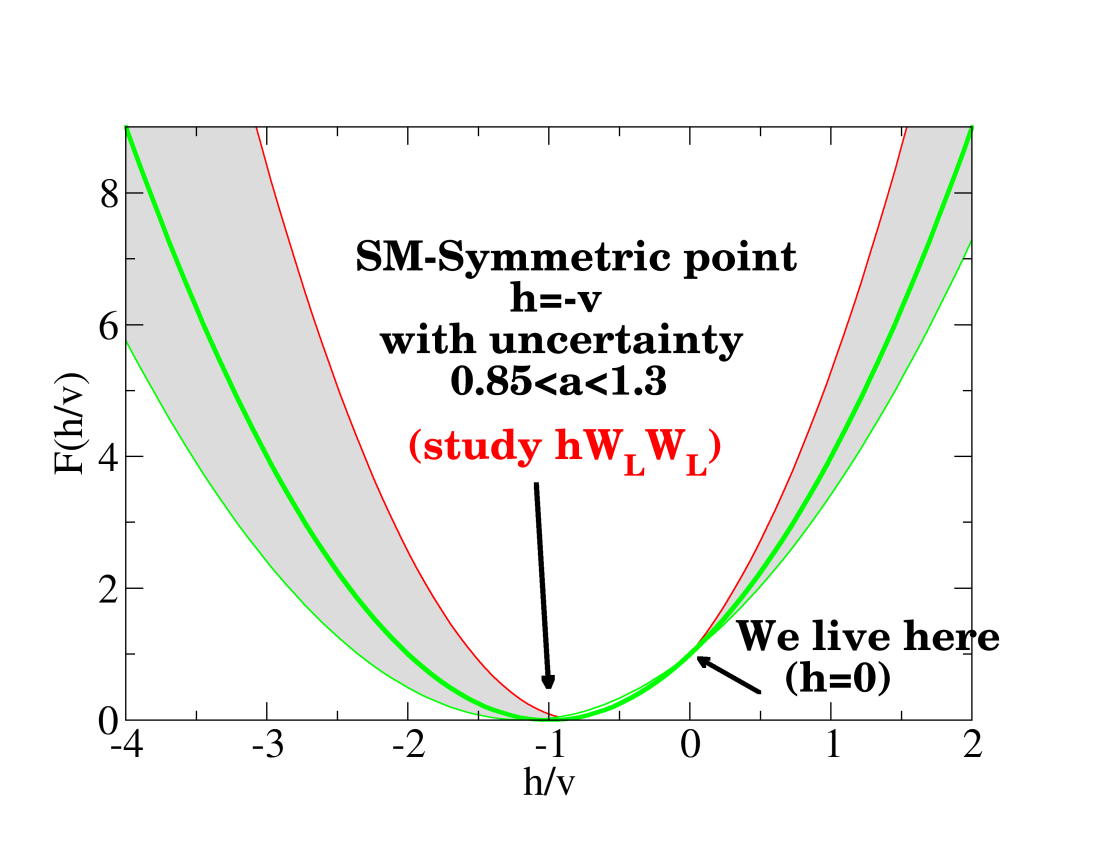
SMEFT is deployable if and only if
(statement about the HEFT Lagrangian)

- $\exists h^*$ where $\mathcal{F}(h^*) = 0$, and
- $\mathcal{F}$ is analytic between our vacuum $h = 0$ and h^*.
  All odd derivatives of $\mathcal{F}$ must vanish!

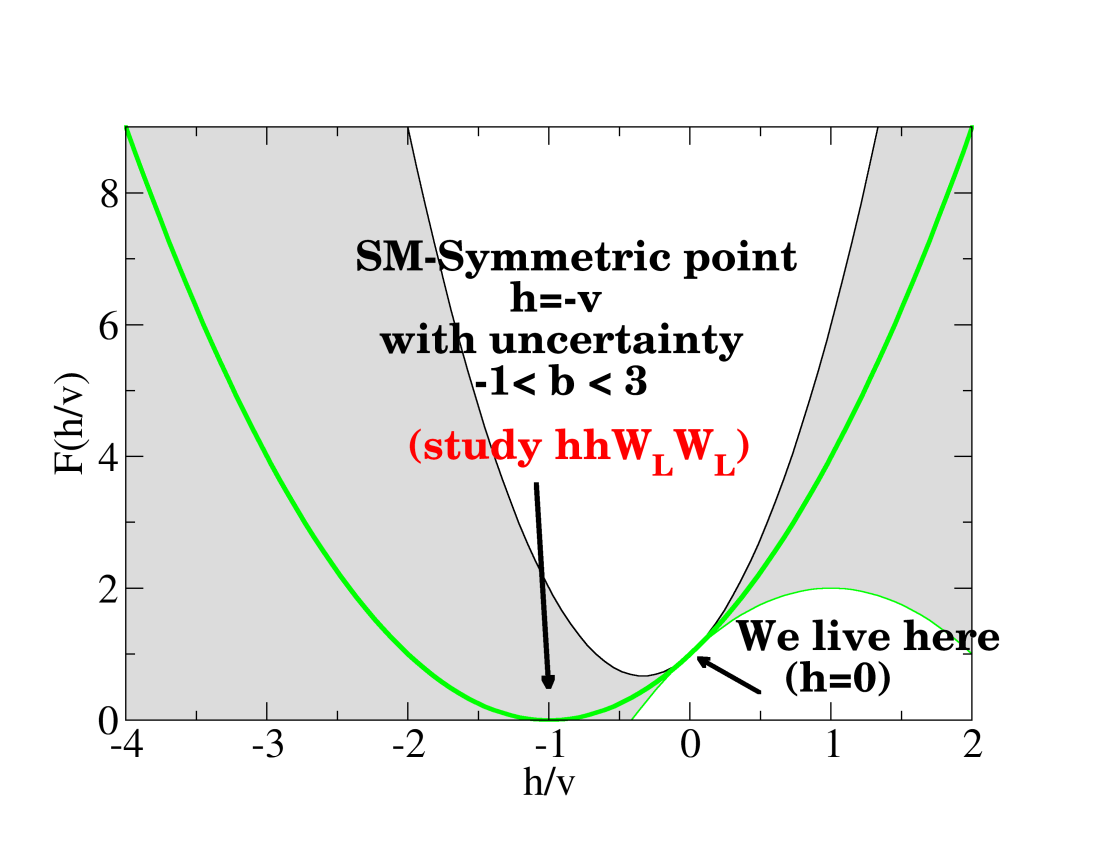
Note: The SM has just such point, $h = -v$ ($H = 0$), where $\mathcal{F} = (1 + h/v)^2 = 0$

Alonso, Jenkins, Manohar JHEP **08** (2016) 101
Dobado, Espriu Prog.Part.Nucl.Phys. **115** (2020) 103813
Cohen, Craig, Lu, Sutherland JHEP **03** (2021) 237

Current status: vary *a* from 1

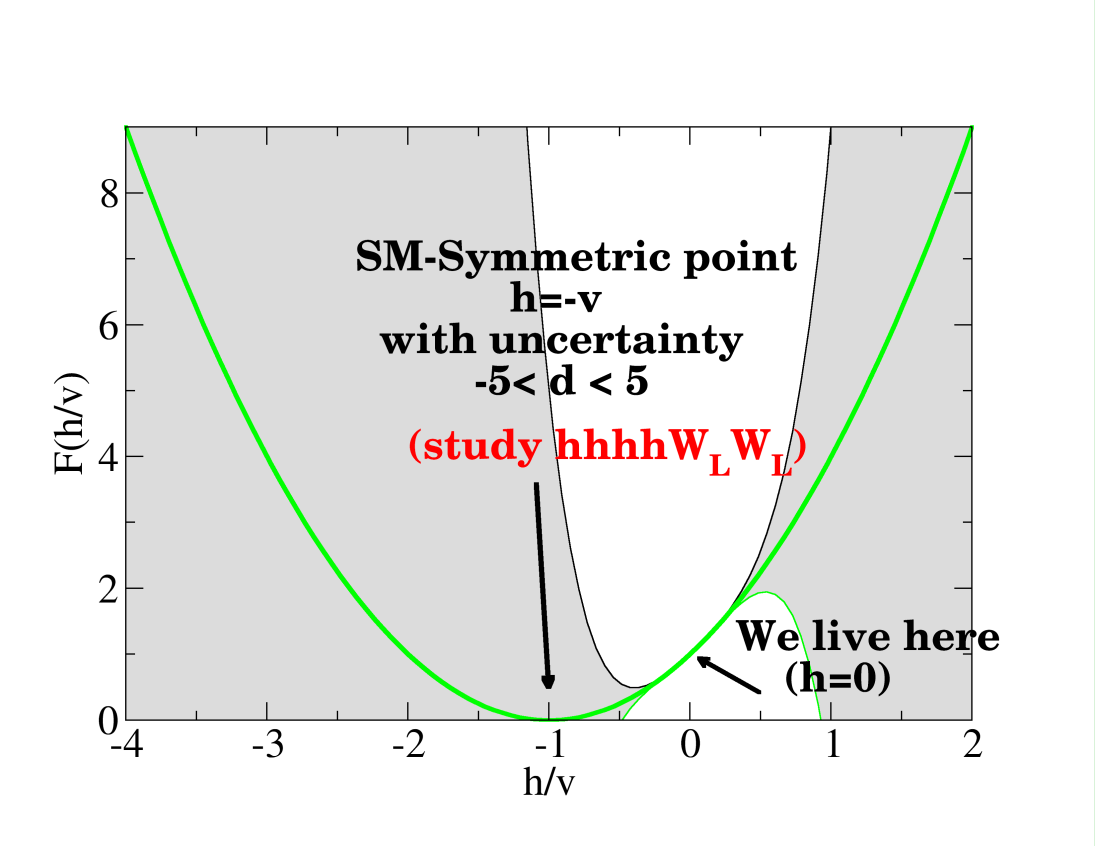


Current status: vary b from a^2



Delgado, Dobado, FLE Phys.Rev.Lett. **114** (2015) 22, 221803

Current status: vary h^4 coefficient



SMEFT inside HEFT

Predict HEFT $\mathcal{F}(h)$ coefficients:

$$a_1 = 2a = 2\left(1 + v^2 \frac{c_{H\Box}}{\Lambda^2}\right) \quad , \quad a_2 = b = 1 + 4v^2 \frac{c_{H\Box}}{\Lambda^2}$$

$$a_3 = \frac{8v^2}{3} \frac{c_{H\Box}}{\Lambda^2} \quad , \quad a_4 = \frac{2v^2}{3} \frac{c_{H\Box}}{\Lambda^2}$$

Eliminating the SMEFT coefficient, or equivalently matching the expansions of $\mathcal{F}(h - h_*)$ and $\mathcal{F}(h)$, obtain...

Correlations among HEFT $\mathcal{F}(h)$ coefficients

Correlations accurate at order Λ^{-2}	Correlations accurate at order Λ^{-4}
$\Delta a_2 = 2\Delta a_1$	
$a_3 = \frac{4}{3}\Delta a_1$	$\left(a_3 - \frac{4}{3}\Delta a_1\right) - \frac{8}{3}(\Delta a_2 - 2\Delta a_1) = -\frac{1}{3}\left(\Delta a_1\right)^2$
$a_4 = \frac{1}{3}\Delta a_1$	$\left(a_4 - \frac{1}{3}\Delta a_1\right) = \frac{5}{3}\Delta a_1 - 2\Delta a_2 + \frac{7}{4}a_3$ $= \frac{8}{3}(\Delta a_2 - 2\Delta a_1) - \frac{7}{12}\left(\Delta a_1\right)^2$
$a_5 = 0$	$a_5 = \frac{8}{5}\Delta a_1 - \frac{22}{15}\Delta a_2 + a_3$ $= \frac{6}{5}(\Delta a_2 - 2\Delta a_1) - \frac{1}{3}\left(\Delta a_1\right)^2$
$a_6 = 0$	$a_6 = \frac{1}{6}a_5$

(At order $1/\Lambda^4$, assuming SMEFT perturbativity, can use $|\Delta a_2| \leq 5|\Delta a_1|$)

With current ATLAS bounds

Consistent SMEFT range at order Λ^{-2}	Consistent SMEFT range at order Λ^{-4}	Perturbativity of Λ^{-4} SMEFT
$\Delta a_2 \in [-0.12, 0.36]$	ATLAS $\Delta a_2 \in [-1.4, 1.6]$	$\Delta a_2 \in [-0.3, 0.9]$
$a_3 \in [-0.08, 0.24]$	$a_3 \in [-4.5, 4.4]$	$a_3 \in [-3.1, 1.7]$
$a_4 \in [-0.02, 0.06]$	$a_4 \in [-4.7, 4.4]$	$a_4 \in [-3.3, 1.5]$
$a_5 = 0$	$a_5 \in [-2.2, 2.0]$	$a_5 \in [-1.5, 0.6]$
$a_6 = 0$	$a_6 = a_5$	$a_6 = a_5$

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

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

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

$$\begin{aligned}
T_{\omega\omega\to hhh} &= -\frac{s}{8v^3}\Bigg(a_1^3\Big[4f_1f_3^2\left(\frac{z_{23}(f_1z_{23}-1)}{f_3(z_3-2f_1z_{23})+f_2z_2}+\frac{z_{13}(f_1z_{13}-1)}{f_1(z_1-2f_3z_{13})+f_3z_3}\right)+\\
&+2f_3\left(f_1\left(\frac{z_{23}-2f_2z_{23}}{-2f_1f_3z_{23}+f_2z_2+f_3z_3}+\frac{z_{13}-2f_1z_{13}}{-2f_1f_3z_{13}+f_1z_1+f_3z_3}+z_{13}+z_{23}\right)+3(z_3-2)\right)+\\
&+\frac{2f_1f_2z_{12}(2f_1(f_2z_{12}-1)-2f_2+1)}{f_1(z_1-2f_2z_{12})+f_2z_2}+2f_1(f_2z_{12}+3z_1-6)+6f_2z_2-12f_2+9\Big]+\\
&+4a_1a_2\Big[\frac{f_1^2\left(2z_1(-2f_2z_{12}+f_3(z_{13}+z_{23})-3)-4f_2z_{12}(f_3(z_{13}+z_{23})-2)+3z_1^2\right)}{2f_1f_2z_{12}-f_1z_1-f_2z_2}+\\
&+\frac{2f_1f_2(-2f_2z_{12}(z_2+1)+z_2(f_3(z_{13}+z_{23})+3z_1-3)+z_{12})+3f_2^2z_2^2}{2f_1f_2z_{12}-f_1z_1-f_2z_2}+6(f_2+f_3-1)-\\
&-\frac{2f_1f_3z_{23}(2f_3(f_1z_{23}-1)-2f_2+1)}{f_3(z_3-2f_1z_{23})+f_2z_2}-\frac{2f_1f_3z_{13}(2f_1(f_3z_{13}-1)-2f_3+1)}{f_1(z_1-2f_3z_{13})+f_3z_3}-3f_3z_3\Big]+24a_3\Bigg).
\end{aligned}$$

($f_i \equiv ||\vec{p}_i||/\sqrt{s}$; $z_i(\omega_1, h_i) \equiv 2\sin^2(\theta_i/2)$; $z_{ij}(h_i, h_j) \equiv 2\sin^2(\theta_{ij}/2)$)
(JHEP 12 (2021) 003 by Cohen, Craig, Lu and Sutherland addresses the contact terms: we provide all tree-level amplitudes)

Ratio of cross-sections independent of SMEFT coefficient

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

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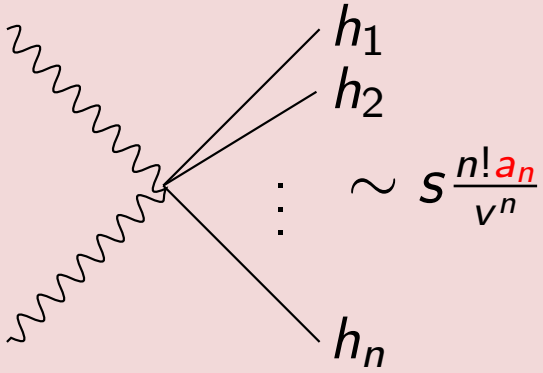

$\sim s \frac{n! a_n}{v^n}$ *Higgsflare...*

To all orders:
produce a Higgs gas in ultrahigh energy collisions, such as RHIC for pions

$V(h)$ correlations: low-$\sqrt{s}$, no need for equiv. theorem

$$V_{\mathrm{HEFT}} = \frac{m_h^2 v^2}{2} \cdot \left[\left(\frac{h_1}{v}\right)^2 + v_3 \left(\frac{h_1}{v}\right)^3 + v_4 \left(\frac{h_1}{v}\right)^4 + \dots \right]$$

$v_4 = \frac{1}{4}(-5 + 6v_3)$	$\Delta v_4 = \frac{3}{2}\Delta v_3$
$v_5 = \frac{3}{4}(v_3 - 1)$	$\Delta v_5 = \frac{3}{4}\Delta v_3$
$v_6 = \frac{1}{8}(v_3 - 1)$	$\Delta v_6 = \frac{1}{8}\Delta v_3$

(Preliminary!)

Conclusion: mass gap to new physics

- Use EFT tools
- SMEFT popular; HEFT a bit more general
- This allows to falsify SMEFT in experiment even without new particles
- We have presented the correlations of HEFT coefficients whose violation falsifies SMEFT

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HEFT Lagrangian for electroweak symmetry breaking

Compact, seven-number version of agnostic TeV-scale new physics

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}\left(1+2a\frac{h}{v}+b\left(\frac{h}{v}\right)^2\right)\partial_\mu\omega^a\partial^\mu\omega^b\left(\delta_{ab}+\frac{\omega^a\omega^b}{v^2}\right) \\
&+ \frac{4a_4}{v^4}\partial_\mu\omega^a\partial_\nu\omega^a\partial^\mu\omega^b\partial^\nu\omega^b+\frac{4a_5}{v^4}\partial_\mu\omega^a\partial^\mu\omega^a\partial_\nu\omega^b\partial^\nu\omega^b \\
&+ \frac{1}{2}\partial_\mu h\partial^\mu h+\frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2 \\
&+ \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^a\partial^\nu\omega^a+\frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^a\partial_\nu\omega^a.
\end{aligned}
$$

R. L. Delgado, A. Dobado and FJLE, PRD **91**, 075017 2015

Derivative expansion ($\simeq$ ChPT)

$$
\begin{aligned}
\mathcal{L} &= \frac{1}{2}\left(1+2a\frac{h}{v}+b\left(\frac{h}{v}\right)^2\right)\boxed{\partial_\mu\omega^a\partial^\mu\omega^b}\left(\delta_{ab}+\frac{\omega^a\omega^b}{v^2}\right)\\
&+ \frac{4a_4}{v^4}\partial_\mu\omega^a\partial_\nu\omega^a\partial^\mu\omega^b\partial^\nu\omega^b+\frac{4a_5}{v^4}\boxed{\partial_\mu\omega^a\partial^\mu\omega^a\partial_\nu\omega^b\partial^\nu\omega^b}\\
&+ \frac{1}{2}\partial_\mu h\partial^\mu h+\frac{g}{v^4}(\partial_\mu h\partial^\mu h)^2\\
&+ \frac{2d}{v^4}\partial_\mu h\partial^\mu h\partial_\nu\omega^a\partial^\nu\omega^a+\frac{2e}{v^4}\partial_\mu h\partial^\nu h\partial^\mu\omega^a\partial_\nu\omega^a.
\end{aligned}
$$

R. L. Delgado, A. Dobado and FJLE, PRD **91**, 075017 2015

Special cases

Interesting particular cases ($M = G/H$):

The Minimal Standar Model: $a = b = c = c_i = d_i = 1$ $f = v$ $a_i = 0$ $R = 0$

Linear, renormalizable, unitary and weakly interacting

No Higgs Model $f = v$ $a = b = c = 0$ → Old EWCL (ChPT)

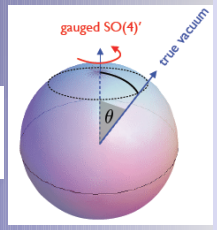
Minimal Dilaton Model $h = \varphi$ new scale f $R = \frac{6}{v^2(1+\frac{h}{f})^2}\left(1 - \frac{v^2}{f^2}\right)$

$V(\varphi) = \frac{M_\varphi^2}{4f^2}(\varphi + f)^2\left[\log\left(1 + \frac{\varphi}{f}\right) - \frac{1}{4}\right]$ $a^2 = b = \frac{v^2}{\hat{f}^2}$

Halyo, Goldberber, Grinstein, Skiba

Minimal Composite Higgs Model (maximally symmetric spaces)

$S^4 = SO(5)/SO(4)$ → $a^2 = 1 - \frac{v^2}{f^2}$ $b = 1 - 2\frac{v^2}{f^2}$ $R = \frac{12}{f^2} > 0$



Agashe, Contino, Pomarol, Da Rold

$\xi = v^2/f^2$ $\sin\theta = \sqrt{\xi}$

$\mathcal{H}^4 = SO(1,4)/SO(4)$ → $a^2 = 1 + \frac{v^2}{f^2}$ $b = 1 + 2\frac{v^2}{f^2}$ $R = \frac{12}{f^2} > 0$

Alonso, Jenkins, Manohar

Courtesy of A. Dobado