Higgs EFTs, and ALPs in Multi-Boson Production

Alexandre Salas-Bernárdez; IPARCOS Congress 2025, UCM.

10th December 2025

Recent Multiboson Measurements: outline

- H, HH, HHH (not yet)

[ATLAS], Nature **607** (2022) no.7917, 52-59
[ATLAS], Phys. Rev. Lett. **133** (2024) no.10, 101801
[ATLAS], Phys. Rev. D **111** (2025) no.3, 032006

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Used to test linear (SMEFT-like) and non-linear (HEFT-like) ALP EFT.

1. Distinguishing Electroweak EFTs

Based on : Phys. Rev. D **106** (2022) no.5, 053004

Commun. Theor. Phys. **75** (2023) no.9, 095202 EPJ Web Conf. **274** (2022), 08013

JHEP **03** (2024), 037 Phys. Rev. D (2025), to appear

The Electroweak scalar sector extensions

"Two" EW EFT candidates

- Standard Model Effective Field Theory (SMEFT)

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

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- Higgs Effective Field Theory (HEFT):
  Chiral Lagrangian

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

The Electroweak scalar sector extensions

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What is their relation?

In a few words...

Basically, SMEFT assumes the SM EWSB structure, where the Higgs boson is part of an $SU(2)_L$ doublet.

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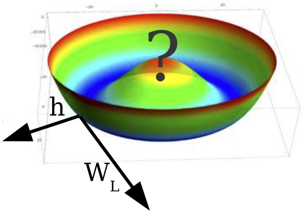
On the other hand, HEFT casts the Higgs boson h as an $SU(2)_L$ singlet.

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].



Conditions on $\mathcal{F}$ for SMEFT's validity

In 2204.01763 we found an easier analytical criterion for SMEFT to be valid:

1. $\boxed{\mathcal{F}(h_1^*) = 0}$ must have a double zero. h_1^* is the symmetric point.
2. At that point h_1^*,
$$\boxed{\mathcal{F}'(h_1^*) = 0\ ,\ \ \mathcal{F}''(h_1^*) = \frac{2}{v^2}}\ .$$
3. Analyticity of the SMEFT Lagrangian: all even derivatives to vanish at the symmetric point, $F^{(\ell)}(h_1^*) = 0$ for even ℓ. From the point of view of $\mathcal{F}$ this implies the vanishing of all odd derivatives, $\boxed{\mathcal{F}^{(2\ell+1)}(h_1^*) = 0}$.

Conditions on V for SMEFT's validity

The expansion of $V_{\rm HEFT}(h_1)$ can only contain even terms in its $(h_1 - h_*)^n$ expansion:

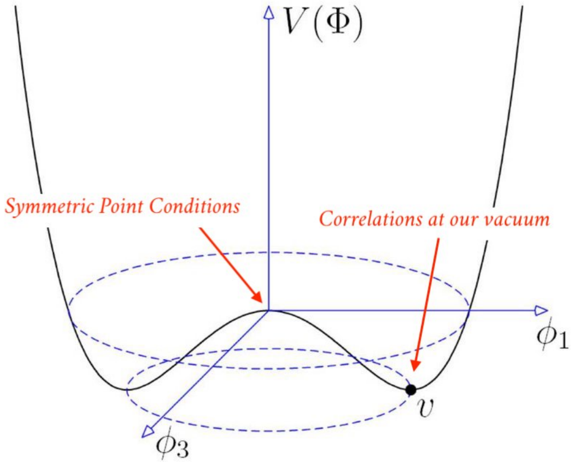
$$V_{\rm HEFT}(h_1) = \frac{m_h^2 v^2}{2}\left[\frac{v_2^*}{v^2}(h_1 - h_*)^2 + \frac{v_4^*}{v^4}(h_1 - h_*)^4 + \frac{v_6^*}{v^6}(h_1 - h_*)^6 + \dots\right]$$

The HEFT coefficients

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

are determined by the v_4^*, $v_6^* \dots,$ coefficients around the symmetric vacuum

Origin of SMEFT correlations: just match two Taylor exp.



HEFT and SMEFT UV completion examples

- Strong UV dynamics can still match to SMEFT:

- Minimally Composite Higgs Model

$$\mathcal{F}(h) = \frac{f^2}{v^2}\sin^2\left(\frac{h}{f} + \arcsin\frac{v}{f}\right)$$

Contino et al.[1109.1570]

- Pure-HEFT models:

- Two Higgs Doublet Model (in the quasi-alignment regime) Arco et al. [2307.15693]
- Dilaton Model $\mathcal{F}(h) = (1 + a\frac{h}{v})^2$.

$$\mathcal{F}''(h^*) = 2\frac{a^2}{v^2} \neq \frac{2}{v^2}$$

Mod.Phys.Lett.A 8 (1993) 275-284; Goldberger et al. [0708.1463]; Hernandez-Leon and Merlo [1703.02064]

High energy measurements

The flare function $\mathcal{F}$ accompanies the GB kinetic term $(\partial\omega\partial\omega)$

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

At high energies (Equivalence Theorem) $\omega \simeq W_L$

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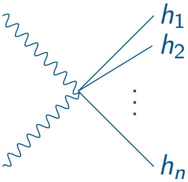
$\Rightarrow \omega\omega \to n \times h$ can test SMEFT framework.



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

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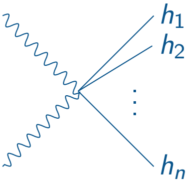


$$= -\frac{n!\boldsymbol{a_n}}{2v^n} s \Longrightarrow \boldsymbol{\kappa_{nV}} \quad \text{of } \kappa\text{-framework}$$

SMEFT vs HEFT phenomenology (JHEP 03 (2024) 037)

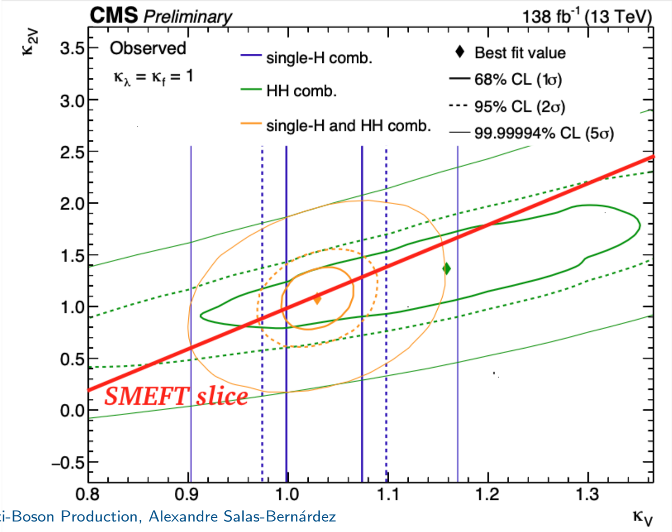
Dimension 6 (8) SMEFT operators contributing to $\mathcal{F}(h)$ are
$\mathcal{O}_{H\Box}^{(6)((8))} = c_{H\Box}^{(6)((8))}|H|^{2(4)}\Box|H|^2/\Lambda^{2(4)}$ (also $\mathcal{O}_{\Phi D}$)

$$\begin{aligned}
a_1/2 &= a = 1 + \frac{d}{2} + \frac{d^2}{2}\left(\frac{3}{4}+\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_2 &= b = 1 + 2d + 3d^2\left(1+\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_3 &= \frac{4}{3}d + d^2\left(\frac{14}{3}+4\rho\right) + \mathcal{O}\left(d^3\right) ,\\
a_4 &= \frac{1}{3}d + d^2\left(\frac{11}{3}+3\rho\right) + \mathcal{O}\left(d^3\right) , ,
\end{aligned}$$

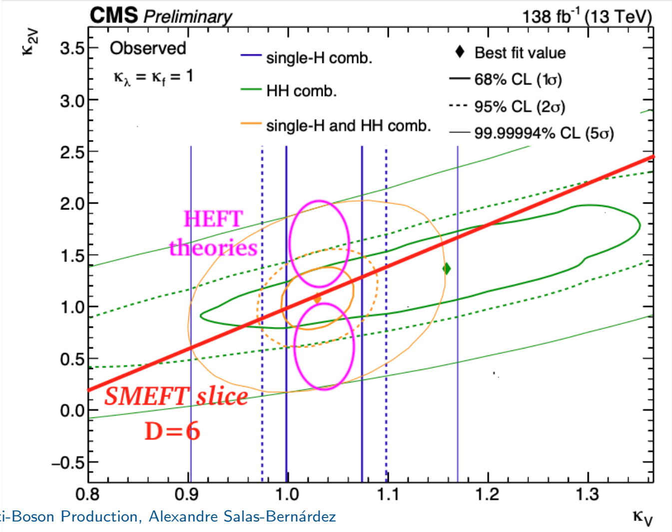
with,

$$d = \frac{2v^2 c_{H\Box}^{(6)}}{\Lambda^2} , \qquad \rho = \frac{c_{H\Box}^{(8)}}{2(c_{H\Box}^{(6)})^2} .$$

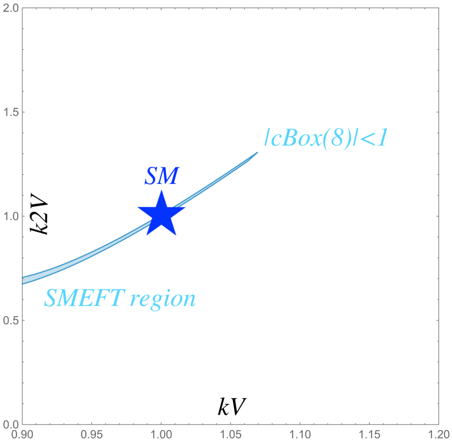
Recent combination of analyses: CMS-HIG-23-006



Recent combination of analyses: HEFT regions



In case you are wondering... $D = 8$



for $d \in (-0.36, 0.121)$ (FitMaker bounds, J. Ellis, M. Madigan, K. Mimasu, V. Sanz and T. You, JHEP **04** (2021), 279)

and $|c^{(8)}_{H\Box}| \leq 1$.

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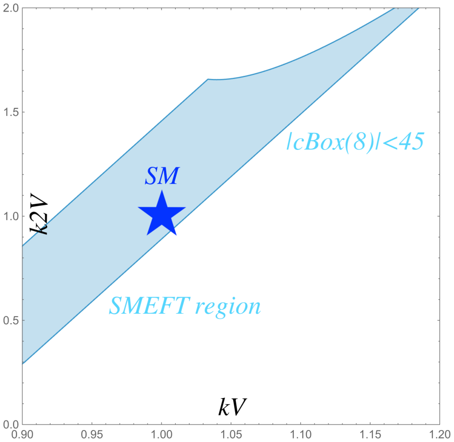

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and $|c^{(8)}_{H\Box}| \leq 45$ (inside CMS allowed region)

In case you are wondering... $D = 8$

$$
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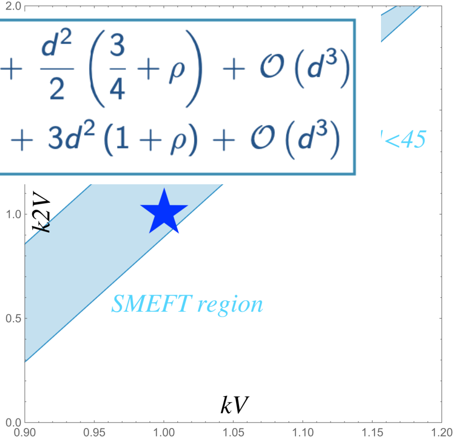
$$



Testing the SMEFT: Measure $\mathcal{F}$ expansion in multi-Higgs final states (JHEP 03 (2024) 037)

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

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

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Obtained in Contino et al. JHEP 02 (2014), 006

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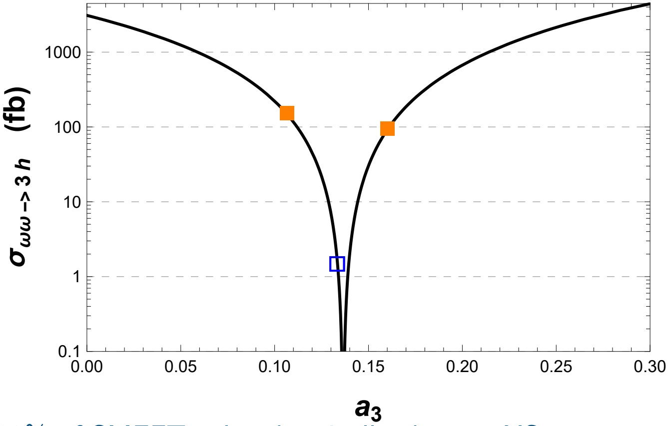
$$T_{\omega\omega\to 4h} = -\frac{4s}{v^4}\left(3\hat{a}_4 + \hat{a}_2^2\left(B-1\right)\right),$$

where $\hat{a}_2 = a_2 - a_1^2/4$ and $\hat{a}_4 = a_4 - \frac{3}{4}a_1 a_3 + \frac{5}{12}a_1^2\left(a_2 - a_1^2/4\right)$.

Cross section comparison: triple Higgs production (JHEP 03 (2024) 037).



Deviating a_3 only 10% of SMEFT value drastically changes XS.

Same game for the Higgs potential and Yukawas 2207.09848

$$v_3 = 1 + \frac{3v^2 c_{H\Box}}{\Lambda^2} + \epsilon_{c_H}\,, \quad v_4 = \frac{1}{4} + \frac{25 v^2 c_{H\Box}}{6\Lambda^2} + \frac{3}{2}\epsilon_{c_H}\,,$$

$$v_5 = \frac{2v^2 c_{H\Box}}{\Lambda^2} + \frac{3}{4}\epsilon_{c_H}\,, \quad v_6 = \frac{v^2 c_{H\Box}}{3\Lambda^2} + \frac{1}{8}\epsilon_{c_H}\,,$$

$$v_{n\geq 7} = 0\,,$$

with $m_h^2 = -2\mu^2\left(1 + \frac{2c_{H\Box}v^2}{\Lambda^2} + \frac{3}{4}\epsilon_{c_H}\right)$, $2\langle|H|^2\rangle = v^2 = -\frac{\mu^2}{\lambda}\left(1 - \frac{3}{4}\epsilon_{c_H}\right)$ and $\epsilon_{c_H} = -\frac{2v^4 c_H}{m_h^2\Lambda^2} = \frac{\mu^2 c_H}{\lambda^2\Lambda^2}$.

$$c_1 = 1 - \frac{v^3}{\sqrt{2}m_t}\frac{c_{tH^+}}{\Lambda^2} + \frac{c_{H\Box}v^2}{\Lambda^2} + \mathcal{O}(1/\Lambda^4)$$

$$\Delta v_4 = \frac{3}{2}\Delta v_3 - \frac{1}{6}\Delta a_1$$

$$v_5 = 6v_6 = \frac{3}{4}\Delta v_3 - \frac{1}{8}\Delta a_1$$

$$c_2 = 3c_3 = \frac{3}{2}(c_1 - 1) - \frac{1}{4}\Delta a_1$$

Matching SMEFT at D=6 to NLO HEFT for triple Higgs production

Inspired by geometric arguments, in [2506.21716], we match SMEFT at D=6

$$\begin{aligned}\mathcal{L}^{(6)}_{\rm SMEFT} \quad = \quad & \frac{c_\Phi}{\Lambda^2}(\Phi^\dagger\Phi)^3 + \frac{c_{\Phi\Box}}{\Lambda^2}(\Phi^\dagger\Phi)\Box(\Phi^\dagger\Phi) + \frac{c_{\Phi D}}{\Lambda^2}(\Phi^\dagger D^\mu\Phi)^*(\Phi^\dagger D_\mu\Phi) \\ & + \frac{c_{\Phi W}}{\Lambda^2}(\Phi^\dagger\Phi)W^I_{\mu\nu}W^{I\,\mu\nu} + \frac{c_{\Phi B}}{\Lambda^2}(\Phi^\dagger\Phi)B_{\mu\nu}B^{\mu\nu} + \frac{c_{\Phi WB}}{\Lambda^2}(\Phi^\dagger\tau^I\Phi)W^I_{\mu\nu}B^{\mu\nu}\end{aligned}$$

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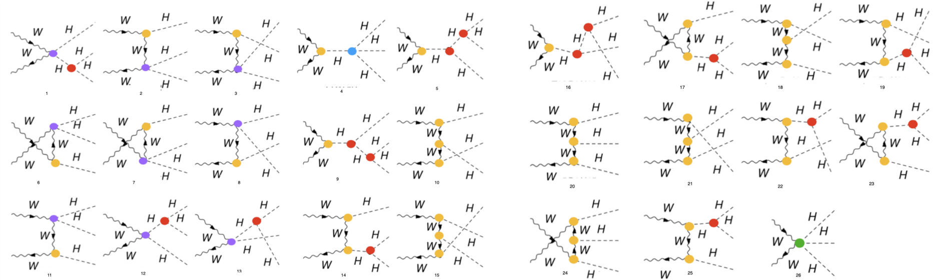
to NLO HEFT

$$\begin{aligned}\mathcal{L}_{LO} &= \frac{v^2}{4}\mathcal{F}(h)\mathrm{Tr}[D_\mu U^\dagger D^\mu U] + \frac{1}{2}\partial_\mu h\partial^\mu h - V(h)\\ &-\frac{1}{2g^2}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}] - \frac{1}{2g'^2}\mathrm{Tr}[\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}] + \mathcal{L}_{GF} + \mathcal{L}_{FP},\end{aligned} \qquad \mathcal{L}_{NLO} = \mathcal{O}(\partial^4)$$

using field-redefinition (geometric) invariants: the scattering amplitudes.

Matching SMEFT at D=6 to NLO HEFT for VBF triple Higgs production

By matching amplitudes in the two theories:



Matching SMEFT at D=6 to NLO HEFT for VBF triple Higgs production

We find the following correlations of HEFT parameters by assuming the SMEFT structure:

$$\Delta a = \frac{v^2}{\Lambda^2}(-c_{\Phi\Box} + \frac{1}{4}c_{\Phi D})$$

$$\Delta b = \frac{4v^2}{\Lambda^2}(-c_{\Phi\Box} + \frac{1}{4}c_{\Phi D})$$

$$\Delta\kappa_3 = \frac{2v^4}{m_H^2\Lambda^2}c_\Phi + \frac{3v^2}{\Lambda^2}(-c_{\Phi\Box} + \frac{1}{4}c_{\Phi D})$$

$$a_{HWW} = -\frac{v^4}{2m_W^2\Lambda^2}c_{\Phi W}$$

$$a_{HHWW} = -\frac{v^4}{4m_W^2\Lambda^2}c_{\Phi W}$$

$$\Delta\kappa_3 = \frac{2v^4}{m_H^2\Lambda^2}c_\Phi + \frac{3v^2}{\Lambda^2}(-c_{\Phi\Box} + \frac{1}{4}c_{\Phi D})$$

$$\Delta\kappa_4 = \frac{12v^4}{m_H^2\Lambda^2}c_\Phi + \frac{50v^2}{3\Lambda^2}(-c_{\Phi\Box} + \frac{1}{4}c_{\Phi D})$$

$$s_W^2 a_{HBB} = -\frac{v^4}{2m_Z^2\Lambda^2}c_{\Phi B}$$

$$s_W^2 a_{HHBB} = -\frac{v^4}{4m_Z^2\Lambda^2}c_{\Phi B}$$

$$s_W^2 a_{H0} = -\frac{v^4}{8m_Z^2\Lambda^2}c_{\Phi D}$$

$$s_W^2 a_{HH0} = -\frac{5v^4}{16m_Z^2\Lambda^2}c_{\Phi D}$$

$$s_W c_W a_{H1} = -\frac{v^4}{2m_Z^2\Lambda^2}c_{\Phi WB}$$

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2. Axion-Like Particle EFTs

Based on : JHEP **10** (2024), 164 [2510.24873]

Adding the ALPs

Axion-like Particles (ALPs) are strong candidates for SM extensions:

- Introduced for solving the strong CP problem (?).
- ALPs appear in scenarios of global symmetry breaking in new confining sectors (pNGB) and can be very light.

Linear vs. chiral ALP: linear (SMEFT-like) (Brivio et al. 1701.05379)

Linear ALP theory (expansion in terms of the inverse of the ALP scale f_a). Dimension-five interactions with the SM gauge fields,

$$\mathcal{L} \supset -\frac{a}{f_a}\left(c_{\tilde{B}} B_{\mu\nu}\tilde{B}^{\mu\nu} + c_{\tilde{W}} W^a_{\mu\nu}\tilde{W}^{a,\mu\nu} + c_{\tilde{G}} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right) \ .$$

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Coupling to the Higgs doublet, H,

$$\mathcal{O}_{aH} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\frac{\partial^\mu a}{f_a} \ ,$$

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Coupling to the Higgs doublet, H,

$$\mathcal{O}_{aH} = i\left(H^\dagger \overleftrightarrow{D}_\mu H\right)\frac{\partial^\mu a}{f_a} \; ,$$

which leads to fermionic couplings proportional to the Yukawas,

$$\mathcal{O}_{a\Psi} = i\frac{a}{f_a}\left(\bar{Q}_L Y_U \tilde{H} u_R + \ldots\right) + h.c.$$

Linear vs. chiral ALP: chiral (HEFT-like) 1701.05379

17 possibilities for coupling the ALP to SM fields,

$$\mathcal{L}_{\rm chiral} = \sum_{i=\tilde{B},\tilde{W},\tilde{G}} c_i\,\mathcal{O}_i + \sum_{j=1}^{17} c_j\,\mathcal{O}_j\,,$$

Linear vs. chiral ALP: chiral (HEFT-like) 1701.05379

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where each of the operators $\mathcal{O}_1$ - $\mathcal{O}_{17}$ is proportional to a Higgs flare function as before

$$\mathcal{F}_i(h) = 1 + a_i\,\frac{h}{v} + b_i\,\left(\frac{h}{v}\right)^2 + \ldots\,,$$

New couplings: c_{2D}, which induces $Z^\mu\partial_\mu a$.
Other relevant operators: such as the operator c_{17} which accompanies $\frac{1}{f_a}\,V_\mu\partial^\mu\Box a$.

Targeting Di-Higgs: CP conserving ALP interactions

In [2404.08062] we study Di-Higgs production via a non-resonant ALP.

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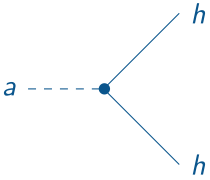
ALPs are pseudoscalar particles (0^-).



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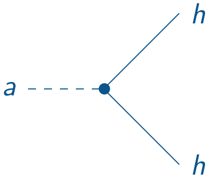
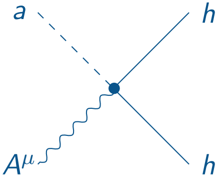


$= 0$

⇒Need for an extra γ or Z boson.

Targeting Di-Higgs: CP conserving ALP interactions



$$\frac{1}{2\pi v^2 f_a}\left(\tilde{b}_3 c_W + \tilde{b}_{10} s_W\right)\left(p_\gamma^\mu p_a^2 - p_\gamma^2 p_a^\mu\right) \overset{\text{on shell}}{=} 0$$

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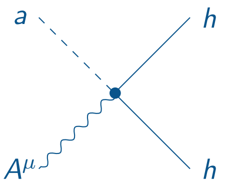

$$\frac{1}{2\pi v^2 f_a}\left(\tilde{b}_3 c_W + \tilde{b}_{10} s_W\right)\left(p_\gamma^\mu p_a^2 - p_\gamma^2 p_a^\mu\right) \overset{\text{on shell}}{=} 0$$

This is due to CP conservation $\Rightarrow$

$0^- \longrightarrow 0^-$ which needs **longitudinal polarization** of outgoing vector boson.

Process of this analysis: Di-Higgs production in the chiral ALP

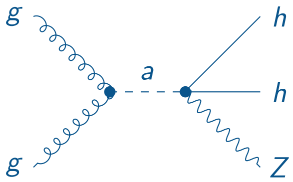

Figure: Feynman diagram for di-Higgs production with an associated Z-boson via a non-resonant ALP.

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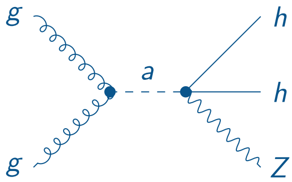
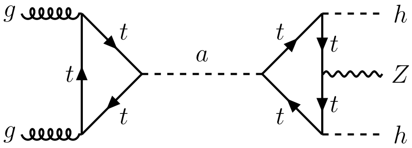


Figure: Feynman diagram for di-Higgs production with an associated Z-boson via a non-resonant ALP.

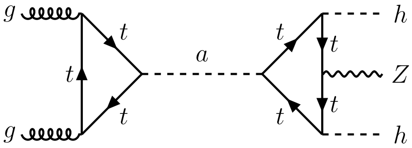
Using ATLAS (CMS) $HH(Z)$ [2310.12301] ([2404.08462]) data we can set bounds on couplings. For HHZ there is very little SM background!

Comparing to linear theory: top loops



$$\mathcal{L} = -i\, c_t \, \frac{m_t a}{f_a} \, (\bar{t} \gamma^5 t)$$

Comparing to linear theory: top loops

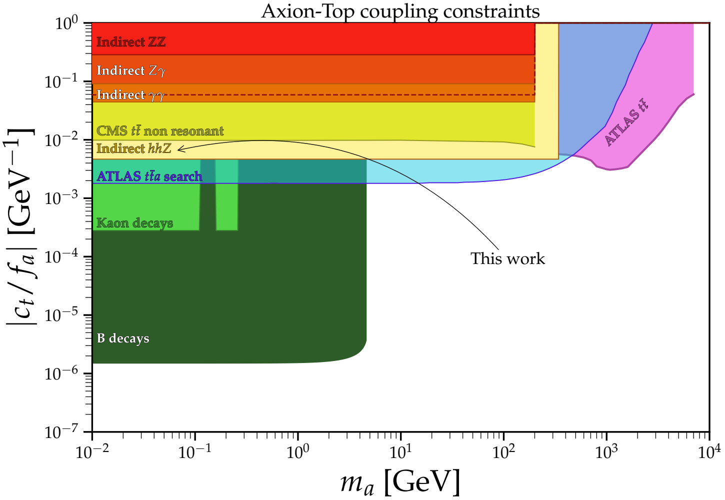


$$\mathcal{L} = -i\, c_t \frac{m_t a}{f_a} (\bar{t}\gamma^5 t)$$

Using Naive Dimensional Analysis (NDA) we can interpret the results from the last section in terms of loop contributions as

$$\frac{c}{f_a^2} \simeq \frac{\alpha_s}{8\pi c_W} \frac{c_t^2}{f_a^2}\,.$$

Bounds on top-axion couplings



Previous ALP analyses at colliders

Previous work has analysed individual ALP off-shell signatures at the Large Hadron Collider,

- Di-photon, massive di-boson, or vector-boson–scattering processes
  I. Brivio, M.B. Gavela, L. Merlo, K. Mimasu, J.M. No, R. del Rey et al. [1701.05379]; M. Bauer, M. Neubert and A. Thamm, [1708.00443];
  M.B. Gavela, J.M. No, V. Sanz and J.F. de Trocóniz,[1905.12953].
- Couplings to the top quark and gluons
  F. Esser, M. Madigan, V. Sanz and M. Ubiali [2303.17634]; J. Butterworth, M. Cullingworth, J. Egan, F. Esser, V. Sanz and M. Ubiali, [2508.21660];
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However, a comprehensive treatment of ALP-mediated multiboson production has not yet been undertaken (only partially as in J.Bonilla, I. Brivio, Machado-Rodríguez and J.F. de Trocóniz [2202.03450] where VBF channels were explored.)

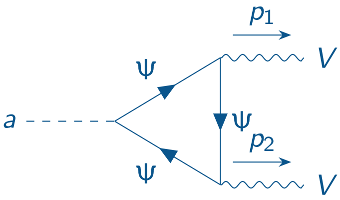
Using multiboson data to constrain the linear ALP EFT

Latest work with F. Esser, V. Sanz and M. Ubiali [2510.24873]. Global fit for the linear ALP:

vertex	Feynman Rule in linear ALP EFT
$a\gamma\gamma$	$-\frac{4i}{f_a}\left(c_\theta^2 c_{\tilde{B}} + s_\theta^2 c_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}\left(p_{\gamma 1}\right)_\rho \left(p_{\gamma 2}\right)_\sigma$
$a\gamma Z$	$\frac{2i}{f_a} s_{2\theta}\left(c_{\tilde{B}} - c_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}\left(p_Z\right)_\rho \left(p_\gamma\right)_\sigma$
aZZ	$-\frac{4i}{f_a}\left(s_\theta^2 c_{\tilde{B}} + c_\theta^2 c_{\tilde{W}}\right)\epsilon^{\mu\nu\rho\sigma}\left(p_{Z1}\right)_\rho \left(p_{Z2}\right)_\sigma$
aW^+W^-	$-\frac{4i}{f_a} c_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}\left(p_{W^+}\right)_\rho \left(p_{W^-}\right)_\sigma$
agg	$-\frac{4i}{f_a} c_{\tilde{G}}\delta_{ab}\epsilon^{\mu\nu\rho\sigma}\left(p_{g1}\right)_\rho \left(p_{g2}\right)_\sigma$
$a\gamma W^+W^-$	$\frac{4ie}{f_a} c_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}\left(p_{WW\gamma}\right)_\sigma$
aZW^+W^-	$\frac{4ie}{f_a}\frac{c_\theta}{s_\theta} c_{\tilde{W}}\epsilon^{\mu\nu\rho\sigma}\left(p_{WWZ}\right)_\sigma$
$aggg$	$\frac{4}{f_a} g_s c_{\tilde{G}} f_{abc}\epsilon^{\mu\nu\rho\sigma}\left(p_{ggg}\right)_\sigma$

ALP coupling only to gauge bosons

Naturally arises when having a heavy fermion, Ψ, carrying an an approximate global $U(1)$ and in some representation under the SM gauge groups

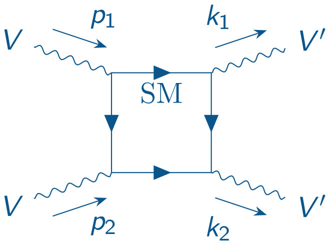


Generates, after integrating out the heavy fermion, through the chiral anomaly

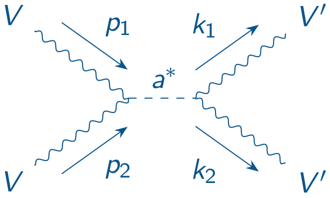
$$\mathcal{L}_{\rm ALP} = \frac{a}{f_a}\left[c_{\tilde{G}}\, G\tilde{G} + c_{\tilde{W}}\, W\tilde{W} + c_{\tilde{B}}\, B\tilde{B}\right],$$

and no coupling to H or fermions.

Global Fit to ATLAS and CMS data: non-resonant regime of the ALP



(a) SM continuum (no ALP resonance)



(b) Off-shell ALP exchange in the s-channel

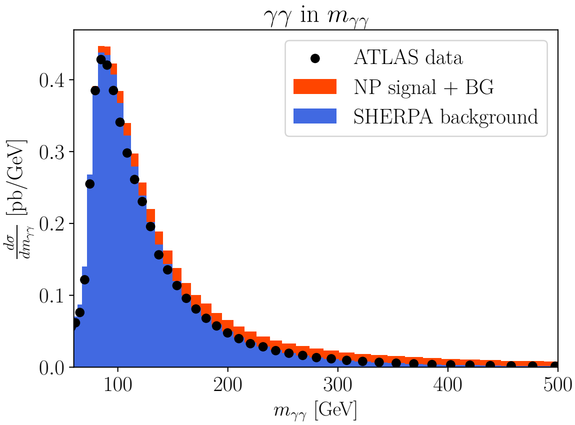
Off-shell exchange of the ALP will modify typically distribution tails.

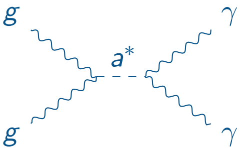
$$\hat{\sigma}(V_1 V_2 \to V_3 V_4) \propto \frac{(c_{V_1 V_2} c_{V_3 V_4})^2}{f_a^4} \hat{s},$$

Experimental data used for the global fit

final state	experiment	$\sqrt{s}$ (TeV)	luminosity	observables
$\gamma\gamma$	CMS	7	$5\,\text{fb}^{-1}$	$d\sigma_{\gamma\gamma}/dm_{\gamma\gamma}$
	ATLAS	13	$139\,\text{fb}^{-1}$	$d\sigma_{\gamma\gamma}/dm_{\gamma\gamma}$
ZZ	CMS	13	$137\,\text{fb}^{-1}$	$d\sigma/m_{ZZ}$, $d\sigma/p_T^l$
	ATLAS	13.6	$29\,\text{fb}^{-1}$	$d\sigma/dm_{4l}$
W^+W^-	CMS	13	$34.8\,\text{fb}^{-1}$	total cross section
	ATLAS	13	$36.1\,\text{fb}^{-1}$	$d\sigma_{WW}/dm_{e\mu}$
dijet (gg)	**ATLAS**	13	$3.2\,\text{fb}^{-1}$	$d^2\sigma_{jj}/dm_{jj}dy*$
	CMS	13	$2.3\,\text{fb}^{-1}$	$d^2\sigma_{jj}/dm_{jet}dp_T$
	CMS	13	$2.6\,\text{fb}^{-1}$	$1/\sigma d^2\sigma_{jj}/d\chi dm_{jj}$
	CMS	13	$35.9\,\text{fb}^{-1}$	$1/\sigma d^2\sigma_{jj}/d\chi dm_{jj}$
γZjj (VBF)	**CMS**	13	$139\,\text{fb}^{-1}$	$\mathbf{d\sigma/dp_T^\gamma}$, $d\sigma/dp_T^{lead,l}$, $d\sigma/p_T^{lead,j}$, $d^2\sigma/dy_{jj}dm_{jj}$
$ZZjj, W^+W^-jj$ (VBF)	**ATLAS**	13	$140\,\text{fb}^{-1}$	Events/ 200 GeV in m_{VV} bins

$\gamma\gamma$ final state. ATLAS [2107.09330].

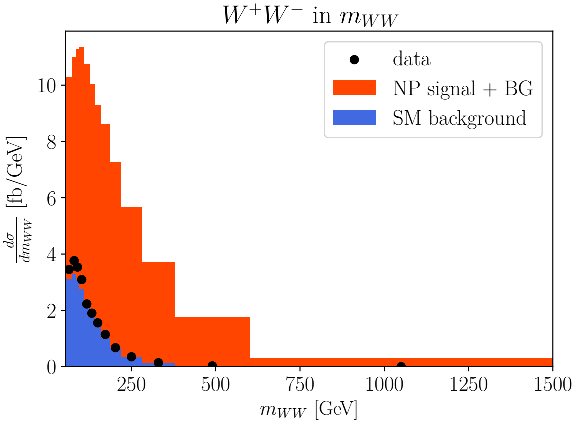


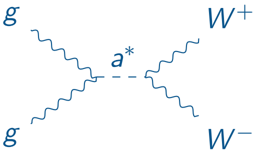


testing

$$c_{\tilde{G}}\left(c_{\tilde{B}}\cos^2\theta_W + c_{\tilde{W}}\sin^2\theta_W\right)$$

W^+W^- final state ATLAS [1905.04242]

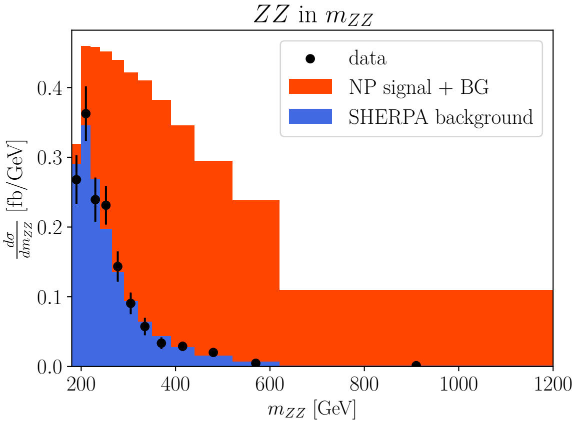


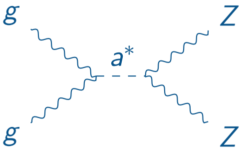


testing

$c_{\tilde{G}}\ c_{\tilde{W}}$

ZZ final state ATLAS [2311.09715]

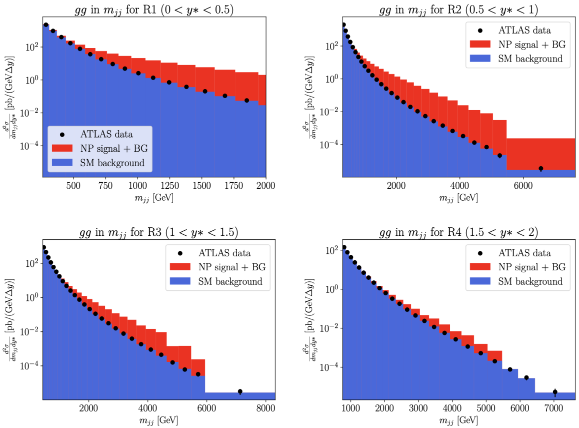


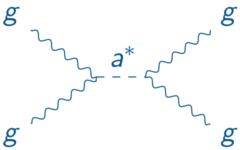


testing

$$c_{\tilde{G}} \left(\sin^2\theta_W \, c_{\tilde{B}} + \cos^2\theta_W \, c_{\tilde{W}}\right)$$

Dijet final state ATLAS collaboration, JHEP 05 (2018) 195 [1711.02692].



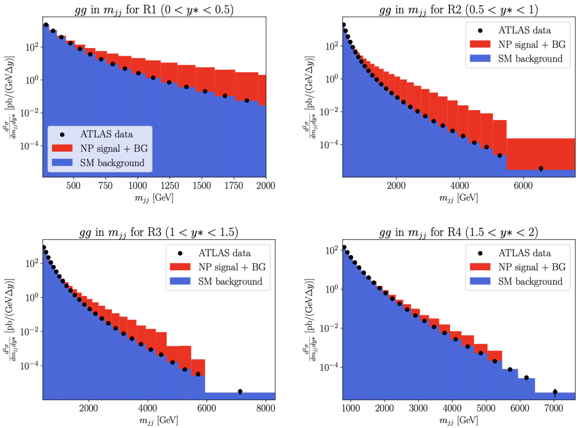


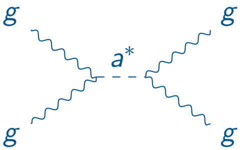
testing

$c_{\tilde{G}}^2$

($c_{\tilde{G}} = 3$ for visibility)

Dijet final state ATLAS collaboration, JHEP 05 (2018) 195 [1711.02692].





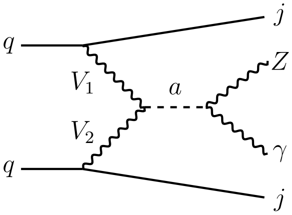
testing

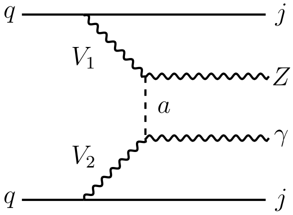
$c_{\tilde{G}}^2$

($c_{\tilde{G}} = 3$ for visibility)

BG not given, calculated with NNLOJET.

VBF/VBS $Z\gamma$ final state





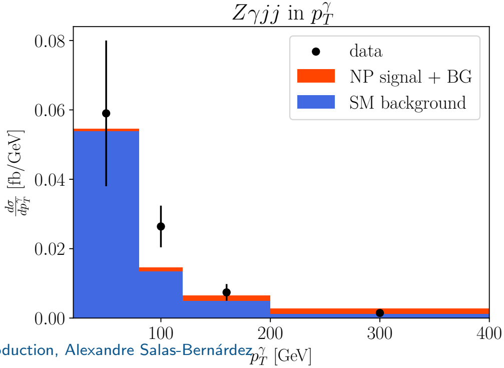
we calculate the cross section in MG5 looping over various combinations for values of $c_{\tilde{W}}$ and $c_{\tilde{B}}$ and fit a quartic polynomial of the form

$$\sigma_{Z\gamma jj}(c_{\tilde{W}}, c_{\tilde{B}}) = \sum_{m,n=0}^{4, n+m\leq 4} \alpha_{nm}\, c_{\tilde{W}}^{n}\, c_{\tilde{B}}^{m},$$

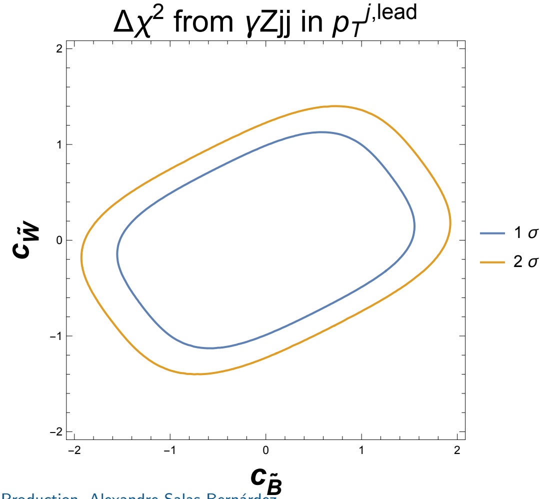
VBF/VBS $Z\gamma$ final state CMS, Phys. Rev. D 104 (2021) 072001 [2106.11082].

With the fit at hand, the number of events for arbitrary $c_{\tilde{W}}$ and $c_{\tilde{B}}$ can be obtained from

$$N^{\rm ALP}(c_{\tilde{W}}, c_{\tilde{B}}) = N^{\rm ALP}(c_{\tilde{W}} = 1, c_{\tilde{B}} = 0)\frac{\sigma_{Z\gamma jj}(c_{\tilde{W}}, c_{\tilde{B}})}{\sigma_{Z\gamma jj}(c_{\tilde{W}} = 1, c_{\tilde{B}} = 0)}$$

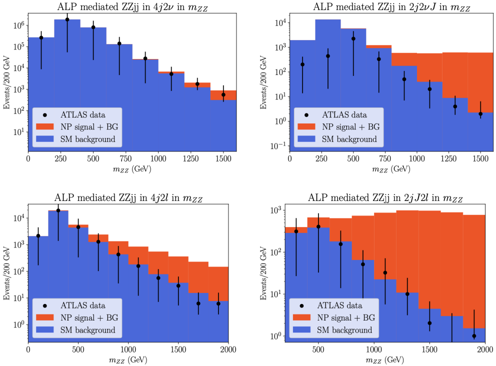


VBF/VBS $Z\gamma$ final state

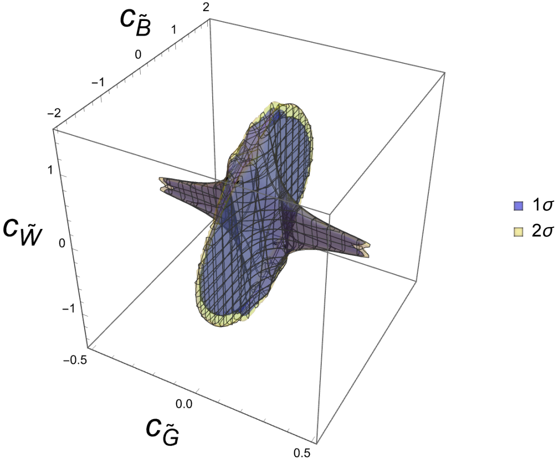


Adding VBF/VBS $VVjj$ final state ATLAS, 2503.17461

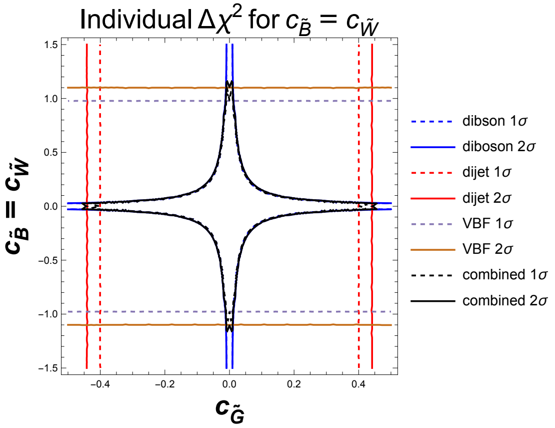
- $ZZjj$ with $Z \to \nu\bar{\nu}$ (0ℓ),
- $ZZjj$ with $Z \to \ell^+\ell^-$ (2ℓ),
- W^+W^-jj with $W^\pm \to \ell^\pm\nu$ (1ℓ).



Global fit for all channels



Global fit for all channels: projection



Summary:

- HEFT and SMEFT can be distinguished via multi-Higgs measurements. We match the full bosonic $D = 6$ SMEFT to the NLO HEFT.

- Multiboson measurements are a good probe for ALP interactions. Global fits to multi-boson measurements can be performed for constraining ALP couplings.

Acknowledgments

Funded by research grant PID2023-148162NB-C21 and PID2022-137003NB-I00 from Spanish MCIN/AEI/10.13039/501100011033/ and EU FEDER.