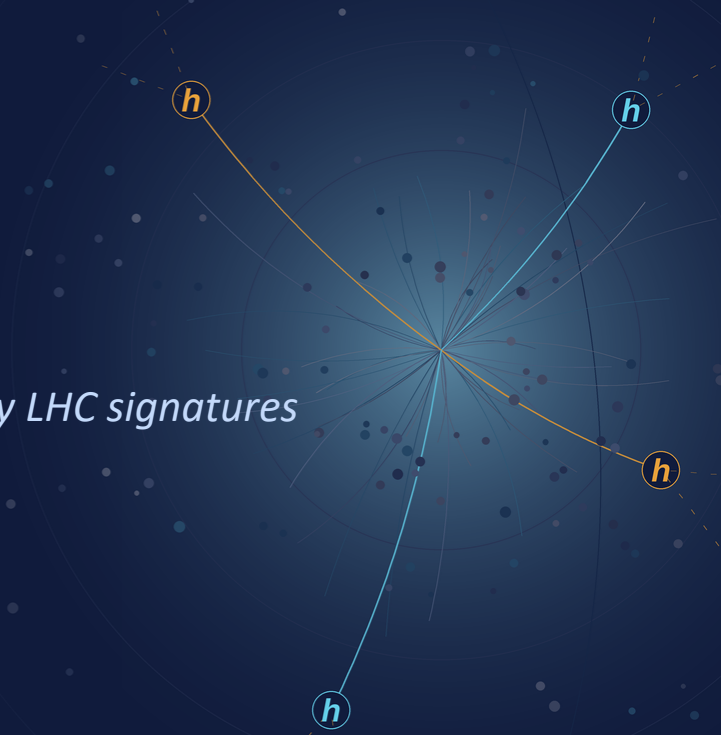
Alignment and Enhanced Multi-Higgs Production

*A new BSM discovery regime: **hh, hhh and hhhh** as primary LHC signatures*

in collaboration with Carlos E. M. Wagner

arXiv: 2605.29345

(accepted for publication in PRD)



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PIKIMO 21 · Nov 7, 2026

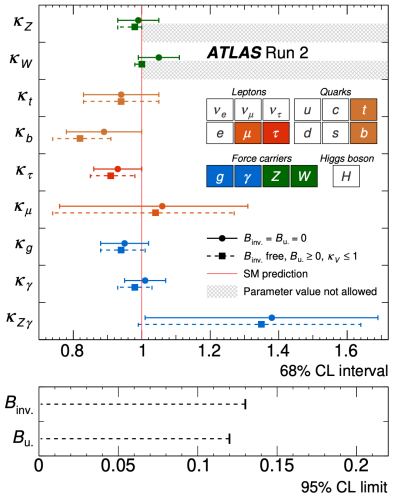
University of Pittsburgh

From h to hh to hhh

Mapping out the Higgs potential $V(h) \supset \lambda_3 v h^3 + \frac{1}{4}\lambda_4 h^4$

Single Higgs

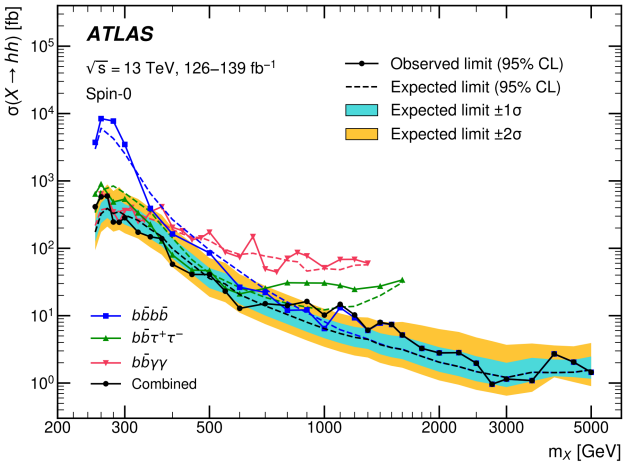
couplings SM-like at current precision



ATLAS, Nature 607 (2022) 52

Di-Higgs

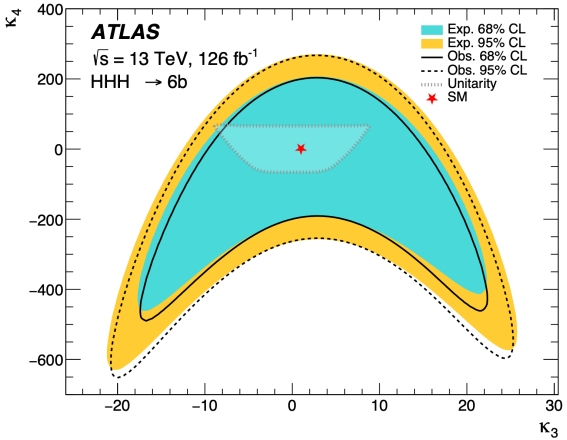
λ_3, and resonant X → hh searches



ATLAS, arXiv:2311.15956

Triple Higgs

λ_4, and the first hhh → 6b searches



ATLAS, arXiv:2411.02040

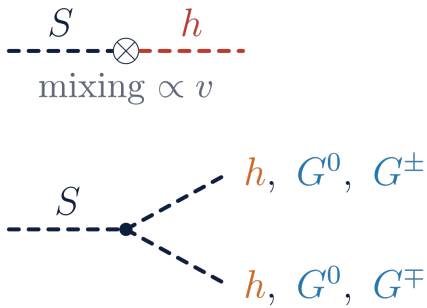
What one usually expects from a new scalar

A gauge singlet S couples to the SM only through $H^\dagger H$ at the renormalizable level:

$$S\,H^\dagger H \;\supset\; S\left[v\,h \;+\; \tfrac{1}{2}\,h^2 \;+\; \tfrac{1}{2}\,(G^0)^2 + G^+G^-\right]$$

Goldstone equivalence ($m_S \gg m_W$): $Z_L \simeq G^0$, $W^\pm_L \simeq G^\pm$, hence

$$\boxed{\Gamma(S \to hh) \;\simeq\; \Gamma(S \to ZZ) \;\simeq\; \tfrac{1}{2}\,\Gamma(S \to W^+W^-) \;\propto\; \sin^2\theta}$$



decays from the same $S\,H^\dagger H$ vertex

One generically expects correlated BSM signatures involving final states with vector bosons.

- hh always comes with ZZ and WW (and fermions, via mixing)
- all of them switch off together as sin θ → 0
- hhh and hhhh are further suppressed

⇒ **Can hh, hhh, hhhh dominate while WW, ZZ and fermion pairs are suppressed?**

Present work: **A New Regime — Multi-Higgs as the Leading Discovery Mode**

- Parametrically breaks this correlation *Br(S→hh) = Br(S→ZZ) = ½ Br(S→WW)*

- Identify scenarios where WW, ZZ, $f\bar{f}$ final states are all parametrically suppressed by alignment, while hh, hhh and hhhh final states emerge as the primary, and potentially unique, discovery signatures of extended scalar sectors at the LHC.

$$pp \to \begin{cases} \text{cascade:} & s_1 \to h s_2 \ \ (s_2 \to hh) \ \to hhh, \\ & s_1 \to s_2 s_2 \ \ (s_2 \to hh) \ \to hhhh, \\ \text{direct:} & s \to hh,\ hhh,\ hhhh\,. \end{cases}$$

Phenomenologically motivated Model Setup: (Cascade scenario)

Two Real Singlet Scalars + VLQ

SM extended by S_1, S_2 (real gauge singlets) and vector-like quark T ~ (3, 1, 2/3)

Lagrangian & Key Operators:

- $V(H, S_1, S_2) = V_{\text{ren}} + V_{\text{dim5}}.$

  - $$V_{\text{ren}} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{m_1^2}{2} S_1^2 + \frac{m_2^2}{2} S_2^2 + \mu_{12}^2 S_1 S_2 + a_1 S_1 H^\dagger H + a_2 S_2 H^\dagger H + \kappa S_1 S_2 H^\dagger H + \frac{\lambda_{HS_1}}{2} S_1^2 H^\dagger H + \frac{\lambda_{HS_2}}{2} S_2^2 H^\dagger H + \frac{\lambda_1}{4} S_1^4 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_{12}}{2} S_1^2 S_2^2,$$

  - $$V_{\text{dim5}} = \frac{c_5}{\Lambda} S_2 (H^\dagger H)^2$$

- $$H = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}, \qquad S_1 = v_1 + s_1, \qquad S_2 = v_2 + s_2,$$

- $$\mathcal{L} \supset \frac{1}{2}(\partial_\mu S_1)^2 + \frac{1}{2}(\partial_\mu S_2)^2 - V(H, S_1, S_2) + \bar{T}(i\not{D} - M_T)T - y_T S_1 \bar{T} T\,.$$

- $$\mathcal{L}_{\text{eff}} \supset c_{g1}\, s_1\, G^a_{\mu\nu} G^{a\mu\nu}, \qquad c_{g1} = \frac{\alpha_s}{12\pi} \frac{y_T}{M_T}$$

S_2 Decay: Mixing vs. Trilinear Coupling

- Naively, the decays of the singlet S_2 are expected to be controlled by its Higgs-doublet admixture, which is determined by the **h – S_2** mass mixing (**$\partial^2 V/\partial s_2 \partial h$**).
- The trilinear coupling **S_2hh**, however, is determined by a different quantity, namely **$\partial^3 V/\partial s_2 \partial h \partial h$**.
- Up to dimension-4 operators, **SU(2)** symmetry forces these two quantities to be proportional, leading to **correlated mixing and decay.**
- **Higher-dimensional operators** break this correlation, allowing small **h – S_2** mixing while maintaining a sizable **S_2hh** coupling.

Separating the mixing from the hh coupling

mixing $$M^2_{hs_2} = v\,(a_2 + \kappa v_1 + \lambda_{HS_2} v_2) \;+\; 1 \cdot \frac{c_5}{\Lambda}\, v^3$$

hh coupling $$g_{s_2hh} = a_2 + \kappa v_1 + \lambda_{HS_2} v_2 \;+\; 3 \cdot \frac{c_5}{\Lambda}\, v^2 \;=\; \frac{M^2_{hs_2}}{v} + 2\,\frac{c_5}{\Lambda}\, v^2$$

Goldstones $$g_{s_2G^0G^0},\; g_{s_2G^+G^-} \;\propto\; \frac{M^2_{hs_2}}{v}$$

$$M^2_{hs_2} \simeq 0 \implies g_{s_2hh} \simeq 2\,\frac{c_5}{\Lambda}\, v^2\,, \qquad g_{s_2GG} \to 0$$

Renormalizable terms alone give $g_{s2hh} = g_{s2GG} = M^2_{hs2}/v$, and alignment would remove hh as well.

Origin of the 3

$H^\dagger H = \tfrac{1}{2}(v+h)^2 + G^+G^- + \tfrac{1}{2}(G^0)^2$

$$(H^\dagger H)^2 \supset v^3 h + \underbrace{\tfrac{3}{2} v^2 h^2}_{6\text{ ways}} + \underbrace{\tfrac{1}{2} v^2 (G^0)^2 + v^2\, G^+G^-}_{2\text{ ways each}} + \dots$$

Two h's from $(v+h)^4$: six ways.
A Goldstone pair: two ways.
The mixing term v^3h comes with weight one.

⇒ s_2 stays singlet-like ($\sin\theta_2 \lesssim 10^{-2}$) yet decays almost entirely into hh

Branching Fractions: Quantitative Demonstration

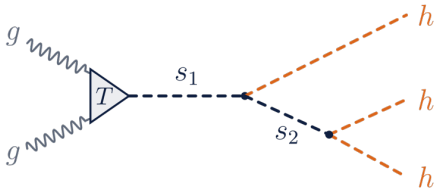
Mass-squared matrix elements

$$
\begin{aligned}
M^2_{hh} &= 2\lambda_H v^2 + \frac{2c_5}{\Lambda} v^2 v_2, \\
M^2_{hs_1} &= v(a_1 + \kappa v_2 + \lambda_{H1} v_1), \\
M^2_{hs_2} &= v(a_2 + \kappa v_1 + \lambda_{H2} v_2) + \frac{c_5}{\Lambda} v^3, \\
M^2_{s_1 s_1} &= m_1^2 + \frac{1}{2}\lambda_{H1} v^2 + 3\lambda_1 v_1^2 + \lambda_{12} v_2^2, \\
M^2_{s_2 s_2} &= m_2^2 + \frac{1}{2}\lambda_{H2} v^2 + 3\lambda_2 v_2^2 + \lambda_{12} v_1^2, \\
M^2_{s_1 s_2} &= \mu_{12}^2 + \frac{1}{2}\kappa v^2 + 2\lambda_{12} v_1 v_2.
\end{aligned}
$$

Alignment Conditions

$$
\begin{aligned}
a_1 + \kappa v_2 + \lambda_{H1} v_1 &\simeq 0, \\
a_2 + \kappa v_1 + \lambda_{H2} v_2 + \frac{c_5}{\Lambda} v^2 &\simeq 0, \\
\mu_{12}^2 + \frac{1}{2}\kappa v^2 + 2\lambda_{12} v_1 v_2 &\simeq 0.
\end{aligned}
$$

$s_1 \to h\, s_2 \to hhh$ *(6b)*

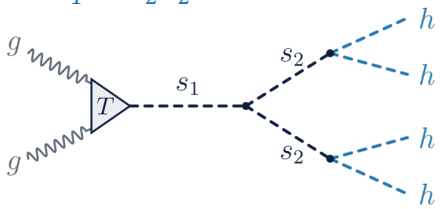


Cascade couplings that survive alignment:

$g_{s_1 s_2 h} = \kappa v$ *controls* $s_1 \to h s_2 \;\; (s_2 \to hh) \;\to hhh,$ *(asymmetric topology)*

$g_{s_1 s_2 s_2} = 2\lambda_{12} v$, *controls* $s_1 \to s_2 s_2 \;\; (s_2 \to hh) \;\to hhhh,$ *(symmetric topology)*

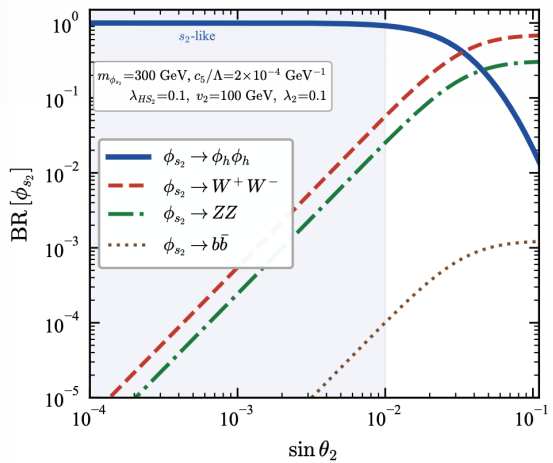
$s_1 \to s_2 s_2 \to hhhh$ *(8b)*

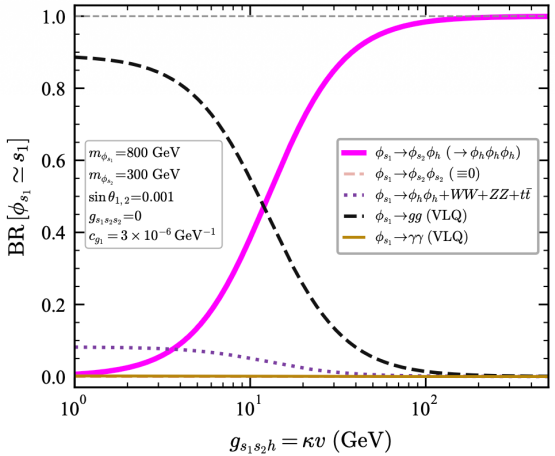


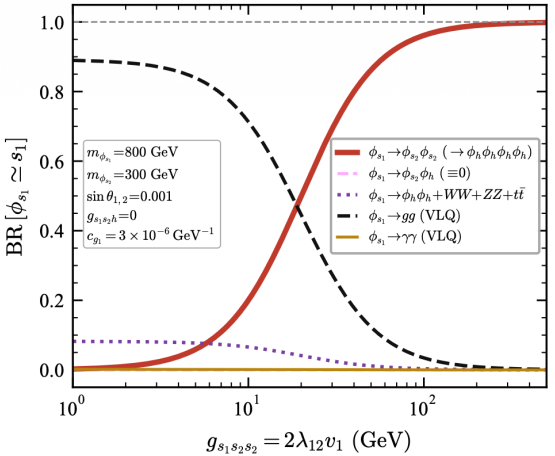
S_1 production cross-section will depend on the effective coupling with gluons

Branching Fractions: Quantitative Demonstration

Benchmark (m_{s1}, m_{s2}) = (800, 300) GeV, $c_5/\Lambda = 2\times10^{-4}$ GeV^{-1}, $c_g_1 = 3\times10^{-6}$ GeV^{-1}







$s_2 \to hh$ dominates for $\sin\theta_2 \lesssim 10^{-2}$

$s_1 \to s_2 h$ as κv grows $\Rightarrow$ hhh

$s_1 \to s_2 s_2$ as $2\lambda_{12} v_1$ grows $\Rightarrow$ hhhh

$$\mathrm{BR}_{\mathrm{eff}}(hhh) = \mathrm{BR}(s_1 \to s_2 h)\,\mathrm{BR}(s_2 \to hh), \qquad \mathrm{BR}_{\mathrm{eff}}(hhhh) = \mathrm{BR}(s_1 \to s_2 s_2)\left[\mathrm{BR}(s_2 \to hh)\right]^2$$

$\Rightarrow$ Loop-induced gg, γγ become subleading; BR(hh), $\mathrm{BR}_{\mathrm{eff}}$(hhh) and $\mathrm{BR}_{\mathrm{eff}}$(hhhh) can all approach one

Signal rates and current bounds

$$\sigma(pp \to hhh,\, hhhh) \;\simeq\; \sigma(pp \to s_1) \times \mathrm{BR}_{\mathrm{eff}} \;\approx\; 15\ \mathrm{fb} \times 1$$

$\sigma(pp \to s_1)$ at LO with MG5_aMC@NLO, $\sqrt{s}$ = 14 TeV, $c_{g1} = 3\times10^{-6}$ GeV^{-1}

Search ($\sqrt{s}$ = 13 TeV, 95% CL)	**Bound**
CMS, non-resonant hhh → 6b CMS-PAS-HIG-24-012	$\lesssim$ 44 fb
ATLAS, non-resonant hhh → 6b arXiv:2411.02040	$\lesssim$ 59 fb
ATLAS, resonant X → Sh → hhh at (800, 300) GeV arXiv:2411.02040	≈ 17 – 20 fb

resonant bound: narrow / large width

- hhhh → 8b: no dedicated search yet
- many b-jets and large combinatorics, but correlated mass peaks help
- no excess: lower c_{g1}; the decay pattern is unchanged

⇒ The benchmark is allowed and close to current sensitivity: a target for Run 3 and the HL-LHC

Reconstructing the cascade

1. Higgs candidates

$$\chi^2_h = \sum_{i=1}^{N} \left(m^{(i)}_{b\bar{b}} - m_h\right)^2$$

used only to rank the b-jet pairings

2. Intermediate s_2

$$\Delta_{s_2} = \left|m^{(1)}_{hh} - m^{(2)}_{hh}\right|$$

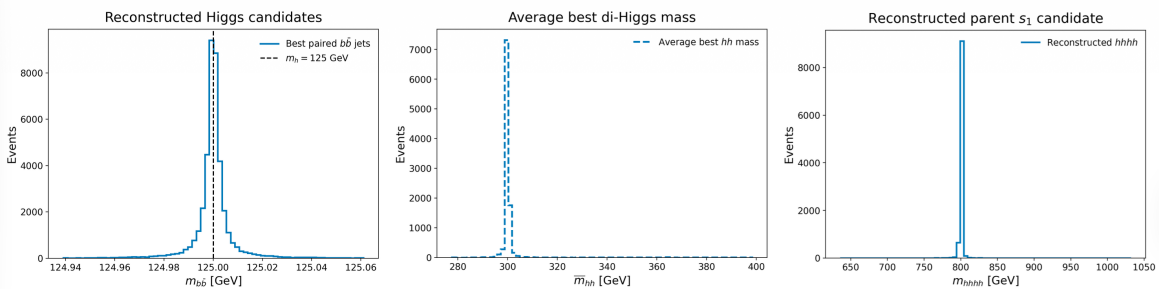
hhhh: clean $\bar{m}_{hh}$ peak; hhh: one true pair of three, on a combinatorial floor

3. Parent s_1

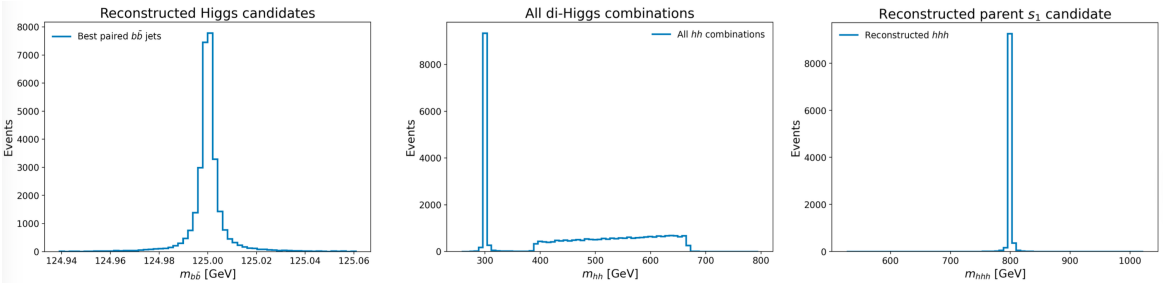
$$m^2_{h^N} = \left(\sum_{i=1}^{N} p_{h_i}\right)^2$$

the full system peaks at m_{s1}

$s_1 \to s_2 s_2 \to hhhh$ — *parton level, (m_{s1}, m_{s2}) = (800, 300) GeV*



$s_1 \to s_2 h \to hhh$



⇒ Correlated peaks at m_h, m_{s2}, m_{s1} separate hhh from hhhh

A one-singlet realization

$$V(H,S) \supset a_1\, S H^\dagger H + \frac{c_5}{\Lambda}\, S (H^\dagger H)^2 + \frac{c_7}{\Lambda^3}\, S (H^\dagger H)^3$$

Alignment, $M^2_{hs} = 0$, leaves

$$g_{shh}^{\text{align}} = \frac{3c_7 v^4 + 2c_5 v^2 \Lambda^2}{\Lambda^3}, \qquad g_{shhh}^{\text{align}} = \frac{3\left(5c_7 v^3 + 2c_5 v \Lambda^2\right)}{\Lambda^3}$$

Cancelling the di-Higgs coupling:

$$c_5 = -\frac{3c_7 v^2}{2\Lambda^2} \implies g_{shh} = 0, \qquad g_{shhh} = \frac{6\, c_7 v^3}{\Lambda^3}$$

$s \to hhh$ dominates; hhhh would need $c_9 S(H^\dagger H)^4$ and further correlated cancellations.

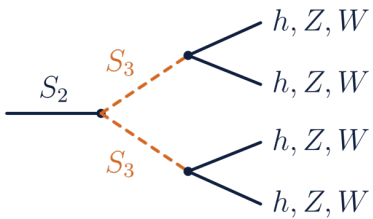
	Cascade	**Direct**
intermediate state	s_2 resonance	none
kinematics	peaks at m_h, m_{s2}, m_{s1}	single scale, smooth
tuning	alignment relations	cancellations across operator dimensions
final states	hhh, hhhh	hh, hhh

⇒ Same final states, different kinematics: the mass spectra identify the mechanism

UV completion and the 2HDM analogy

Heavy singlet S_3 $(m_{S_3} > \sqrt{s})$

$$V_{\rm UV} \supset \tfrac{1}{2} M_3^2 S_3^2 + \frac{\mu_{23}}{2} S_2 S_3^2 + \mu_{3H}\, S_3\, (H^\dagger H)$$



$$\frac{c_5}{\Lambda} = \frac{\mu_{23}\, \mu_{3H}^2}{2 M_3^4}$$

The 3 comes from expanding H†H after EWSB, not from the matching.

Gluon coupling

$c_{g1} = (\alpha_s/12\pi)(y_{T,1}/M_T) = 3\times10^{-6}$ GeV^{-1} needs $M_T \sim$ TeV for

$y_{T,1} \sim 1$, compatible with VLQ searches.

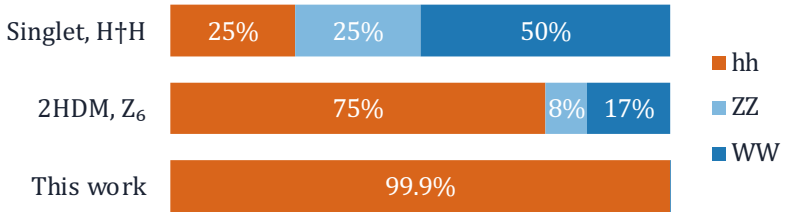
⇒ Same origin as in the 2HDM, but here the Goldstone couplings vanish at alignment while g_{s2hh} survives

2HDM, Higgs basis

$$Z_6\, (H_1^\dagger H_1)(H_1^\dagger H_2) + \text{h.c.} \implies g_{Hhh} = 3\, g_{HG^0G^0}$$

$$\Gamma(H \to hh) : \Gamma(H \to W^+W^-) : \Gamma(H \to ZZ) \simeq 9 : 2 : 1$$

Same counting as for $(H^\dagger H)^2$, but Z_6 also sets the h–H mixing: hh switches off with WW and ZZ at alignment.



bosonic decays; 2HDM: Coloretti, Crivellin, Haber, 2512.24868

– Higher-dimensional Higgs operators enhancing Higgs-rich final states, complementary to the alignment regime studied here [Li, Liu, Wang, 2604.14284];

Conclusions

- Extended scalar sectors can naturally realise regimes where hh, hhh and hhhh are the dominant, often unique, collider signatures, contrary to standard lore (away from $Br(S \to hh) = Br(S \to ZZ) = \frac{1}{2} Br(S \to WW)$ regime).

- Two ingredients: alignment suppresses S→WW, ZZ, ff, while a higher-dimensional operator mismatch between the mixing and various couplings — a parametric separation not possible with renormalisable terms alone.

- Two complementary realisations:
  - Two-singlet cascade (robust, accommodates both hhh and hhhh via intermediate s_2)
  - single-singlet EFT (direct decays, requires correlated operator tuning). Same final states, distinct kinematics.

- Benchmark 15 fb signal ($\sqrt{s}$=14 TeV) is compatible with current LHC limits — within prospective reach of Run 3 and HL-LHC dedicated searches

Triple- and quadruple-Higgs final states: powerful & largely unexplored discovery channel for BSM physics at the LHC

Backup

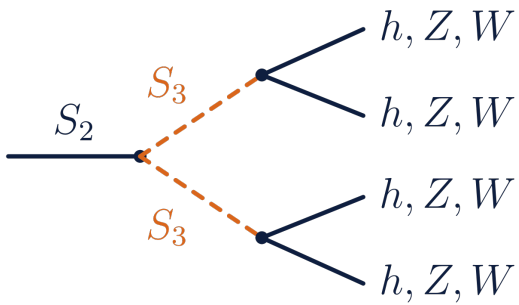
Integrating out S_3

Heavy real singlet S_3, $M_3 \gg v, m_{s2}$:

$$V_{\rm UV} \supset \tfrac{1}{2} M_3^2 S_3^2 + \frac{\mu_{23}}{2} S_2 S_3^2 + \mu_{3H}\, S_3\, (H^\dagger H)$$

Tree-level equation of motion, derivatives neglected:

$$S_3 \simeq -\frac{\mu_{3H}\,(H^\dagger H)}{M_3^2 + \mu_{23} S_2}$$



Expanding in $1/M_3$:

$$\Delta V_{\rm eff} = -\frac{\mu_{3H}^2}{2M_3^2}(H^\dagger H)^2 + \frac{\mu_{23}\mu_{3H}^2}{2M_3^4}\, S_2 (H^\dagger H)^2 - \frac{\mu_{23}^2\mu_{3H}^2}{2M_3^6}\, S_2^2 (H^\dagger H)^2 + \cdots$$

$$\frac{c_5}{\Lambda} = \frac{\mu_{23}\,\mu_{3H}^2}{2M_3^4}$$

The first term shifts λ_H , the second is the operator of the main text.

Mass matrix, alignment and cascade couplings

$$V_{\rm ren} = -\mu_H^2 H^\dagger H + \lambda_H (H^\dagger H)^2 + \frac{m_1^2}{2} S_1^2 + \frac{m_2^2}{2} S_2^2 + \mu_{12}^2 S_1 S_2 + a_1 S_1 H^\dagger H + a_2 S_2 H^\dagger H + \kappa S_1 S_2 H^\dagger H + \frac{\lambda_{HS_1}}{2} S_1^2 H^\dagger H + \frac{\lambda_{HS_2}}{2} S_2^2 H^\dagger H + \frac{\lambda_1}{4} S_1^4 + \frac{\lambda_2}{4} S_2^4 + \frac{\lambda_{12}}{2} S_1^2 S_2^2$$

CP-even mass matrix in the (h, s_1, s_2) basis

$$\begin{aligned} M^2_{hh} &= 2\lambda_H v^2 + \tfrac{2c_5}{\Lambda} v^2 v_2 \\ M^2_{hs_1} &= v\,(a_1 + \kappa v_2 + \lambda_{HS_1} v_1) \\ M^2_{hs_2} &= v\,(a_2 + \kappa v_1 + \lambda_{HS_2} v_2) + \tfrac{c_5}{\Lambda} v^3 \\ M^2_{s_1 s_1} &= m_1^2 + \tfrac{1}{2}\lambda_{HS_1} v^2 + 3\lambda_1 v_1^2 + \lambda_{12} v_2^2 \\ M^2_{s_2 s_2} &= m_2^2 + \tfrac{1}{2}\lambda_{HS_2} v^2 + 3\lambda_2 v_2^2 + \lambda_{12} v_1^2 \\ M^2_{s_1 s_2} &= \mu_{12}^2 + \tfrac{1}{2}\kappa v^2 + 2\lambda_{12} v_1 v_2 \end{aligned}$$

Alignment, $|M^2_{hsi}| \ll$ mass splittings

$$\begin{aligned} a_1 + \kappa v_2 + \lambda_{HS_1} v_1 &\simeq 0 \\ a_2 + \kappa v_1 + \lambda_{HS_2} v_2 + \tfrac{c_5}{\Lambda} v^2 &\simeq 0 \\ \mu_{12}^2 + \tfrac{1}{2}\kappa v^2 + 2\lambda_{12} v_1 v_2 &\simeq 0 \end{aligned}$$

Cubic couplings in the aligned regime

$$\begin{aligned} g_{s_1 hh} &= a_1 + \kappa v_2 + \lambda_{HS_1} v_1 \;\simeq\; 0 \\ g_{s_2 hh} &= a_2 + \kappa v_1 + \lambda_{HS_2} v_2 + 3\tfrac{c_5}{\Lambda} v^2 \;\simeq\; 2\tfrac{c_5}{\Lambda} v^2 \\ g_{s_1 s_2 h} &= \kappa v, \qquad g_{s_1 s_2 s_2} = 2\lambda_{12} v_1 \end{aligned}$$

$\tan 2\theta_i \simeq 2M^2_{hsi} / (M^2_{sisi} - M^2_{hh})$; residual s_1–s_2 mixing is $O(\theta_1\theta_2)$.