Φαινό 2026
The 2026 Phenomenology Symposium
An odyssey through particle physics and related encounters in astrophysics and cosmology

A Busy Higgs Signal

Multi-Higgs final states as leading discovery modes for new resonances

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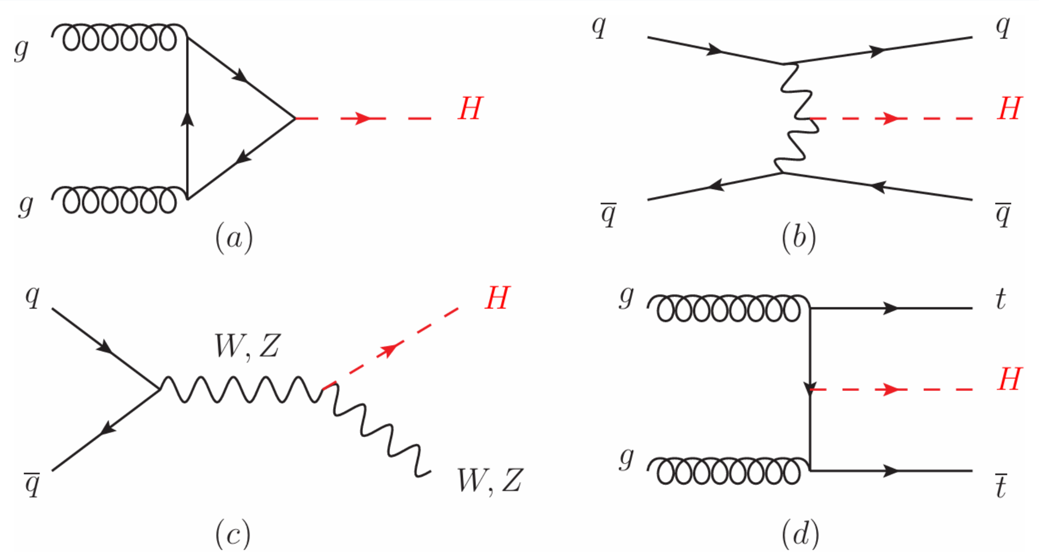
Collaborate with Zhen Liu and Lian-Tao Wang

arXiv:2604.14284

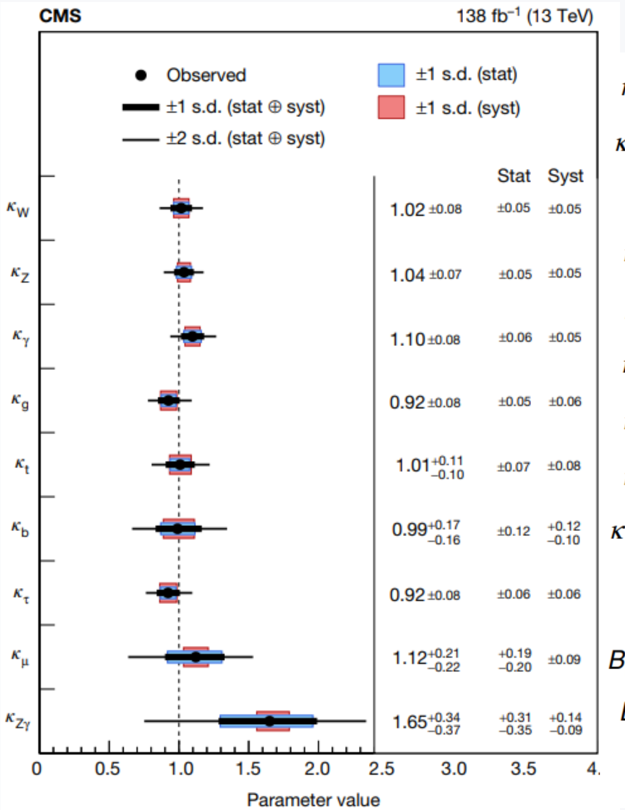
Motivation

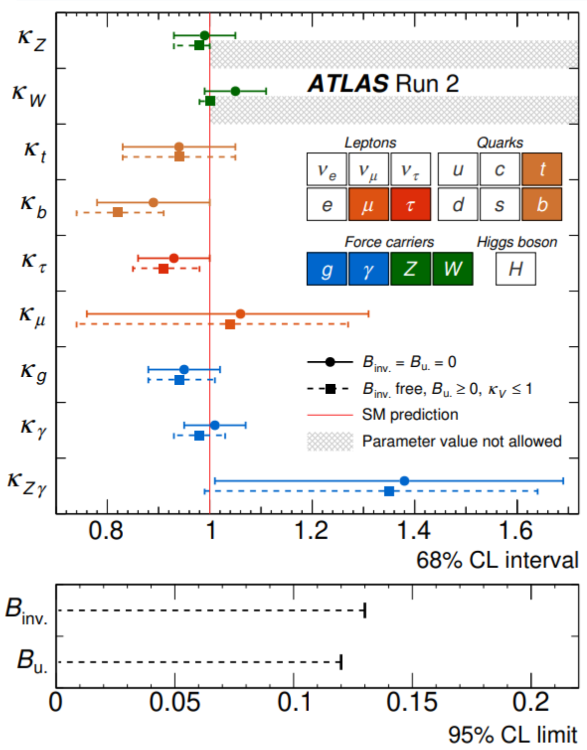
Higgs measurements at the LHC

- Higgs decays: measurements of Higgs couplings



Single Higgs study



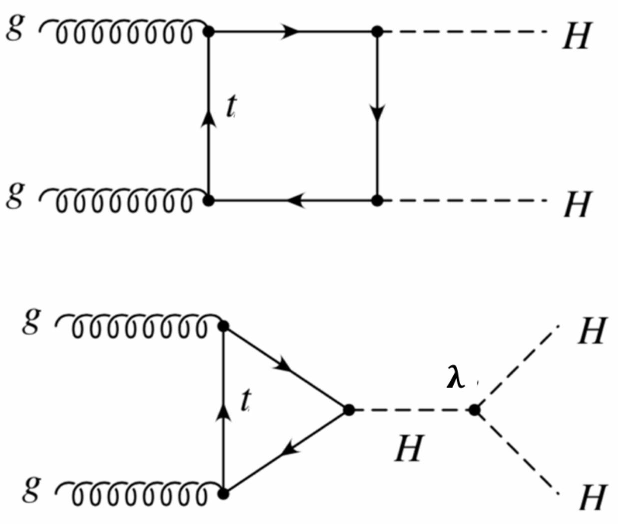


[2207.00092] A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery
[2207.00043] A portrait of the Higgs boson by the CMS experiment ten years after the discovery
etc.

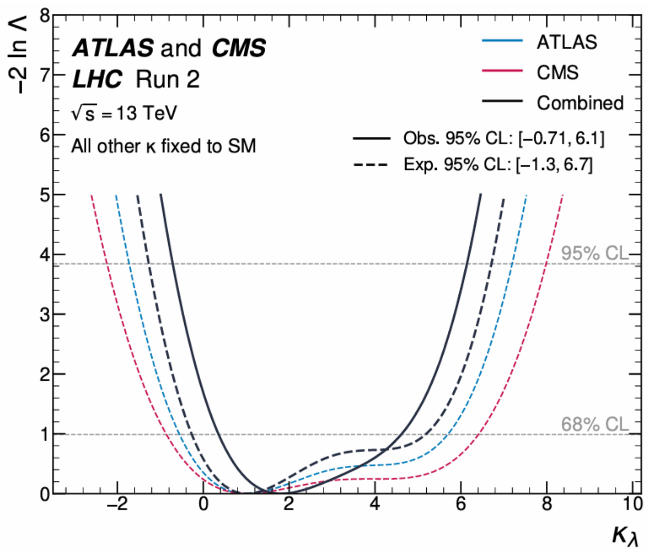
Motivation

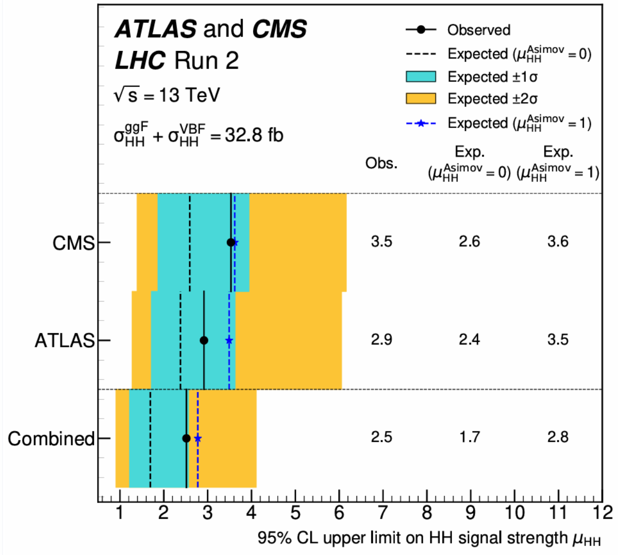
Higgs measurements at the LHC

- Higgs decays: measurements of Higgs couplings
- di-Higgs probes the Higgs self-coupling λ_3



Di-Higgs study





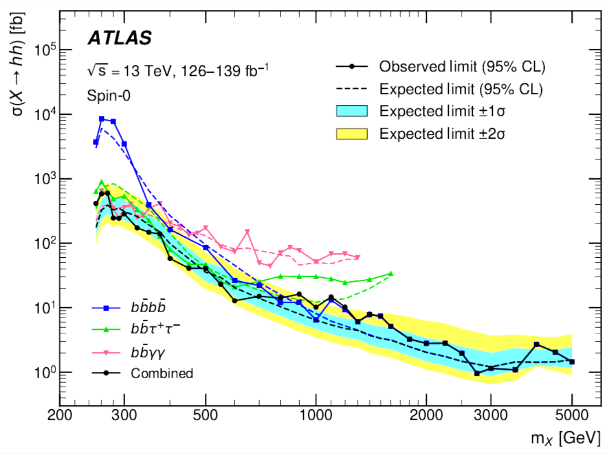
[2602.23991] Combination of ATLAS and CMS searches for Higgs boson pair production
[2406.09971] Searches for Higgs boson pair production in pp collisions at 13 TeV with the ATLAS detector
[2510.07527] Searches for nonresonant Higgs boson pair production in proton-proton collisions at 13 TeV
etc.

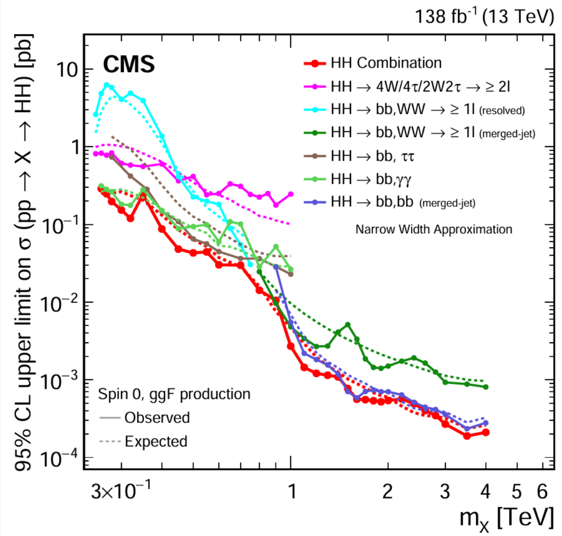
Motivation

Higgs measurements at the LHC

- Higgs decays: measurements of Higgs couplings
- di-Higgs probes the Higgs self-coupling λ_3
- new resonances coupled to Higgs can appear as X → hh

Large experimental effort in X → hh





- many dedicated ATLAS/CMS searches
- bbγγ, bbττ, bbbb, bbWW, multileptons, …

[2311.15956] Combination of searches for resonant Higgs boson pair production using pp collisions at 13 TeV with the ATLAS detector
[2403.16926] Searches for Higgs boson production through decays of heavy resonances
[2202.07288] Search for resonant pair production of Higgs bosons in the 4b final state using pp collisions at 13 TeV with the ATLAS detector
[2112.11876] Search for Higgs boson pair production in the two bottom quarks plus two photons final state in pp collisions at 13 TeV with the ATLAS detector
[2006.06391] Search for resonant pair production of Higgs bosons in the bbZZ channel in proton-proton collisions at 13 TeV
etc.

Motivation

Higgs measurements at the LHC

- Higgs decays: measurements of Higgs couplings
- di-Higgs probes the Higgs self-coupling λ_3
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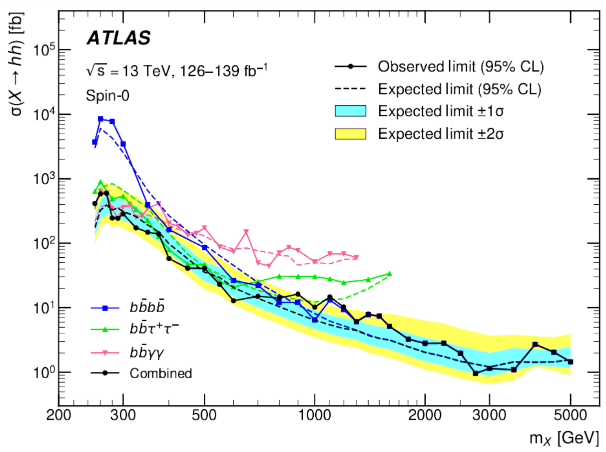
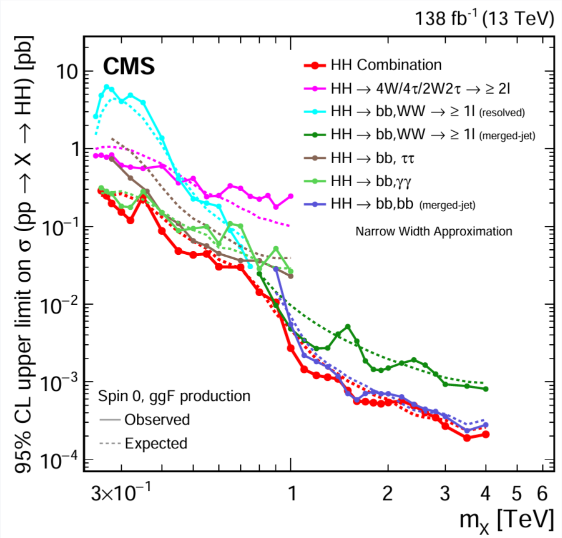
$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} a_1 + i a_2 \\ v + h + i a_0 \end{pmatrix}$$

$$a^0 \sim Z_L \qquad a_{1,2} \sim W_L^{\pm}$$

If a heavy resonance couples to hh, it can easily couple to $Z_L Z_L$ and $W_L W_L$.

Large experimental effort in X → hh





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But wait: H contains not only h, but also Goldstones
Is hh final state really a special channel?
So why not just search in ZZ / WW instead?

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} a_1 + ia_2 \\ v + h + ia_0 \end{pmatrix}$$

The conventional expectation

Heavy resonance coupled through the Higgs portal

$$\mathcal{L} \supset \boldsymbol{g\, SH^\dagger H} + \frac{1}{2}M^2 S^2$$

$$H^\dagger H \;=\; ½[(v+h)^2 + a_0{}^2 + a_1{}^2 + a_2{}^2]$$

$$\mathcal{L} \supset \boldsymbol{g\, S(h^2 + a_0^2 + a_1^2 + a_2^2)}$$

At quadratic order:
h and Goldstones enter symmetrically

Goldstone Equivalence Theorem

BR(S→hh) : BR(S→ZZ) : BR(S→WW)
= 1 : 1 : 2

- Diboson and di-Higgs searches are comparable
- No obvious reason for **hh** to be better

The conventional expectation

Heavy resonance coupled through the Higgs portal

$$\mathcal{L} \supset g\, S (D^\mu H)^\dagger (D_\mu H)$$

or

$$\mathcal{L} \supset g\, \partial_\mu S \partial^\mu (H^\dagger H)$$

...

At quadratic order:
h and Goldstones enter symmetrically

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Question: can Higgs final states drive the discovery?

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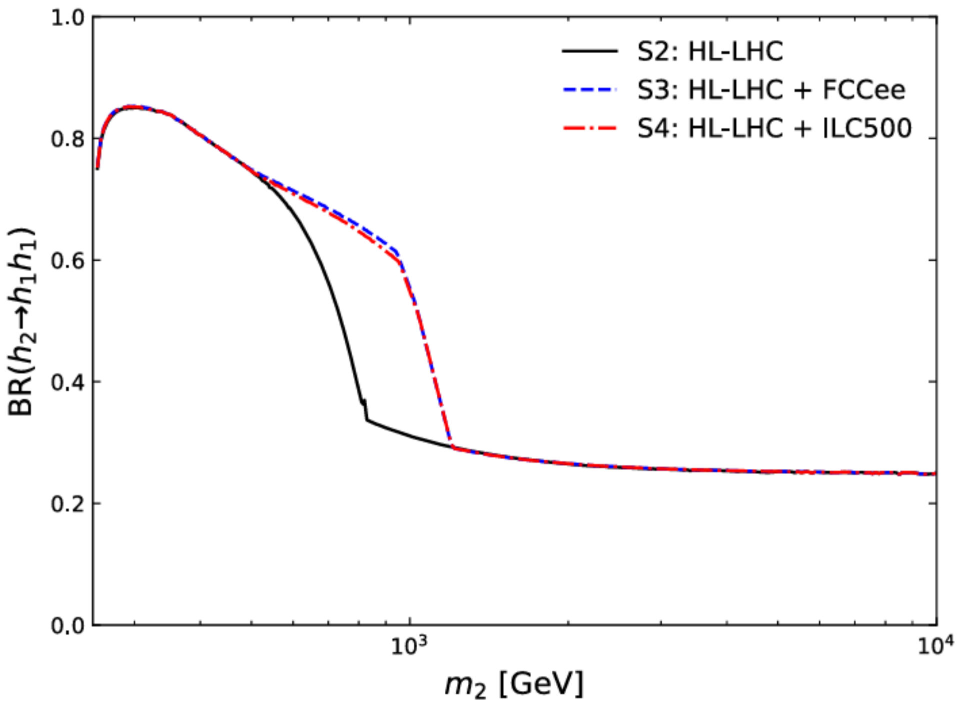
Heavy resonance coupled through the Higgs portal



Ian M. Lewis, Jacob Scott, Miguel A. Soto Alcaraz, Matthew Sullivan [2410.08275]

Goldstone Equivalence Theorem

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Question: can Higgs final states drive the discovery?

Punchline: a higher-order Higgs structure changes the story

$$H = \frac{1}{\sqrt{2}}\begin{pmatrix} a_1 + i a_2 \\ v + h + i a_0 \end{pmatrix}$$

$$\mathcal{L} \supset S\left(H^\dagger H\right)^n$$
$$\rightarrow S\left[(v+h)^2 + a_i^2\right]^n$$
$$\rightarrow n * S a_i^2 v^{2n-2} + \binom{2n}{2} * S h^2 v^{2n-2} + \cdots$$

BR(S→hh) : BR(S→ZZ) : BR(S→WW)
= $(2n\text{-}1)^2$: 1 : 2

- The branching ratio remain as $m_S \gg v$

Punchline: a higher-order Higgs structure changes the story

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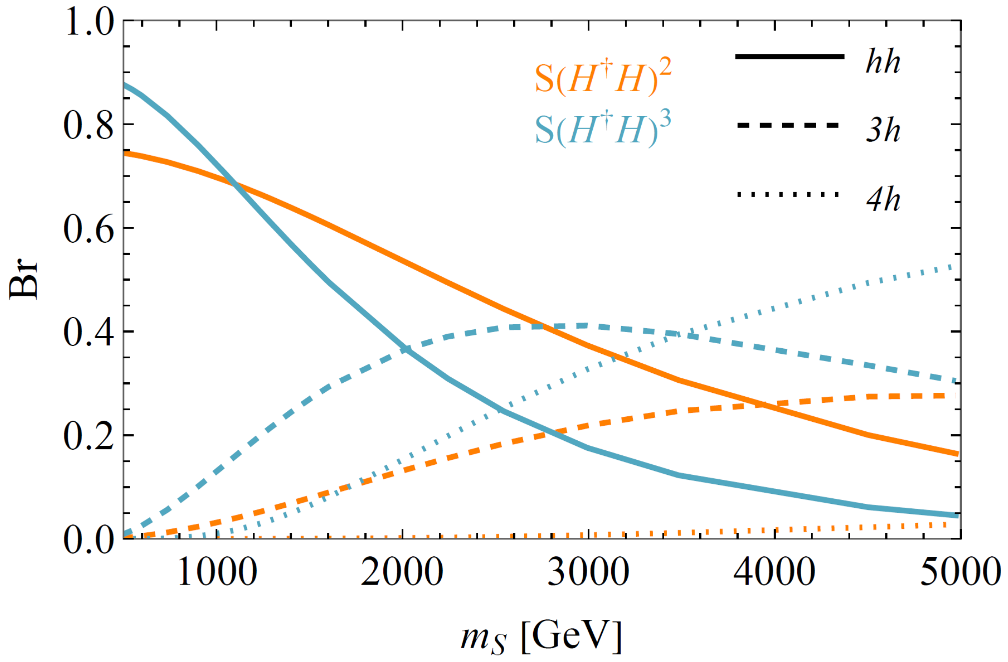
$$\rightarrow S\left[(v+h)^2 + a_i^2\right]^n$$
$$\rightarrow n * S a_i^2 v^{2n-2} + \binom{2n}{2} * S h^2 v^{2n-2}$$
$$+ \binom{2n}{3} * S h^3 v^{2n-3} + \binom{2n}{4} * S h^4 v^{2n-4}$$
$$\dots$$

BR(S→hh) : BR(S→ZZ) : BR(S→WW)
= $(2n-1)^2$: 1 : 2

- The branching ratio remain as $m_S \gg v$
- Result: Higgs-rich channels can become leading search modes

Busy Higgs Signal

At high mass: multi-Higgs modes become motivated



- Three- and four-body final states are phase-space suppressed at low mass
- But multi-body phase space grows with m_S

$$\Phi_n = \int \delta^4(P - \sum_i^n p_i) \prod_i^n \frac{d^3 p_i}{(2\pi)^3 2E_i}$$

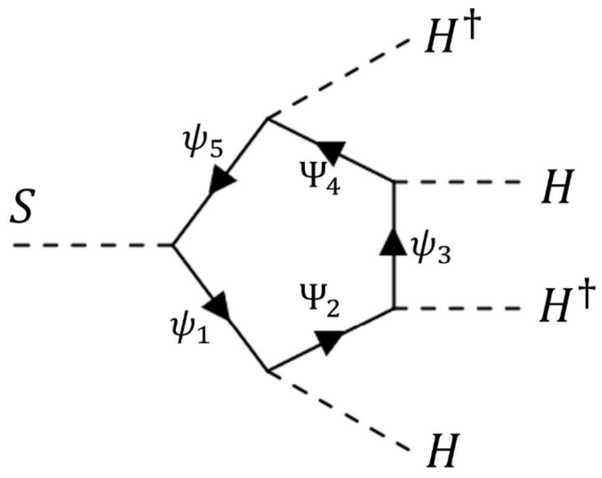
$$\Phi_2 = 1/(8\pi), \qquad \Phi_3 = m_S^2/(256\pi)$$

- The same busy operator gives large Sh^3 and Sh^4 combinatorics

$$\binom{2n}{3} * Sh^3 v^{2n-3} + \binom{2n}{4} * Sh^4 v^{2n-4}$$

Resonant hhh and hhhh searches are natural follow-ups for multi-TeV S.

UV story: how to make these busy operator? $\frac{c_n}{\Lambda^{2n-3}} S\left(H^\dagger H\right)^n$



$$\mathcal{L} \supset -(\overline{\Psi}_2 H)\psi_1 - \overline{\psi}_3(H^\dagger \Psi_2) - (\overline{\Psi}_4 H)\psi_3 - \overline{\psi}_5(H^\dagger \Psi_4) - S\overline{\psi}_1\psi_5 + \text{h.c.}$$

- 2HDM/Froggatt–Nielsen-like charge assignments can control the leading operator: Promote $H^\dagger H$ to $H_u H_d$ in order to assign charges for symmetry protection.

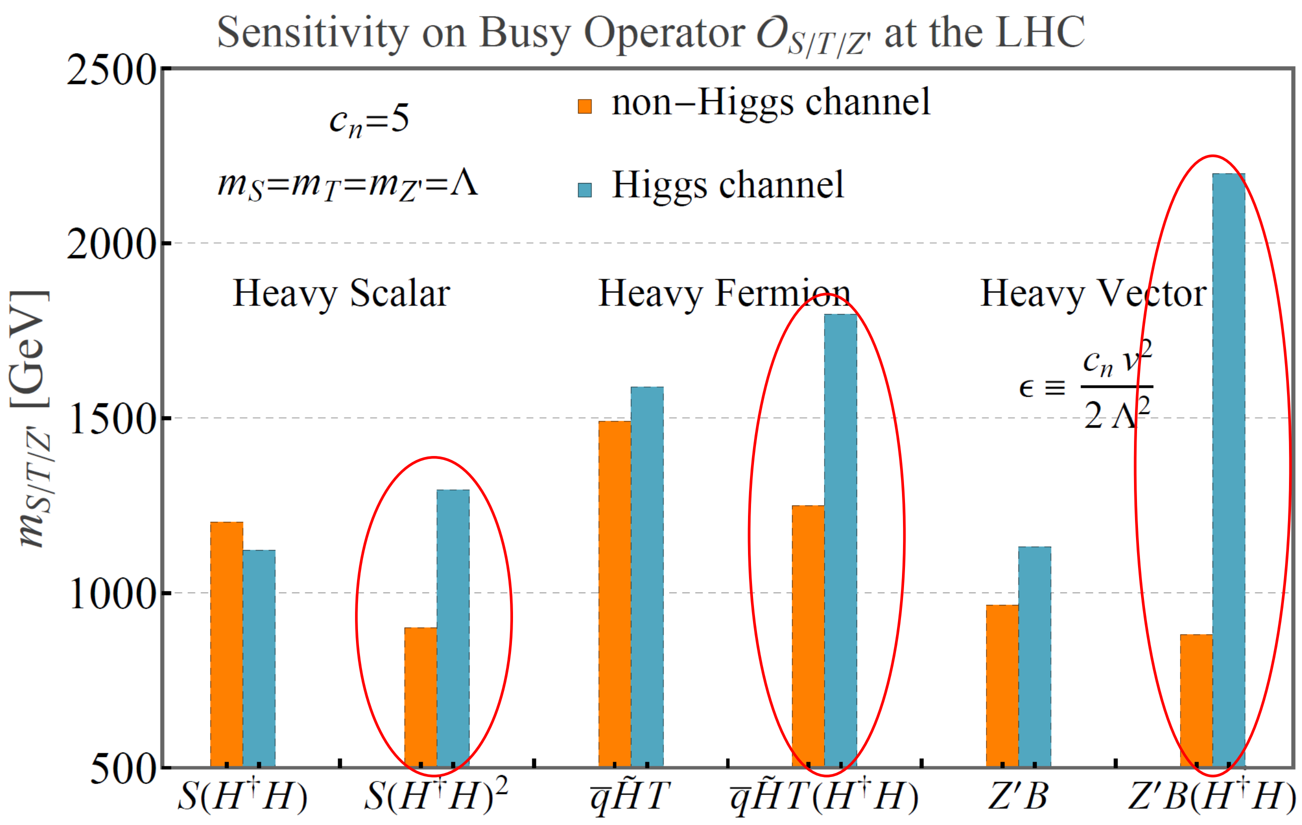
$$\mathcal{L} \supset -(\overline{\Psi}_2 H_u)\psi_1 - \overline{\psi}_3(\Psi_2^T \epsilon H_d) - (\overline{\Psi}_4 H_u)\psi_3 - \overline{\psi}_5(\Psi_4^T \epsilon H_d) - \Phi\overline{\psi}_1\psi_5 + \text{h.c.}$$

The same logic extends beyond scalars

Resonance	Busy operator	Enhanced channel
Scalar S	$S(H^\dagger H)^2$	**Br(hh) : Br(ZZ) ≈ 9 : 1**
Fermion T	$(H^\dagger H)\,\bar{q}\tilde{H}T$	**Br(ht) : Br(Zt) ≈ 9 : 1**
Vector Z'	$Z'_{\mu\nu}\,B^{\mu\nu}\,(H^\dagger H)$	**Br(Zh/γh) : Br(WW) ≈ 30 : 1** **($m_{Z'}$= 1 TeV)**
Spin-2	$h_{\mu\nu}D^\mu H^\dagger D^\nu H \cdot (H^\dagger H)^n$	**hhh,...**

The busy Higgs operator can be generalized.

Combined reach: Higgs channels become leading channels



$$\frac{c_n}{\Lambda^{2n-3}} S\left(H^\dagger H\right)^n, \quad \frac{c_n}{\Lambda^{2n}} \left(H^\dagger H\right)^n \bar{q}\tilde{H}T, \quad \frac{c_n}{\Lambda^{2n}} Z'_{\mu\nu} B^{\mu\nu} \left(H^\dagger H\right)^n$$

- Heavy scalar: $hh > ZZ/WW$
- Heavy fermion: $ht > Zt/Wb$
- Heavy vector: $Zh/\gamma h \gg WW$

Higgs-rich final states can outperform conventional non-Higgs channels.

Summary

1 Higher-order Higgs structures can violate the usual hh–VV correlation.

BR(S→hh) : BR(S→ZZ) : BR(S→WW)
= 1 : 1 : 2

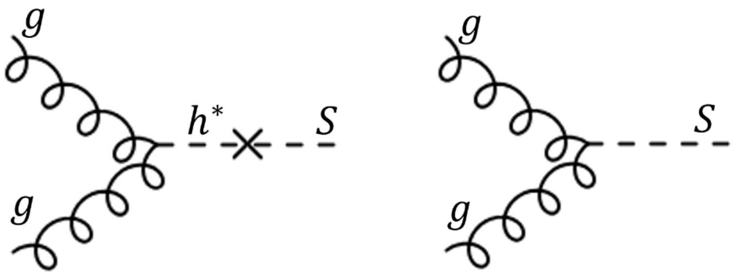
2 For scalars, di-Higgs and even multi-Higgs final states can become leading signals.

3 The same mechanism motivates ht, Zh, and γh searches for fermion/vector resonances.

Thank you!

Back Up

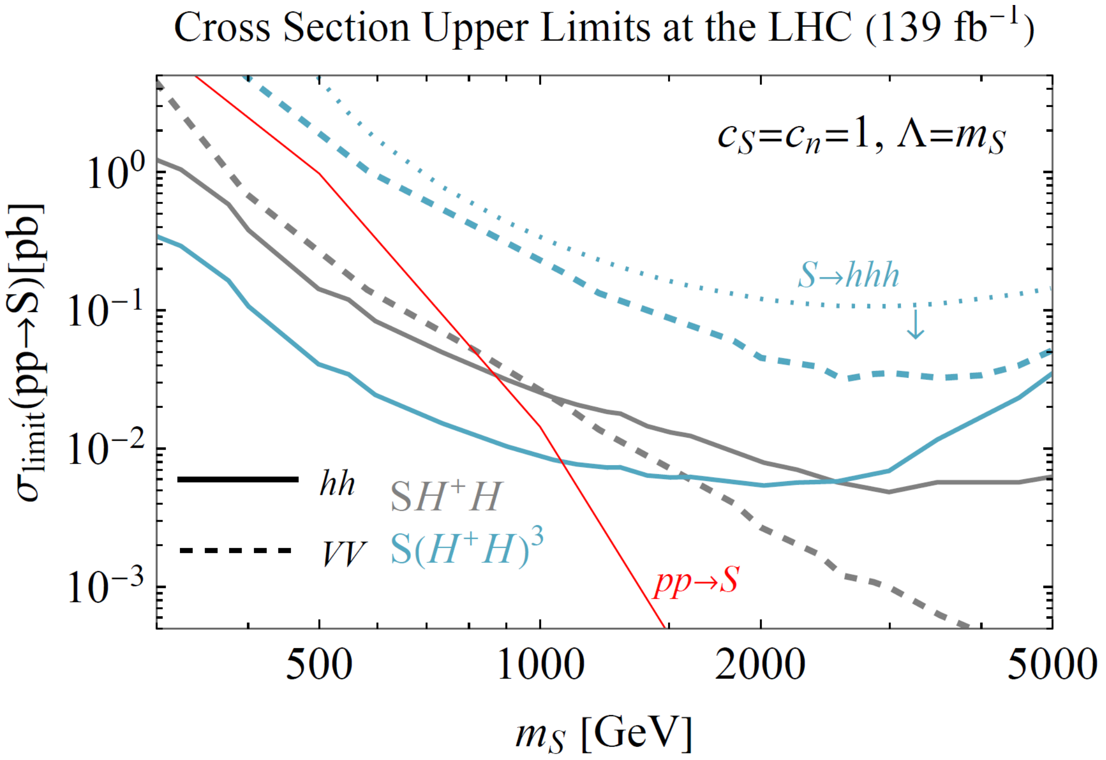
Collider picture: produce S, then let it decay into multi-Higgs



- At the LHC: mainly gluon fusion
- Either through S-h mixing or let S couple to gluons

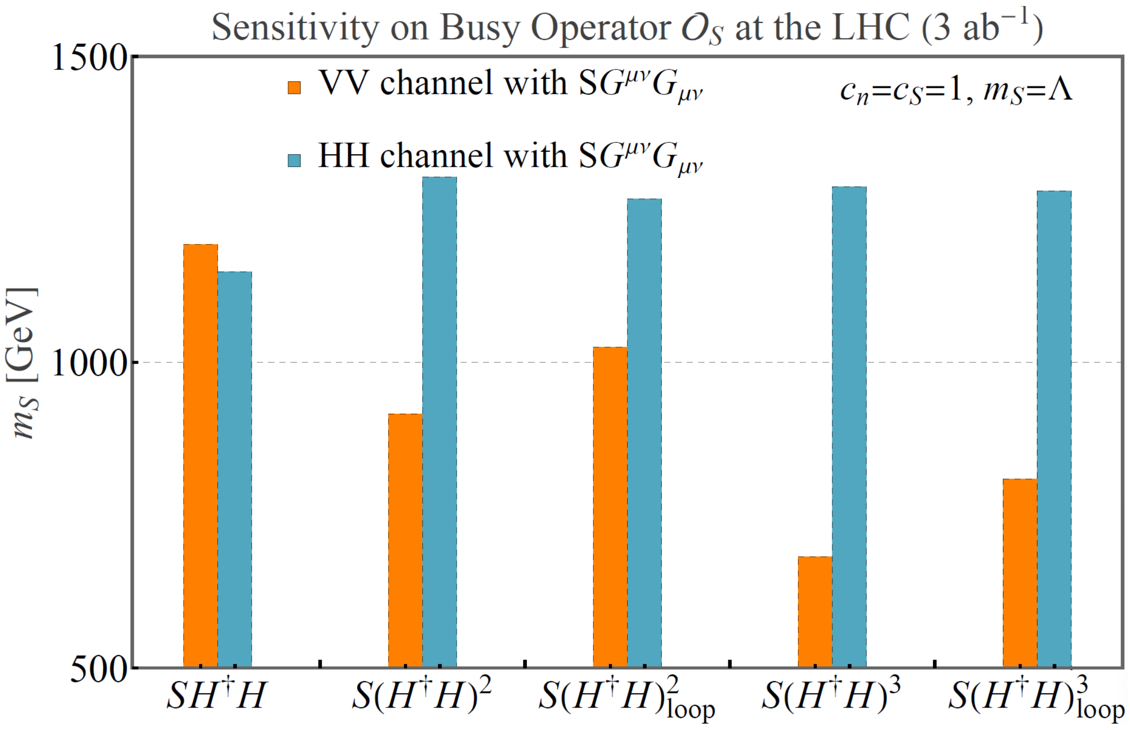
$$\mathcal{L} \supset S\,(H^\dagger H)^n + S\,G_{\mu\nu}G^{\mu\nu}$$

- Use existing hh, VV and hhh searches and rescale by branching ratio



Existing searches already show the pattern: hh can beat VV for busy operators.

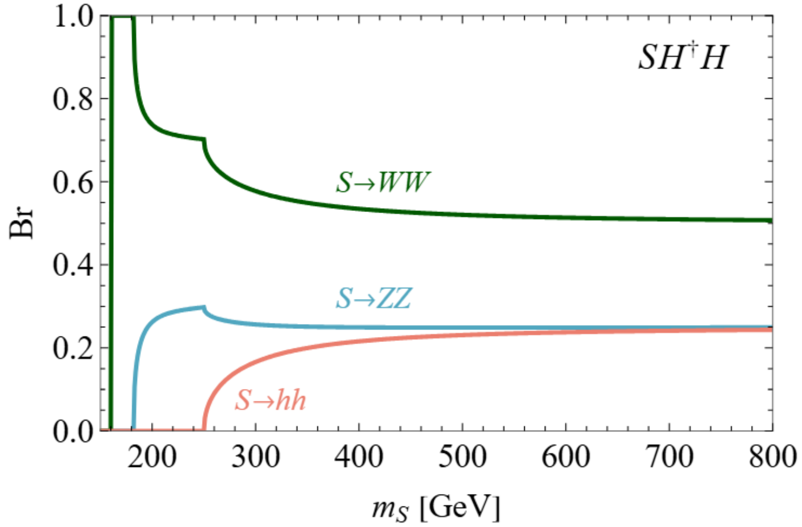
HL-LHC scalar reach: di-Higgs wins

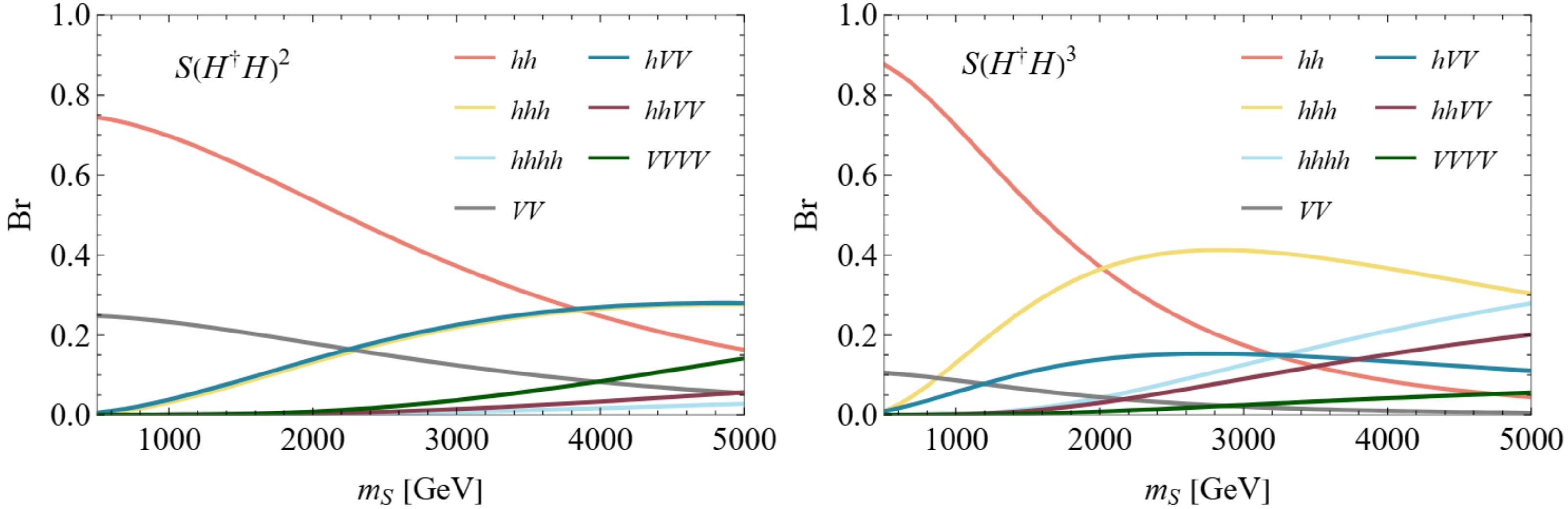


- Projection: 3 ab^{-1} at the HL-LHC
- Compare HH vs VV channels after BR rescaling
- Busy operators are probed better by HH over much of the benchmark space
- Loop-induced lower-dimensional operators change the reach only mildly

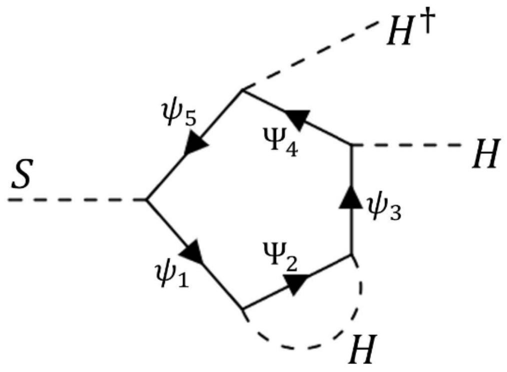
Takeaway: the "standard" diboson channel is not always the best discovery path.

Backup: branching-ratio patterns up to four-body final states

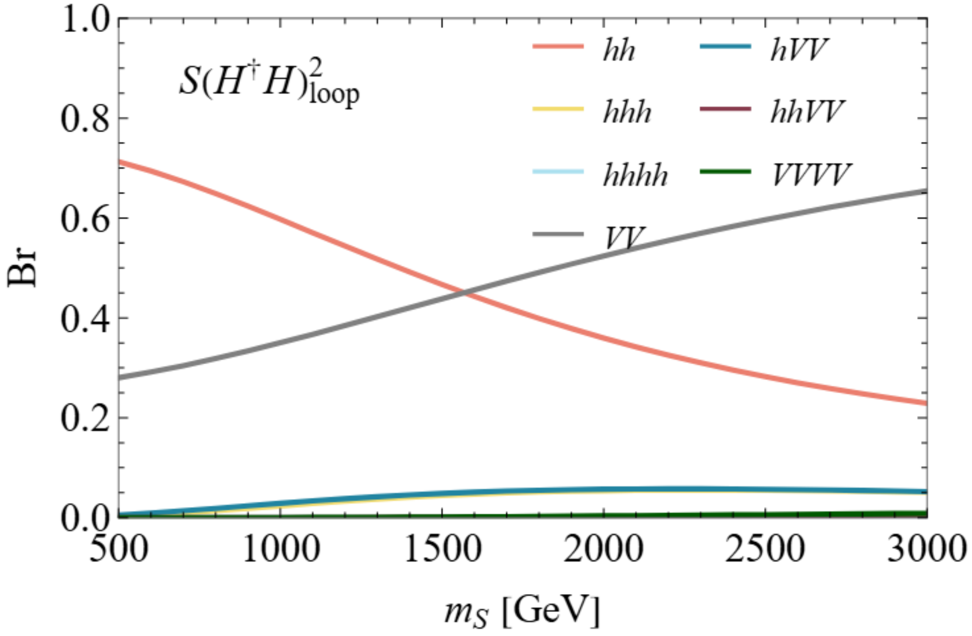


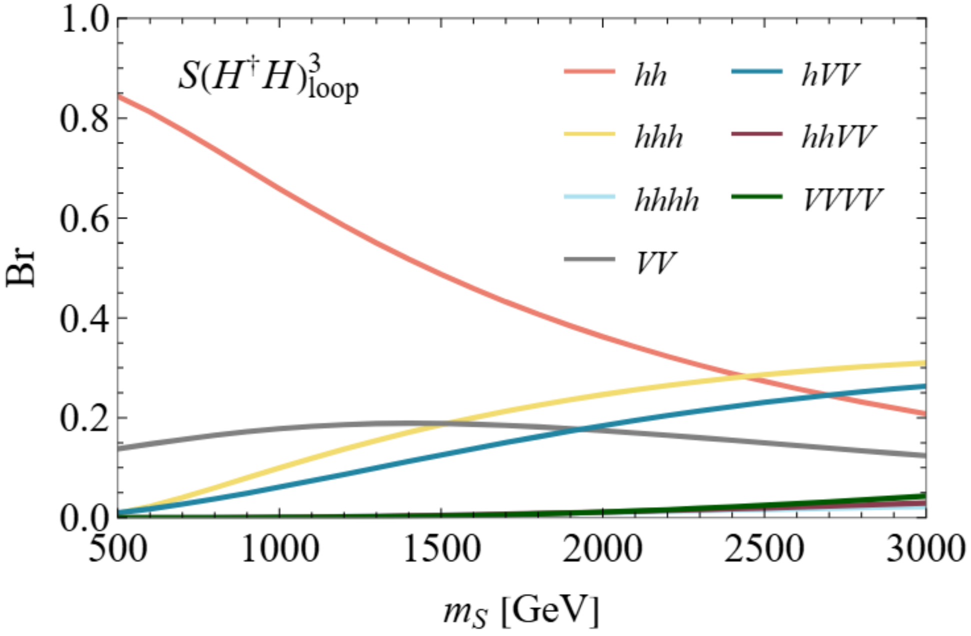


Backup: loop-induced lower-dimensional operators



$$\Delta\mathcal{O}_{n-1} \sim \frac{n^2\Lambda^2}{16\pi^2}\frac{c_n}{\Lambda^{2n-3}}S(H^\dagger H)^{n-1}$$

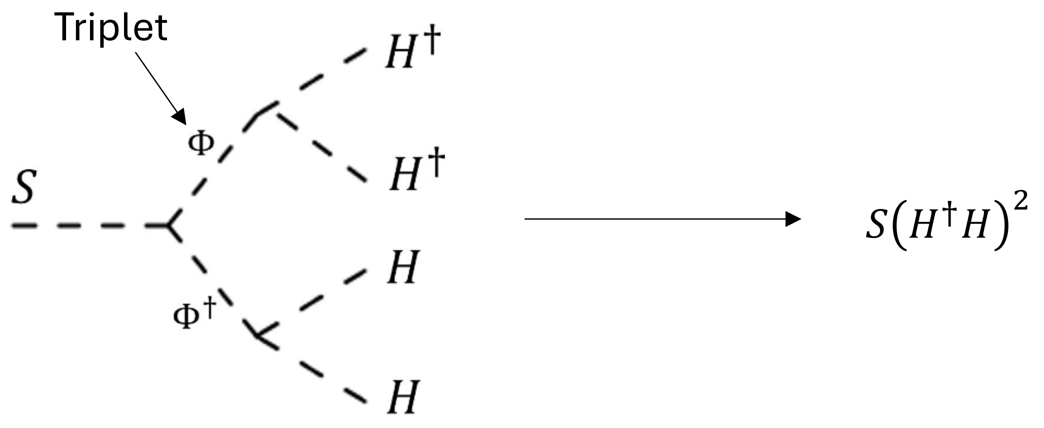




Backup: simple model

$$\mathcal{L} \supset \mu S \Phi^\dagger \Phi + \kappa \Phi^*_{ab} H^a H^b + M_\Phi^2 \Phi^\dagger \Phi + \text{h.c.}$$

$$\Phi_{11} = \Phi^{++},\ \Phi_{22} = \Phi^0,\ \Phi_{12} = \Phi_{21} = \frac{1}{\sqrt{2}}\Phi^+$$



Higher representation can provide higher power of $(H^\dagger H)^n$