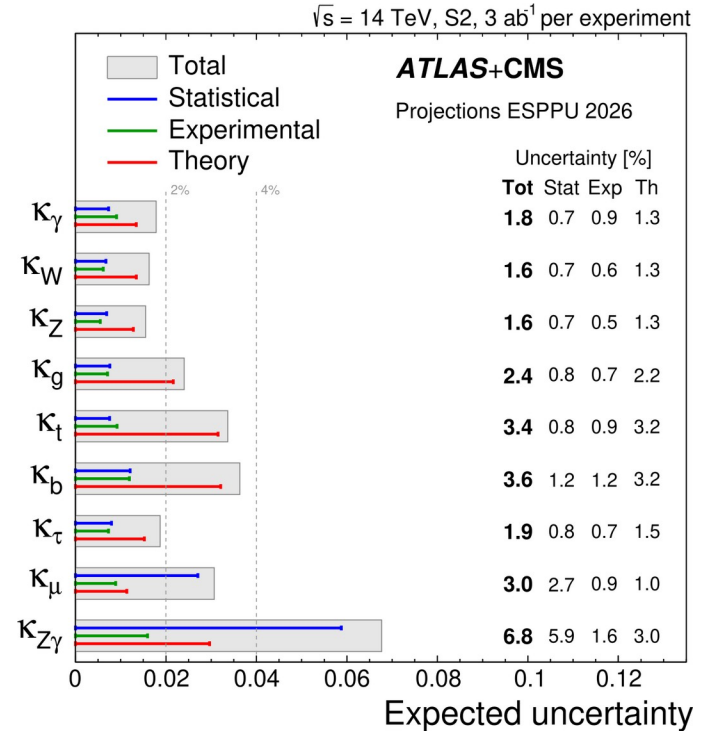
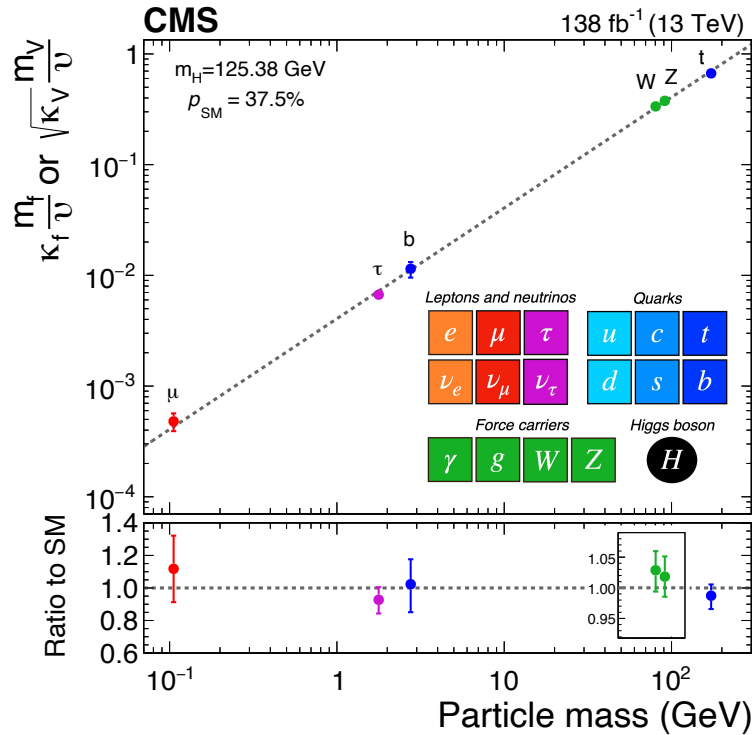


Real singlet scalar benchmarks in the multi-TeV resonance regime

Ian M. Lewis
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[IML, J. Scott, M. Soto Alcaraz, M. Sullivan PRD 112 \(2025\) 9](#)

Higgs Precision Program



ATLAS CMS, arXiv:2504.00672

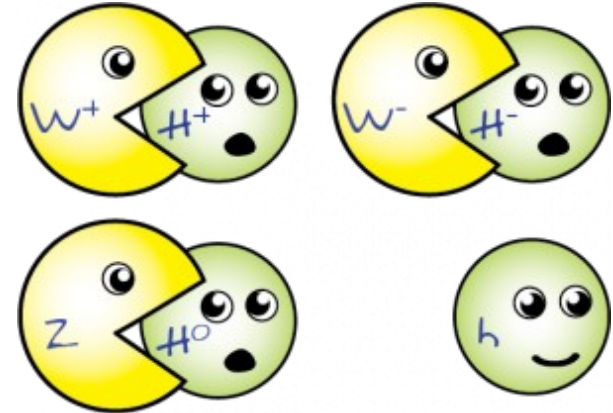
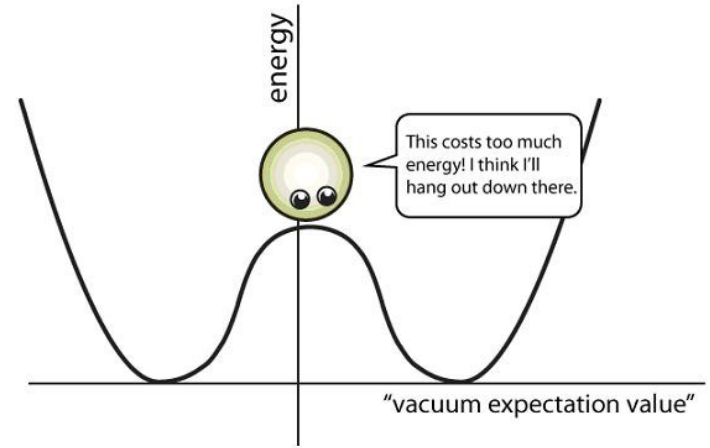
- Testing that Higgs is associated with mass generating mechanism.
- Still have not answered where the mass comes from.

The Higgs Potential

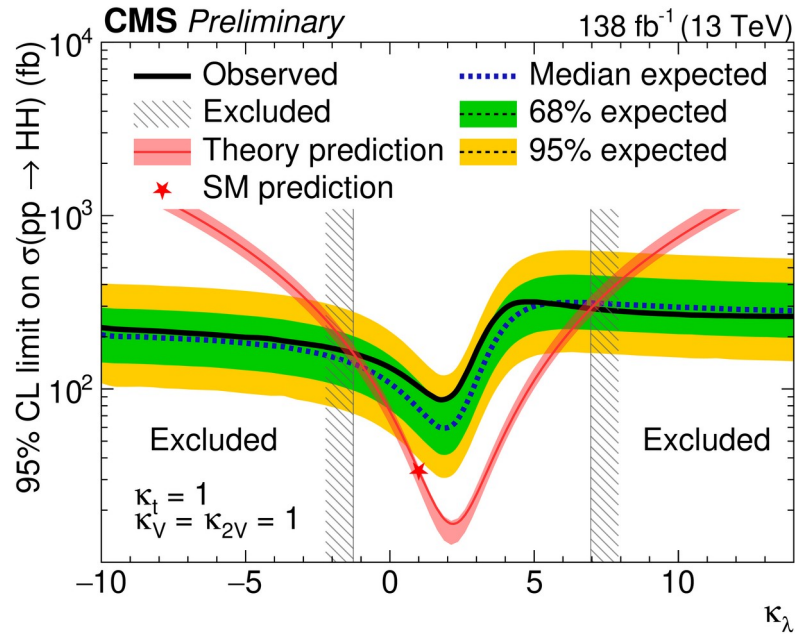
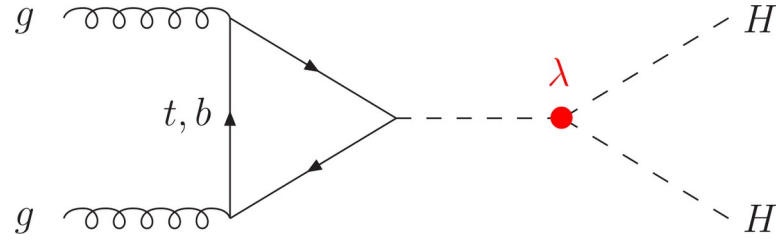
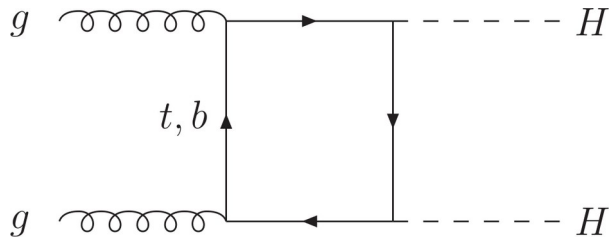
- All precision measurements look Standard Model like so far.
- It appears like the observed scalar is related to the mass generating mechanism for the SM fermions and gauge bosons.
- We still have not determined precisely how the Higgs obtains a vacuum expectation value.
- The vev comes from the shape of the scalar potential:

$$V(\Phi) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 \supset \frac{1}{2} m_h^2 h^2 + \frac{\lambda_{hhh}}{3!} h^3 + \frac{\lambda_{hhhh}}{4!} h^4$$

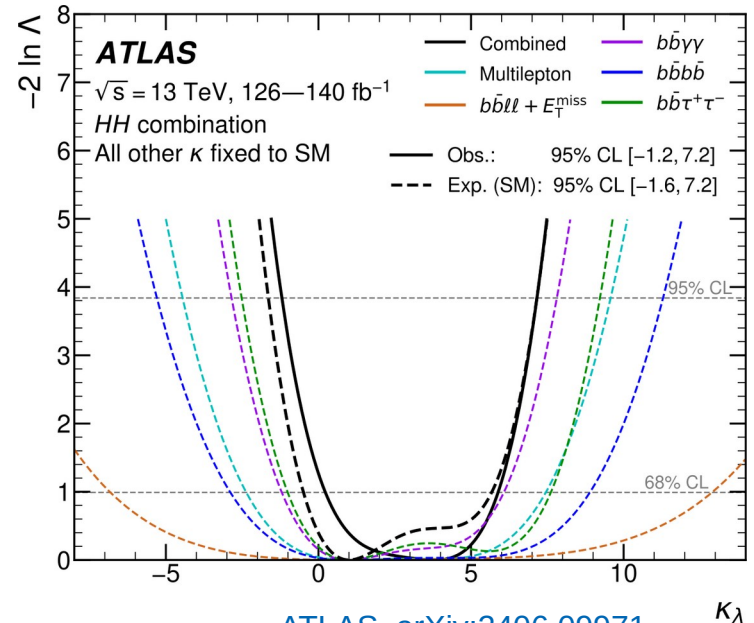
- In the long run, need to measure Higgs trilinear (and maybe quartic?) couplings to get a handle on the mechanism that generates the vev.



Measuring the Trilinear through Double Higgs



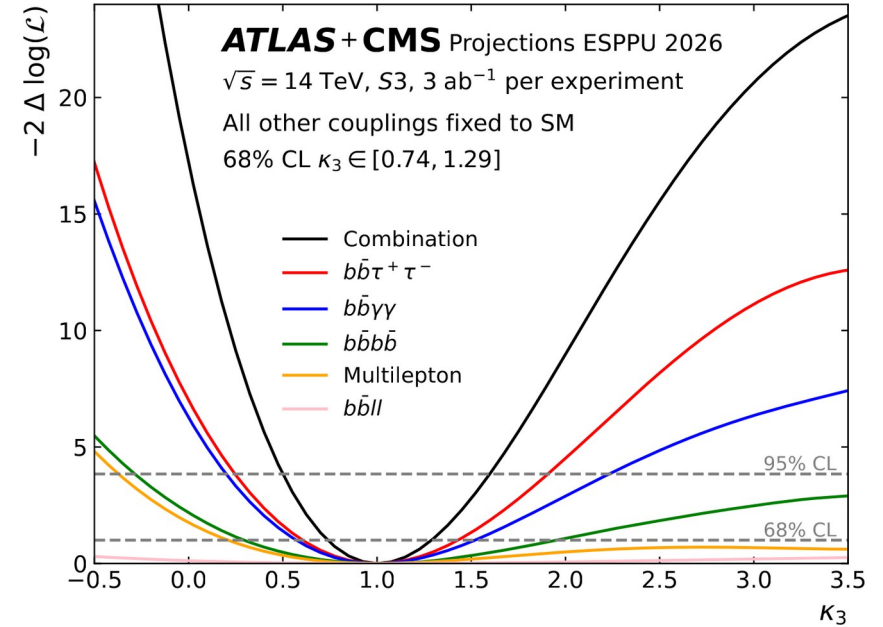
CMS-PAS-HIG-20-011



ATLAS, arXiv:2406.09971

Double Higgs Standard Model

	$2 \text{ ab}^{-1} (S2)$		$3 \text{ ab}^{-1} (S2)$		$3 \text{ ab}^{-1} (S3)$	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
<i>HH</i> statistical significance						
$b\bar{b}\tau^+\tau^-$	3.0^\dagger	1.9	3.5^\dagger	2.4	3.8^\dagger	2.7
$b\bar{b}\gamma\gamma$	2.1^\dagger	2.0^\dagger	2.4^\dagger	2.4^\dagger	2.6^\dagger	2.6^\dagger
$b\bar{b}b\bar{b}$ resolved	0.9	1.0^\dagger	1.0	1.2^\dagger	1.0	1.3^\dagger
$b\bar{b}b\bar{b}$ boosted	–	1.8^\dagger	–	2.2^\dagger	–	2.2^\dagger
Multilepton	0.8^\dagger	–	1.0^\dagger	–	1.0^\dagger	–
$b\bar{b}\ell^+\ell^-$	0.4^\dagger	–	0.5^\dagger	–	0.5^\dagger	–
Combination	3.7	3.5	4.3	4.2	4.5	4.5
ATLAS+CMS	6.0		7.2		7.6	



ATLAS CMS, arXiv:2504.00672

- Measurement prospects

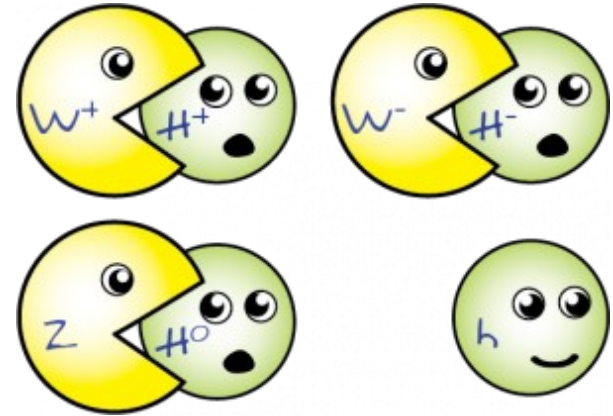
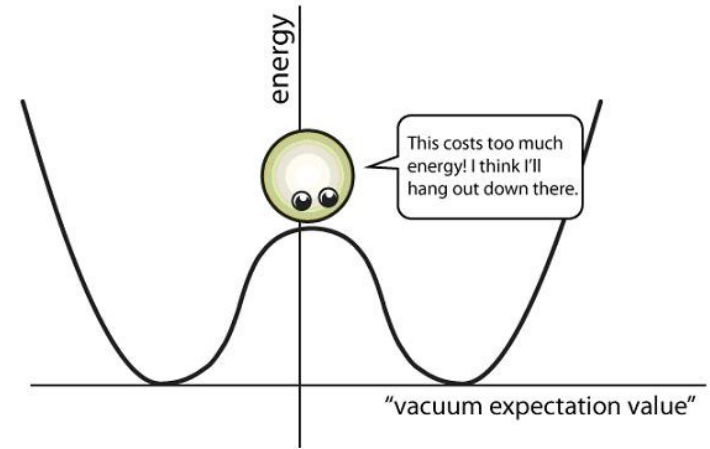
Scalar Extensions

- Scalar Extensions:

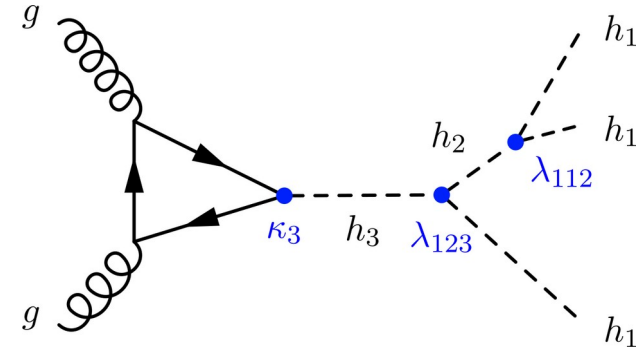
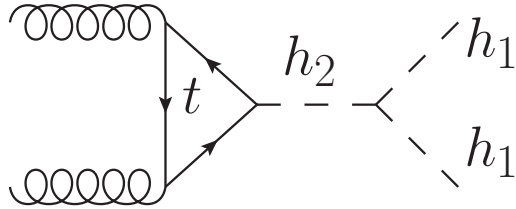
- Adding new scalars will alter the Higgs potential.
- The Higgs is unique in the Standard Model in that you cannot forbid the Higgs portal:

$$|\Phi|^2|S|^2$$

- Scalar extensions are simple extensions of the SM that can provide a lot of interesting phenomenology.
- They can also help solve many particle physics problems.
- With new scalar, have more scalar trilinear and quartic couplings.
- New production modes of di-scalar final states.
 - Interesting Higgs resonances can enhance di-Higgs rates.



Resonance Production



Papaefstathiou, Tetlalmatzi-Xolocotzi, arXiv:2501.14866
Lane, IML, Sullivan, PRD110 (2024) 5

- Many models: 2HDM, C2HDM, N2HDM, NMSSM, TRSM
HHH Whitepaper, arXiv:2407.03015; Robens, Stefaniak, Wittbrodt, EPJC (2020); Abouabid, etc. JHEP (20220), etc, etc,
- Many experimental searches.
- Focus on my recent work with the real singlet .
 - Project maximal Di-Higgs and trilinear variations in 4 scenarios:
 - S1: Current LHC Constraints
 - S2: HL-LHC
 - S3: HL-LHC+FCCee
 - S4: HL-LHC+ILC500

Additional trilinears

- Simplest extension: Real gauge singlet scalar

$$V(\Phi, S) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 + \frac{1}{2} a_1 |\Phi|^2 S + \frac{1}{2} a_2 |\Phi|^2 S^2 + b_1 S + \frac{1}{2} b_2 S^2 + \frac{1}{3} b_3 S^3 + \frac{1}{4} b_4 S^4$$

- After EW symmetry breaking and mixing, these couplings will give rise to additional trilinear couplings between mass eigenstates:



- Can get interesting new resonant decays: $h_2 \rightarrow h_1 h_1$
- Couplings of scalar resonances to fermions and gauge bosons suppressed by mixing angle:



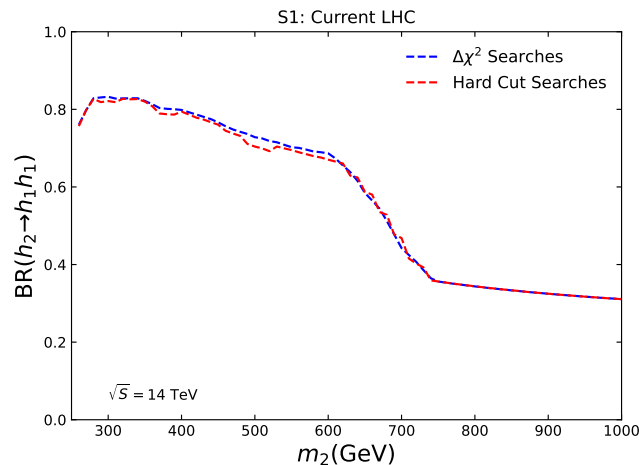
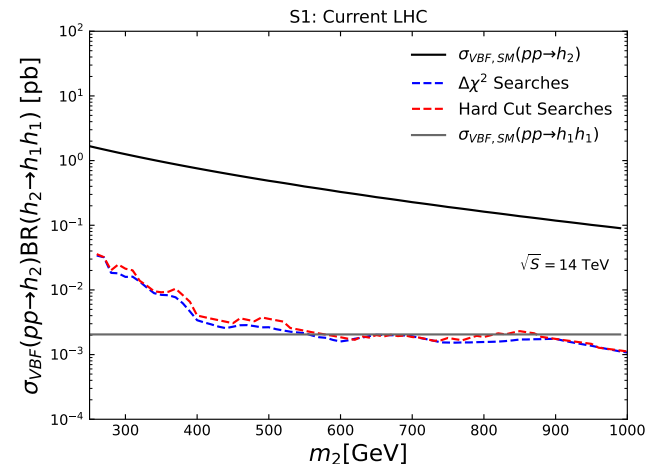
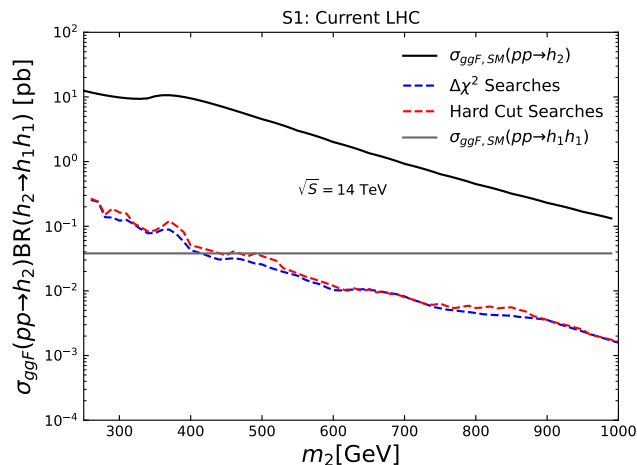
- Produced and decays similar to a SM-like Higgs with the addition of $h_2 \rightarrow h_1 h_1$

Maximum Resonant Di-Higgs Rates: Current LHC

- Max rates and corresponding branching ratios.
- Narrow Width approximation:

$$\frac{\sigma(pp \rightarrow h_2 \rightarrow h_1 h_1)}{\sigma_{SM}(pp \rightarrow h_2)} \approx \sin^2 \theta BR(h_2 \rightarrow h_1 h_1)$$

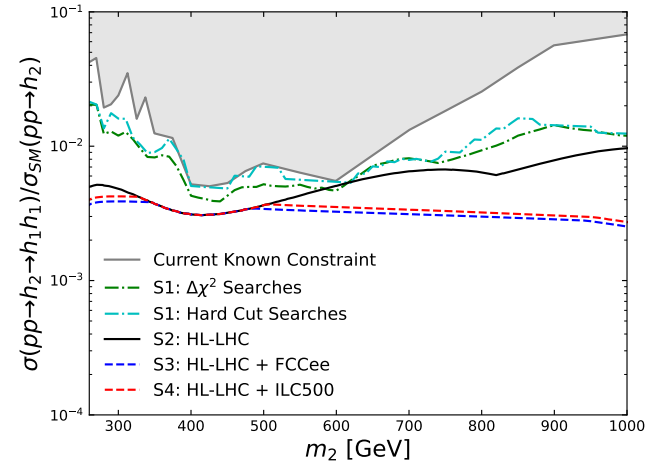
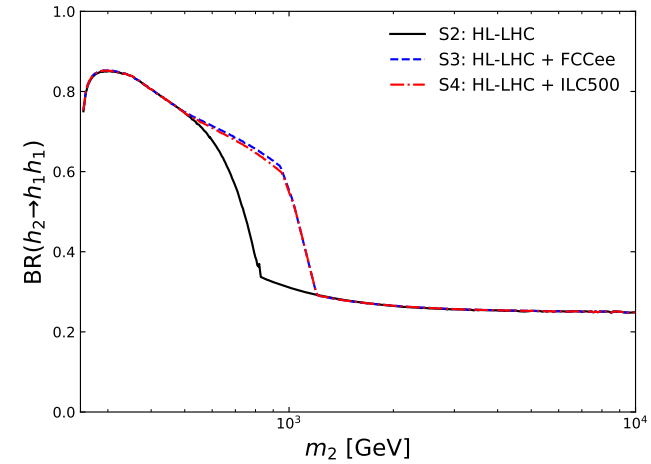
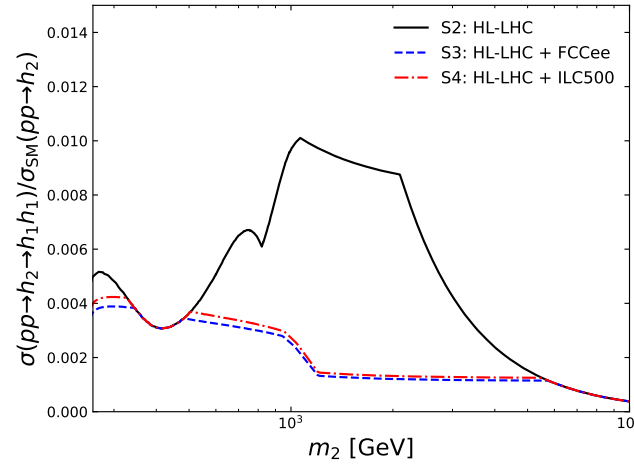
IML, J. Scott, M. Soto Alcaraz, M. Sullivan PRD 112 (2025) 9



Maximum Resonant Di-Higgs Rates: Future

- Max rates and corresponding branching ratios.
- Narrow Width approximation:

$$\frac{\sigma(pp \rightarrow h_2 \rightarrow h_1 h_1)}{\sigma_{SM}(pp \rightarrow h_2)} \approx \sin^2 \theta BR(h_2 \rightarrow h_1 h_1)$$



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Phenomenology Symposium
May 11, 2026

Ian Lewis
(University of Kansas)

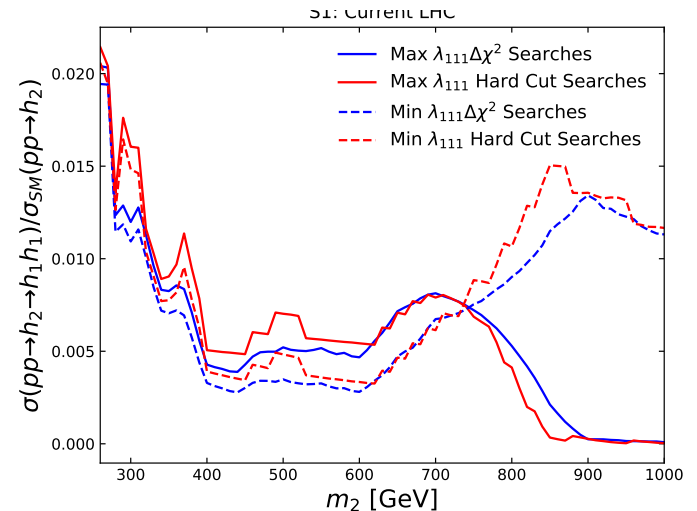
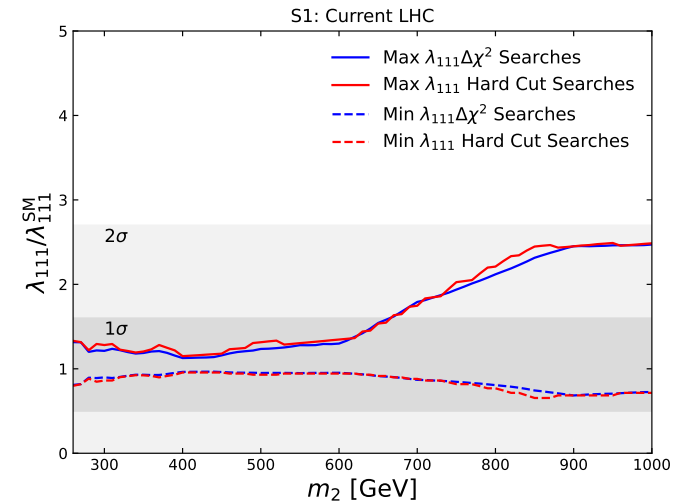
The Higgs Trilinear Change

IML, J. Scott, M. Soto Alcaraz, M. Sullivan PRD 112 (2025) 9

- Have a resonance.
 - Easier to search for di-Higgs resonance.
 - Why is Higgs trilinear coupling interesting?
- What happens when we maximize deviations in the Higgs trilinear.
 - When deviation is maximized, resonant rate is suppressed at high masses.
- Current LHC constraints:
 - Regions of parameter space where could see deviations in trilinear before resonance.
 - Complementarity.
- Note: newer projections

68% CL : $0.74 \leq \kappa \leq 1.29$
 95% CL : $0.5 \leq \kappa \leq 1.5 - 1.6$

ATLAS CMS, arXiv:2504.00672



The Higgs Trilinear Change

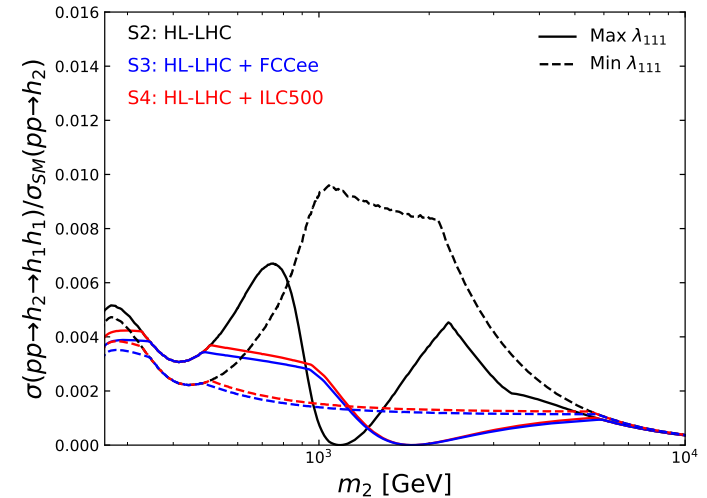
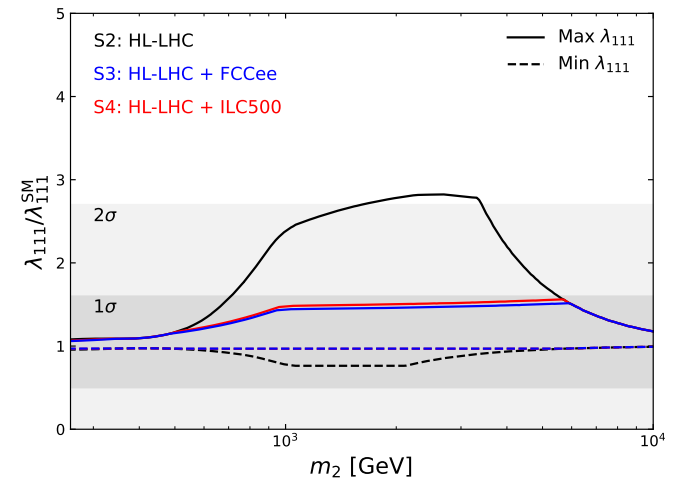
IML, J. Scott, M. Soto Alcaraz, M. Sullivan PRD 112 (2025) 9

- Have a resonance.
 - Easier to search for.
 - Why is Higgs trilinear coupling?
- What happens when we maximize deviations in the Higgs trilinear.
 - When deviation is maximized, resonant rate is suppressed at high masses.
- Future scenarios:
 - Regions of parameter space where could see deviations in trilinear before resonance.
 - Complementarity.
- Note: new projections:

68% CL : $0.74 \leq \kappa \leq 1.29$

95% CL : $0.5 \leq \kappa \leq 1.5 - 1.6$

ATLAS CMS, arXiv:2504.00672



Conclusions

- Di-Higgs observation and measurement is one of the long term goals of the LHC and future collider program.
 - Important for understanding electroweak symmetry breaking.
 - Sensitive to scalar extensions of the SM that change the nature of the Higgs potential
- Presented current and future projections for resonance di-Higgs production and variations in Higgs trilinear
- Real singlet model.
 - Still regions of parameter space where trilinear Higgs coupling variations are large and di-Higgs resonance production is small.
 - Even in mass range where LHC could produce a resonance.

Thank You

The Higgs Potential

- Previous processes sensitive to trilinear coupling.
- Still missing a term in the potential, the quartic coupling:

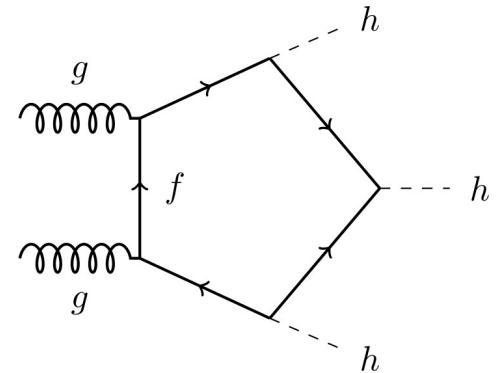
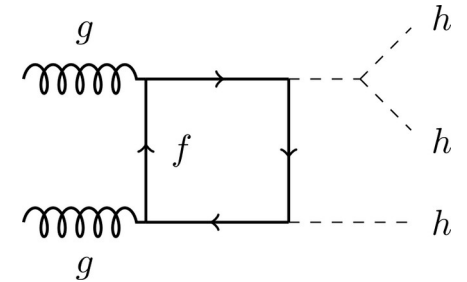
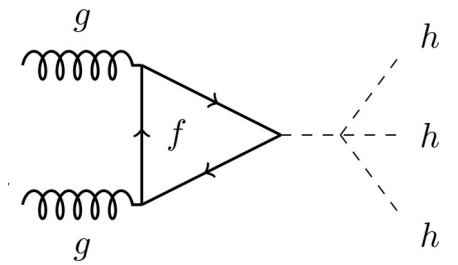
$$V(\Phi) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 \supset \frac{1}{2} m_h^2 h^2 + \frac{\lambda_{hhh}}{3!} h^3 + \frac{\lambda_{hhhh}}{4!} h^4$$

- For (direct) sensitivity, go to triple Higgs production:
- Suffers from low rates.
 - To extract quartic coupling need to measure triple coupling well.

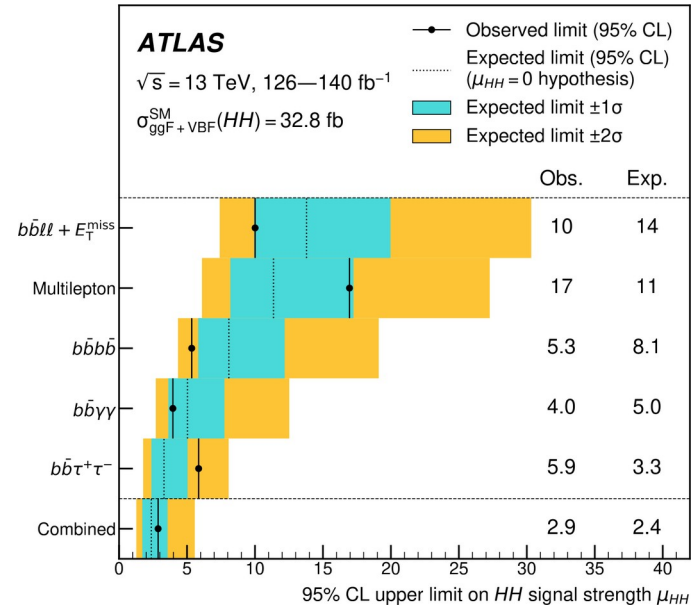
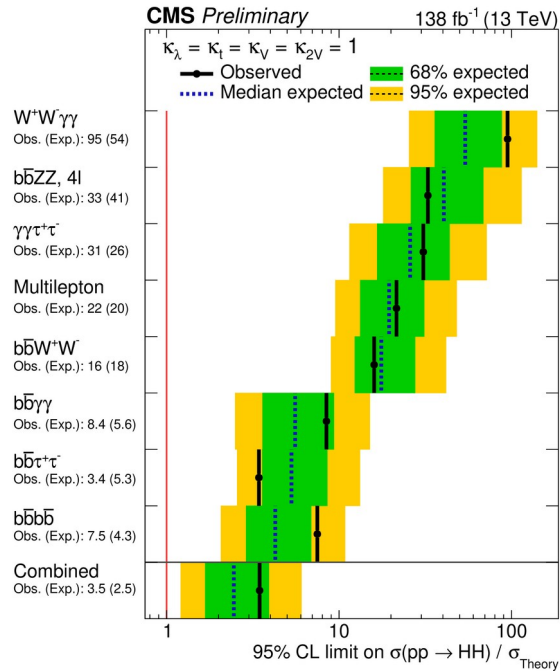
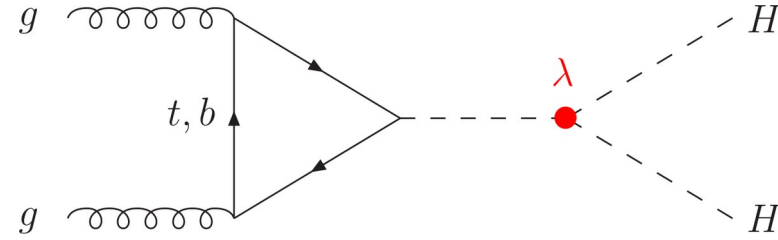
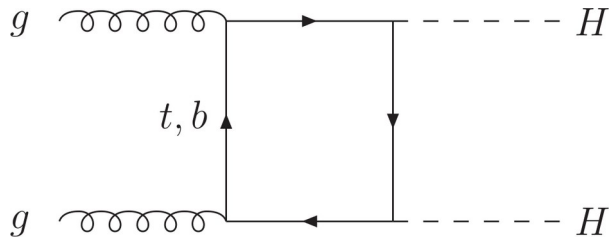
	HH	HHH
σ_{NNLO} at $\sqrt{s} = 14$ TeV [fb]	$36.69^{+2.1\%}_{-4.9\%} \pm 3.0\%$	$0.103^{+5\%}_{-8\%} \pm 15\%$

Table 1: Cross-section of the gluon-gluon fusion production mode for HH [129–131] and HHH [30] production at NNLO at a center-of-mass $\sqrt{s} = 14$ TeV. The uncertainties include the available QCD corrections, as well as the renormalisation and factorisation scales set to $m_{HH}/2$ and $m_{HHH}/2$.

[HHH Whitepaper, arXiv:2407.03015](#)



Measuring the Trilinear Through Double Higgs

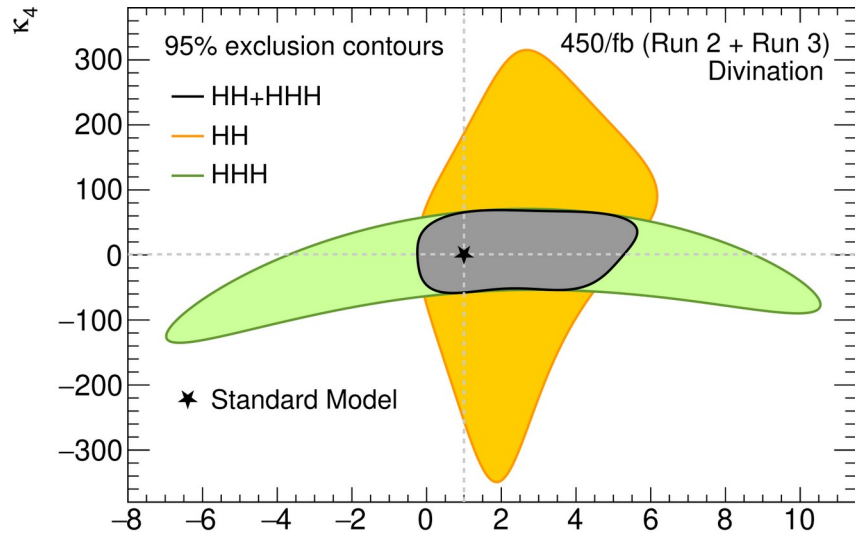


ATLAS, arXiv:2406.09971

Triple Higgs and Measuring the Quartic

\mathcal{L} at 13 TeV	Pessimistic	Optimistic
139 fb^{-1}	$150 \times \text{SM}$	$64 \times \text{SM}$
300 fb^{-1}	$100 \times \text{SM}$	$40 \times \text{SM}$
500 fb^{-1}	$80 \times \text{SM}$	$35 \times \text{SM}$
3000 fb^{-1}	$30 \times \text{SM}$	$15 \times \text{SM}$

Table 6: Estimated limit on the triple Higgs production from a combination of the $HHH \rightarrow b\bar{b}b\bar{b}b\bar{b}$, $HHH \rightarrow b\bar{b}b\bar{b}\tau^+\tau^-$ and $HHH \rightarrow b\bar{b}b\bar{b}\gamma\gamma$ at 95% confidence level for different luminosities at a center-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$.



	HL-LHC 68%	HL-LHC 95%	FCC-hh 68%	FCC-hh 95%
d_4	$[-6.6, 12.4]$	$[-10.0, 21.3]$	$[-3.9, 10.5]$	$[-10.6, 18.8]$
c_{t3}	$[-0.6, 1.1]$	$[-0.9, 3.6]$	$[-0.1, 0.3]$	$[-0.4, 0.6]$

- Difficult, even at future machines.

[HHH Whitepaper, arXiv:2407.03015](#)

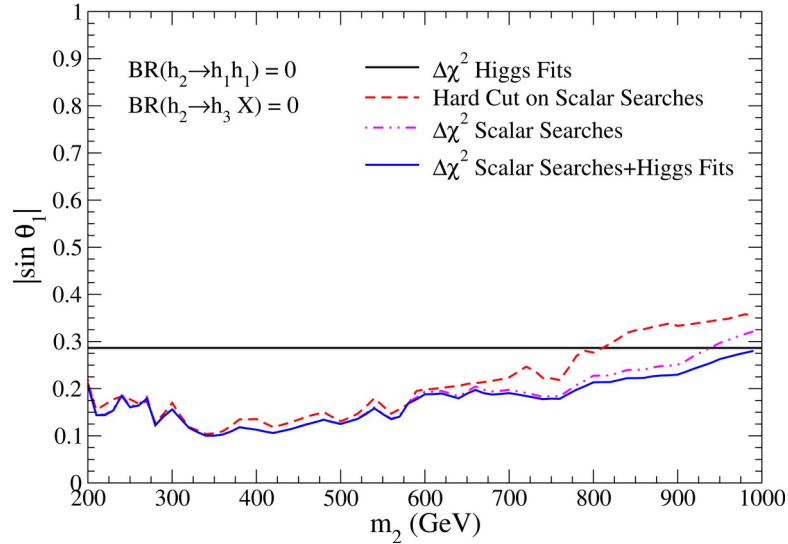
κ_3
Ian Lewis
(University of Kansas)

Theory Constraints

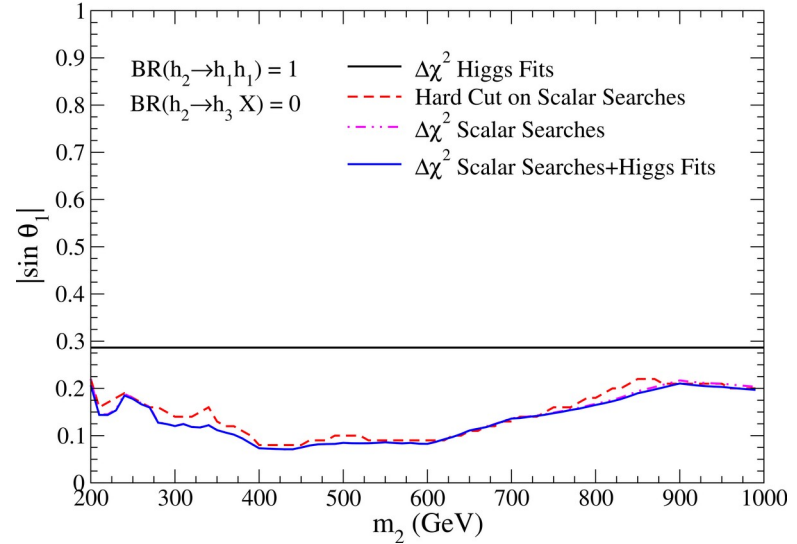
- Will use perturbative unitarity constraints on possible $2 \rightarrow 2$ scalar scattering.
 - Ensures that quartic couplings are perturbative.
- Correct global minimum.
 - Singlet scalar cannot couple to SM fermions or gauge bosons at tree level.
 - Cannot contribute to gauge boson mass.
 - Make sure the global minimum can create the correct masses:
- Potential is bounded from below.
- Require a narrow width approximation:
 - $\Gamma_{\text{Tot}}(h_2) \leq 0.1 m_2$
 - Helps ensure calculations are reliable.
 - Experimental searches are often in narrow width regime.

Constraints on Mixing Angle

95% CL



95% CL



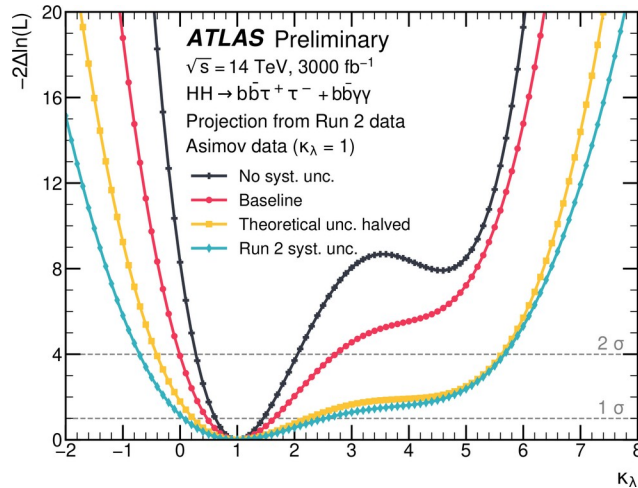
Lane, IML, Sullivan arXiv:2403.18003

- Universal suppression of couplings to h_1 by $\cos \theta_1$
 - Easy interpretation of precision Higgs measurements.
- Coupling of h_2 to SM fermions and gauge bosons like a SM-Higgs suppressed by $\sin \theta_1$
 - Include WW, ZZ, $h_1 h_1$ resonance searches.
 - Different assumptions for

Double Higgs in the SM

$$V(\Phi) = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4 \supset \frac{1}{2} m_h^2 h^2 + \frac{\lambda_{hhh}}{3!} h^3 + \frac{\lambda_{hhhh}}{4!} h^4$$

- SM scalar potential contains two parameters, completely determined by the mass and vev.
- Search for Higgs pair production to directly measure shape of potential:



collider	Indirect- h	hh	combined
HL-LHC [77]	100-200%	50%	50%
ILC ₂₅₀ /C ³ -250 [50] [51]	49%	—	49%
ILC ₅₀₀ /C ³ -550 [50] [51]	38%	20%	20%
CLIC ₃₈₀ [53]	50%	—	50%
CLIC ₁₅₀₀ [53]	49%	36%	29%
CLIC ₃₀₀₀ [53]	49%	9%	9%
FCC-ee [54]	33%	—	33%
FCC-ee (4 IPs) [54]	24%	—	24%
FCC-hh [78]	-	3.4-7.8%	3.4-7.8%
$\mu(3 \text{ TeV})$ [63]	-	15-30%	15-30%
$\mu(10 \text{ TeV})$ [63]	-	4%	4%