# Resonant Multi-Scalar Production in the Generic Complex Singlet Model in the Multi-TeV Region

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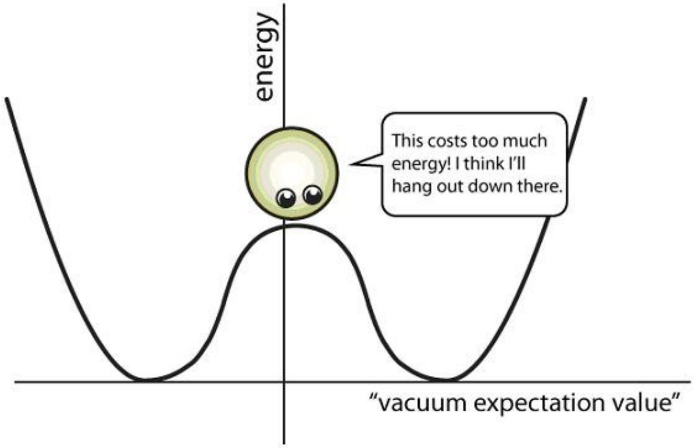
S.D. Lane, M. Sullivan
arXiv:2403.18003 [hep-ph]

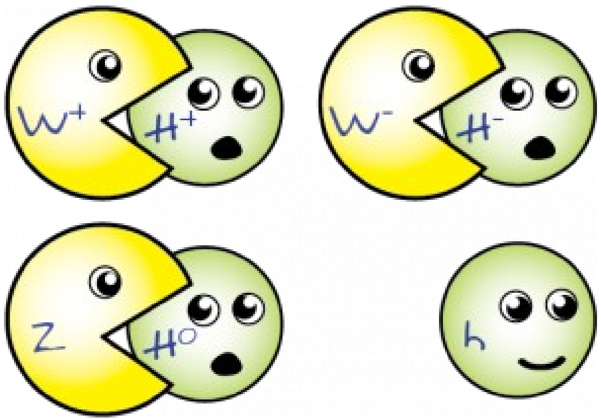
# The Higgs Potential

- 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.



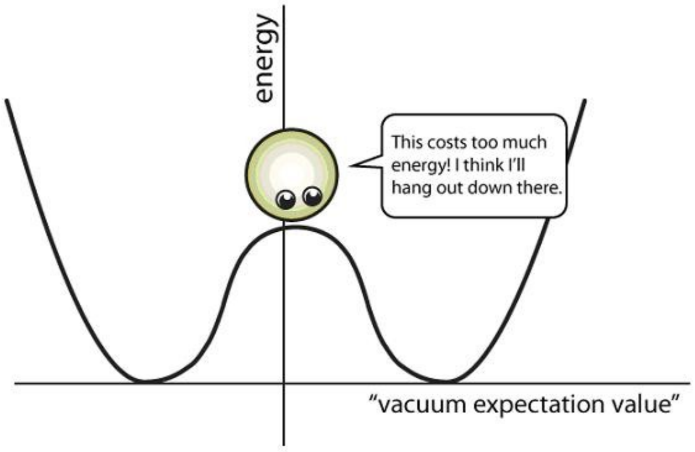



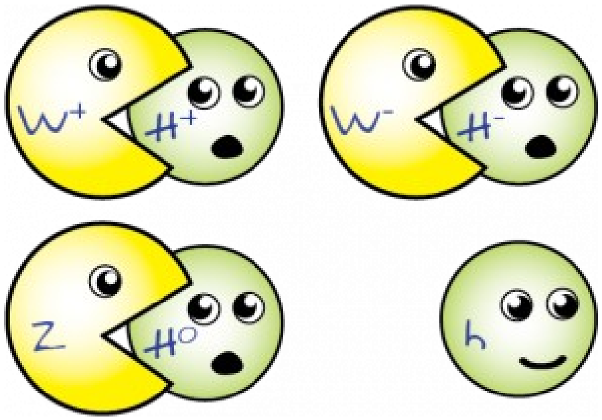
# Scalar Extensions

- 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.



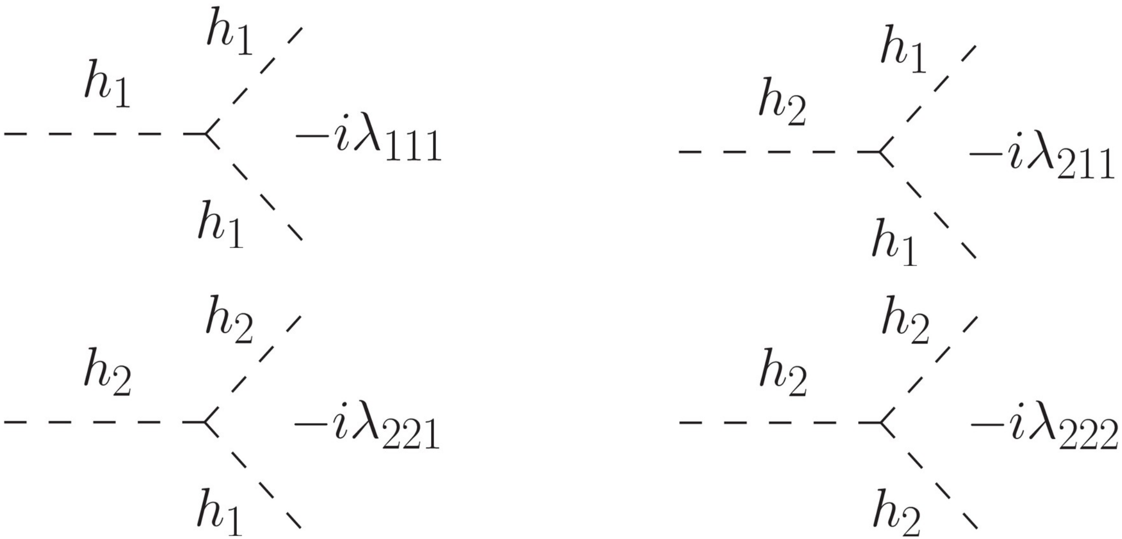
# Additional trilinears

- 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:




- Need to search for more scalar production than just di-Higgs to map out the full potential.
- Can get interesting new resonant decays: $h_2 \rightarrow h_1 h_1$ See talk tomorrow by Miguel Soto Alcaraz, or

Robens, arXiv:2209.15544; etc. etc.

# Complex Singlet Scalar Extension

- Introduce a complex singlet scalar with no additional symmetries: $S_c = (S_0 + i\,A)/\sqrt{2}$
  - At the renormalizable level, can only couple to Higgs doublet through scalar potential:

$$\begin{aligned}V(\Phi, S_c) \;=\; & -\frac{\mu^2}{2}\Phi^\dagger\Phi + \frac{\lambda}{4}(\Phi^\dagger\Phi)^4 + \frac{b_2}{2}|S_c|^2 + \frac{d_2}{4}|S_c|^4 + \frac{\delta_2}{2}\Phi^\dagger\Phi|S_c|^2 \\ & + \left(a_1\,S_c + \frac{b_1}{4}\,S_c^2 + \frac{e_1}{6}\,S_c^3 + \frac{e_2}{6}S_c|S_c|^2 + \frac{\delta_1}{4}\Phi^\dagger\Phi\,S_c + \frac{\delta_3}{4}\Phi^\dagger\Phi\,S_c^2\right. \\ & \left. + \frac{d_1}{8}S_c^4 + \frac{d_3}{8}S_c^2|S_c|^2 + \text{h.c.}\right)\end{aligned}$$

- Equivalent to adding two new real scalars.
- After EWSB, have three massive scalars that mix (in the small :

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 & 0 \\ \sin\theta_1 & \cos\theta_1 & \sin\theta_2 \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2 & -1 \end{pmatrix} \begin{pmatrix} h \\ S_0 \\ A \end{pmatrix} + \mathcal{O}(\sin^2\theta_2)$$

  - All coupling to fermions and gauge bosons inherited from SM Higgs boson-h.

# Complex Singlet Scalar Extension

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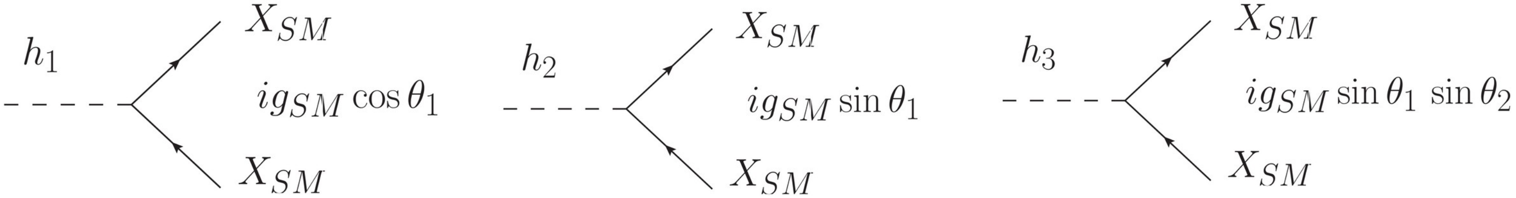



  - $h_3$ has doubly suppressed coupling.

- Dominant production of $h_3$ may be through decays of another scalar:


- Can discover two new scalars at once!

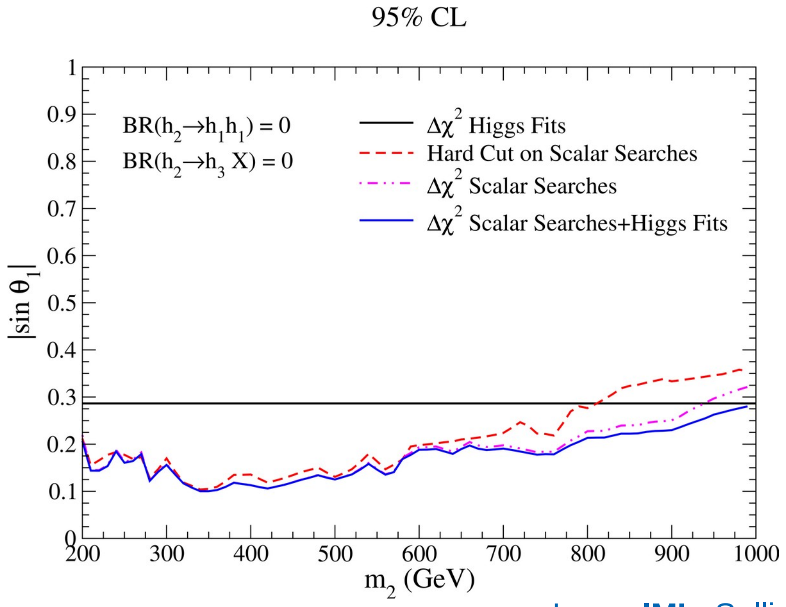
# Complex Singlet Scalar Extension

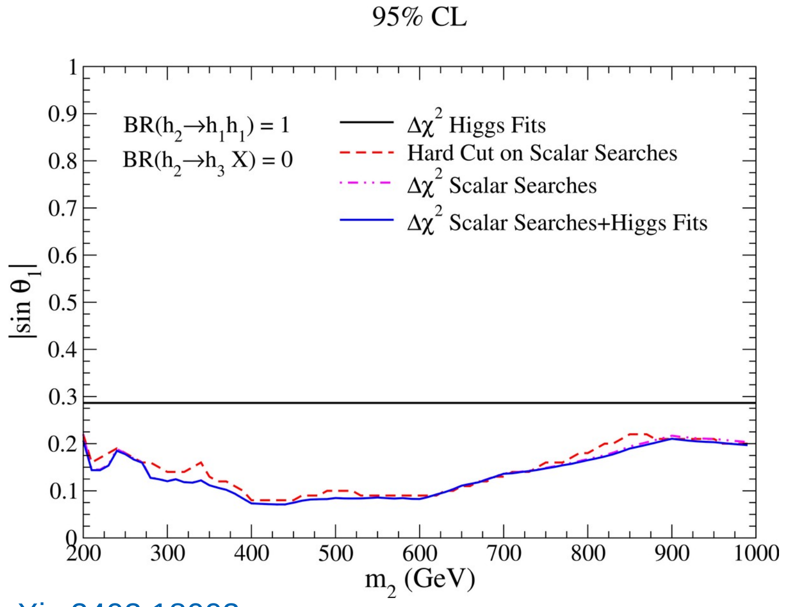
- We will consider the mass ordering of $h_2 \rightarrow h_1 h_1, h_2 \rightarrow h_1 h_3, h_2 \rightarrow h_3 h_3$
- The goal is to find maximum rates for $m_2 > m_3 > m_1 = 125\, GeV$
- Will consider three scenarios for $m_3$ to have different collider phenomenology
  - $m_3 = 130\, GeV$
    - Decays like SM Higgs boson at this mass: $h_2 \to h_1 h_3 / h_3 h_3 \to 2b\, 2\bar{b}$.
  - $m_3 = 200\, GeV$
    - Decays like SM Higgs boson at the mass, i.e. into Ws: $h_2 \to h_1 h_3 \to b\bar{b} W^{\pm} W^{\mp} \quad \text{and} \quad h_2 \to h_3 h_3 \to 2W^{\pm}\, 2W^{\mp}$.
  - $m_3 = 270\, GeV$
    - Di-Higgs modes open with possible multi-Higgs signals: $h_2 \to h_1 h_3 \to 3\, h_1 \quad \text{and} \quad h_2 \to h_3 h_3 \to 4\, h_1$.
- Will consider four scenarios for limits:
  - Current limits on mixing angle.
  - Limits from HL-LHC
  - Limits from HL-LHC+FCCee
  - Limits from HL-LHC+ILC500

# 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:
  - $\Gamma_{Tot}(h_2) \leq 0.1 m_2$
  - Helps ensure calculations are reliable.
  - Experimental searches are often in narrow width regime.

# Current Constraints on Mixing Angle




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

# Current Maximum Rates

Lane, **IML**, Sullivan arXiv:2403.18003

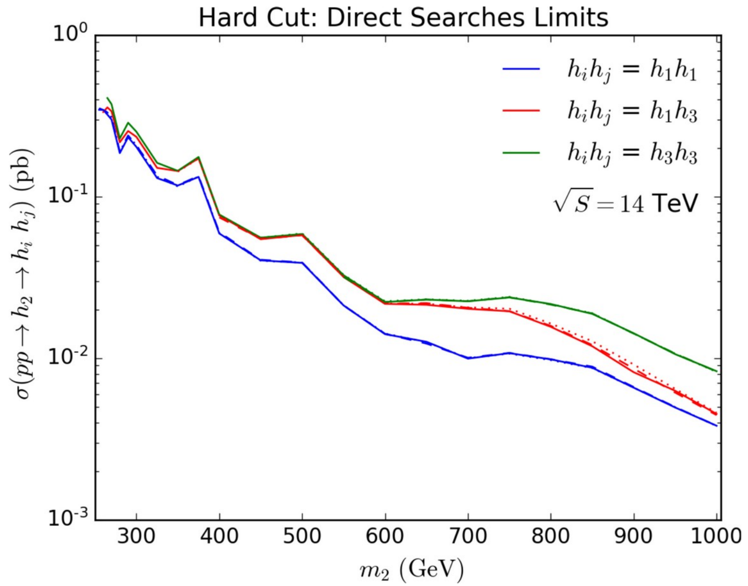
- Use the most constraining limits on mixing angles.
- For $h_2 \to h_1 h_1$, Goldstone boson equivalence theorem prevents $\Gamma(h_2 \to h_1 h_1)$ from deviating too much from $\Gamma(h_2 \to ZZ/W^+ W^-)$
- $h_2 \to h_1 h_3$ has constraints from global minimum, perturbative unitarity, boundedness, and narrow width approximation:
  - Can find an upper bound on the triple coupling and mixing angle:

$$|\lambda_{123}| \lesssim 4\sqrt{\frac{\pi}{3}}\,(m_1 + 2\,m_2|\sin\theta_1|) \qquad |\sin\theta_1| \lesssim 2\sqrt{\frac{\pi}{5}}\frac{v_{\rm EW}}{m_2}$$

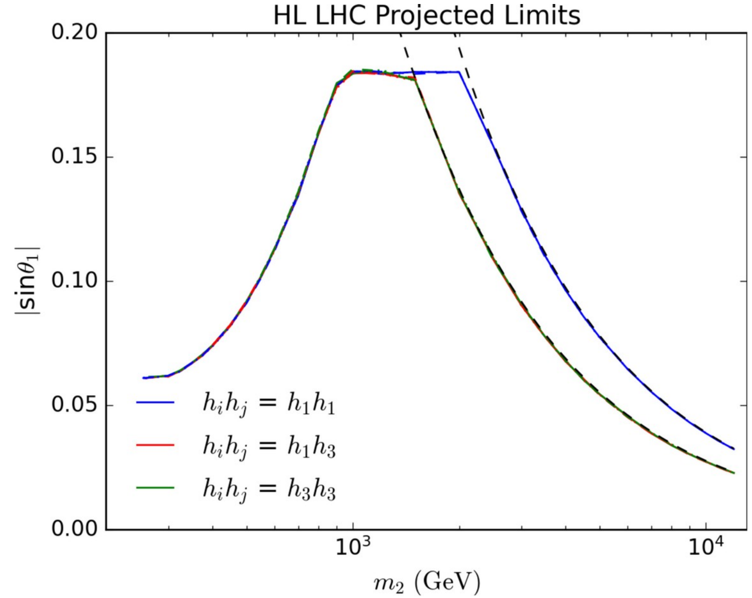
  - Leads to an upper bound on the branching ratio:

$$\mathrm{BR}(h_2 \to h_1 h_3) \lesssim \frac{32\,\pi}{3}\left(1 + \frac{1}{4}\sqrt{\frac{5}{\pi}}\right)^2 \frac{v_{\rm EW}^2}{m_2^2} \approx 0.11\left(\frac{m_2}{5\ \mathrm{TeV}}\right)^{-2}.$$

  - Goes to zero as $h_2$ mass increases.




# Mixing angles at Future Colliders

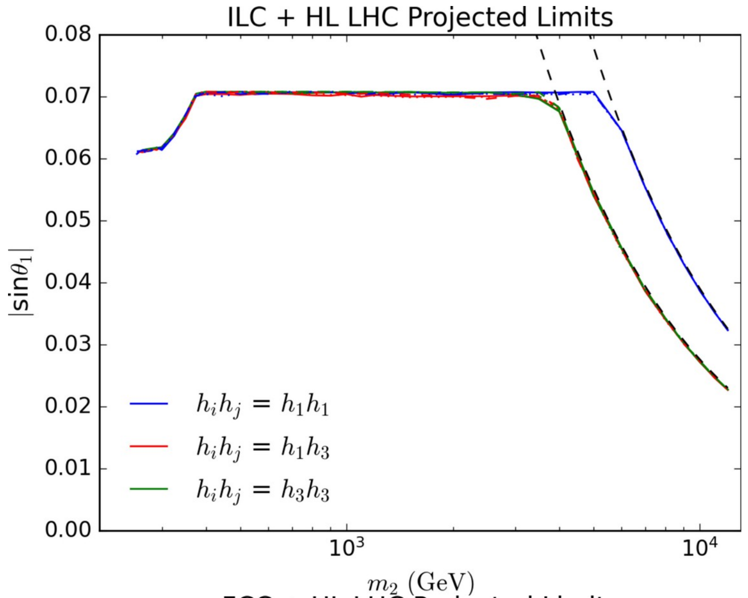


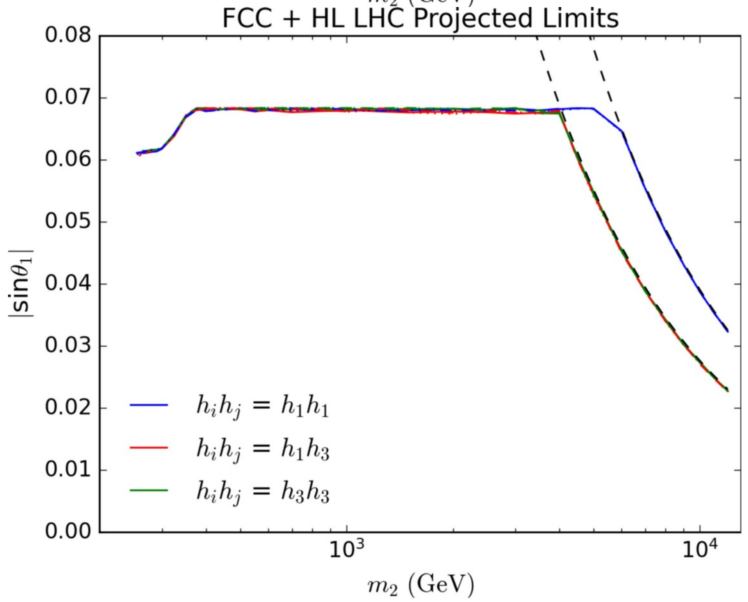

Lane, **IML**, Sullivan arXiv:2403.18003

- Consider three scenarios: HL-LHC, HL-LHC+FCCee, and HL-LHC+ILC500.

  Snowmass Higgs Report, arXiv:2209.07510; EPR arXiv:1910.11775

- Some interesting behaviors in the multi-TeV regime



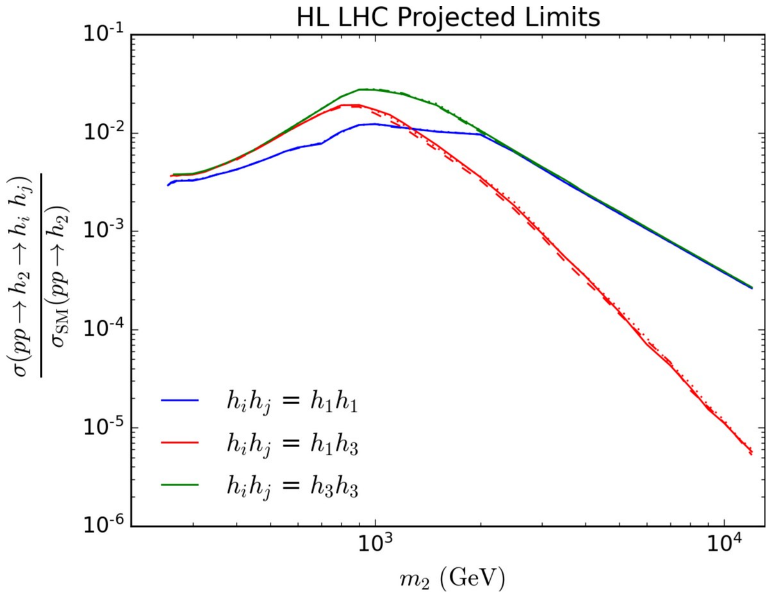
# Maximum Rates with HL-LHC

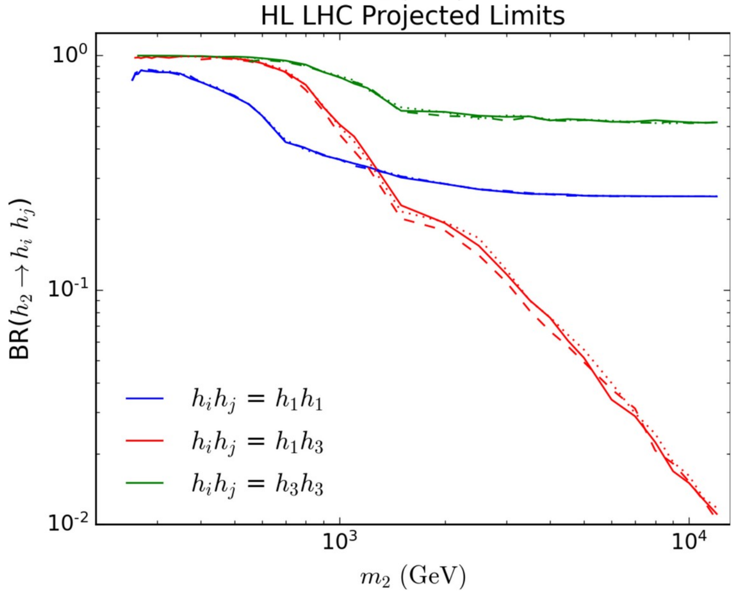
- To maximize rates and be agnostic about what type of future collider is built in the long run, we maximize the ratio of rates:

$$\frac{\sigma(pp\rightarrow h_2\rightarrow h_i h_j)}{\sigma_{SM}(pp\rightarrow h_2)}\approx\frac{\sigma(pp\rightarrow h_2)}{\sigma_{SM}(pp\rightarrow h_2)}BR(h_2\rightarrow h_i h_j)$$

$$=\sin^2\theta_1 BR(h_2\rightarrow h_i h_j)$$

- Behaviors already covered:
  - Goldstone boson equivalence theorem: $BR(h_2\rightarrow h_1 h_1)\rightarrow 1/4$
  - $BR(h_2\rightarrow h_1 h_3)\rightarrow 0$ due to a combination of theory constraints
- Other interesting behaviors:
  - $BR(h_2\rightarrow h_3 h_3)\approx 1/2$ in the multi-TeV regime
  - The max rates of $h_2\rightarrow h_1 h_1$ and $h_2\rightarrow h_3 h_3$ approach the same value

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# Maximum Rates with HL-LHC

- Understanding $h_2 \to h_3 h_3$ :
  - To maximize rate, set $BR(h_2 \to h_1 h_3) = 0$
  - Set the partial widths

$$\Gamma(h_2 \to W^+ W^-) \approx 2\,\Gamma(h_2 \to ZZ) \approx 2\,\Gamma(h_2 \to h_1 h_1)$$

  - Derive equation for max rate:

$$\begin{aligned}\sin^2\theta_1 \mathrm{BR}(h_2 \to h_3 h_3) &= \sin^2\theta_1 \left(1 - \mathrm{BR}(h_2 \to W^\pm W^\mp) - \mathrm{BR}(h_2 \to ZZ) - \mathrm{BR}(h_2 \to h_1 h_1)\right) \\ &\approx \sin^2\theta_1 \left(1 - \frac{4}{3}\sin^2\theta_1 \frac{\Gamma_{\mathrm{SM}}(h_2)}{\Gamma_{\mathrm{Tot}}(h_2)}\right),\end{aligned}$$

  - Max rate is found with narrow width approximation is saturated ( $\kappa = 0.1$ in our case):

$$\kappa\, m_2 \geq \Gamma_{\mathrm{Tot}}(h_2),$$

  - Can maximize and find corresponding sin theta and Branching ratios:

$$\begin{aligned}\sin^2\theta_{1,\max} &= \frac{3}{8}\frac{\kappa\, m_2}{\Gamma_{\mathrm{SM}}(h_2)}, \\ \mathrm{BR}_{\max}(h_2 \to h_3 h_3) &= \frac{1}{2}, \\ \sin^2\theta_{1,\max}\mathrm{BR}_{\max}(h_2 \to h_3 h_3) &= \frac{3}{16}\frac{\kappa\, m_2}{\Gamma_{\mathrm{SM}}(h_2)},\end{aligned}$$

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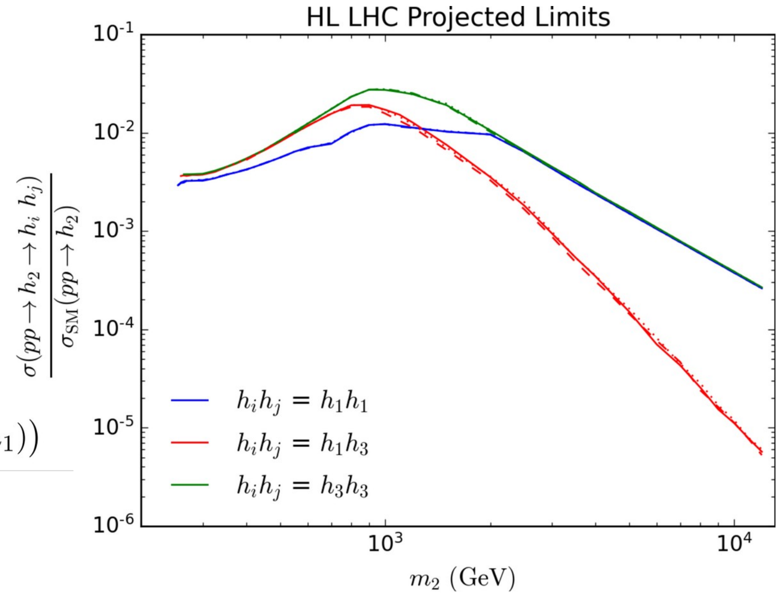


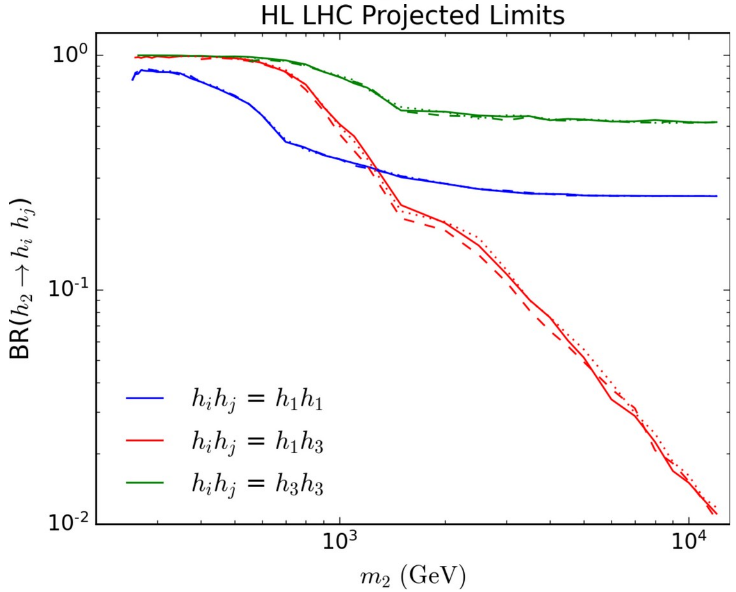

# Maximum Rates with HL-LHC

- Understanding $h_2 \rightarrow h_1 h_1$:
  - To maximize rate, set $\Gamma(h_2 \to h_1 h_3) = \Gamma(h_2 \to h_3 h_3) = 0$
  - Goldstone boson equivalence theorem sets:

$$\sin^2\theta_{1,\max}\mathrm{BR}_{\max}(h_2 \to h_1 h_1) \approx \frac{1}{4}\sin^2\theta_{1,\max}$$

  - Maximum rate when mixing angle maximized.
  - Total width grows like cubic power of mass, the narrow width assumption place upper bound on mixing angle:

$$\kappa\, m_2 \gtrsim \Gamma_{\rm Tot}(h_2) \approx \frac{4}{3}\sin^2\theta_1\,\Gamma_{\rm Tot,SM}(h_2).$$

  - Max rate and corresponding mixing angle is then.

$$\sin^2\theta_{1,\max} = \frac{3}{4}\frac{\kappa\, m_2}{\Gamma_{\rm SM}(h_2)}$$
$$\sin^2\theta_{1,\max}\mathrm{BR}_{\max}(h_2 \to h_1 h_1) = \frac{3}{16}\frac{\kappa\, m_2}{\Gamma_{\rm SM}(h_2)}.$$

  - Even though branching ratios and mixing angles are different, the rates for $h_1 h_1$ and $h_3 h_3$ are the same when these bounds are saturated.

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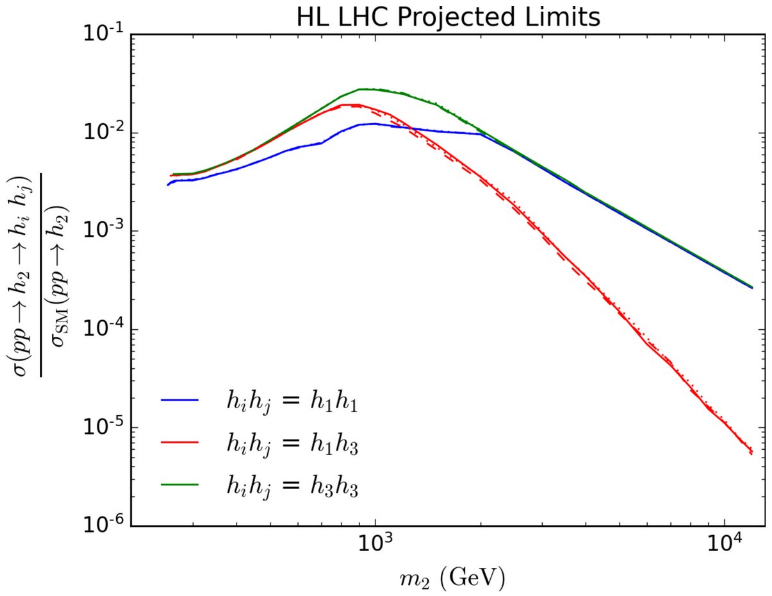
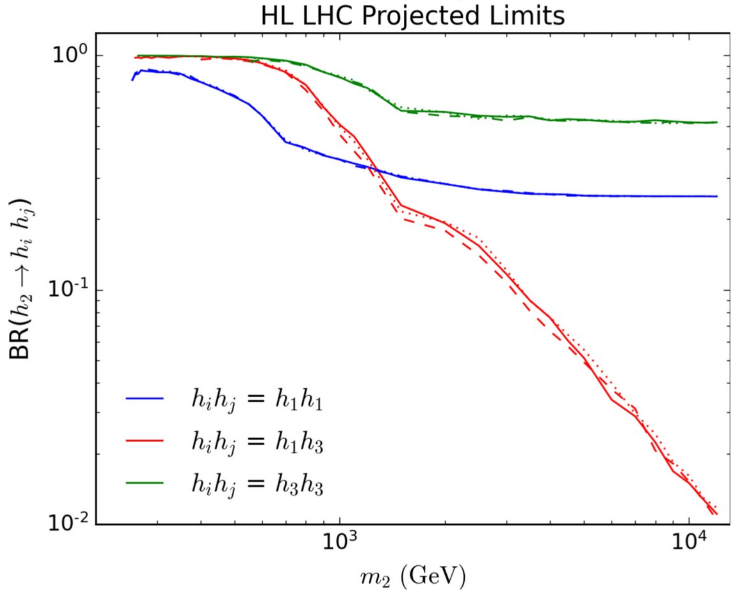
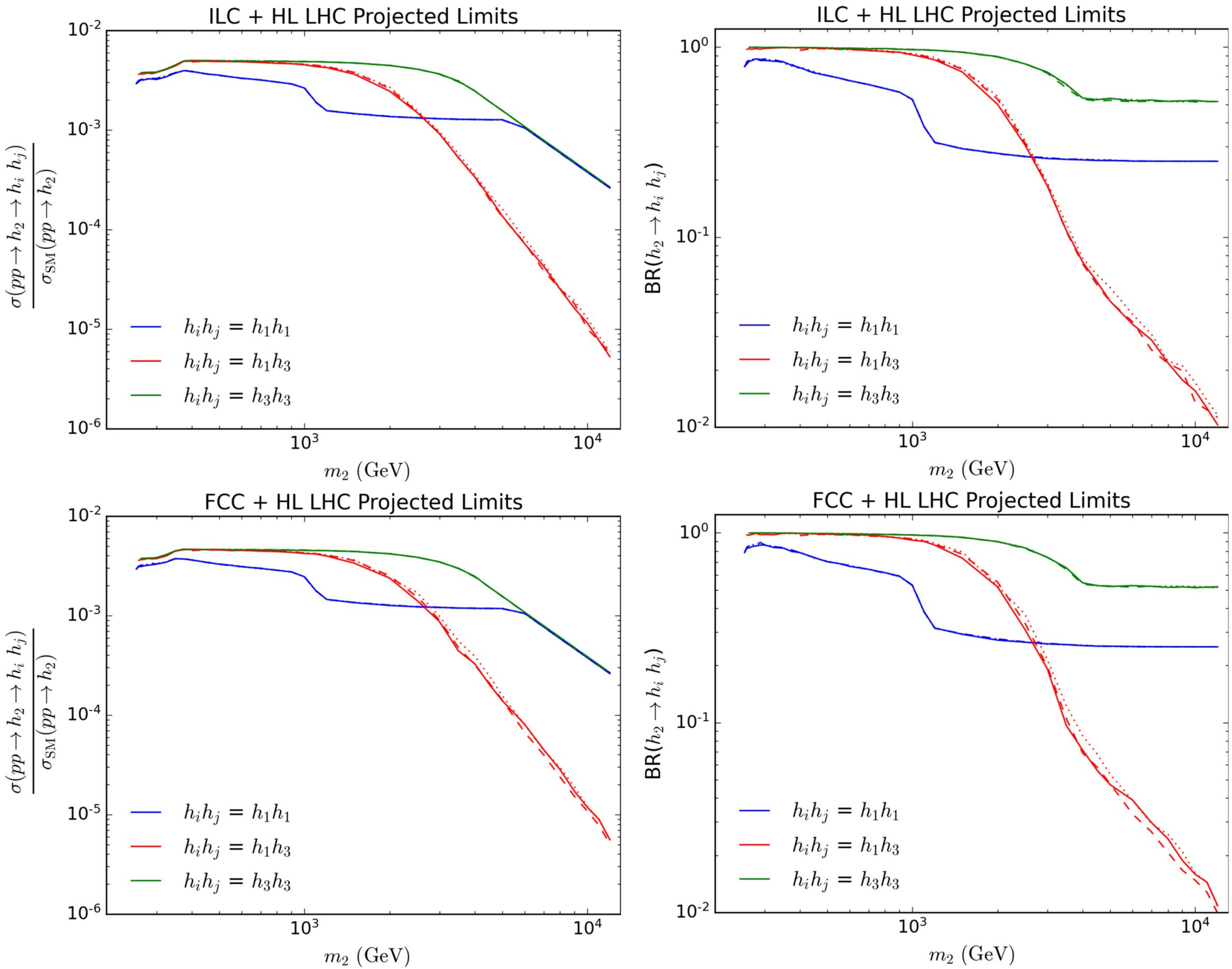


ILC500:

FCCee:

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Phenomenology Symposium
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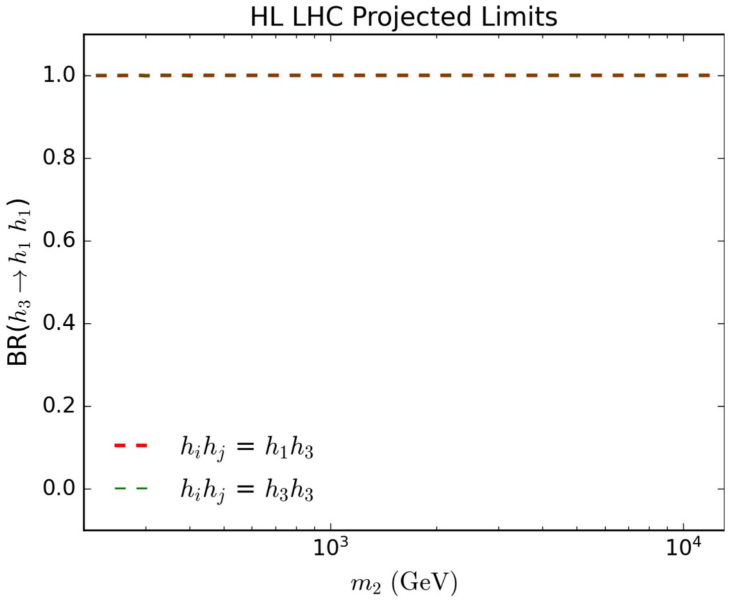
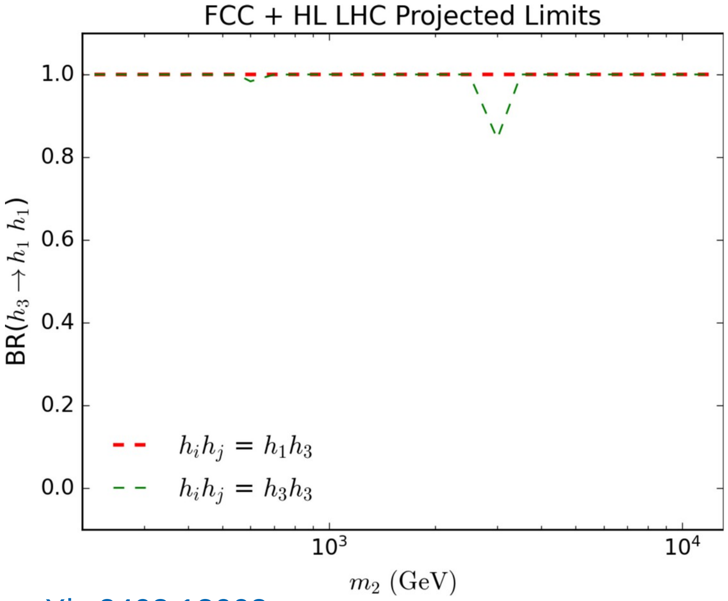
# Multi-Higgs phenomenology




Lane, **IML**, Sullivan arXiv:2403.18003

- For $m_3 = 270\, GeV$, can have three and four Higgs final states: $h_2 \to h_1 h_3 \to 3\, h_1$ and $h_2 \to h_3 h_3 \to 4\, h_1$.
- Showing $BR(h_3 \to h_1 h_1)$ for the previous benchmark points.
  - When available, this branching ratio dominates $h_3$ decays.
- Below 1 TeV, maximum two, three, and four Higgs rates are similar.
- This model has the surprising conclusion that in the multi-TeV range, the four Higgs signal may be a more promising search channel than the three Higgs.
- Very similar results for all collider scenarios.

# Conclusions

- We studied resonant di-scalar production in the generic complex singlet scalar model.

$$h_2 \rightarrow h_1 h_1, h_2 \rightarrow h_1 h_3, h_2 \rightarrow h_3 h_3$$

  - Two new scalars in addition to the SM-Higgs.
  - Could discover two new scalars at once.
- Considered four possible collider scenarios:
  - Current constraints from LHC
  - HL-LHC
  - HL-LHC+FCCee
  - HL-LHC+ILC500
- Considered three possible scenarios for h3 masses:
  - $m_3 = 130\,GeV$ : predominantly multi-b signals. $h_2 \to h_1 h_3 / h_3 h_3 \to 2b\,2\bar{b}$.
  - $m_3 = 200\,GeV$ : $h_3$ predominantly decays into Ws: $h_2 \to h_1 h_3 \to b\bar{b} W^\pm W^\mp$ and $h_2 \to h_3 h_3 \to 2W^\pm\,2W^\mp$.
  - $m_3 = 270\,GeV$ : $h_3 \rightarrow h_1 h_1$ opens up: $h_2 \to h_1 h_3 \to 3\,h_1$ and $h_2 \to h_3 h_3 \to 4\,h_1$.
- Below 1 TeV, the maximum two, three, and four Higgs rates are similar.
- In the multi-TeV regime, this model has the surprising result that four Higgs final states could be produced at much higher rates than three Higgs.
- Many other studies on asymmetric decays in other models:

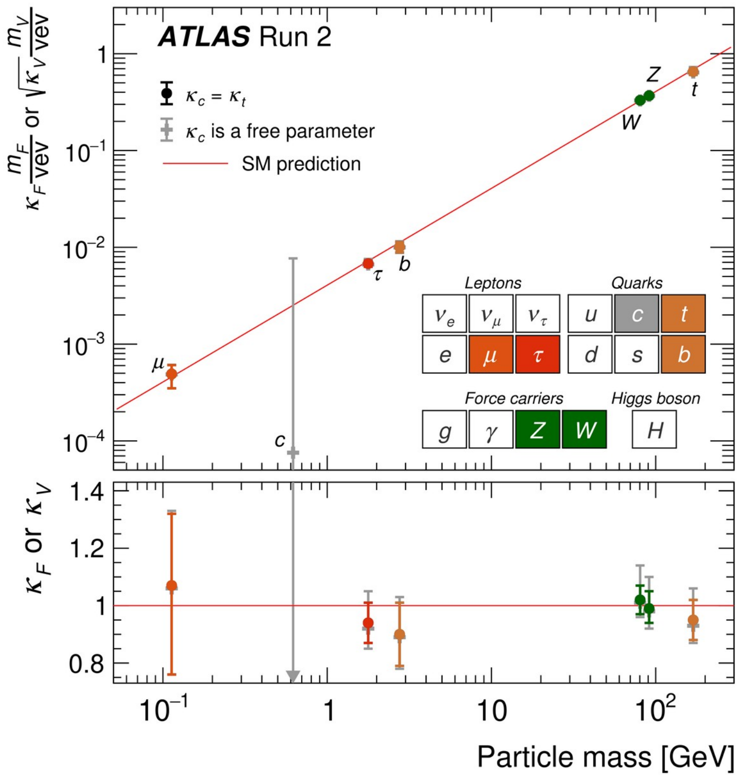
Dawson, Sullivan, PRD97 (2018) 015022; Adhikari, Lane, **IML**, Sullivan, arXiv:2203.07455; Abouabid et al arXiv:2112.12515; Basler, Dawson, Englert, Mühlleitner, PRD101 (2020) 015019; Robens, arXiv:2209.10996; etc.

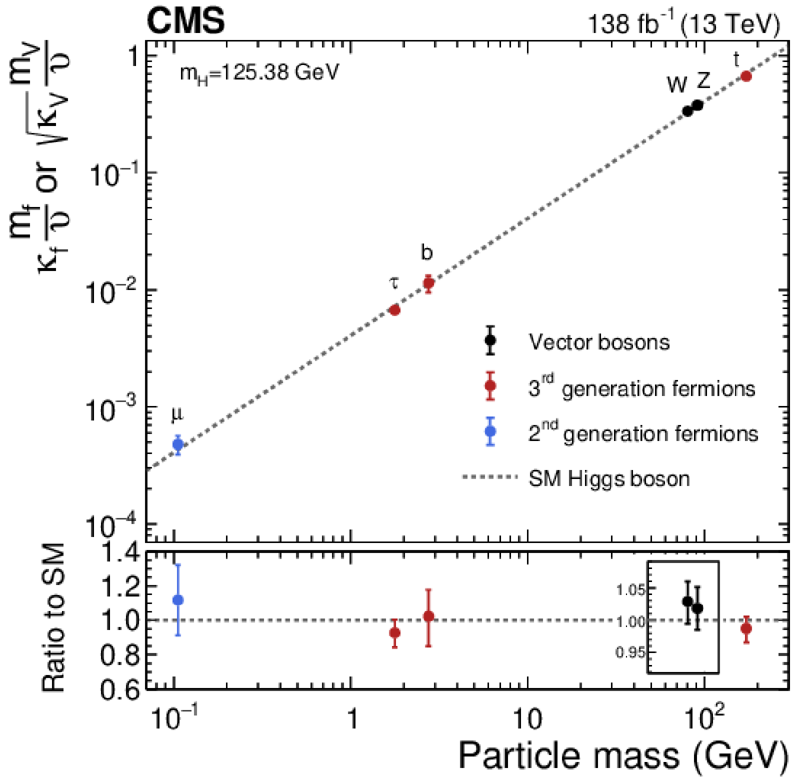
# Thank You

# Where We're At

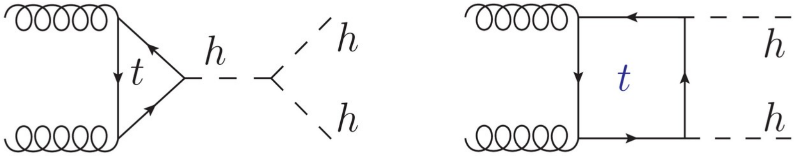
CMS, Nature, arXiv:2207.00043

ATLAS, Nature, arXiv:2207.00092



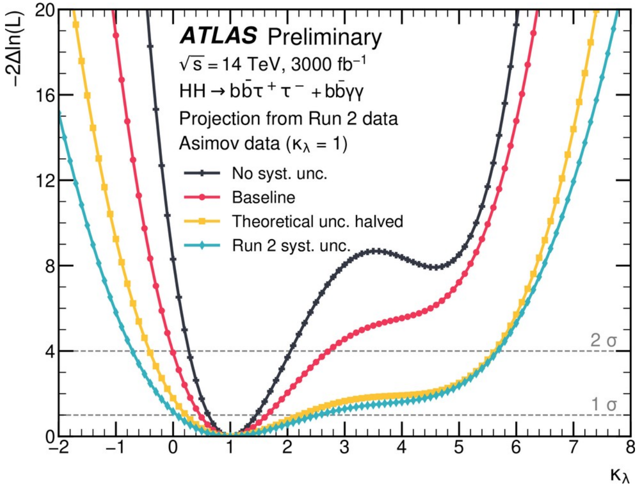



# Double Higgs in the SM




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

- 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 TeV) [63] | - | 15-30% | 15-30% |
| $\mu$(10 TeV) [63] | - | 4% | 4% |

ATL-PHYS-PUB-2022-005

Snowmass Higgs Topical Group Report, arXiv:2209.07510

# Current Maximum Rates

Lane, **IML**, Sullivan arXiv:2403.18003

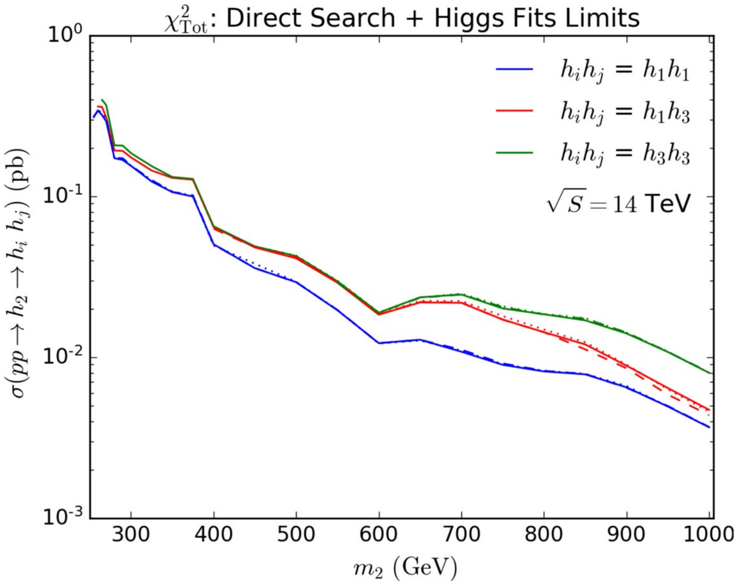
- Use the most constraining limits on mixing angles.
- For $h_2 \to h_1 h_1$, Goldstone boson equivalence theorem prevents $\Gamma(h_2 \to h_1 h_1)$ from deviating too much from $\Gamma(h_2 \to ZZ/W^+W^-)$
- $h_2 \to h_1 h_3$ has constraints from global minimum, perturbative unitarity, boundedness, and narrow width approximation:
  - Can find an upper bound on the triple coupling and mixing angle:

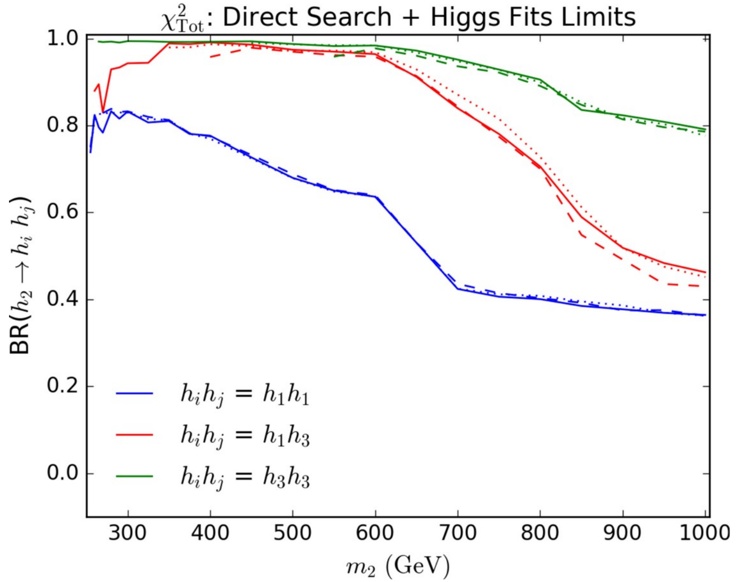
$$|\lambda_{123}| \lesssim 4\sqrt{\frac{\pi}{3}}\,(m_1 + 2\,m_2|\sin\theta_1|) \qquad |\sin\theta_1| \lesssim 2\sqrt{\frac{\pi}{5}}\frac{v_{\rm EW}}{m_2}$$

  - Leads to an upper bound on the branching ratio:

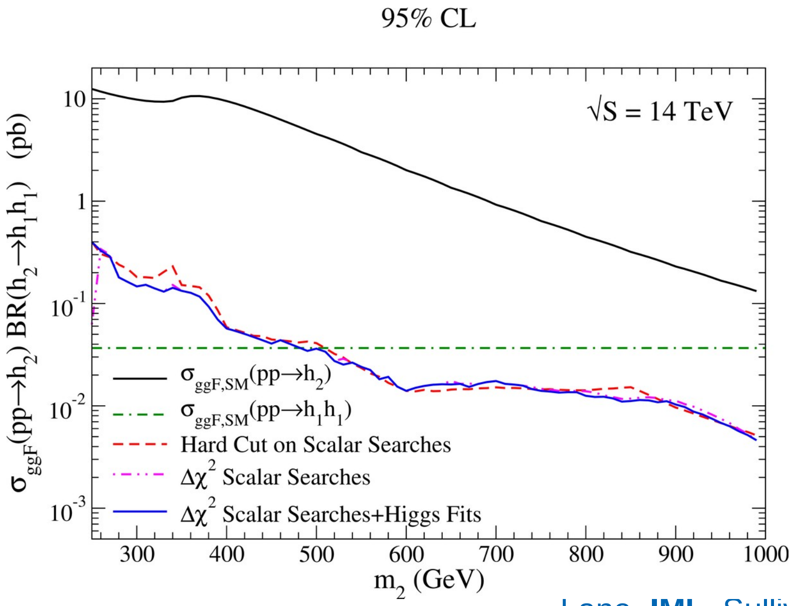
$$\mathrm{BR}(h_2 \to h_1 h_3) \lesssim \frac{32\,\pi}{3}\left(1 + \frac{1}{4}\sqrt{\frac{5}{\pi}}\right)^2 \frac{v_{\rm EW}^2}{m_2^2} \approx 0.11\left(\frac{m_2}{5\ \mathrm{TeV}}\right)^{-2}.$$

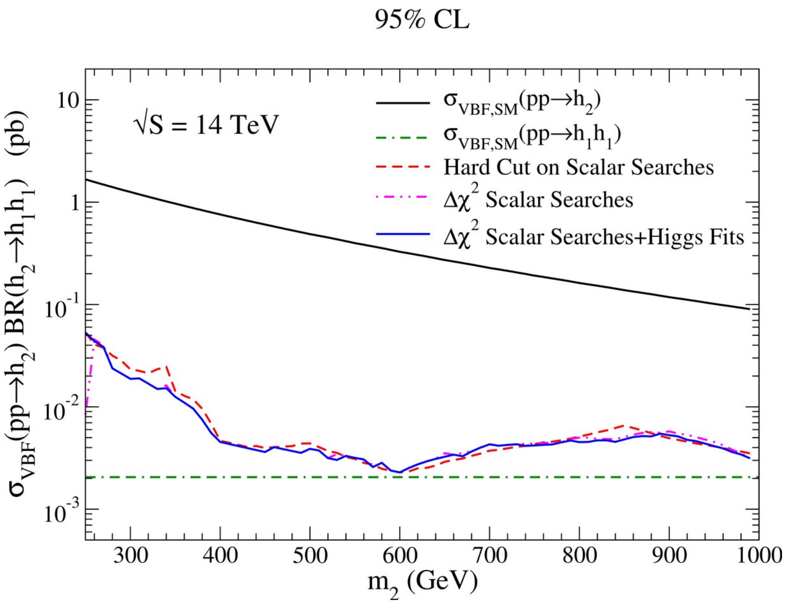
  - Goes to zero as $h_2$ mass increases.



# Upper Bounds on Di-Higgs




Lane, **IML**, Sullivan arXiv:2403.18003