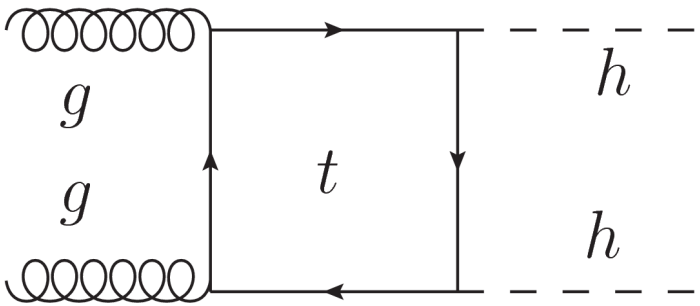
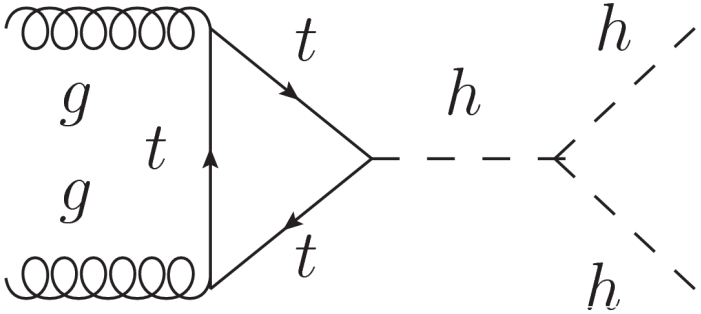
Beyond the Standard Model HH production

Ian Lewis
University of Kansas

BSM in Double Higgs





- Now that we know mass, completely predictive.

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 = -\frac{1}{8}m_h^2 v^2 + \frac{1}{2}m_h^2 h^2 + \frac{m_1^2}{2v}h^3 + \frac{m_1^2}{8v^2}h^4$$

  - $\lambda_{hhh} = m_h^2/2v = 0.13\,v$
  - $y_t = m_t/v = 0.70$

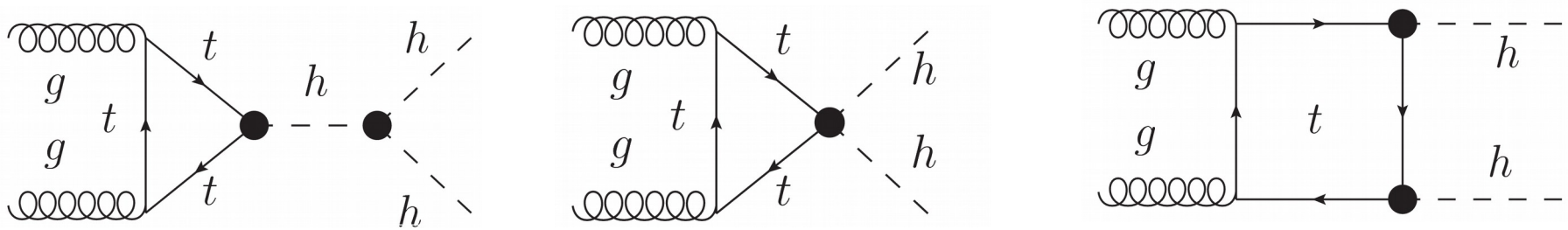
- Precise predictions for the SM:

$$\sigma_{NNLO}(13\ \mathrm{TeV}) = 31.05^{+2.2\%}_{-5.0\%}\ \mathrm{fb}$$

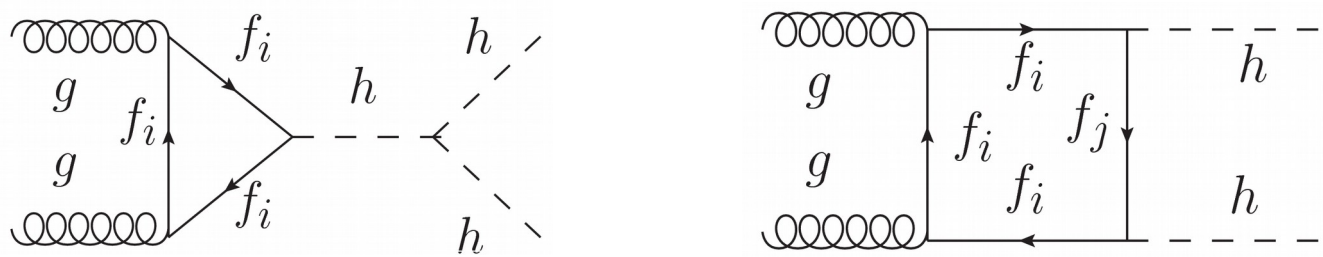
Borowka et al., PRL 117 (2016) 012001 JHEP 1610 (2016) 107;
Grazzini, et al, JHEP 1805 (2018) 059;
Julien Baglio's talk yesterday; Mazzitelli talk on Tuesday

BSM in Double Higgs

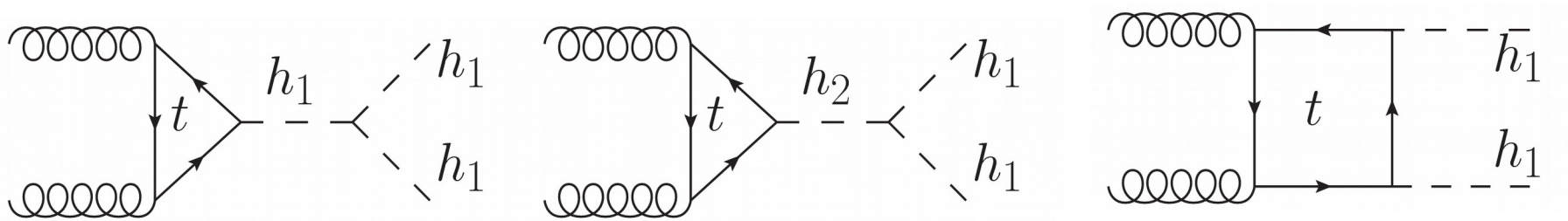
- Couplings different from the SM and/or EFT



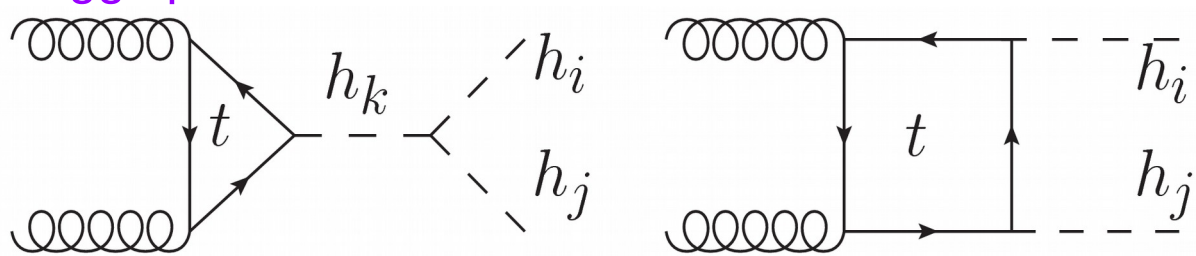
- New physics in the loop.



- New resonances.



- Double exotic Higgs production.



New Physics in the Loop

- Any colored particles that enter the loops can effect single and double Higgs production.
- Potentially have two contributions to EFT:

$$\mathcal{L}_{EFT} = c_1 \frac{\Phi^\dagger \Phi}{v^2} G^a_{\mu\nu} G^{a,\mu\nu} + c_2 \log\left(\frac{\Phi^\dagger \Phi}{v^2}\right) G^a_{\mu\nu} G^{a,\mu\nu}$$

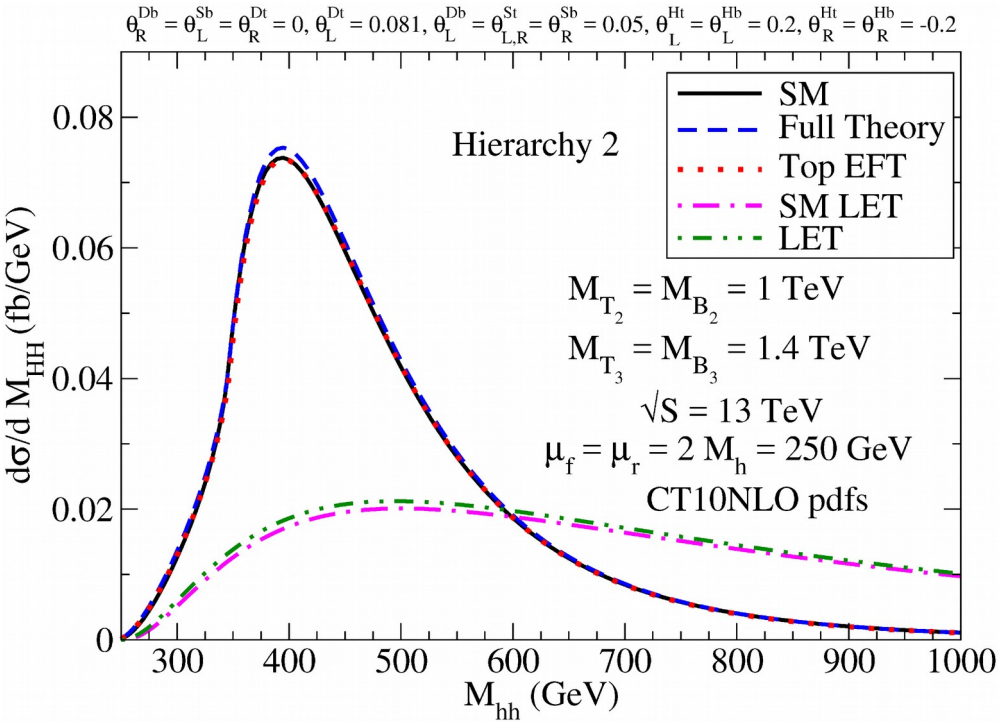
  - c_2 operator appears if particles get all their mass from the Higgs.
- Single and double Higgs coefficients linearly independent:

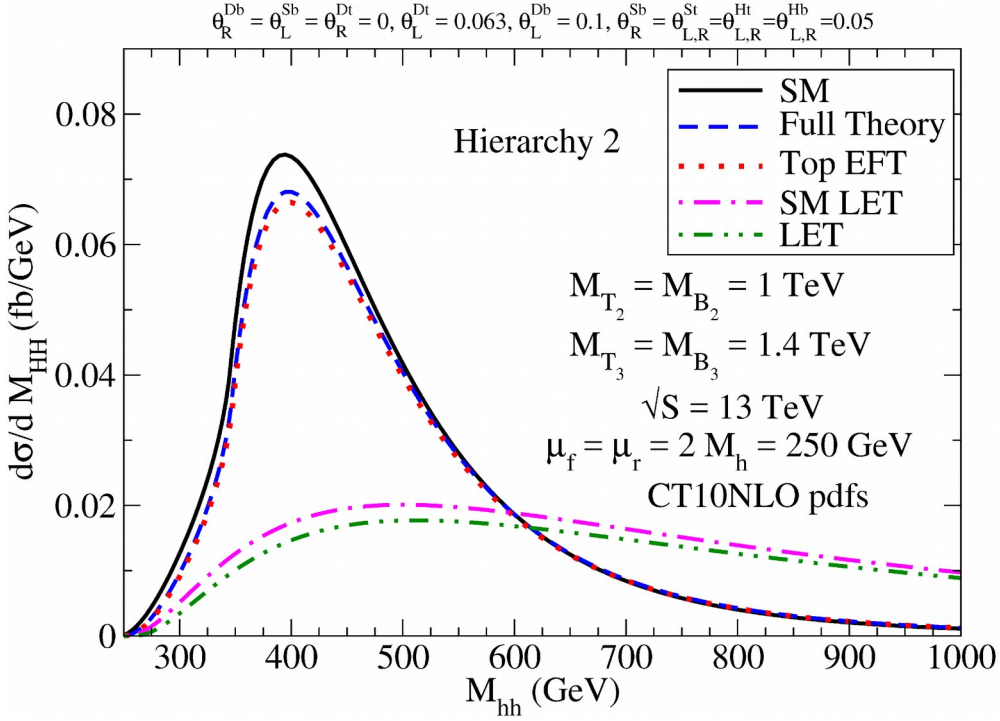
$$\mathcal{L}_{EFT} = 2(c_1 + c_2)\frac{h}{v} G^a_{\mu\nu} G^{a,\mu\nu} + (c_1 - c_2)\frac{h^2}{v^2} G^a_{\mu\nu} G^{a,\mu\nu}$$

Pierce, Thaler, Wang JHEP 0705 (2007) 070

- In principle, single and double Higgs can contain different information.
  - Learned early on that there does not appear like new physics interacts strongly with the Higgs.

New Fermions in the Loop

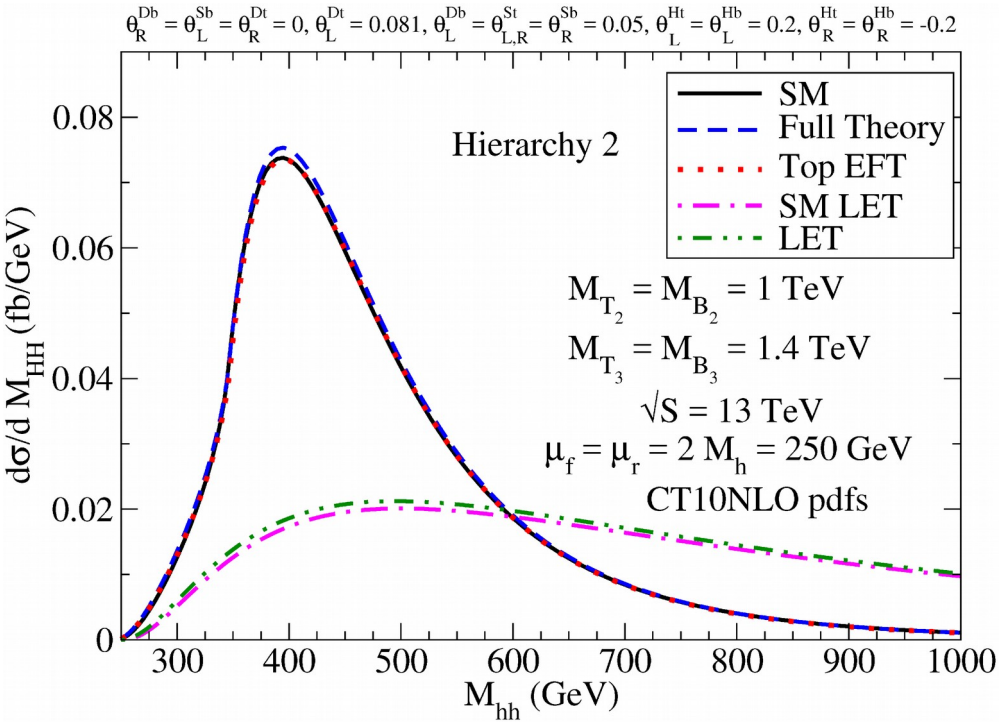


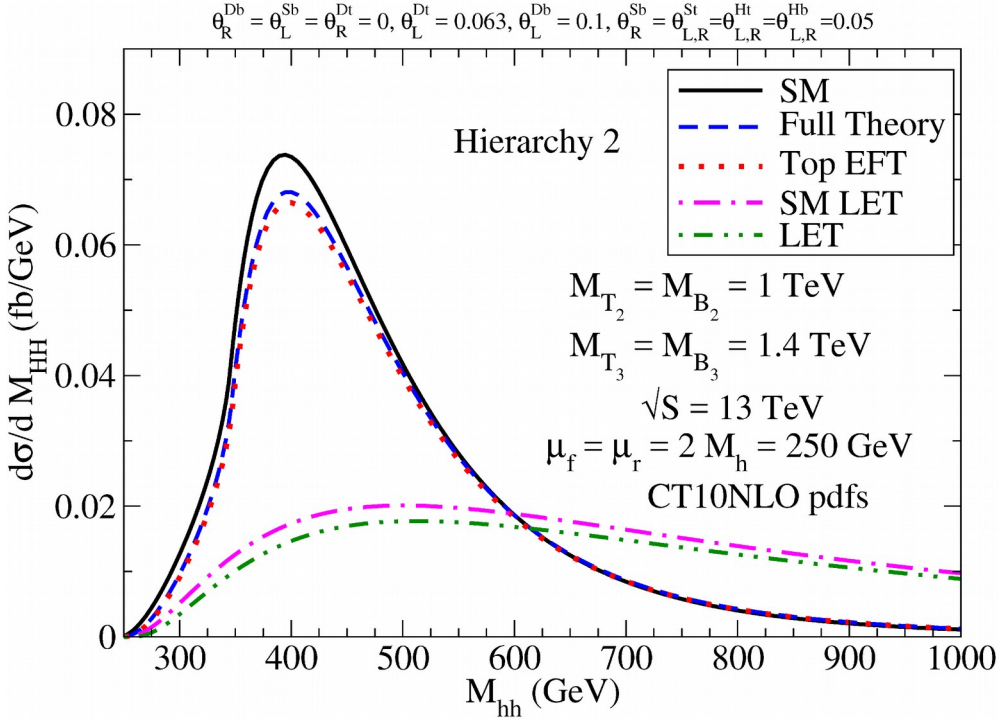


Dawson, Furlan, **IL** PRD87 (2013) 014007; Chen, Dawson, **IL** PRD90 (2014) 035016

- Assume full vector-like quark generation:
  - SU(2) Doublet: $Q = (T, B)^{\mathrm{t}}$
  - Two SU(2) Singlets: $U,\ D$
- Two up-type and two down-type heavy quarks: $T_2,\ T_3,\ B_2,\ B_3$

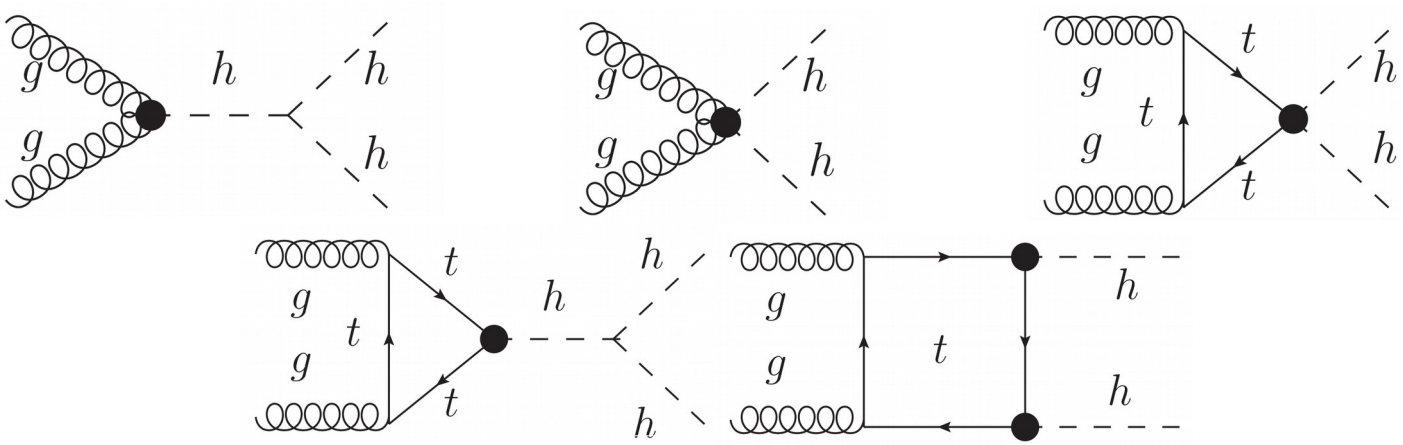
Validity of the EFT





Dawson, Furlan, **IL** PRD87 (2013) 014007; Chen, Dawson, **IL** PRD90 (2014) 035016

- Top EFT: Integrating out new heavy quarks creating new vertices:

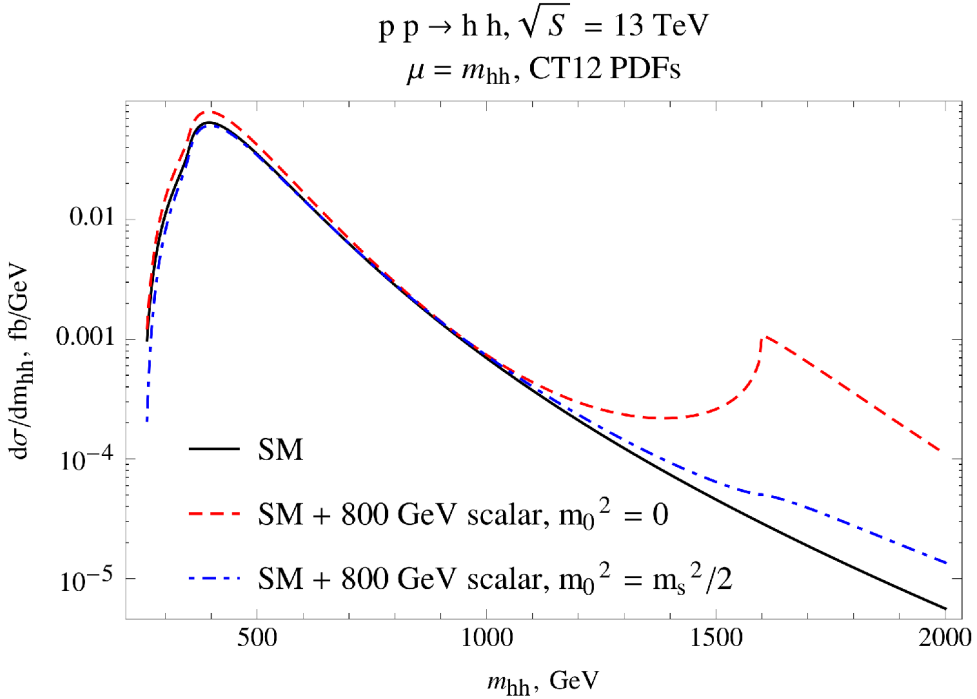


Thresholds in the Loops

- Very heavy new particles:
  - If most of the mass from the Higgs, has to be strongly coupled.
  - If weakly coupled most mass from another source.
  - EFT gluon couplings from one source :

$$\mathcal{L}_{EFT} = c_1 \frac{\Phi^\dagger \Phi}{v^2} G^a_{\mu\nu} G^{a,\mu\nu}$$

  - Single and double Higgs rate highly correlated.

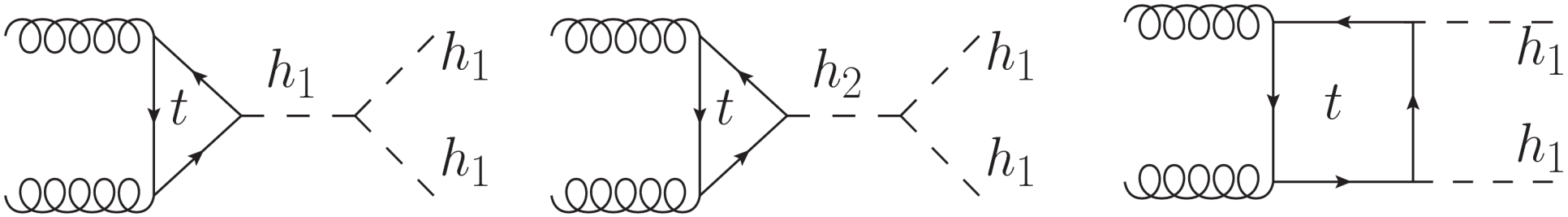


Dawson, Ismail, Low PRD91 (2015) 115008

- Probe high enough invariant masses can see thresholds.
  - Does not depend explicitly on decay of new particles since they appear inside a loop.
  - Can fine tune light colored particles to be hard to see and still significantly enhance double Higgs rates. Batell, McCullough, Stolarski, Verhaaren JHEP 1509 (2015) 216; Kribs, Martin PRD86 (2012) 095023

- More complete models will often include alterations in Higgs couplings as well as new particles in the loop. Huang, Joglekar, Li, Wagner PRD97 (2018) 075001

Resonant Production

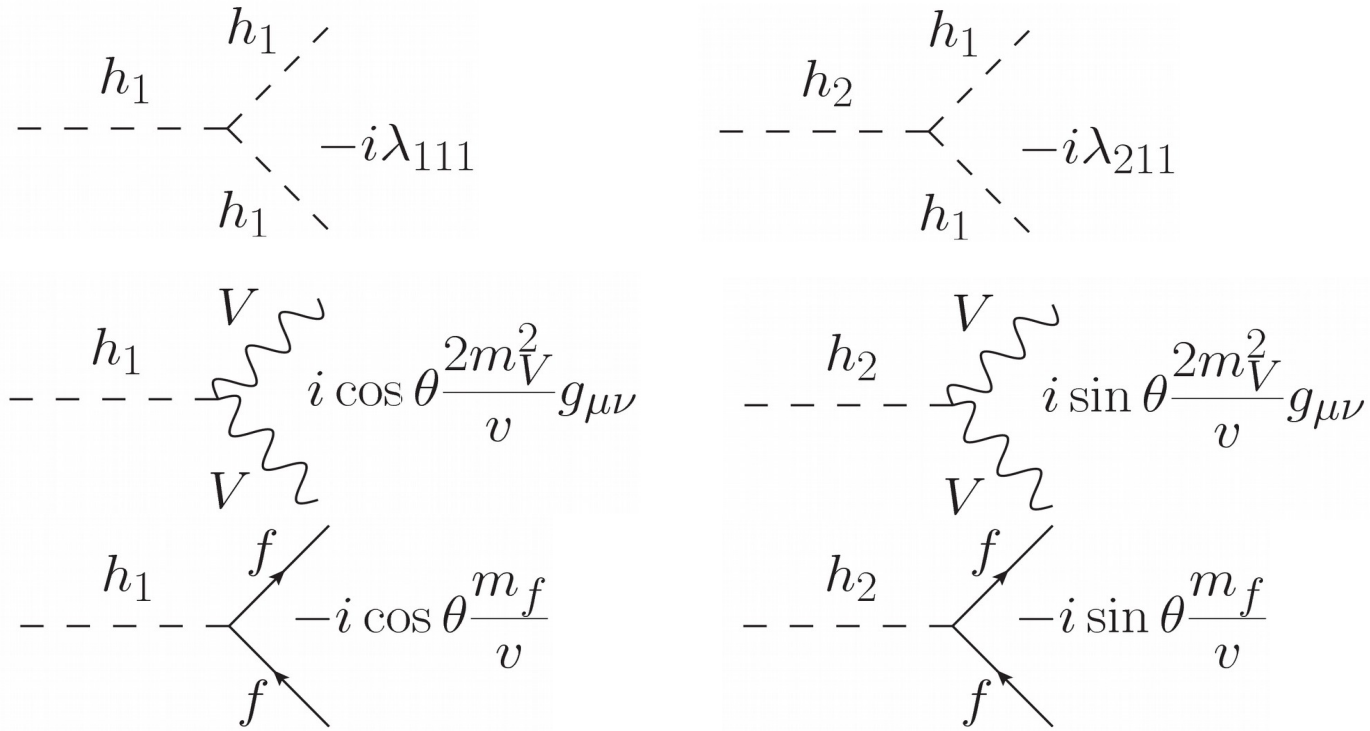


- Focus on the simplest possibility for a scalar resonance, the addition of a real singlet scalar:
  - At the renormalizable level, only couples to the Higgs doublet:

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

- Free parameters:
  - Two masses: $m_2 > 2m_1 = 2(125\ \mathrm{GeV})$
  - Mixing angle: θ
  - Potential parameters: $a_2,\ b_3,\ b_4$

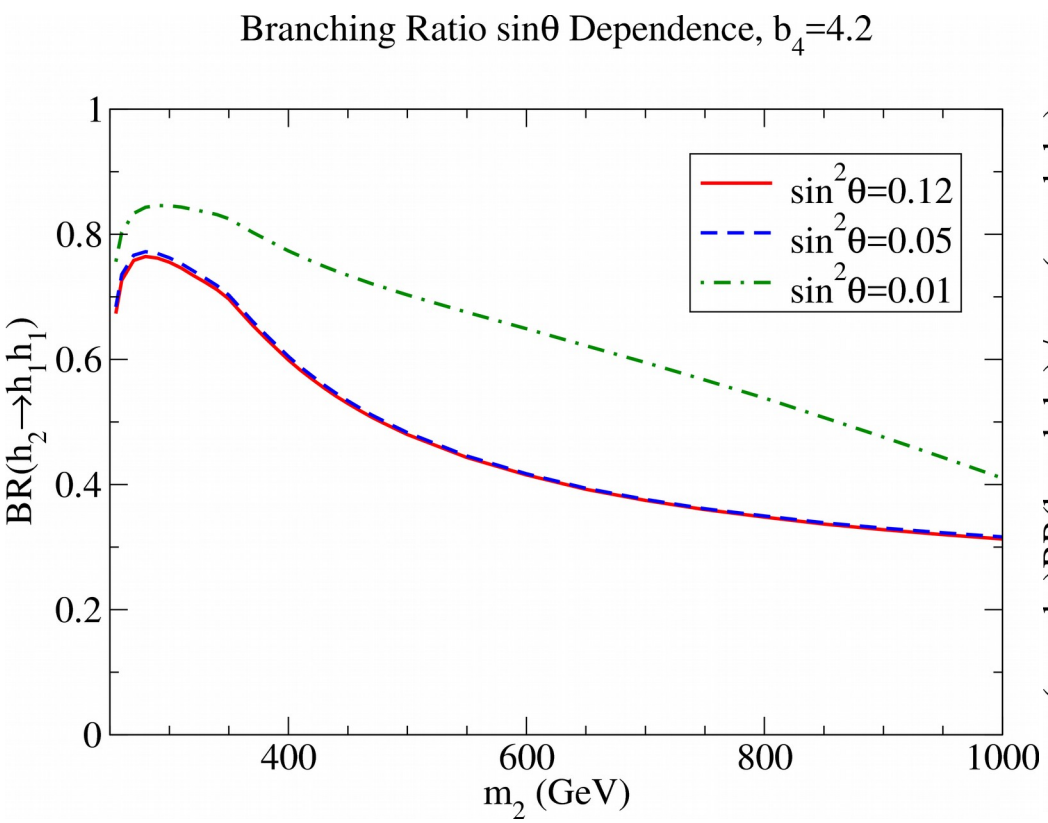
Couplings after Mixing With Higgs

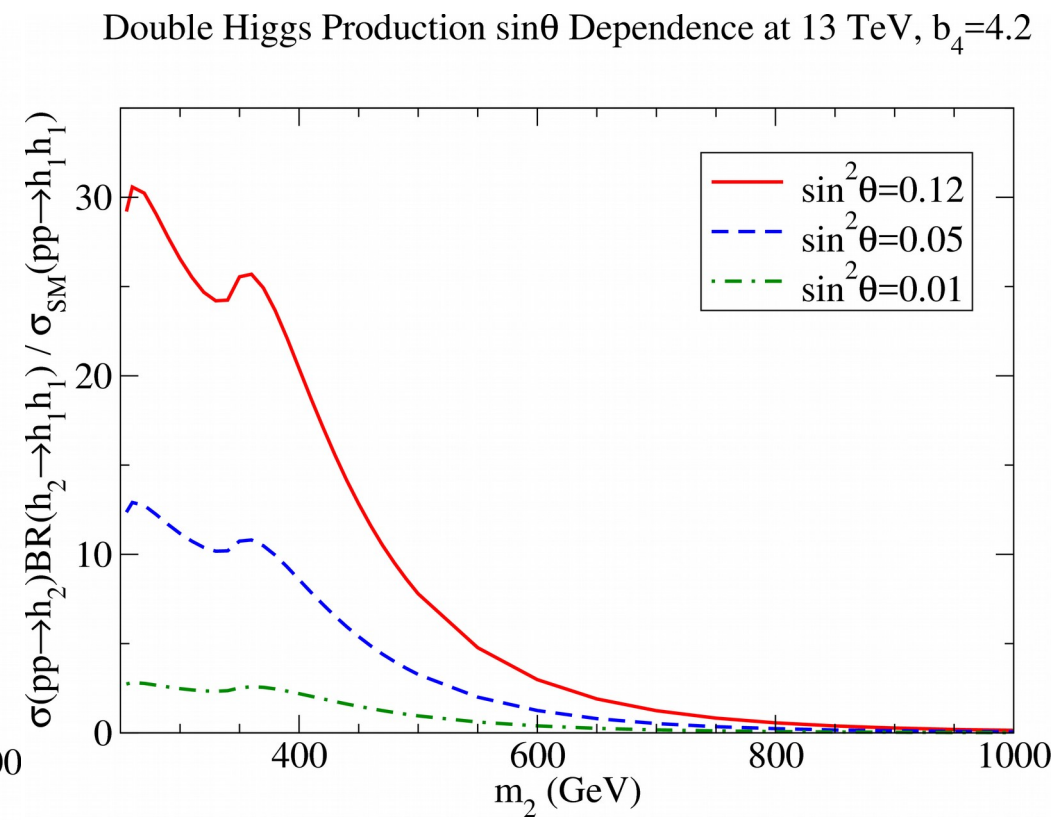


- If kinematically available, resonant double Higgs production possible.
- Production of h_2 same as SM Higgs suppressed by $\sin^2\theta$
- Decays of h2 similar to SM Higgs with new channel $h_2 \rightarrow h_1\, h_1$
- Precision Higgs limits mixing of scalar singlet and Higgs boson.
  - Branching ratios unchanged.
  - Universal suppression of $\cos^2\theta$ for production of h_1

Constraints on $pp \to h_2 \to h_1 h_1$ rates

- Cannot arbitrarily increase Higgs branching ratios.
  - More complicated scalar potential, more minima: 6 extrema in total
  - Singlet cannot contribute to fermion and vector boson masses.
  - Have to guarantee that global minimum has Higgs doublet vev is 246 GeV.





IL, M. Sullivan PRD96 (2017) 035037

Benchmark Points

m_2	a_2	b_3/v_{EW}	$\mathrm{BR}(h_2 \to h_1 h_2)$	$\sigma(pp \to h_2)\mathrm{BR}(h_2 \to h_1 h_1)$
300 GeV	−0.79	−2.7	0.76	0.89 pb
400 GeV	−0.40	−3.9	0.60	0.68 pb
500 GeV	0.059	−5.4	0.48	0.26 pb
600 GeV	0.56	−7.1	0.42	0.10 pb
700 GeV	1.0	−8.7	0.37	0.042 pb
800 GeV	1.6	−11	0.35	0.019 pb

TABLE I: Benchmark points that maximize $\mathrm{BR}(h_2 \to h_1 h_1)$ with $b_4 = 4.2$ and $\sin^2\theta = 0.12$. The cross sections are evaluated at a lab frame energy of $\sqrt{S_H} = 13$ TeV.

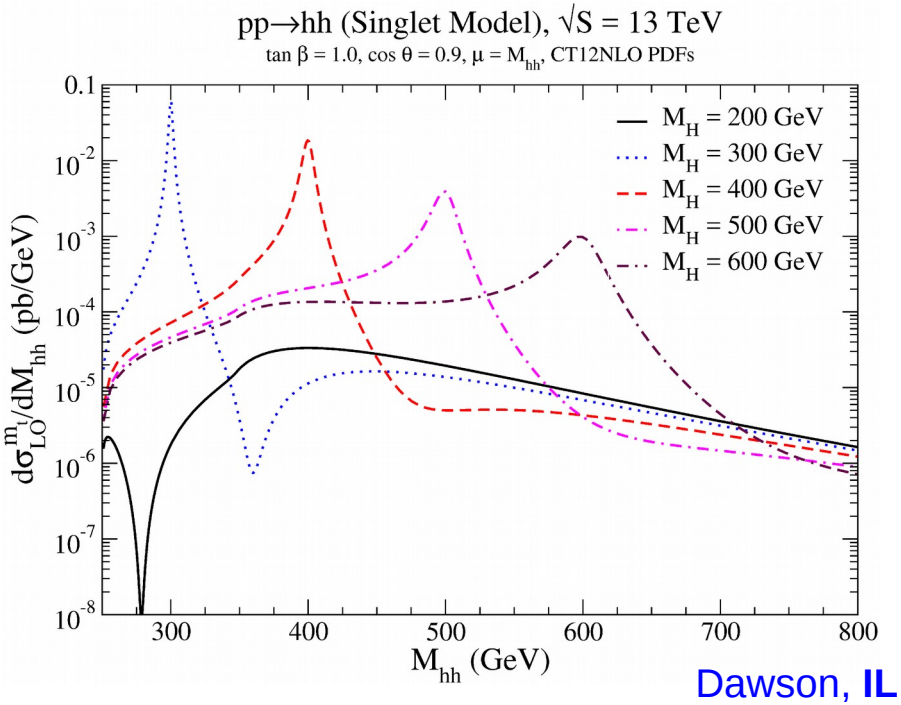
m_2	a_2	b_3/v_{EW}	$\mathrm{BR}(h_2 \to h_1 h_2)$	$\sigma(pp \to h_2)\mathrm{BR}(h_2 \to h_1 h_1)$
300 GeV	−1.2	−1.6	0.76	0.37 pb
400 GeV	−1.0	−2.7	0.60	0.29 pb
500 GeV	−0.78	−3.9	0.48	0.11 pb
600 GeV	−0.59	−5.0	0.42	0.042 pb
700 GeV	−0.31	−6.5	0.38	0.017 pb
800 GeV	−0.015	−8.1	0.35	0.0079 pb

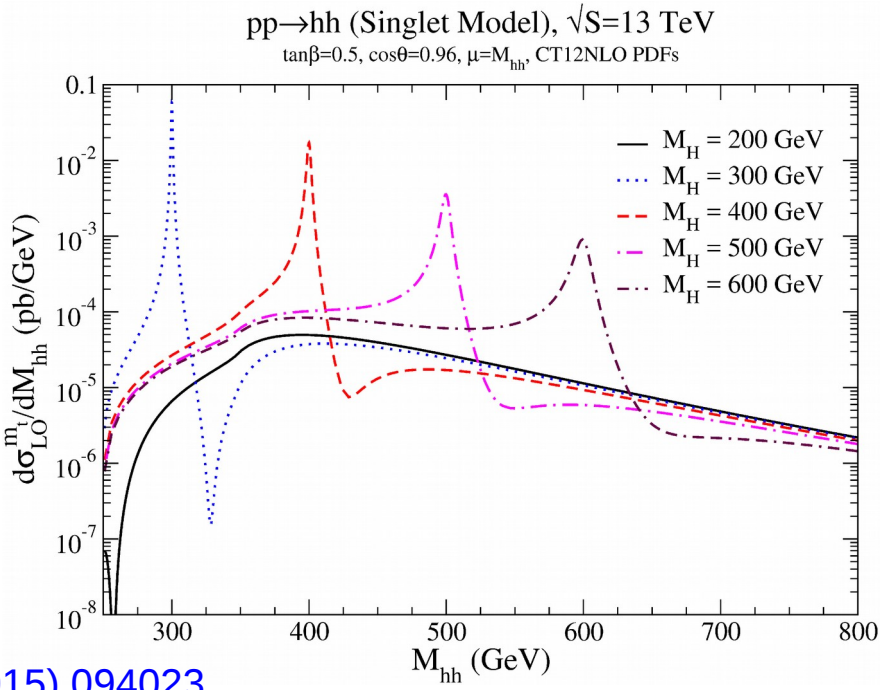
TABLE II: Benchmark points that maximize $\mathrm{BR}(h_2 \to h_1 h_1)$ with $b_4 = 4.2$ and $\sin^2\theta = 0.05$. The cross sections are evaluated at a lab frame energy of $\sqrt{S_H} = 13$ TeV.

IL, M. Sullivan PRD96 (2017) 035037

- Benchmark points for singlet model with Z_2 parity S → -S have also been developed. Robens, Stefaniak EPJ C76 (2016) 268
  - Not as many degrees of freedom, not as large a branching ratio $h_2 \to h_1 h_1$
  - We calculated NLO corrections for Robens, Stefaniak benchmark points for Yellow Report 4. Dawson, **IL** PRD91 (2015) 074012

Importance of Interference





Dawson, **IL** PRD92 (2015) 094023

- S-channel propagator: $\frac{\cos\theta\,\lambda_{111}v}{s-m_1^2+i\Gamma_1 m_1} - \frac{\sin\theta\lambda_{112}\,v}{s-m_2^2+i\Gamma_2 m_2}$
- Take limit $s, m_1^2 \ll m_2^2 \Rightarrow \lambda_{112} \to \frac{m_2^2}{2\,v}\sin 2\theta\,\left(\cos\theta + \sin\theta\tan\beta\right)$
- Propagator becomes $\frac{\cos\theta\,\lambda_{111}v}{s-m_1^2+i\Gamma_1 m_1} + \frac{\sin\theta\sin 2\theta}{2}\left(\cos\theta + \sin\theta\tan\beta\right)$
-
- No explicit dependence on m_2

Importance of Interference

- Off-shell interference:
  - Higher mass resonance, more important

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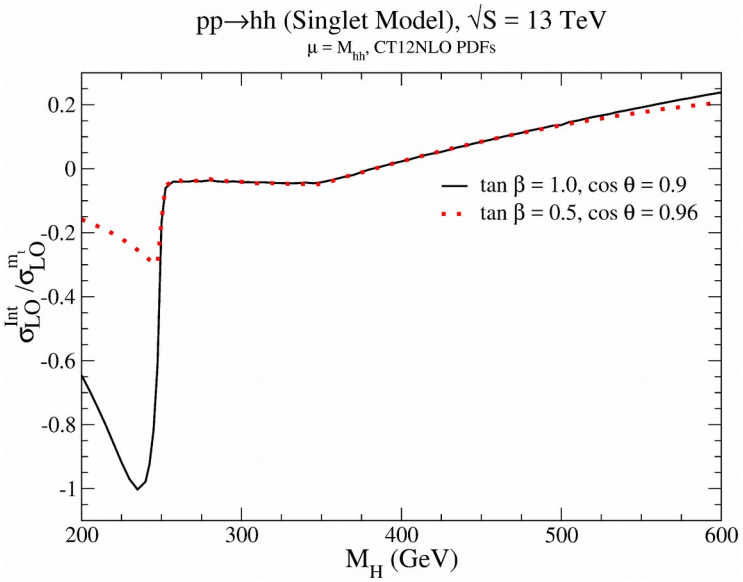
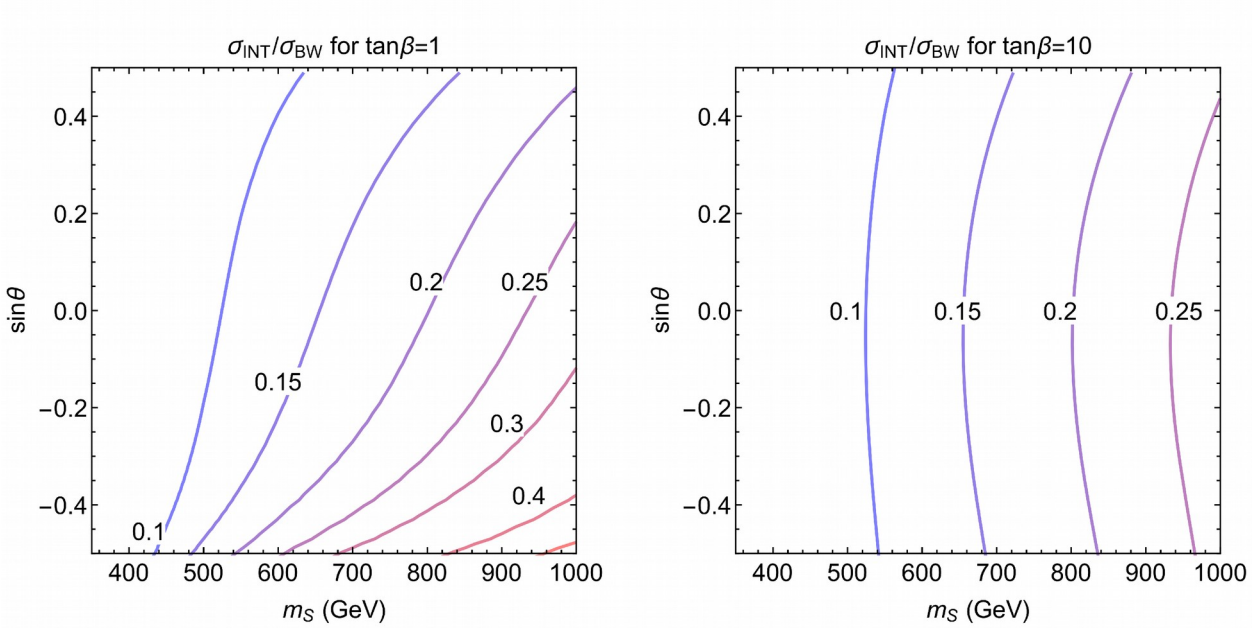
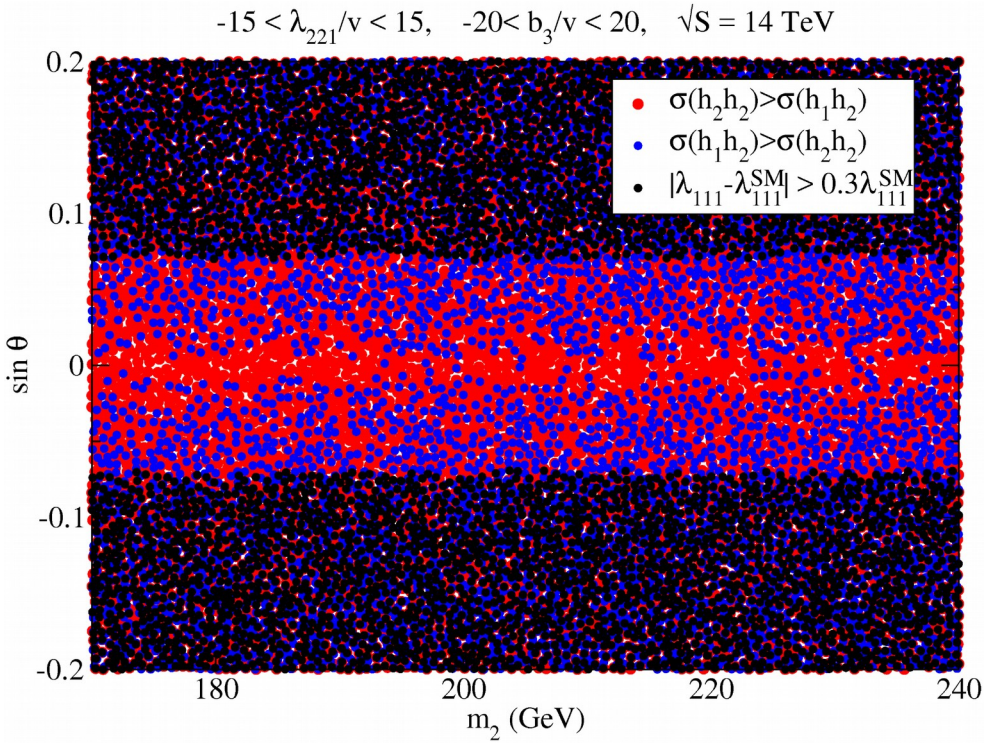


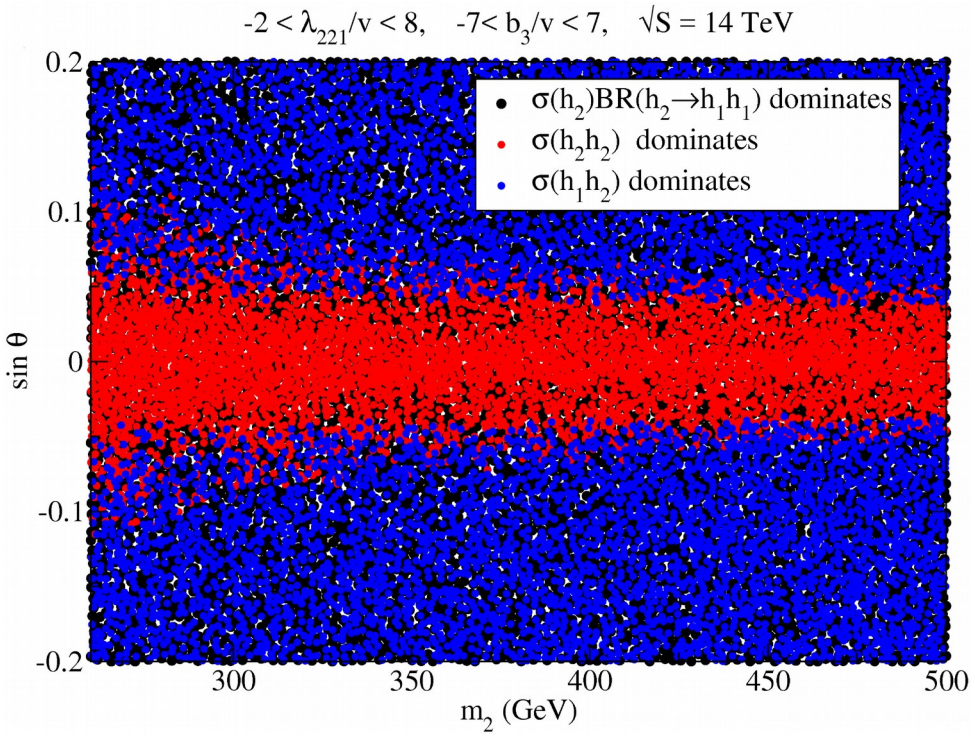
- On-shell interference:
  - Need phase between loops and imaginary part of propagator.

Carena, Liu, Riembau
PRD 97 (2018) 095032



Additional Non-Resonant Modes





Chen, Kozaczuk, **IL** JHEP 1708 (2017) 096

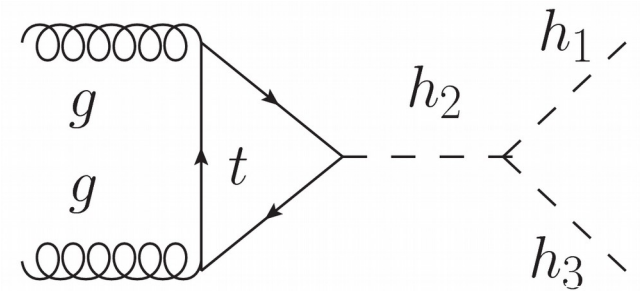
- New final states h_1h_2 and h_2h_2
- Different production modes dominate in different regions.

Complex Singlet Model

- Consider a complex singlet: $S_c = S_1 + i\,S_2$
  - At renormalizable level only appears in Higgs potential
  - Three real scalars: $h,\ S_1,\ S_2$
  - Hence three physical scalar bosons exist in this model:

$$h_1,\ h_2,\ h_3$$

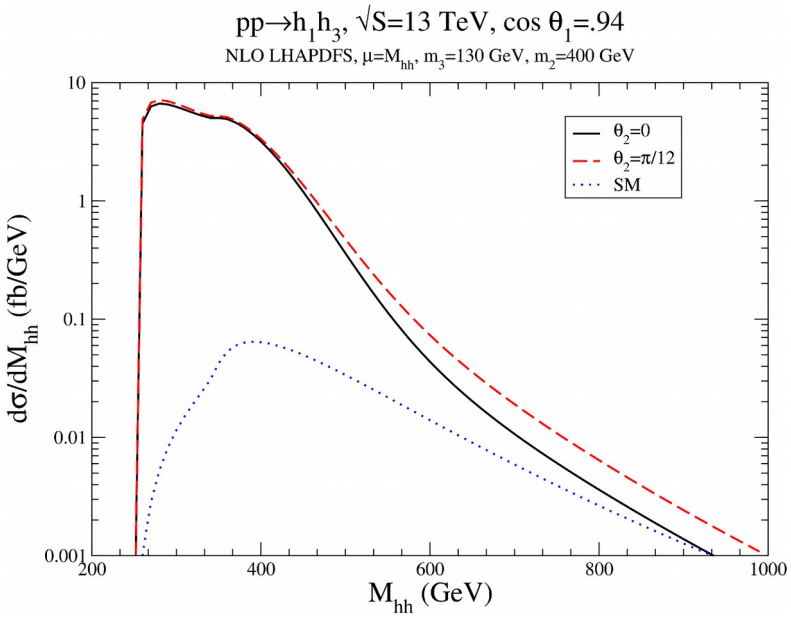
  - h_1 the observed 125 GeV Higgs.
  - All CP even, mix with the Higgs, and inherent Higgs like couplings to SM fermions and gauge boson.
- Possible to have $h_2 \to h_1\, h_3$ resonant production.

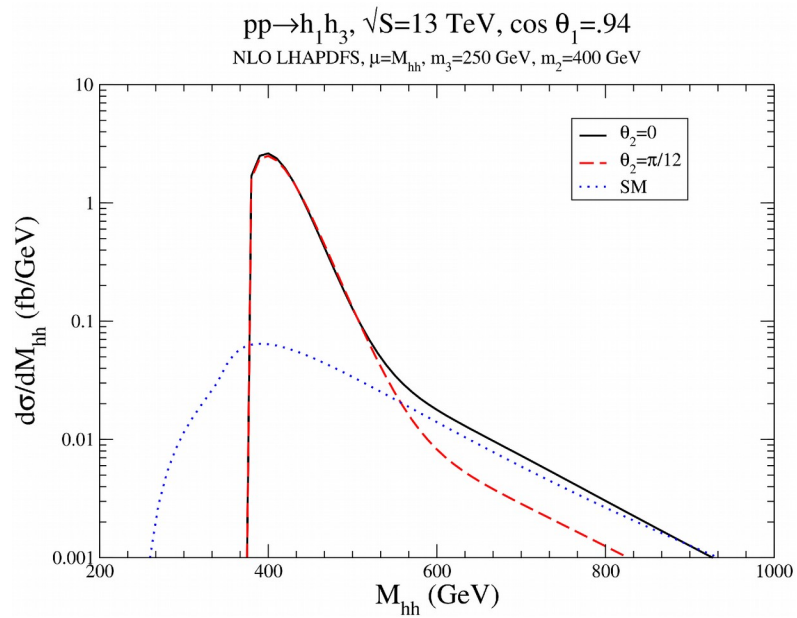


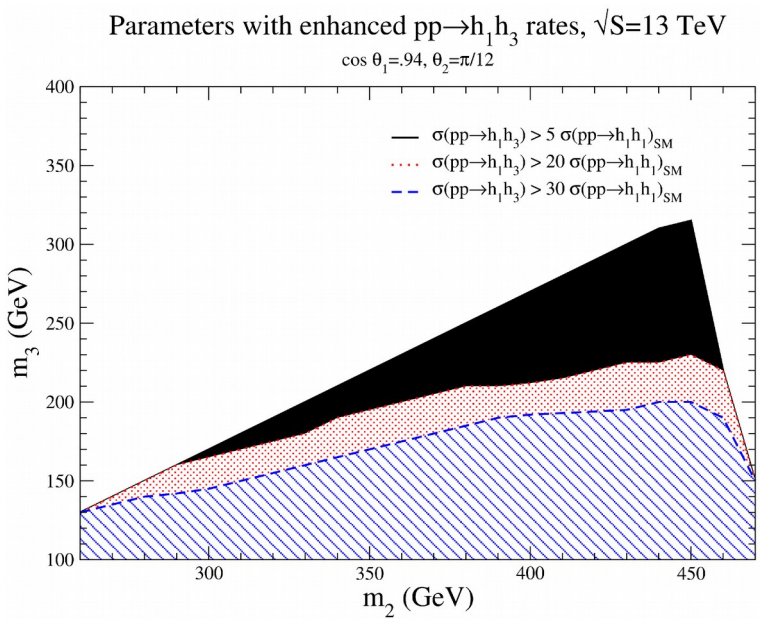
  - In fact, in the limit that h_3 does not mix, this is the only way to produce h_3.

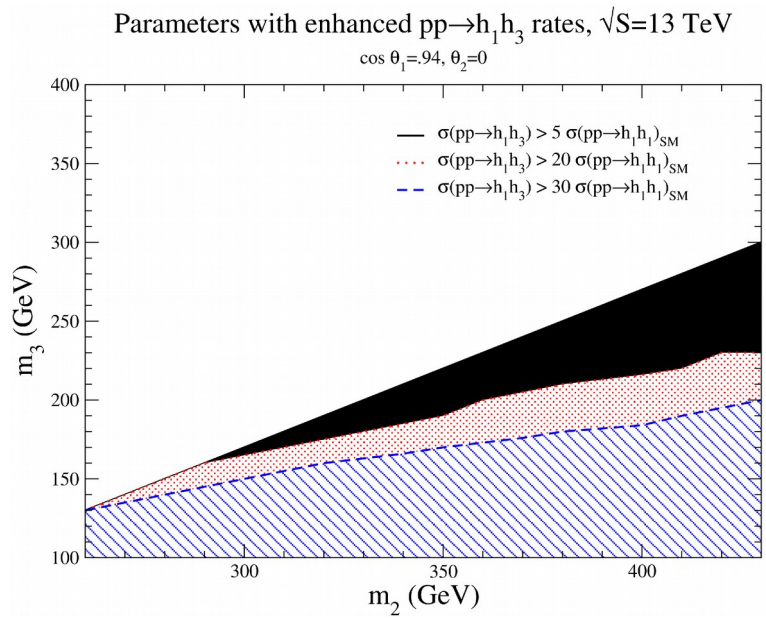
Dawson, Sullivan PRD97 (2018) 015022

Exotic decay $h_2 \rightarrow h_3\, h_1$









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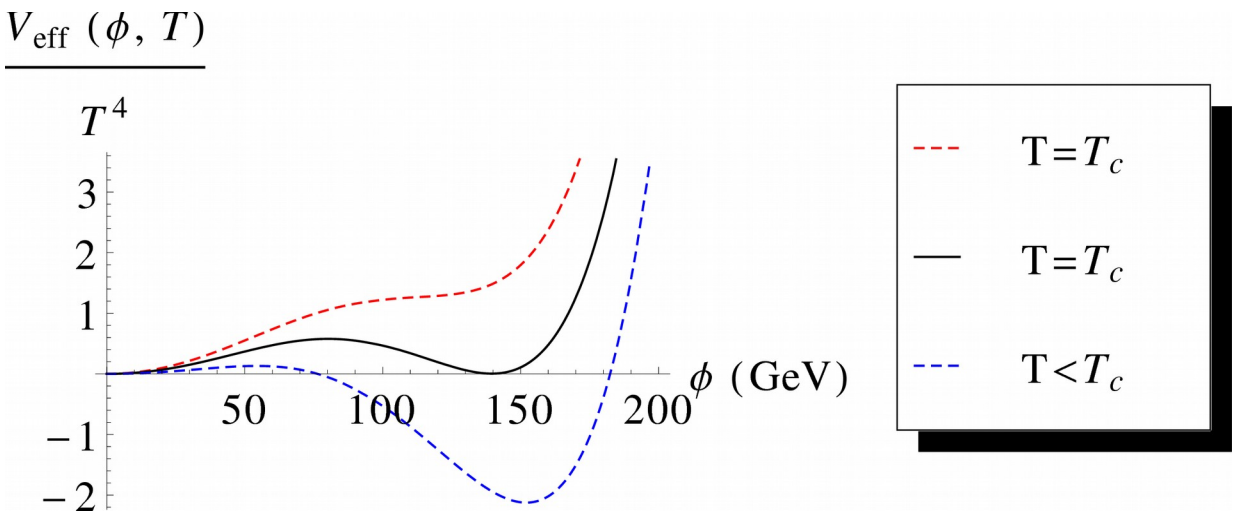
What good is the real singlet model?

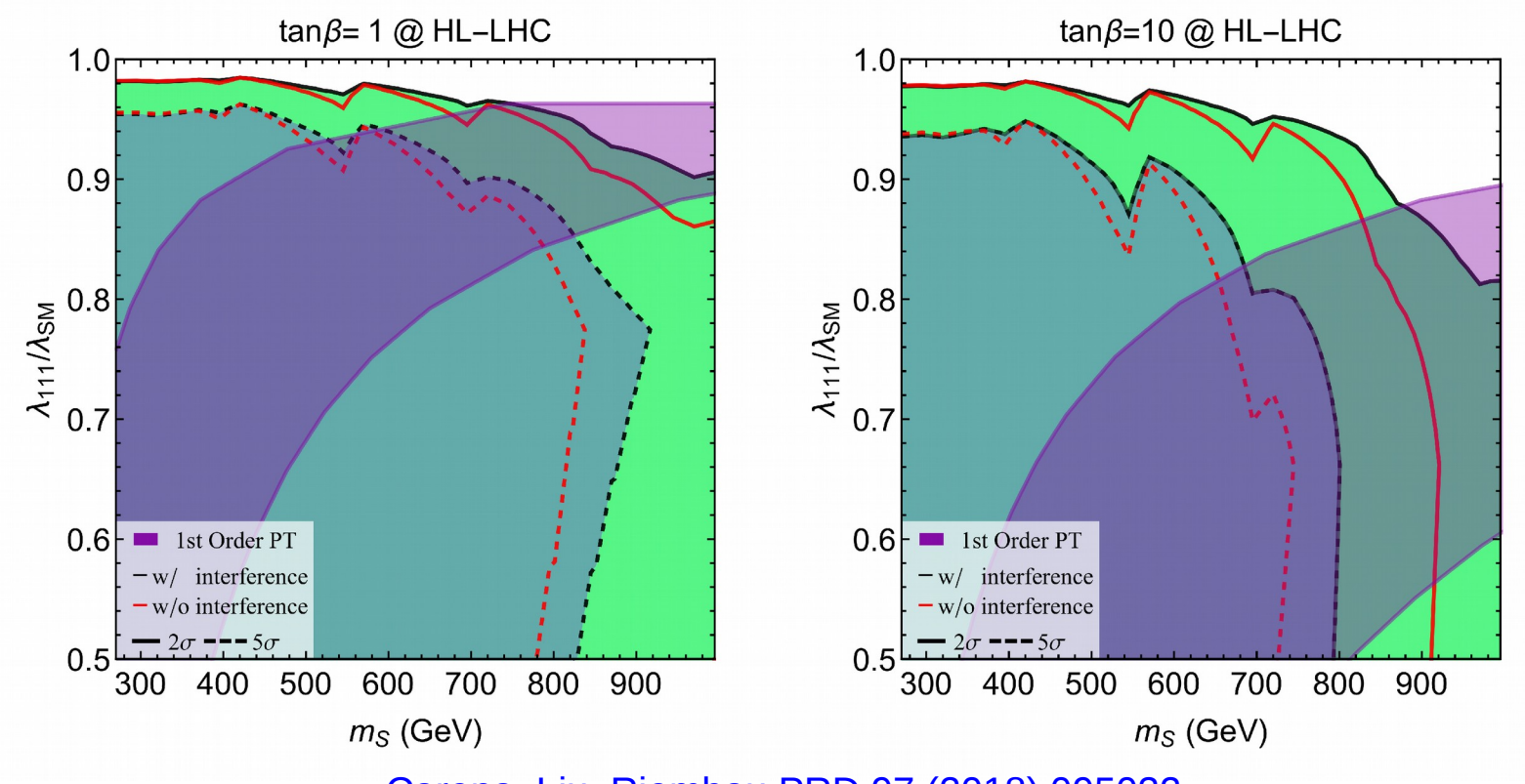
- Simplest extension of standard model.
- Changes just the scalar potential.
- Can help provide a strong first order electroweak phase transition.
- Can provide an interesting and simple benchmark model.



Resonant Double Higgs Production

- Much focus on relationship between resonant double Higgs production and a strong electroweak phase transition in the singlet model

Huang, et. Al PRD96 (2017) 035007; Profumo et al PRD91 (2015) 035018; Alves, Ghosh, Guo, Sinha 1808.08974; etc.



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- Including interference effects important for determining viable parameter regions for strong first order electroweak phase transition.

Importance of pp → h_2h_2+X

- Couplings between scalar and Higgs:

$$V_{\Phi,S} = \frac{a_1}{2}\Phi^\dagger\Phi S + \frac{a_2}{2}\Phi^\dagger\Phi S^2$$

- After symmetry breaking $\Phi = (0, (h+v)/\sqrt{2})^t$
  - Source of Higgs-scalar mixing is (assuming $\langle S \rangle = 0$)

$$V_{\Phi,S} \supset \frac{a_1 v}{2} h S$$

  - In the limit of zero mixing, $a_1 \to 0$ and only a_2 survives:

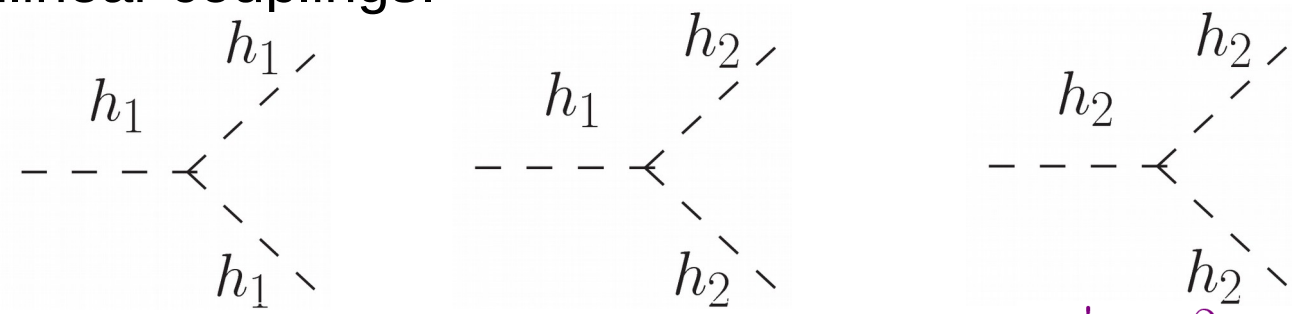
$$V_{\Phi,S} \to \frac{a_2}{2}\Phi^\dagger\Phi S^2$$

Importance of pp → h_2h_2+X

- Small mixing limit

$$V \to -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{a_2}{2}\Phi^\dagger\Phi S^2$$
$$+b_1 S + \frac{b}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

- Surviving trilinear couplings.



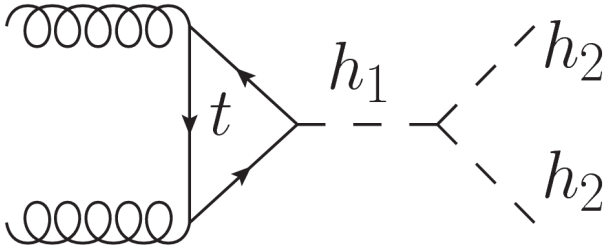
- Electroweak phase transition places lower limit on $\Phi^\dagger\Phi S^2$ and h_1-h_2-h_2 coupling
  - $\Phi^\dagger\Phi S^2$ is only surviving coupling between singlet and Higgs, so has to drive the strong first order phase transition.
  - h_1-h_2-h_2 coupling arises from a_2

Importance of pp→ h_2h_2+X

- Small mixing limit

$$V \to -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 + \frac{a_2}{2}\Phi^\dagger\Phi S^2$$
$$+b_1 S + \frac{b}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4$$

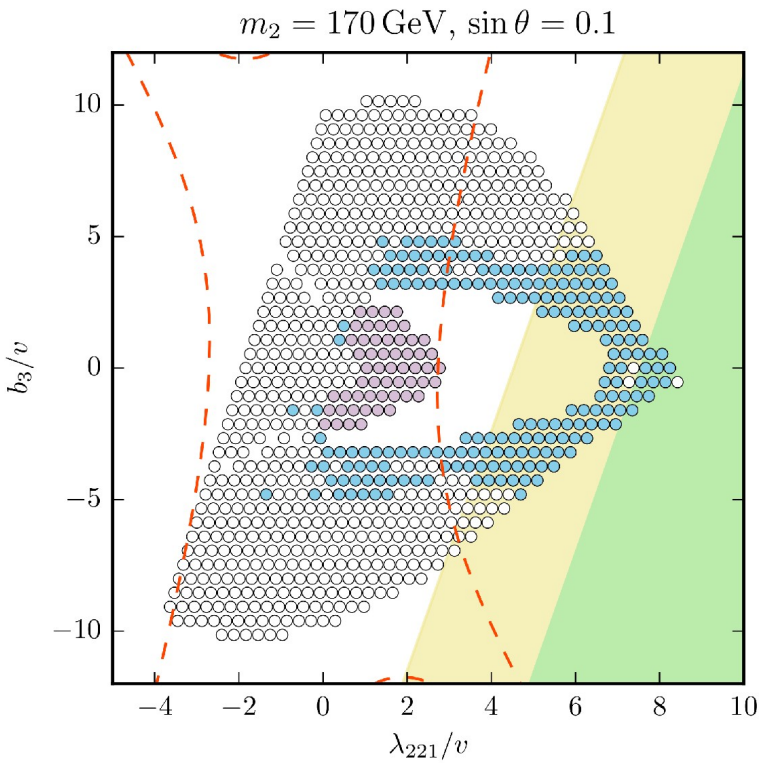
- Example of surviving new physics production (also have VBF):

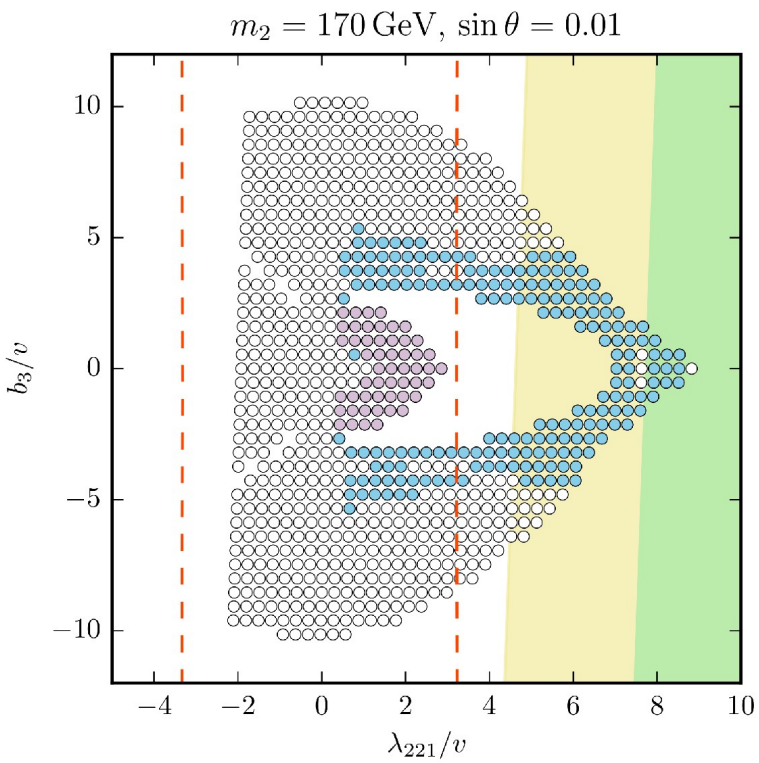


- Exactly zero mixing, h_2 is stable Curtin, Meade, Yu JHEP 1411 (2014) 127
  - Search for jets+MET, trilinear Higgs deviations, Z-h deviation
- Small but non-zero mixing in mass range $2m_W < m_2 < 2m_1$
  - $h_2 \to h_1h_1$ forbidden, $h_2 \to$ WW dominant decay mode
  - Search for the signal $pp \to h_2h_2 \to 4W \to 2j2\ell^\pm\ell'^\mp 3\nu$

Chen, Kozaczuk, **IL** JHEP 1708 (2017) 096

HL-LHC



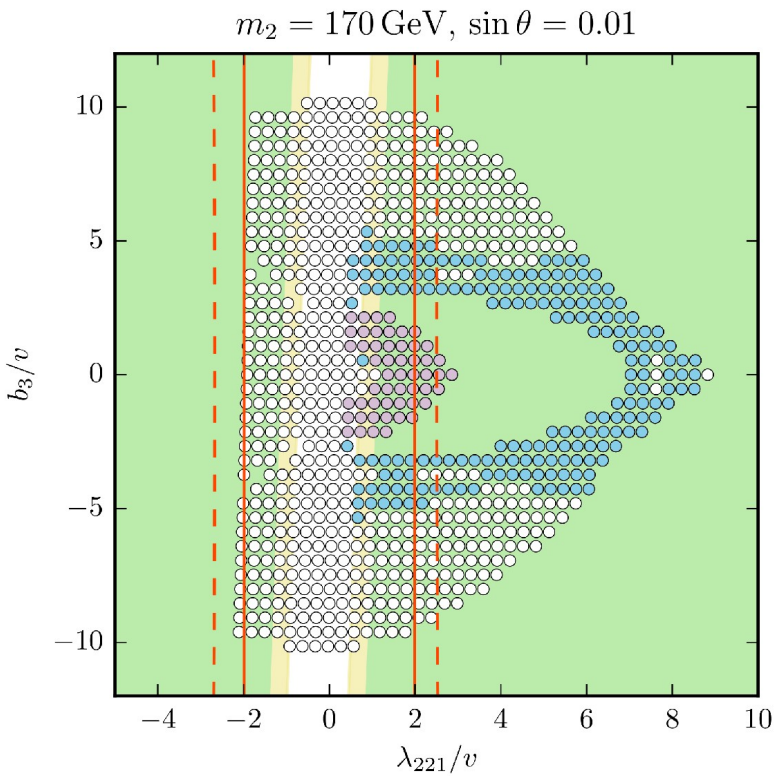


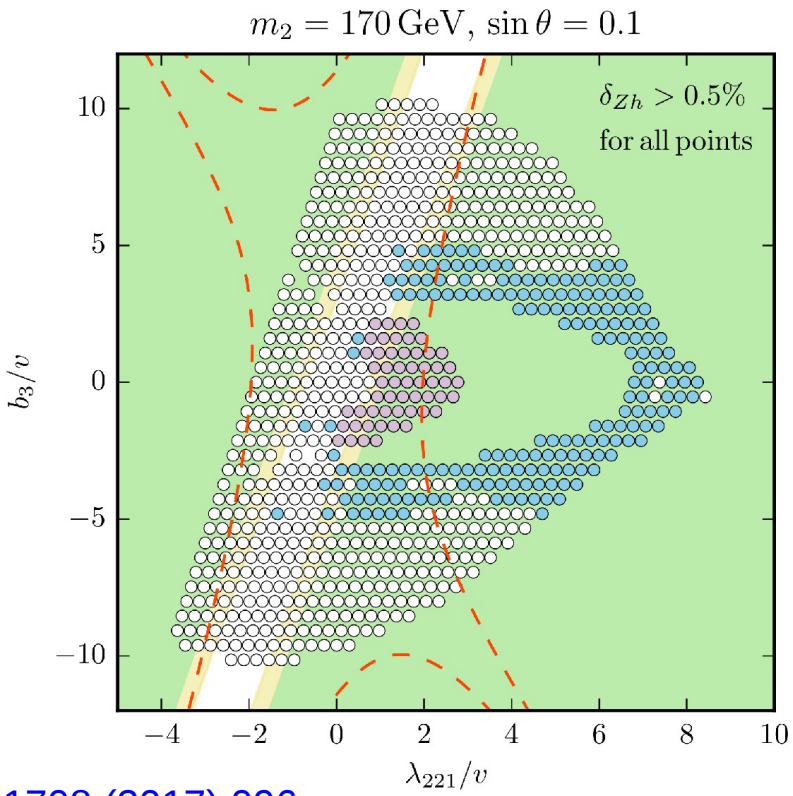
Chen, Kozaczuk, **IL** JHEP 1708 (2017) 096

$$\sigma_{h_2 h_2} \gtrsim 53\,\mathrm{fb} \quad (2\sigma), \quad 147\,\mathrm{fb} \quad (5\sigma)$$

- Colored Dots: Compatible with strong first order electroweak phase transition.
- Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs trilinear limits at 30%.

100 TeV





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$$m_2 = 170\,\mathrm{GeV}: \quad \sigma_{h_2h_2} \gtrsim 56\,\mathrm{fb} \quad (2\sigma), \quad 142\,\mathrm{fb} \quad (5\sigma)$$

$$m_2 = 240\,\mathrm{GeV}: \quad \sigma_{h_2h_2} \gtrsim 202\,\mathrm{fb} \quad (2\sigma), \quad 519\,\mathrm{fb} \quad (5\sigma)$$

- 30 ab^{-1} at 100 TeV
- Colored Dots: Compatible with strong first order electroweak phase transition.
- Yellow: Exclusion, Green: Discovery
- Red dashed curves: Higgs trilinear to 15%. Solid lines: Z-h limits to 0.5%

Conclusions

- Many possibilities for new physics in double Higgs production.
  - Higgs couplings can be altered.
  - New colored particles can run in the loops.
  - Can have resonant production.
- Difficult to change rates much with new physics in the loops.
  - Light colored particles strongly constrained.
  - Still possible with some fine-tuning.
  - Loops do not explicitly depend on how internal particles' decays.
- Resonant production has spectacular signal.
  - In singlet model, double Higgs can be dominant decay mode of new heavy scalar.
  - Interference effects between SM-like triangle and box diagrams, and resonance can be significant.
  - With new scalars, new double scalar modes open up and can be important.
  - Searches for new scalar production can be important to probe new regions compatible with a strong first order electroweak phase transition.

Thank You