Di-Higgs Production in Extended Higgs Sectors

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Overview

Introduction

Introduction

- A scalar particle was discovered in 2012[1,2] that is so far compatible with the SM Higgs boson...
- ...but we need new physics. Dark matter, baryon asymmetry, neutrino masses, among others. It can be provided by extended scalar sectors.
- Observed channels contain one scalar, thus only HXX (X some SM particle) can be inferred from signal rates.
- Di-Higgs production allows to peer into the scalar self-couplings, which uncovers the scalar potential and EWSB patterns.
- Problem: in the SM there is destructive interference between its box and triangle diagrams.
- BSM physics can in many ways overcome this!

[1] Phys. Lett. B 716 (2012) 1-29
[2] Phys. Lett. B 716 (2012) 30

Goals

- How and by how much BSM extended sectors can enhance di-Higgs production.
- The impact of di-Higgs constraints ($pp \to (...) \to h_{SM} h_{SM}$) on the parameter spaces of BSM.
- Promising di-scalar exotic channels and cascading scalar decays with multiple SM-like Higgs (not discussed).
- Validity between BSM - SMEFT mapping for cross-section computation (not discussed).

The models:

- R2HDM - CP-conserving - (h, H, A , $H^{\pm}$)
- C2HDM - CP-violating - (H_1, H_2, H_3, $H^{\pm}$)
- N2HDM - CP-conserving - (H_1, H_2, H_3, A, $H^{\pm}$)
- NMSSM - CP-conserving - (H_1, H_2, H_3, A_1, A_2 $H^{\pm}$)[3]

$\to$ We considered the $\mathbb{Z}_2$ symmetric versions to inhibit FCNC.

[3] Capitalization and subscript numbering refer to mass ordering.

Methodology

Main codes: `ScannerS`[4] and `NMSSMCalc`[5]

- Most pertinent theoretical and experimental constraints.
- We applied di-Higgs constraints manually.

Cross-sections computations:

- Single Higgs rates w/ `SusHi`[6] @13TeV@NNLO_QCD.
  - **Resonant searches constrain this quantity!**
- Double Higgs rates w/ `HPAIR`[7] (and variations):
  - NLO born-improved heavy top-quark mass limit.
  - Preliminary scans: $2 * \sigma_{HH}$ @ LO @ 14 TeV, due to computational time.
  - K-factors are in the ballpark of 1.4 (non SM-like Higgs) and 1.9 (for SM-like Higgs)[8].
  - **Non-resonant searches constrain this quantity, under conditions!**

→ In forthcoming paper, our specific BPs are presented @NLO.

→ Please contact us if you need specific benchmarks for di-scalars production (inc. non-SM-like) and cascading scalar processes (multiple scalar final state).

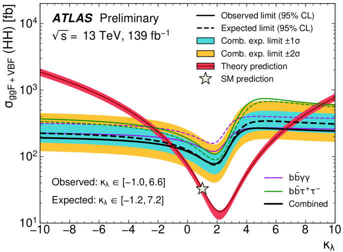
[4] arXiv: 2007.02985
[5] arXiv: 1312.4788
[6] arXiv: 1605.03190
[7] http://tiger.web.psi.ch/proglist.html
[8] arXiv: 1705.05314

Experimental state-of-the-art

ATLAS-CONF-2021-052

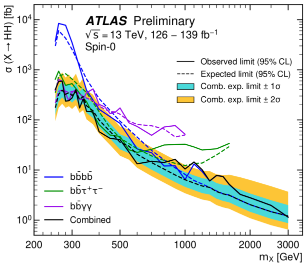
→ Analyses are divided into non-resonant (SM) and resonant ones (SM + HSP).

Continuum



k_λ lim.	Obs.	Exp.
$b\bar{b}\gamma\gamma$	$[-1.6, 6.7]$	$[-2.4, 7.7]$
$b\bar{b}\tau\bar{\tau}$	$[-2.4, 9.2]$	$[-2.0, 9.0]$

Resonant



- $b\bar{b}\gamma\gamma$ - low mass region
- $b\bar{b}\tau\bar{\tau}$ - intermediate mass region
- $b\bar{b}b\bar{b}$ - intermediate mass region

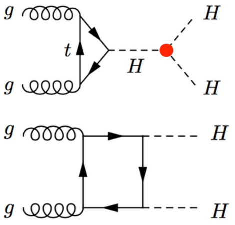
→ We considered the individual channels limits.
→ Extended scalar sectors include both contributions and interferences.

How to enhance di-Higgs production

Cross-section recommendations by the LHCXSWG

$\sqrt{s}$	7 TeV	8 TeV	13 TeV	14 TeV	27 TeV	100 TeV
$\sigma_{\text{NNLO FTapprox}}$ [fb]	6.572	9.441	31.05	36.69	139.9	1224

By varying the trilinear and Yukawa couplings



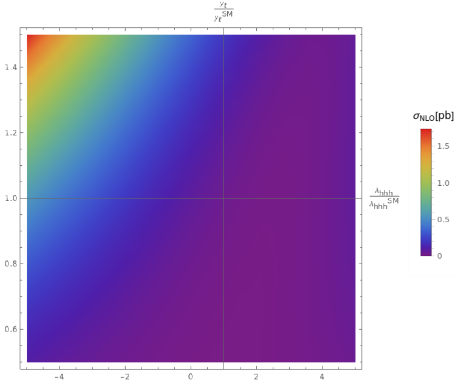
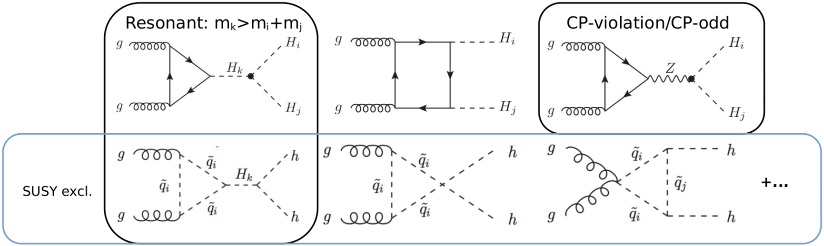


Figure: Di-Higgs XS @ NLO(HTML) @ 13TeV

How to enchance di-Higgs production

By the inclusion of additional diagrams



New contributions and interferences will depend:

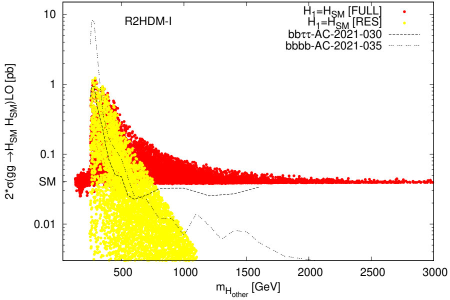
- Trilinear couplings (many!).
- Masses.
- Particle widths.

Main results

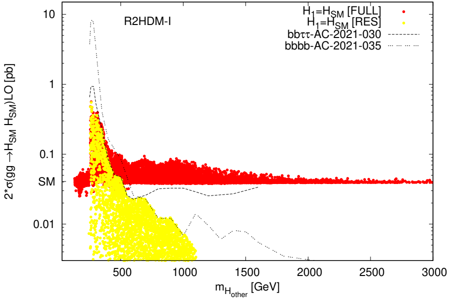
Impact of resonant searches

R2HDM-I: h is SM-like

Before resonant bounds



After resonant bounds

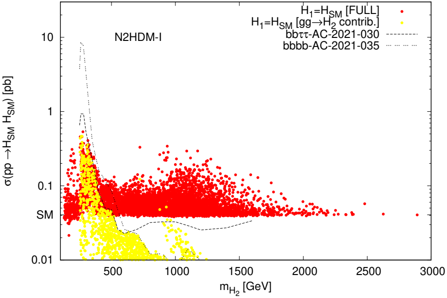


- Resonant searches are sensitive to all models.
- $b\bar{b}\gamma\gamma$ constrains the lowest resonant mass region.
- For heavy second Higgs mass $\rightarrow$ decoupling limit $\rightarrow$ retrieve SM rates.
- For models considered, there is a low value for di-Higgs rates.

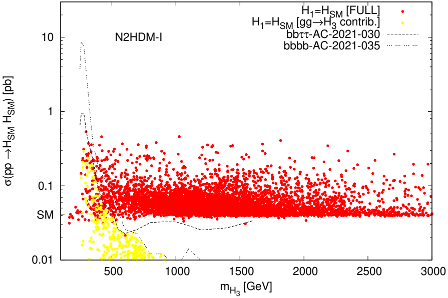
Impact of resonant searches

N2HDM-I: H_1 is SM-like

H_2 contribution



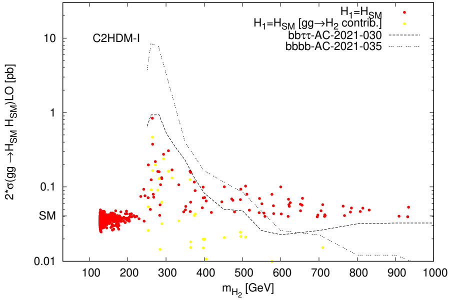
H_3 contribution



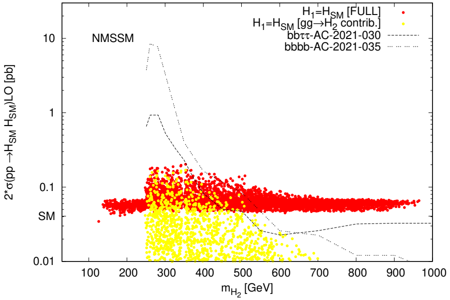
- Resonant searches are sensitive to both contributions.
- Further constraint on trilinear $\lambda_{ijk} < \lambda_{SM}(m_h = 700 \text{ GeV}) = 5976.61$ GeV $\rightarrow 1/3$ of points removed.
- Resonances can have $\Gamma(H_i)/m_i > 5\%$ $\rightarrow$ NWA is not valid.
- Exclude points where $\Gamma(H_i)/m_i > 50\%$ $\rightarrow$ minor impact.

Impact of resonant searches

C2HDM-I



NMSSM



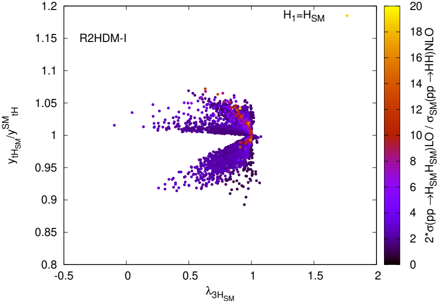
- Constraints push model to degeneracy $m_2 \approx m_3 \rightarrow$ takes longer to produce valid parameter points.
- Experimentally, model is very similar to R2HDM, in this channel.

- Parameter space is more constrained due to SUSY relations $\rightarrow$ di-Higgs limits had small impact.
- Some points also have $\Gamma(H_i)/m_i > 5\% \rightarrow$ NWA is not valid.

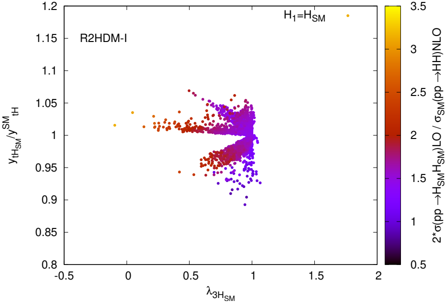
Impact of resonant searches

R2HDM-I: H_1 is SM-like

Full sample



Resonant contribution $< 0.1 * \sigma_{SM}$

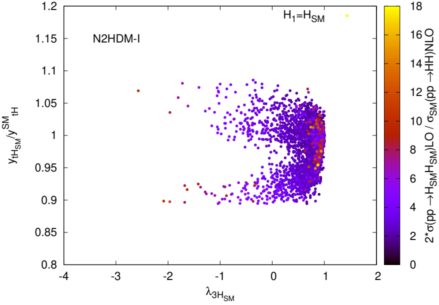


- Trilinear upper limits are mainly due to perturbative unitarily.
- Wedge is due to unitarily too, present in all T1 models where H_1 is SM-like and R2HDM T2 where H_1 is SM-like.
- Type 2 models, top Yukawa is more constrained from single Higgs data.
- For the models considered, resonant searches (alone) do not constrain this projection of the parameter space.

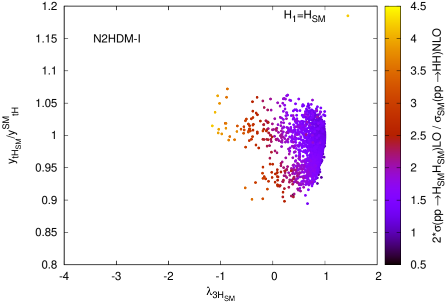
Impact of non-resonant searches

- The strongest constraint comes from $b\bar{b}\gamma\gamma$: $\sigma_{hh} < 4.3 * \sigma_{hh}^{\rm SM}$.
- We apply non-resonant limits if $\sigma_{hh}^{\rm res} < 0.1 * \sigma_{hh}^{\rm SM}$.

Full sample



Resonant contribution $< 0.1 * \sigma_{\rm SM}$



- Non-resonant alone also cannot constrain trilinear coupling.
- **Need both resonant and non-resonant** to constrain the parameter space on these models.

Conclusions

Conclusions

- Resonant searches are sensitive to all our models.
- Resonant searches are essential for second Higgs searches.
- We need **both resonant and non-resonant** searches to constrain the SM-like trilinear.
- Di-Higgs rates have a lower minimum, which in principle would allow for full exclusion (very far future).

$\rightarrow$ Please contact us if you need specific benchmarks for di-scalars production (inc. non-SM-like) and cascading scalar processes (multiple scalar final state).

Thank you!