Di-Higgs Production in Extended Higgs Sectors

Duarte Azevedo

In collaboration with: H. Abouabid, A. Arhrib, J. Falaki, P. Ferreira, M. M. Mühlleitner, R. Santos.

Institute for Theoretical Physics (ITP)
Institute for Astroparticle Physics (IAP)
Karlsruher Institut für Technologie
Germany
duarte.azevedo@kit.edu

The 18th Workshop of the LHC Higgs Working Group

December 1st-3rd, 2021

Karlsruhe Institute of Technology

Overview

1. Introduction
   - Experimental results
   - How to enhance di-Higgs production
2. Main results
   - Impact of resonant and non-res. searches
   - Allowed Yukawa and trilinear couplings
   - Benchmarks
3. Conclusions

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.
- Di-Higgs production through gluon fusion is dominant at LHC.
- 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.
- Impact of the relevant the. and exp. constraints on BSM di-Higgs signals.
- Benchmark scenarios for BSM pair production:
  - SM-like Higgs pairs.
  - SM-like + non-SM-like Higgs pairs.
- Promising di-scalar exotic channels and cascading scalar decays with multiple SM-like Higgs.

The models:

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

→ We considered the $\mathbb{Z}_2$ symmetric versions (first three models) to inhibit FCNC.

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

Methodology

Main codes: ScannerS[4] and NMSSMCALC[5]

- Theoretical and experimental constraints.
- We applied di-Higgs constraints manually.

Cross-sections computations:

- Single Higgs rates w/ SusHi[6] @13TeV@NNLO_QCD.
- Double Higgs rates w/ HPAIR[7] (and variations):
  - NLO born-improved heavy top-quark mass limit.
  - Scans: $2 * (\sigma_{HH}^{LO}$@14 TeV), approximate QCD correction.
  - K-factor around 1.9 for SM-like Higgs [8].

→ Benchmarks are presented @NLO.

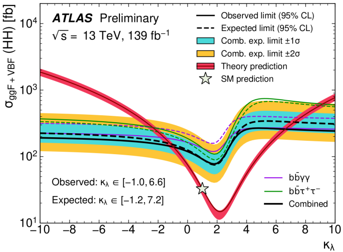
[4] M. Mühlleitner, M. Sampaio, R. Santos, J. Wittbrodt (2007.02985)
[5] J. Baglio, R. Grober, M. Muhlleitner, D.T. Nhung, H. Rzehak, M. Spira, J. Streicher, K. Walz (1312.4788)
[6] R. V. Harlander, S. Liebler, H. Mantler (1605.03190)
[7] http://tiger.web.psi.ch/proglist.html
[8] Dawson et al. (hep-ph/9806304), Grober et. al. (1705.05314), Dawson et al. (hep-ph/9806304), Buchalla et al. (1806.05162)

Experimental results

ATLAS-CONF-2021-052

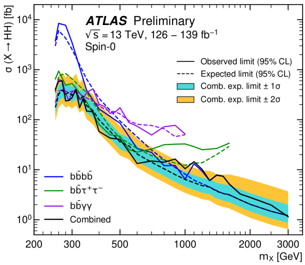
→ Analyses are divided into non-resonant (SM) and resonant ones (SM + HSP).

Non-resonant



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
- $b\bar{b}b\bar{b}$ - high mass region

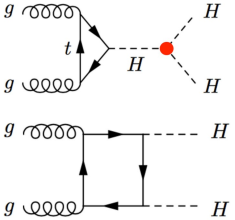
→ Non-resonant considers $y_t = y_t^{SM}$ fixed.
→ We considered the individual channels limits.

How to enhance di-Higgs production 1/2

SM 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



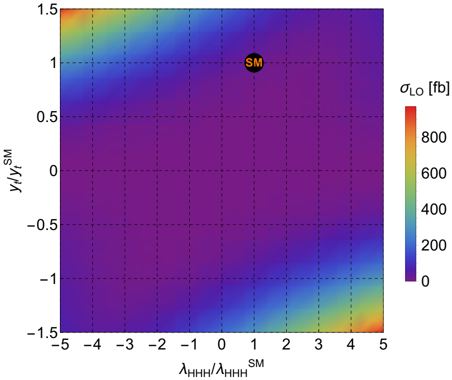
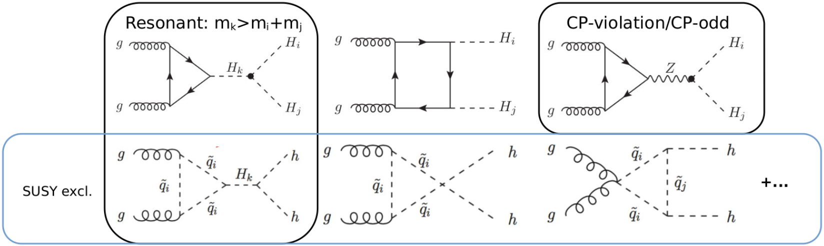


Figure: σ_{HH}^{SM} @ LO @ 13TeV

How to enchance di-Higgs production 2/2

From the existence of additional diagrams



New contributions and interferences will depend on:

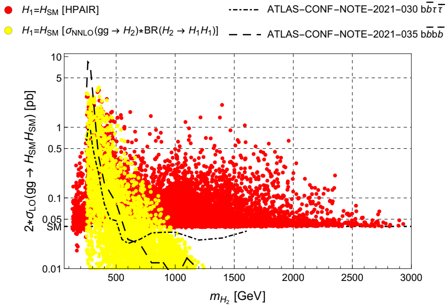
- Trilinear couplings (many!).
- Masses.
- Particle widths.

Main results
(Preliminary)

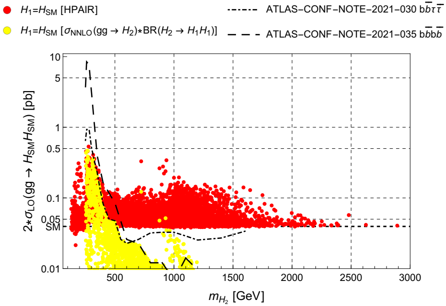
Impact of resonant searches

N2HDM-I: H_1 is SM-like

Before resonant bounds



After resonant bounds

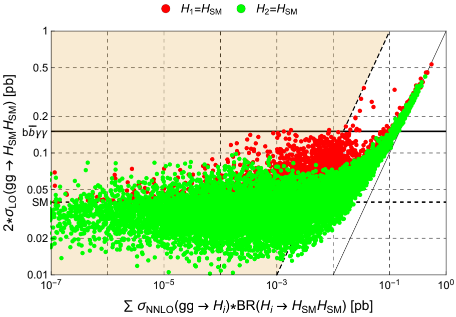


- Resonant searches constrain $\sigma(gg \to H_i) * \text{BR}(H_i \to H_{SM}H_{SM})$
- Resonances can have $\Gamma(H_i)/m_i > 5\%$ → NWA is not valid.

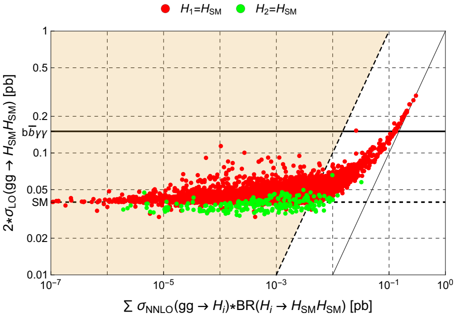
Impact of non-resonant searches

N2HDM

Type I



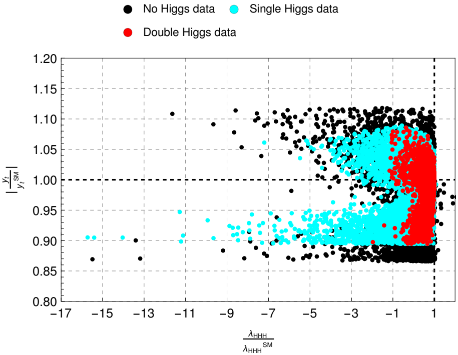
Type II



- For the largest XS, very good correlation between resonant and full result.
- Defined the non-resonant region as: $\sigma_{HH}^{\text{full}} > 10 * \sigma_{HH}^{\text{res}}$ (shaded area).
- Leading non-resonant constraint is $b\bar{b}\gamma\gamma$: $\sigma_{HH}^{\text{non-res}} < 4.1 * \sigma_{HH}^{\text{SM}}$.

Impact of all searches

N2HDM-I: H_1 is SM-like



- Single Higgs data constrains the Yukawas.
- Additional bound $\lambda_{ijk} < \lambda_{HHH}^{SM}(m_H = 700 \text{ GeV}) = 5975.6$ GeV cuts lower branch.
- Di-Higgs data is starting to constrain trilinears.

Allowed Yukawa and trilinear couplings

	R2HDM		C2HDM	
	$y^{R2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{R2HDM}_{3H_{SM}}/\lambda_{3H}$	$y^{C2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{C2HDM}_{3H_{SM}}/\lambda_{3H}$
light T1	0.893...1.072	-0.096...1.076	0.898...1.035	-0.035...1.227
medium T1	n.a.	n.a.	0.889...1.028	0.251...1.172
heavy T1	0.946...1.054	0.481...1.027	0.893...1.019	0.671...1.229
light T2	0.951...1.042	0.692...1.000	0.956...1.046	0.096...0.999
medium T2	n.a.	n.a.	–	–
heavy T2	–	–	–	–

	N2HDM		NMSSM	
	$y^{N2HDM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{N2HDM}_{3H_{SM}}/\lambda_{3H}$	$y^{NMSSM}_{t,H_{SM}}/y_{t,H}$	$\lambda^{NMSSM}_{3H_{SM}}/\lambda_{3H}$
light T1	0.895...1.086	-1.966...1.004	n.a.	n.a.
medium T1	0.874...1.058	-1.247...1.168	n.a.	n.a.
heavy T1	0.890...1.033	0.770...1.149	n.a.	n.a.
light T2	0.942...1.039	-0.608...0.999	0.826...1.003	0.024...0.747
medium T2	0.942...1.034	0.613...0.994	0.916...1.000	-0.502...0.666
heavy T2	–	–	–	–

- Values obtained with blind parameter scans, take them with a grain of salt.
- Bound $m_{H^+} > 800$ GeV on T2 models[9], eliminates all $H_3 \equiv H_{SM}$ points.
- Several scenarios with $\lambda_{3H} = 0$ allowed.

[9] M. Misiak, A. Rehman, M. Steinhauser (2002.01548)

$H_{SM}H_{SM}$ production benchmarks

All rates 2*LO! [fb]

Non-resonant

	H_1	H_2	H_3
R2HDM-I	93	50	n.a.
R2HDM-II	61	–	n.a.
C2HDM-I	99	43	35
C2HDM-II	78	–	–
N2HDM-I	154	98.15	45.92
N2HDM-II	113.94	49.71	–
NMSSM	75.30	66.95	–

Resonant

	H_1	H_2
R2HDM-I	562	n.a.
R2HDM-II	83.2	n.a.
C2HDM-I	839	48.68
C2HDM-II	145.86	–
N2HDM-I	533	425
N2HDM-II	295	66
NMSSM	202	67

- Non-resonant: rates can be up to 4 times the SM expectation.
- Resonant: rates can be up to 20 times the expectation.

Benchmark for resonant production N2HDM-I

→ **Input values:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_{H_3} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan\beta$
125.09	277.06	298.08	257.65	272.55	3.725
α_1	α_2	α_3	v_s [GeV]	m_{12}^2 [GeV^2]	
1.297	0.293	-0.111	2448	18000	

→ **Branching ratios:**

$$\begin{aligned} \mathrm{BR}(H_2 \to H_1 H_1) &= 0.342, \quad \mathrm{BR}(H_2 \to WW) = 0.424, \quad \mathrm{BR}(H_2 \to ZZ) = 0.185 \\ \mathrm{BR}(H_3 \to H_1 H_1) &= 0.299, \quad \mathrm{BR}(H_3 \to WW) = 0.485, \quad \mathrm{BR}(H_3 \to ZZ) = 0.215 \\ \mathrm{BR}(A \to bb) &= 0.278, \quad \mathrm{BR}(A \to ZH_1) = 0.0927, \quad \mathrm{BR}(H^\pm \to tb) = 0.998 \end{aligned} \tag{1}$$

→ **Production rates:**

$$\boxed{\begin{aligned} \sigma(H_2) \times \mathrm{BR}(H_2 \to H_1 H_1) &= 1.046 \text{ pb} \times 0.342 = 357 \text{ fb} \\ \sigma(H_3) \times \mathrm{BR}(H_3 \to H_1 H_1) &= 0.650 \text{ pb} \times 0.299 = 194 \text{ fb} \end{aligned}} \tag{2}$$

$2 * \sigma^{LO}_{H_1 H_1}$ [pb]	$\Gamma^{tot}_{H_1}$ [GeV]	$\Gamma^{tot}_{H_2}$ [GeV]	$\Gamma^{tot}_{H_3}$ [GeV]	Γ^{tot}_{A} [GeV]	$\Gamma^{tot}_{H^\pm}$ [GeV]	$\lambda_{3H_1}/\lambda^{SM}_{3H}$
533.4	3.717 10^{-3}	0.018	0.931	0.001	0.491	0.878

- Two clear peaks in invariant mass distribution.
- All $H_{SM} H_{SM}$ production BP are given in the paper to come.

Mixed di-Higgs production into 4b final state

All rates 2*LO! [fb]

$gg \to H_{SM} H_j / A_j \to b\bar{b}b\bar{b}$

Model	Mixed Higgs State	Rate [fb]
R2HDM-I	$AH_1(\equiv H_{SM})$	46
	$H_1H_2(\equiv H_{SM})$	35
C2HDM-I	$H_2H_1(\equiv H_{SM})$	19
	$H_1H_2(\equiv H_{SM})$	14
	$H_1H_3(\equiv H_{SM})$	11
N2HDM-I	$H_2H_1(\equiv H_{SM})$	105
	$AH_1(\equiv H_{SM})$	808
	$H_1H_2(\equiv H_{SM})$	2017
	$AH_2(\equiv H_{SM})$	271
	$H_1H_3(\equiv H_{SM})$	44
	$H_2H_3(\equiv H_{SM})$	32
	$AH_3(\equiv H_{SM})$	19
NMSSM	$A_1H_1(\equiv H_{SM})$	209
	$H_2H_1(\equiv H_{SM})$	45
	$A_1H_2(\equiv H_{SM})$	42
	$H_1H_2(\equiv H_{SM})$	62

- Details on these points can be provided on request.

Mixed di-Higgs production and cascade decay into 6b final state

All rates 2*LO! [fb]

$gg \to H_{SM}H_i \to H_jH_kH_l \to b\bar{b}b\bar{b}b\bar{b}$

Model	Mixed Higgs State	Rate [fb]
N2HDM-I	$H_2H_3(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	15
	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	41
	$H_2H_1(\equiv H_{SM}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	33
	$H_1H_2(\equiv H_{SM}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	106
	$H_3H_2(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	10
	$H_3H_2(\equiv H_{SM}) \to H_1H_2(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	7
NMSSM	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	12
	$H_2H_1(\equiv H_{SM}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	38

- Details on these points can be provided on request.

Conclusions

Conclusions

- Resonant searches already constrain all our models.
- We need both resonant and non-resonant searches to constrain the SM-like trilinear.
- Limits are beginning to constrain trilinears on the N2HDM.
- Experimental input for benchmarks is more than welcome!

$\rightarrow$ We provide on request benchmarks for di-scalars production (inc. non-SM-like) and cascading scalar processes (multiple scalars final state).

Thank you!