Benchmarking di-Higgs production in extended scalar sectors at the LHC

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

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Overview

Introduction

Introduction

→ **Scalar particle discovered in 2012 with mass of $\sim$ 125 GeV at the Large Hadron Collider (LHC)**.

Phys.Lett. B716 (2012), Phys. Lett. B 716 (2012)

- Observed channels contain one scalar, thus only *HXX* can be inferred from signal rates.
- Scalar potential and EWSB patterns → processes with self-interactions, e.g. di-Higgs production (dominant at LHC).
- Problem: in the SM there is destructive interference between its box and triangle diagrams.
- ...we need new physics. Dark matter, baryon asymmetry, neutrino masses, among others. It can be provided by extended scalar sectors.
- BSM physics can enhance significantly di-Higgs production.

Goals

→ Impact of di-Higgs constraints on BSM
→ How and by how much models with extended sectors can enhance di-Higgs production
→ Provide interesting benchmarks for pair production:

- SM-like Higgs pairs
- SM-like + non-SM-like Higgs pairs
- Exotic di-scalar channels (with possible cascading)

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 - $(H_1,\ H_2,\ H_3,\ A_1,\ A_2,\ H^{\pm})$[1]

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

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

Methodology

Main codes: ScannerS Mühlleitner et al. (2007.02985) and NMSSMCALC Baglio et al. (1312.4788)

- Random parameter space scans
- Theoretical and experimental constraints
- We applied di-Higgs constraints manually

Cross-sections computations:

- Single Higgs rates w/ SusHi Harlander et al. (1605.03190) @13/14 TeV@NNLO_QCD.
- Double Higgs rates w/ HPAIR[2] (and variations):
  - NLO born-improved heavy top-quark mass limit.
  - Scans: $2 * (\sigma_{HH}^{LO}$@14 TeV), approximate QCD correction.
  - K-factor around 2 for di-Higgs production Dawson et al. (hep-ph/9806304), Grober et al. (1705.05314), Dawson et al. (hep-ph/9806304), Buchalla et al. (1806.05162).

→ Benchmarks are presented at 14 TeV and NLO.

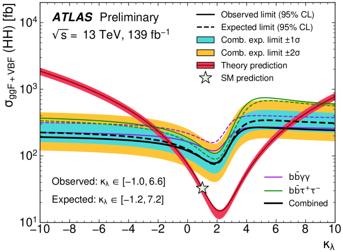
[2] http://tiger.web.psi.ch/proglist.html

Experimental state-of-the-art

ATLAS-CONF-2021-052

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

Non-resonant

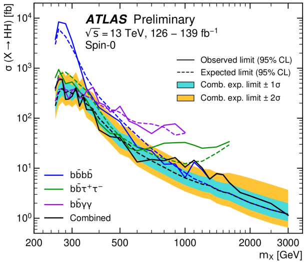


k_λ lim.	Obs.	Exp.
$b\bar{b}\gamma\gamma$	$[-\mathbf{1.6}, \mathbf{6.7}]$	$[-2.4, 7.7]$
$b\bar{b}\tau\bar{\tau}$	$[-\mathbf{2.4}, \mathbf{9.2}]$	$[-2.0, 9.0]$
$b\bar{b}b\bar{b}$	$[-\mathbf{2.3}, \mathbf{9.4}]$	$[-5.0, 12.0]$

CMS-PAS-HIG-20-005

→ Non-resonant considers $y_t = y_t^{SM}$ fixed.

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
- $b\bar{b}b\bar{b}$ - very high (> 1 TeV) mass region

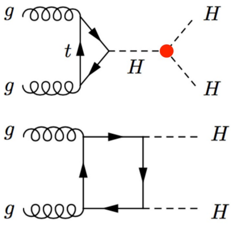
CMS-PAS-B2G-20-004

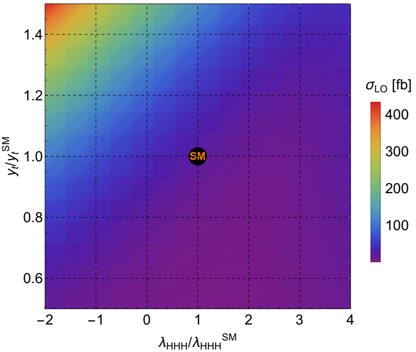
How to enhance di-Higgs production 1/2

SM cross-section recommendations by the LHCXSWG[3]

$\sqrt{s}$	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

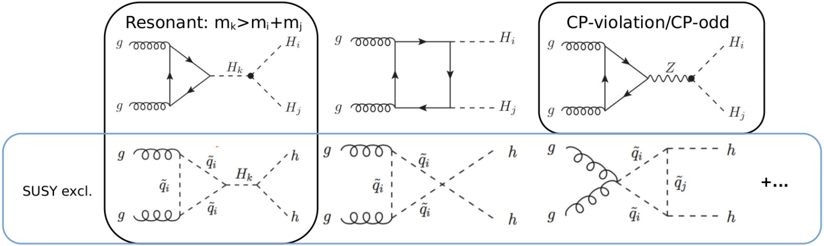




[3] FT approx: QCD@NNLO in the heavy-top limit, full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

How to enchance di-Higgs production 2/2

From the existence of additional particles



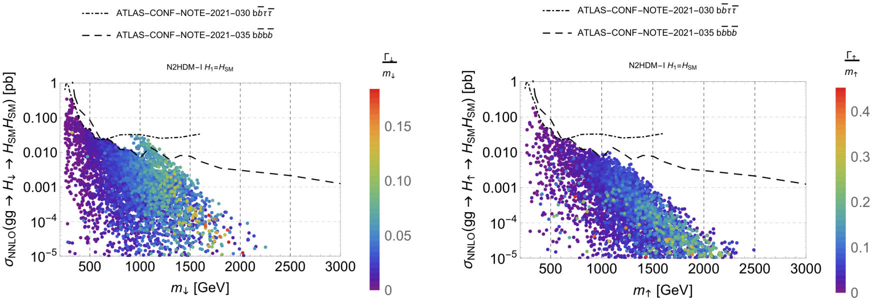
New contributions and interferences will depend on:

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

Main results

Resonant production

N2HDM-I: H_1 is SM-like

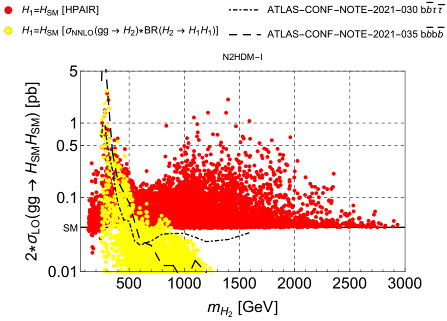


- Resonant searches constrain $\sigma(gg \to H_i) * \mathrm{BR}(H_i \to H_{SM}H_{SM})$
- Assume that non-resonant contribution is SM-like and no interferences
- Resonances can have $\Gamma(H_i)/m_i > 5\%$ $\to$ NWA is not valid
- Cut points where $\Gamma(H_i)/m_i > 50\%$

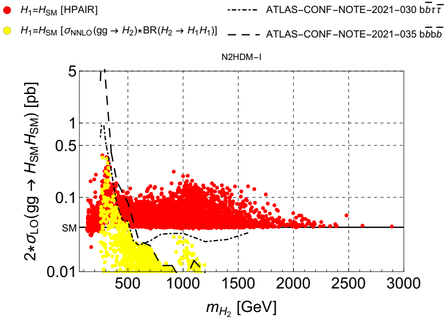
Impact of resonant searches

N2HDM-I: H_1 is SM-like

Before resonant bounds



After resonant bounds

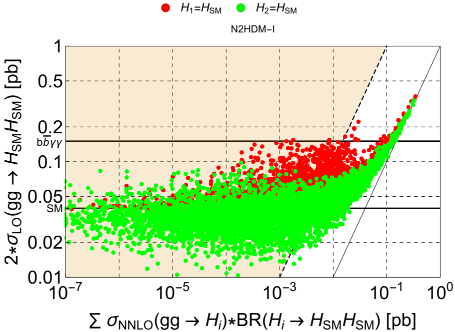


Impact of non-resonant searches

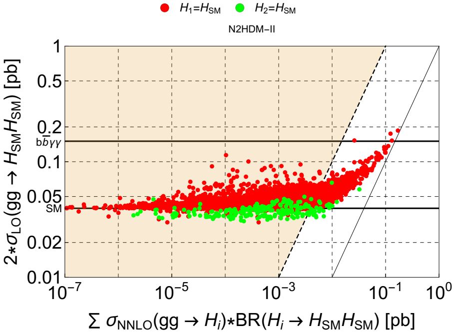
Definition: Resonant contribution is negligible with regards to the total XS

- Non-resonant region: $\sigma_{HH}^{\text{full}} > 10 * \sigma_{HH}^{\text{res}}$ (shaded area)

Type I



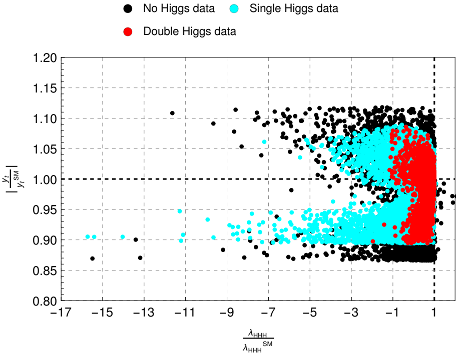
Type II



- Leading non-resonant constraint is $b\bar{b}\gamma\gamma$: $\sigma_{HH}^{\text{non-res}} < 4.1 * \sigma_{HH}^{\text{SM}}$
- For the largest XS, linear correlation between resonant and full result

Impact of all searches

N2HDM-I: H_1 is SM-like

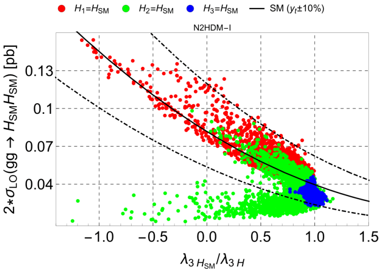


- Single Higgs data constrains the Yukawa coupling.
- Additional bound $\lambda_{ijk} < \lambda^{SM}_{HHH}(m_H = 700 \text{ GeV}) = 5975.6$ GeV cuts lower branch.
- Di-Higgs data is starting to constrain trilinears.

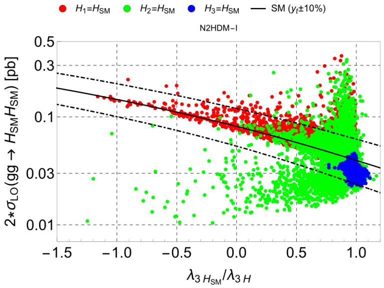
Impact of all searches

N2HDM-I

Non-resonant



Full sample



- In H_2=SM-like case, large negative deviations from the SM
- Res. and non-res. searches needed to constrain BSM SM-like trilinear

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

All rates @NLO [fb]

Non-resonant

$\sigma(H_i \to H_{SM}H_{SM}) < 0.1 * \sigma(H_{SM}H_{SM})$

	H_1	H_2	H_3
R2HDM-I	92	49	
R2HDM-II	59	–	
C2HDM-I	98	44	42
C2HDM-II	75	–	–
N2HDM-I	151	96	44
N2HDM-II	112	58	–
NMSSM	73	65	–

Resonant

	H_1	H_2
R2HDM-I	444	n.a.
R2HDM-II	81	n.a.
C2HDM-I	387	47
C2HDM-II	130	–
N2HDM-I	376	344
N2HDM-II	188	63
NMSSM	183	65

- Non-resonant: rates can be up to 4 times the SM expectation
- Resonant: rates can be up to 11 times the expectation

Resonant production of R2HDM-I

→ **Input values:**

m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	α	$\tan\beta$	m_{12}^2 [GeV^2]
125.09	267	512	516	-0.259	4.276	15020

→ **Branching ratios:**

$$\begin{aligned} \mathrm{BR}(H_2 \to H_1 H_1) &= 0.544, & \mathrm{BR}(H_2 \to WW) &= 0.280, \\ \mathrm{BR}(H_2 \to ZZ) &= 0.121, & \mathrm{BR}(A \to ZH_2) &= 0.912, \\ \mathrm{BR}(A \to t\bar{t}) &= 0.086, & \mathrm{BR}(H^\pm \to W^\pm H_2) &= 0.922, \end{aligned} \tag{1}$$

→ **Production rates:**

$$\boxed{\begin{array}{c} \sigma(H_2) \times \mathrm{BR}(H_2 \to H_1 H_1) = 0.916 \text{ pb} \times 0.544 = 498 \text{ fb} \\ \sigma(A) \times \mathrm{BR}(A \to ZH_2 \to ZH_1 H_1) = 0.489 \text{ pb} \times 0.912 \times 0.544 = 243 \text{ fb} \end{array}} \tag{2}$$

$\sigma^{\mathrm{NLO}}_{H_1 H_1}$ [fb]	K-factor	$\Gamma^{\mathrm{tot}}_{H_1}$ [GeV]	$\Gamma^{\mathrm{tot}}_{H_2}$ [GeV]	$\Gamma^{\mathrm{tot}}_{A}$ [GeV]	$\Gamma^{\mathrm{tot}}_{H^\pm}$ [GeV]
444	2.06	4.029×10^{-3}	0.011	14.57	16.07
$\lambda_{3H_1}/\lambda_{3H}$	$y_{t,H_1}/y_{t,H}$	$\sigma^{\mathrm{NNLO}}_{H_1}$ [pb]	$\sigma^{\mathrm{NNLO}}_{H_2}$ [pb]	$\sigma^{\mathrm{NNLO}}_{A}$ [pb]	
0.993	0.993	48.56	0.916	0.489	

Mixed di-Higgs production into 4b final state

All rates @NLO! [fb]

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

Model	Mixed Higgs State	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{SM})$	46	2.02
	$H_1 H_2(\equiv H_{SM})$	35	1.97
C2HDM-I	$H_2 H_1(\equiv H_{SM})$	19	2.02
	$H_1 H_2(\equiv H_{SM})$	14	2.01
	$H_1 H_3(\equiv H_{SM})$	11	1.96
N2HDM-I	$H_2 H_1(\equiv H_{SM})$	105	2.01
	$AH_1(\equiv H_{SM})$	830	2.06
	$H_1 H_2(\equiv H_{SM})$	2110	2.09
	$AH_2(\equiv H_{SM})$	277	2.04
	$H_1 H_3(\equiv H_{SM})$	44	1.97
	$H_2 H_3(\equiv H_{SM})$	30	1.97
	$AH_3(\equiv H_{SM})$	19	2.01
N2HDM-II	$H_1 H_2(\equiv H_{SM})$	18	1.86
NMSSM	$A_1 H_1(\equiv H_{SM})$	201	1.92
	$H_2 H_1(\equiv H_{SM})$	43	1.91
	$A_1 H_2(\equiv H_{SM})$	40	1.94
	$H_1 H_2(\equiv H_{SM})$	59	1.90

- Details on these points can be provided on request.

Conclusions

Conclusions

- A first perspective of the application and impact of di-Higgs constraints on BSM models
- 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 trilinear on the N2HDM
- Large XS: possibility for model exclusion
- Exotic channels might help with model distinction

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

Check our paper at: 2112.12515
Thank you!

Backup

Mixed-state full-table $4b$

Model	Mixed Higgs State	$m_{res.}$ [GeV]	res. rate [fb]	m_Φ [GeV]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{SM})$	—	—	82	46	2.02
	$H_1H_2(\equiv H_{SM})$	—	—	68	35	1.97
C2HDM-I	$H_2H_1(\equiv H_{SM})$	266	9	128	19	2.02
	$H_1H_2(\equiv H_{SM})$	—	—	122	14	2.01
	$H_1H_3(\equiv H_{SM})$	—	—	99	11	1.96
N2HDM-I	$H_2H_1(\equiv H_{SM})$	360	109	146	105	2.01
	$AH_1(\equiv H_{SM})$	—	—	75	830	2.06
	$H_1H_2(\equiv H_{SM})$	229	2260	54	2110	2.09
	$AH_2(\equiv H_{SM})$	—	—	101	277	2.04
	$H_1H_3(\equiv H_{SM})$	—	—	73	44	1.97
	$H_2H_3(\equiv H_{SM})$	—	—	83	30	1.97
	$AH_3(\equiv H_{SM})$	—	—	69	19	2.01
N2HDM-II	$H_1H_2(\equiv H_{SM})$	640	18	103	18	1.86
NMSSM	$A_1H_1(\equiv H_{SM})$	553	210	113	201	1.92
	$H_2H_1(\equiv H_{SM})$	535	42	167	43	1.91
	$A_1H_2(\equiv H_{SM})$	511	42	87	40	1.94
	$H_1H_2(\equiv H_{SM})$	714	58	80	59	1.90

Table: Maximum rates at NLO QCD in the $4b$ final state for different mixed Higgs pair final states in the investigated models; the corresponding K-factor is given in the last column. In case of resonantly enhanced production, we give in the third and fourth column, respectively, the mass of the resonant Higgs boson and the resonant cross section as defined in the text. The fifth column contains the mass of the non-SM-like final state Higgs boson. More details on these points can be provided on request.

Mixed-state full-table $2b2W$

Model	Mixed Higgs State	$m_{res.}$ [GeV]	res. rate [fb]	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2 H_1 (\equiv H_{SM})$	406	497	179	498	1.98
	$H_1 H_2 (\equiv H_{SM})$	304	615	113	590	2.04
NMSSM	$H_2 H_1 (\equiv H_{SM})$	531	45	205	47	1.92

Table: Maximum rates at NLO QCD in the $(b\bar{b})(WW)$ final state for different mixed Higgs pair final states in the investigated models with the non-SM-like Higgs decaying into WW; the corresponding K-factor is given in the last column. In case of resonantly enhanced production, we give in the third and fourth column, respectively, the mass of the resonant Higgs boson and the resonant cross section as defined in the text. The fifth column contains the mass of the non-SM-like final state Higgs boson. More details on these points can be provided on request.

Mixed-state full-table $2b2t$

Model	Mixed Higgs State	$m_{\text{res.}}$ [GeV]	res. rate [fb]	m_Φ [GeV]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{SM})$	—	—	346	11	1.94
N2HDM-I	$H_2H_1(\equiv H_{SM})$	634	81	444	88	1.86
	$AH_1(\equiv H_{SM})$	—	—	363	15	1.90
N2HDM-II	$H_2H_1(\equiv H_{SM})$	813	23	511	34	1.79
NMSSM	$A_1H_1(\equiv H_{SM})$	—	—	53	82	1.88
	$H_2H_1(\equiv H_{SM})$	535	19	371	19	1.91

Table: Maximum rates at NLO QCD in the $(b\bar{b})(t\bar{t})$ final state at NLO for different mixed Higgs pair final states in the investigated models with the non-SM-like Higgs decaying into $t\bar{t}$; the corresponding K-factor is given in the last column. In case of resonantly enhanced production, we give in the third and fourth column, respectively, the mass of the resonant Higgs boson and the resonant cross section as defined in the text. The fifth column contains the mass of the non-SM-like final state Higgs boson. More details on these points can be provided on request.

Mixed state full-table ($6b$)

Model	Mixed Higgs State	m_{Φ_1} [GeV]	m_{Φ_2} [GeV]	Rate [fb]	K-factor
N2HDM-I	$H_2H_3(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	98	41	15	1.95
	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	282	-	40	1.96
	$H_2H_1(\equiv H_{SM}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	157	73	33	2.05
	$H_1H_2(\equiv H_{SM}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	54	-	111	2.09
	$H_3H_2(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	212	83	8	1.93
N2HDM-II	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	271	-	3	1.87
NMSSM	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	319	-	11	1.90
	$H_2H_1(\equiv H_{SM}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	253	116	26	1.92

Model	Mixed Higgs State	$m_{res.}$ [GeV]	res. rate [fb]
N2HDM-I	$H_2H_3(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	—	—
	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	441	39
	$H_2H_1(\equiv H_{SM}) \to AA(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	294	37
	$H_1H_2(\equiv H_{SM}) \to (b\bar{b})H_1H_1 \to (b\bar{b})(b\bar{b})(b\bar{b})$	229	119
	$H_3H_2(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	—	—
N2HDM-II	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	615	2
NMSSM	$H_2H_1(\equiv H_{SM}) \to H_1H_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	560	11
	$H_2H_1(\equiv H_{SM}) \to A_1A_1(b\bar{b}) \to (b\bar{b})(b\bar{b})(b\bar{b})$	518	26

Table: Upper: Maximum rates for multi-Higgs final states given at NLO QCD. The K-factor is given in the last column. In the third and fourth column we also give the mass values m_{Φ_1} and m_{Φ_2} of the non-SM-like Higgs bosons involved in the process, in the order of their appearance. Lower: In case of resonantly enhanced production the mass of the resonantly produced Higgs boson is given together with the NNLO QCD production rate. More details on these points can be provided on request.

Multi-Higgs final state 1/2

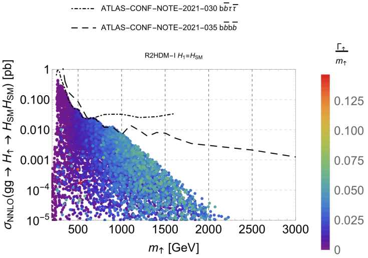
Model	SM-like Higgs	Signature	m_Φ [GeV]	Rate [fb]	K-factor
N2HDM-I	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	41	14538	2.18
	H_3	$H_1H_1 \to (4b); (4\gamma)$	41	4545 ; 700	2.24
	H_1	$AA \to (b\bar{b})(b\bar{b})$	75	6117	2.11
	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	146	73	2.01
	H_2	$AA \to (b\bar{b})(b\bar{b})$	80	2875	2.13
	H_2	$AH_1 \to (b\bar{b})(b\bar{b})$	m_A : 87 m_{H_1} : 91	921	2.09
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	47	8968	2.17
N2HDM-II	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	44	1146	2.18
C2HDM-I	H_1	$H_2H_2 \to (b\bar{b})(b\bar{b})$	128	475	2.07
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	66	814	2.16
	H_3	$H_1H_1 \to (b\bar{b})(b\bar{b})$	84	31	2.09
NMSSM	H_1	$A_1A_1 \to (b\bar{b})(b\bar{b})$	166	359	1.95
	H_1	$A_1A_1 \to (\gamma\gamma)(\gamma\gamma)$	179	34	1.96
	H_2	$H_1H_1 \to (b\bar{b})(b\bar{b})$	48	3359	2.18
	H_2	$A_1A_1 \to (b\bar{b})(b\bar{b})$	54	1100	2.18
	H_1	$A_1A_1 \to (t\bar{t})(t\bar{t})$	350	20	1.82

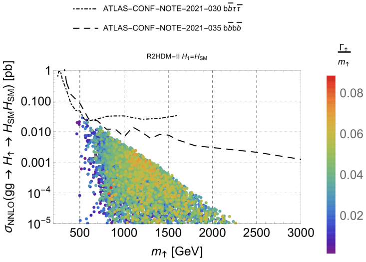
Multi-Higgs final state 1/2

Model	Signature	$m_{\text{res.}}$ [GeV]	res. rate [fb]	$m_{\text{res.}}$ 2 [GeV]	res. rate 2 [fb]
N2HDM-I	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	125.09	621	98	17137
	$H_1 H_1 \to (4b); (4\gamma)$	125.09	126; 19	94	5445;839
	$AA \to (b\bar{b})(b\bar{b})$	1535	<0.1	323	482
	$H_2 H_2 \to (b\bar{b})(b\bar{b})$	360	76	—	—
	$AA \to (b\bar{b})(b\bar{b})$	178	3191	—	—
	$AH_1 \to (b\bar{b})(b\bar{b})$	—	—	—	—
	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	588	22	125.09	997
N2HDM-II	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	520	< 0.1	125.09	1330
C2HDM-I	$H_2 H_2 \to (b\bar{b})(b\bar{b})$	266	497	—	—
	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	151	598	—	—
	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	—	—	—	—
NMSSM	$A_1 A_1 \to (b\bar{b})(b\bar{b})$	552	31	453	332
	$A_1 A_1 \to (\gamma\gamma)(\gamma\gamma)$	796	< 0.01	444	34
	$H_1 H_1 \to (b\bar{b})(b\bar{b})$	882	<0.1	125.59	4173
	$A_1 A_1 \to (b\bar{b})(b\bar{b})$	676	< 0.1	122.99	1353
	$A_1 A_1 \to (t\bar{t})(t\bar{t})$	741	7	705	14

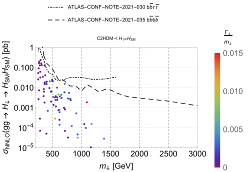
Table: Upper: Selected rates for non-SM-like Higgs pair final states at NLO QCD. We specify the model, which of the Higgs bosons is the SM-like one, the signature and its rate as well as the K-factor. In the fourth column we also give the mass value m_Φ of the non-SM-like Higgs boson involved in the process. Lower: In case of resonantly enhanced cross sections, the mass of the resonantly produced Higgs boson is given together with the NNLO QCD production rate. Some scenarios contain two heavier Higgs bosons that can contribute to resonant production. All benchmark details can be provided on request.

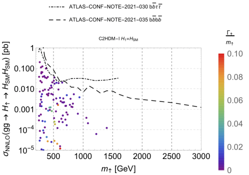
Resonant production R2HDM

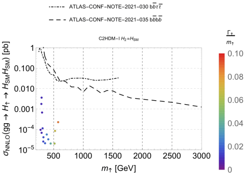


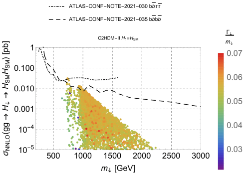


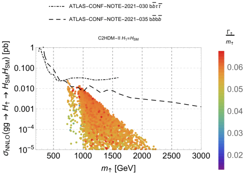
Resonant production C2HDM



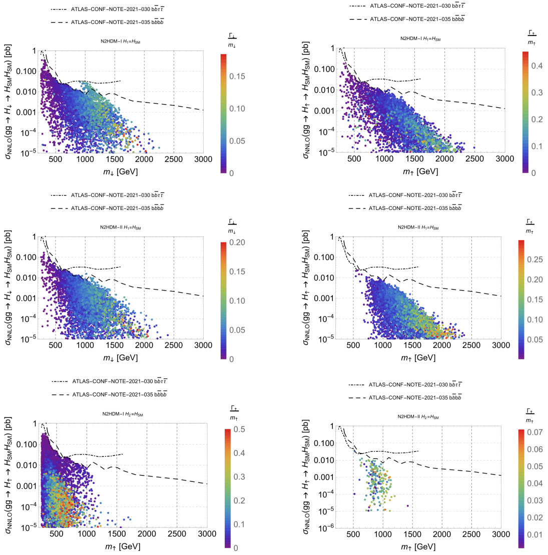




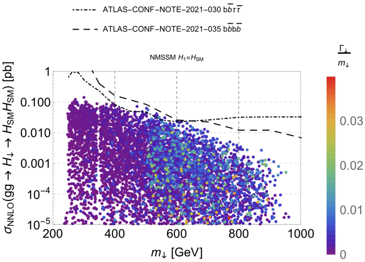


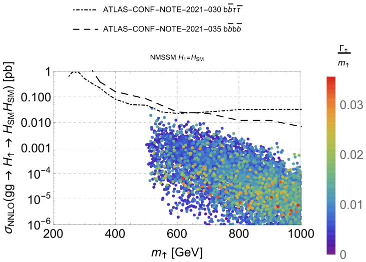


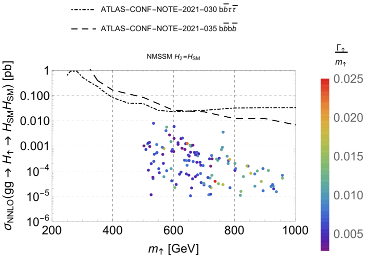
Resonant production N2HDM



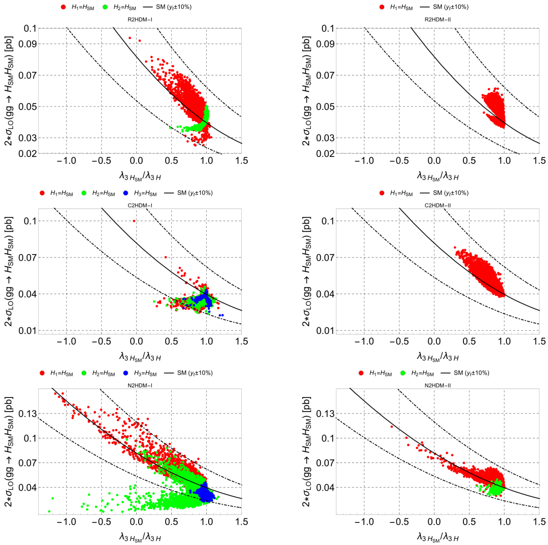
Resonant production NMSSM







Non-resonant production



Non-resonant production NMSSM