Di-Higgs production in extended scalar sectors

Duarte Azevedo

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

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

HPNP 2023

Based on: JHEP 11 (2022) [2112.12515]

June 6th, 2023

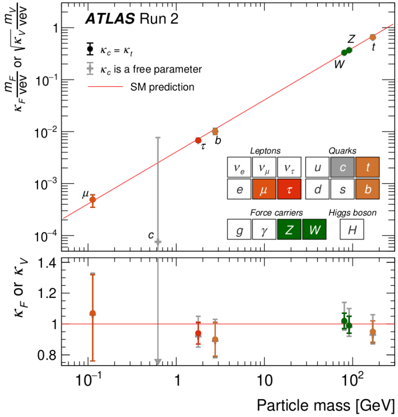
Karlsruhe Institute of Technology

DA acknowledges support from the Deutsche Forschungsgemeinschaft (DFG) under grant 396021762 - TRR 257.

Introduction

→ **Scalar particle discovered in 2012 experimentally completing the SM**

Phys. Lett. B 716 (2012) 1-29, Phys. Lett. B 716 (2012) 30



- ... we need new physics: Dark Matter, baryon asymmetry, among others...
- Extended scalar sectors can tackle these
- Di-Higgs prod. is pertinent to measure self-interactions → probe scalar potential
- SM: destructive interference
- BSM: can enhance significantly di-Higgs rates

Goals

→ Impact of di-Higgs constraints on archetypical extended scalar sectors
→ What is the allowed enhancement to di-Higgs post fact?
→ Provide interesting benchmarks for pair production

- **Main focus:** SM-like Higgs pairs.
- SM-like + non-SM-like Higgs pairs [not covered]
- Exotic di-scalar or cascading production [not covered]

→ Mapping to EFT [not covered]

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 (for first three models) to inhibit FCNC

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

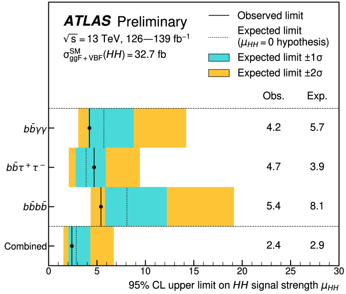
Overview

1. Introduction
   - Experimental searches
   - Di-Higgs production in BSM
2. Main results
   - Methodology
   - Impact of resonant and non-res. searches
   - Benchmarks
3. Conclusions

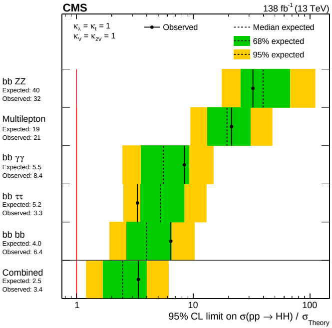
Non-resonant searches

Disclaimer: Not most up-to-date [Sep. 22]

ATLAS ATLAS-CONF-2022-050



CMS Nature 607(2022)60

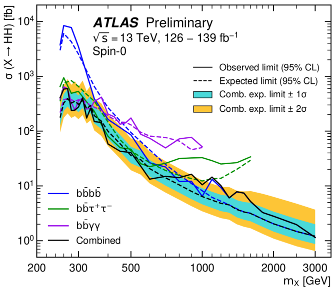


k_λ lim.	Obs.	Exp.
ATLAS $b\bar{b}\gamma\gamma$	$[-\mathbf{1.6}, \mathbf{6.7}]$	$[-2.4, 7.7]$
CMS $b\bar{b}\tau\bar{\tau}$	$[-\mathbf{1.7}, \mathbf{8.7}]$	$[-2.9, 9.8]$

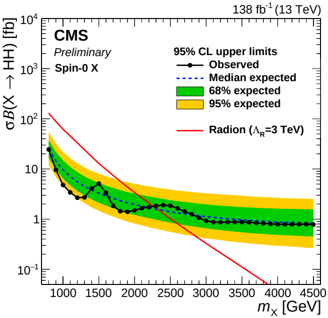
→ Non-resonant searches considers $y_t = y_t^{SM}$.

Resonant searches

ATLAS ATLAS-CONF-2021-052



CMS CMS-PAS-B2G-20-004



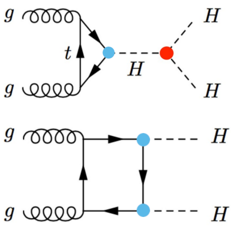
- Low mass regime - $b\bar{b}\gamma\gamma$ [ATLAS]
- Intermediate mass regime - $b\bar{b}\tau\bar{\tau}$ [ATLAS]
- High mass regime - $b\bar{b}b\bar{b}$ [ATLAS]
- Very high mass regime ($>$ 1 TeV) - $b\bar{b}b\bar{b}$ [CMS]

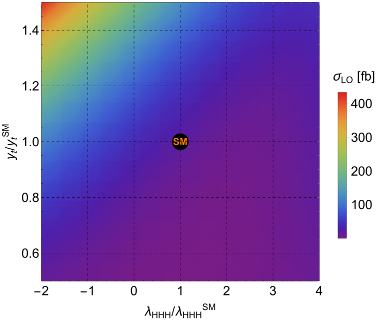
Enhancing di-Higgs production

SM cross-section recommendations by the LHCXSWG[2]

√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 λ_{HHH} and y_t couplings

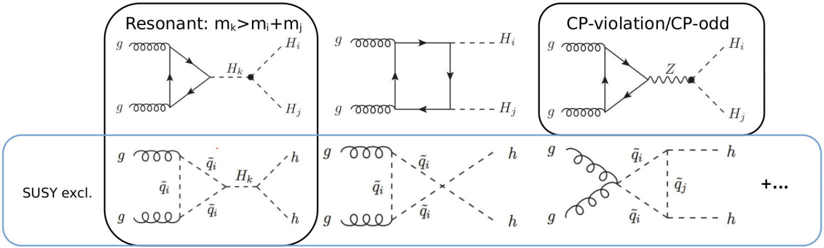




[2]FT approx: QCD@NNLO in the heavy-top limit, full LO and NLO mass effects and full mass dependence in the one-loop double real corrections at NNLO QCD

Enhancing di-Higgs production

From the existence of additional diagrams



New contributions and interferences will depend on:

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

→ Resonant and (non-SM-like) non-resonant prod. are **simultaneously** present

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:

- Single Higgs rates w/ `SusHi` Harlander et al. (1605.03190) @13/14TeV@NNLO_QCD.
- Double Higgs rates w/ `HPAIR`[3] (and variations):
  - NLO born-improved heavy top-quark mass limit.
  - Scans: $2 * (\sigma_{HH}^{\mathrm{LO}}$@14 TeV) to 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 @14 TeV@NLO.

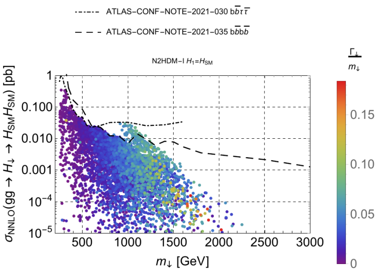
[3] http://tiger.web.psi.ch/proglist.html

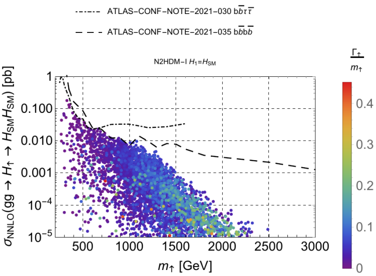
Impact of resonant searches

→ Due to NW exp. searches: constrain $\underline{\sigma(gg \to H_i) * \mathrm{BR}(H_i \to H_{SM} H_{SM})}$

→ Assumes small widths, SM-like non-resonant bkg and no interference

N2HDM-I: H_1 is SM-like (two resonances)



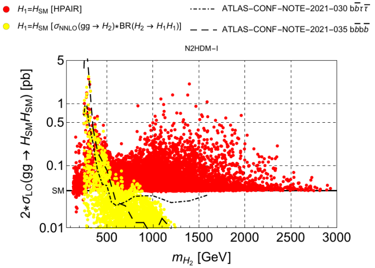


- Points where $\Gamma(H_i)/m_i > 5\%$ → NWA is not valid
- Points where $\Gamma(H_i)/m_i > 50\%$ → not considered

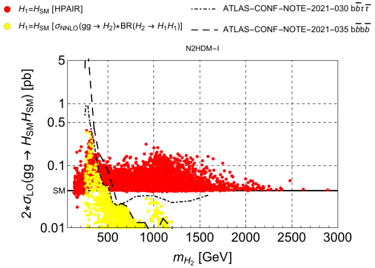
Impact of resonant searches

N2HDM-I: H_1 is SM-like (two resonances)

Before resonant bounds



After resonant bounds

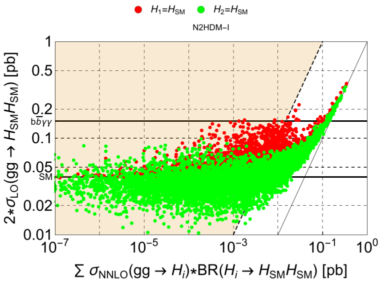


Impact of non-resonant searches

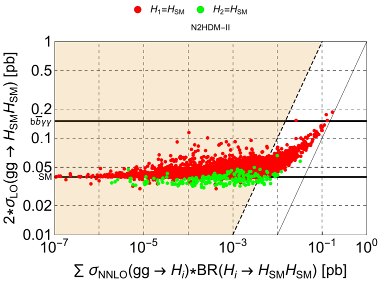
We apply non-resonant constraints to **non-resonant points**.

- **Definition:** non-resonant point fulfils $\sigma_{HH}^{\text{full}} > 10 * \sigma_{HH}^{\text{res}}$ [shaded area]

Type I



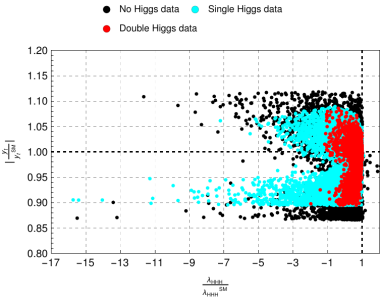
Type II



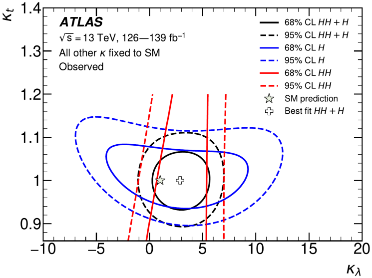
- Leading non-resonant constraint is $b\bar{b}\gamma\gamma$: $\sigma_{HH}^{\text{non-res}} < 4.1 * \sigma_{HH}^{\text{SM}}$.
- For the largest XS, linear correlation between resonant and full result

Impact of all searches

N2HDM-I: H_1 is SM-like



ATLAS 2211.01216



- Single Higgs data constrains the Yukawa coupling
- Additional bound $\lambda_{ijk} < \lambda^{SM}_{HHH}(m_H = 700 \text{ GeV}) \approx 6$ TeV cuts lower branch
- Di-Higgs data is starting to constrain trilinears

$H_{SM}H_{SM}$ 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

Conclusions

- A first analysis of the application and impact of di-Higgs constraints on archetypical BSM models.
- Resonant searches already constrain all the models
- In the N2HDM: trilinears are now being constrained by **both res. and non-res. searches**
- Large XS across the board, several potential searches to be exploited

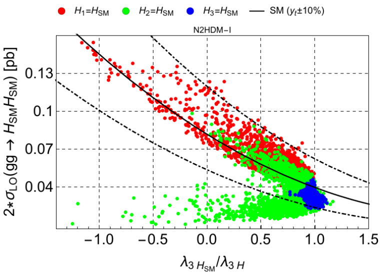
Check out our results and benchmarks: JHEP 11 (2022) [2112.12515]
Thank you!

Backup

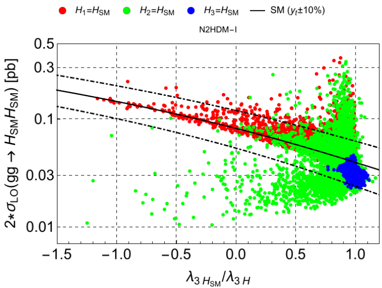
Impact from all searches

N2HDM-I

Non-resonant sample



Full sample

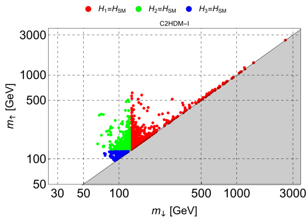


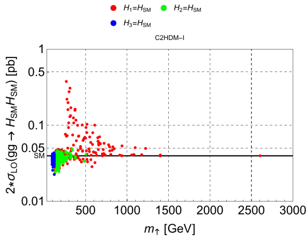
→ **Resonant** and **non-resonant** searches needed to constrain BSM SM-like trilinear

→ $H_2 = H_{SM}$ scenario suffers from destructive interference

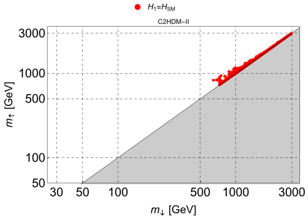
Overview C2HDM

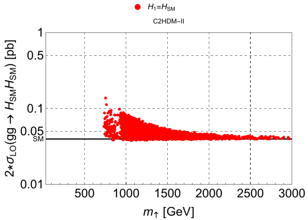
Type I





Type II

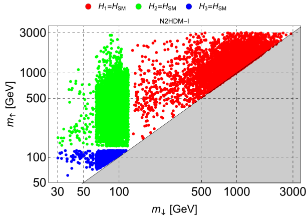


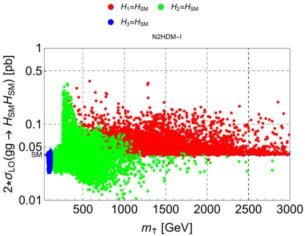


- EDM constraints favor degeneracy
- For type II: flavor constraints force $m_{H^{\pm}} > 800$ GeV
- Decoupling limit is visible

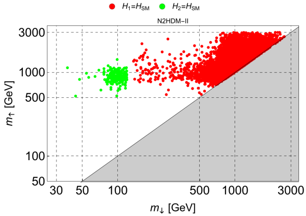
Overview N2HDM

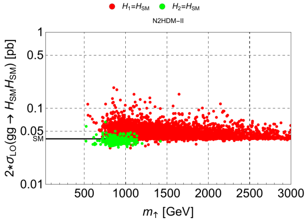
Type I





Type II





- Destructive interference in type I: $H_2 = H_{SM}$

$h_{SM}\phi_{BSM}$ production

All rates @NLO [fb]

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

Model	Mixed Higgs State	$m_{\text{res.}}$ [GeV]	res. rate [fb]	Rate [fb]	K-factor
R2HDM-I	$AH_1(\equiv H_{SM})$	—	—	46	2.02
	$H_1H_2(\equiv H_{SM})$	—	—	35	1.97
C2HDM-I	$H_2H_1(\equiv H_{SM})$	266	9	19	2.02
	$H_1H_2(\equiv H_{SM})$	—	—	14	2.01
	$H_1H_3(\equiv H_{SM})$	—	—	11	1.96
N2HDM-I	$H_2H_1(\equiv H_{SM})$	360	109	105	2.01
	$\mathbf{AH_1(\equiv H_{SM})}$	—	—	**830**	2.06
	$\mathbf{H_1H_2(\equiv H_{SM})}$	229	2260	**2110**	2.09
	$AH_2(\equiv H_{SM})$	—	—	277	2.04
	$H_1H_3(\equiv H_{SM})$	—	—	44	1.97
	$H_2H_3(\equiv H_{SM})$	—	—	30	1.97
	$AH_3(\equiv H_{SM})$	—	—	19	2.01
N2HDM-II	$H_1H_2(\equiv H_{SM})$	640	18	18	1.86
NMSSM	$A_1H_1(\equiv H_{SM})$	553	210	201	1.92
	$H_2H_1(\equiv H_{SM})$	535	42	43	1.91
	$A_1H_2(\equiv H_{SM})$	511	42	40	1.94
	$H_1H_2(\equiv H_{SM})$	714	58	59	1.90

- Details on these points can be provided on request.

$h_{SM}\phi_{BSM}$ production

All rates @NLO [fb]

$\mathbf{gg \to H_{SM} H_j/A_j \to b\bar{b}W^+W^-}$

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

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

Model	Mixed Higgs State	$m_{res.}$ [GeV]	res. rate [fb]	Rate [fb]	K-factor
R2HDM-I	$A H_1 (\equiv H_{SM})$	—	—	11	1.94
N2HDM-I	$H_2 H_1 (\equiv H_{SM})$	634	81	88	1.86
	$A H_1 (\equiv H_{SM})$	—	—	15	1.90
N2HDM-II	$H_2 H_1 (\equiv H_{SM})$	813	23	34	1.79
NMSSM	$A_1 H_1 (\equiv H_{SM})$	—	—	82	1.88
	$H_2 H_1 (\equiv H_{SM})$	535	19	19	1.91

$h_{SM}\phi_{BSM}$ production

N2HDM-I overview