

# Physics with singlets

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# After Higgs discovery: Open questions

**Higgs discovery in 2012  $\Rightarrow$  last building block discovered**

**? Any remaining questions ?**

- Why is the SM the way it is ??  
 $\Rightarrow$  search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**  
 $\Rightarrow$  e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

$\Rightarrow$  **main test ground for this: particle colliders**  $\Leftarrow$

# Special role of the scalar sector

- **Higgs potential in the SM**

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2, \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

⇒ **mass** for Higgs Boson and Gauge Bosons

$$m_h^2 = 2\lambda v^2, \quad m_W = g \frac{v}{2}, \quad m_Z = \sqrt{g^2 + (g')^2} \frac{v}{2}$$

where  $v$ : Vacuum expectation value of the Higgs field,  $g, g'$ : couplings in  $SU(2) \times U(1)$

⇒ **everything determined in terms of gauge couplings,  $v$ , and  $\lambda$**

**form of potential determines minimum,  
electroweak vacuum structure**

⇒ stability of the Universe, electroweak phase transition, etc

- **full test requires checks of  $hhh$ ,  $hhhh$  couplings**

⇒ **so far: only limits; possible only at future machines** [HL-LHC: constraints on  $hhhh$ ]

# Current (large) collider landscape

[<https://europeanstrategy.cern/home>]

**$pp$  colliders: LHC, FCC-hh**

**LHC: center-of-mass energy: 8/ 13/ 13.6 TeV, since 2009/ ongoing**

HL-LHC: 14 TeV, high luminosity (2027-2040)

FCC-hh: 100 TeV, under discussion

**$e^+e^-$  colliders: ILC/ CLIC/ FCC-ee, CePC**

in plan, high priority in Europe, various center-of-mass energies discussed, priority  $\sim 240 - 250$  GeV "Higgs factories"

**$\mu^+\mu^-$  colliders**

under discussion, early stages [EU-funded design study MuCol started 1.3.23]

# LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151]

## ADDING TWO REAL SCALAR SINGLETS

Scalar potential ( $\Phi$ :  $SU(2)_L$  doublet,  $S, X$ :  $SU(2)_L$  singlets)

$$\mathcal{V} = \mu_\Phi^2 \Phi^\dagger \Phi + \mu_S^2 S^2 + \mu_X^2 X^2 + \lambda_\Phi (\Phi^\dagger \Phi)^2 + \lambda_S S^4 + \lambda_X X^4 + \lambda_{\Phi S} \Phi^\dagger \Phi S^2 + \lambda_{\Phi X} \Phi^\dagger \Phi X^2 + \lambda_{SX} S^2 X^2.$$

Imposed  $\mathbb{Z}_2 \times \mathbb{Z}'_2$  symmetry, which is spontaneously broken by singlet vevs.

$\Rightarrow$  three  $\mathcal{CP}$ -even neutral Higgs bosons:  $h_1, h_2, h_3$

Two interesting cases:

**Case (a):**  $\langle S \rangle \neq 0, \langle X \rangle = 0 \Rightarrow X$  is DM candidate;

**Case (b):**  $\langle S \rangle \neq 0, \langle X \rangle \neq 0 \Rightarrow$  all scalar fields mix.

Again, Higgs couplings to SM fermions and bosons are *universally reduced by mixing*.

# Possible production and decay patterns

$$M_1 \leq M_2 \leq M_3$$

## Production modes at $pp$ and decays

$$pp \rightarrow h_3 \rightarrow h_1 h_1; \quad pp \rightarrow h_3 \rightarrow h_2 h_2;$$

$$pp \rightarrow h_2 \rightarrow h_1 h_1; \quad pp \rightarrow h_3 \rightarrow h_1 h_2$$

$$h_2 \rightarrow \text{SM}; \quad h_2 \rightarrow h_1 h_1; \quad h_1 \rightarrow \text{SM}$$

$\Rightarrow$  **two scalars with same or different mass decaying directly to SM, or  $h_1 h_1 h_1$ , or  $h_1 h_1 h_1 h_1$**

[ $h_1$  decays further into SM particles]

$$[\text{BRs of } h_i \text{ into } X_{\text{SM}} = \frac{\kappa_i \Gamma_{h_i \rightarrow X}^{\text{SM}}(M_i)}{\kappa_i \Gamma_{\text{tot}}^{\text{SM}}(M_i) + \sum_{j,k} \Gamma_{h_i \rightarrow h_j h_k}}; \quad \kappa_i: \text{rescaling for } h_i]$$

# Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:**  $h_3 \rightarrow h_1 h_2$  ( $h_3 = h_{125}$ )

SM-like decays for both scalars:  $\sim 3$  pb;  $h_1^3$  final states:  $\sim 3$ pb

AS **BP2:**  $h_3 \rightarrow h_1 h_2$  ( $h_2 = h_{125}$ )

SM-like decays for both scalars:  $\sim 0.6$  pb

AS **BP3:**  $h_3 \rightarrow h_1 h_2$  ( $h_1 = h_{125}$ )

(a) SM-like decays for both scalars  $\sim 0.3$  pb; (b)  $h_1^3$  final states:  $\sim 0.14$  pb

S **BP4:**  $h_2 \rightarrow h_1 h_1$  ( $h_3 = h_{125}$ )

up to 60 pb

S **BP5:**  $h_3 \rightarrow h_1 h_1$  ( $h_2 = h_{125}$ )

up to 2.5 pb

S **BP6:**  $h_3 \rightarrow h_2 h_2$  ( $h_1 = h_{125}$ )

SM-like decays: up to 0.5 pb;  $h_1^4$  final states: around 14 fb

# LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151;

updates from arXiv:2305.08595, HHH Workshop talk, 16.7.23, and for this conference]

2 real singlet extension  $\Rightarrow$  2 additional scalars ( $M_1 \leq M_2 \leq M_3$ ;  $M_i \in [0; 1\text{TeV}]$ )

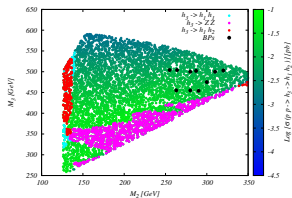
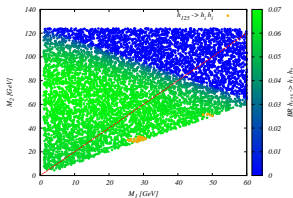
[1 mass always at 125 GeV, others free]

new plots: **updates from paper with full Run II results**

[arXiv:2402.13358,  $b\bar{b}\tau^+\tau^-$  and  $b\bar{b}\mu^+\mu^-$  final states]

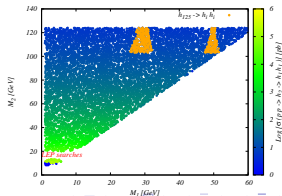
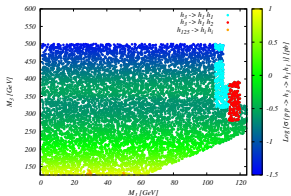
asymmetric,  
triple  $h_1$

(3.5/ 0.25 pb)



symmetric, no  
 $h_{125}$  involved

(2.5/ 60 pb)





## Another important topic: finite width effects

- Experiments: often use factorized approach:

$$pp \rightarrow X, X \rightarrow YZ$$

- quantum mechanics: **only stable particles are defined in S-matrix elements**, everything else approximation
- in reality: **case by case study**
- **wrong: assume factorization always works**

## Another topic: finite width effects

[in collaboration with F. Feuerstake/ E. Fuchs/ D. Winterbottom]

- scenario: heavy resonance decaying to  $h_{125} h_{125}$   
[already partially discussed in Rev.Phys. 5 (2020) 100045 and references therein ]
- scenario discussed here:

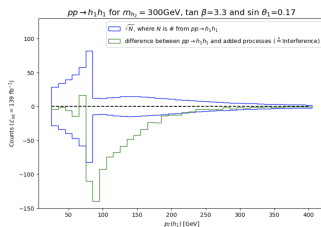
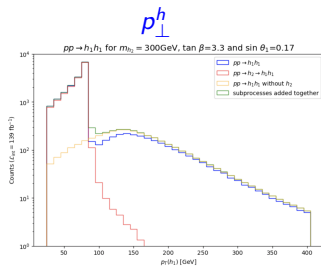
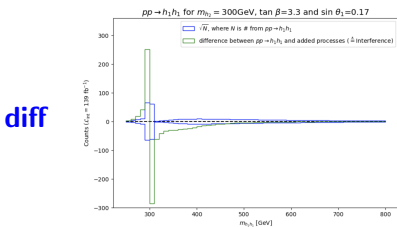
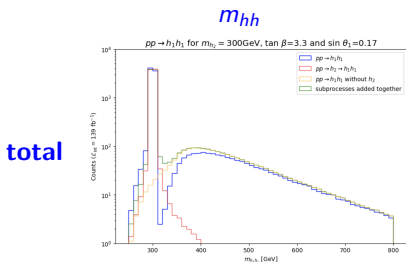
$$m_H = 300 \text{ GeV}; \sin \theta = 0.17; \tan \beta = 3.3$$

$$\Gamma_H = 0.54 \text{ GeV}, \text{BR}_{H \rightarrow hh} = 0.55$$

$$\sigma_{hh} = 69.77(4) \text{ fb}, \sigma_{\text{via}H} = 58.65(2) \text{ fb}, \sigma_{\text{no}H} = 14.195(7) \text{ fb}$$

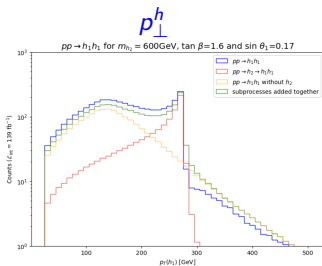
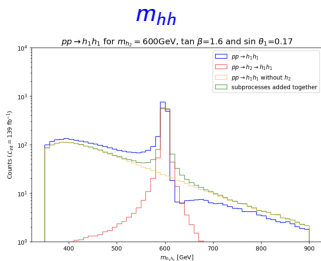
$$\text{Interference: } \sigma_{hh} - (\sigma_{\text{via}H} + \sigma_{\text{no}H}) [= -3.08(5) \text{ fb}]$$

# Results [13 TeV, $\int \mathcal{L} = 139 \text{ fb}^{-1}$ ]

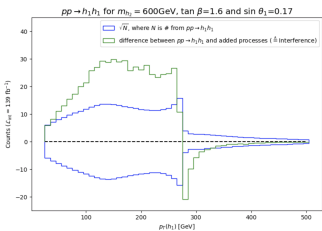
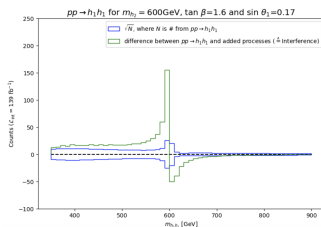


# Results [13 TeV, $\int \mathcal{L} = 139 \text{ fb}^{-1}$ ]

total



diff



# Extra scalars at Higgs factories ( $e^+ e^- @ 240 - 250 \text{ GeV}$ )

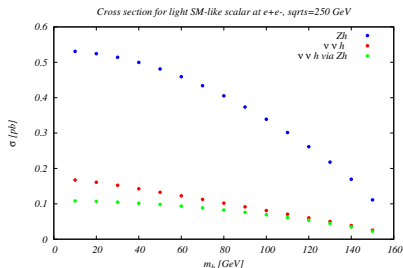
**various production modes possible**

- 1) **easiest example:**  $e^+ e^- \rightarrow Z h_1$ , onshell production  
interesting up to  $m_1 \sim 160 \text{ GeV}$
- 2) in **models with various scalars:** e.g. also  $e^+ e^- \rightarrow h_1 h_2$   
(e.g. from 2HDMs); example processes and bounds from LEP  
in Eur.Phys.J.C 47 (2006) 547-587  
again: for onshell production,  $\sum_i m_i \leq 250 \text{ GeV}$
- 3) another (final) option: **look at**  $e^+ e^- \rightarrow h_i Z, h_i \rightarrow h_j h_k$

**already quite a few studies for 1), 3) available**

# Scalar strahlung for additional light scalars

$$e^+ e^- \rightarrow Z^* \rightarrow Zh, e^+ e^- \rightarrow \nu\bar{\nu}h (\text{VBF})$$



[cross sections for  $e^+ e^-$  at  $\sqrt{s} = 250$  GeV using Madgraph5;

LO analytic expressions e.g. in Kilian et al, Phys.Lett.B 373 (1996) 135-140]

- rule of thumb: **rescaling**  $\lesssim 0.1$
- $\Rightarrow$  maximal production **cross sections around 50 fb**
- $\sim 10^5$  **events using full luminosity**

# Possible model reach

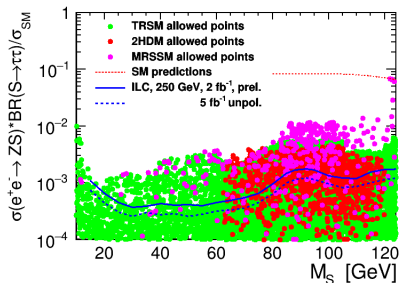
[slide from A.F.Zarnecki, CEPC 2024]

$$S \rightarrow \tau^+ \tau^-$$



## Cross section limits

Cross section limits for  $\sigma(e^+e^- \rightarrow ZS) \cdot BR(S \rightarrow \tau\tau)$   
compared with allowed scenarios in different models



## Two-Real-Singlet Model

thanks to Tania Robens

see [arXiv:2209.10996](https://arxiv.org/abs/2209.10996) [arXiv:2305.08595](https://arxiv.org/abs/2305.08595)

## Two Higgs-Doublet Model

thanks to Kateryna Radchenko

thdmTool package, see [arXiv:2309.17431](https://arxiv.org/abs/2309.17431)

## Minimal R-symmetric Supersymmetric SM

thanks to Wojciech Kotlarski [arXiv:1511.09334](https://arxiv.org/abs/1511.09334)

# Ongoing ECFA study: Direct discovery potential at Higgs factories, Extra scalar subgroup [CERN e-group: ECFA-WHF-WG1-SRCH, see also J. de Blas et al., arXiv:2401.07564]

## Expert team activities

Second meeting on zoom on **June 20**

### Discussion on the choice of benchmark scenarios

Two targets identified:

- search for light exotic scalars in the scalar-strahlung process

$$e^+e^- \rightarrow Z \phi$$

with different possible decay channels:  $bb$ ,  $\tau\tau$ , invisible, ...

- light scalar production in 125 GeV Higgs boson decays

$$h_{125} \rightarrow \phi \phi$$

again assuming different decay channels for  $\phi$  ( $bb$ ,  $\tau\tau$ , invisible,...)

Overview of light scalar scenarios prepared by Tania Robens and included in shared google document.

**Want to get involved ? Let us know !**

Target: **Whitepaper, input for next European Strategy report**



# Summary

**Models with extended scalar sectors provide an interesting setup to introduce new scalar particles, with different CP/ charge quantum numbers**

⇒ leads to many **new interesting signatures**, some of which are not yet covered by current searches

some of these: also interesting connections of electroweak phase transitions/ gravitational waves/ etc

**Next steps**

- **(re) investigate models with extended scalar sectors at  $e^+e^-$  colliders** [ECFA effort ongoing]

**Many things to do**

# Do not miss

**(informal)  $HH(H)$  WS in Zagreb 29.-31.7.24**

⇒ contact me if you want to come ⇐

**Extended Scalars from all angles, CERN,  
21.-25.10.24**

<https://indico.cern.ch/e/scalars2024>

# Appendix

# Models

- new scalars  $\Rightarrow$  **models with scalar extensions**
- many possibilities: introduce new  $SU(2) \times U(1)$  **singlets, doublets, triplets, ...**
- unitarity  $\Rightarrow$  important **sum rule**\*

$$\sum_i g_i^2 (h_i) = g_{SM}^2$$

for coupling  $g$  to vector bosons

- many scenarios  $\Rightarrow$  **signal strength poses strong constraints**

\* modified in presence e.g. of doubly charged scalars, see Gunion, Haber, Wudka, PRD 43 (1991) 904-912.

# What about extensions ?

- in principle: **no limit**

**can add more singlets/ doublets/ triplets/ ...**

- ⇒ consequence: **will enhance particle content**

**additional (pseudo)scalar neutral, additional charged, doubly charged, etc particles**

- common feature:

**new scalar states, which can now also be produced/ decay into each other/ etc**

# Particle content

**typical content:**  
**singlet extensions  $\Rightarrow$  additional CP-even/ odd mass eigenstates**  
**2HDMs, 3HDMs: add additional charged scalars**

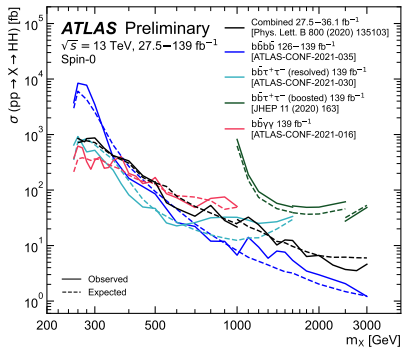
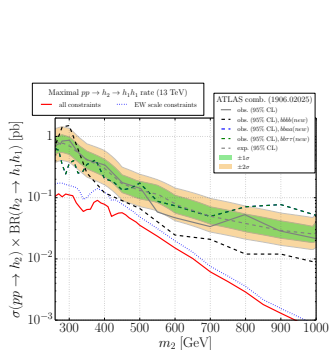
- e.g. 2 real scalars  $\Rightarrow$  **3 CP-even neutral scalars**
- 2HDM  $\rightarrow$  **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

# How can we see new physics ?

## Different ways to see new physics effects

- **Option 1:** see a **direct deviation**, in best of all cases a bump, and/ or something similar  $\Rightarrow$  **clear enhanced rates for certain final states, mediated by new physics**
- **Option 2:** observe **signatures that do not exist in SM**, e.g. events with large missing energy (hint of model containing DM)
- **Option 3:** observe **deviations in SM-like quantities which are small(ish)**:  $\Rightarrow$  loop-induced deviations, requiring precision measurements
- NB: **these can in principle also be large !!**  $\Rightarrow$  all models floating around to explain  $m_W^{\text{CDF}}$

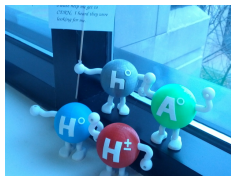
## ATLAS-PHYS-PUB-2021-031





# Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at  $\sim 125$  GeV**
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...
  - ⇒ **new scalar states** ⇐



# Models with extended scalar sectors

## Constraints

- **Theory**

minimization of vacuum (tadpole equations), vacuum stability, positivity, perturbative unitarity, perturbativity of couplings

- **Experiment**

provide viable candidate @ 125 GeV (coupling strength/ width/ ...);  
agree with null-results from additional searches and ew gauge boson measurements (widths);  
agree with electroweak precision tests (typically via S,T,U);  
agree with astrophysical observations (if feasible)

**Limited time  $\Rightarrow$  next slides highly selective...**

[long list of models, see e.g. <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG3>]

tools used: HiggsBounds, HiggsSignals, 2HDMC, micrOMEGAs, ...

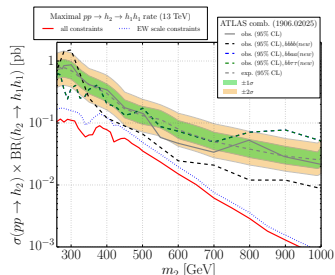
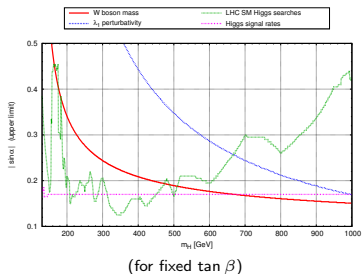
# Examples for current constraints:

## Singlet extension, $Z_2$ symmetric: + 1 scalar particle

[TR, arXiv:2209.15544; updated using HiggsTools]

$$V(\Phi, S) = -m^2 \Phi^\dagger \Phi - \mu^2 S^2 + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 S^4 + \lambda_3 \Phi^\dagger \Phi S^2$$

new parameters:  $m_2$ ,  $\sin \alpha$  [= 0 for SM],  $\tan \beta$  [= ratio of vevs]



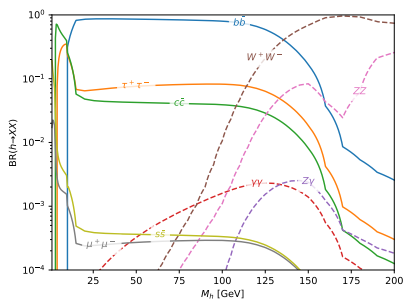
[update from Review in Physics (2020) 100045]

[see e.g. Pruna, TR, Phys. Rev. D 90, 114018;

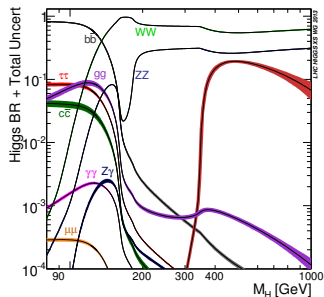
(Bojarski, Chalons,) Lopez-Val, TR, Phys. Rev. D 90, 114018, JHEP 1602 (2016) 147;

(Ilnicka), TR, Stefaniak, EPJC (2015) 75:105, Eur.Phys.J. C76 (2016) no.5, 268, Mod.Phys.Lett. A33 (2018)]

# Reminder: decays of a SM-like Higgs of mass $M \neq 125$ GeV



(using HDecay, courtesy J.Wittbrodt)



(<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWGCrossSectionsFigures>)

# Testing the Higgs potential

- remember:

$$\mathbf{V} = -\mu^2 \Phi^\dagger \Phi + \lambda \left( \Phi^\dagger \Phi \right)^2, \quad \Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathbf{v} + \mathbf{h}(\mathbf{x}) \end{pmatrix}$$

**also predicts  $hhh$  and  $hhhh$  interactions**

- so far: only constraints

$\Rightarrow$  **future accessibility ?**  $\Leftarrow$

**Start with resonance enhanced BSM scenarios for  $hhh$**

# BP3: $h_3 \rightarrow h_1 h_2$ ( $h_1 = h_{125}$ ) [up to 0.3 pb]

## BP3

$$\sigma(pp \rightarrow h_3) \simeq 0.06 \cdot \sigma(pp \rightarrow h_{SM})|_{m=M_3}$$

BR( $h_3 \rightarrow h_{125} h_2$ ) mostly  
 $\sim 50\%$ .

if  $M_2 < 250$  GeV:  $\Rightarrow h_2 \rightarrow$  SM  
 particles.

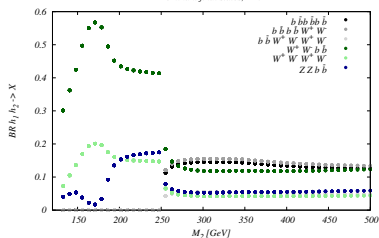
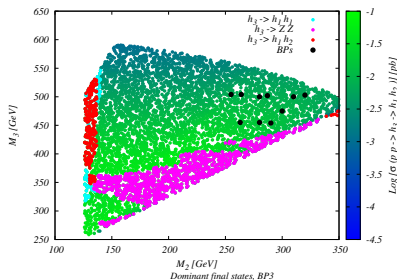
if  $M_2 > 250$  GeV:

$\Rightarrow$  BR( $h_2 \rightarrow h_{125} h_{125}$ )  $\sim 70\%$ ,

$\Rightarrow$  **spectacular triple-Higgs  
 signature**

[up to 140 fb; maximal close to thresholds]

$$[\kappa_3 = 0.24] [\Gamma_3/M_3 \leq 0.05]$$



**bounds from  $pp \rightarrow h_3 \rightarrow h_1 h_2$**  [CMS, Run II, JHEP 11 (2021) 057]

# Exploration of $h_1 h_1 h_1$ final state at HL-LHC

[A. Papaefstathiou, TR, G. Tetlalmatzi-Xolocotzi, JHEP 05 (2021) 193]

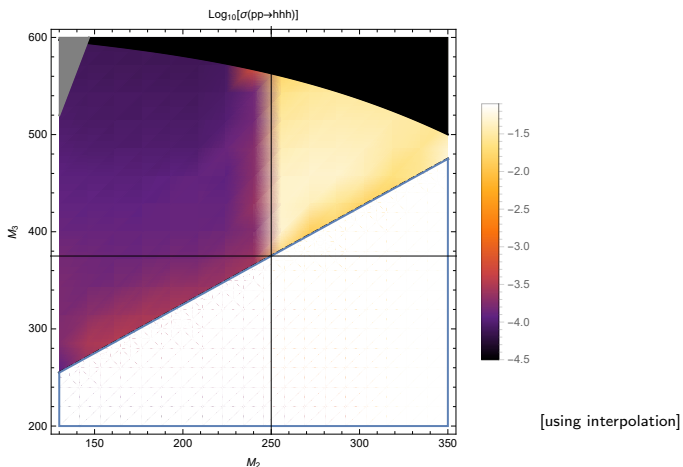
- 3 scalar states  $h_1, h_2, h_3$  that mix

concentrate on

$$pp \rightarrow h_3 \rightarrow h_2 h_1 \rightarrow h_1 h_1 h_1 \rightarrow b \bar{b} b \bar{b} b \bar{b}$$

- ⇒ **select points** on BP3 which might be **accessible at HL-LHC**
- ⇒ perform detailed analysis including SM background, hadronization, ...
- tools: implementation using **full  $t, b$  mass dependence, leading order** [UFO/ Madgraph/ Herwig] [analysis: use K-factors]

# $h_1 h_1 h_1$ production cross sections, leading order [pb]



**highest values:**  $\sim 50\text{fb}$  for  $M_2 \sim 250\text{ GeV}$ ,  $M_3 \sim 400 - 450\text{ GeV}$



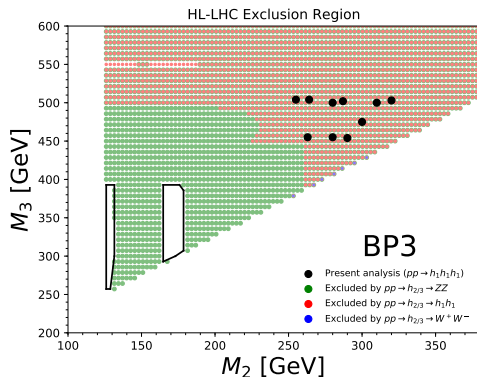
# Benchmark points and results

$(M_2, M_3)$ [GeV]	$\sigma(pp \rightarrow h_1 h_1 h_1)$ [fb]	$\sigma(pp \rightarrow 3b\bar{b})$ [fb]	$\text{sig} _{300\text{fb}^{-1}}$	$\text{sig} _{3000\text{fb}^{-1}}$
(255, 504)	32.40	6.40	2.92	9.23
(263, 455)	50.36	9.95	4.78	15.11
(287, 502)	39.61	7.82	4.01	12.68
(290, 454)	49.00	9.68	5.02	15.86
(320, 503)	35.88	7.09	3.76	11.88
(264, 504)	37.67	7.44	3.56	11.27
(280, 455)	51.00	10.07	5.18	16.39
(300, 475)	43.92	8.68	4.64	14.68
(310, 500)	37.90	7.49	4.09	12.94
(280, 500)	40.26	7.95	4.00	12.65

**discovery, exclusion**

**⇒ at HL-LHC, all points within reach ⇐**

# What about other channels ?



[extrapolation of  $36 \text{ fb}^{-1}$  and HL projections]

$\Rightarrow$  model can be tested from various angles  $\Leftarrow$

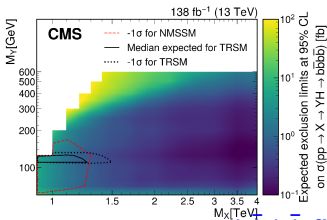
[Phys. Rev. Lett. 122 (2019) 121803; Phys. Lett. B800 (2020) 135103; JHEP 06 (2018) 127; CERN Yellow Rep. Monogr. 7 (2019) 221; Eur. Phys. J. C78 (2018) 24; ATL-PHYS-PUB-2018-022]

# What about LHC search interpretations ?

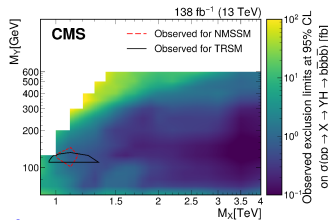
- so far: **2 searches (by CMS) with public results and TRSM interpretations**
- both target  $pp \rightarrow X \rightarrow Y h$
- final states:  $b\bar{b}b\bar{b}$  [2204.12413],  $b\bar{b}\gamma\gamma$  [CMS-PAS-HIG-21-011]
- compares to **maximal rates** in TRSM and NMSSM  
[TRSM rates available from <https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX>]
- Work in progress: **Optimized automated scan for maximal rates for any final states** [A. Ghosh, TR, J. Veatch, R. Zhang]

# Results [using non-optimized scan]

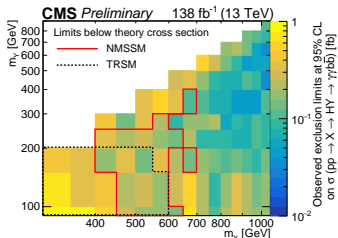
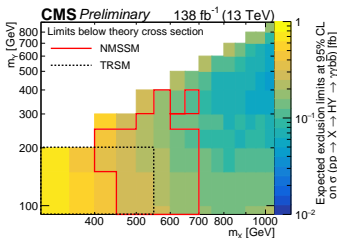
expected



observed



$b\bar{b}b\bar{b}$  final states



$b\bar{b}\gamma\gamma$  final states

# Current back of the envelope accuracy estimates

[for triple couplings, from M. Selvaggis talk at Higgs Pairs mini-workshop 09/21, and Snowmass WPs arXiv:2203.07622 (ILC)/ arXiv:2203.07646 ( $C^3$ )]

- HL-LHC/ ILC<sub>250</sub>/ CLIC<sub>380</sub>/ CEPC<sub>240</sub>/  $C_{250}^3 \sim 50\%$
- FCC-ee<sub>240/365</sub>, ILC<sub>500</sub>,  $C_{550}^3 \sim 20 - 27\%$
- ILC<sub>500-1000GeV</sub>, CLIC<sub>3TeV</sub>  $\sim 8 - 11\%$
- FCC-hh  $\sim 3.5 - 8\%$
- $\mu\mu_{30TeV} \sim 2 - 3\%$

[ $HH$ / single  $H$ ; recent updates not included]

? What about quartic couplings ?

# Incomplete list of papers looking at quartic coupling

- W. Bizon, U. Haisch and L. Rottoli, *Constraints on the quartic Higgs self-coupling from double-Higgs production at future hadron colliders*, JHEP 10 (2019) 267 [1810.04665].
- S. Borowka, C. Duhr, F. Maltoni, D. Pagani, A. Shivaji and X. Zhao, *Probing the scalar potential via double Higgs boson production at hadron colliders*, JHEP 04 (2019) 016 [1811.12366].
- T. Liu, K.-F. Lyu, J. Ren and H.X. Zhu, *Probing the quartic Higgs boson self-interaction*, Phys. Rev. D98 (2018) 093004 [1803.04359].
- J. Alison et al., *Higgs boson potential at colliders: Status and perspectives*, Rev. Phys. 5 (2020) 100045 [1910.00012].
- A. Papaefstathiou and K. Sakurai, *Triple Higgs boson production at a 100 TeV proton-proton collider*, JHEP 02 (2016) 006 [1508.06524].
- C.-Y. Chen, Q.-S. Yan, X. Zhao, Y.-M. Zhong and Z. Zhao, *Probing triple-Higgs productions via  $4b2\gamma$  decay channel at a 100 TeV hadron collider*, Phys. Rev. D93 (2016) 013007 [1510.04013].
- D.A. Dicus, C. Kao and W.W. Repko, *Self Coupling of the Higgs boson in the processes  $p p \rightarrow ZHHH + X$  and  $p p \rightarrow WHHH + X$* , Phys. Rev. D93 (2016) 113003 [1602.05849].
- R. Contino et al., *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*, CERN Yellow Rep. (2017) 255 [1606.09408].
- B. Fuks, J.H. Kim and S.J. Lee, *Scrutinizing the Higgs quartic coupling at a future 100 TeV proton-proton collider with taus and b-jets*, Phys. Lett. B771 (2017) 354 [1704.04298].
- A. Papaefstathiou, G. Tetlalmatzi-Xolocotzi and M. Zaro, *Triple Higgs boson production to six b-jets at a 100 TeV proton collider*, Eur. Phys. J. C 79 (2019) 947 [1909.09166]. [**-1.7; 13**]
- F. Maltoni, D. Pagani and X. Zhao, *Constraining the Higgs self-couplings at  $e+e-$  colliders*, JHEP 07 (2018) 087 [1802.07616]. **CLIC<sub>3TeV</sub> [-5; 7]**
- M. Chiesa, F. Maltoni, L. Mantani, B. Mele, F. Piccinini and X. Zhao, *Measuring the quartic Higgs self-coupling at a multi-TeV muon collider*, JHEP 09 (2020) 098 [2003.13628]. **all [0; 2] best (30TeV) [0.7; 1.5]**

# Finite width: Input and crucial quantities

	Benchmark scan no 1	benchmark scan no 2
$m_{h_1}$	125.09 GeV	125.09 GeV
$m_{h_2}$	300GeV	600GeV
$\tan \beta$	3.3	1.6
$\sin \theta$	0.17	0.17
$\Gamma_{h_2}$	0.5408GeV	4.9802GeV
$\text{BR}_{h_2 \rightarrow h_1 h_1}$	0.5519	0.3396
$\Gamma_{\tilde{h}_2}$	20MeV	20MeV
	Cross Sections	
$pp \rightarrow h_1 h_1$	$(69.858 \pm 0.015)\text{fb}$	$(25.573 \pm 0.101)\text{fb}$
$pp \rightarrow h_2$	$(106.47 \pm 0.003)\text{fb}$	$(23.075 \pm 0.0007)\text{fb}$
$pp \rightarrow h_2 \rightarrow h_1 h_1$	$(58.628 \pm 0.002)\text{fb}$	$(7.8852 \pm 0.0003)\text{fb}$
$pp \rightarrow h_1 h_1 \setminus h_2$	$(14.179 \pm 0.0008)\text{fb}$	$(14.083 \pm 0.0007)\text{fb}$
$pp \rightarrow \tilde{h}_2 \rightarrow h_1 h_1$	$(1588.6 \pm 0.08)\text{fb}$	$(1951.2 \pm 0.05)\text{fb}$

## Another topic: finite width effects

[in collaboration with F. Feuerstake/ E. Fuchs/ D. Winterbottom]

- scenario: heavy resonance decaying to  $h_{125} h_{125}$   
[already partially discussed in Rev.Phys. 5 (2020) 100045 and references therein ]
- scenario discussed here:

$$m_H = 600 \text{ GeV}; \sin \theta = 0.17; \tan \beta = 1.6$$

$$\Gamma_H = 4.98 \text{ GeV}, \text{BR}_{H \rightarrow hh} = 0.34$$

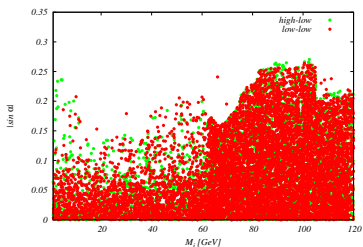
$$\sigma_{hh} = 26.746(7) \text{ fb}, \sigma_{\text{via}H} = 7.90(1) \text{ fb}, \sigma_{\text{no}H} = 15.11(1) \text{ fb}$$

$$\text{Interference: } \sigma_{hh} - (\sigma_{\text{via}H} + \sigma_{\text{no}H}) [= 3.74(2) \text{ fb}]$$

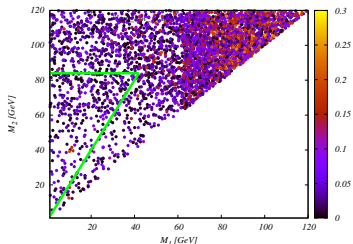


# Singlet extensions [TR, arXiv:2203.08210 and Symmetry 2023, 15(1), 27]

## TRSM: 2 real singlets [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



mass and mixing angle



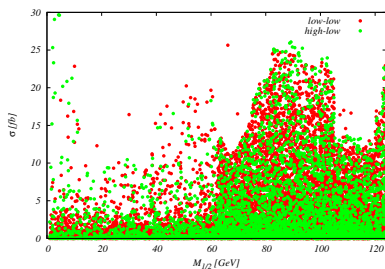
case with two light scalars;  
color coding:  $h_1$  rescaling

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV

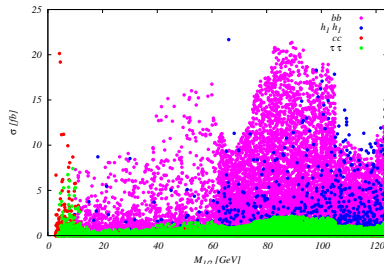
# Singlet extensions

[TR, Symmetry 2023, 15(1), 27 and Springer Proc.Phys. 292 (2023) 141-152]

**TRSM: 2 real singlets** [TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J.C 80 (2020) 2, 151]



cross sections at 250 GeV



convoluted with decay rates

final states:  $Z b \bar{b}$ ,  $Z h_1 h_1$ ,  $Z c \bar{c}$ ,  $Z \tau^+ \tau^-$

courtesy of A.F.Zarnecki, 01/24

