

Extended scalar sectors 10 years after the Higgs discovery

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Theory Challenges in the Precision Era
of the Large Hadron Collider

GGI, Florence

01.09.23

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 λ**

**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 $hhhh$]

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

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^{CDF}

Example: Two Higgs Doublet Models

a popular extension: **Two Higgs Doublet models**

- extend SM scalar sector by **one additional doublet**
- a priori: can lead to flavour changing neutral currents
- way to prevent this: **introduce additional symmetries in potential**

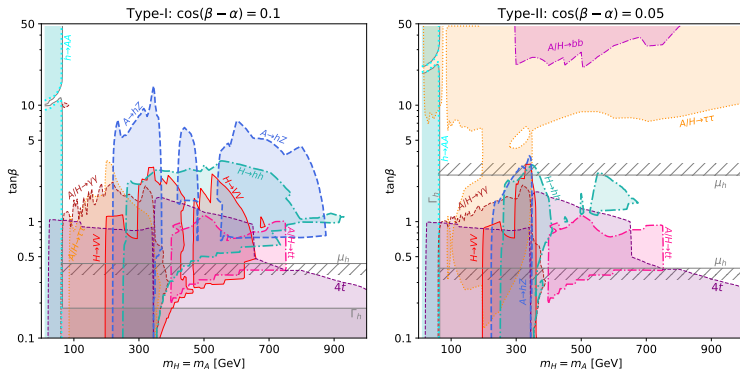
particle content: $\underbrace{h, H}_{\text{CP-even}}, \underbrace{A}_{\text{CP-odd}}, H^\pm$

parameters: **masses**, $+\tan\beta$, $\cos(\beta - \alpha)$, m_{12}

- also subject to various constraints: **B-physics, direct searches, signal strength, ...**
- different types of Yukawa couplings $\Rightarrow$ different effects of constraints

2HDM parameter space

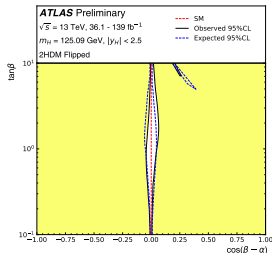
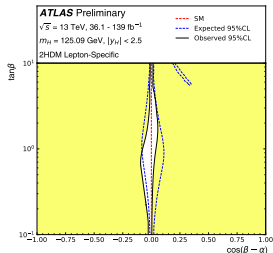
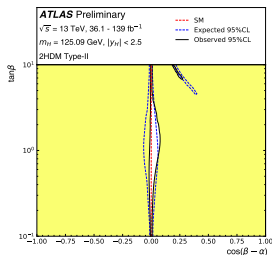
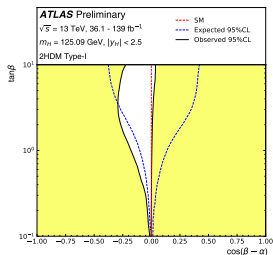
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



combination of various direct searches,
ATLAS/ CMS, at 8/ 13 TeV

Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]



Recent search results...

How are the experiments doing ?

[slides from TR, Higgs Working Group meeting 11/22, prepared by N. Rompotis/ L. Zivkovic [ATLAS], S. Laurila/
M. D'Alfonso [CMS]]

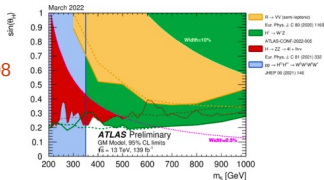
Recent ATLAS Extended Higgs results

- Overlay plots

ATL-PHYS-PUB-2022-008

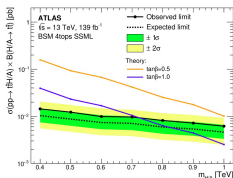
(March 2022)

Georgi-Machacek



- $ttA/H \rightarrow tt$

EXOT-2019-26

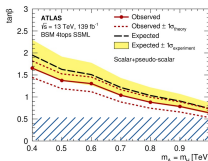


Nikolaos Rompotis (Liverpool)

Lidija Zivkovic (Belgrade)

Tania Robens

NEW



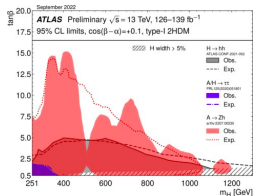
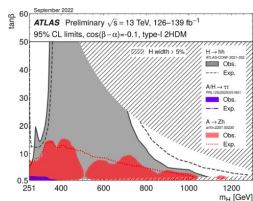
Type-II 2HDM

LHC Higgs workshop – December 2022

Extended scalar sectors

ATL-PHYS-PUB-2022-043

(Sept 2022) 2HDM



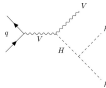
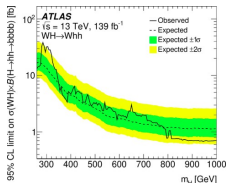
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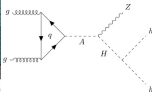
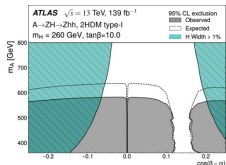
Theory Challenges in the Precision Era

Recent ATLAS Extended Higgs results

- ZH and WH production with $H \rightarrow hh$



HDBS-2019-31 (October 2022)

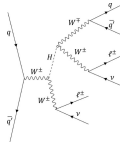
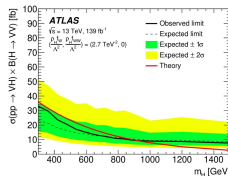


Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

Tania Robens

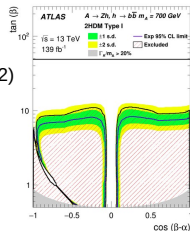
- WH with $H \rightarrow WW$ **NEW**

HDBS-2019-16



- A $\rightarrow$ Zh

HDBS-2020-19 (July 2022)



LHC Higgs workshop – December 2022

Extended scalar sectors

Theory Challenges in the Precision Era



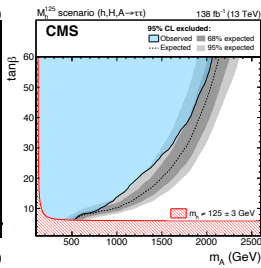
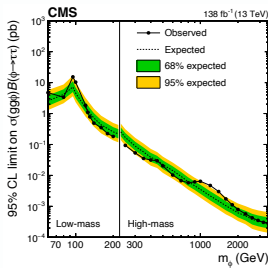
Recent CMS Extended Higgs Results



* MSSM: $\phi(h/H/A) \rightarrow \tau\tau$

- * Model independent limits for $gg\phi$ and $bb\phi$ (pseudo)scalars in 60-3500 GeV mass range
- * MSSM interpretations from a simultaneous fit of the 125 GeV plus another resonance

arXiv:2208.02717

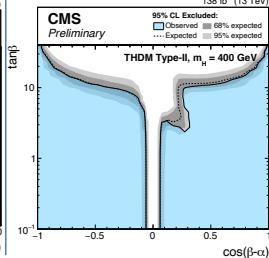
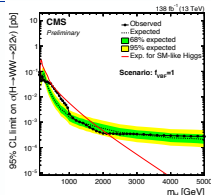


Santeri Laurila (CERN)
Mariarosaria D'Alfonso (MIT)

* MSSM/2HDM: $H \rightarrow WW$

CMS-PAS-HIG-20-016

- * ggH & VBF , 155-5000 GeV
- * Fully leptonic

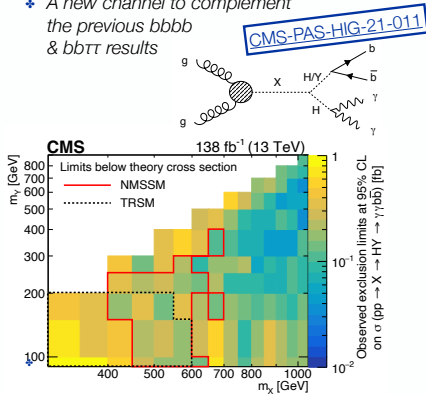


LHC Higgs Workshop – December 2022



- ✦ **NMSSM, TRSM: $X \rightarrow YH \rightarrow b\bar{b}\gamma\gamma$**

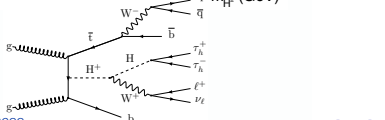
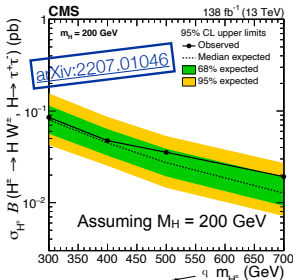
- A new channel to complement the previous $b\bar{b}b\bar{b}$ & $b\bar{b}\tau\tau$ results



- TRSM benchmark values available here:
<https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX>

- ✧ **2HDM:** $H^+ \rightarrow H(\tau\tau)W^+$

- ✦ *First LHC limits on $H^+ \rightarrow HW^+$*



Consequences of combining constraints: flavour, electroweak precision, and signal strength

- non-singlet scenarios: **also strong constraints from flavour**
- typical example: **2HDMs, constraints in the $(m_{H^\pm}, \tan \beta)$ plane**
- ⇒ **sets lower limit on charged mass**
- ⇒ **strongly correlated to other additional masses via electroweak precision measurements (S, T, U)**

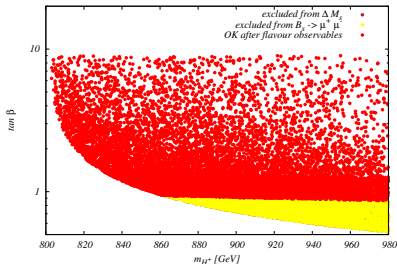
Lower mass bound on additional scalars

- Consequence: "typical" channels at e^+e^- colliders [e.g. HA] require higher center of mass energies [e.g. TeV range]
- example here: **THDMa (2HDM+ singlet)** [TR, Symmetry 13 (2021) 12, 2341]

Example: B- physics constraints [TR, PoS ICHEP2022 176]

Constraints from $B \rightarrow X_s \gamma$, $B_s \rightarrow \mu^+ \mu^-$, ΔM_s

- $B \rightarrow X_s \gamma$: use fit from updated calculation of Misiak et al., [JHEP 2006 (2020) 175, Eur.Phys.J. C77 (2017) no.3, 201], $\Rightarrow \tan \beta_{\min}(m_{H^\pm})$
- $B_s \rightarrow \mu^+ \mu^-$, ΔM_s : via SPheno, compare to PDG value, HFLAV value [Eur.Phys.J.C 81 (2021) 3, 226]

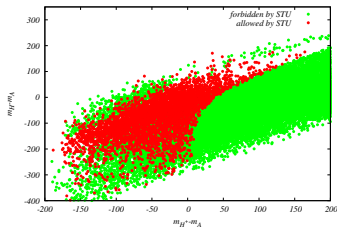
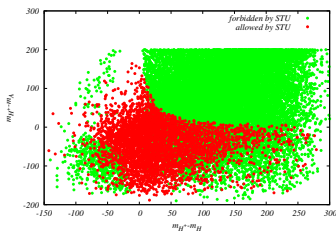


$$R_\gamma^{\text{exp}} \equiv \frac{\mathcal{B}(s+d)\gamma}{\mathcal{B}_{c\ell\nu}} = (3.22 \pm 0.15) \times 10^3,$$

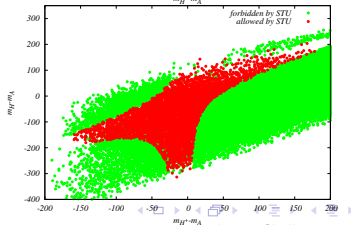
$$\Delta M_s (\text{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

$$(B_s \rightarrow \mu^+ \mu^-)^{\text{PDG}} = [3.01 \pm 0.35] \times 10^{-9}$$

Constraints on mass differences $m_{H^\pm} - m_H, m_{H^\pm} - m_A, m_A - m_H$



compare to THDM $\Rightarrow$



In this particular case: ...

- In a general scan [letting 10 parameters float]:

heavy scalar masses $\gtrsim 500 \text{ GeV}$

Consequence

- channels as e.g. HA only accessible for $\gtrsim 1 \text{ TeV}$
"partonic" center of mass energies

[statement different for other Yukawa structures]

LHC: Multi scalar production modes

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

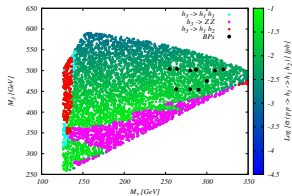
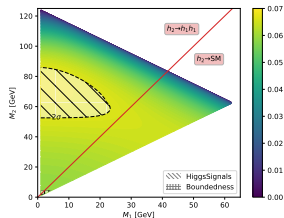
updates from arXiv:2305.08595 and HHH Workshop talk, 16.7.23]

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

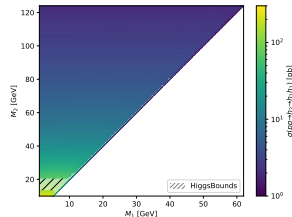
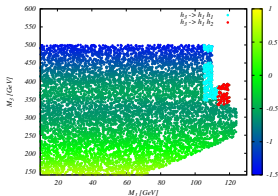
[1 mass always at 125 GeV, others free]

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

asymmetric,
triple h_1
(3.5/ 0.25 pb)



symmetric, no
 h_{125} involved
(2.5/ 60 pb)



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

BP3

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

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

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

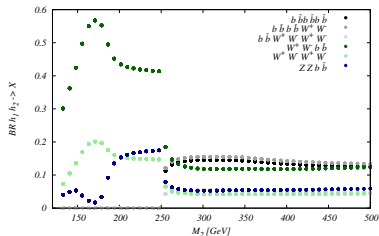
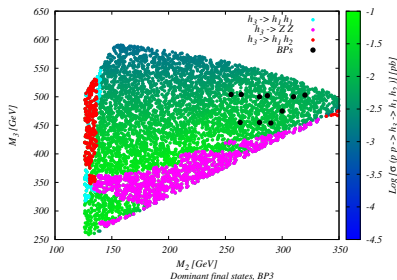
if $M_2 > 250$ GeV:

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

$\Rightarrow$ **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

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

- ⇒ **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]

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

$\Rightarrow$ at HL-LHC, all points within reach $\Leftarrow$

Another topic: finite width effects

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

- scenario: heavy resonance decaying to $h_{125} h_{125}$

[already partially discussed in Rev.Phys. 5 (2020) 100045 and references therein]

- scenario discussed here:

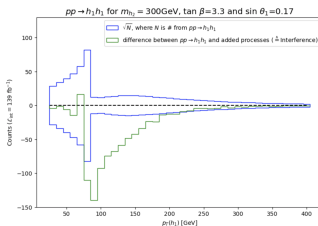
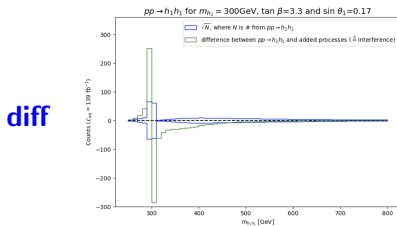
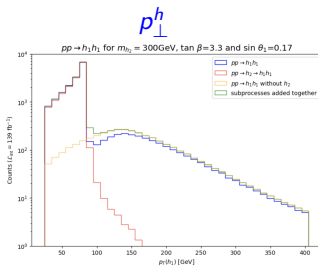
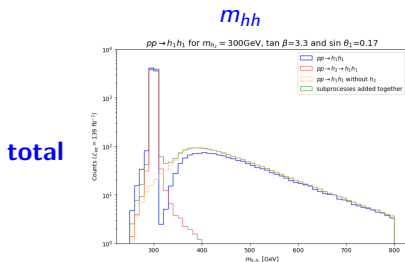
$$m_H = 300 \text{ GeV}; \sin \theta = 0.7; \tan \beta = 3.3$$

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

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

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

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



Extra scalars at Higgs factories ($e^+ e^-$ @ 240 - 250 GeV)

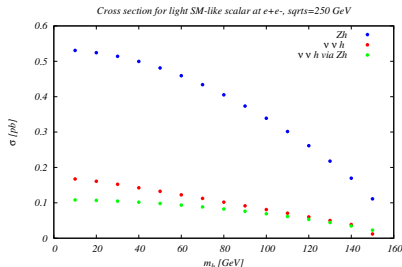
various production modes possible

- 1) **easiest example:** $e^+ e^- \rightarrow Z h_1$, onshell production
interesting up to $m_1 \sim 160$ 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, $\sum_i m_i \leq 250$ 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;

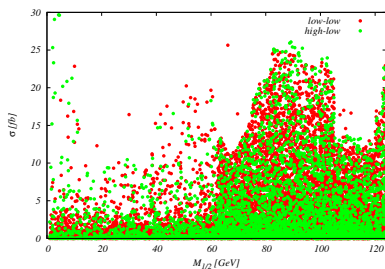
LO analytic expressions e.g. in Kilian et al, Phys.Lett.B 373 (1996) 135-140]

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

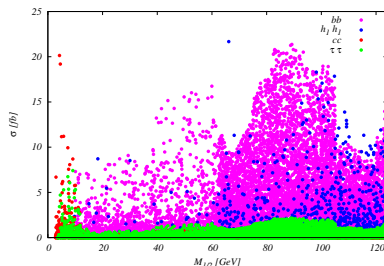
Singlet extensions

[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

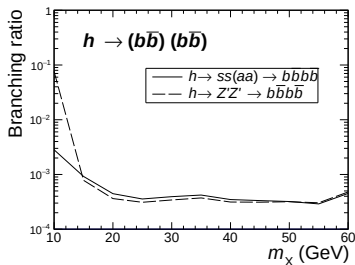
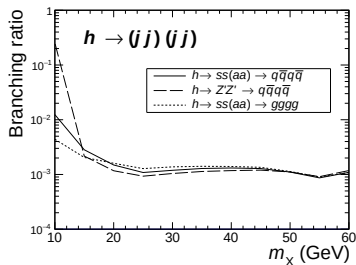


convoluted with decay rates

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

$h \rightarrow 4j/4b/4c$ final states, $Z h$ production

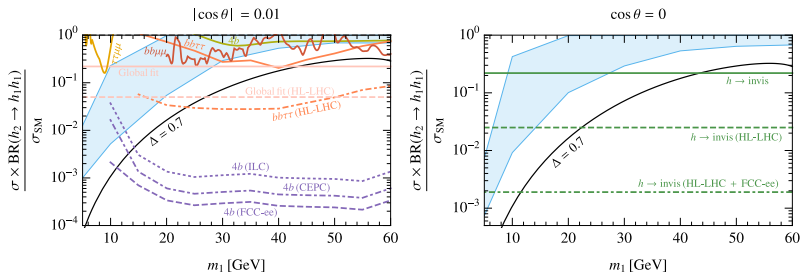
[Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys.C 41 (2017) 6, 063102]



95% CL bounds, $\sqrt{s} = 240$ GeV, $\int \mathcal{L} = 5 \text{ ab}^{-1}$

Singlet extension, with connection to strong first-order electroweak phase transition

[J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Phys.Rev.D 101 (2020) 11, 115035]



blue band = strong first-order electroweak phase transition

comment: **current constraints lead to prediction $\lesssim 10^{-1}$**

[invisible BR, signal strength, assumes SM-like decay to bs]

[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]

Tania Robens

Extended scalar sectors

Theory Challenges in the Precision Era

Ongoing ECFA study: Direct discovery potential at Higgs factories, Extra scalar subgroup [CERN e-group: ECFA-WHF-WG1-SRCH]

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 ϕ (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

Appendix

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)

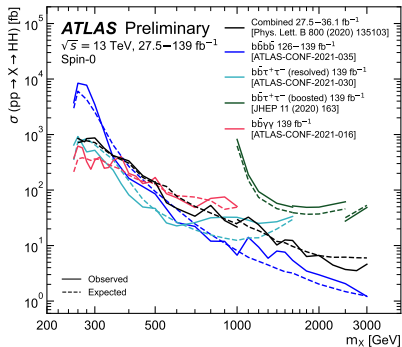
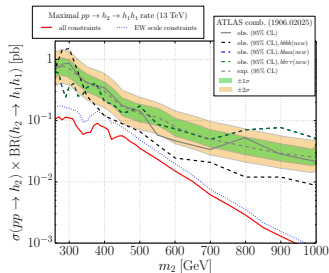
FCC-hh: 100 TeV, under discussion

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]



What about other extensions ?

- in principle: **no limit**

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

⇒ consequence: **will enhance particle content**

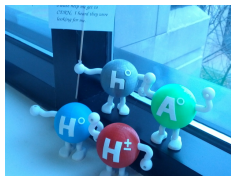
additional (pseudo)scalar neutral, additional charged, doubly charged, etc particles

- common feature:

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

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 ~ 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...
 $\Rightarrow$ **new scalar states** $\Leftarrow$



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, ...

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**
- ...

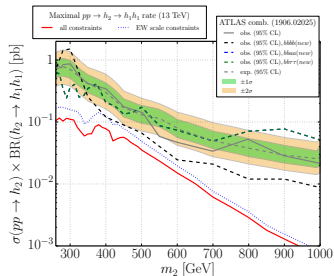
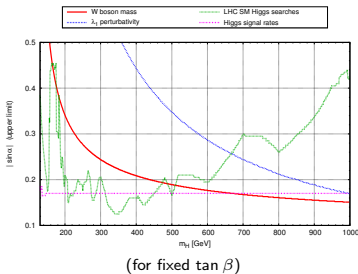
Examples for current constraints:

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]

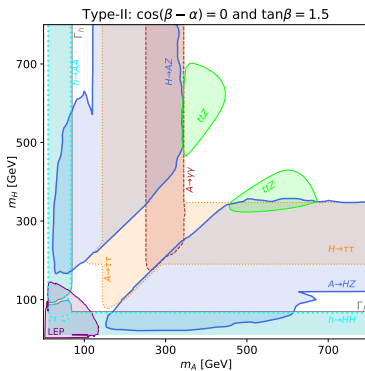
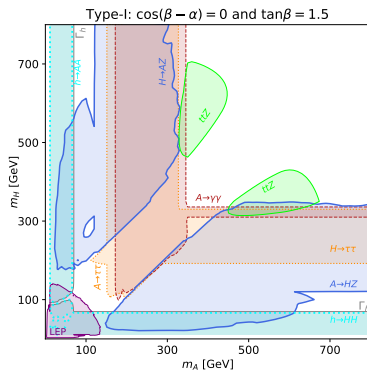


[update from Review in Physics (2020) 100045]

[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)]

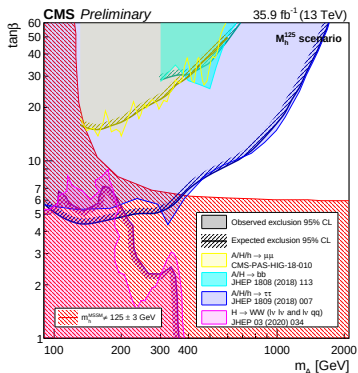
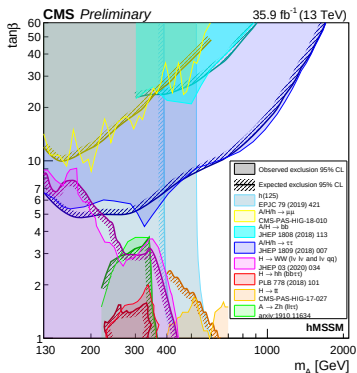
2HDM parameter space

[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



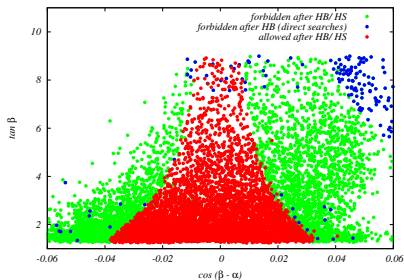
CMS MSSM summary plots, early Run II

[<https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG>]



Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



$\cos(\beta - \alpha) > 0.04$:

$h_{125} \rightarrow ZZ$

[CMS Run I, Phys. Rev. D

89 (2014) 092007]

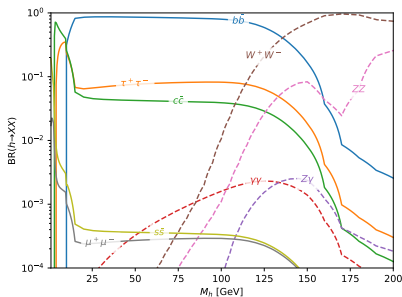
Relevant BSM searches:

$H/A \rightarrow \tau\tau$ [ATLAS Run II, Phys.Rev.Lett. 125 (2020) no.5, 051801],

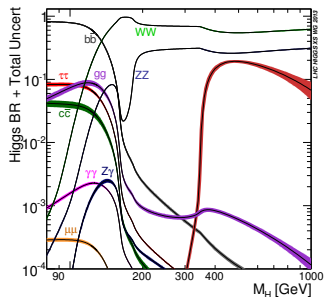
$H \rightarrow h_{125}h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

$A \rightarrow H/h_{125}Z$ [ATLAS 2018/ full Run 2 data, Phys.Lett. B783 (2018) 392-414, ATLAS-CONF-2020-043]

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



(using HDecay, courtesy J.Wittbrodt)



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

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 $(\Phi: SU(2)_L \text{ doublet}, S, X: SU(2)_L \text{ singlets})$

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

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

$$\begin{aligned} pp \rightarrow h_3 \rightarrow h_1 h_1; \quad & pp \rightarrow h_3 \rightarrow h_2 h_2; \\ pp \rightarrow h_2 \rightarrow h_1 h_1; \quad & pp \rightarrow h_3 \rightarrow h_1 h_2 \end{aligned}$$

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

$\Rightarrow$ **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: ~ 3 pb; h_1^3 final states: ~ 3 pb

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

SM-like decays for both scalars: ~ 0.6 pb

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

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

Testing the Higgs potential

- remember:

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

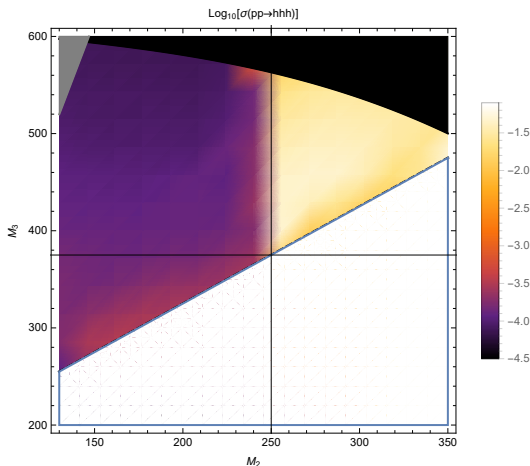
also predicts hhh and $hhhh$ interactions

- so far: only constraints

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

Start with resonance enhanced BSM scenarios for hhh

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



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

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/ ILC₂₅₀/ CLIC₃₈₀/ CEPC₂₄₀/ $C^3_{250} \sim 50\%$
- FCC-ee_{240/365}, ILC₅₀₀, $C^3_{550} \sim 20 - 27\%$
- ILC_{500-1000GeV}, CLIC_{3TeV} $\sim 8 - 11\%$
- 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]. $\text{CLIC}_{3\text{TeV}}$ [$-5; 7$]
- 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
Γ_{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]

- scenario: heavy resonance decaying to $h_{125} h_{125}$

[already partially discussed in Rev.Phys. 5 (2020) 100045 and references therein]

- scenario discussed here:

$$m_H = 600 \text{ GeV}; \sin \theta = 0.7; \tan \beta = 1.6$$

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

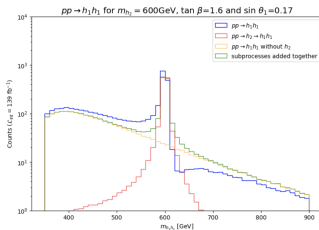
$$\sigma_{hh} = 26.746(7) \text{ fb}, \sigma_{\text{via}H} = 7.90(1) \text{ fb}, \sigma_{\text{no}H} = 15.11(1) \text{ fb}$$

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

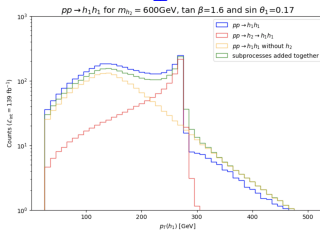
Results [13 TeV, $\int \mathcal{L} = 139 \text{ fb}^{-1}$]

total

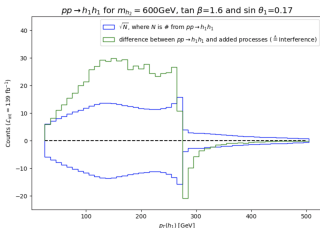
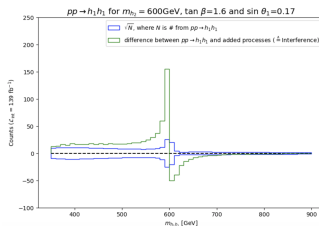
m_{hh}



$p_{\perp}^h$



diff

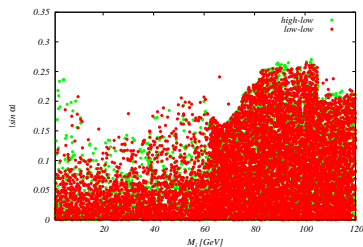


What about different collider reaches ?

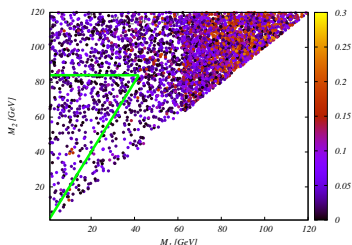
- **many different future colliders are discussed** [past- HL-LHC]
- current focus: **Higgs factories** (e^+e^- , $\sqrt{s} \sim 250$ GeV)
interesting: compare possible reach ?
- will do a _superficial_ comparison for a specific model
- of course more detailed studies called for

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