Extended scalar sectors
10+ years after the Higgs discovery

Tania Robens

Rudjer Boskovic Institute

Theory Challenges in the Precision Era
of the Large Hadron Collider

GGI, Florence
12.10.23

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)**

$\Longrightarrow$ **main test ground for this: particle colliders** $\Longleftarrow$

Special role of the scalar sector

- **Higgs potential in the SM**

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

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

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

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 possibilites: 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 containting 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**

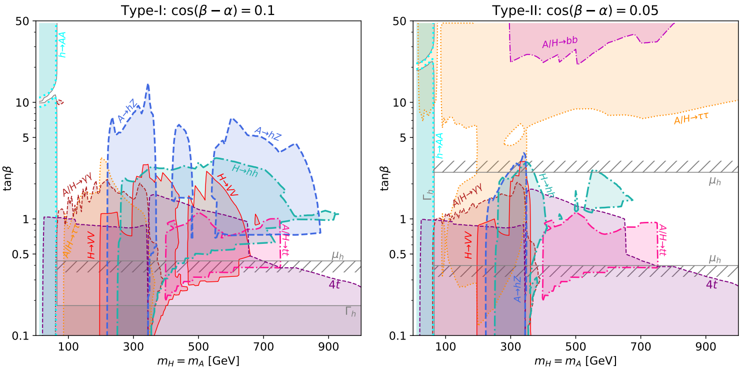
particle content: $\underbrace{h, H}_{\text{CP-even}}, \underbrace{A}_{\text{CP-odd}}, H^{\pm}$

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

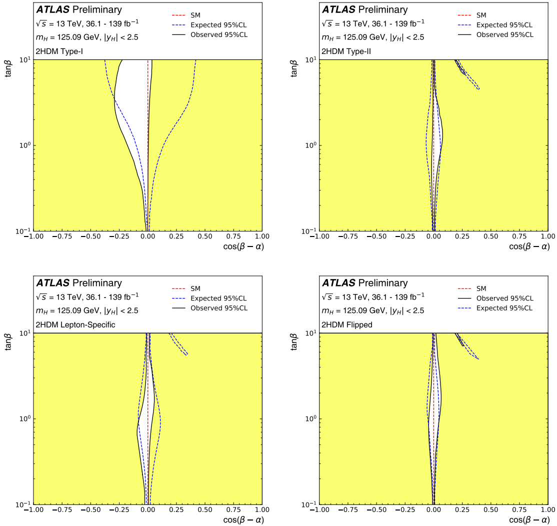
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



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

Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]



Recent search results...

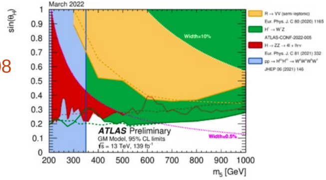
How are the experiments doing ?

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

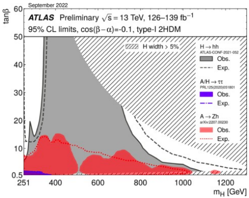
Recent ATLAS Extended Higgs results

- Overlay plots

ATL-PHYS-PUB-2022-008
(March 2022)
Georgi-Machacek

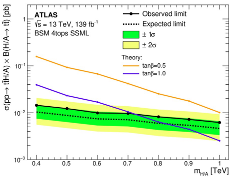


ATL-PHYS-PUB-2022-043
(Sept 2022) 2HDM

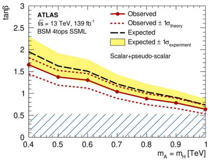


- ttA/H → tt

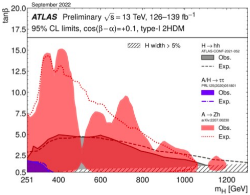
EXOT-2019-26



NEW



Type-II 2HDM

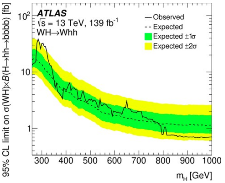


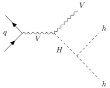
Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

LHC Higgs workshop – December 2022

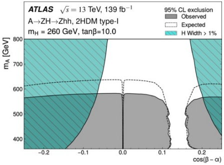
Recent ATLAS Extended Higgs results

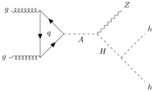
- ZH and WH production with H → hh





HDBS-2019-31 (October 2022)

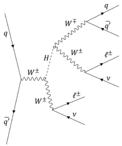


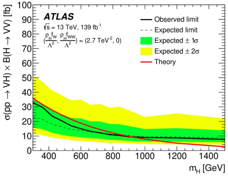


Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

- WH with H → WW **NEW**

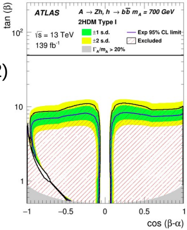
HDBS-2019-16





- A → Zh

HDBS-2020-19 (July 2022)



LHC Higgs workshop – December 2022

Recent CMS Extended Higgs Results

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

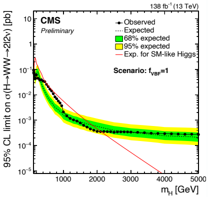
- **MSSM: ϕ(h/H/A) → ττ**
  - *Model independent limits for ggϕ and bbϕ (pseudo)scalars in 60-3500 GeV mass range*
  - *MSSM interpretations from a simultaneous fit of the 125 GeV plus another resonance*

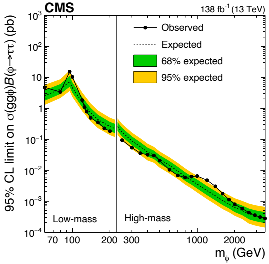
arXiv:2208.02717

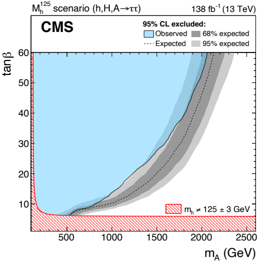
- **MSSM/2HDM: H → WW**

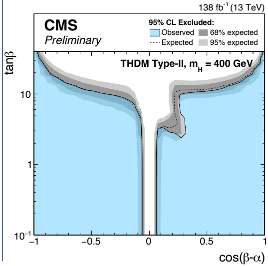
CMS-PAS-HIG-20-016

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









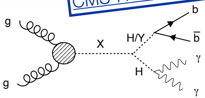
LHC Higgs Workshop – December 2022

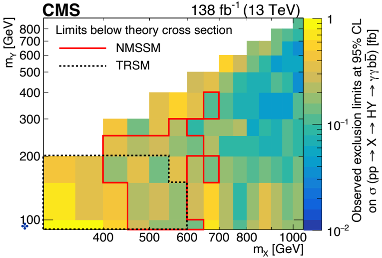
Recent CMS Extended Higgs Results

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

- **NMSSM, TRSM: X → YH → bbγγ**
  - *A new channel to complement the previous bbbb & bbττ results*

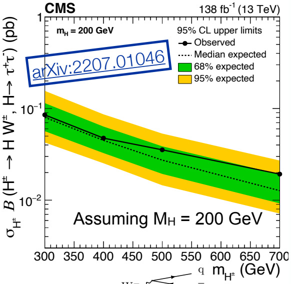
CMS-PAS-HIG-21-011

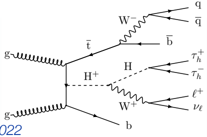




- TRSM benchmark values available here: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX

- **2HDM: H^+ → H(ττ)W^+**
  - *First LHC limits on H^+→HW^+*





LHC Higgs Workshop – December 2022

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**

$\Rightarrow$ **sets lower limit on charged mass**

$\Rightarrow$ **strongly correlated to other additional masses via electroweak precision measurements** (S, T, U)

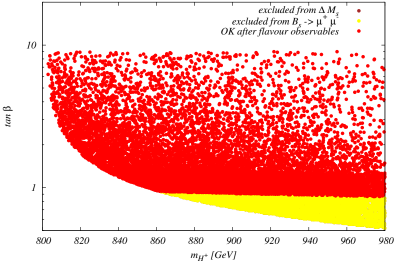
Lower mass bound on additional scalars

- 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 $B \to X_s\,\gamma$, $B_s \to \mu^+\,\mu^-$, ΔM_s

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



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

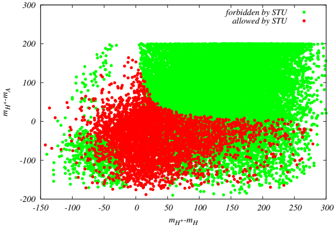
$$\Delta M_s\,(\text{ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

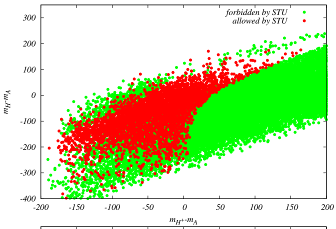
$$\left(B_s \to \mu^+\mu^-\right)^{\text{PDG}} = [3.01 \pm 0.35] \times 10^{-9}$$

Oblique parameters via SPheno, compare to GFitter [Eur. Phys. J., C78(8):675]

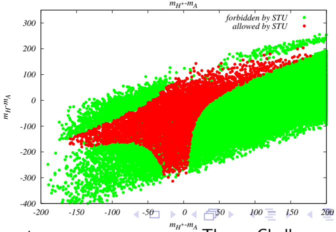
Constraints on mass differences

$$m_{H^\pm} - m_H,\ m_{H^\pm} - m_A,\ m_A - m_H$$





compare to THDM ⇒



In this particular case: ...

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

  heavy scalar masses $\gtrsim 500\,\mathrm{GeV}$

Consequence

- channels as e.g. $H\,A$ **only accessible for** $\gtrsim 1\,\mathrm{TeV}$ **"partonic" center of mass energies**

  [statement different for other Yukawa structures]

LHC: Multi scalar production modes

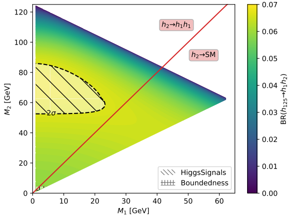
[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151;
updates from arXiv:2305.08595 and HHH Workshop talk, 16.7.23]

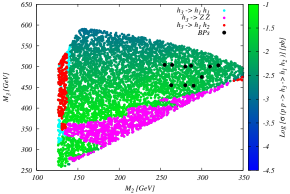
2 real singlet extension ⇒ 2 additional scalars ($M_1 \leq M_2 \leq M_3;\ M_i \in [0; 1\text{TeV}]$)
[1 mass always at 125 GeV, others free]

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

asymmetric, triple h_1

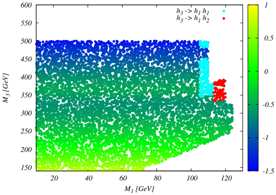
(3.5/ 0.25 pb)

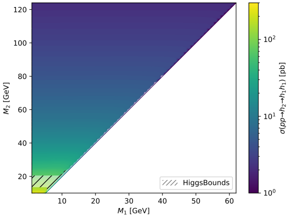




symmetric, no h_{125} involved

(2.5/ 60 pb)





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

BP3

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

$\mathrm{BR}(\mathrm{h}_3 \to \mathrm{h}_{125}\mathrm{h}_2)$ mostly $\sim 50\%$.

if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.

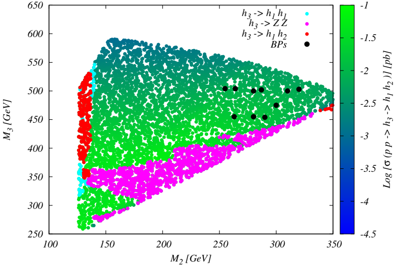
if $M_2 > 250\,\mathrm{GeV}$:

$\Rightarrow \mathrm{BR}(\mathrm{h}_2 \to \mathrm{h}_{125}\mathrm{h}_{125}) \sim 70\%$,

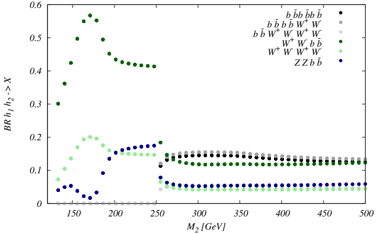
$\Rightarrow$ spectacular triple-Higgs signature

[up to 140 fb; maximal close to thresholds]

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



Dominant final states, BP3



bounds from $p\,p \to h_3 \to h_1\,h_2$ [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

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

$\Rightarrow$ **select points** on BP3 which might be **accessible at HL-LHC**

$\Rightarrow$ 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]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [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:

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

$$\Gamma_H \;=\; 0.54\mathrm{GeV},\ \mathrm{BR}_{H\to h\,h} \;=\; 0.55$$

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

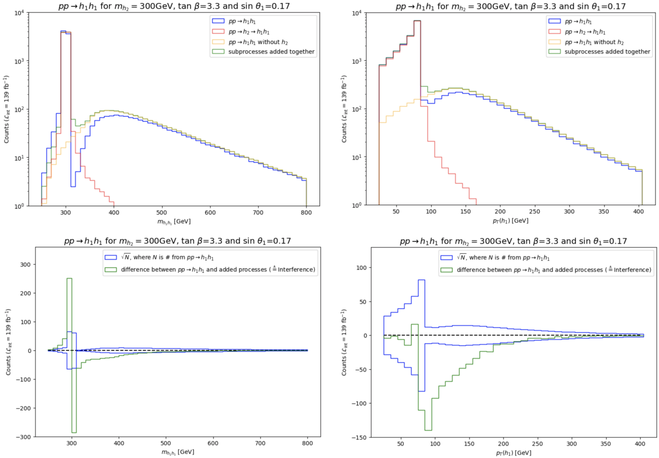
Interference: $\sigma_{hh} - \left(\sigma_{\mathbf{via}H} + \sigma_{\mathbf{no}H}\right)$ $[= -3.08(5)\,\mathrm{fb}]$

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

m_{hh} $\quad$ $p_\perp^h$

total

diff



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

various production modes possible

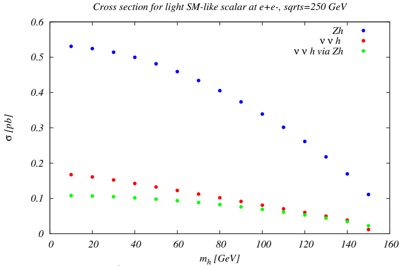
1) **easiest example:** $e^+ e^- \rightarrow Z\, h_1$, onshell production
   interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \rightarrow h_1\, h_2$
   (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

   again: for onshell production, $\sum_i m_i \leq 250\,\mathrm{GeV}$
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

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



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

LO analytic expressions e.g. in Kilian ea, 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**

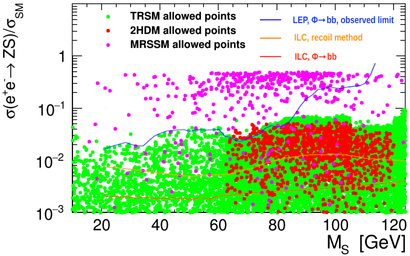
Possible model reach

[slide from A.F.Zarnecki, ECFA meeting 2023]

Previous studies

Light scalar production

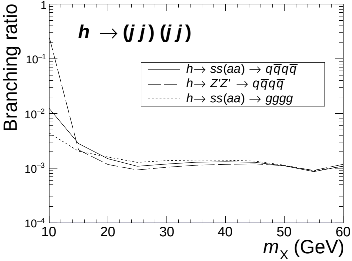
Estimated prospects for new scalar discovery in $S \to b\bar{b}$ decay channel (LEP projection)

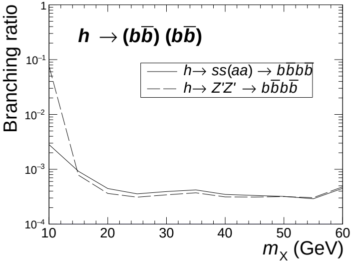


compared with presented benchmark point selections...

$h \to 4j/4b/4c$ final states, Zh production

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

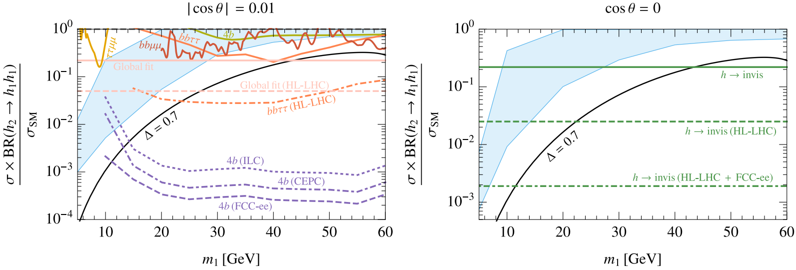




95% **CL bounds**, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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 *b*s]

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

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

  $$e^+e^- \to Z\,\phi$$

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

- light scalar production in 125 GeV Higgs boson decays

  $$h_{125} \to \phi\,\phi$$

  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.

A.F.Żarnecki (U. of Warsaw) EXscalar report June 27, 2023 6

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

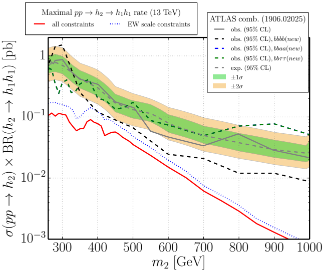
e^+e^- colliders: ILC/ CLIC/ FCC-ee, CePC

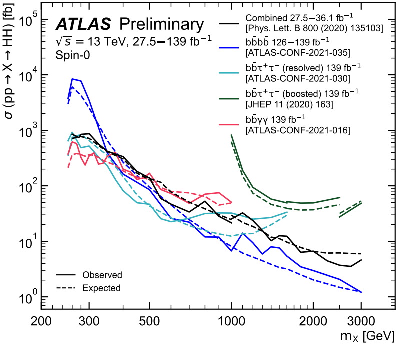
in plan, high priority in Europe, various center-of-mass energies discussed, priority $\sim 240-250\,\mathrm{GeV}$ "Higgs factories"

$\mu^+\mu^-$ colliders

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

ATLAS-PHYS-PUB-2021-031





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

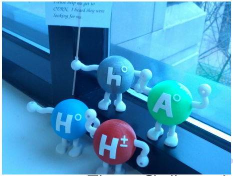
- common feature:

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** $\sim 125\,\mathrm{GeV}$
  - 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`, ...

Particle content

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

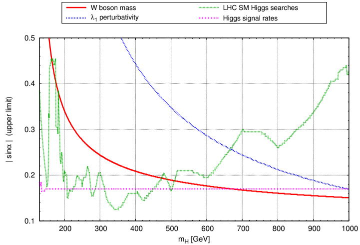
- e.g. 2 real scalars ⇒ **3 CP-even neutral scalars**
- 2HDM → **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

Examples for current constraints: Singlet extension, Z_2 symmetric: + 1 scalar particle

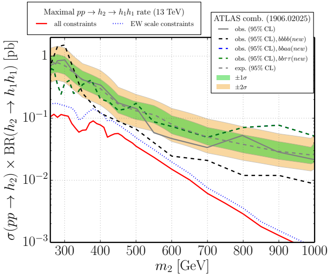
[TR, arXiv:2209.15544; updated using HiggsTools]

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

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



(for fixed $\tan\beta$)

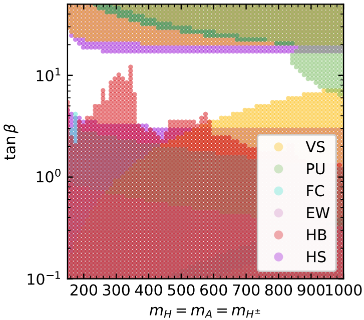


[update from Review in Physics (2020) 100045]

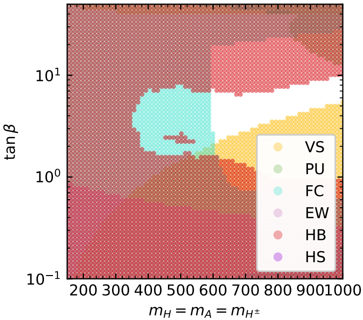
[see e.g. Pruna, TR, Phys. Rev. D 90, 114018;
(Bojarski, Chalons,) Lopez-Val, TR, Phys. Rev. D 90, 114018, JHEP 1602 (2016) 147;
(Ilnicka), TR, Stefaniak, EPJC (2015) 75:105, Eur.Phys.J. C76 (2016) no.5, 268, Mod.Phys.Lett. A33 (2018)]

2HDM parameter space, previous plots w all constraints

[thanks to K. Radychenko, tool presented in 2309.17431]



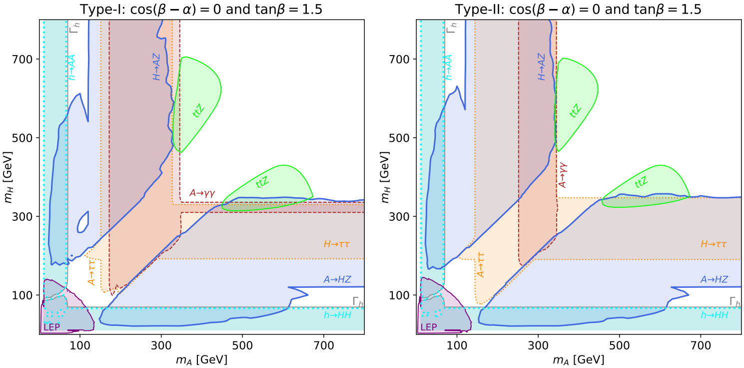
Type I, $\cos(\beta - \alpha) = 0.1$



Type II, $\cos(\beta - \alpha) = 0.05$

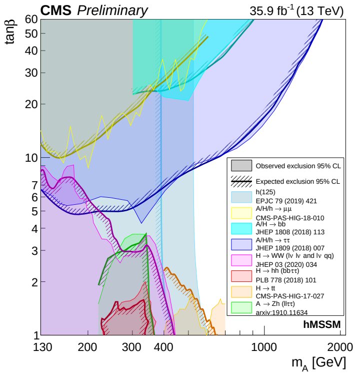
2HDM parameter space

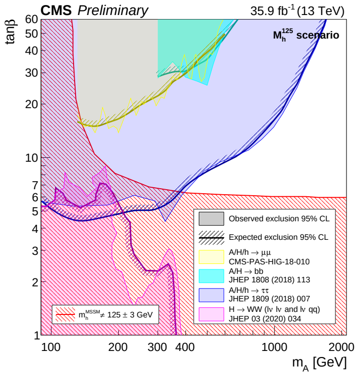
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



CMS MSSM summary plots, early Run II

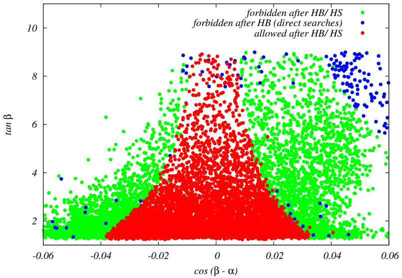
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG]





Direct searches and signal strength

Via HiggsBounds/ HiggsSignals



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

$h_{125} \rightarrow Z\,Z$

[CMS Run I, Phys. Rev. D 89 (2014) 092007]

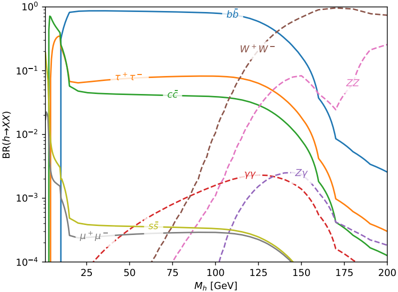
Relevant BSM searches:

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

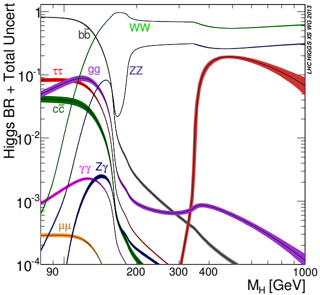
$H \rightarrow h_{125}h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

$A \rightarrow H/h_{125}Z$ [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 $M \neq 125\,\mathrm{GeV}$



(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 (Φ: $SU(2)_L$ 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

$$pp \to h_3 \to h_1\,h_1; \qquad pp \to h_3 \to h_2\,h_2;$$
$$pp \to h_2 \to h_1\,h_1; \qquad pp \to h_3 \to h_1\,h_2$$

$$h_2 \to \text{SM};\; h_2 \to h_1\,h_1;\; h_1 \to \text{SM}$$

$\Rightarrow$ **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]

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

Benchmark points/ planes [ASymmetric/ Symmetric]

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

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

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

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

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

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

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

up to 60 pb

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

up to 2.5 pb

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

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

Testing the Higgs potential

- remember:

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

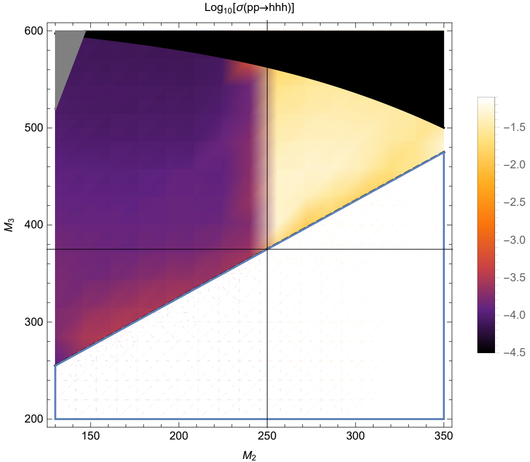
also predicts *hhh* and *hhhh* interactions

- so far: only constraints

$\Longrightarrow$ **future accessibility ?** $\Longleftarrow$

Start with resonance enhanced BSM scenarios for *hhh*

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



[using interpolation]

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

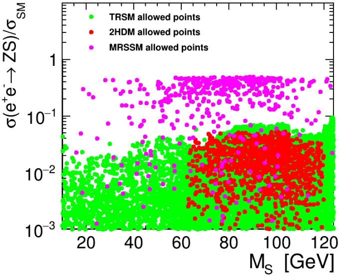
Possible model reach

[slide from A.F.Zarnecki, ECFA meeting 2023]

Motivation

Possible scenarios

Benchmark points consistent with current experimental and theoretical bounds



Two-Real-Singlet Model
thanks to Tania Robens
see arXiv:2209.10996 arXiv:2305.08595

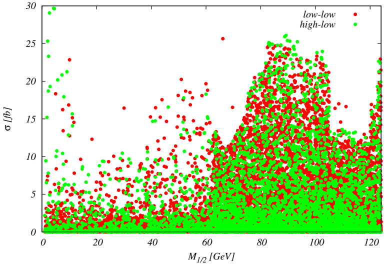
Two Higgs-Doublet Model
thanks to Kateryna Radchenko
thdmTool package, see arXiv:2309.17431

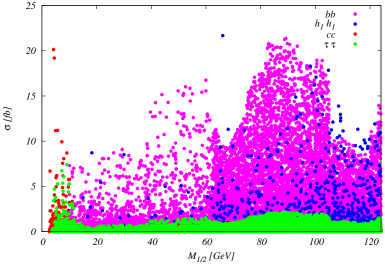
Minimal R-symmetric Supersymmetric SM
thanks to Wojciech Kotlarski arXiv:1511.09334

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

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_{250}/ $CLIC_{380}$/ $CEPC_{240}/C^3_{250}$ $\sim$ 50%
- FCC-$ee_{240/365}$, **ILC**$_{500}$, C^3_{550} $\sim 20-27\%$
- **ILC**$_{500-1000\text{GeV}}$, **CLIC**$_{3\text{TeV}}$ $\sim 8-11\%$
- **FCC-hh** $\sim 3.5-8\%$
- $\mu\mu_{30\text{TeV}}$ $\sim 2-3\%$

[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 $p\ p \to ZHHH + X$ and $p\ p \to WHHH + X$*, 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
$\text{BR}_{h_2\to h_1 h_1}$	0.5519	0.3396
$\Gamma_{\tilde{h}_2}$	20MeV	20MeV
	Cross Sections	
$pp \to h_1 h_1$	(69.858 ± 0.015)fb	(25.573 ± 0.101)fb
$pp \to h_2$	(106.47 ± 0.003)fb	(23.075 ± 0.0007)fb
$pp \to h_2 \to h_1 h_1$	(58.628 ± 0.002)fb	(7.8852 ± 0.0003)fb
$pp \to h_1 h_1 \backslash h_2$	(14.179 ± 0.0008)fb	(14.083 ± 0.0007)fb
$pp \to \tilde{h}_2 \to h_1 h_1$	(1588.6 ± 0.08)fb	(1951.2 ± 0.05)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:

$$m_H = 600\,\mathrm{GeV};\ \sin\theta = 0.7;\ \tan\beta = 1.6$$
$$\Gamma_H = 4.98\mathrm{GeV},\ \mathrm{BR}_{H\to h\,h} = 0.34$$
$$\sigma_{hh} = 26.746(7)\mathrm{fb},\ \sigma_{\mathrm{via}H} = 7.90(1)\mathrm{fb},\ \sigma_{\mathrm{no}H} = 15.11(1)\mathrm{fb}$$

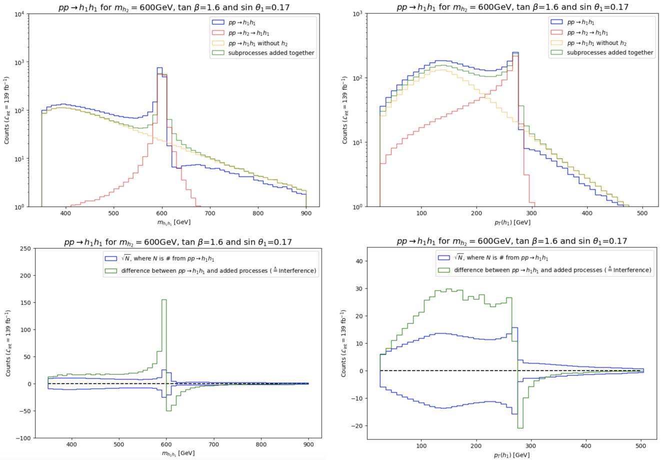
Interference: $\sigma_{hh} - (\sigma_{\mathbf{via}H} + \sigma_{\mathbf{no}H})$ [$= 3.74(2)$ fb]

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

m_{hh} $p_\perp^h$

total

diff

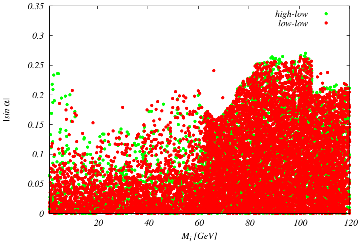


What about different collider reaches ?

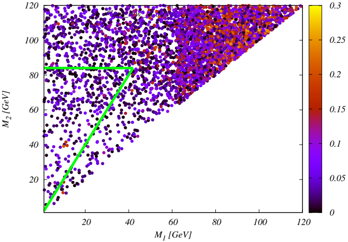
- **many different future colliders are discussed** [past- HL-LHC]
- current focus: **Higgs factories (e^+e^-, $\sqrt{s} \sim 250\,\text{GeV}$)**
  interesting: compare possible reach ?
- will do a _superficial_ comparison for a specific model
- of course more detailed studies called for

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