Extended scalar sectors
10 years after the Higgs discovery

Tania Robens

Rudjer Boskovic Institute/ CERN

Pushing the Limits of Theoretical Physics
MITP, Mainz
8.5.23

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**

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

$\Rightarrow$ **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 $SU(2) \times U(1)$

$\Rightarrow$ **everything determined in terms of gauge couplings, v, and λ**

form of potential determines minimum,
electroweak vacuum structure

$\Rightarrow$ stability of the Universe, electroweak phase transition, etc

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

$\Rightarrow$ **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

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**
- ...

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**

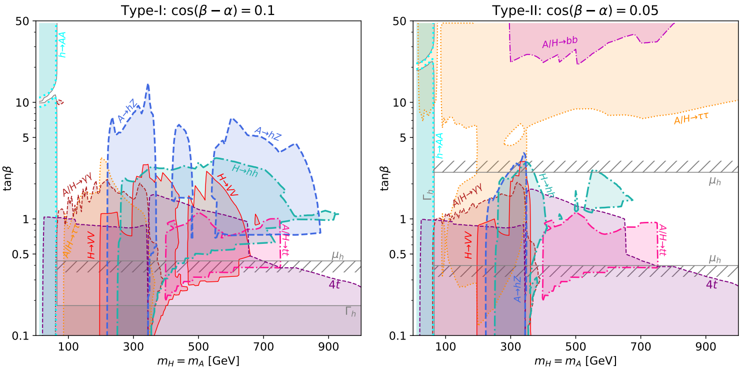
> **particle content:** $\underbrace{h,\, H}_{\text{CP-even}}\,,\ \underbrace{A}_{\text{CP-odd}}\,,\ H^{\pm}$

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

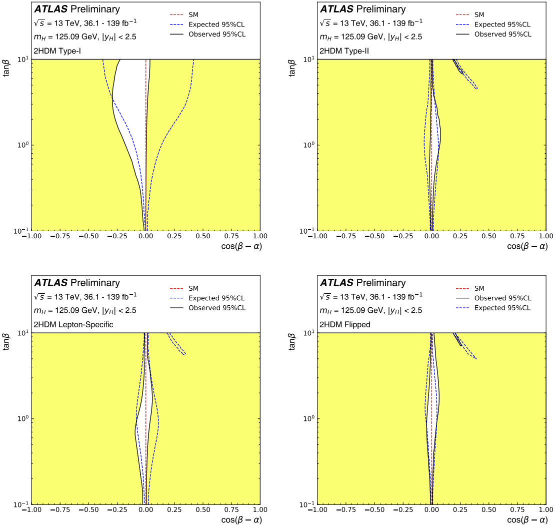
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



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

Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]



Recent search results...

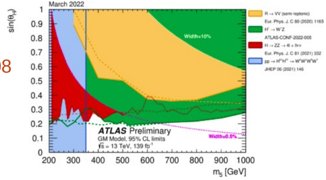
How are the experiments doing ?

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

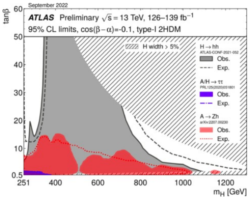
Recent ATLAS Extended Higgs results

- Overlay plots

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

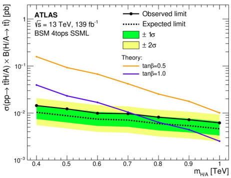


ATL-PHYS-PUB-2022-043
(Sept 2022) 2HDM

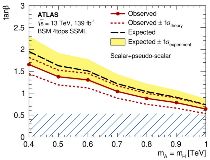


- ttA/H → tt

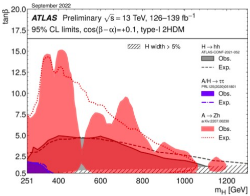
EXOT-2019-26



NEW



Type-II 2HDM



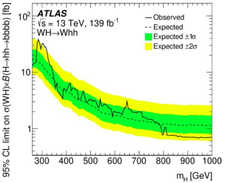
Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

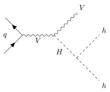
LHC Higgs workshop – December 2022

1

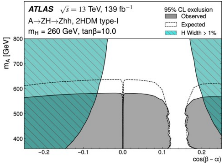
Recent ATLAS Extended Higgs results

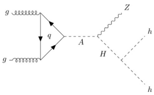
- ZH and WH production with H → hh





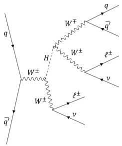
HDBS-2019-31 (October 2022)

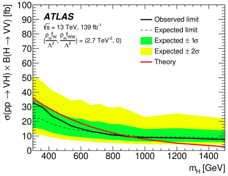




- WH with H → WW **NEW**

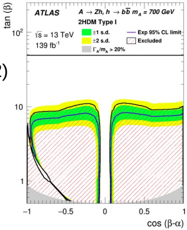
HDBS-2019-16





- A → Zh

HDBS-2020-19 (July 2022)



Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

LHC Higgs workshop – December 2022

Recent CMS Extended Higgs Results

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

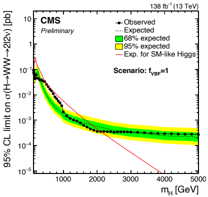
- **MSSM: φ(h/H/A) → ττ**
  - *Model independent limits for ggφ and bbφ (pseudo)scalars in 60-3500 GeV mass range*
  - *MSSM interpretations from a simultaneous fit of the 125 GeV plus another resonance*

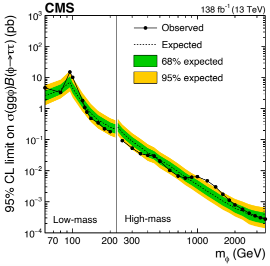
arXiv:2208.02717

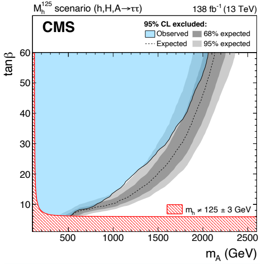
- **MSSM/2HDM: H → WW**

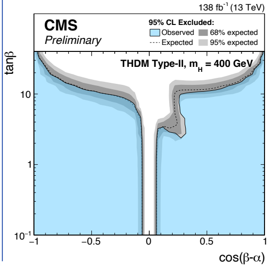
CMS-PAS-HIG-20-016

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









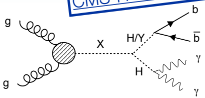
LHC Higgs Workshop – December 2022

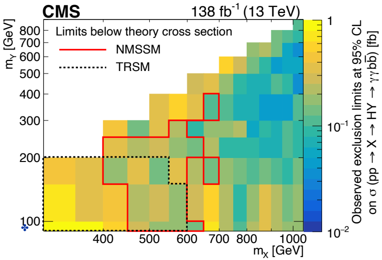
Recent CMS Extended Higgs Results

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

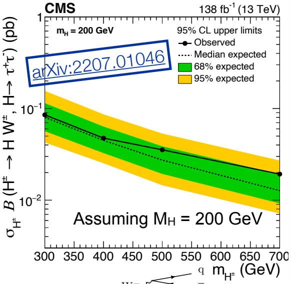


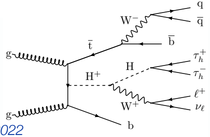


- TRSM benchmark values available here: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX

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

arXiv:2207.01046





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**

⇒ **sets lower limit on charged mass**

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

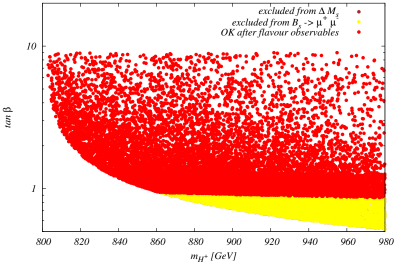
Lower mass bound on additional scalars

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



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

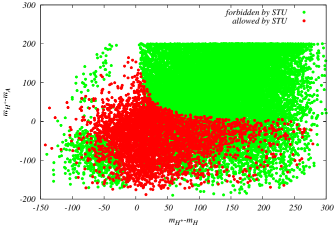
$$\Delta M_s \,({\rm ps}^{-1}) = 17.757 \pm 0.020 \pm 0.007,$$

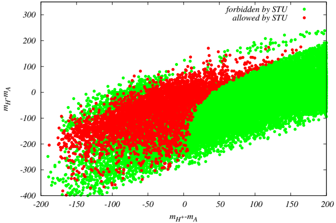
$$\left(B_s \to \mu^+\mu^-\right)^{\rm PDG} = [3.01 \pm 0.35] \times 10^{-9}$$

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

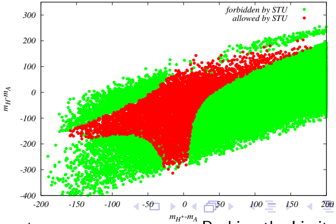
Constraints on mass differences

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





compare to THDM ⇒



In this particular case: ...

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

heavy scalar masses $\gtrsim$ 500 GeV

Consequence

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

[statement different for other Yukawa structures]

Testing the Higgs potential

- remember:

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

also predicts *hhh* and *hhhh* interactions

- so far: only constraints

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

Start with resonance enhanced BSM scenarios for *hhh*

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

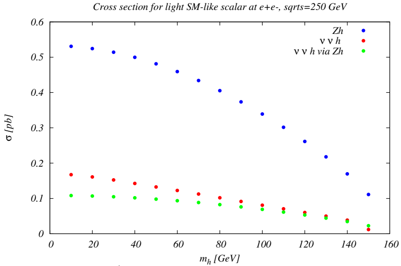
(M_2, M_3) [GeV]	$\sigma(pp \to h_1 h_1 h_1)$ [fb]	$\sigma(pp \to 3b\bar{b})$ [fb]	$\text{sig}\|_{300\text{fb}^{-1}}$	$\text{sig}\|_{3000\text{fb}^{-1}}$
$(255, 504)$	32.40	6.40	2.92	9.23
$(263, 455)$	50.36	9.95	4.78	15.11
$(287, 502)$	39.61	7.82	4.01	12.68
$(290, 454)$	49.00	9.68	5.02	15.86
$(320, 503)$	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 $\Leftarrow$

What about Higgs factories ?

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



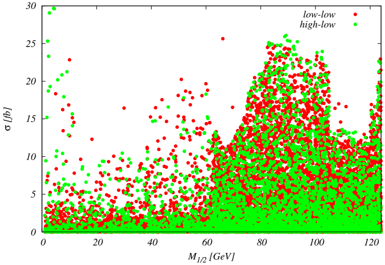
[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;

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

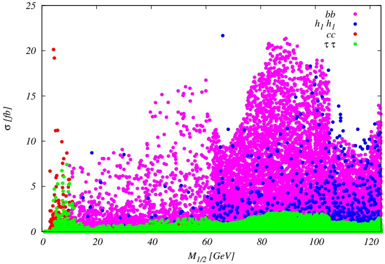
- rule of thumb: **rescaling** $\lesssim 0.1$
- $\Rightarrow$ maximal production **cross sections around 50 fb**
- $\sim 10^5$ **events using full luminosity**

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]



cross sections at 250 GeV

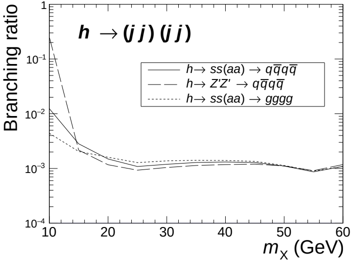


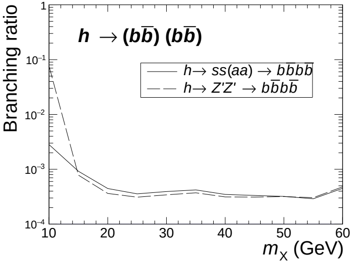
convoluted with decay rates

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

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

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

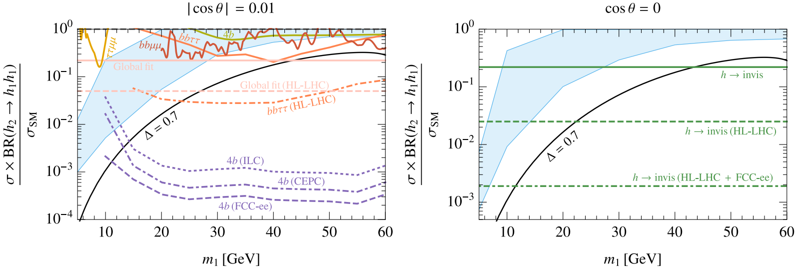




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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)]

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**

Many things to do

Commercial...


HHH workshop
14-16th of July 2023 Dubrovnik / Croatia
Organising committee
Vuko Brigljević, Ruđer Bošković Institute
Dinko Ferenček, Ruđer Bošković Institute
Greg Landsberg, Brown University
Tania Robens, Ruđer Bošković Institute
Marko Stamenkovic, Brown University
Tatjana Šuša, Ruđer Bošković Institute
https://indico.cern.ch/e/hhh2023

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

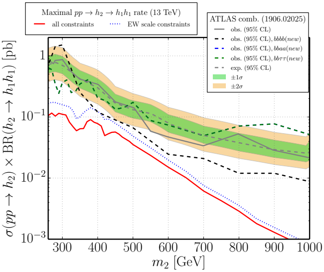
e^+e^- colliders: ILC/ CLIC/ FCC-ee, CePC

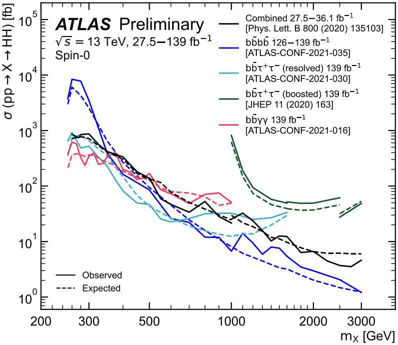
in plan, high priority in Europe, various center-of-mass energies discussed, priority $\sim 240-250\,\mathrm{GeV}$ "Higgs factories"

$\mu^+\mu^-$ colliders

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

ATLAS-PHYS-PUB-2021-031





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}

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

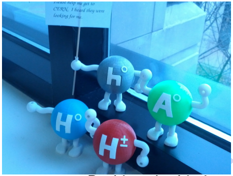
- common feature:

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 ⇒ next slides highly selective...

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

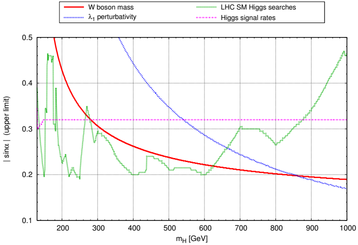
tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

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

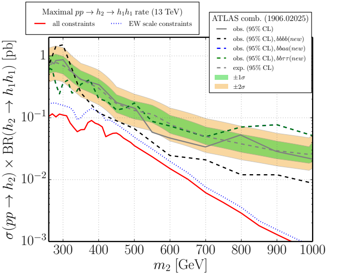
[TR, arXiv:2209.15544; updated using HiggsTools]

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

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



(for fixed $\tan\beta$)

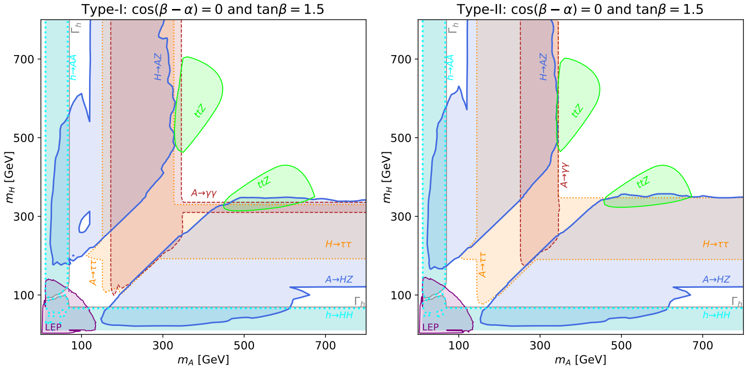


[update from Review in Physics (2020) 100045]

[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)]

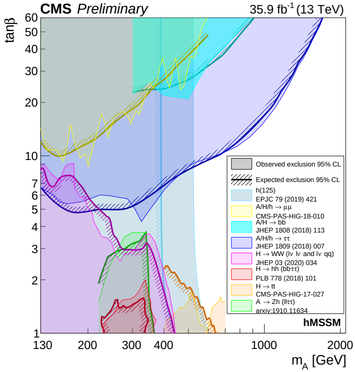
2HDM parameter space

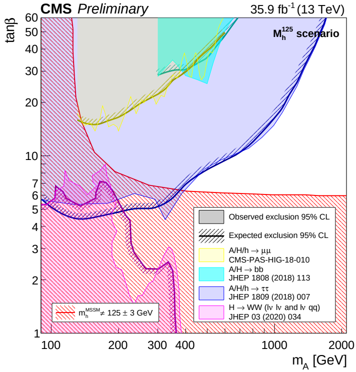
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



CMS MSSM summary plots, early Run II

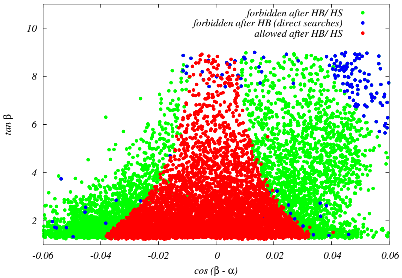
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG]





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]

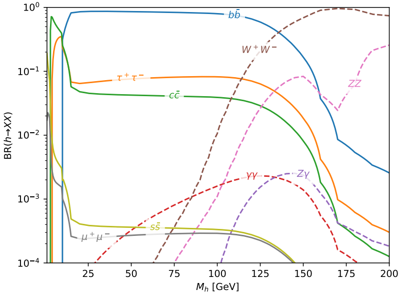
Relevant BSM searches:

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

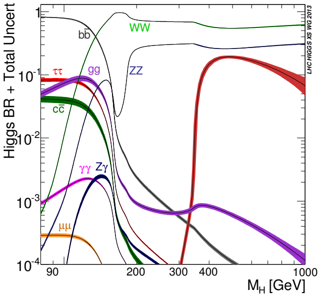
$H \rightarrow h_{125}h_{125}$ [ATLAS 2018 data, JHEP 1901 (2019) 030],

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



(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*.

[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

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**

LHC: Multi scalar production modes

[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151; updates from Moriond QCD talk 29.3.23]

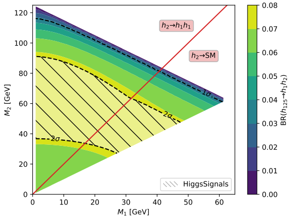
2 real singlet extension $\Rightarrow$ 2 additional scalars $(M_1 \leq M_2 \leq M_3;\; M_i \in [0; 1\,\mathrm{TeV}])$

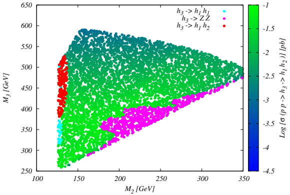
[1 mass always at 125 GeV, others free]

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

asymmetric, triple h_1

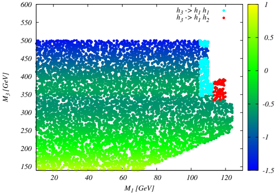
(3.5/ 0.25 pb)

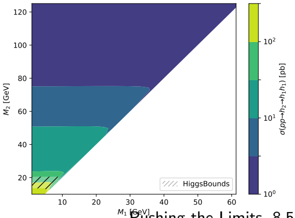




symmetric, no h_{125} involved

(2.5/ 60 pb)





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

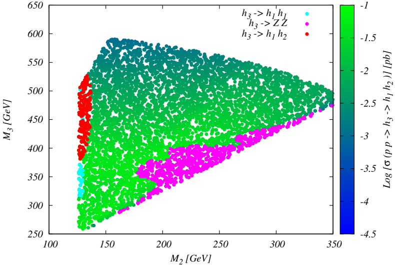
BP3

$\sigma(pp \to h_3) \simeq 0.06 \cdot \sigma(pp \to h_{SM})|_{m=M_3}$
$\mathrm{BR}(h_3 \to h_{125} h_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \to$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(h_2 \to h_{125} h_{125}) \sim 70\%$,

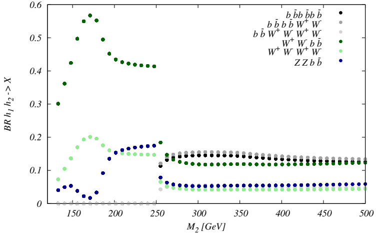
$\Rightarrow$ spectacular triple-Higgs signature

[up to 140 fb; maximal close to thresholds]

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

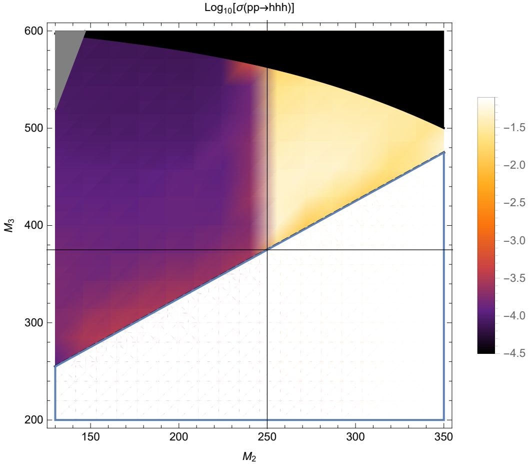


Dominant final states, BP3



bounds from $p\,p \to h_3 \to h_1\,h_2$ [CMS, Run II, JHEP 11 (2021) 057]

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



[using interpolation]

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

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/ 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 4b2γ 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) $[0.7; 1.5]$

What about different collider reaches ?

- **many different future colliders are discussed** [past- HL-LHC]
- current focus: **Higgs factories (e^+e^-, $\sqrt{s} \sim 250\,\mathrm{GeV}$)**

  interesting: compare possible reach ?
- will do a _superficial_ comparison for a specific model
- of course more detailed studies called for

Typical processes at Higgs factories

various production modes possible

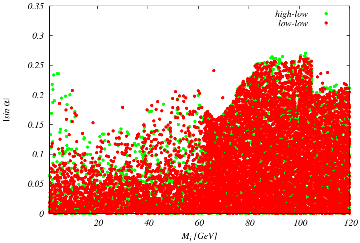
1) **easiest example:** $e^+ e^- \rightarrow Z\, h_1$, onshell production
   interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \rightarrow h_1\, h_2$
   (e.g. from 2HDMs); example processes and bounds from LEP
   in Eur.Phys.J.C 47 (2006) 547-587

   again: for onshell production, $\sum_i m_i \leq 250\,\mathrm{GeV}$
3) another (final) option: **look at** $e^+ e^- \rightarrow h_i\, Z,\; h_i \rightarrow h_j\, h_k$

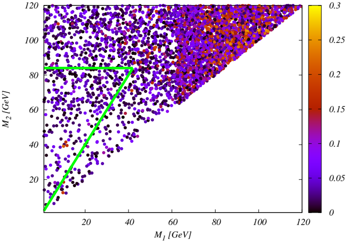
already quite a few studies for 1), 3) available

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