Extended scalar sectors
- Focus on singlet extensions -

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After Higgs discovery: Open questions

Higgs discovery in 2012 ⇒ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  ⇒ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  ⇒ 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)**

⟹ main test ground for this: particle colliders ⟸

Special role of the scalar sector

- **Higgs potential in the SM**

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

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

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

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

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

for coupling g to vector bosons

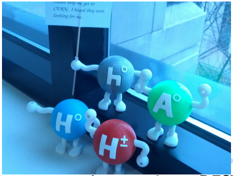
- many scenarios ⇒ **signal strength poses strong constraints**

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

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** $\sim 125\,\text{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - can **push vacuum breakdown to higher scales**
  - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
  - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...

  ⇒ **new scalar states** ⇐



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}

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]

Very often: simple singlet extension

- rule of thumb: **if you want to understand something complicated, start with an easy model**
- simplest scenario for BSM scalars: **Higgs singlet extension**

$\Rightarrow$ **add an additional scalar field that transforms as a singlet under SM gauge group**

- can add additional symmetry: **very few free parameters**
- simplest case:

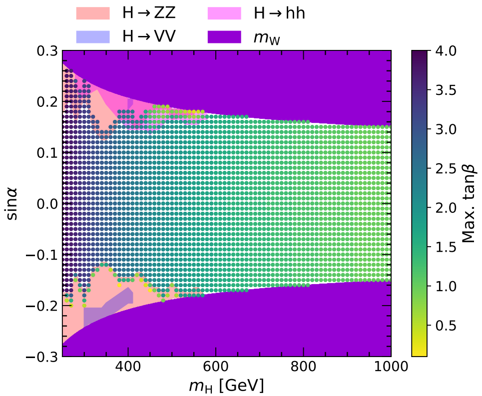
$$\mathbf{m_H},\ \sin\alpha,\ \tan\beta$$

- $\sin\alpha$: mixing angle relating gauge and mass eigenstates; $\tan\beta$**:** ratio of vevs, can be replaced by Γ_H, $\Gamma_{H\rightarrow hh}$, ...

Model subject to many constraints...

- many theoretical/ experimental constraints
- thorough description: see e.g. TR, T. Stefaniak, Eur.Phys.J.C 75 (2015) 104, Eur.Phys.J.C 76 (2016) 5, 268

[more recent update in F. Feuerstake, E. Fuchs, TR, D. Winterbottom, arXiv:2409.06651]



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

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

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

⇒ 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: $\sim 3\,\mathrm{pb}$; h_1^3 final states: $\sim 3\mathrm{pb}$

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

SM-like decays for both scalars: $\sim 0.6\,\mathrm{pb}$

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

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

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 $2.5\,\mathrm{pb}$

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

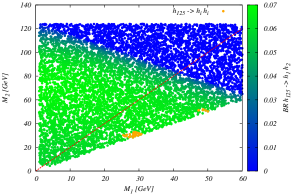
[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151;
updates from arXiv:2305.08595, HHH Workshop talk, 16.7.23, for Catch22+2 Dublin, 05/24, and for this workshop]

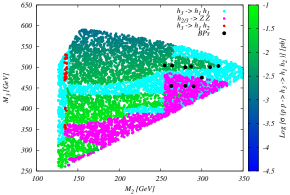
2 real singlet extension ⇒ 2 additional scalars $(M_1 \leq M_2 \leq M_3;\; M_i \in [0; 1\text{TeV}])$
[1 mass always at 125 GeV, others free]

new plots: **updates from paper with full Run II results**
[Eur.Phys.J.C 84 (2024) 5, 493, $b\,\bar{b}\tau^+\tau^-$ and $b\,\bar{b}\mu^+\mu^-$ final states] [JHEP 07 (2023) 040, $b\,\bar{b}\tau^+\tau^-$]

asymmetric, triple h_1

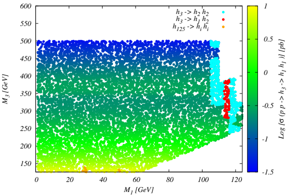
(3.5/ 0.25 pb)

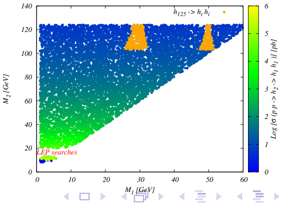




symmetric, no h_{125} involved

(2.5/ 60 pb)





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

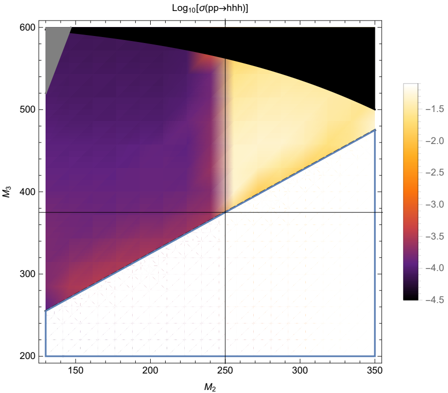
$$p\,p \rightarrow h_3 \rightarrow h_2\,h_1 \rightarrow h_1\,h_1\,h_1 \rightarrow b\,\bar{b}\,b\,\bar{b}\,b\,\bar{b}$$

⇒ **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]

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



[using interpolation]

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

This plane was investigated in first experimental *hhh* search !! ATLAS, Run 2, arXiv:2411.02040

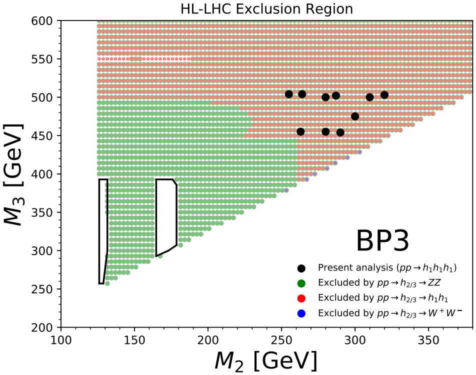
Benchmark points and results

(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, still viable

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

What about other channels ?



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

⇒ model can be tested from various angles ⇐

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

Another important topic: finite width effects

- Experiments: often use factorized approach:

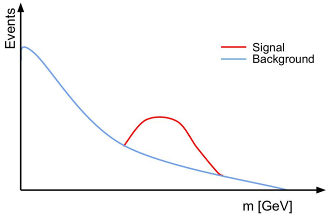
$$p\,p \to X,\; X \to Y\,Z$$

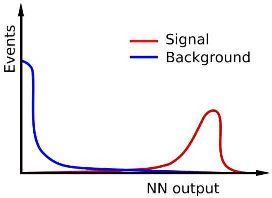
- quantum mechanics: **only stable particles are defined in S-matrix elements**, everything else approximation
- in reality: **case by case study**
- **wrong: assume factorization always works**

From a recent overview talk at Higgs 2024...

Search strategy

- Most analyses are designed to perform (quasi) **model-independent searches for a bump in a smoothly falling mass spectrum**
  - Perform maximum likelihood fit to **set upper limits** on production cross section and/or branching fraction
  - Interpretation in a large variety of different models





- For complicated final states, train neural networks (NNs) or boosted decision trees (BDTs) to separate signal from backgrounds
  - Probe BDT/NN response distribution

4

(slide from D. Duda, "Search for new high-mass scalars at the LHC", Higgs 2024)

Is this really what we will see ??

Width from the theory prespective - a mini-introduction

Introduction of width

- **S-matrix: complex quantity;**
  at leading order, **poles can appear for $p^2 = M^2$**

  artefact of finite order calculation

- solution: **resummation of self-energy contributions near resonance** $\Rightarrow$ leads to modification $\frac{1}{p^2 - M^2 + \Sigma_R(p^2)}$
- **$\Sigma_R(M^2)$ related to total width Γ via optical theorem**

  $$\text{Im}\Sigma_R = M\,\Gamma$$

  with $\Gamma = \sum_i \Gamma_i$, i denoting partial widths
- **leads to form** $\sim \frac{1}{p^2 - M^2 + i\,M\,\Gamma}$ [Breit-Wigner]

still many open issues, in particular gauge dependence $\Rightarrow$ several solutions exist, important for electroweak precision measurements

Narrow width approximation

[see e.g. also Nucl.Phys.B 814 (2009) 195-211; Diploma thesis C. Uhlemann, Wuerzburg, '07]

- in the limit $\Gamma \to 0$:

$$\frac{1}{|p^2 - M^2 + i\,M\,\Gamma|^2} \to \frac{\pi}{M\,\Gamma}\,\delta\left(p^2 - M^2\right)$$

$\Rightarrow$ leads to **factorized approach:**

$$\sigma_{ab \to c \to d\,e} \to \sigma_{ab \to c} \times \underbrace{\frac{\Gamma_{c \to d\,e}}{\Gamma}}_{\mathrm{BR}_{c \to d\,e}}$$

- formal error: $\mathcal{O}\left(\frac{\Gamma}{M}\right)$

factorized approach

- even QM says: **should really consider**

$$\mathcal{M}_{ab \to de}$$

with all contributions, and interferences

Interference effects

- matrix element $\mathcal{M}$ for process **going through s-channel resonance** as well as other diagrams:

$$\mathcal{M}_{\text{tot}} = \mathcal{M}_{\mathbf{S}} + \mathcal{M}_{\text{rest}}$$

- **squared ME** going into phase space integration:

$$|\mathcal{M}_{\text{tot}}|^2 = |\mathcal{M}_{\mathbf{S}}|^2 + |\mathcal{M}_{\text{rest}}|^2 + \underbrace{2\,\text{Re}\left[\mathcal{M}_S\,\mathcal{M}^*_{\text{rest}}\right]}_{\text{Interference}}$$

- **resonance: first term dominant**
  ⇒ this is what goes into NWA
- factorized approach:

assume $|\mathcal{M}_S|^2$ is dominant,
and in addition that NWA holds

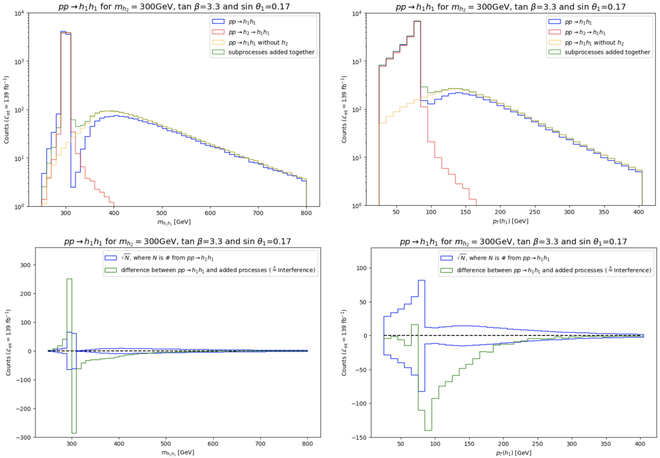
Results for specific point $[13\,\mathrm{TeV},\ \int\mathcal{L} = 139\,\mathrm{fb}^{-1}]$

[in collaboration with F. Feuerstake, E. Fuchs, D. Winterbottom, arXiv:2409.06651]

m_{hh} $p_\perp^h$

total

diff



- **studied several benchmark points in detail**
- they are **defined via distinct features** that could or could not have an impact (for time reasons, can only show 2 !)

Benchmark	$\sin\alpha$	$\tan\beta$	m_H [GeV]	Γ_H [GeV]	$\kappa_{\lambda_{hhh}}$	σ [fb]	$\sigma_{\text{S}_\text{H}}$ [fb]	Accessible in Run-3	Feature
BM1	0.16	1.0	620	4.6	0.96	50.5	13.5	✓	Max $(\Delta\sigma)_{\text{rel}}$
BM2	0.16	0.5	440	1.5	0.96	91.6	56.4	✓	Max $(\Delta\sigma)_{\text{rel}}^{\sum}$
BM3	0.16	0.5	380	0.8	0.96	119.8	90.1	✓	Max $(\Delta\sigma)_{\text{rel}}^{\sum}$ with $(\Delta\sigma)_{\text{rel}} < 1\%$
BM4	-0.16	0.5	560	3.0	0.96	51.4	15.5	✓	Max non-res. within $m_H \pm 10\%$
BM5	0.08	0.5	500	0.6	0.99	40.6	8.1		Max non-res. within $m_H \pm 10\%$
BM6	0.16	1.0	680	6.1	0.96	44.8	8.4	✓	Max m_H
BM7	0.15	1.1	870	9.5	0.96	36.8	2.3		Max m_H
BM8	0.24	3.5	260	0.6	0.87	374.2	357.3	✓	Max $\lvert\kappa_{\lambda_{hhh}} - 1\rvert$
BM9	0.16	1.0	800	9.8	0.96	38.9	3.6		Max $\frac{\Gamma_H}{m_H}$

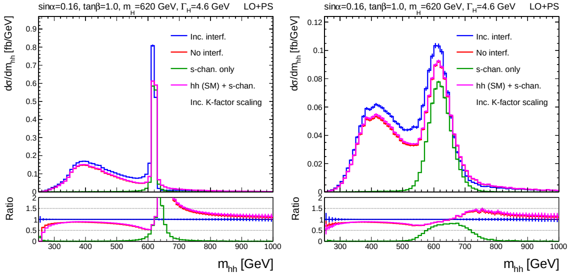
additional quantities:

$(\Delta\sigma)_{\text{rel}}^{\sum}$: often positive/ negative feature before/ after mass peak

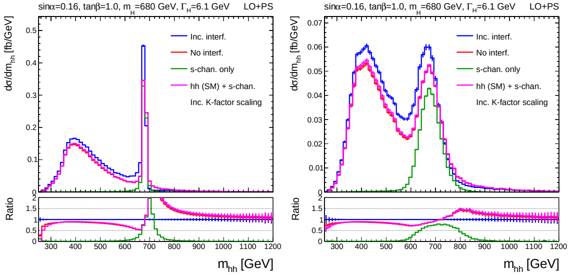
$\Rightarrow$ **sum of absolute values of interferences before and after**

correct,
no interference,
SM+NP,
NP only

left:
before smearing
right:
after smearing



BM 1, IF effects around 12%



BM 6, IF effects around 12%

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

various production modes possible

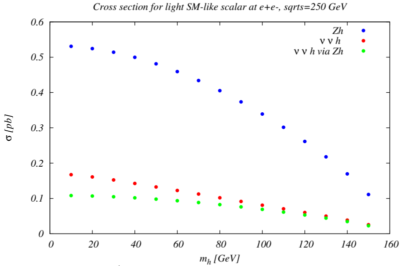
1) **easiest example:** $e^+ e^- \to Z h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \to h_1 h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

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

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

Scalar strahlung for additional light scalars

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



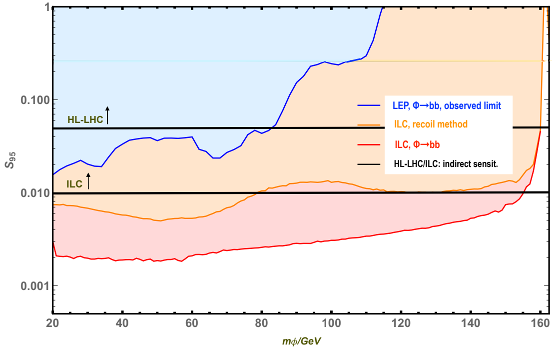
[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;

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**

Projections for additional scalar searches

[P. Drechsel, G. Moortgat-Pick, G. Weiglein, Eur.Phys.J.C 80 (2020) 10, 922]

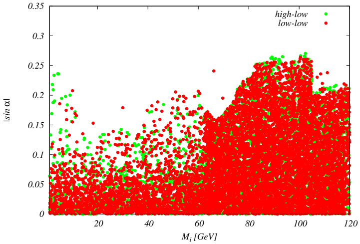


estimate of ILC sensitivity based on validation using LEP results

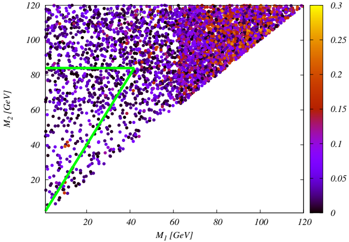
ILC: $\sqrt{s} = 250\,\mathrm{GeV}$, $\int \mathcal{L} = 2\,\mathrm{ab}^{-1}$; S95: rescaling limit

Singlet extensions [TR, arXiv:2203.08210 and Universe 8 (2022) 286]

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



mass and mixing angle

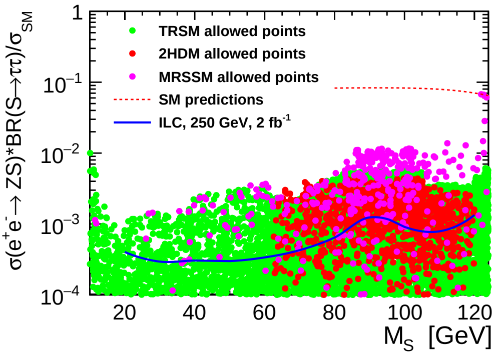


case with two light scalars;
color coding: h_1 rescaling

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

Possible model reach

[plot courtesy of F. Zarnecki, ILC results from Brudnowski ea, arXiv:2409.19761]



Eur.Phys.J.C 80 (2020) 2, 151; Symmetry 15 (2023) 27;
JHEP 01 (2024) 107; JHEP 03 (2016) 007

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

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:

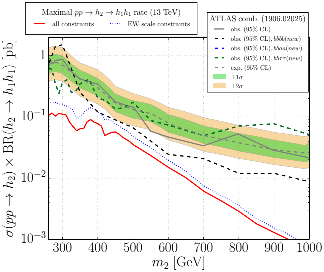
new scalar states, which can now also be produced/ decay into each other/ etc

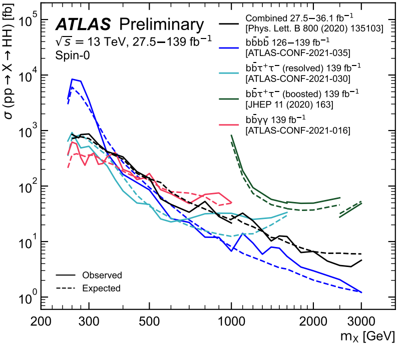
Particle content

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**
- ...

ATLAS-PHYS-PUB-2021-031





Models with extended scalar sectors

Constraints

- **Theory**

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

- **Experiment**

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

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

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

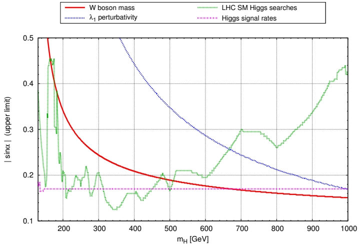
tools used: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

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

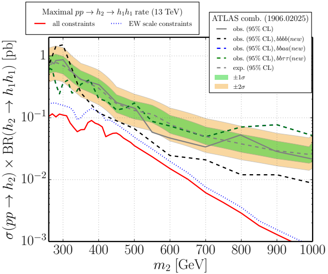
[TR, arXiv:2209.15544; updated using HiggsTools]

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

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



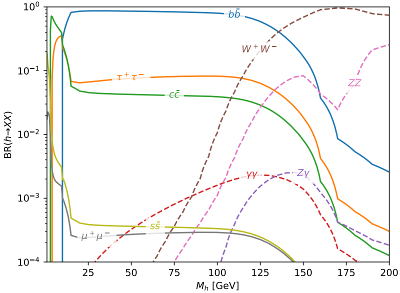
(for fixed $\tan\beta$)



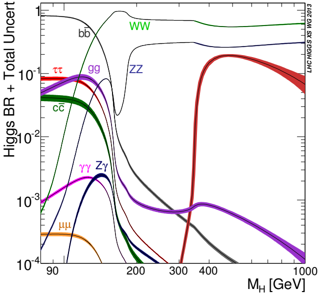
[update from Review in Physics (2020) 100045]

[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)]

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)

Testing the Higgs potential

- remember:

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

also predicts *hhh* and *hhhh* interactions

- so far: only constraints

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

Start with resonance enhanced BSM scenarios for *hhh*

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

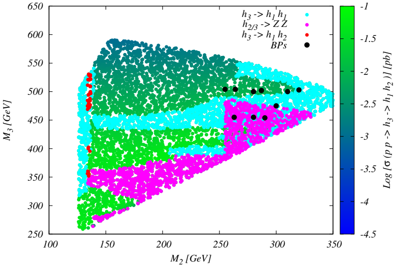
BP3

$\sigma(pp \rightarrow h_3) \simeq 0.06 \cdot \sigma(pp \rightarrow h_{SM})|_{m=M_3}$
$\mathrm{BR}(\mathrm{h}_3 \rightarrow \mathrm{h}_{125}\mathrm{h}_2)$ mostly $\sim 50\%$.
if $M_2 < 250\,\mathrm{GeV}$: $\Rightarrow h_2 \rightarrow$ SM particles.
if $M_2 > 250\,\mathrm{GeV}$:
$\Rightarrow \mathrm{BR}(\mathrm{h}_2 \rightarrow \mathrm{h}_{125}\mathrm{h}_{125}) \sim 70\%$,

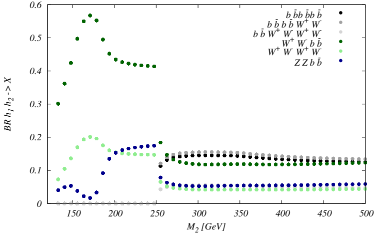
$\Rightarrow$ spectacular triple-Higgs signature

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

What about LHC search interpretations ?

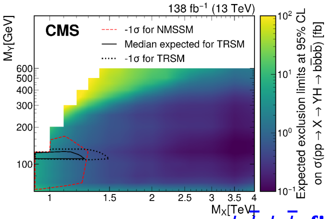
- so far: **2 searches (by CMS) with public results and TRSM interpretations**
- both target $p\,p \rightarrow X \rightarrow Y\,h$
- final states: $b\,\bar{b}\,b\,\bar{b}$ [2204.12413], $b\,\bar{b}\,\gamma\,\gamma$ [CMS-PAS-HIG-21-011]
- compares to **maximal rates** in TRSM and NMSSM

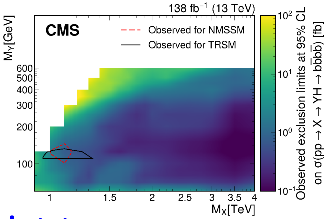
  [TRSM rates available from https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX]

- Work in progress: **Optimized automated scan for maximal rates for any final states** [A. Ghosh, TR, J. Veatch, R. Zhang]

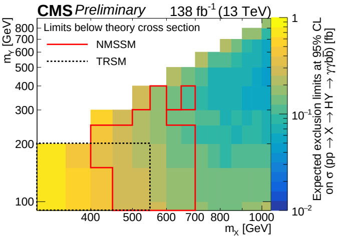
Results [using non-optimized scan]

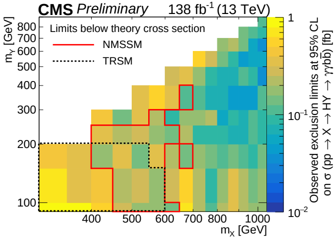
expected **observed**





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





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

Current back of the envelope accuracy estimates

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

- HL-LHC/ ILC_{250}/ CLIC_{380}/ CEPC_{240}/ C^3_{250} $\sim$ 50%
- $\text{FCC-ee}_{240/365}$, **ILC_{500}**, C^3_{550} $\sim 20 - 27\%$
- **$\text{ILC}_{500-1000\text{GeV}}$**, **$\text{CLIC}_{3\text{TeV}}$** $\sim 8 - 11\%$
- **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 $p\,p \rightarrow ZHHH + X$ and $p\,p \rightarrow WHHH + X$*, Phys. Rev. D93 (2016) 113003 [1602.05849].
- R. Contino et al., *Physics at a 100 TeV pp collider: Higgs and EW symmetry breaking studies*, CERN Yellow Rep. (2017) 255 [1606.09408].
- B. Fuks, J.H. Kim and S.J. Lee, *Scrutinizing the Higgs quartic coupling at a future 100 TeV proton-proton collider with taus and b-jets*, Phys. Lett. B771 (2017) 354 [1704.04298].
- A. Papaefstathiou, G. Tetlalmatzi-Xolocotzi and M. Zaro, *Triple Higgs boson production to six b-jets at a 100 TeV proton collider*, Eur. Phys. J. C 79 (2019) 947 [1909.09166]. $[-1.7; 13]$
- F. Maltoni, D. Pagani and X. Zhao, *Constraining the Higgs self-couplings at e+e- colliders*, JHEP 07 (2018) 087 [1802.07616]. CLIC$_{3\mathrm{TeV}}$ $[-5; 7]$
- 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 $(30\mathrm{TeV})$ $[0.7; 1.5]$

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/ D. Winterbottom]

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

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

- scenario discussed here:

$$m_H = 300\,\mathrm{GeV};\ \sin\theta = 0.17;\ \tan\beta = 3.3$$
$$\Gamma_H = 0.54\mathrm{GeV},\ \mathrm{BR}_{H\to h\,h} = 0.55$$
$$\sigma_{hh} = 69.77(4)\mathrm{fb},\ \sigma_{\text{via}H} = 58.65(2)\mathrm{fb},\ \sigma_{\text{no}H} = 14.195(7)\mathrm{fb}$$

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

Another topic: finite width effects

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

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

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

- scenario discussed here:

$$m_H = 600\,\text{GeV};\ \sin\theta = 0.17;\ \tan\beta = 1.6$$
$$\Gamma_H = 4.98\text{GeV},\ \text{BR}_{H\to h\,h} = 0.34$$
$$\sigma_{hh} = 26.746(7)\text{fb},\ \sigma_{\text{via}H} = 7.90(1)\text{fb},\ \sigma_{\text{no}H} = 15.11(1)\text{fb}$$

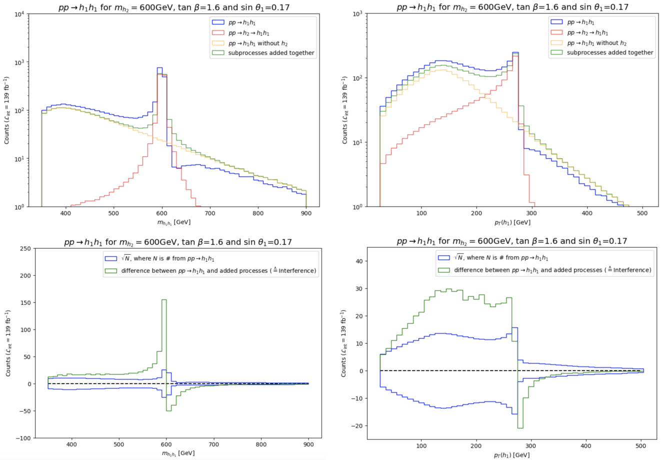
Interference: $\sigma_{hh} - \left(\sigma_{\text{via}H} + \sigma_{\text{no}H}\right)$ [= 3.74(2) fb]

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

m_{hh} $p_\perp^h$

total

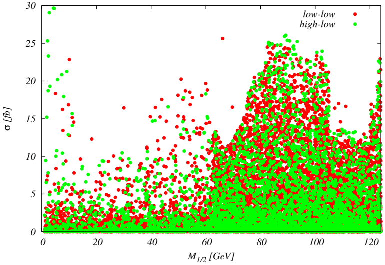
diff



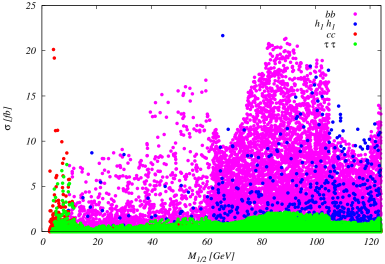
Singlet extensions

[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

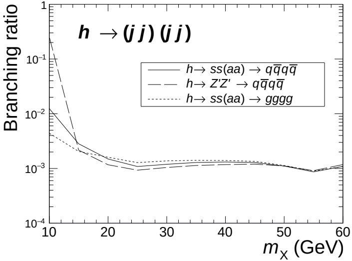


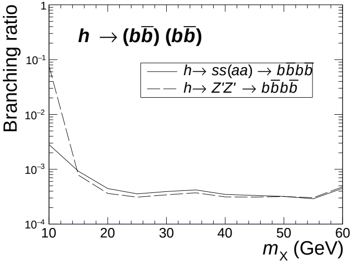
convoluted with decay rates

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

$h \to 4j/4b/4c$ final states

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

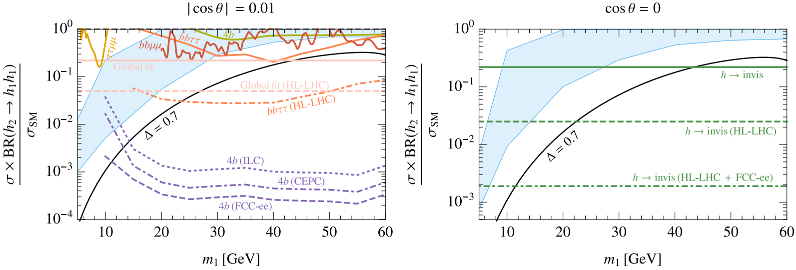




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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] [see also M. Carena, Z. Liu, Y. Wang, JHEP 08 (2020) 107]



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)]

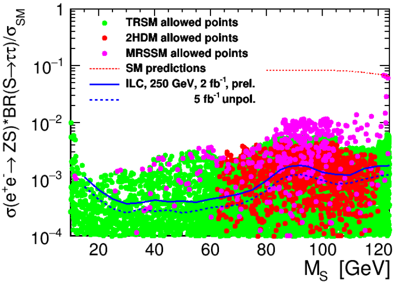
Possible model reach

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

$S \to \tau^+\tau^-$

Cross section limits

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



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