Extended scalar sectors from all angles (in 15 minutes)

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La Thuile
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Croatian Science Foundation

What about scalar extensions ?

- in principle: **no limit in extending SM scalar sector**

can add more $SU(2) \times U(1)$ 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: $\underbrace{h,\,H}_{\text{CP-even}},\;\underbrace{A}_{\text{CP-odd}},\;H^{\pm}$

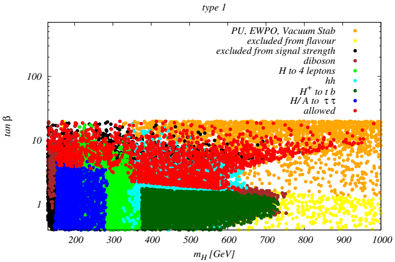
parameters: **masses,** $+\ \tan\beta,\ \cos(\beta-\alpha),\ m_{12}$

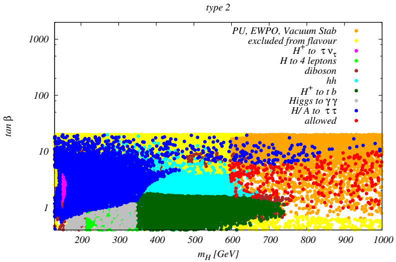
- also subject to various constraints: **B-physics, direct searches, signal strength, ...**
- different types of Yukawa couplings $\Rightarrow$ different effects of constraints

Recent 2HDM scan using thdmtools

[code reference: Biekotter ea, JHEP 01 (2024) 107]

all new scalar masses set equal, rest is floating





type 1: all couplings from Φ_2; type 2: down-type from Φ_1

LHC: Multi scalar production modes

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

Model with 3 CP-even neutral scalars

$$M_1 \leq M_2 \leq M_3$$

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]

LHC: Multi scalar production modes

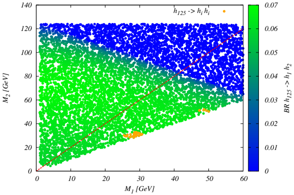
[TR, T. Stefaniak, J. Wittbrodt, Eur.Phys.J. C80 (2020) no.2, 151;
updates from arXiv:2305.08595, HHH Workshop talk, 16.7.23, for Catch22+2 Dublin, 05/24, and Asymptotic Safety meets Particle Physics & Friends, 12/24]

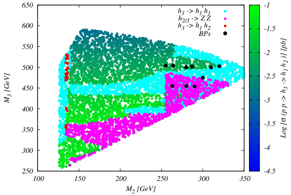
2 real singlet extension ⇒ 2 additional scalars $(M_1 \leq M_2 \leq M_3;\ M_i \in [0; 1\text{TeV}])$
[1 mass always at 125 GeV, others free]

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

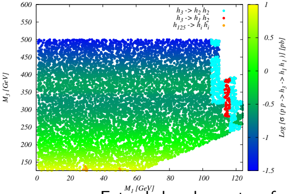
(3.5/ 0.25 pb)

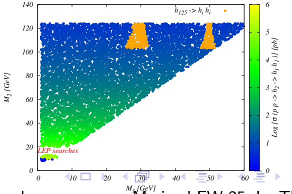




symmetric, no h_{125} involved

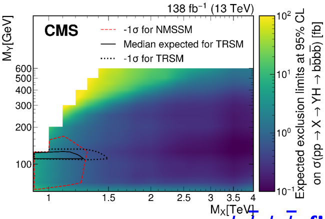
(2.5/ 60 pb)



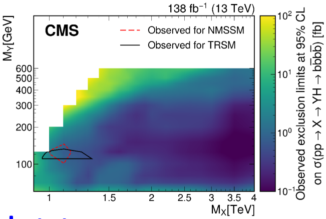


Results [using non-optimized scan] [Phys.Lett.B 842 (2023) 137392; CMS-PAS-HIG-21-011]

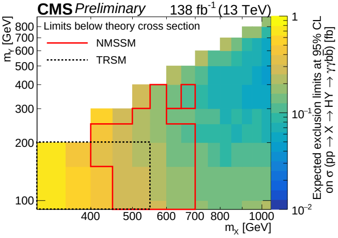
expected

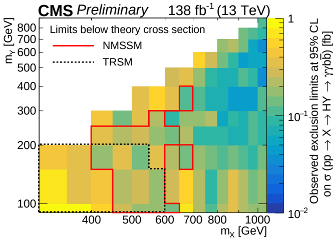


observed



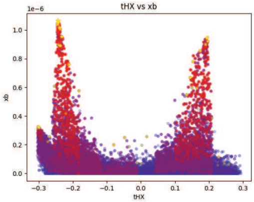
$b\,\bar{b}\,b\,\bar{b}$ final states





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

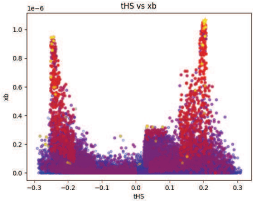
Work in progress: optimized scan (in collaboration w J. Veatch)

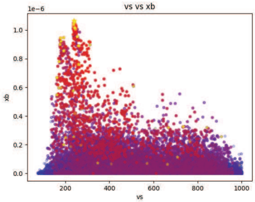


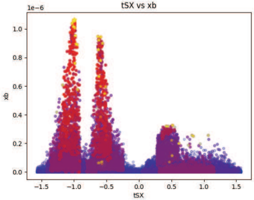
X->SH->bbbb

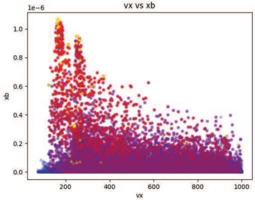
m_X = 1000 GeV

m_S = 300 GeV









Another important topic: finite width effects

- Experiments: often use factorized approach:

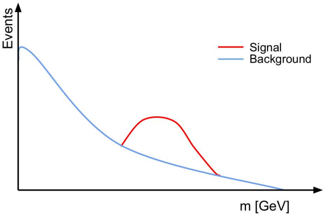
$$p\,p \to X,\, X \to Y\,Z$$

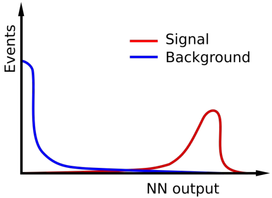
- quantum mechanics: **only stable particles are defined in S-matrix elements**, everything else approximation
- in reality: **case by case study**
- **wrong: assume factorization always works**

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 ??

Interference effects in singlet extension [w F. Feuerstake, E. Fuchs, D. Winterbottom, arXiv:2409.06651

- **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]	σ_{SH} [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 $(\Delta\sigma)^{\Sigma}_{\text{rel}}$
BM3	0.16	0.5	380	0.8	0.96	119.8	90.1	✓	Max $(\Delta\sigma)^{\Sigma}_{\text{rel}}$ 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 $\frac{\Gamma_H}{m_H}$

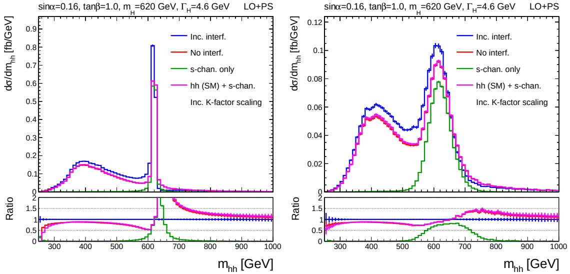
additional quantities:

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

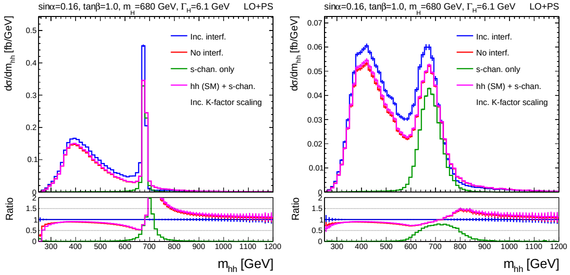
$\Rightarrow$ **sum of absolute values of interferences before and after**

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)

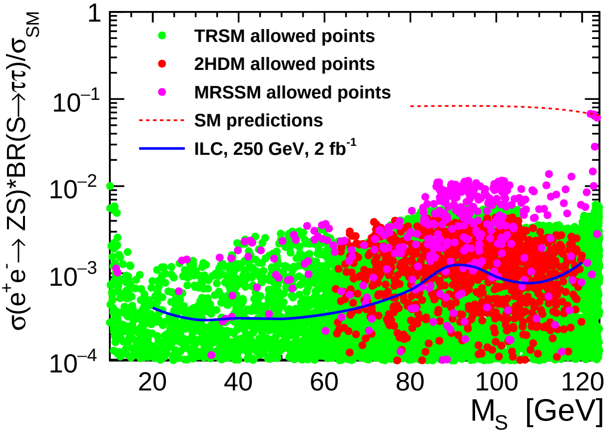
various production modes possible

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

Example for new scalar search and sensitivity for different models



Results from A.F.Zarnecki, ECFA Higgs/Top/EW factory study report as input for European Strategy [to appear]

Summary

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

$\Rightarrow$ 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


HHH workshop
Dubrovnik / Croatia
29th Sept. - 1st Oct. 2025
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/hhh2025

Appendix

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**

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

⇒ **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.

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**
- ...

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]

Analyses for 2hdm constraints

- $A \rightarrow Z\,h$: CMS, Phys.Lett.B 748 (2015) 221-243, Run 1, 20 fb^{-1}; CMS, Eur. Phys. J. C 79 (2019) 564, early Run 2;
- H to 4 leptons: ATLAS, Eur.Phys.J.C 81 (2021) 4, 332, full Run 2;
- diboson: ATLAS, Phys. Rev. D 98, 052008 (2018), early Run 2; CMS, HEP 06 (2018) 127, early Run 2; ATLAS, Eur.Phys.J.C 80 (2020) 12, 1165, full Run 2
- hh: ATLAS, ATLAS-CONF-2021-030, full Run 2; CMS, Phys.Rev.Lett. 122 (2019) 12, 121803 , early Run 2
- $H^+ \rightarrow t\,\bar{b}$: ATLAS, JHEP 06 (2021) 145, full Run 2; CMS, JHEP 07 (2020) 126, early Run 2
- $H \rightarrow \tau^+\tau^-$ CMS, JHEP 07 (2023) 073, full Run 2; CMS, JHEP 09 (2018) 007, early Run 2; ATLAS, Phys.Rev.Lett. 125 (2020) 5, 051801, full Run 2; CMS, CMS-PAS-HIG-14-029, Run 1 combination
- h to 4 leptons: CMS, Phys. Rev. D 89 (2014) 092007, early Run 1
- $H^+ \rightarrow \tau^+\,\nu_\tau$: ATLAS, JHEP 09 (2018) 139, early Run 2
- $H \rightarrow \gamma\gamma$: ATLAS, Phys.Lett.B 822 (2021) 136651, full Run 2

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*.

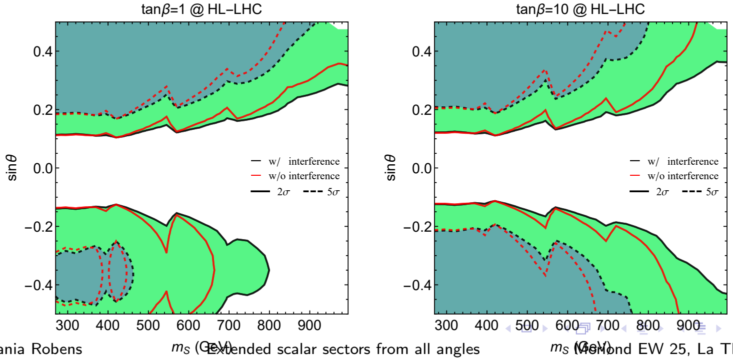
[some material stolen from T. Stefaniak, Talk at ALPS 2019, April '19]

Does it matter ?

Nice work by M. Carena, Z. Liu, M. Riembau, Phys. Rev. D 97, 095032 (2018)

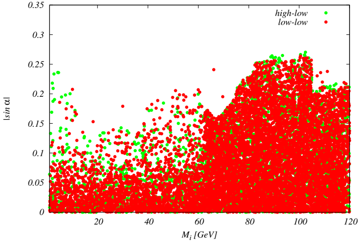
consider singlet extension, projection for HL-LHC

with and without interference

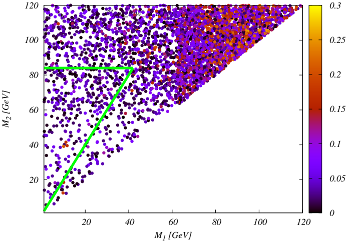


Singlet extensions [TR, arXiv:2203.08210 and Universe 8 (2022) 286]

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



mass and mixing angle

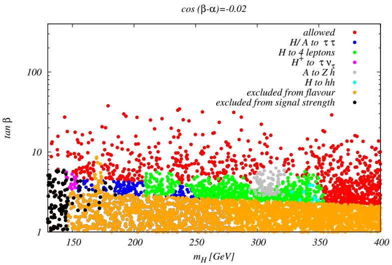


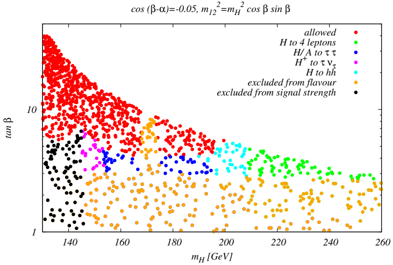
case with two light scalars;
color coding: h_1 rescaling

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

2HDM parameter space for fixed $\cos(\beta - \alpha)$, Type I

TR, EPJ Web Conf. 315 (2024) 01025



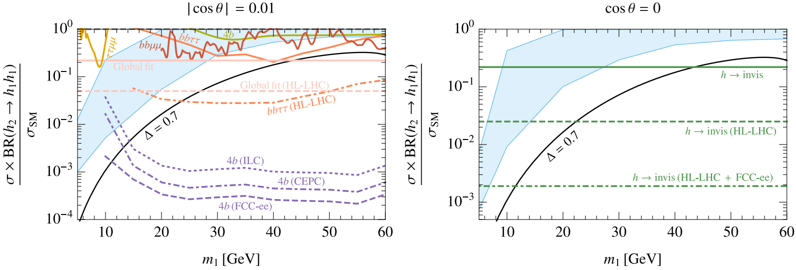


$$m_H = m_A = m_{H^\pm}$$

[using thdmTools, Biekoetter ea, JHEP 01 (2024) 107]

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 bs]

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