

Overview on low mass scalars at e^+e^- facilities - theory

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Models

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

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

for coupling g to vector bosons

- many scenarios $\Rightarrow$ **signal strength poses strong constraints**

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

What about extensions ?

- in principle: **no limit**

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

⇒ consequence: **will enhance particle content**

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

- common feature:

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

Particle content

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

- e.g. 2 real scalars $\Rightarrow$ **3 CP-even neutral scalars**
- 2HDM $\rightarrow$ **2 CP-even, one CP odd neutral scalar, and charged scalars**
- ...

Constraints

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)

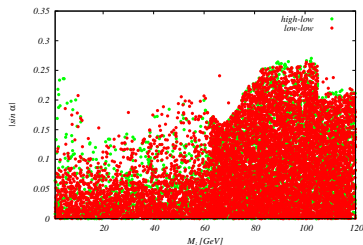
Limited time $\Rightarrow$ next slides highly selective...

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

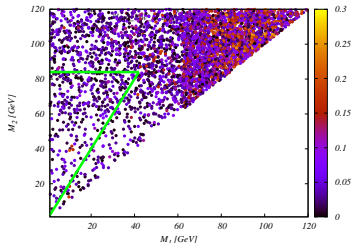
tools used: HiggsTools, ScannerS, ...

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

Two Higgs Doublet Models

another 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**

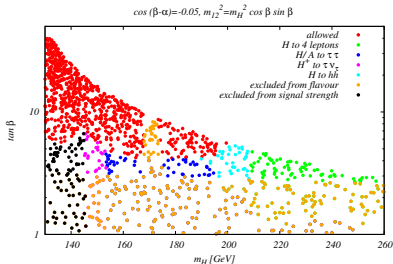
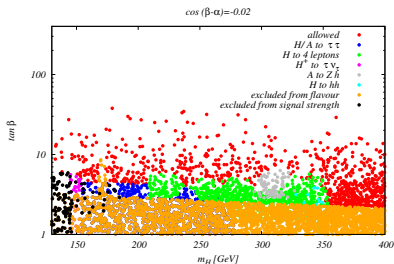
particle content: $\underbrace{h, H}_{\text{CP-even}}, \underbrace{A}_{\text{CP-odd}}, H^\pm$

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 for fixed $\cos(\beta - \alpha)$, Type I

TR, ArXiv:2409.19657



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

[using thdmTools, Biekötter et al, JHEP 01 (2024) 107]

Typical processes at Higgs factories

various production modes possible

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

Production modes in 2HDMs

[notation on this slide $h \equiv h_{125}$]

$$e^+e^- \rightarrow h/HZ, hA, HA, H^+H^-$$

- for on-shell production: **need** $\sum_i m_i \lesssim \sqrt{s}$

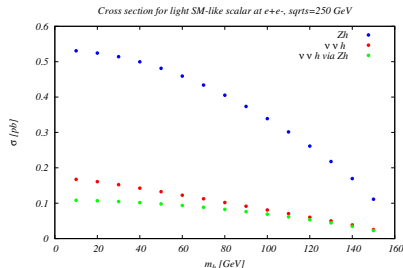
requires relatively light scalars, typically $m \lesssim 160$ GeV

- include suppression/ alignment, and mass range: HZ, hA
suppressed by $\cos(\beta - \alpha)$
- H^+H^- **production: kinematic limit only**
need light(ish) $H^\pm$, $m_A + m_H \lesssim 250$ GeV

Possible production modes and rates

[TR, Universe 2022, 8(5), 286, updated]

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



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

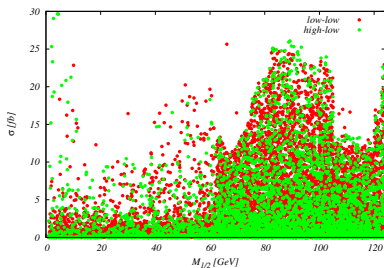
LO analytic expressions e.g. in Kilian et al, Phys.Lett.B 373 (1996) 135-140]

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

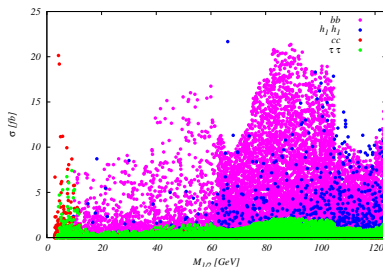
Singlet extensions

[TR, Symmetry 2023, 15(1), 27 and Springer Proc.Phys. 292 (2023) 141-152]

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



cross sections at 250 GeV

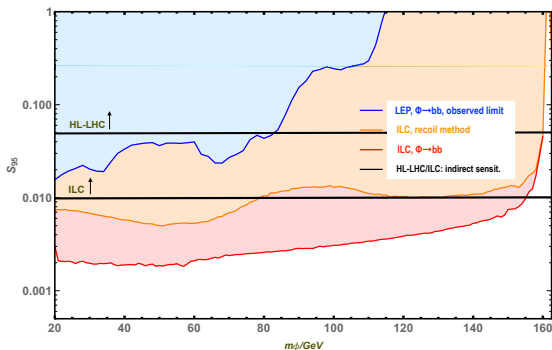


convoluted with decay rates

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

Projections for additional scalar searches

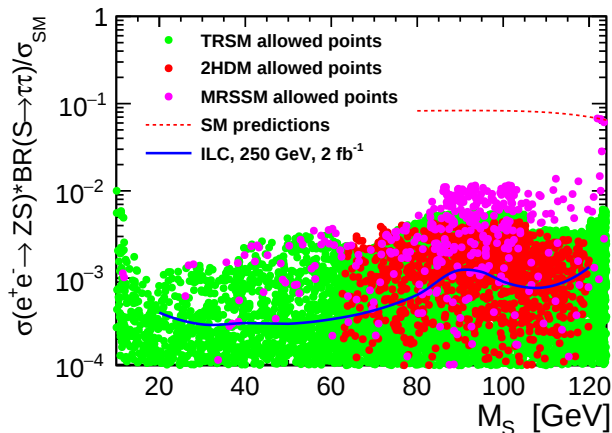
[P. Drechsel, G. Moortgat-Pick, G. Weiglein, Eur.Phys.J.C 80 (2020) 10, 922]



estimate of ILC sensitivity based on validation using LEP results

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

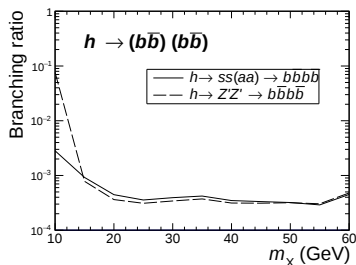
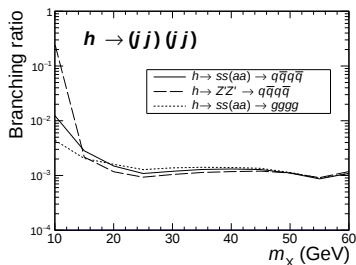
Example for new scalar search and sensitivity for different models



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

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

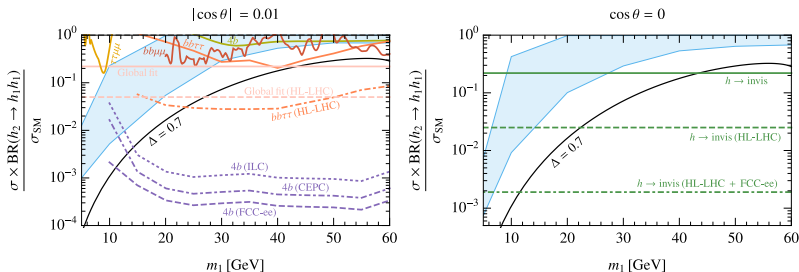
[Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys.C 41 (2017) 6, 063102]



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

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

[J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Phys.Rev.D 101 (2020) 11, 115035] [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 $b\bar{s}$]

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

Conclusions

- **many new physics models predict one/ several scalars below 125 GeV**
- typical decays into $b\bar{b}, \tau^+\tau^-$
- already constraints from current LHC searches, **mainly in context of 2HDMs**
- at ee: cross sections could reach **up to 300/ 60 fb from Zh production**
- decays of $h_{125} \rightarrow ss$ **also within reach**
- important connection to EWSB/ EW phase transitions

Still space for more studies !

Appendix

Special role of the scalar sector

- Higgs potential in the SM**

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

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

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

where v : Vacuum expectation value of the Higgs field, g, g' : couplings in $SU(2) \times U(1)$

⇒ **everything determined in terms of gauge couplings, v , and λ**

**form of potential determines minimum,
electroweak vacuum structure**

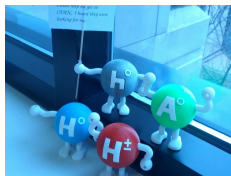
⇒ stability of the Universe, electroweak phase transition, etc

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

⇒ **so far: only limits; possible only at future machines** [HL-LHC: constraints on $hhhh$]

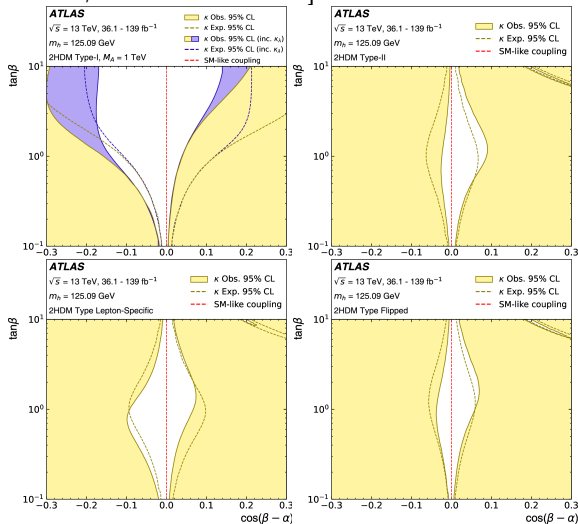
Other possible extensions

- A priori: **no limit to extend scalar sector**
- **make sure you**
 - have a **suitable ew breaking mechanism**, including a **Higgs candidate at ~ 125 GeV**
 - can explain **current measurements**
 - are **not excluded by current searches** and precision observables
- **nice add ons:**
 - can **push vacuum breakdown to higher scales**
 - can **explain additional features**, e.g. dark matter, or hierarchies in quark mass sector
 - ...
- Multitude of models out there
- adding ew gauge singlets/ doublets/ triplets...
 $\Rightarrow$ new scalar states $\Leftarrow$



Current constraints on alignment in 2HDMs

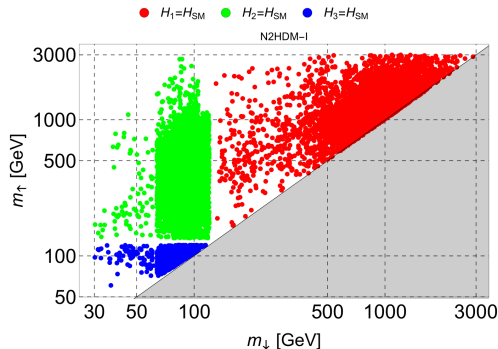
[arXiv:2402.05742, ATLAS Full Run II]



N2HDM example

[H. Abouabid, A. Arhrib, D. Azevedo, J. El Falaki, P. M. Ferreira, M. Muehlleitner, R. Santos, arXiv:2112.12515]

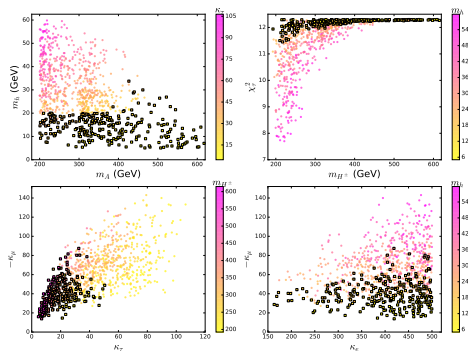
N2HDM: 2HDM+ real singlet



Lepton-specific IDM

[X.-F. Han, T. Li, H.-X. Wang, L. Wang, Y. Zhang, Phys.Rev.D 104 (2021) 11, 115001]

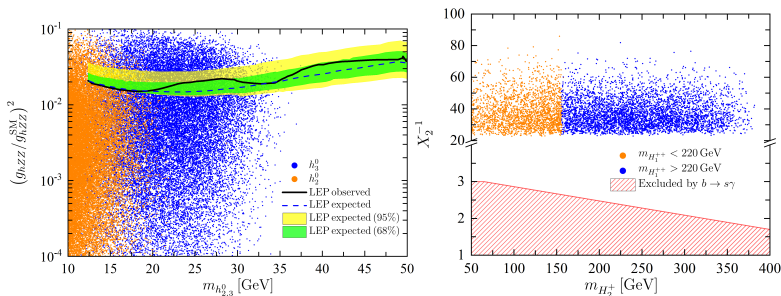
Inert Doublet Model, with $\mathbb{Z}_2$ breaking terms coupling to leptons



various constraints (including agreement with $g_\mu - 2$);
squares: allowed, bullets: forbidden

Scalar triplet model

[P.M. Ferreira, B.L. Gonalves, F.R. Joaquim, JHEP 05 (2022) 105]

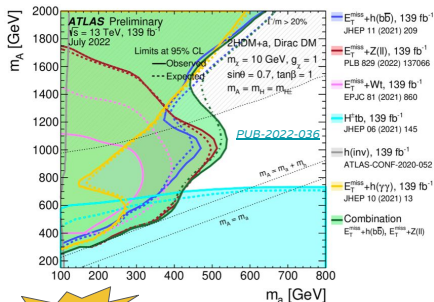


5 neutral, 3 singly charged, 2 doubly charged scalars

[slide from A. Lopez Solis, CERN LHC Seminar, 19.7.22]

A more UV-complete model: 2HDM+a

[Phys.Dark.Univ.Vol.27,100351](#)



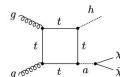
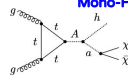
Today!

Latest search in tW +DM final state

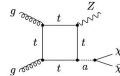
Simplest renormalizable theory with DM singlet Unitarity.

Rich phenomenology in several final states at colliders.

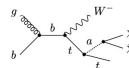
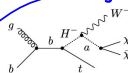
Mono-Higgs



Mono-Z



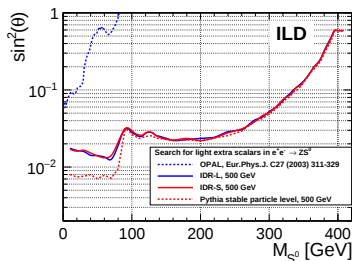
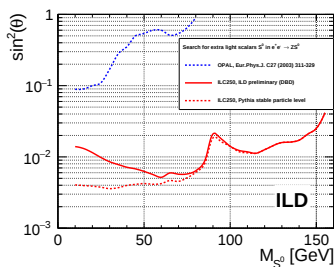
Single-top



!! analysis still fixes many parameter values !!

Projections for additional scalar searches

[Y. Wang, M. Berggren, J. List, arXiv:2005.06265]



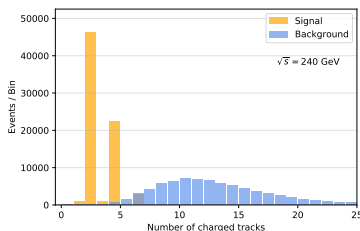
**additional scalar, $\sin\theta$ rescaling wrt SM prediction,
comparison of different detector models
recoil method**

Possible searches

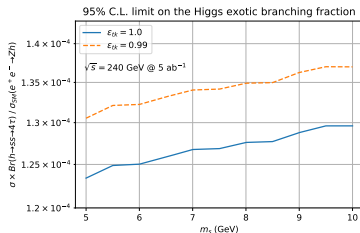
- one option: consider $h_{125} \rightarrow s s$
- also possible: **direct searches**
- for all of these: **dominant decays typically to $b\bar{b}$ or $\tau^+\tau^-$**
- $h_{125} \rightarrow s s$ also constrained from $\Gamma_{125} \leq 9 \text{ MeV}$, and $\text{BR}_{h \rightarrow \text{inv}} \leq 0.11$.

Exotic decays - $h \rightarrow ss \rightarrow 4\tau$

[J. Shelton, D. Xu, arXiv:2110.13225]



[$m_s = 7.5 \text{ GeV}$; background
mainly from $h \rightarrow jj$]



ϵ_{tk} : tracking efficiency

comment: **current constraints lead to prediction $\lesssim 10^{-3}$**

[invisible BR, signal strength, assumes SM-like decay to $\tau\tau$]

Type X 2HDM, 4τ final state via $\tau\tau A$ production

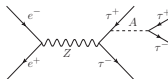
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]

one doublet couples to quarks, other to fermions; CP violation

Searches for light A in 2HDMX at ILC250



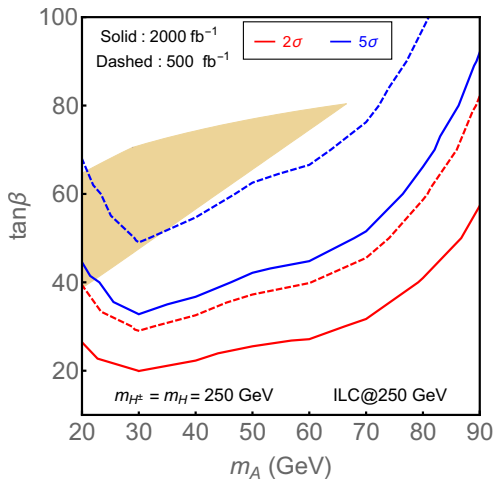
- The channel $Z \rightarrow h_{SM}A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \rightarrow HA$ may not be feasible when H is heavier than 200 GeV.
- Possible option : $Z \rightarrow \tau\tau \rightarrow \tau\tau A \rightarrow 4\tau$. So called Yukawa production.



- This is the equivalent to $t\bar{t}H$ searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 4τ s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

Type X 2HDM, 4τ final state via $\tau\tau A$ production

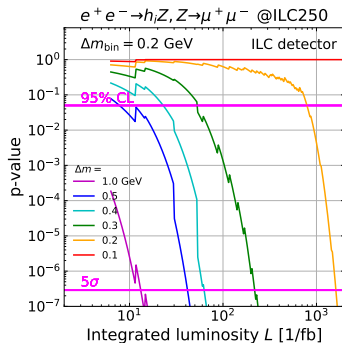
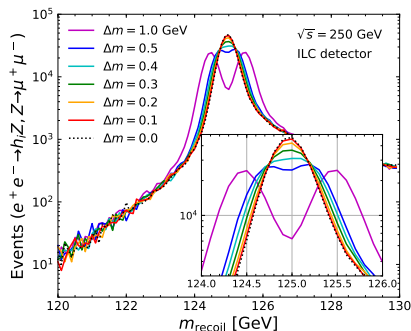
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]



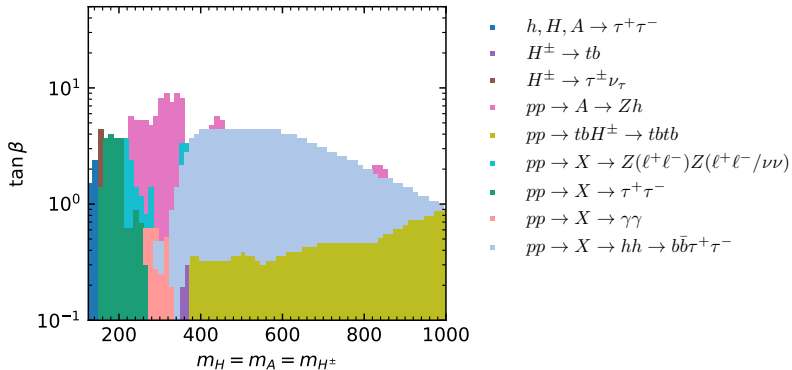
Test of degenerate additional scalar, including dark matter

[S. Abe, G.-C. Cho, K. Mawatari, Phys.Rev.D 104 (2021) 3, 035023]

- setup: complex singlet, including dark matter candidate
- test of degenerate additional scalar

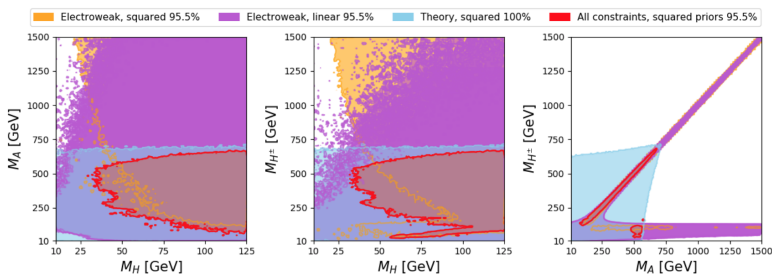


2HDM parameter space w thdmtools, thanks to K. Radchenko



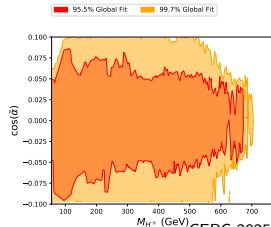
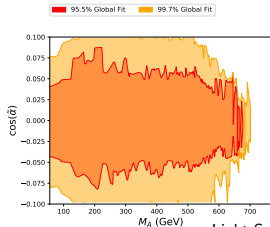
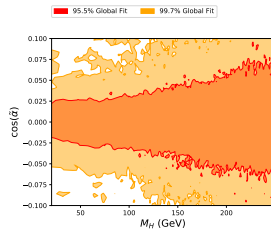
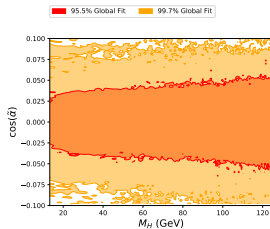
Aligned 2HDM

[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]



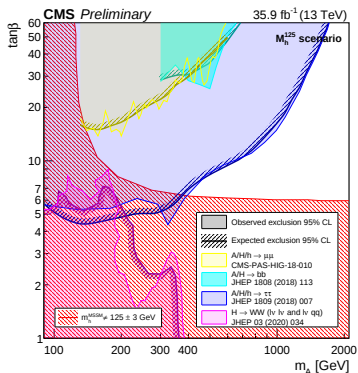
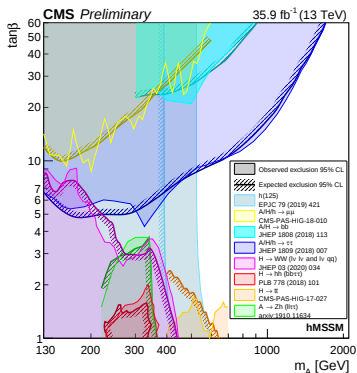
low mass region allowed; however, HZZ typically suppressed by $\cos(\beta - \alpha) [\lesssim 0.25]$

... and in terms of mixing angle...
 [Universe 8 (2022) 286; Thanks to V. Miralles]



CMS MSSM summary plots, early Run II

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

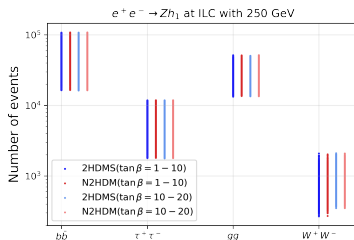
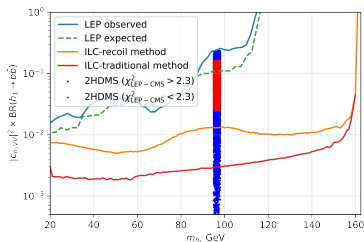


The 96 GeV LEP resonance

[S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, S. Paasch, arXiv:2112.11958]

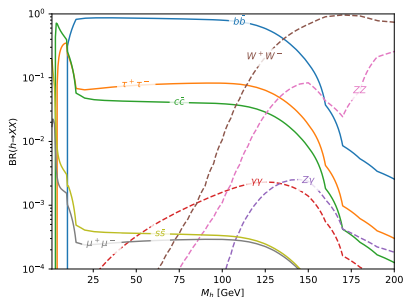
[see also T. Biekötter, M. Chakraborti, S. Heinemeyer, Eur.Phys.J.C 80 (2020) 1, 2]

various BSM models, rates using $\int \mathcal{L} = 2 \text{ ab}^{-1}$

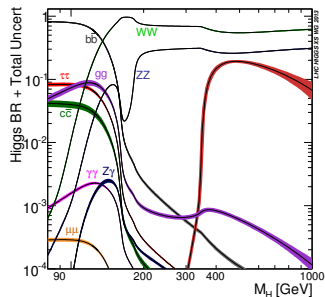


N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside 1σ]

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



(using HDecay, courtesy J.Wittbrodt)



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