

# Light <sup>[Higgses]</sup> Scalars at Higgs factories - theory

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on the Circular Electron-Positron Collider  
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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)

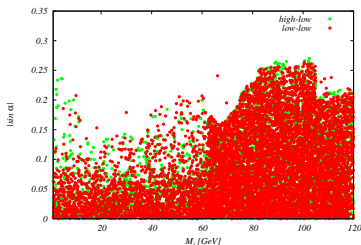
**Limited time  $\Rightarrow$  next slides highly selective...**

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

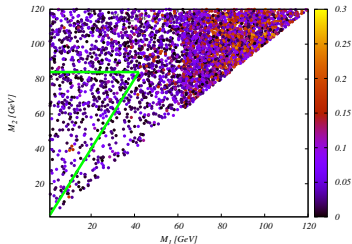
tools used: HiggsTools, ScannerS, ...

# 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**

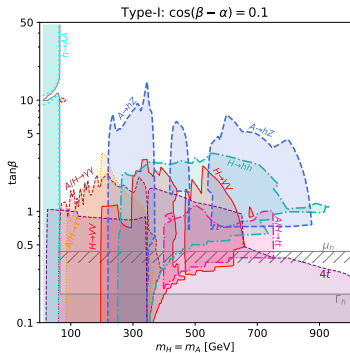
- extend SM scalar sector by **one additional doublet**
- a priori: can lead to flavour changing neutral currents
- way to prevent this: **introduce additional symmetries in potential**

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

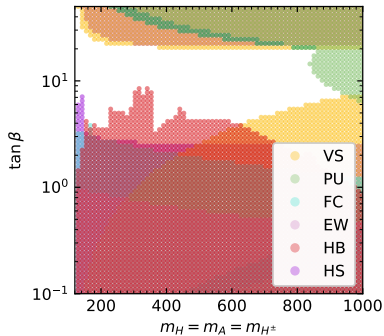
parameters: **masses**,  $+$   $\tan \beta$ ,  $\cos(\beta - \alpha)$ ,  $m_{12}$

- 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 $\cos(\beta - \alpha)$



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

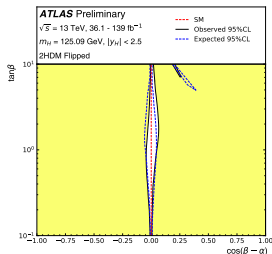
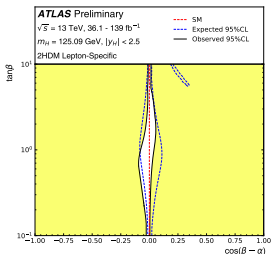
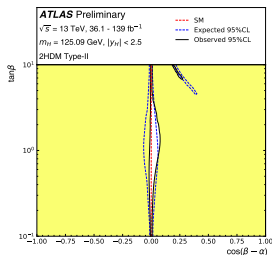
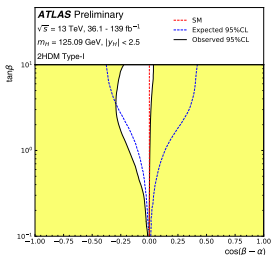


[from thdmtools, thanks to K. Radchenko]



# Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]



# Typical processes at Higgs factories

**various production modes possible**

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

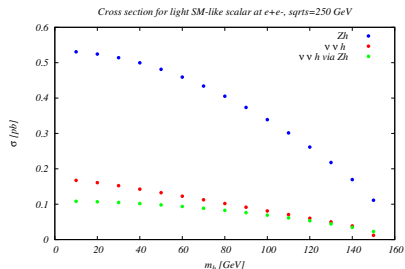
**requires relatively light scalars, typically  $m \lesssim 160$  GeV**

- 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]

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



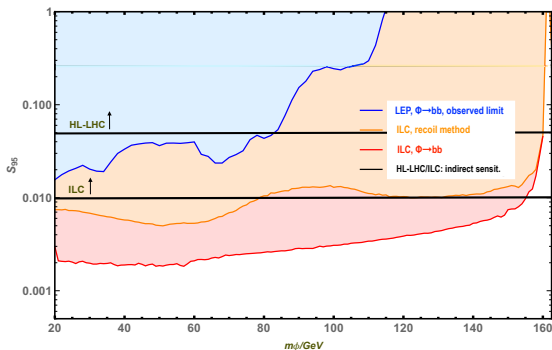
[cross sections for  $e^+ e^-$  at  $\sqrt{s} = 250$  GeV using Madgraph5;

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**

# Projections for additional scalar searches

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

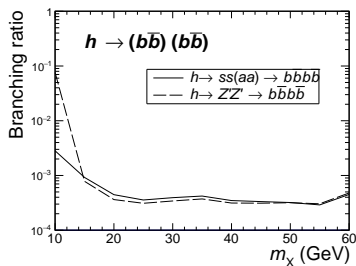
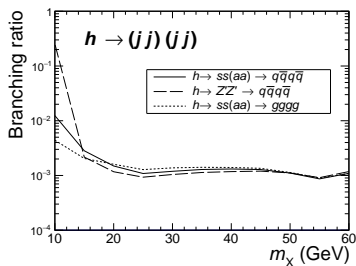


estimate of ILC sensitivity based on validation using LEP results

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

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

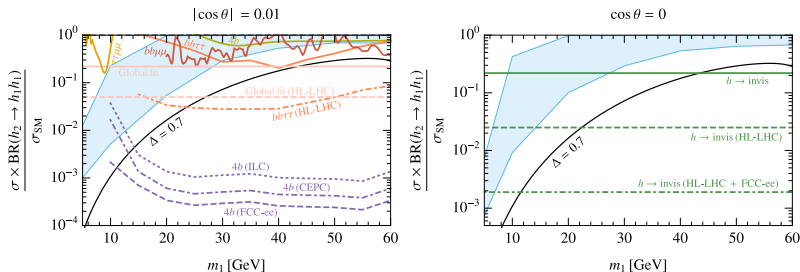
[Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys.C 41 (2017) 6, 063102]



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  $bs$ ]

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

# Ongoing ECFA study: Direct discovery potential at Higgs factories, Extra scalar subgroup [CERN e-group: ECFA-WHF-WG1-SRCH]

## Expert team activities

Second meeting on zoom on **June 20**

### Discussion on the choice of benchmark scenarios

Two targets identified:

- search for light exotic scalars in the scalar-strahlung process

$$e^+e^- \rightarrow Z \phi$$

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

- light scalar production in 125 GeV Higgs boson decays

$$h_{125} \rightarrow \phi \phi$$

again assuming different decay channels for  $\phi$  ( $bb$ ,  $\tau\tau$ , invisible,...)

Overview of light scalar scenarios prepared by Tania Robens and included in shared google document.

**Want to get involved ? Let us know !**

Target: **Whitepaper, input for next European Strategy report**



# 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  $\lambda$**

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

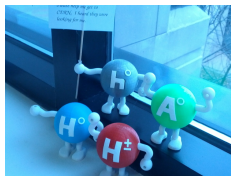
⇒ stability of the Universe, electroweak phase transition, etc

- **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

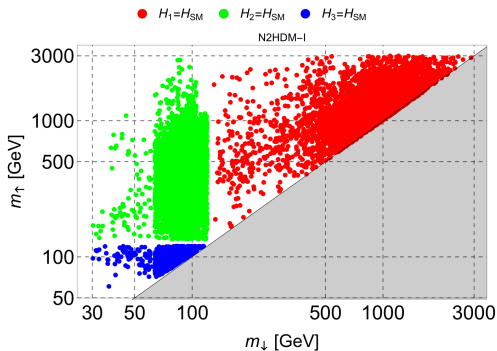
- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at  $\sim 125$  GeV**
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add ons:**
  - 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...
  - ⇒ **new scalar states** ⇐



# N2HDM example

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

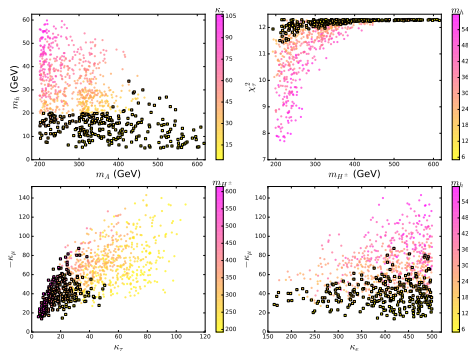
## N2HDM: 2HDM+ real singlet



# Lepton-specific IDM

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

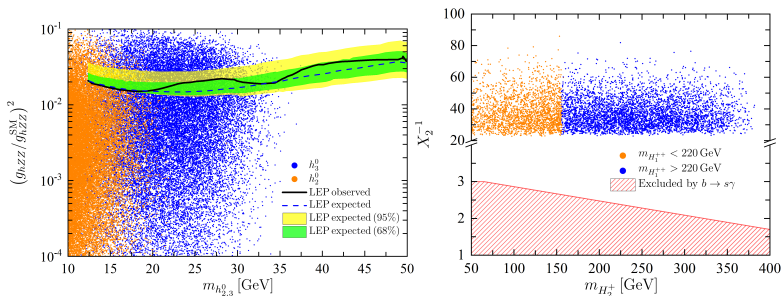
**Inert Doublet Model, with  $\mathbb{Z}_2$  breaking terms coupling to leptons**



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]

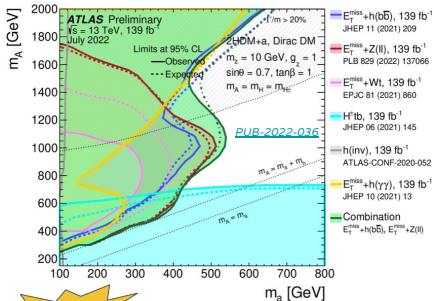


**5 neutral, 3 singly charged, 2 doubly charged scalars**

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

## A more UV-complete model: 2HDM+a

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

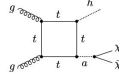
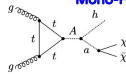


Today!

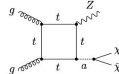
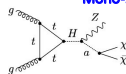
Latest search in tW+DM final state

Simplest renormalizable theory with DM singlet  
 Unicity.  
 Rich phenomenology in several final states at  
 colliders.

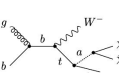
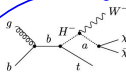
**Mono-Higgs**



**Mono-Z**



**Single-top**

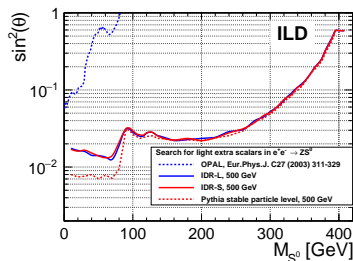
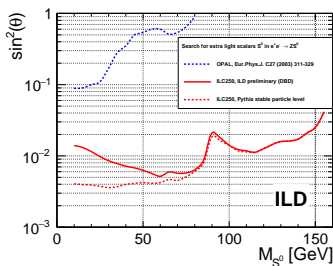


**!! analysis still fixes many parameter values !!**



# Projections for additional scalar searches

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



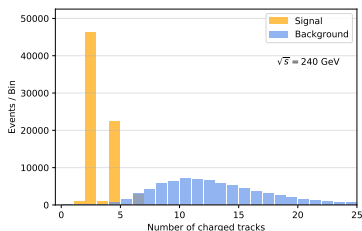
**additional scalar,  $\sin \theta$  rescaling wrt SM prediction,  
comparison of different detector models  
recoil method**

# Possible searches

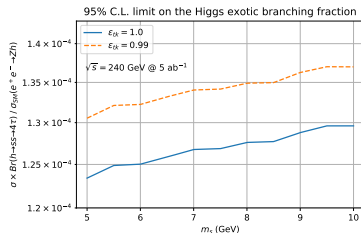
- one option: consider  $h_{125} \rightarrow s s$
- also possible: **direct searches**
- for all of these: **dominant decays typically to  $b\bar{b}$  or  $\tau^+\tau^-$**
- $h_{125} \rightarrow s s$  also constrained from  $\Gamma_{125} \leq 9 \text{ MeV}$ , and  $\text{BR}_{h \rightarrow \text{inv}}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

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

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



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



$\epsilon_{tk}$ : tracking efficiency

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

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

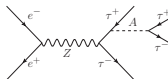
# Type X 2HDM, $4\tau$ final state via $\tau\tau A$ production

[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

KIAS

- 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  $ttH$  searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the  $4\tau$  s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

Navigation icons: back, forward, search, etc.

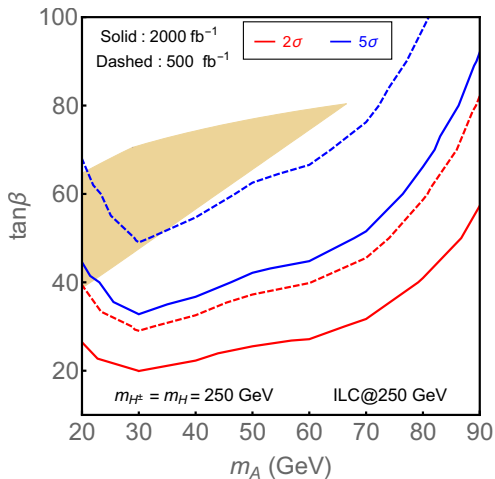
Tanmay Mondal, KIAS, Seoul

ICHEP 2020, Prague

Light (Pseudo)Scalar @ ILC

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

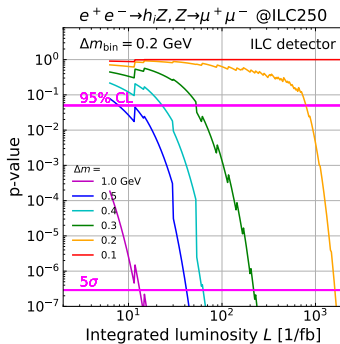
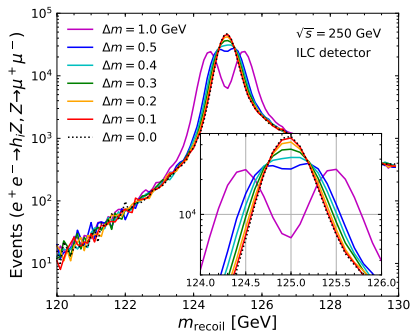
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]



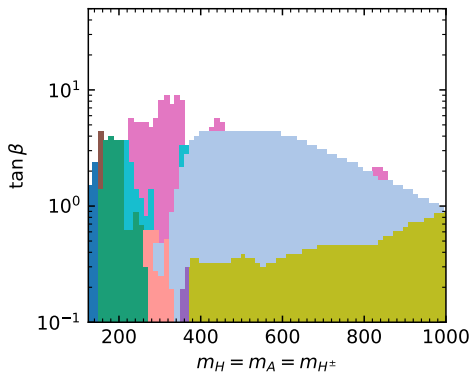
# Test of degenerate additional scalar, including dark matter

[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



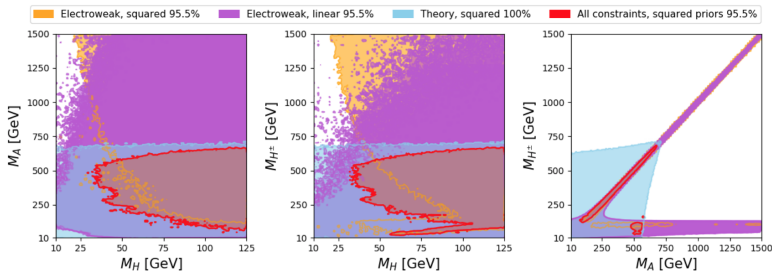
# 2HDM parameter space w thdmtools, thanks to K. Radchenko



- $h, H, A \rightarrow \tau^+ \tau^-$
- $H^\pm \rightarrow tb$
- $H^\pm \rightarrow \tau^\pm \nu_\tau$
- $pp \rightarrow A \rightarrow Zh$
- $pp \rightarrow tbH^\pm \rightarrow tbtb$
- $pp \rightarrow X \rightarrow Z(\ell^+ \ell^-) Z(\ell^+ \ell^- / \nu\nu)$
- $pp \rightarrow X \rightarrow \tau^+ \tau^-$
- $pp \rightarrow X \rightarrow \gamma\gamma$
- $pp \rightarrow X \rightarrow hh \rightarrow b\bar{b}\tau^+\tau^-$

# Aligned 2HDM

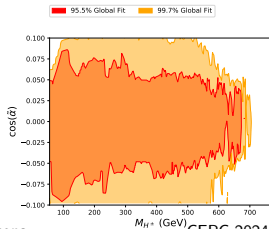
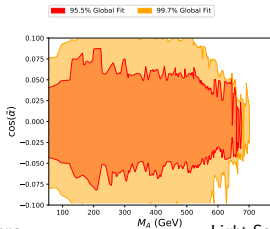
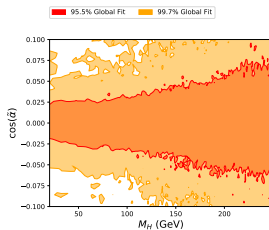
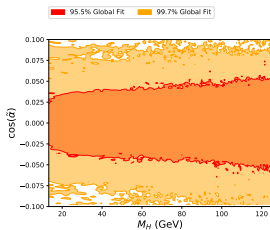
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]



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

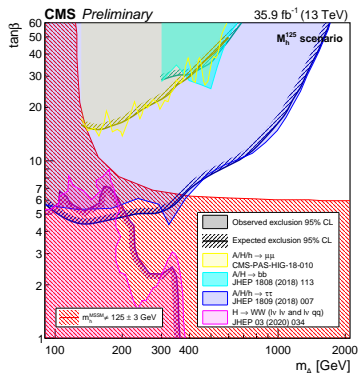
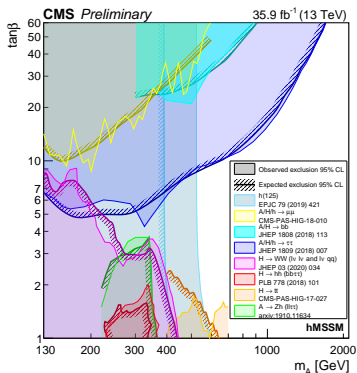


... and in terms of mixing angle...  
 [Universe 8 (2022) 286; Thanks to V. Miralles]



# CMS MSSM summary plots, early Run II

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

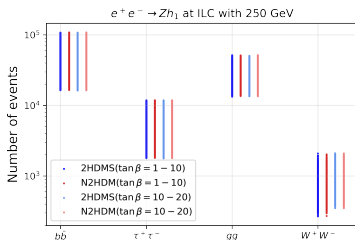
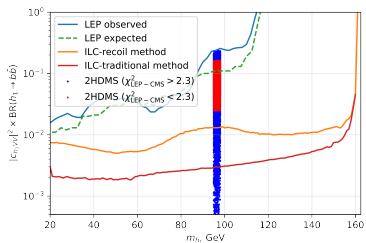


# The 96 GeV LEP resonance

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

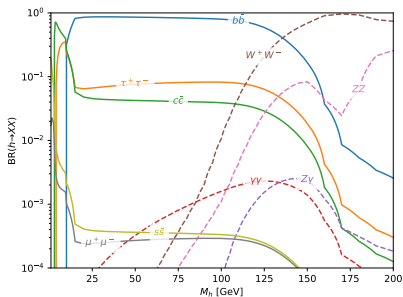
[see also T. Biekötter, M. Chakraborti, S. Heinemeyer, Eur.Phys.J.C 80 (2020) 1, 2]

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

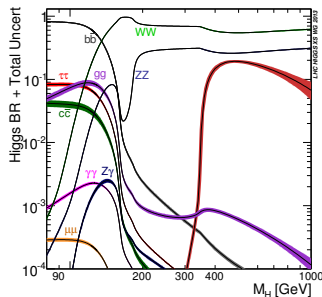


N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside  $1 \sigma$ ]

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



(using HDecay, courtesy J.Wittbrodt)



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