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

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University of Tokyo
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Models

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

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

for coupling g to vector bosons

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

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

What about extensions ?

- in principle: **no limit**

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

$\Rightarrow$ 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**
- ...

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)

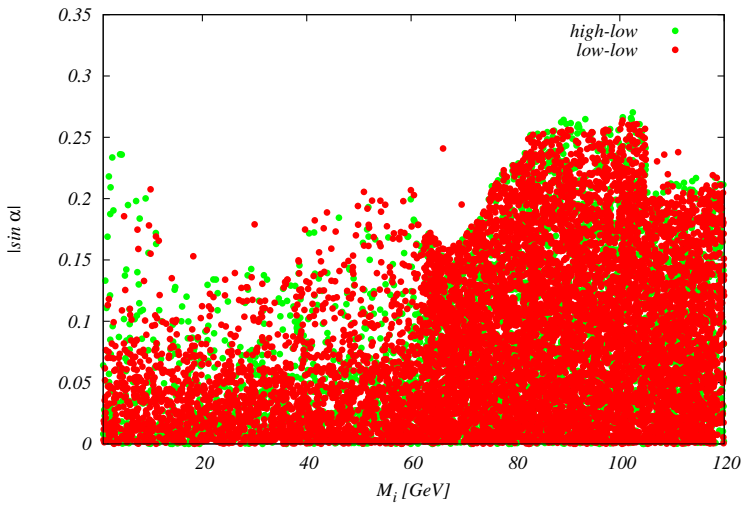
Limited time $\Rightarrow$ next slides highly selective...

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

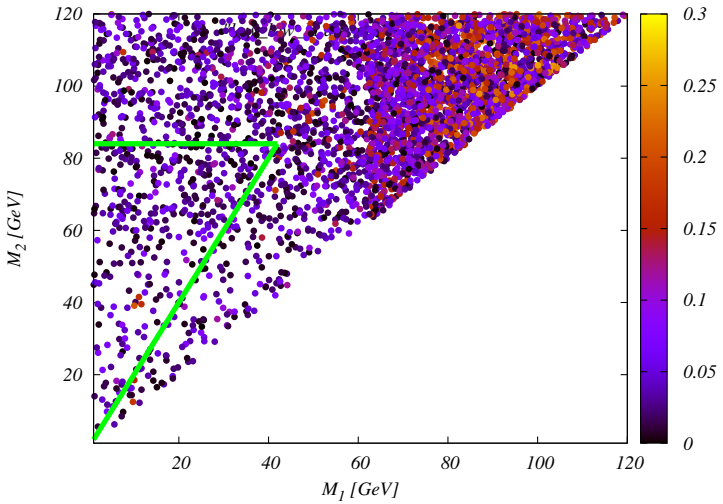
tools used: `HiggsTools`, `ScannerS`, ...

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**

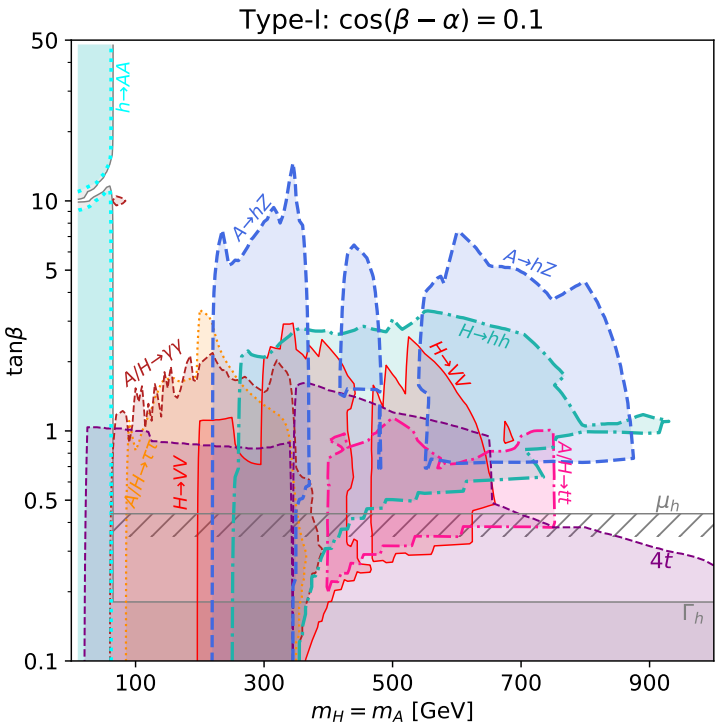
- extend SM scalar sector by **one additional doublet**
- a priori: can lead to flavour changing neutral currents
- way to prevent this: **introduce additional symmetries in potential**

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

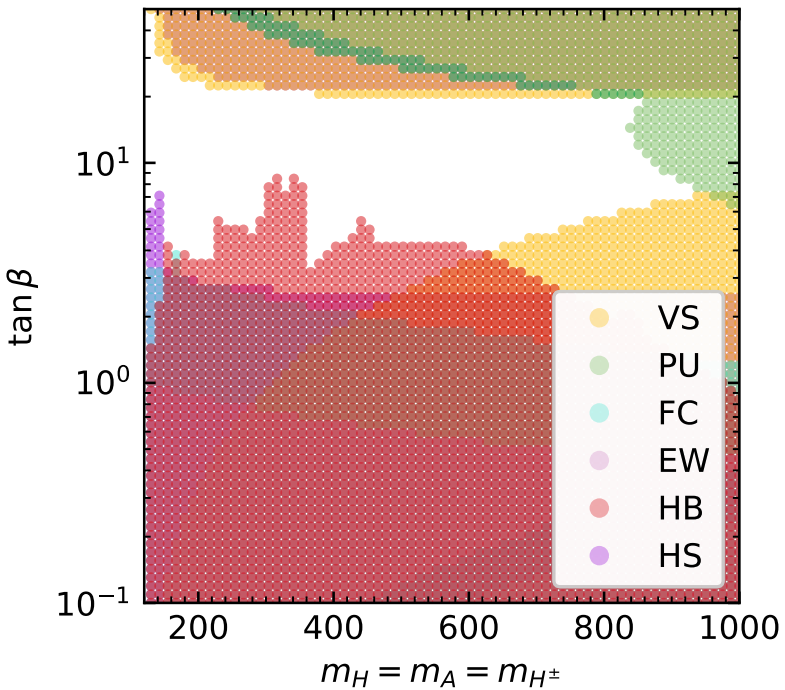
parameters: **masses,** + $\tan\beta$, $\cos(\beta - \alpha)$, m_{12}

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



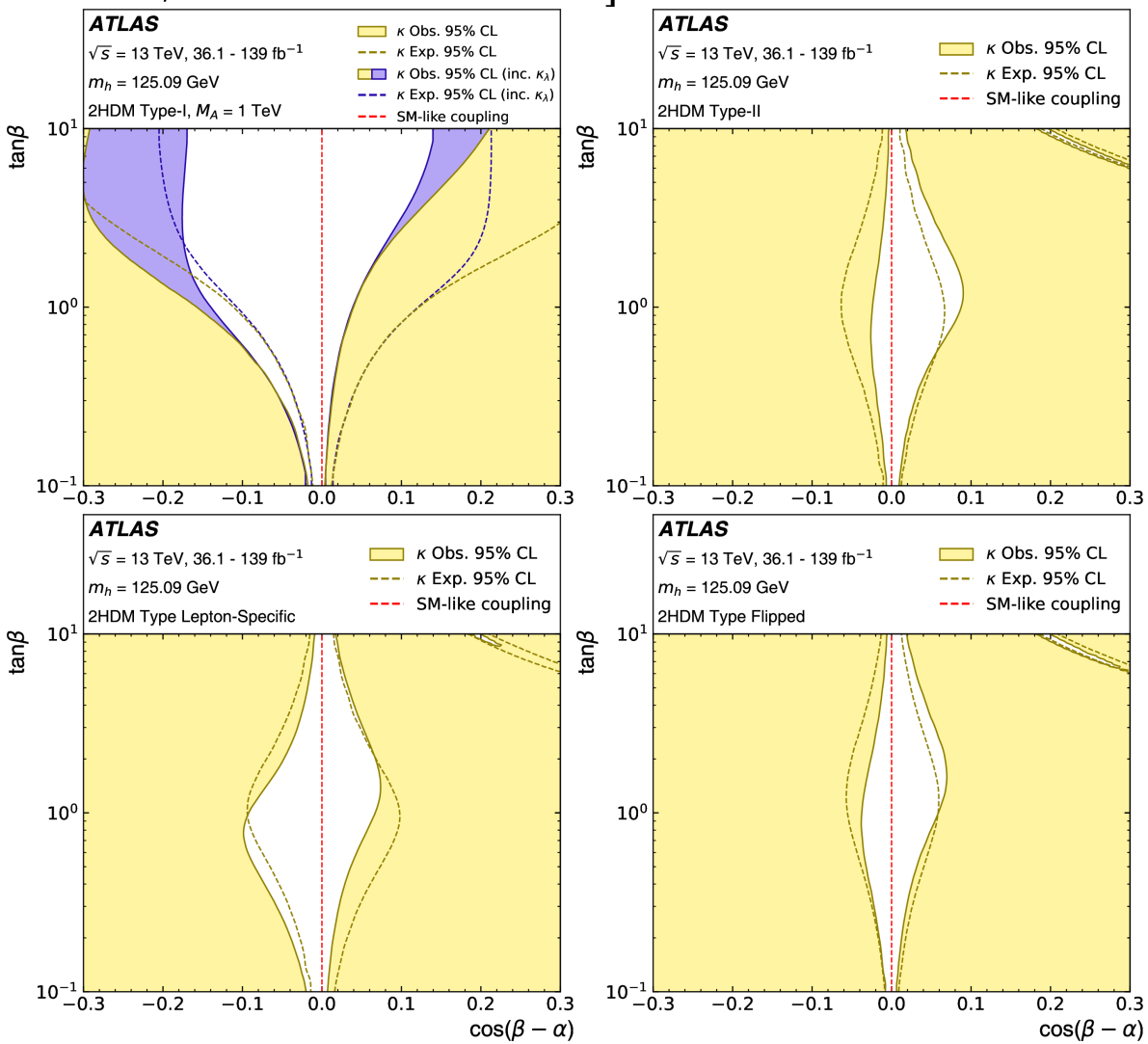
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



[from thdmtools, thanks to K. Radchenko]

Current constraints on alignment in 2HDMs

[arXiv:2402.05742, ATLAS Full Run II]



Typical processes at Higgs factories

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

Production modes in 2HDMs

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

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

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

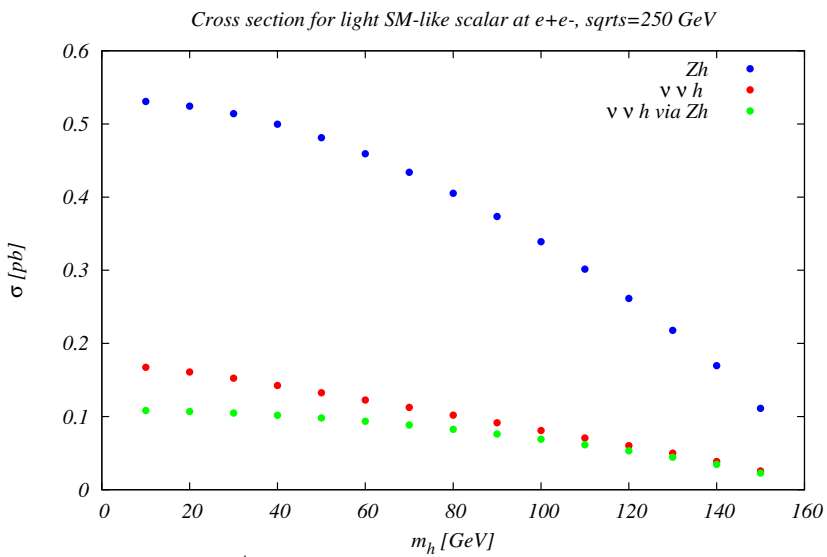
  requires relatively light scalars, typically $m \lesssim 160\,\mathrm{GeV}$

- include suppression/ alignment, and mass range: HZ, hA **supressed by** $\cos(\beta - \alpha)$
- H^+H^- **production: kinematic limit only**

  need light(ish) $H^\pm$, $m_A + m_H \lesssim 250\,\mathrm{GeV}$

Possible production modes and rates
[TR, Universe 2022, 8(5), 286, updated]

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

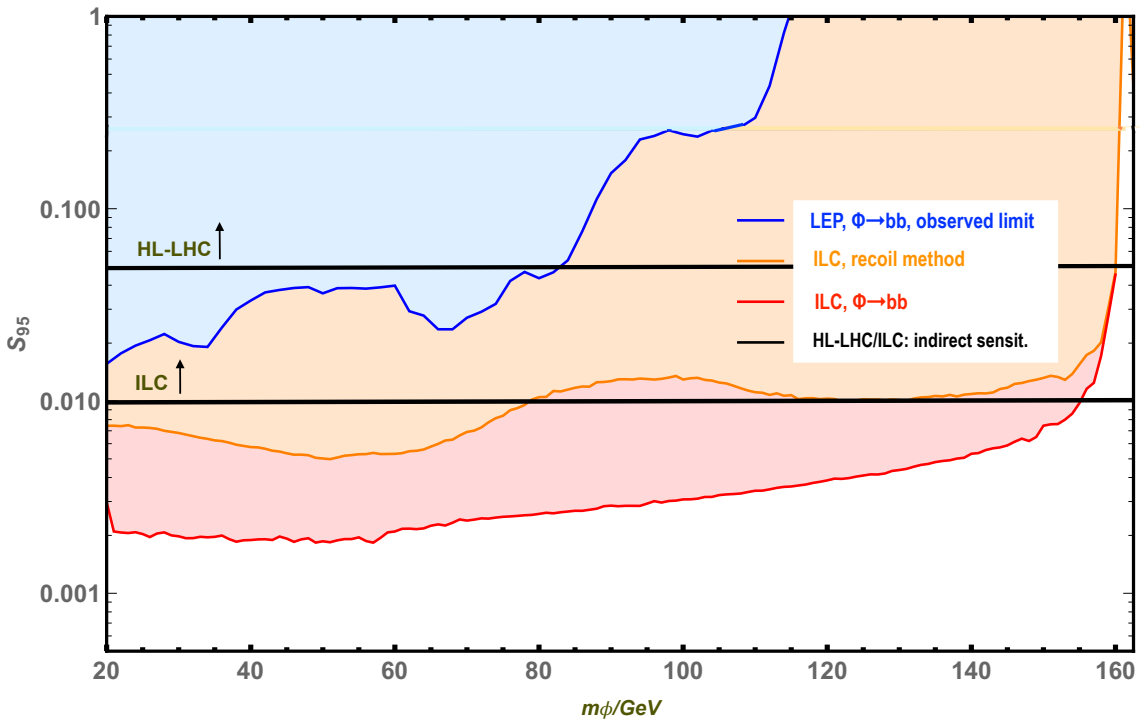


[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;
LO analytic expressions e.g. in Kilian ea, Phys.Lett.B 373 (1996) 135-140]

- 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]

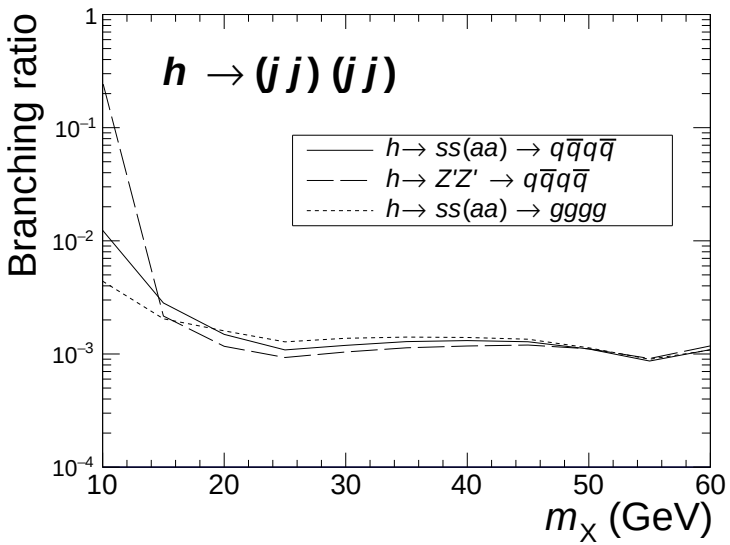


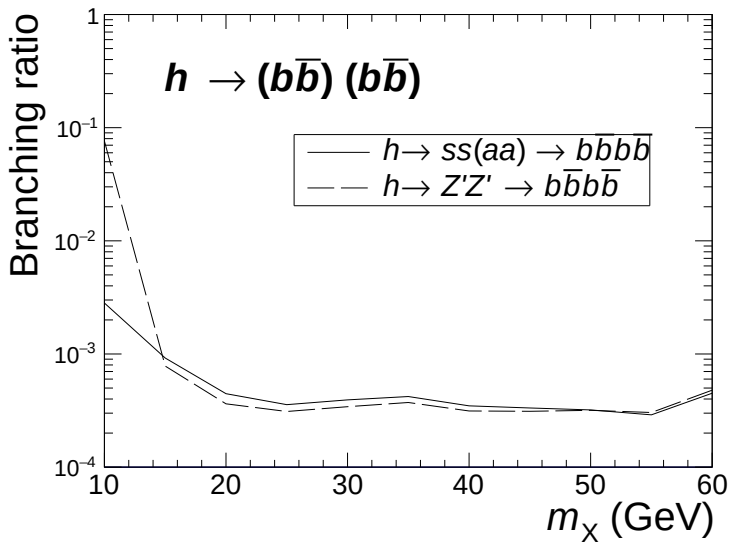
estimate of ILC sensitivity based on validation using LEP results

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

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

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

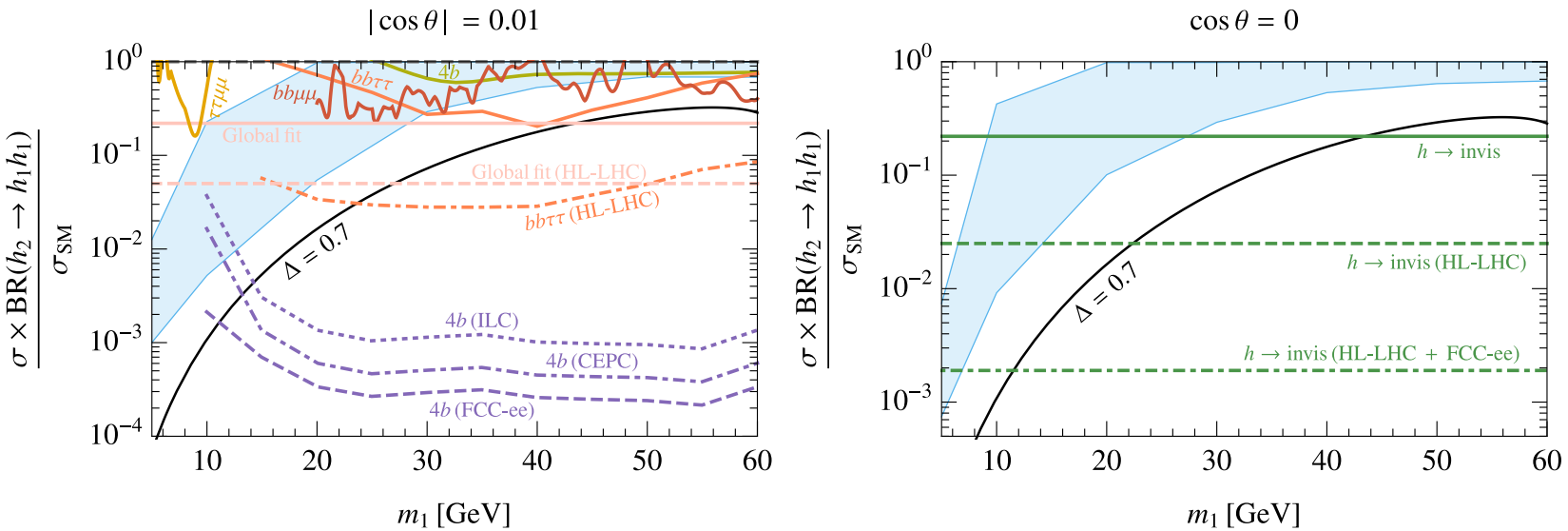




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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 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

  $e^+e^- \to Z\,\phi$

  with different possible decay channels: bb, $\tau\tau$, invisible, ...
- light scalar production in 125 GeV Higgs boson decays

  $h_{125} \to \phi\,\phi$

  again assuming different decay channels for ϕ (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** $300/\,60\,\mathrm{fb}$ **from** Zh **production**
- decays of $h_{125} \rightarrow s\,s$ **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**

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

$\Rightarrow$ **mass** for Higgs Boson and Gauge Bosons

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

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

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

form of potential determines minimum, electroweak vacuum structure

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

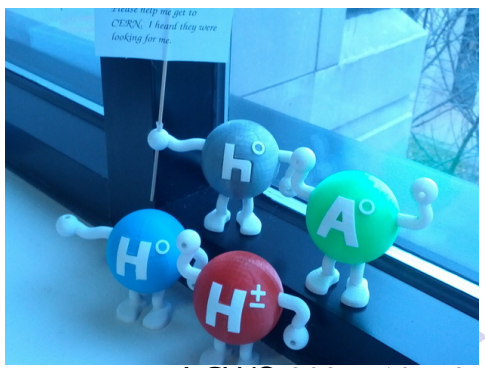
- **full test requires checks of *hhh*, *hhhh* couplings**

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

Other possible extensions

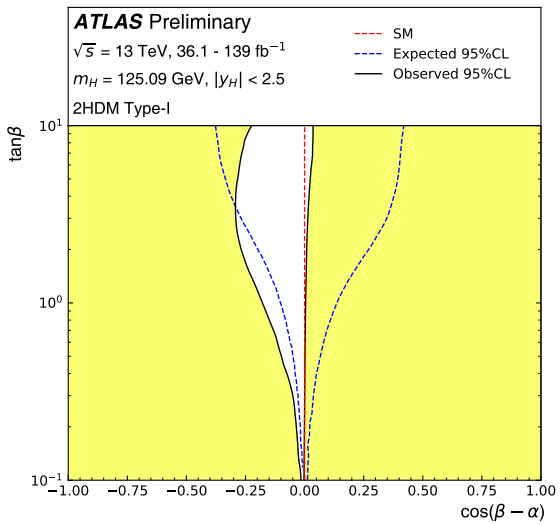
- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add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

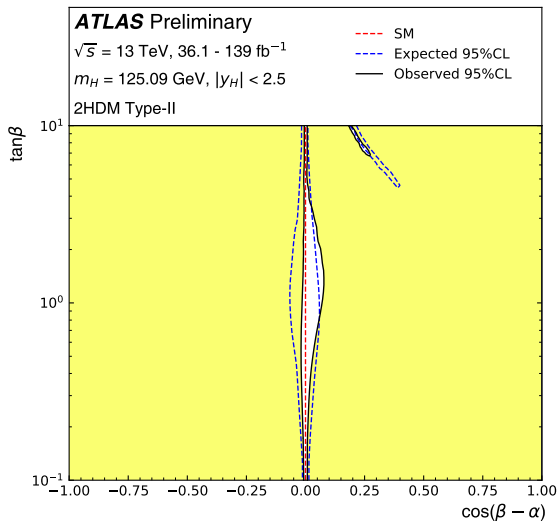
  $\Rightarrow$ **new scalar states** $\Leftarrow$

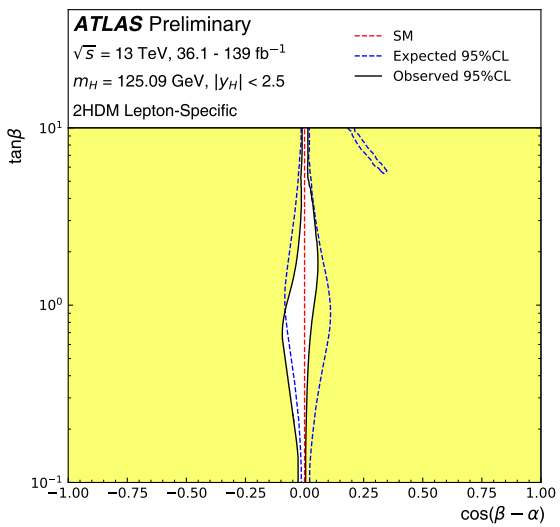


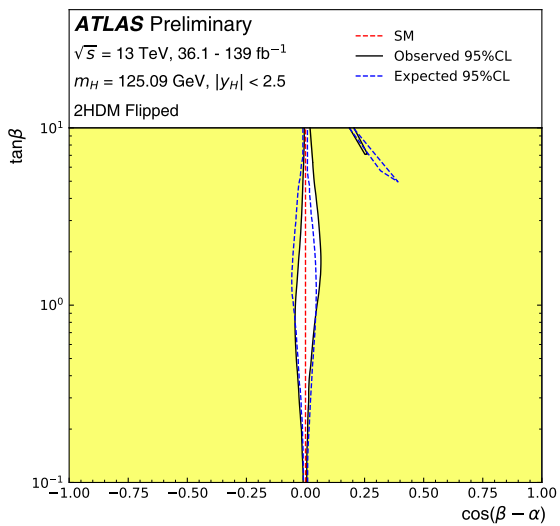
Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]





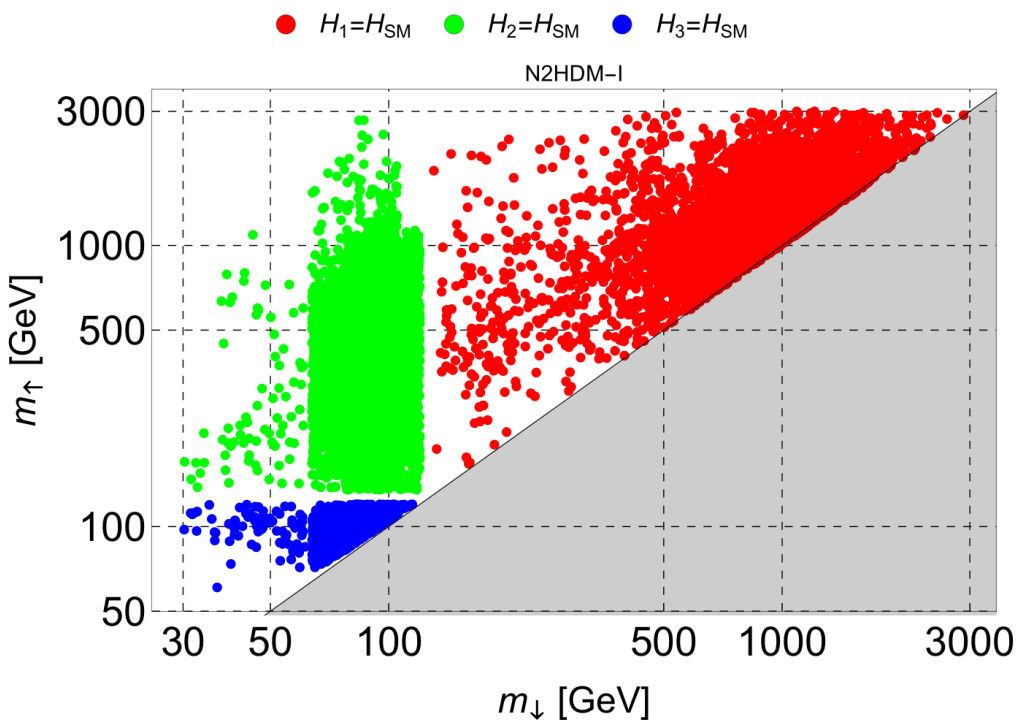




N2HDM example

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

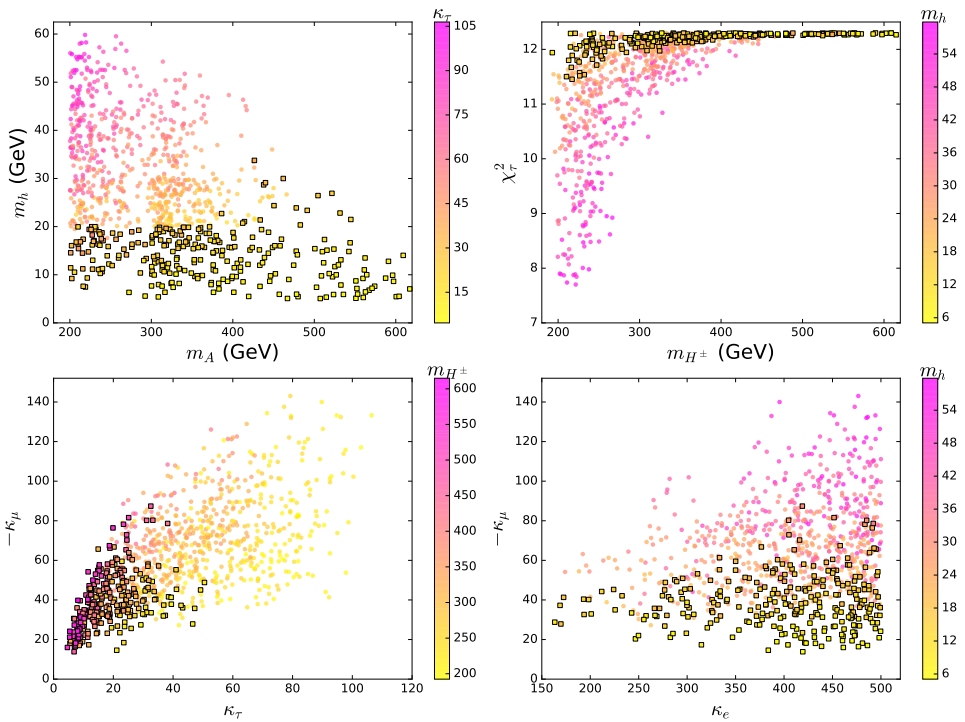
N2HDM: 2HDM+ real singlet



Lepton-specific IDM

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

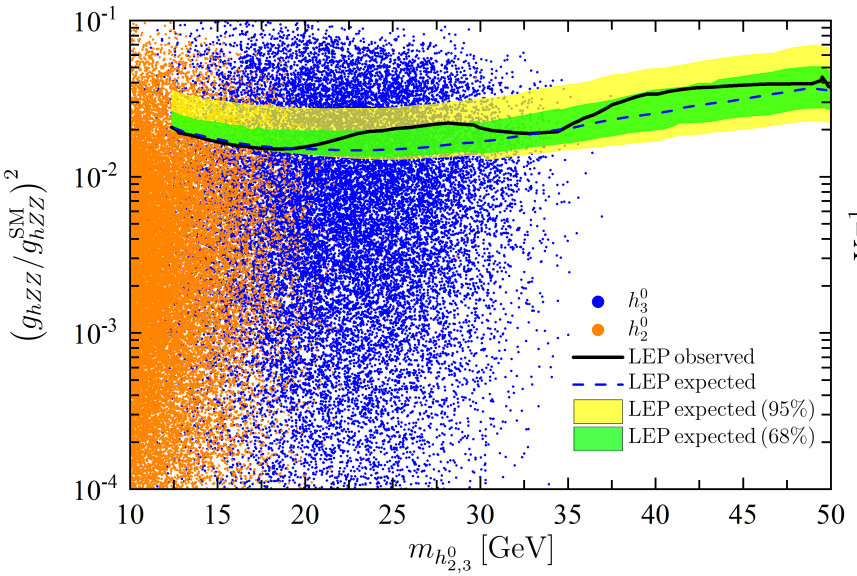
Inert Doublet Model, with $\mathbb{Z}_2$ breaking terms coupling to leptons

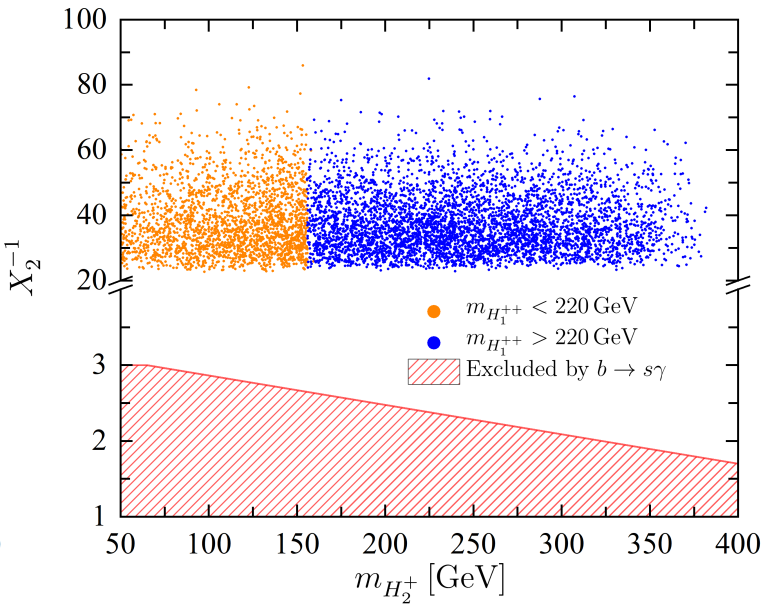


various constraints (including agreement with $g_\mu - 2$);
squares: allowed, bullets: forbidden

Scalar triplet model

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

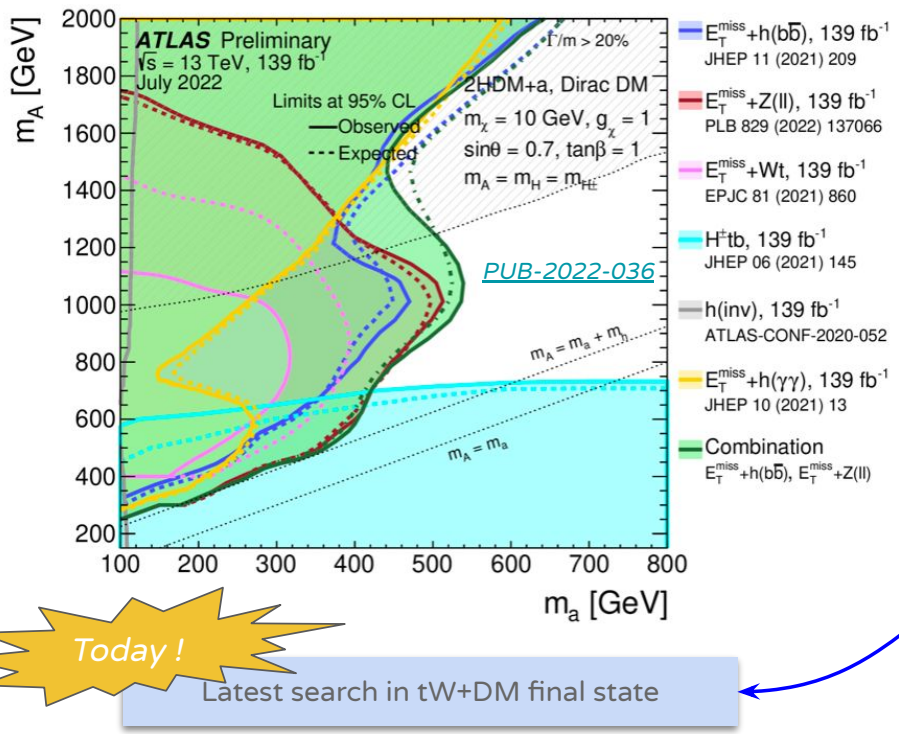




5 neutral, 3 singly charged, 2 doubly charged scalars

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

A more UV-complete model: 2HDM+a

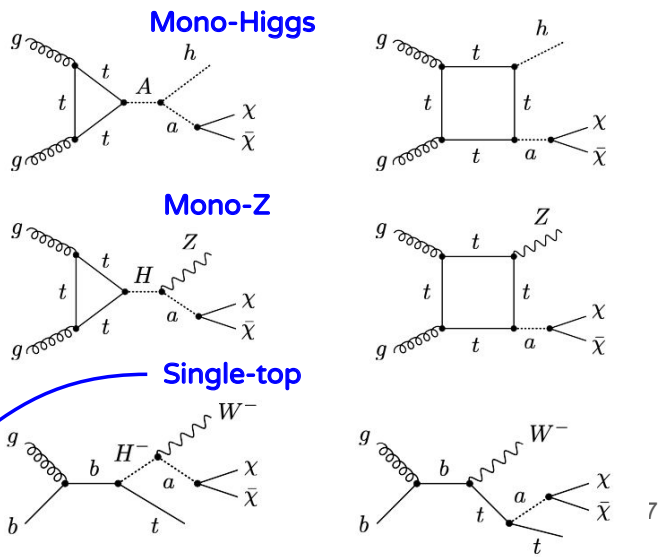


Today !

Latest search in tW+DM final state

Phys.Dark.Univ Vol 27, 100351

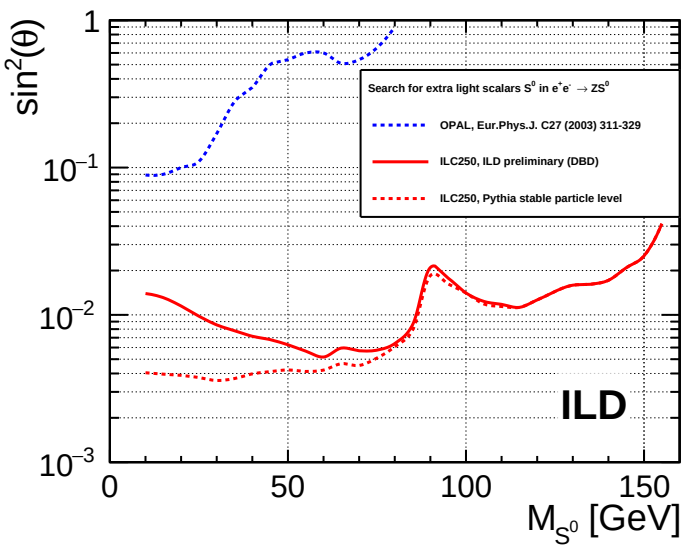
Simplest renormalizable theory with DM singlet
Unitarity.
Rich phenomenology in several final states at colliders.

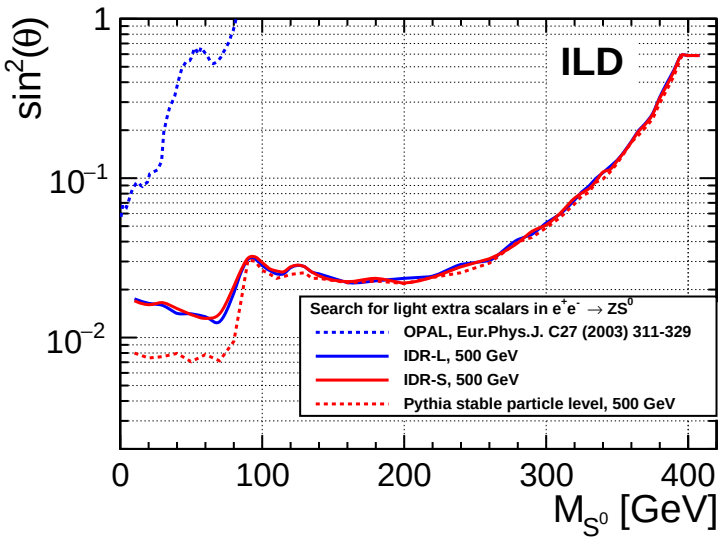


!! analysis still fixes many parameter values !!

Projections for additional scalar searches

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





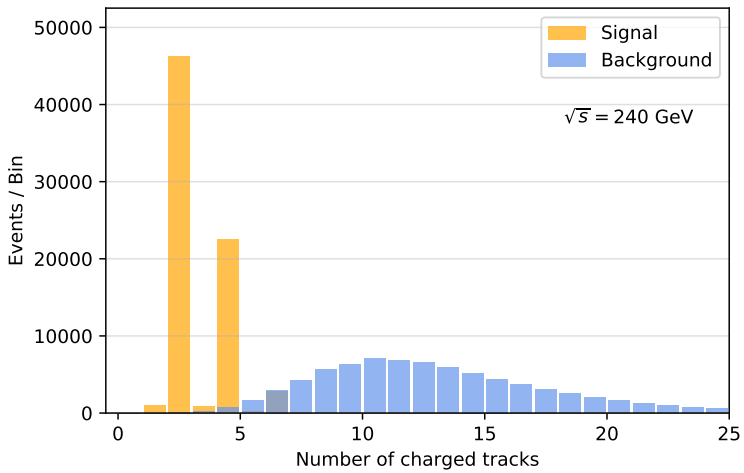
additional scalar, $\sin\theta$ rescaling wrt SM prediction, comparison of different detector models
recoil method

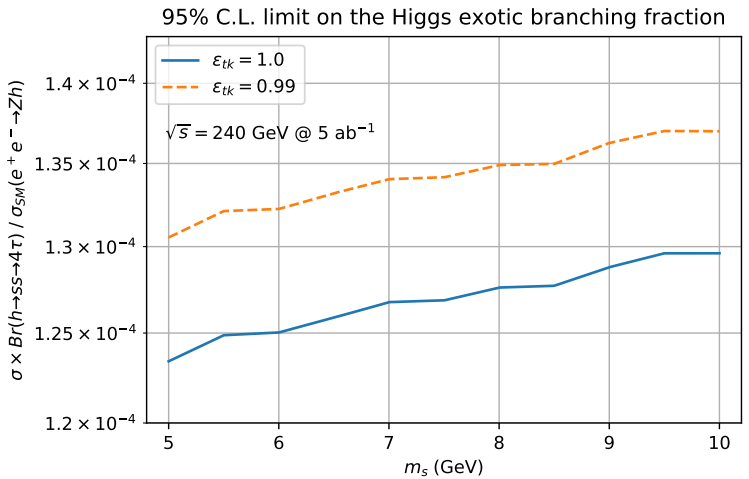
Possible searches

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

Exotic decays - $h \to s\,s \to 4\tau$

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





[$m_s = 7.5\,\mathrm{GeV}$; background mainly from $h \to j\,j$]

ε_{tk}: tracking efficiency

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

[invisible BR, signal strength, assumes SM-like decay to τs]

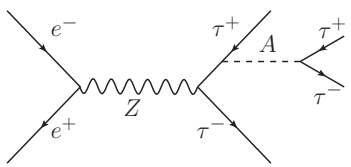
Type X 2HDM, 4τ final state via $\tau\tau A$ production

[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

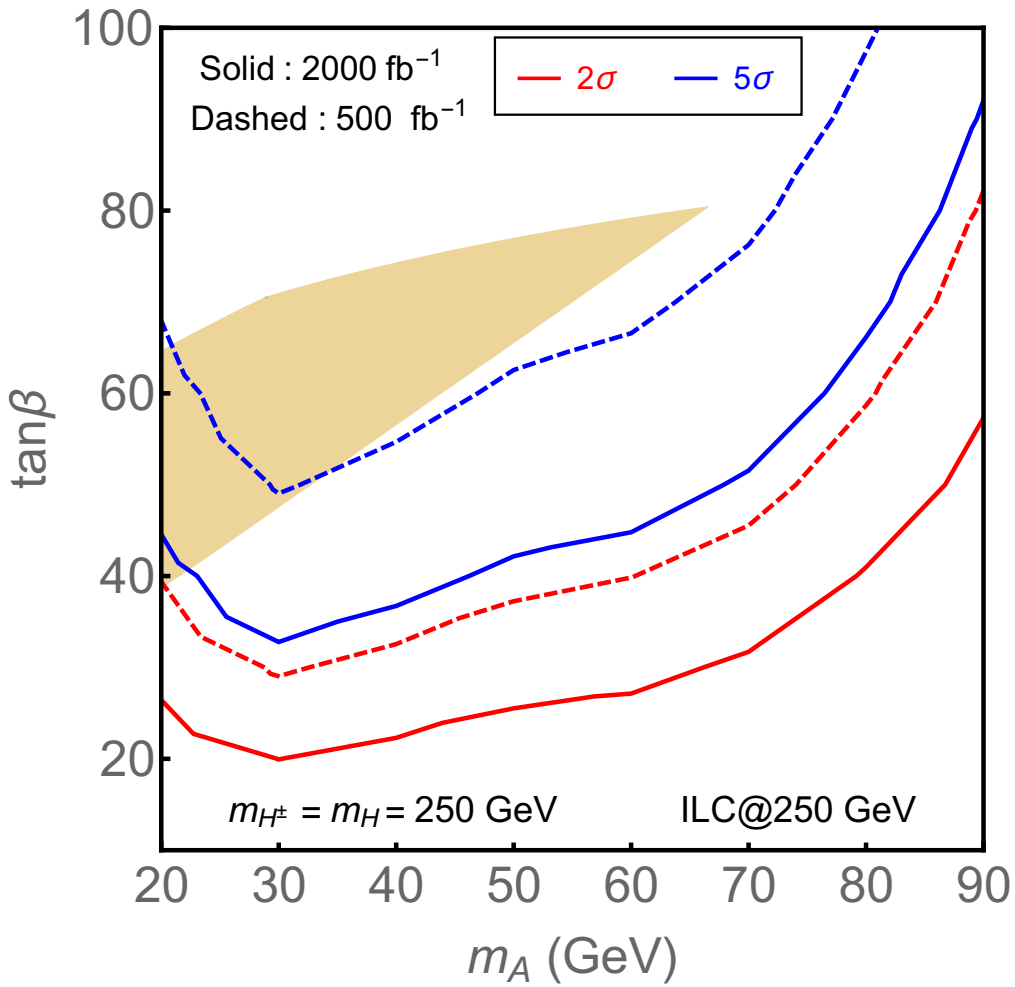
- The channel $Z \to h_{SM} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



- This is the equivalent to ttH searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 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

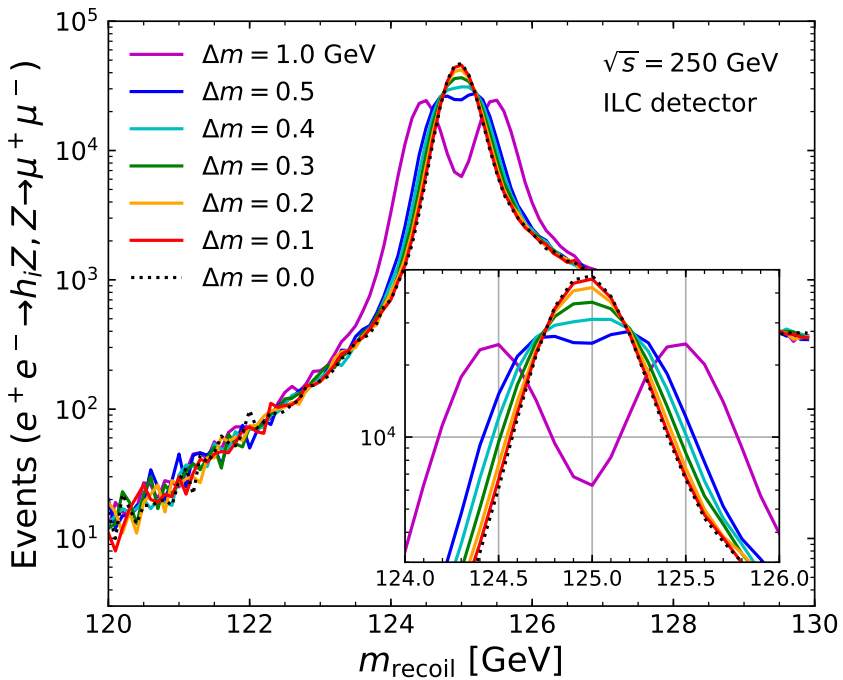
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]

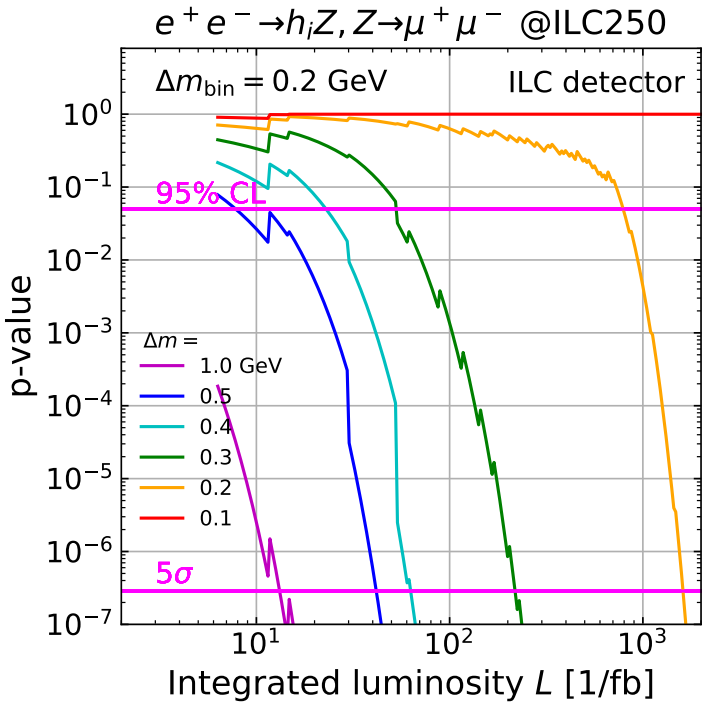


Test of degenerate additional scalar, including dark matter

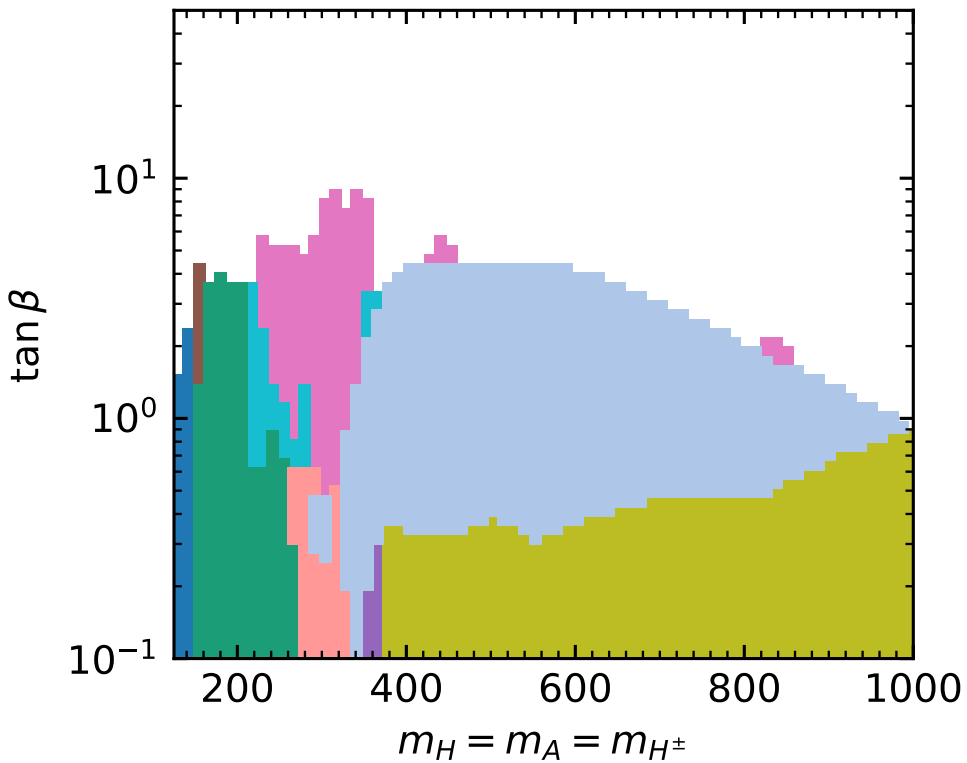
[S. Abe, G.-C. Cho, K. Mawatari, Phys.Rev.D 104 (2021) 3, 035023]

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





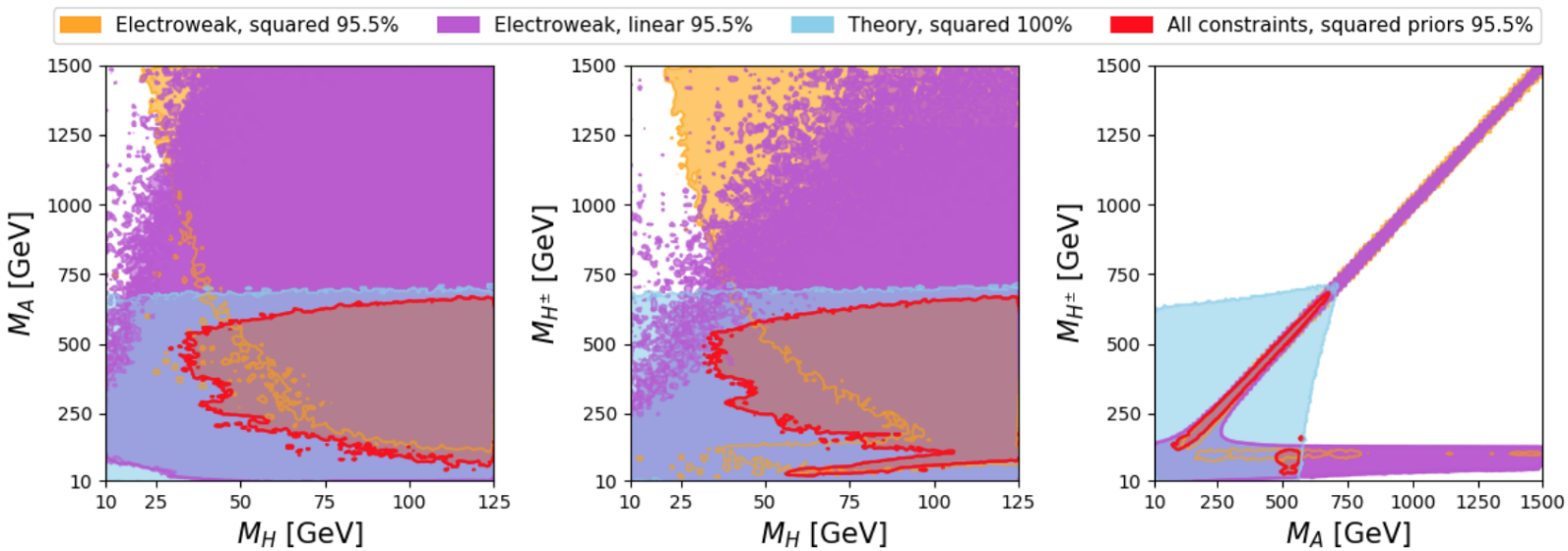
2HDM parameter space w thdmtools, thanks to K. Radchenko



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

Aligned 2HDM

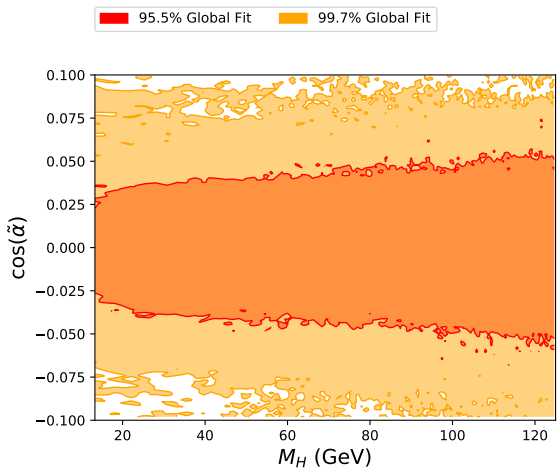
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]

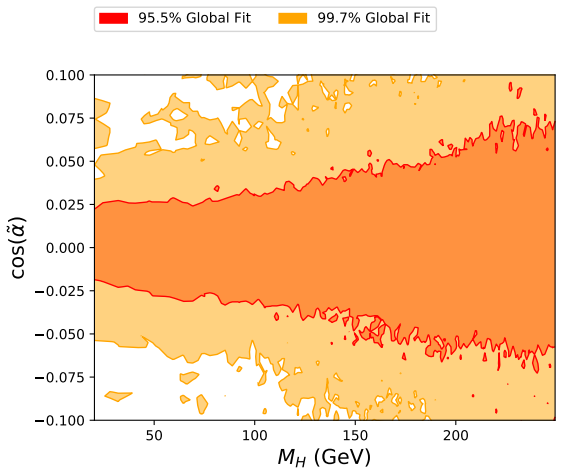


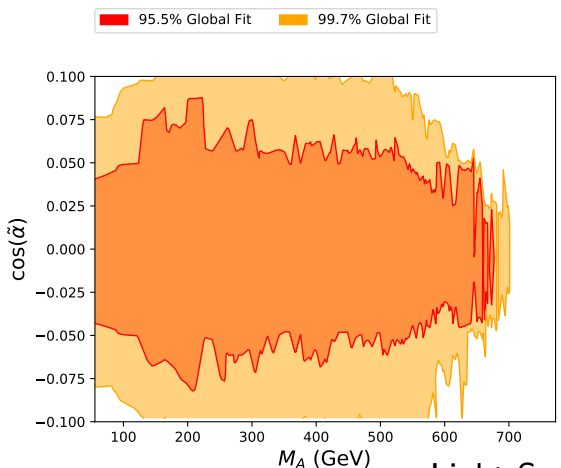
low mass region allowed; however, *HZZ* typically suppressed by $\cos(\beta - \alpha)$ [$\lesssim$ 0.25]

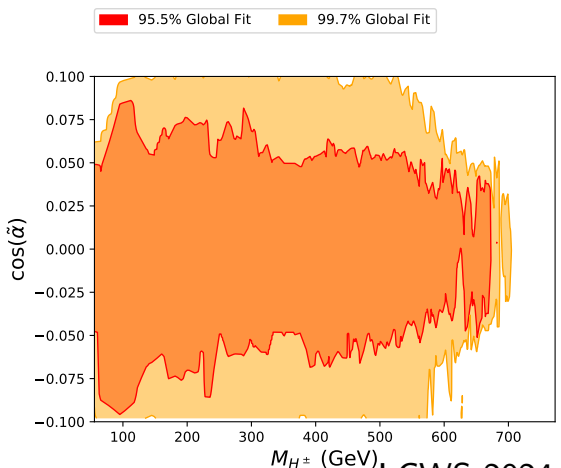
... and in terms of mixing angle...

[Universe 8 (2022) 286; Thanks to V. Miralles]



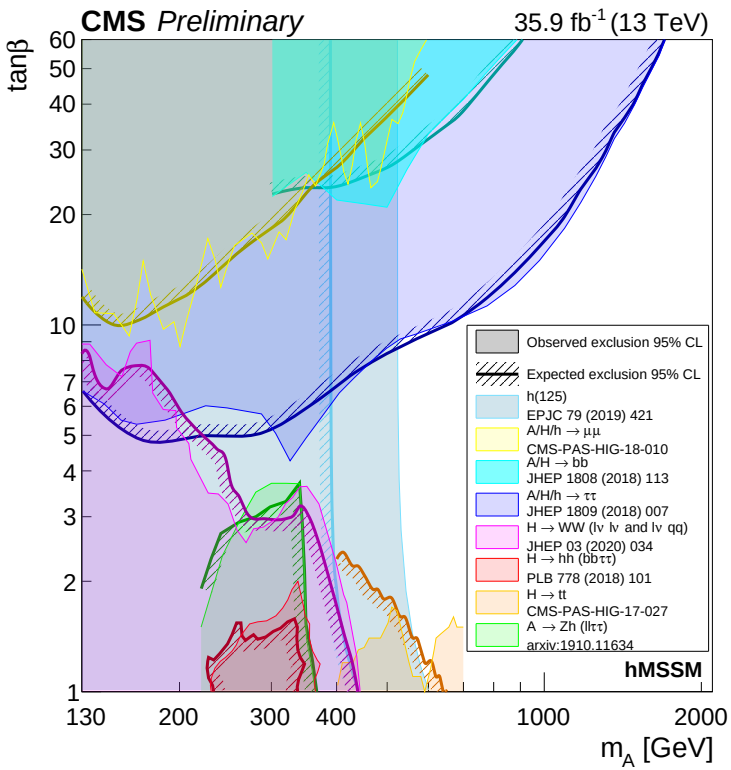


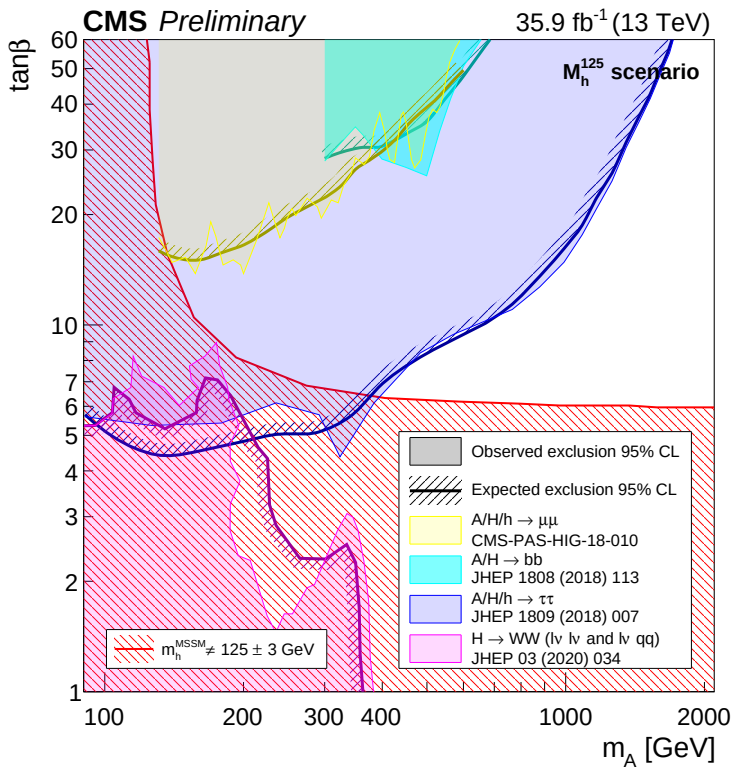




CMS MSSM summary plots, early Run II

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



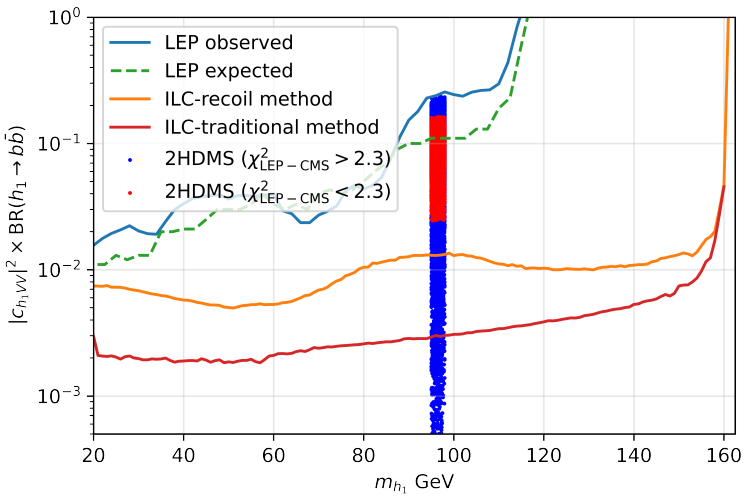


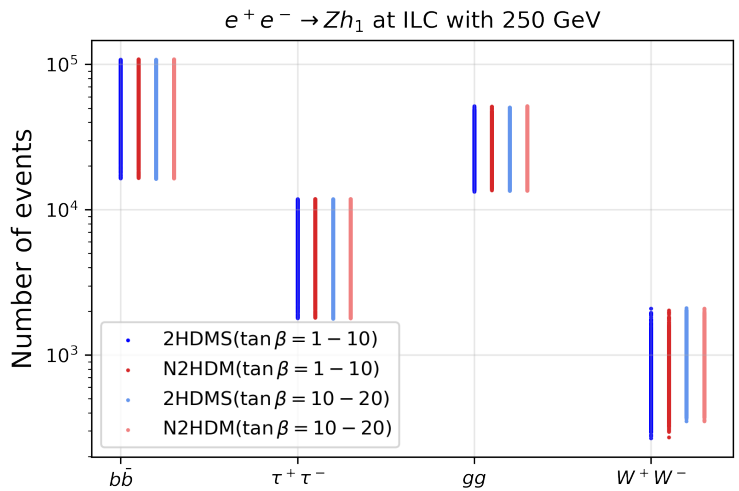
The 96 GeV LEP resonance

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

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

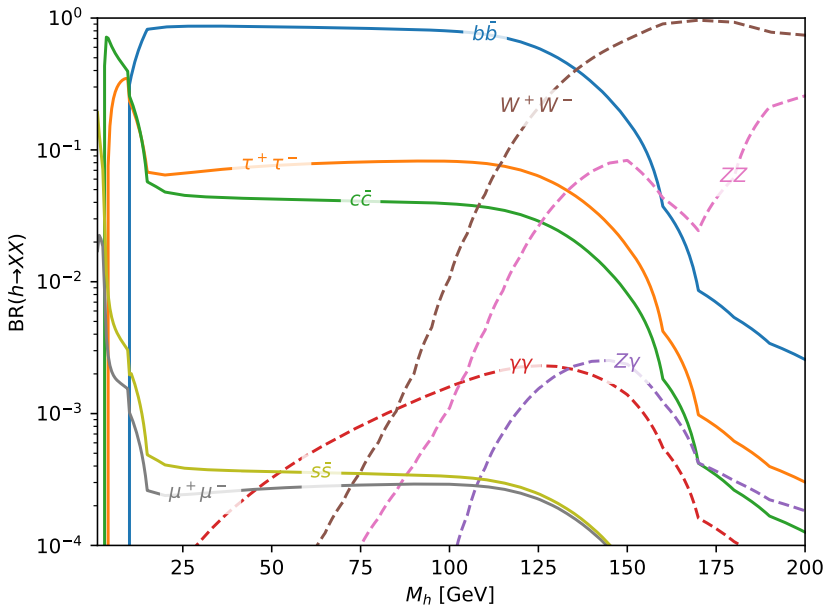
various BSM models, rates using $\int \mathcal{L} = 2\,\mathrm{ab}^{-1}$



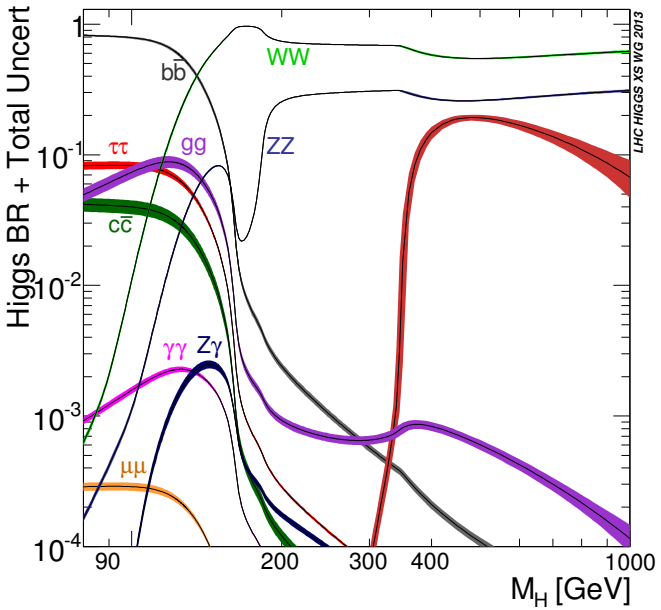


N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside 1 σ]

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)