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

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3rd ECFA workshop on e^+e^- Higgs, Electroweak and Top Factories
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Paris, France
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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)

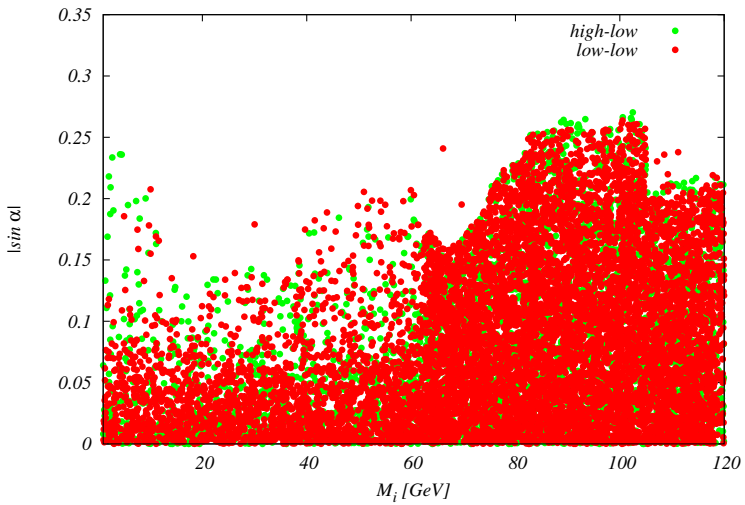
Limited time $\Rightarrow$ next slides highly selective...

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

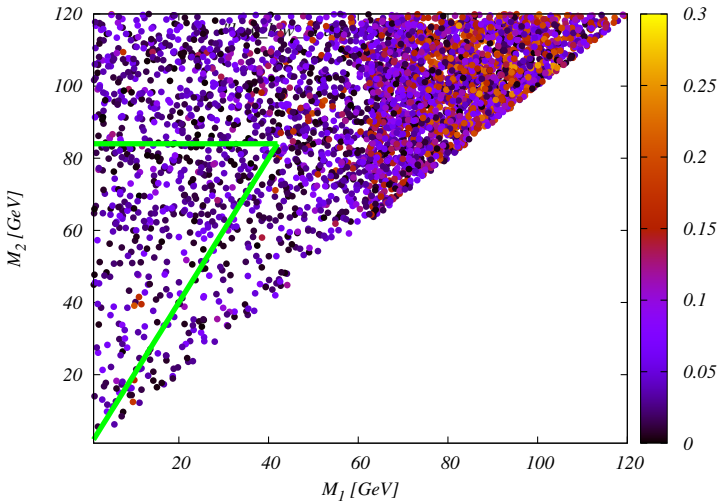
tools used: `HiggsTools`, `ScannerS`, ...

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**

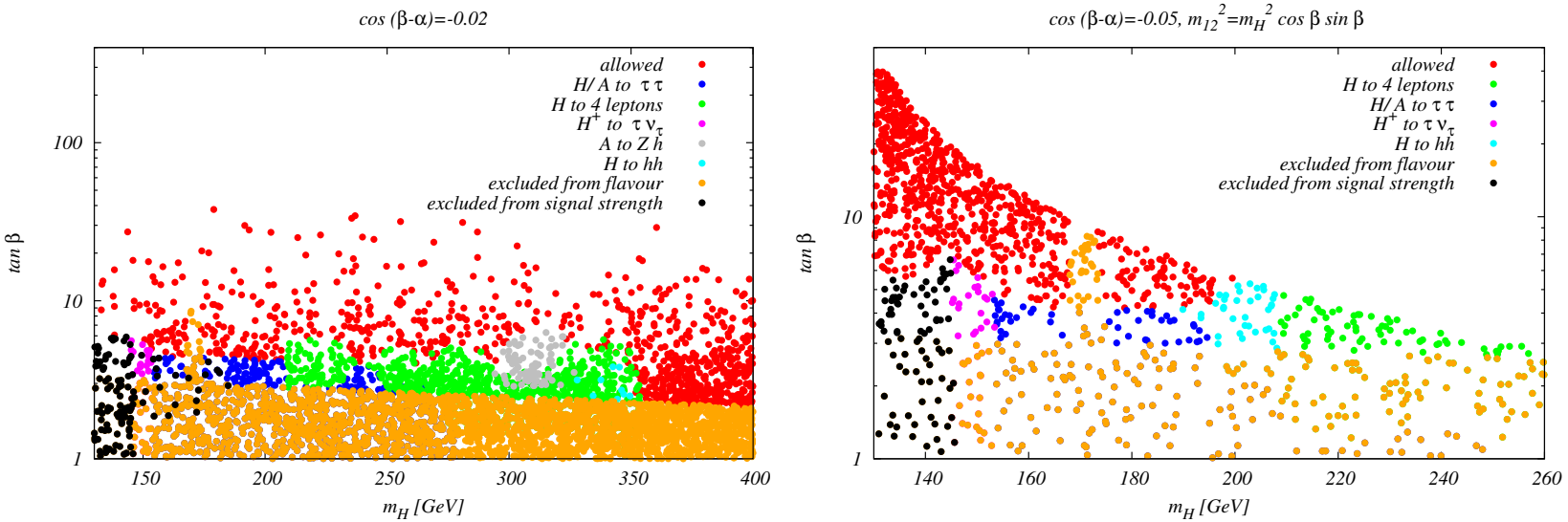
particle content: $\underbrace{h, H}_{\text{CP-even}}$, $\underbrace{A}_{\text{CP-odd}}$, $H^{\pm}$

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

TR, ArXiv:2409.19657

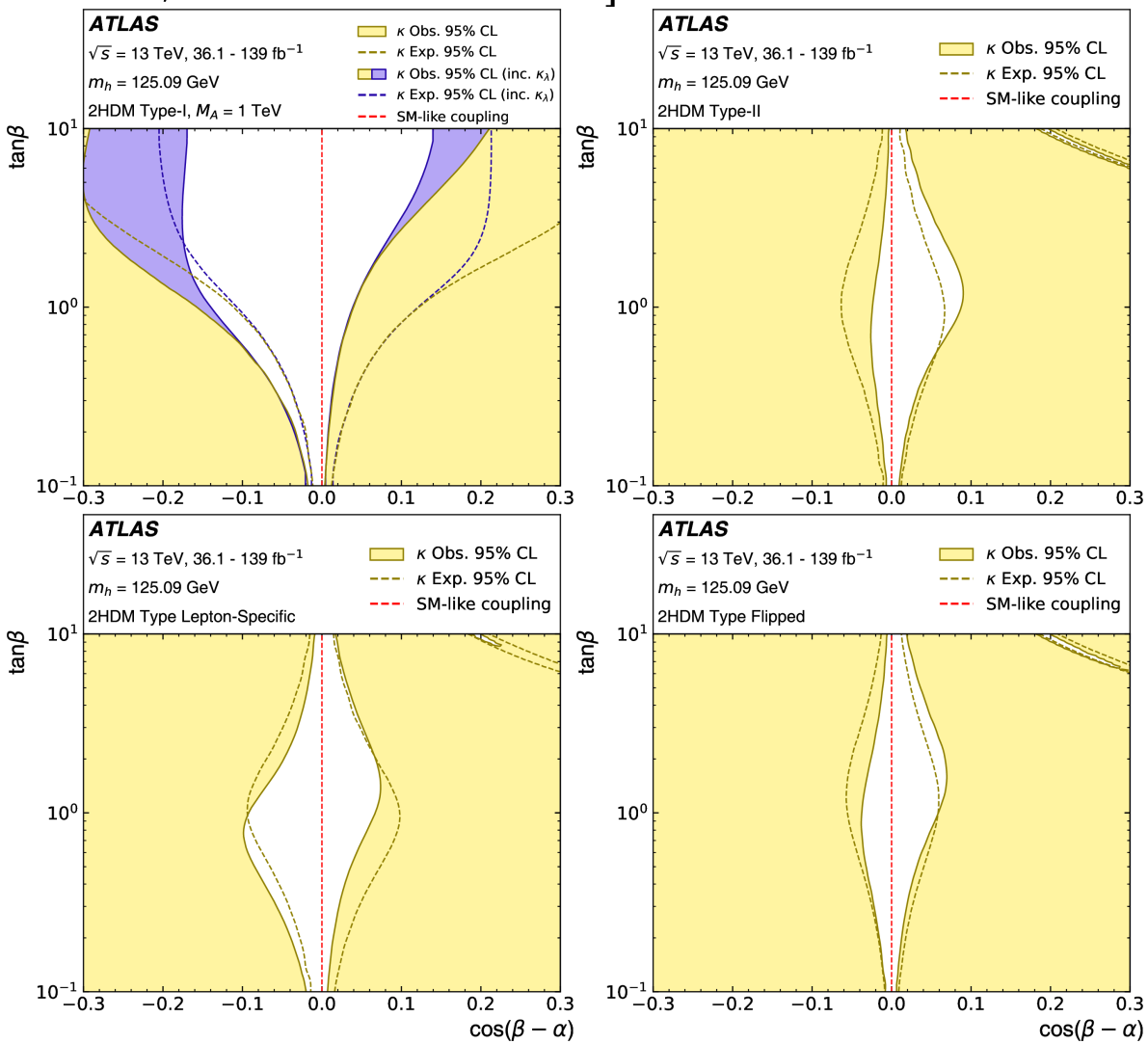


$$m_H = m_A = m_{H^\pm}$$

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

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** $\sum_i m_i \lesssim \sqrt{s}$

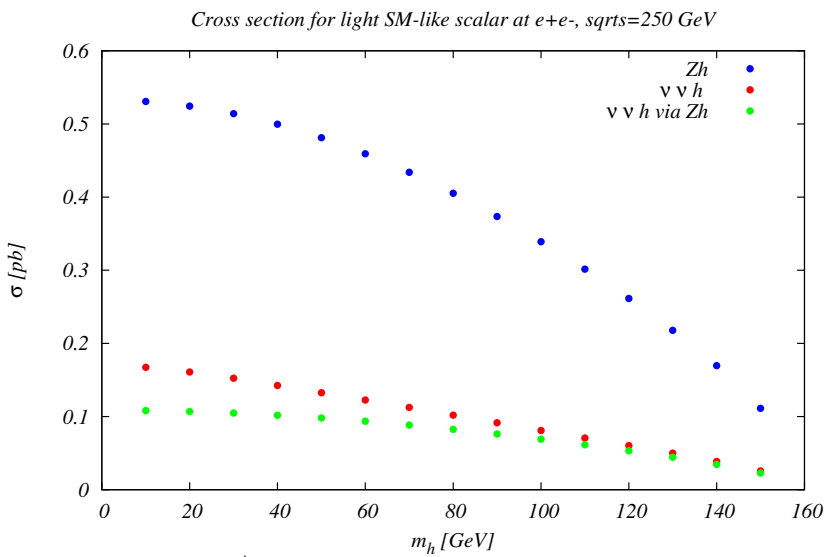
  requires relatively light scalars, typically $m \lesssim 160\,\mathrm{GeV}$

- 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]

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



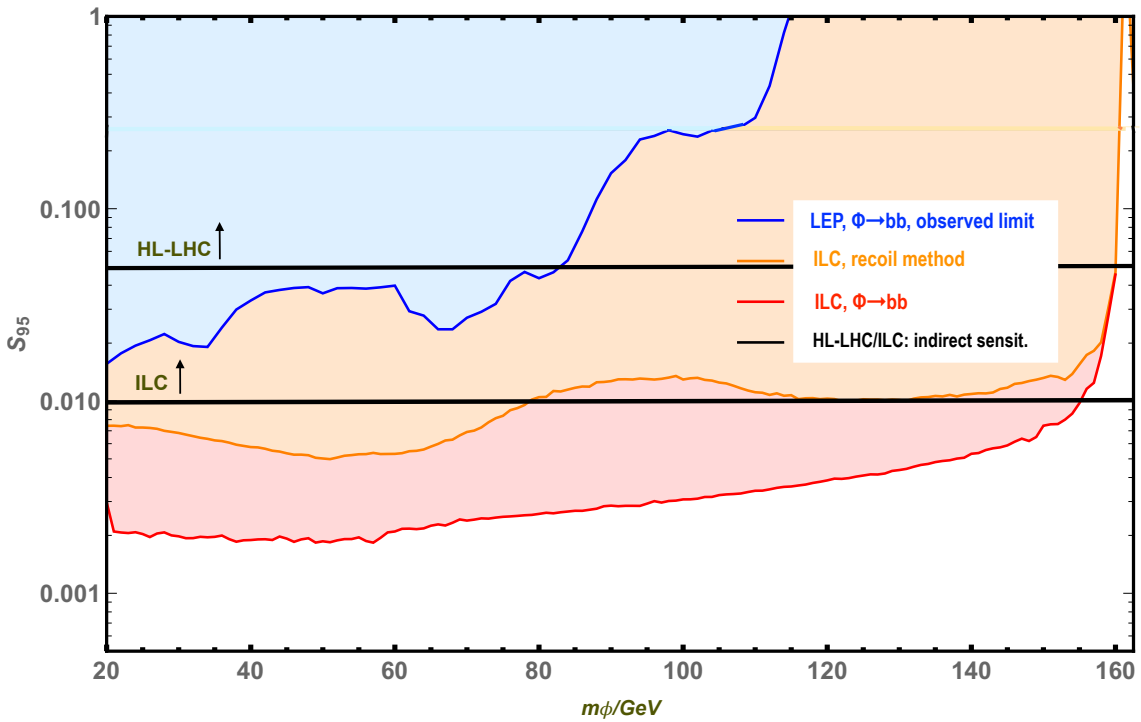
[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;

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]

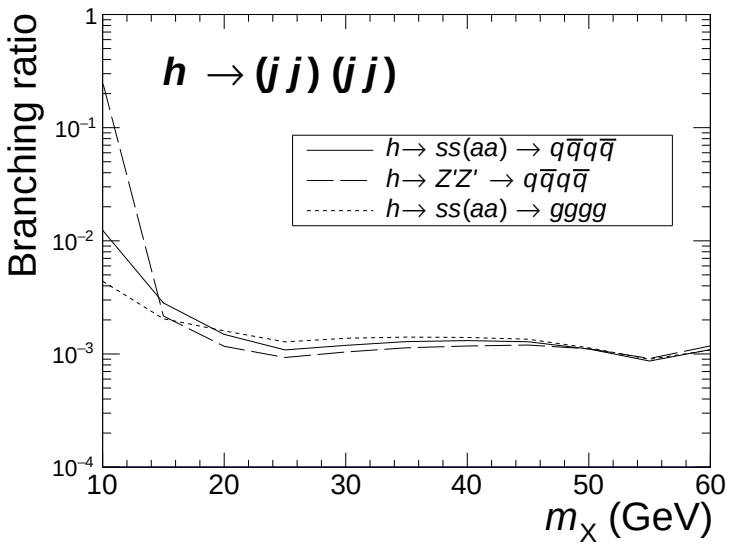


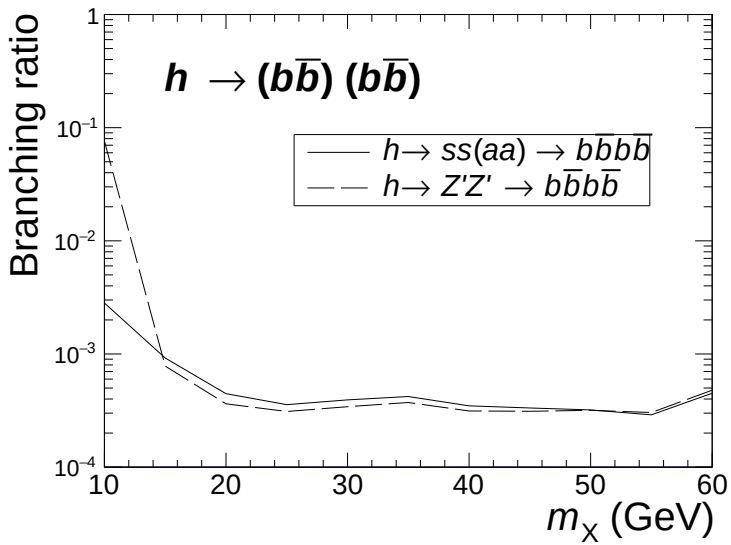
estimate of ILC sensitivity based on validation using LEP results

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]

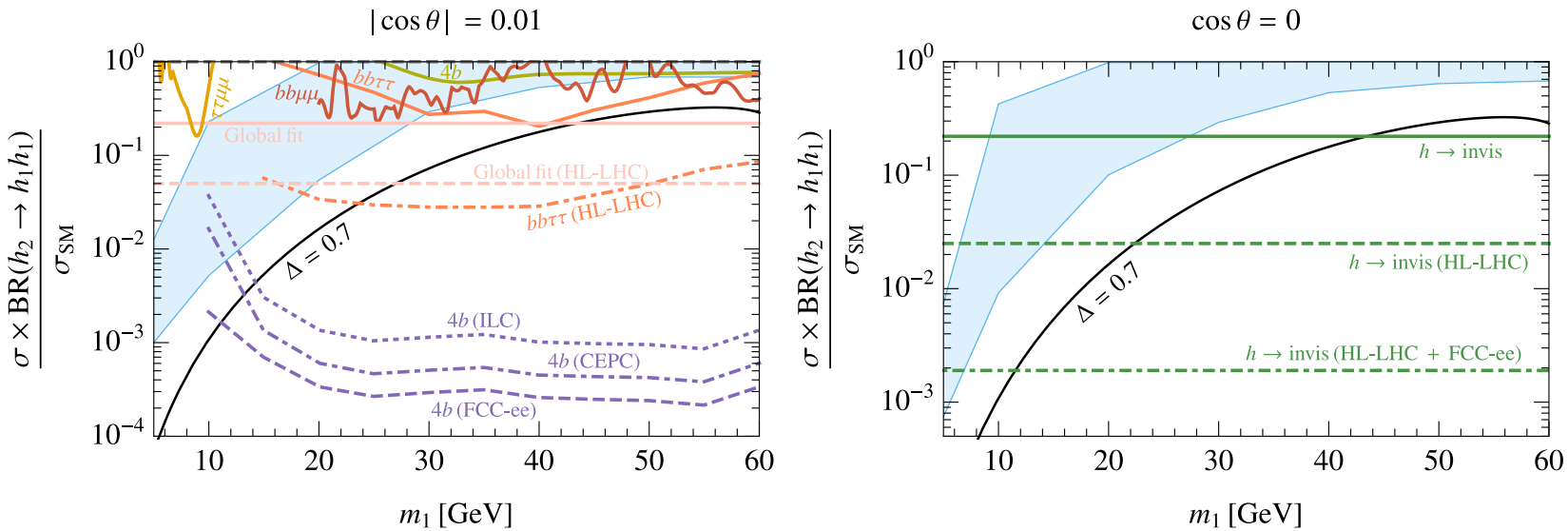




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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 $h_{125} \to s\,s$ **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

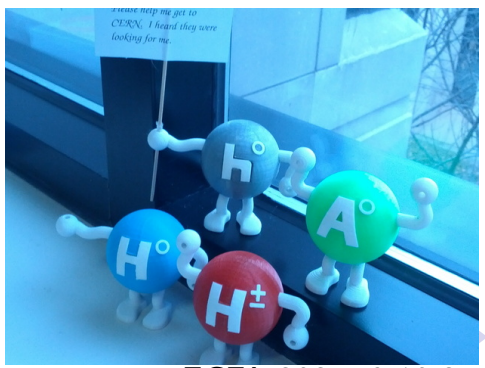
- **full test requires checks of *hhh*, *hhhh* couplings**

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

Other possible extensions

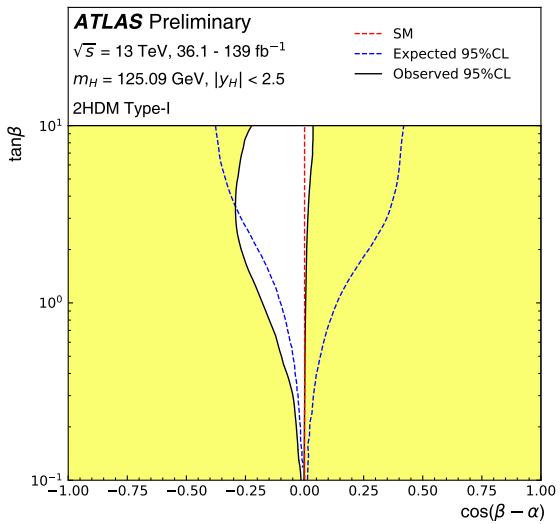
- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add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

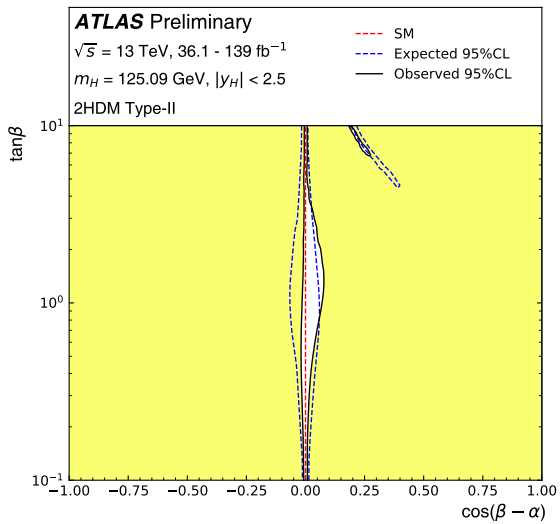
  $\Rightarrow$ **new scalar states** $\Leftarrow$

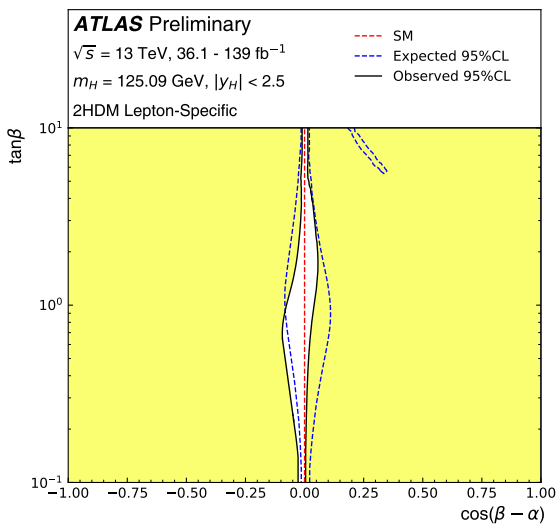


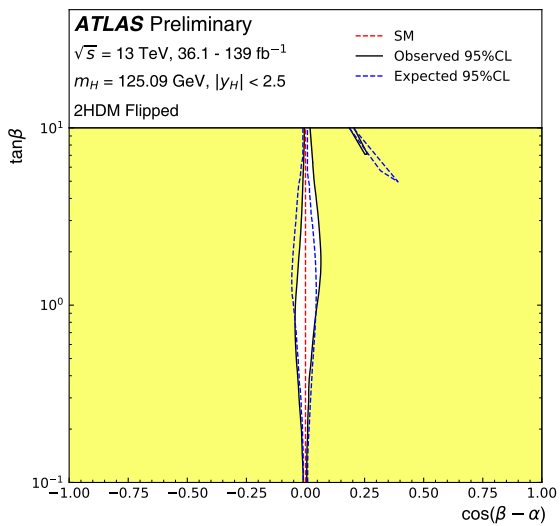
Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]





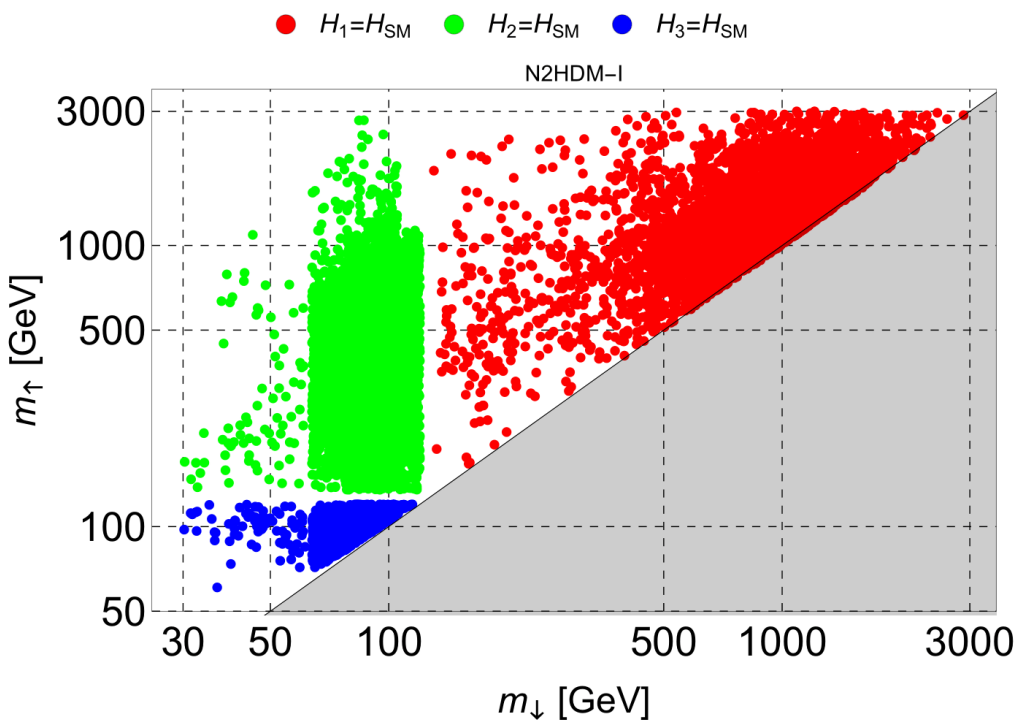




N2HDM example

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

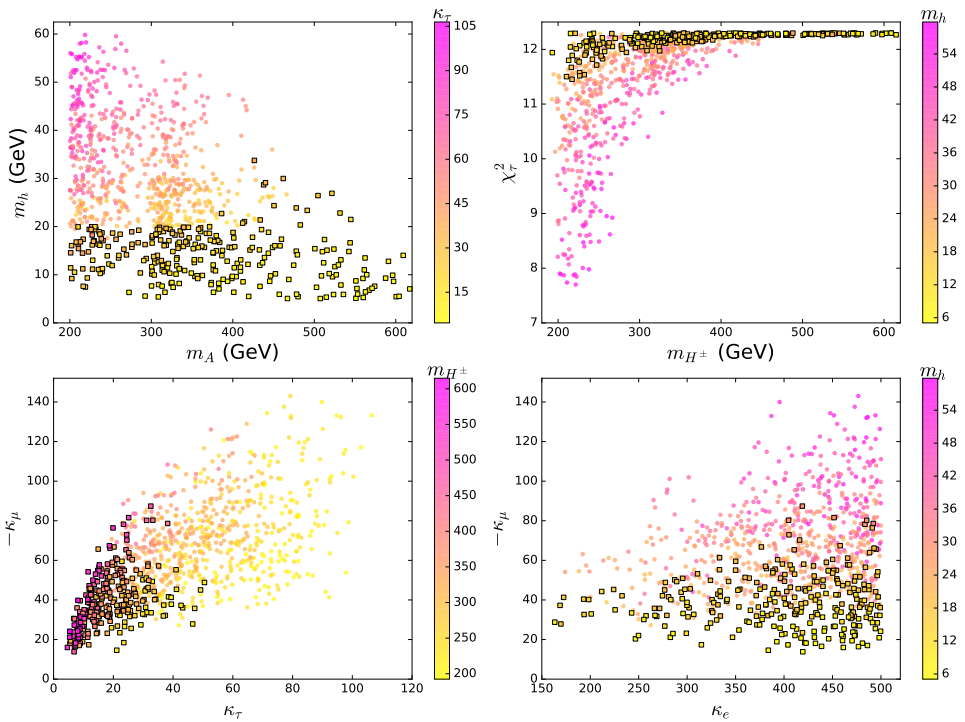
N2HDM: 2HDM+ real singlet



Lepton-specific IDM

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

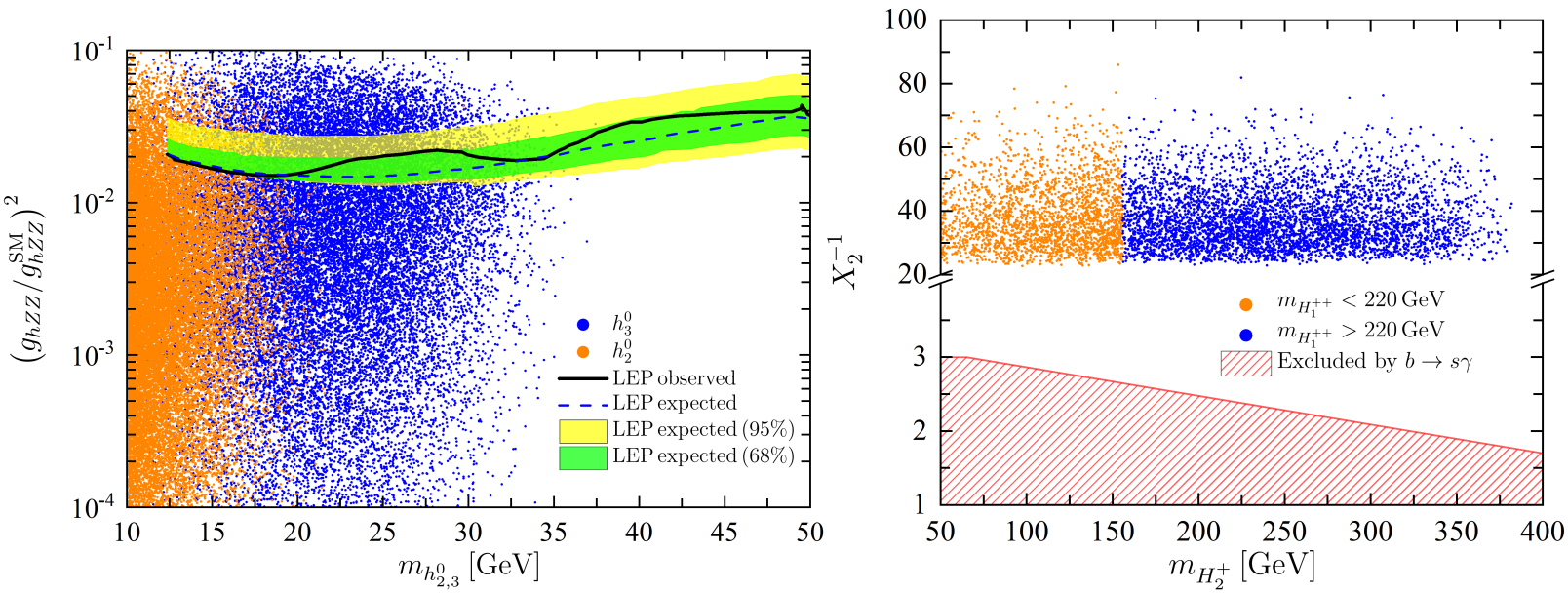
Inert Doublet Model, with $\mathbb{Z}_2$ breaking terms coupling to leptons



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

Scalar triplet model

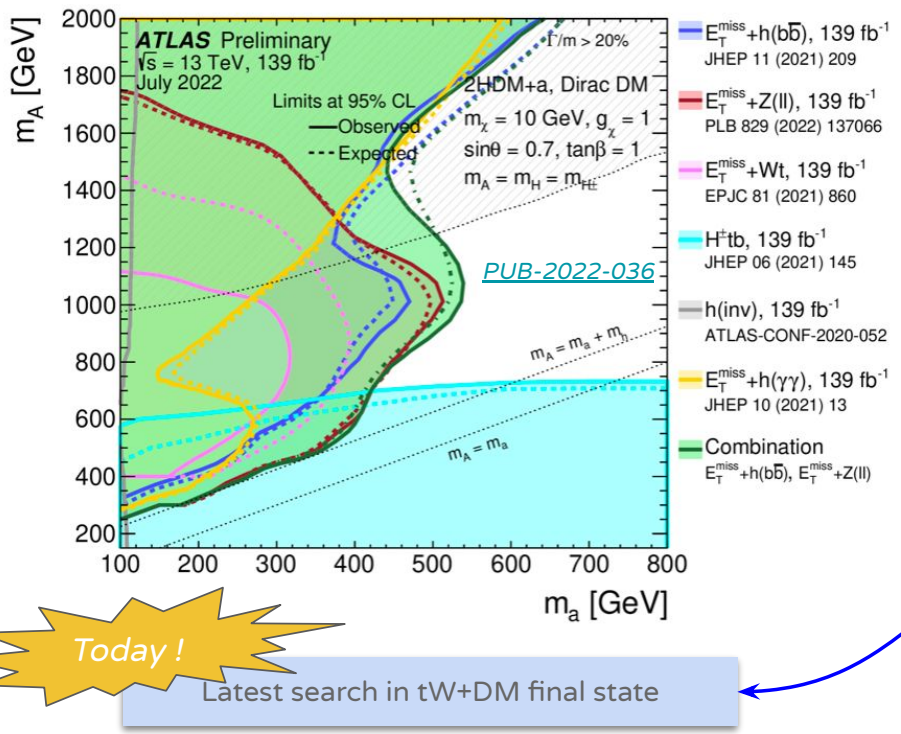
[P.M. Ferreira, B.L. Gonalves, F.R. Joaquim, JHEP 05 (2022) 105]



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

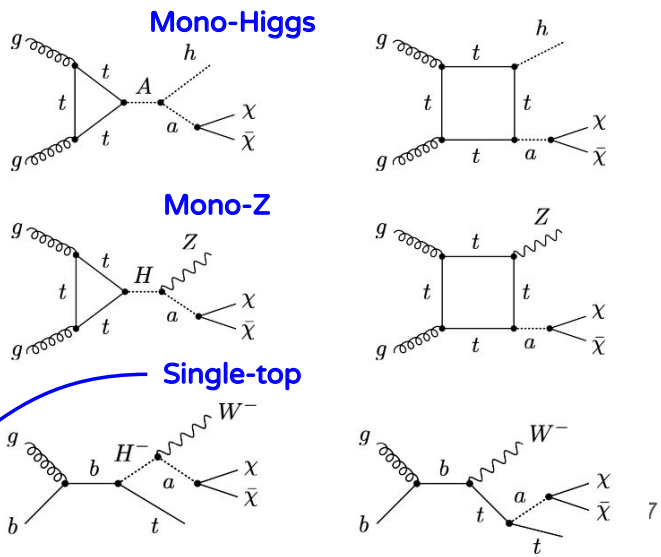


Today !

Latest search in tW+DM final state

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

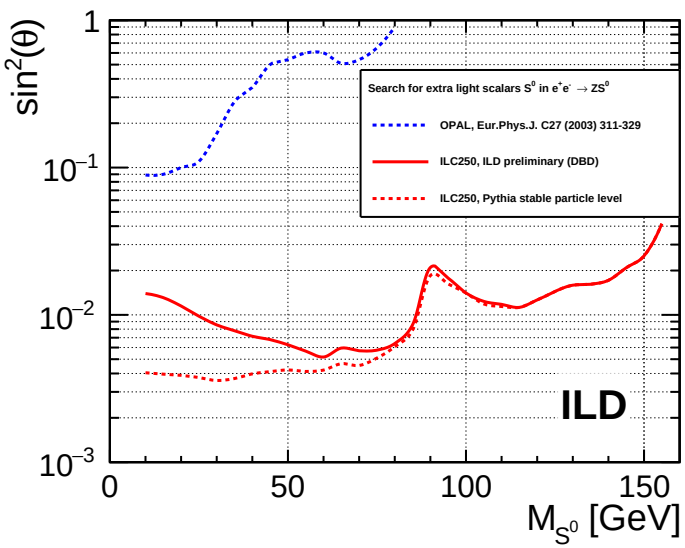
Simplest renormalizable theory with DM singlet
Unitarity.
Rich phenomenology in several final states at colliders.

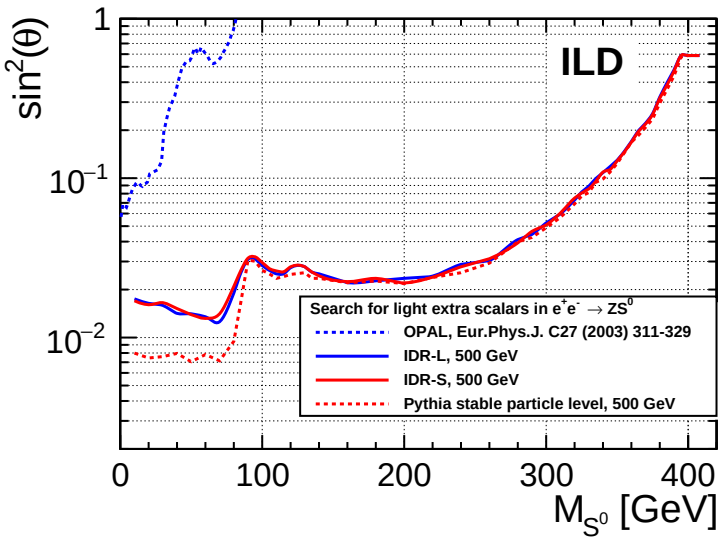


!! analysis still fixes many parameter values !!

Projections for additional scalar searches

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





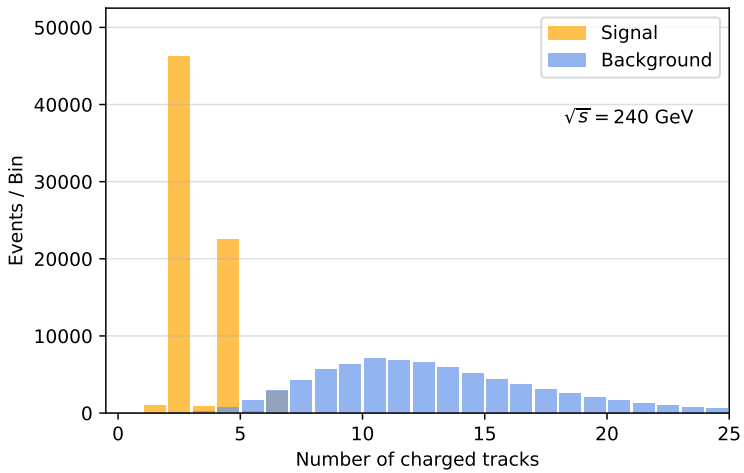
additional scalar, $\sin\theta$ rescaling wrt SM prediction, comparison of different detector models
recoil method

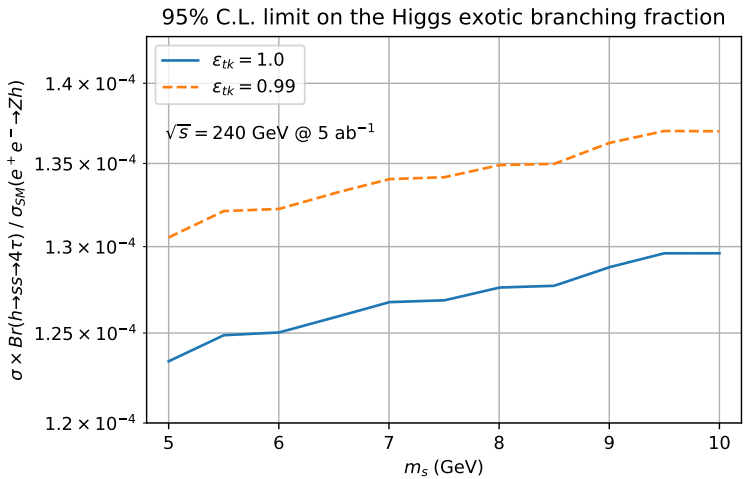
Possible searches

- 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]

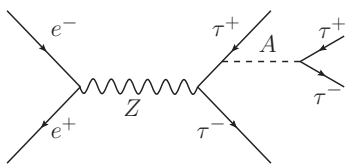
Type X 2HDM, 4τ final state via $\tau\tau A$ production

[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

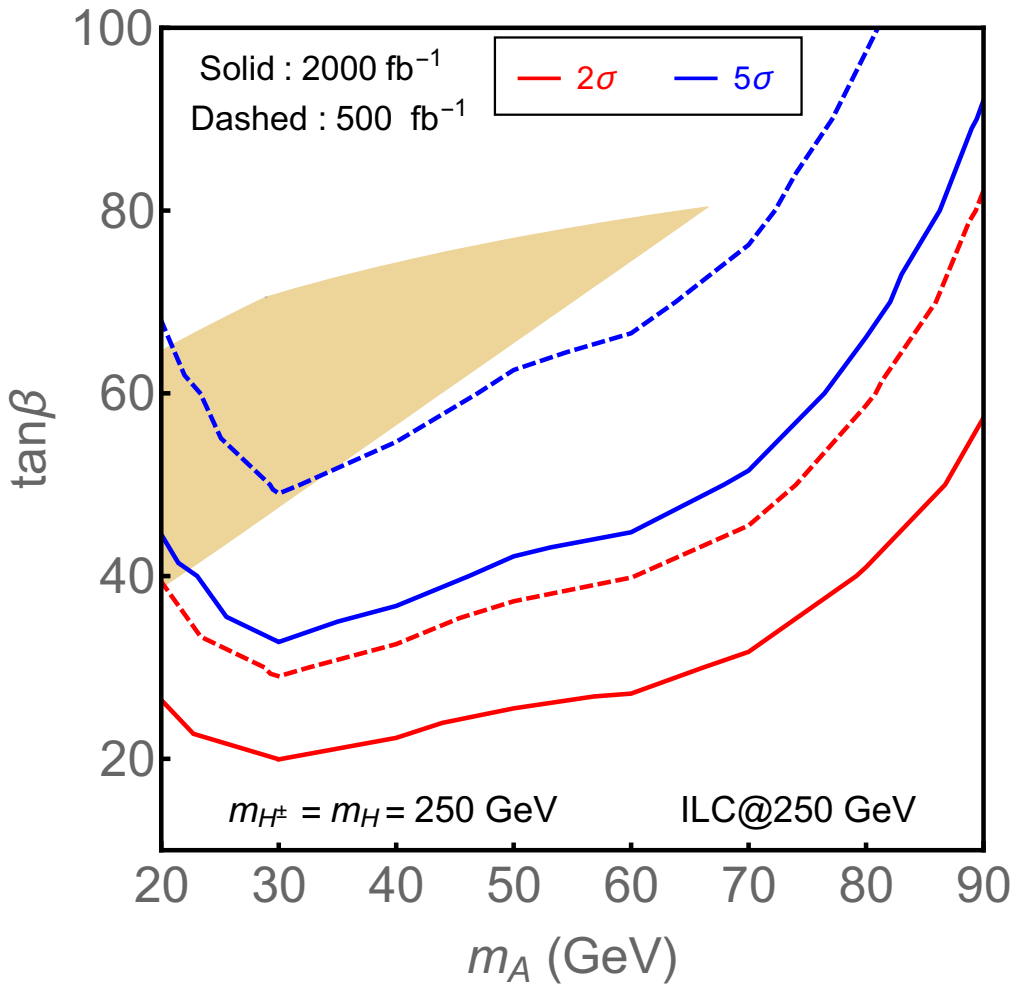
- The channel $Z \to h_{SM} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



- 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

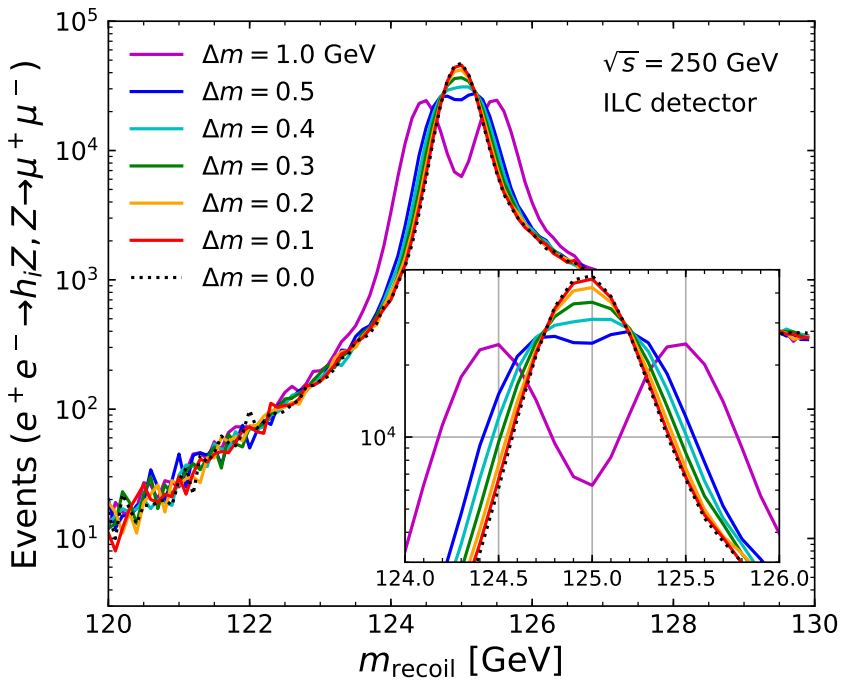
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]

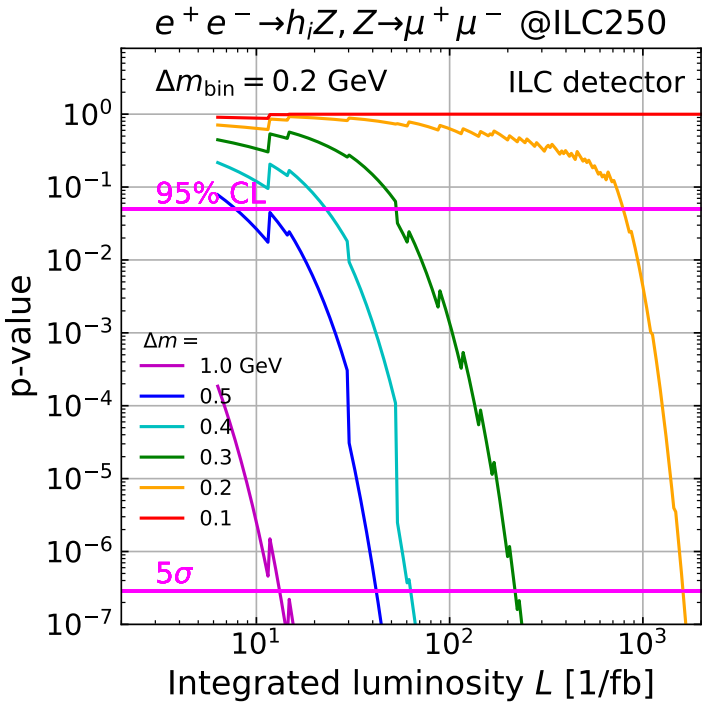


Test of degenerate additional scalar, including dark matter

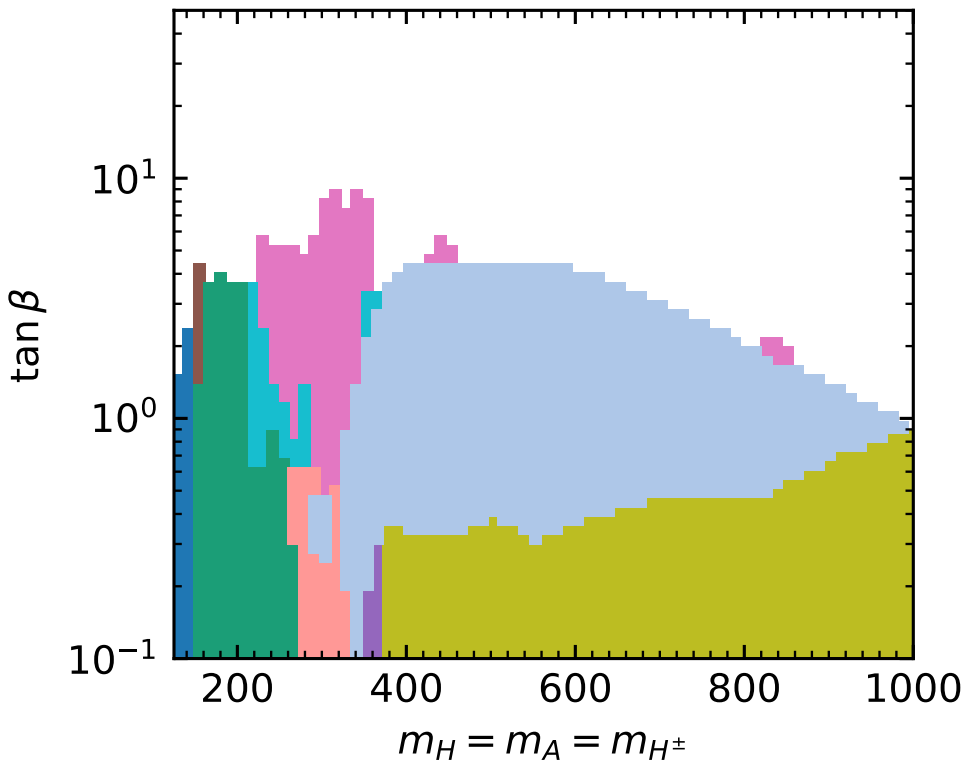
[S. Abe, G.-C. Cho, K. Mawatari, Phys.Rev.D 104 (2021) 3, 035023]

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





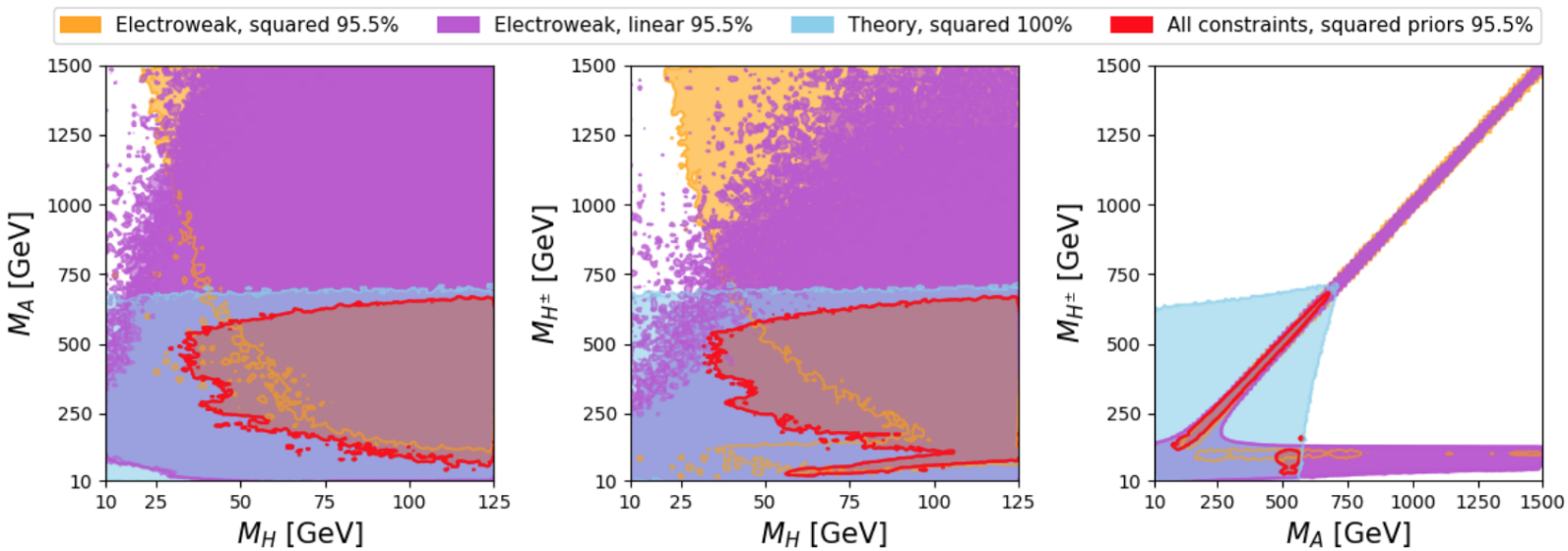
2HDM parameter space w thdmtools, thanks to K. Radchenko



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

Aligned 2HDM

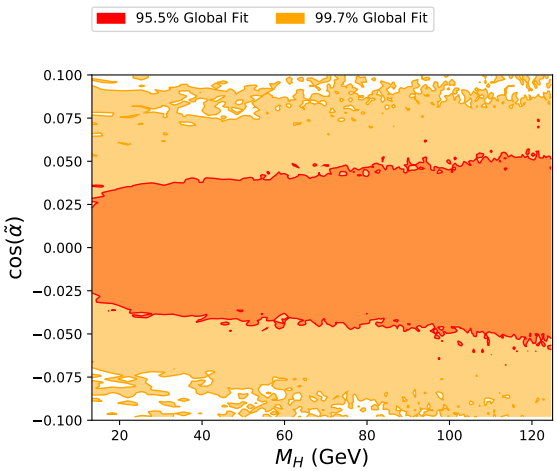
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]

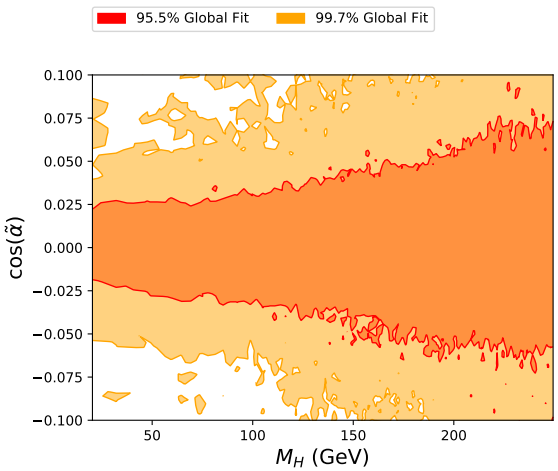


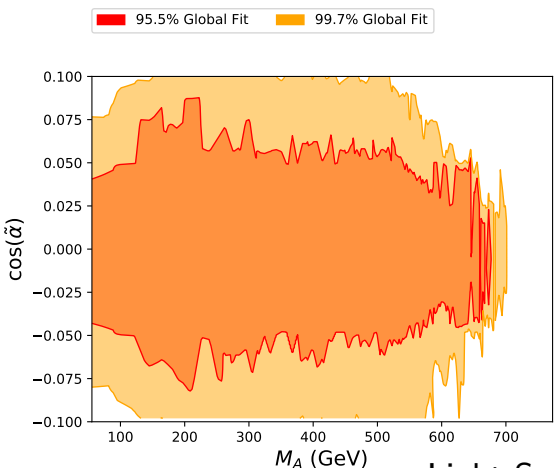
low mass region allowed; however, *HZZ* typically suppressed by $\cos(\beta - \alpha)$ [$\lesssim$ 0.25]

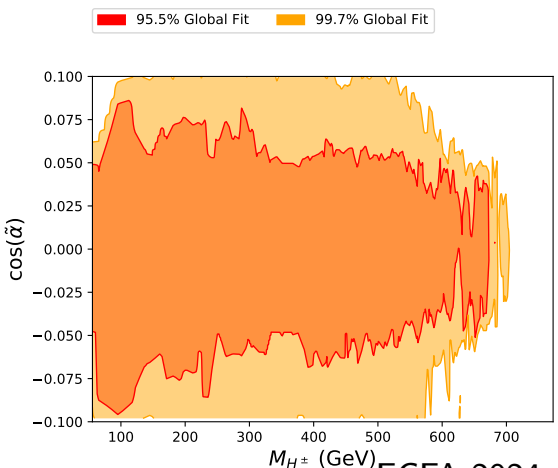
... and in terms of mixing angle...

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



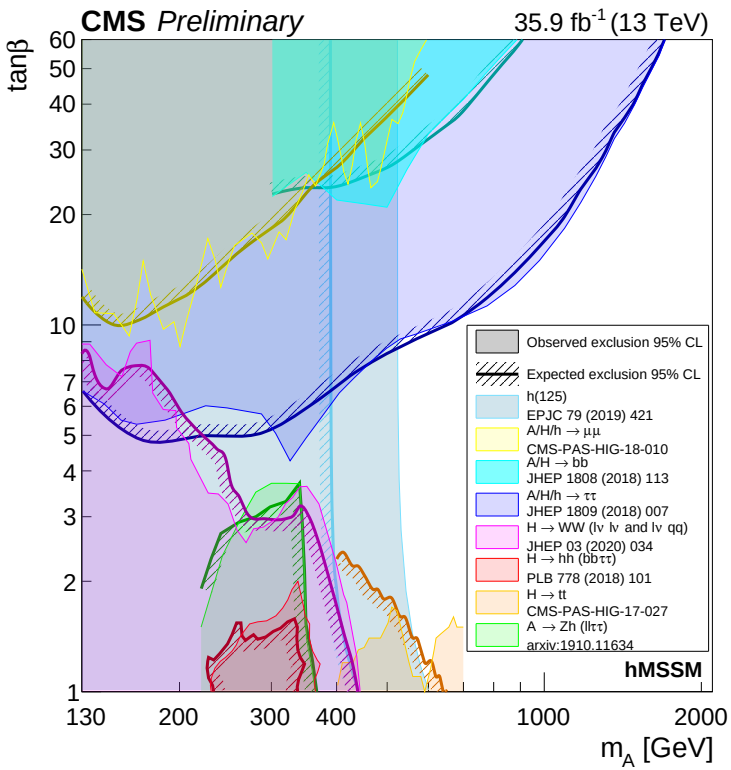


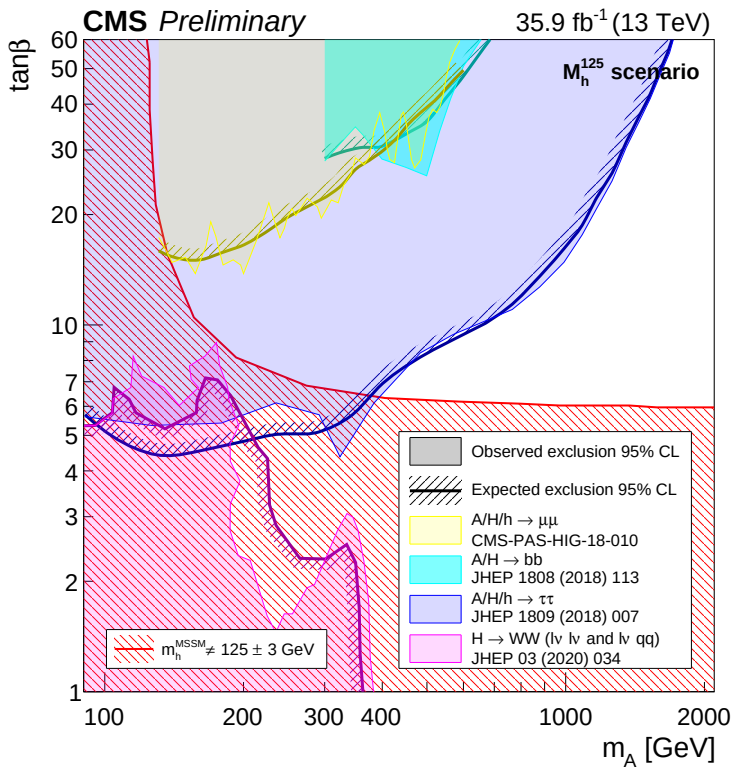




CMS MSSM summary plots, early Run II

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



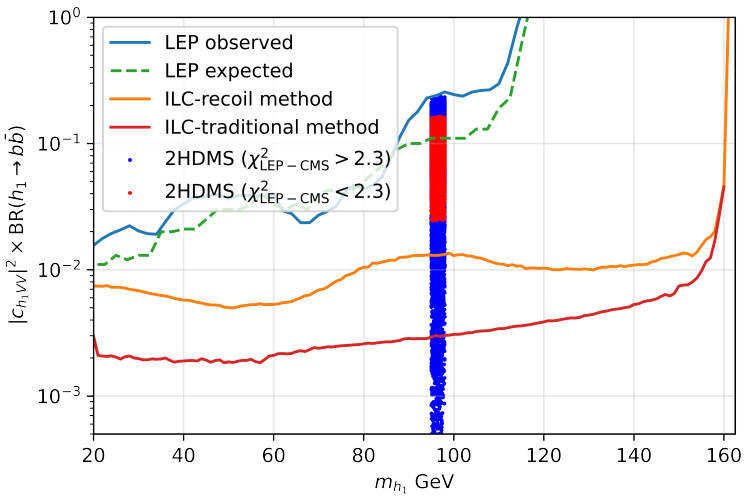


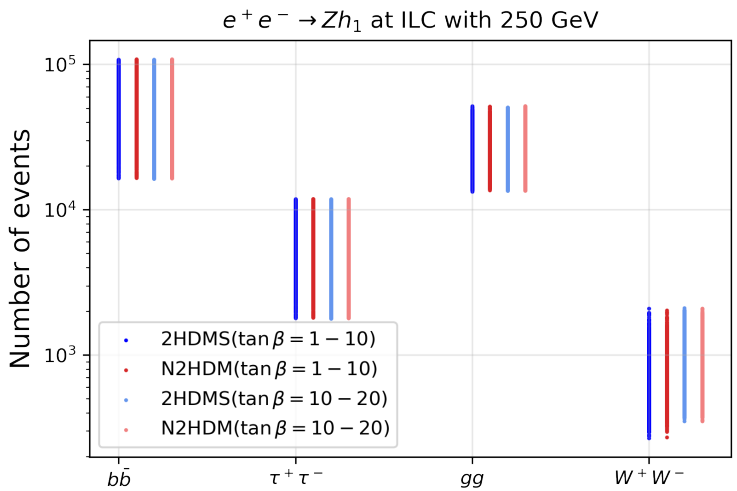
The 96 GeV LEP resonance

[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]

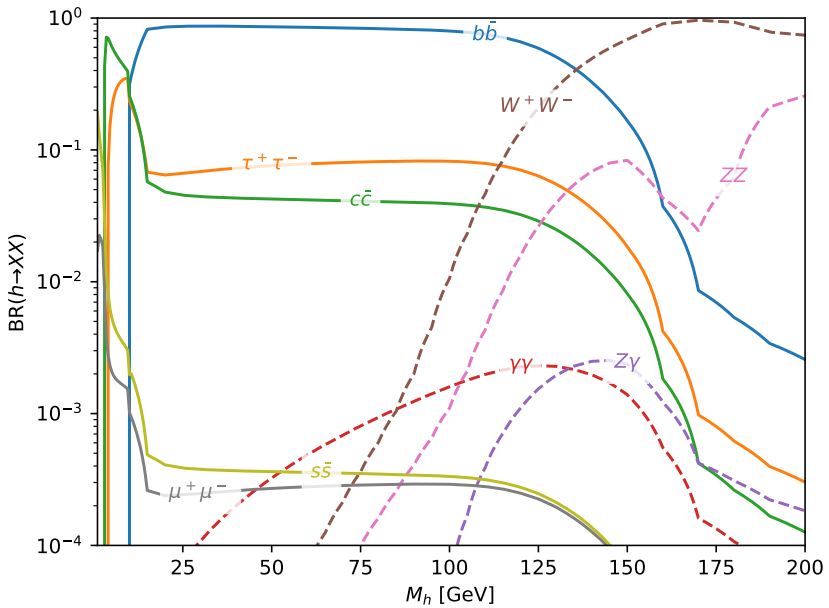
various BSM models, rates using $\int \mathcal{L} = 2\,\mathrm{ab}^{-1}$



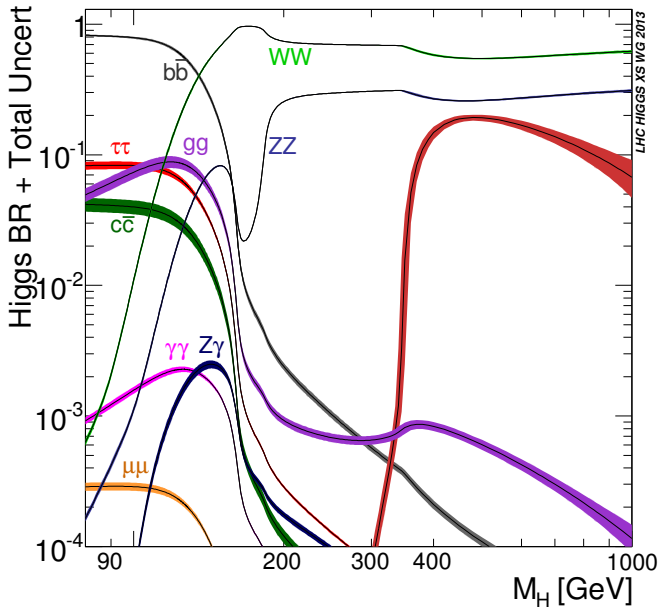


N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside 1 σ]

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)