Extended scalar sectors of interest for Higgs factories

Tania Robens

Rudjer Boskovic Institute/ CERN

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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**

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: `HiggsBounds`, `HiggsSignals`, `2HDMC`, `micrOMEGAs`, ...

Typical processes at Higgs factories

various production modes possible

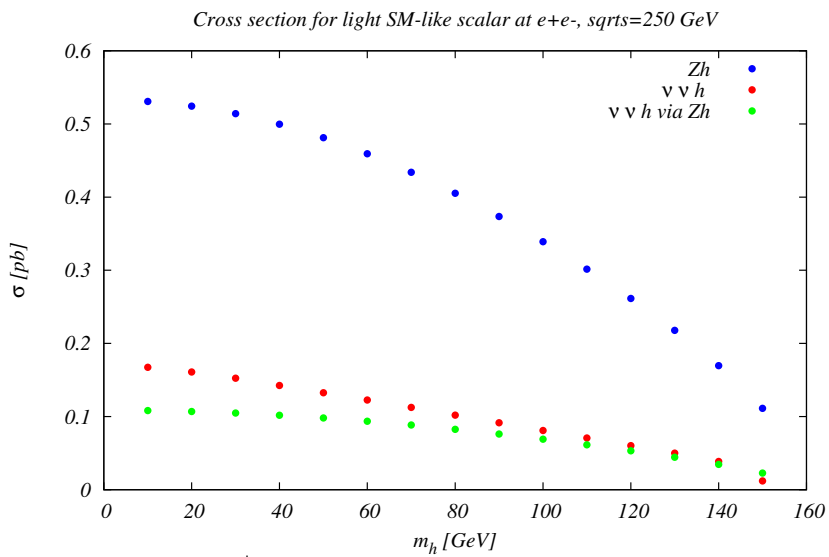
1) **easiest example:** $e^+ e^- \to Z h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \to h_1 h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

   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

Possible production modes and rates
[TR, arXiv:2203.08210, updated]

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



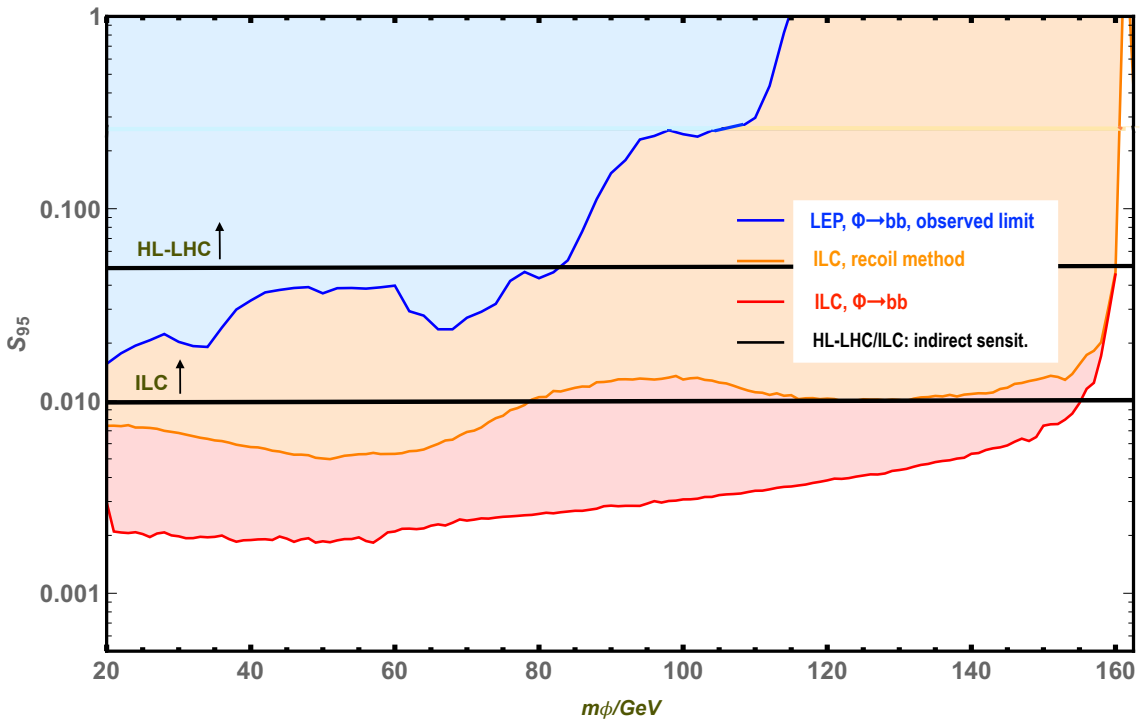
[cross sections for $e^+ e^-$ at $\sqrt{s} = 250\,\mathrm{GeV}$ using Madgraph5;

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

Possible searches

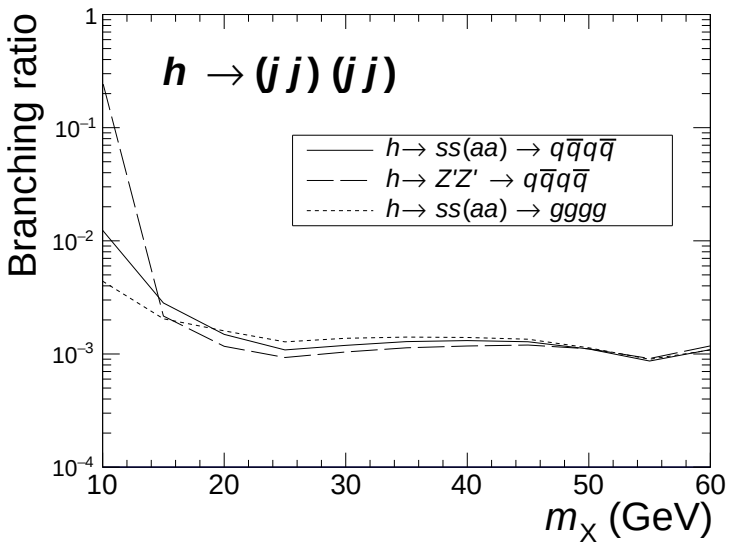
- one option: consider $h_{125} \to s\,s$
- also possible: **direct searches**
- for all of these: **dominant decays typically to $b\,\bar{b}$ or $\tau^+\,\tau^-$**

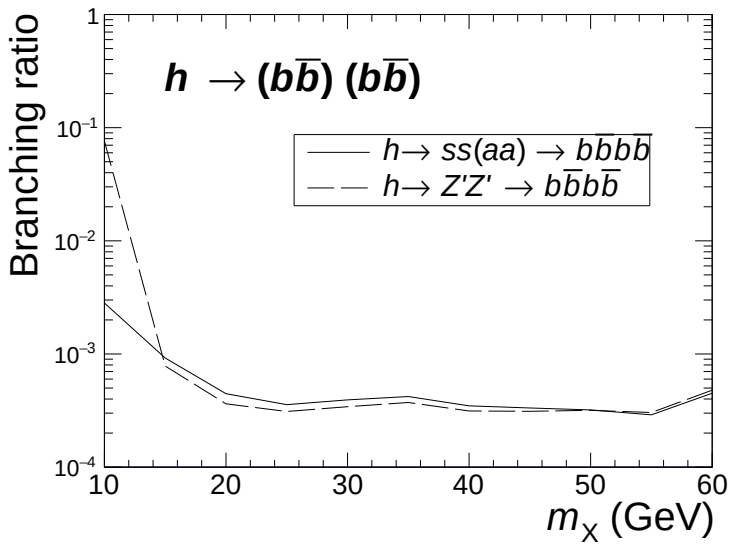
$\Rightarrow$ mainly discussed here $\Leftarrow$

- $h_{125} \to s\,s$ also constrained from $\Gamma_{125} \leq 9\,\mathrm{MeV}$, and $\mathrm{BR}_{h\to\mathrm{inv}} \leq 0.11$.

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

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

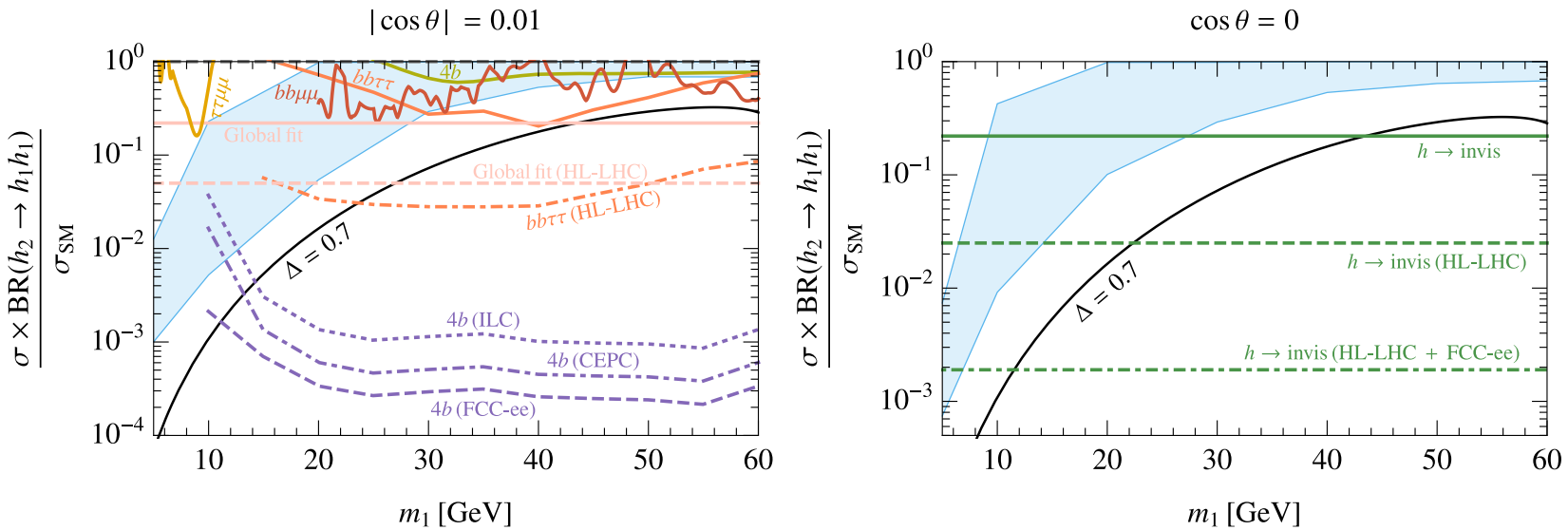




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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]

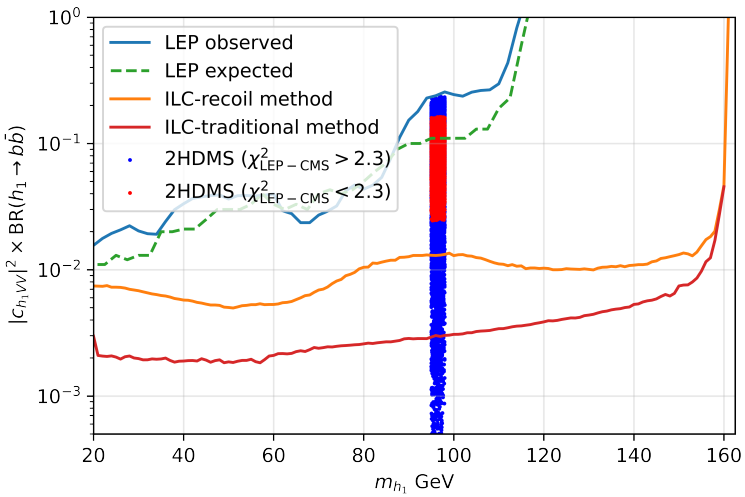
[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]

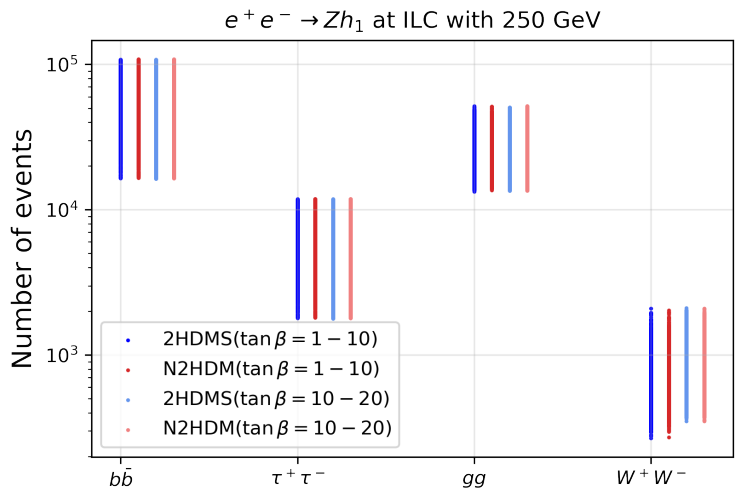
The 96 GeV LEP resonance

[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]

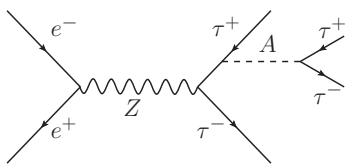
Type X 2HDM, 4τ final state via $\tau\tau A$ production

[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

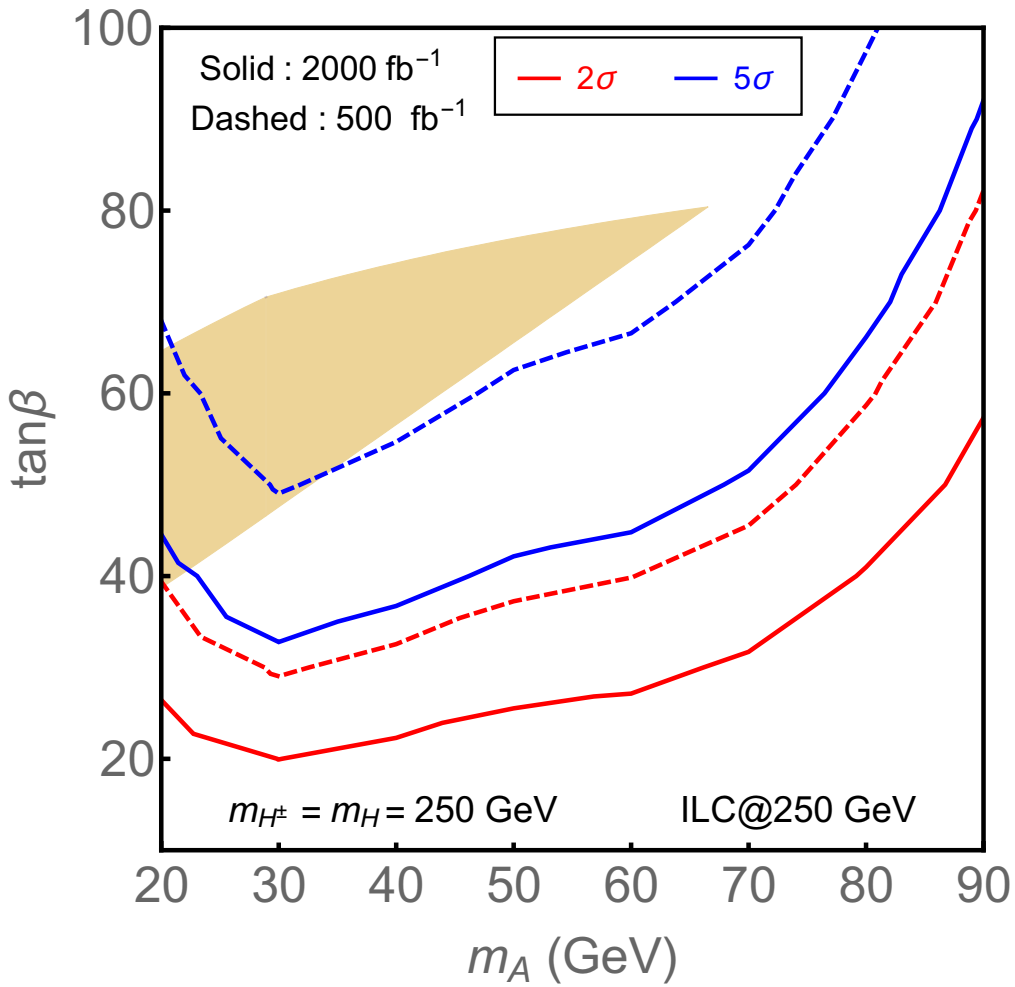
- The channel $Z \to h_{SM} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



- 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.

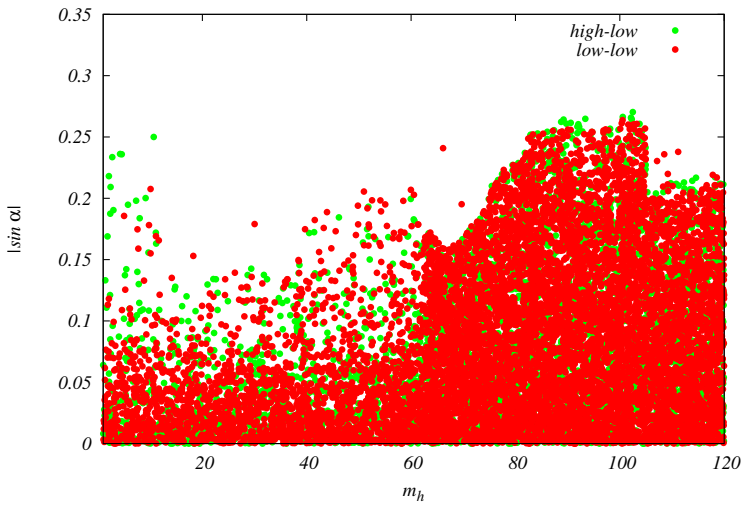
Type X 2HDM, 4τ final state via $\tau\tau A$ production

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

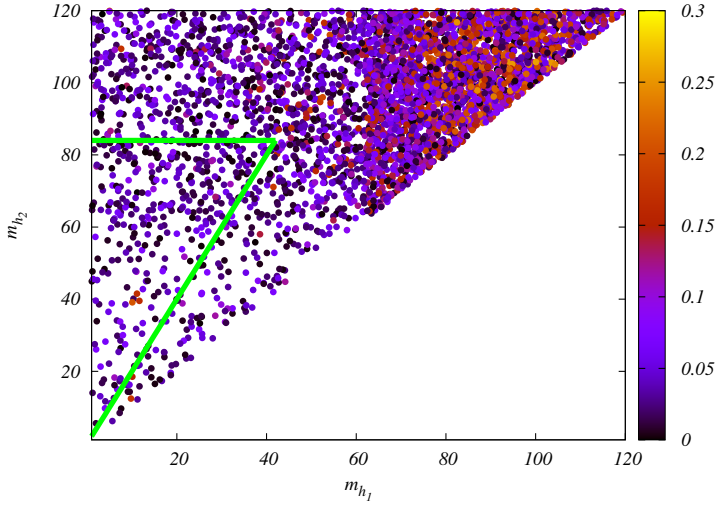


Singlet extensions [TR, arXiv:2203.08210 and Universe *(to appear)*]

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

cross sections for $e^+e^- \to h_{125} \to h_1\, h_2$ and $e^+e^- \to h_2 \to h_1\, h_1$ $\mathcal{O}\,(10-20\text{fb})$ @ 250 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

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

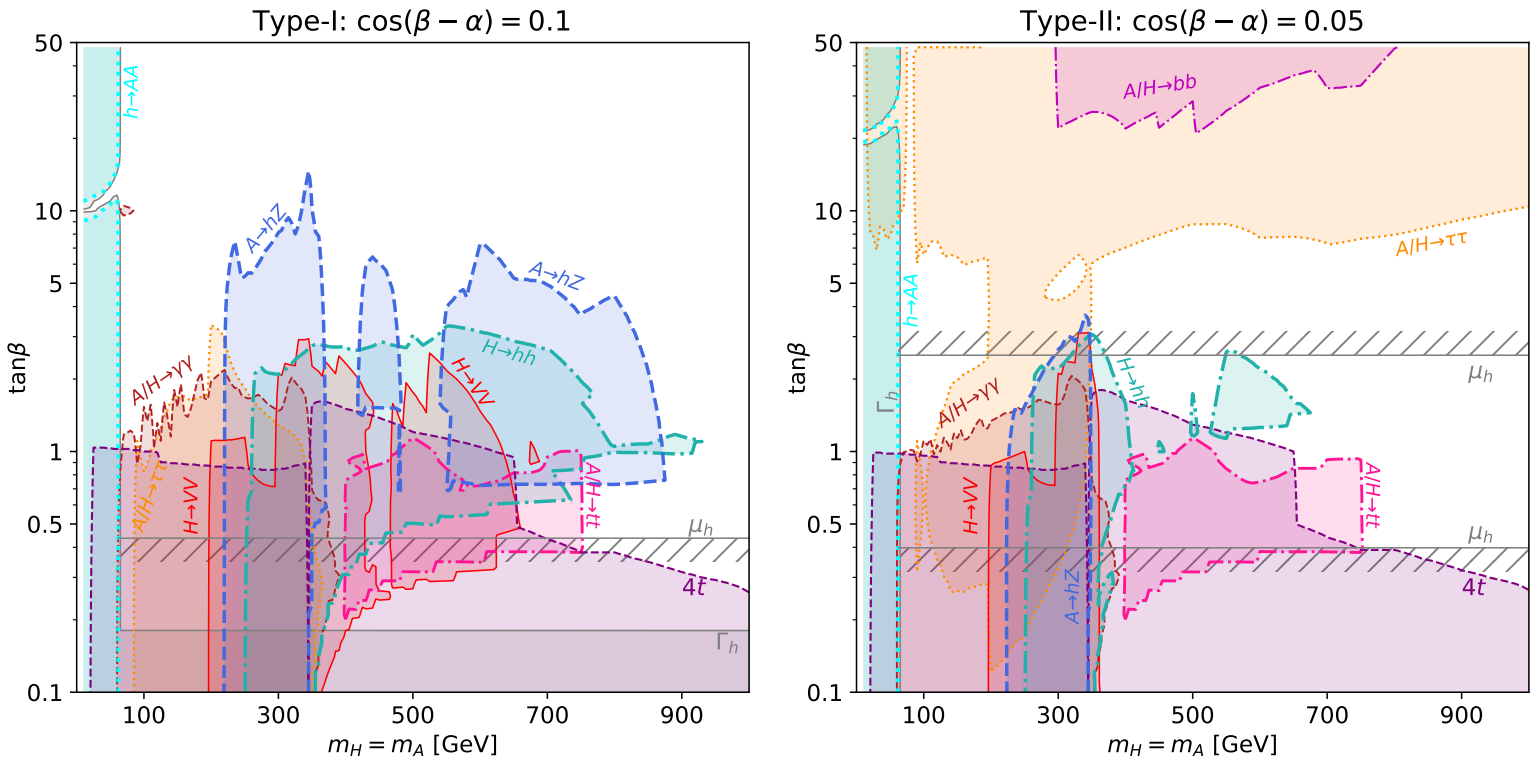
  requires relatively light scalars, typically $m \lesssim 160\,\mathrm{GeV}$

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

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

2HDM parameter space

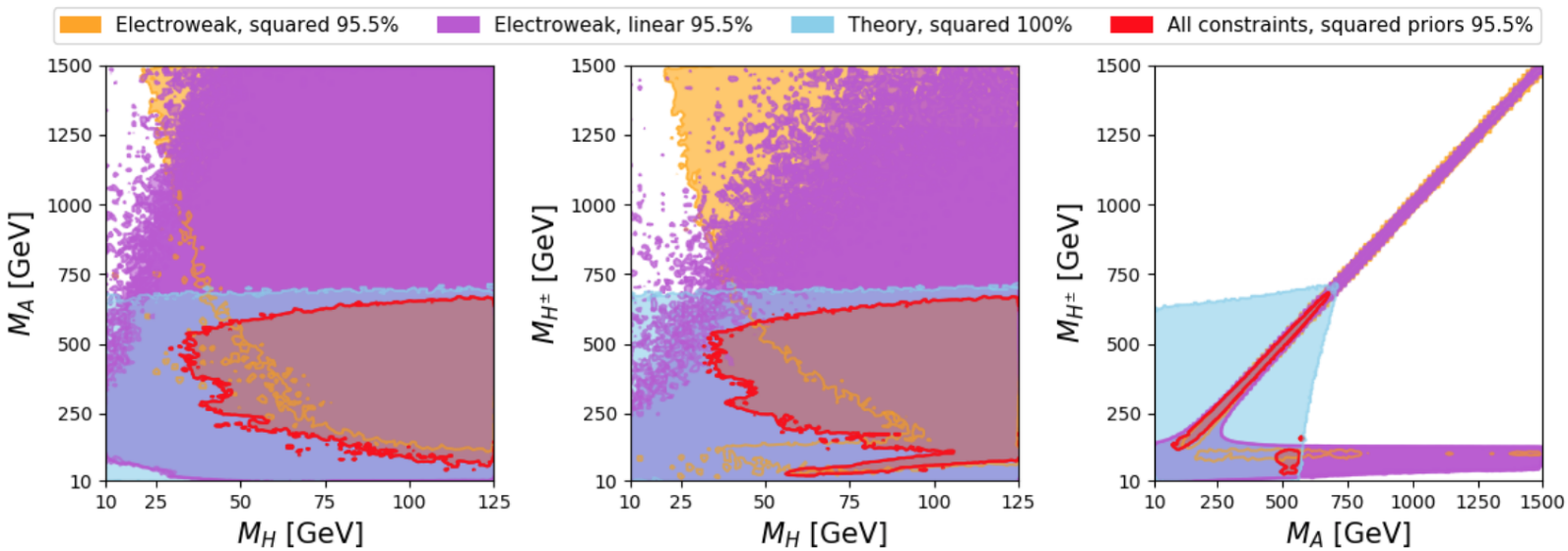
[F. Kling, S. Su, W. Su, JHEP 06 (2020) 163]



combination of various direct searches,
ATLAS/ CMS, at 8/ 13 TeV

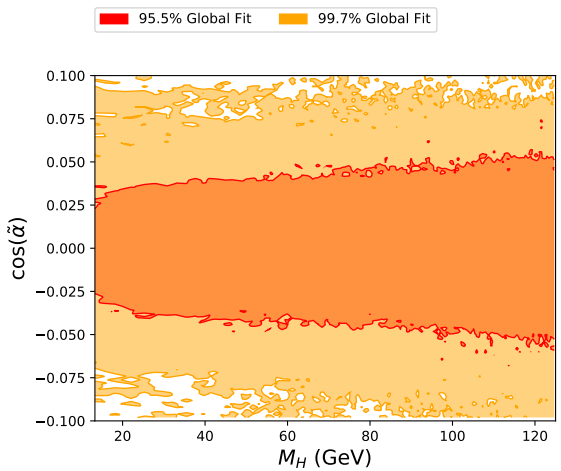
Aligned 2HDM

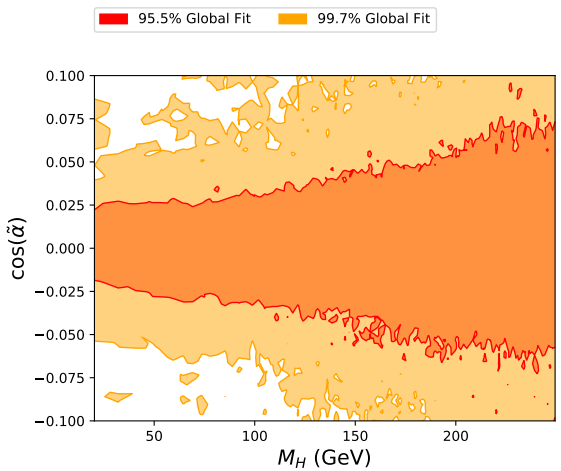
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]

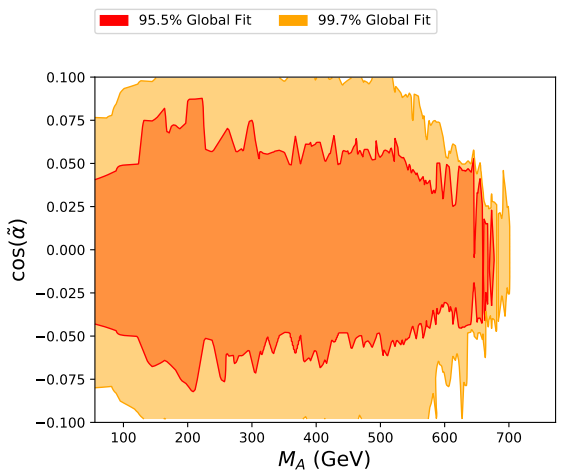


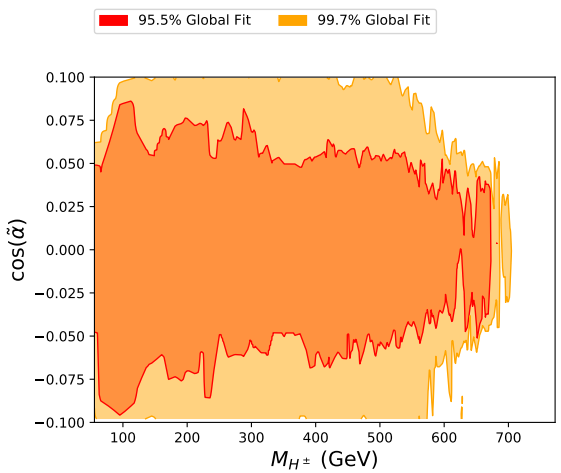
low mass region allowed; however, *HZZ* typically suppressed by $\cos(\beta - \alpha)$ [$\lesssim$ 0.25]

... and in terms of mixing angle... [Thanks to V. Miralles]







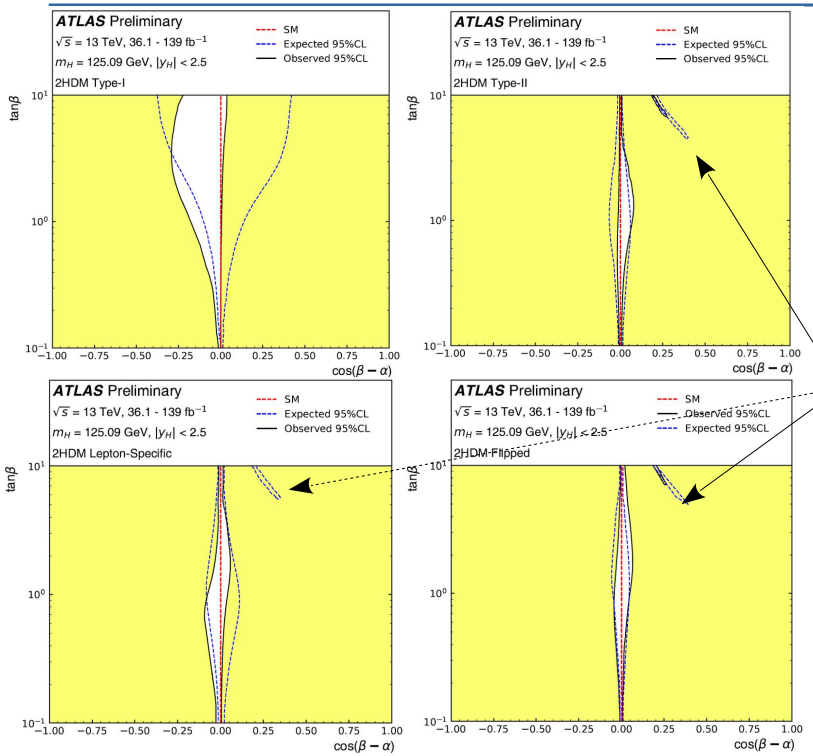


Current constraints on alignment in 2HDMs

[H. Arnold, talk at Higgs 2021]

2HDM interpretation: results

ATLAS-CONF-2021-053



New

$$H_{\mathrm{SM}} = h \cdot \sin(\beta - \alpha) + H \cdot \cos(\beta - \alpha).$$

$\cos(\beta - \alpha) = 0$ ***alignment limit***

→ h indistinguishable from H_{SM}

- The data is consistent with the ***alignment limit*** within 1 std. or better
- "petal" allowed regions: some fermion couplings have the same *magnitude* as in the SM, but the opposite *sign*

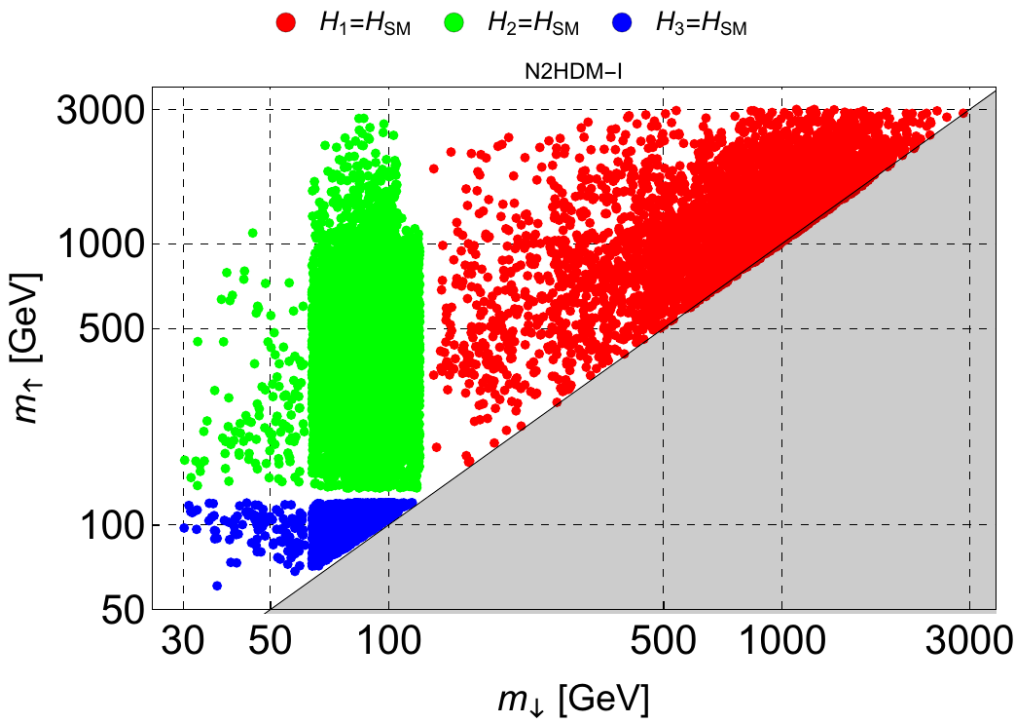
No surprises:
the observed Higgs boson is SM-like

Hannah Arnold Higgs2021: Combined ATLAS Higgs measurements 21/10/21 17

N2HDM example

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

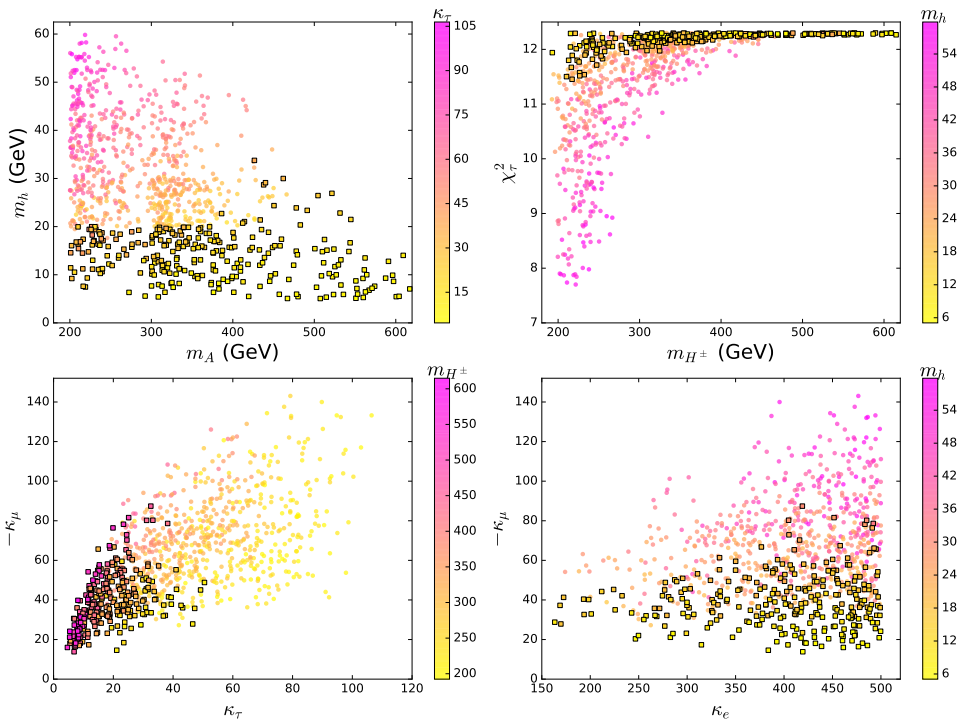
N2HDM: 2HDM+ real singlet



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

Models with dark matter candidates: Inert Doublet Model

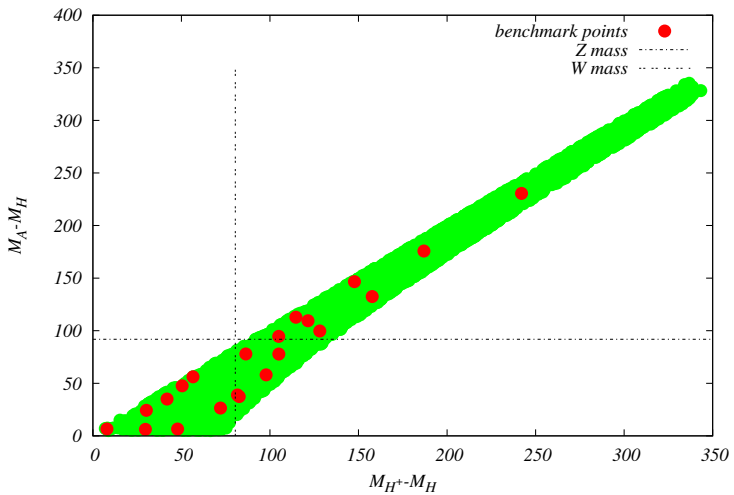
2 Higgs Doublet Model: 4 new scalars $H, A, H^{\pm}$

$\mathbb{Z}_2$ symmetry $\rightarrow$ **DM candidate(s)** (here: choose H)

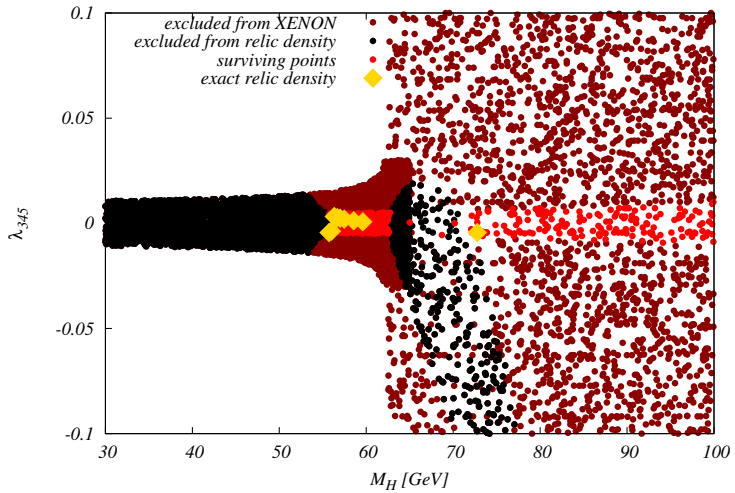
free parameters: **masses,** λ_2, λ_{345} (couplings in V)

signatures: EW gauge boson(s) + MET

$\Rightarrow$ **so far: no LHC analysis** $\Leftarrow$



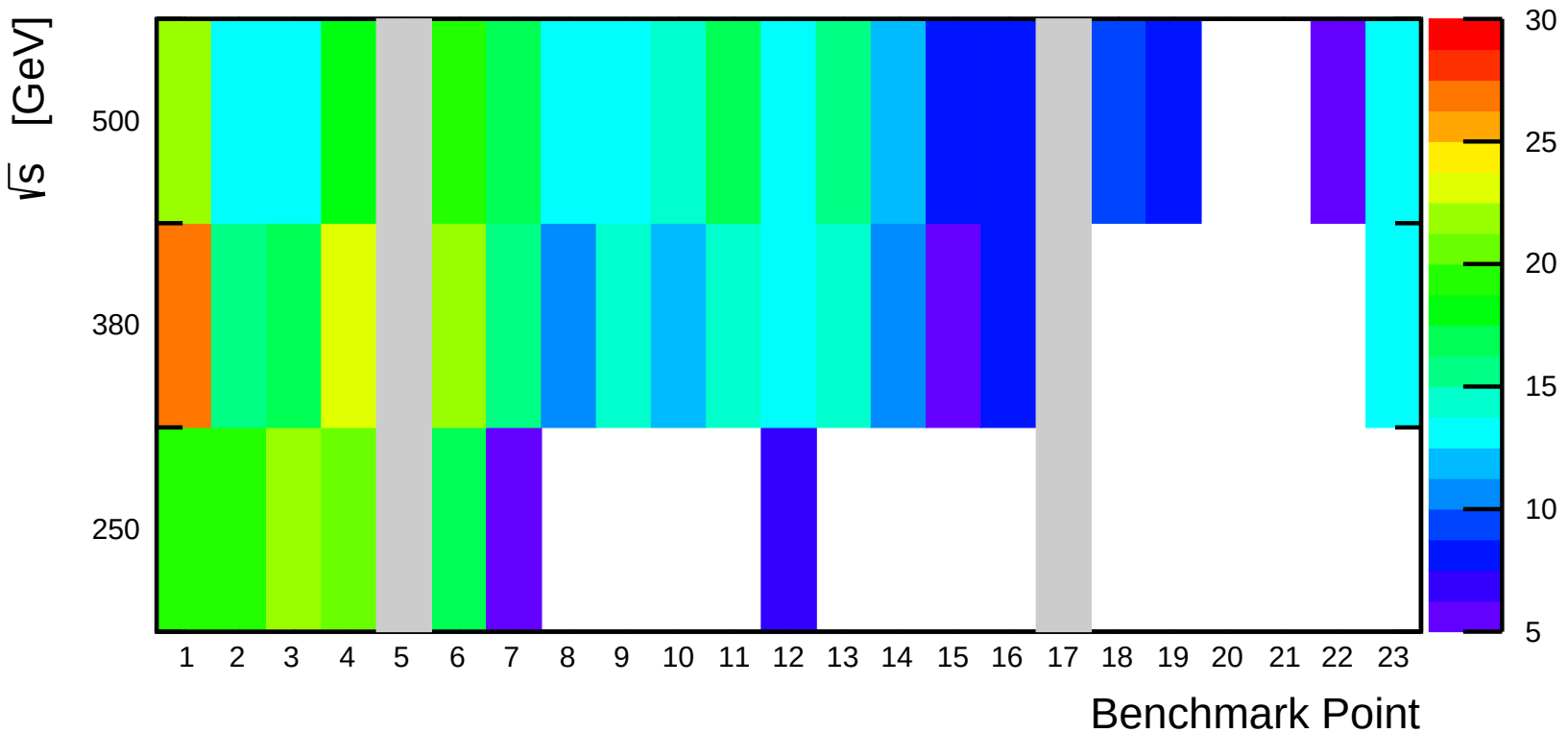
Masses highly constrained from electroweak precision [Kalinowski, Kotlarski, TR, Sokolowska, Zarnecki, JHEP 1812 (2018)]



... and also from signal strength and astrophysical constraints ... [Ilnicka, TR, Stefaniak, Mod.Phys.Lett. A33 (2018) no.10n11, 1830007]

$\mu^+\mu^-$ + MET searches in the IDM at the ILC

[A.F. Zarnecki ea, arXiv:2002.11716]



significance for $e^+ e^- \to \mu^+\mu^-$ + MET, for different com energies

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**

Many things to do

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

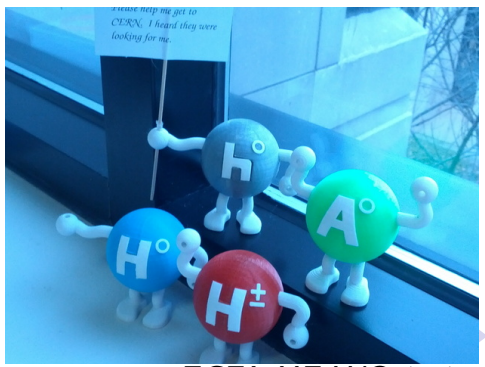
- **full test requires checks of *hhh*, *hhhh* couplings**

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

Other possible extensions

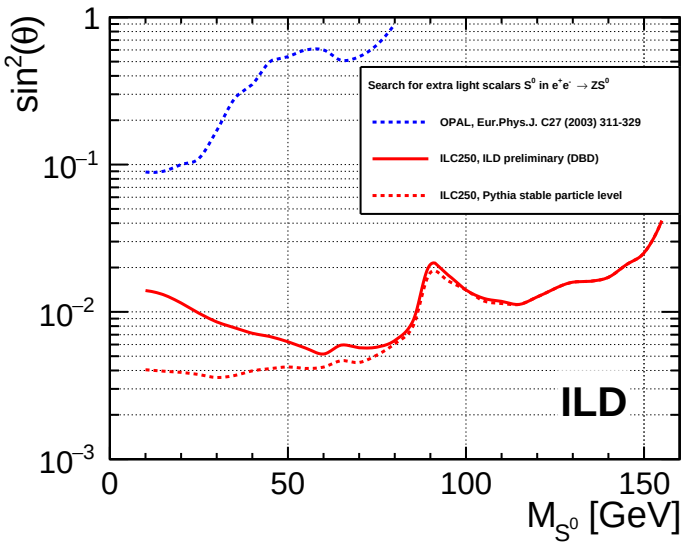
- A priori: **no limit to extend scalar sector**
- **make sure you**
  - have a **suitable ew breaking mechanism**, including a **Higgs candidate at** $\sim 125\,\mathrm{GeV}$
  - can explain **current measurements**
  - are **not excluded by current searches** and precision observables
- **nice add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

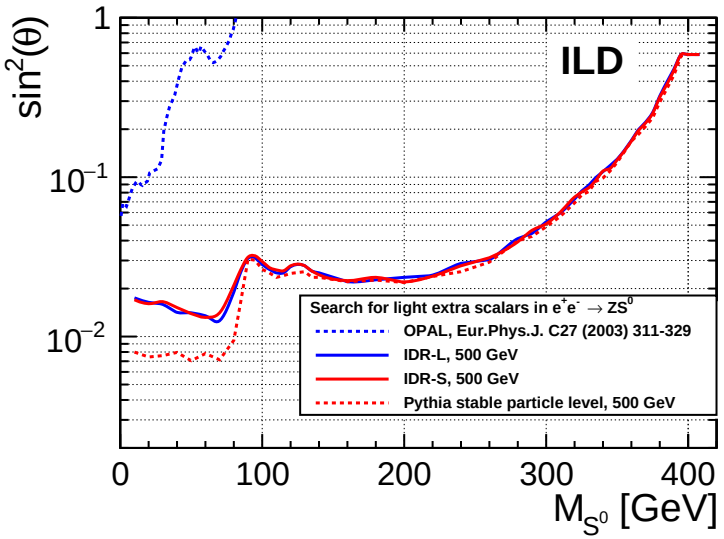
  $\Rightarrow$ **new scalar states** $\Leftarrow$



Projections for additional scalar searches

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

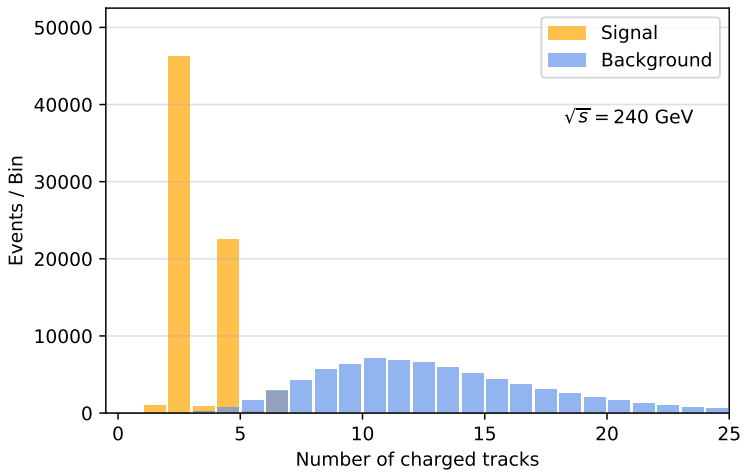


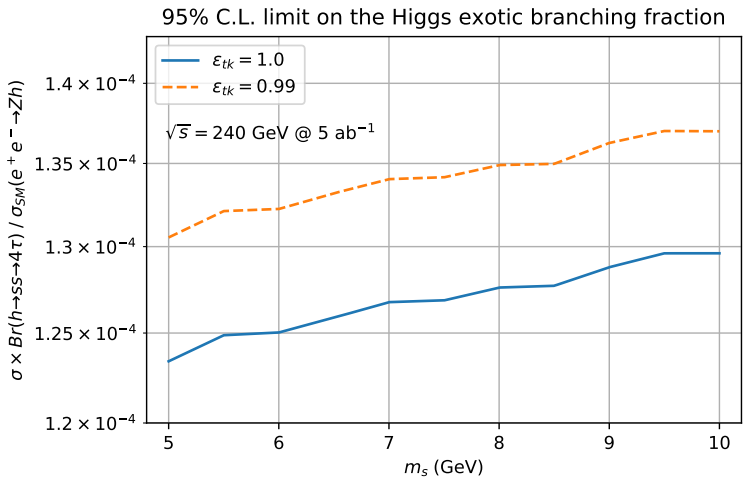


additional scalar, $\sin\theta$ rescaling wrt SM prediction, comparison of different detector models
recoil method

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

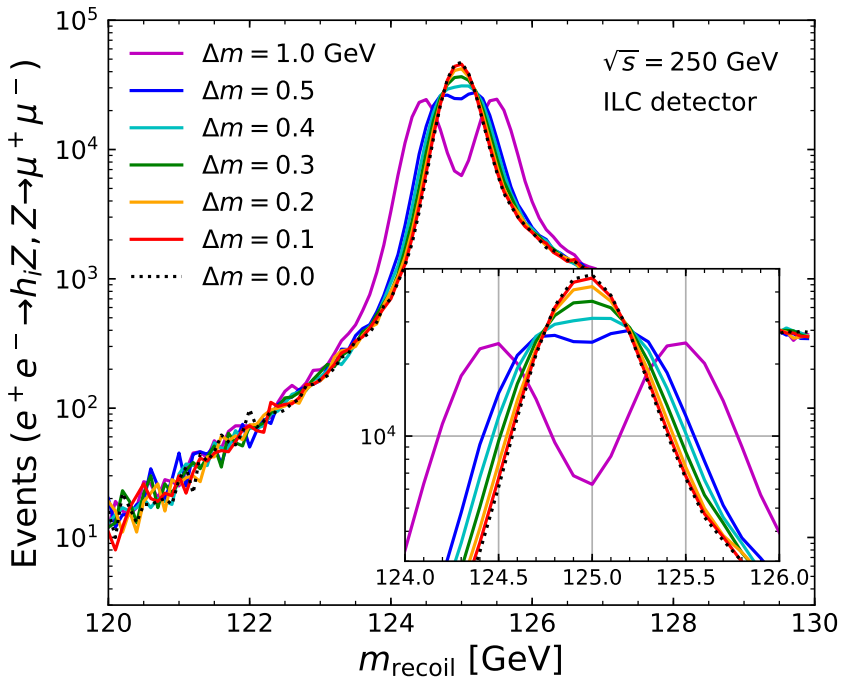
comment: **current constraints lead to prediction** $\lesssim 10^{-3}$

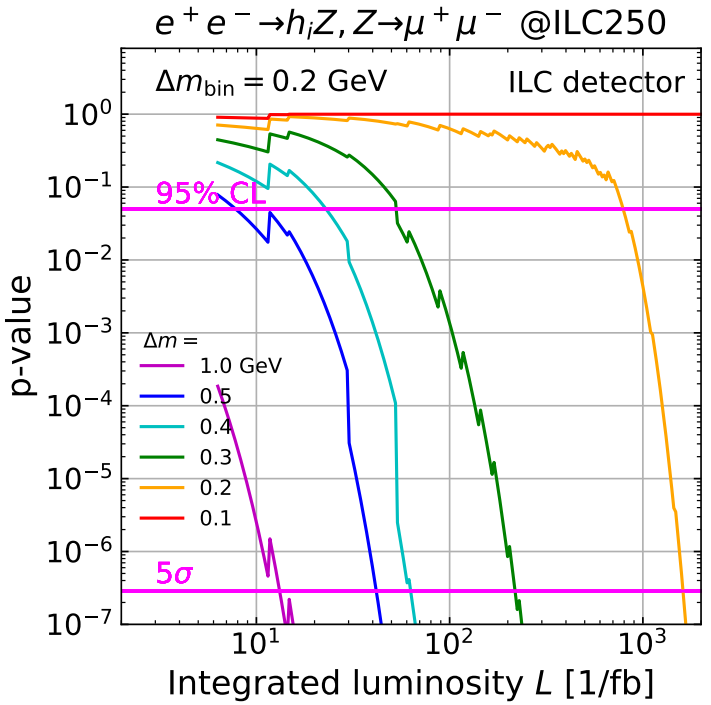
[invisible BR, signal strength, assumes SM-like decay to τs]

Test of degenerate additional scalar, including dark matter

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

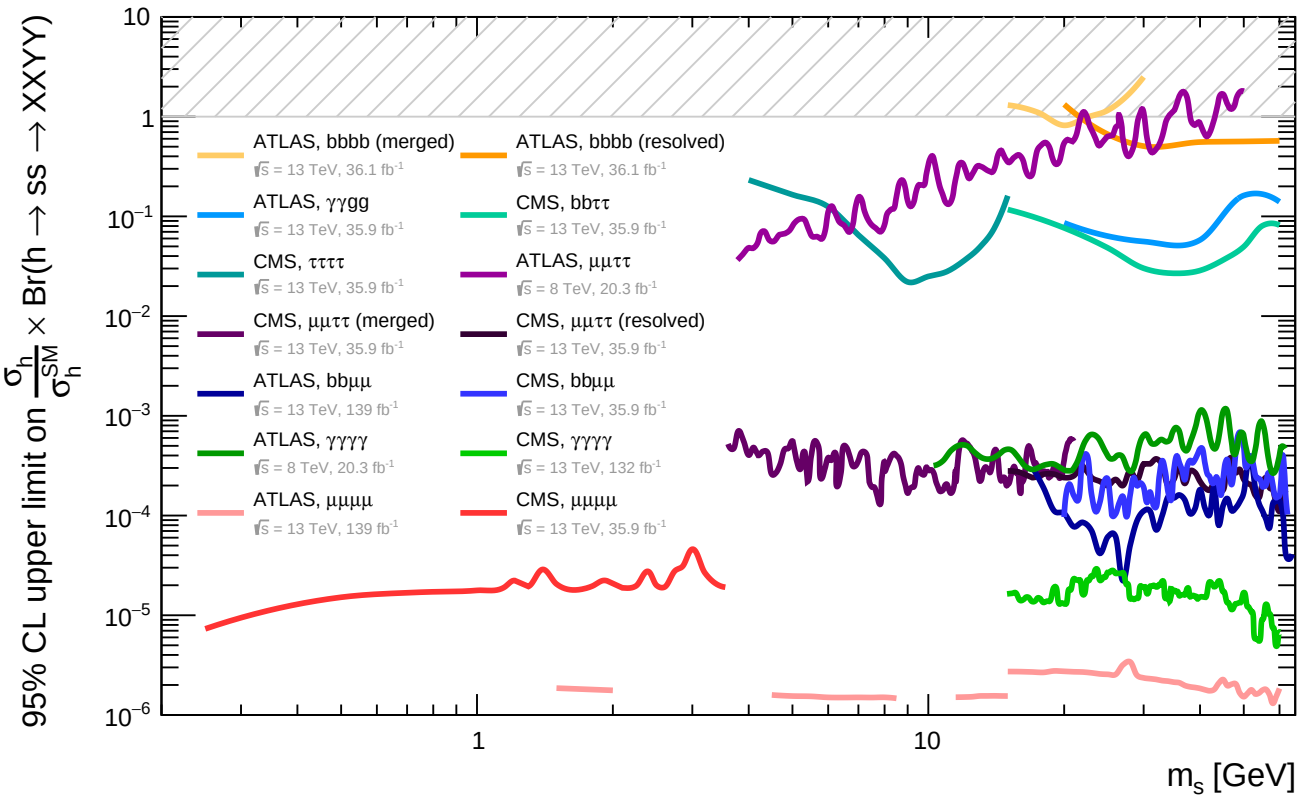
- setup: complex singlet, including dark matter candidate
- test of degenerate additional scalar





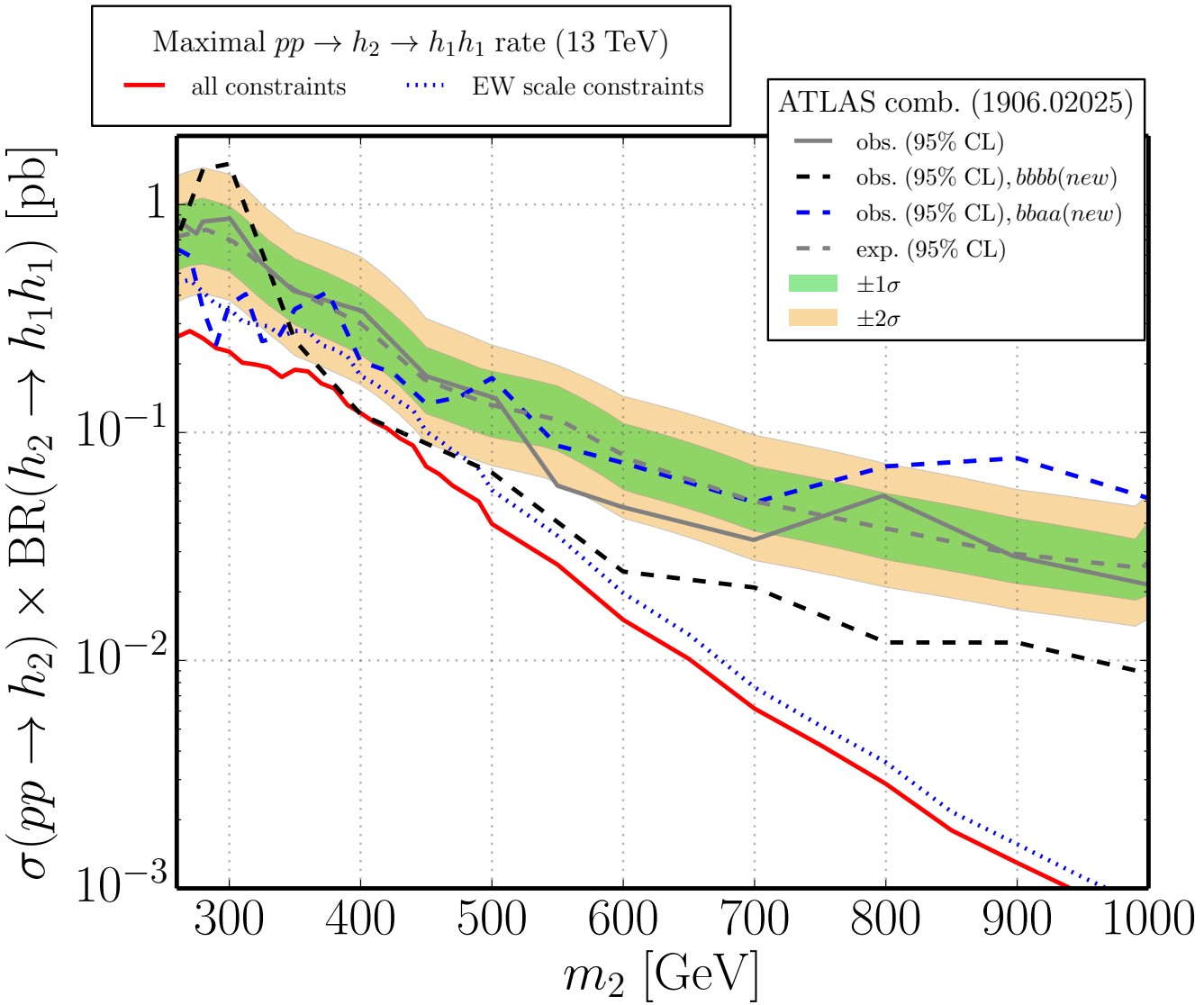
Current constraints for the $h_{125} \to s\,s$ searches at LHC

[M. Cepeda, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751]



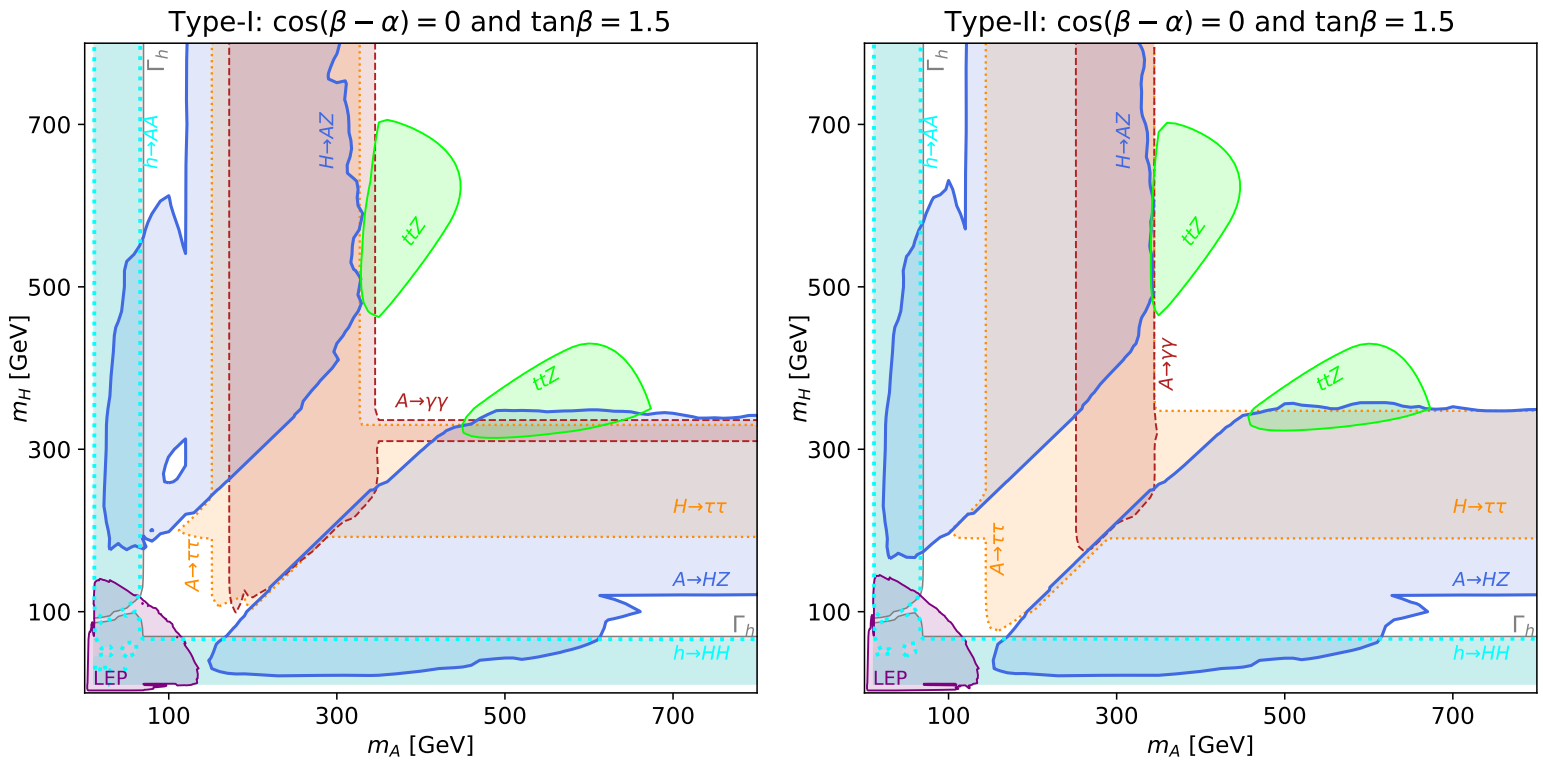
bound on decays into lighter scalars from current searches

TR, arXiv:2205.06295



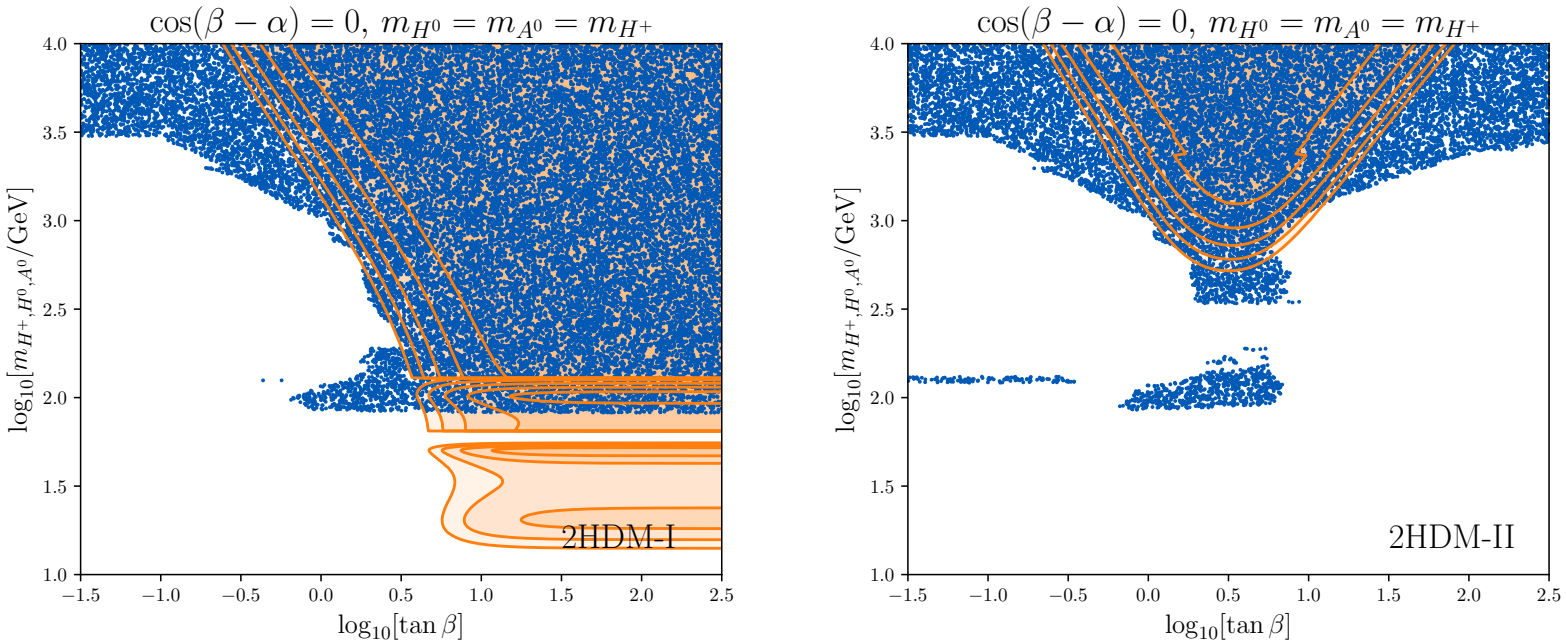
2HDM parameter space

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



Another recent 2HDM study

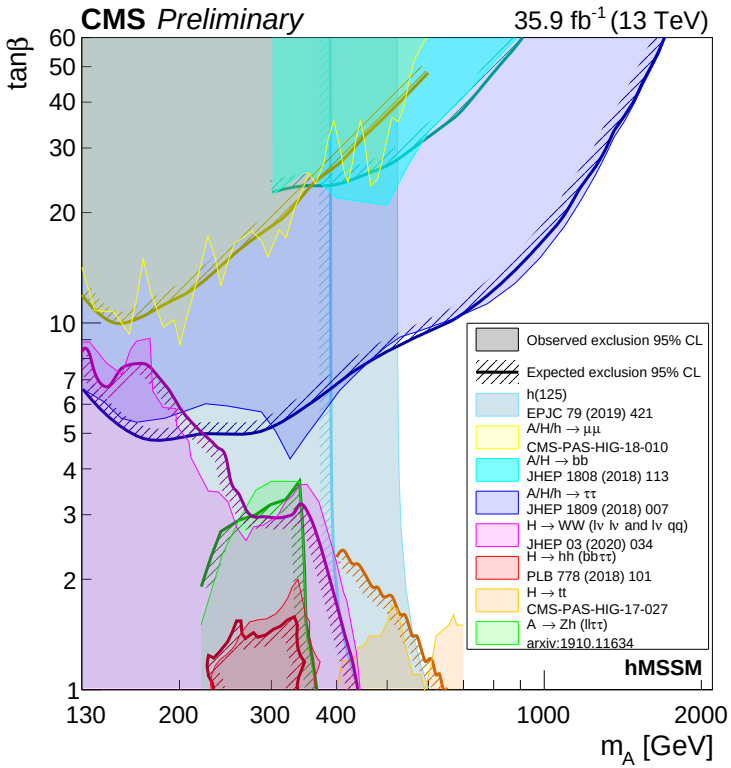
[O. Atkinson, M. Black, C. Englert, A. Lenz, A. Rusov, J. Wynne, arXiv:2202.08807]

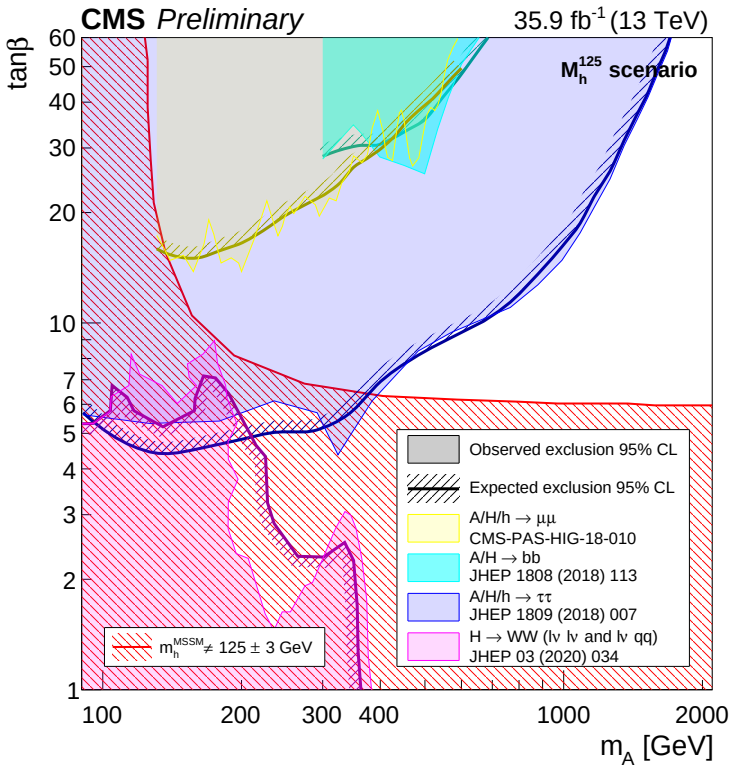


2HDM Types I/II, direct searches, signal strength, and flavour constraints

CMS MSSM summary plots, early Run II

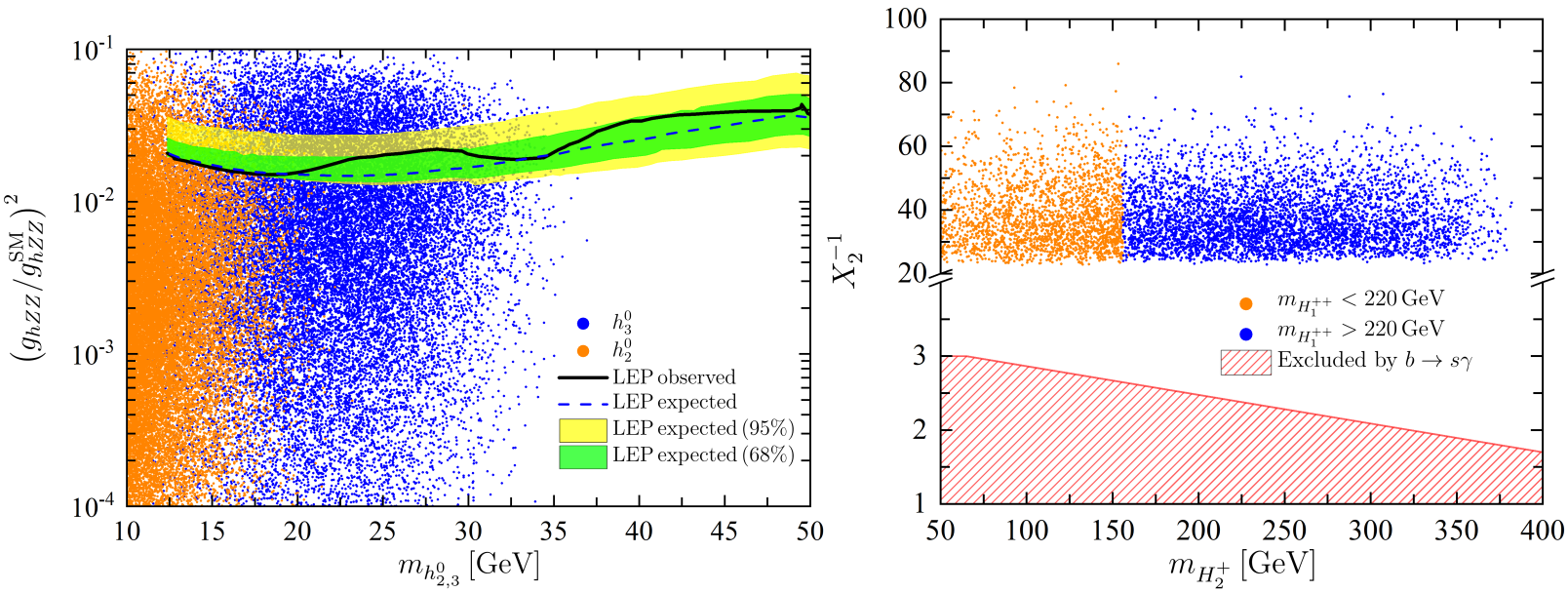
[https://twiki.cern.ch/twiki/bin/view/CMSPublic/SummaryResultsHIG]





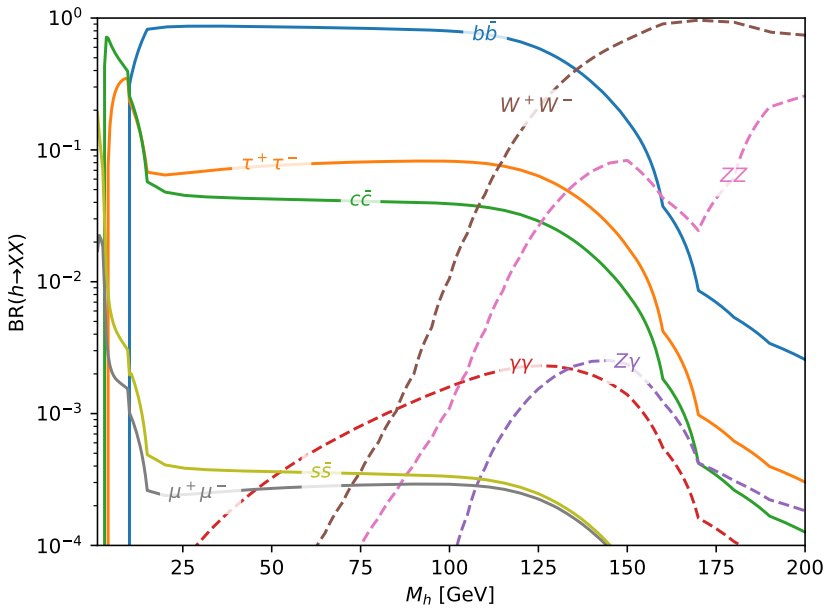
Scalar triplet model

[P.M. Ferreira, B.L. Gonalves, F.R. Joaquim, arXiv:2109.13179]

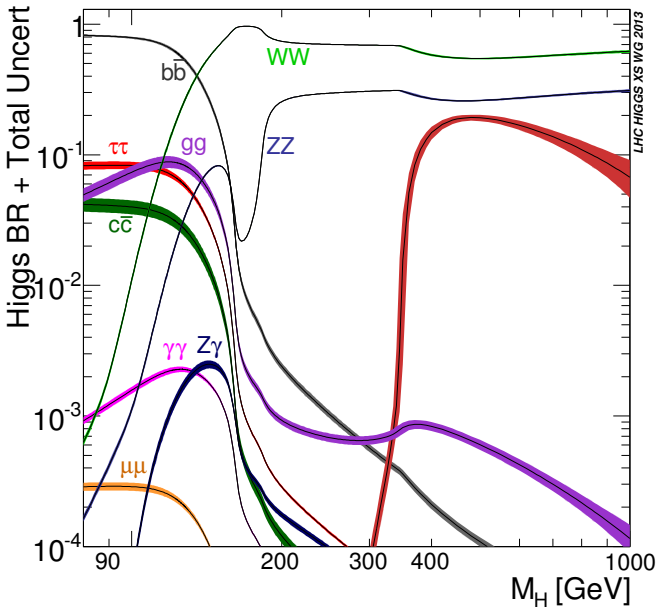


5 neutral, 3 singly charged, 2 doubly charged scalars

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)

Inert doublet model: The model

- idea: take **two Higgs doublet model, add additional $\mathbb{Z}_2$ symmetry**

$$\phi_D \rightarrow -\phi_D, \phi_S \rightarrow \phi_S, \text{SM} \rightarrow \text{SM}$$

(⇒ implies CP conservation)

⇒ obtain a **2HDM with (a) dark matter candidate(s)**

- potential

$$V = -\frac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S)+m_{22}^2(\phi_D^\dagger\phi_D)\right] + \frac{\lambda_1}{2}(\phi_S^\dagger\phi_S)^2+\frac{\lambda_2}{2}(\phi_D^\dagger\phi_D)^2$$
$$+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D)+\lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) + \frac{\lambda_5}{2}\left[(\phi_S^\dagger\phi_D)^2+(\phi_D^\dagger\phi_S)^2\right],$$

- only one doublet acquires VeV v, as in SM
(⇒ implies analogous EWSB)

Number of free parameters and theory constraints

Model has 7 free parameters

- choose e.g.

$$\mathbf{v},\ \mathbf{M_h},\ \mathbf{M_H},\ \mathbf{M_A},\ \mathbf{M_{H^\pm}},\ \lambda_{\mathbf{2}},\ \lambda_{\mathbf{345}}\ [= \lambda_3 + \lambda_4 + \lambda_5]$$

- v, M_h fixed $\Rightarrow$ left with **5 free parameters**

Constraints: Theory

- **vacuum stability, positivity, constraints to be in inert vacuum**
- **perturbative unitarity, perturbativity of couplings**
- **choosing** M_H as dark matter: $M_H \leq M_A, M_{H^\pm}$

Constraints: Experiment

$$M_h = 125.1\,\mathrm{GeV},\ v = 246\,\mathrm{GeV}$$

- total width of M_h ($\Gamma_h < 9\,\mathrm{MeV}$) (CMS, $80\,\mathrm{fb}^{-1}$) [Phys. Rev. D 99, 112003 (2019)]
- total width of W, Z
- collider constraints from signal strength/ direct searches;
- electroweak precision through S, T, U
- unstable $H^{\pm}$
- reinterpreted/ recastet LEP/ LHC SUSY searches

  (Lundstrom ea 2009; Belanger ea, 2015)
- dark matter relic density (upper bound)
- dark matter direct search limits (XENON1T)

$\Rightarrow$ **tools used: 2HDMC, HiggsBounds, HiggsSignals, MicrOmegas**

Parameters tested at colliders: mainly masses

- side remark: all couplings **involving gauge bosons** determined by **electroweak SM parameters**
- **relevant couplings follow from ew parameters (+ derivative couplings)**
- hXX **couplings:** determined by λ_{345} (constrained from direct detection), and **mass differences** $M_X^2 - M_H^2$ $\left(X \in \left[A, H^{\pm}\right]\right)$

important interplay between astroparticle physics and collider searches

in the end kinematic test

(holds for $M_H \geq \frac{M_h}{2}$)