An overview on low mass scalars at future lepton colliders

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based on Universe 8 (2022) 286

Standard and exotic Scalars at future HET factories
14. April '23

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***

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

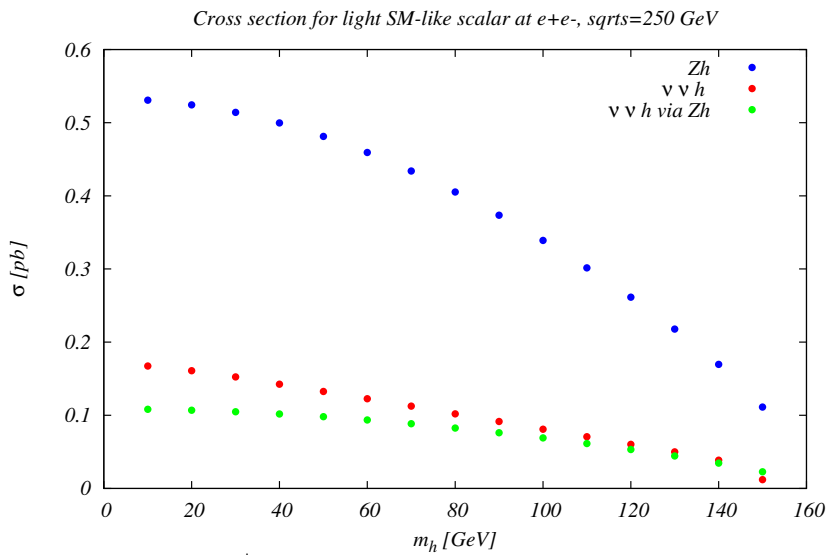
for coupling g to vector bosons

- 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.

Possible production modes and rates

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



[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**

Models

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**
- ...

Typical processes at Higgs factories

various production modes possible

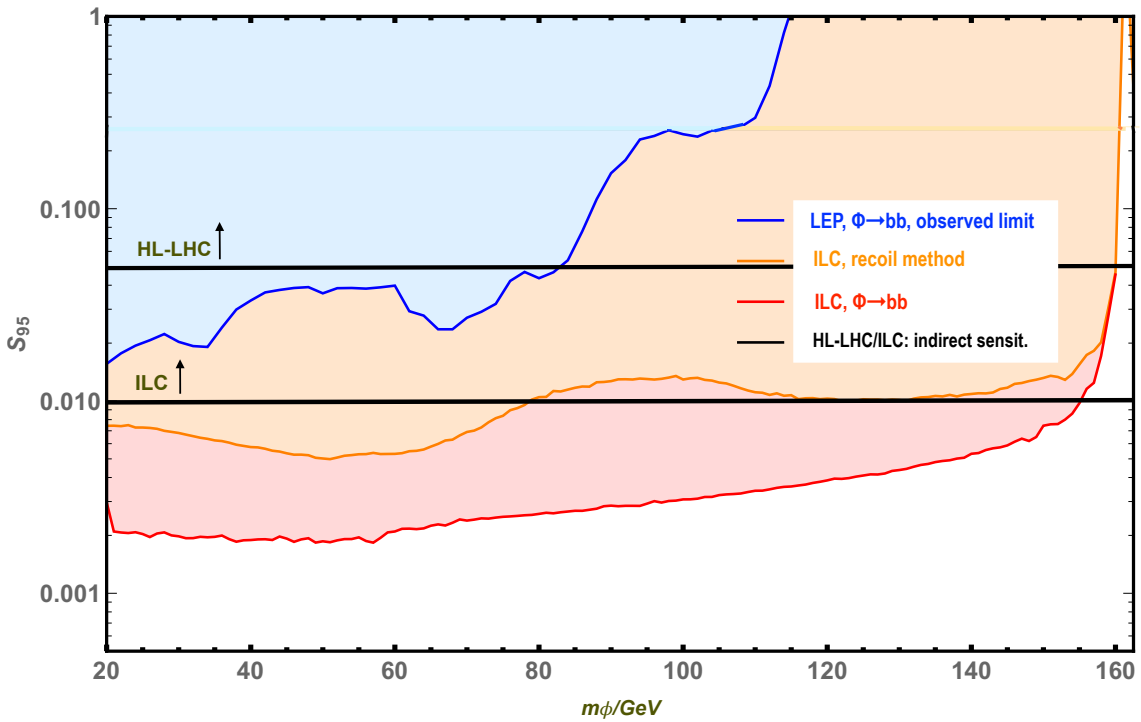
1) **easiest example:** $e^+ e^- \to Z h_1$, onshell production interesting up to $m_1 \sim 160\,\mathrm{GeV}$
2) in **models with various scalars:** e.g. also $e^+ e^- \to h_1 h_2$ (e.g. from 2HDMs); example processes and bounds from LEP in Eur.Phys.J.C 47 (2006) 547-587

   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

Projections for additional scalar searches

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

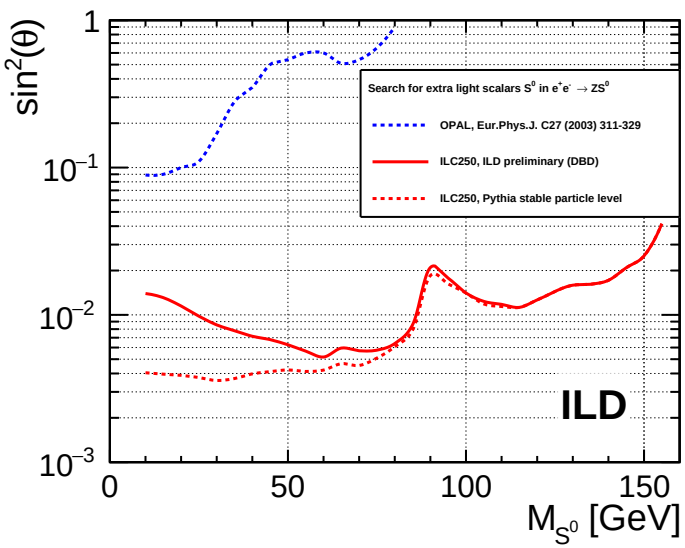


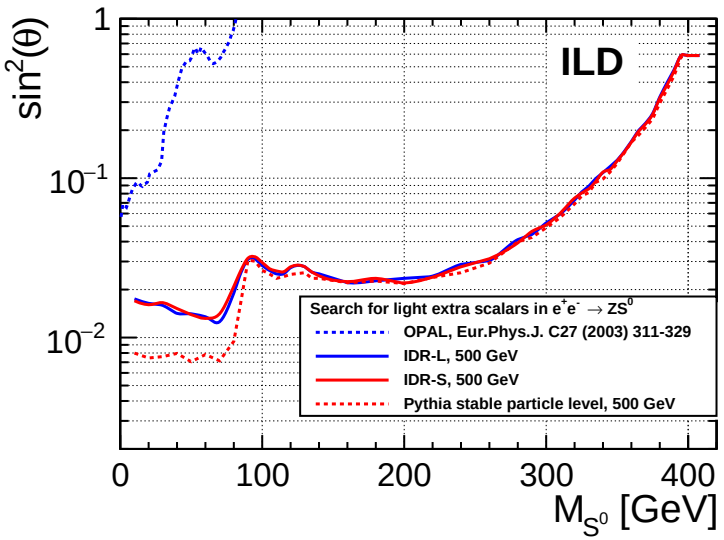
estimate of ILC sensitivity based on validation using LEP results

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

Projections for additional scalar searches

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





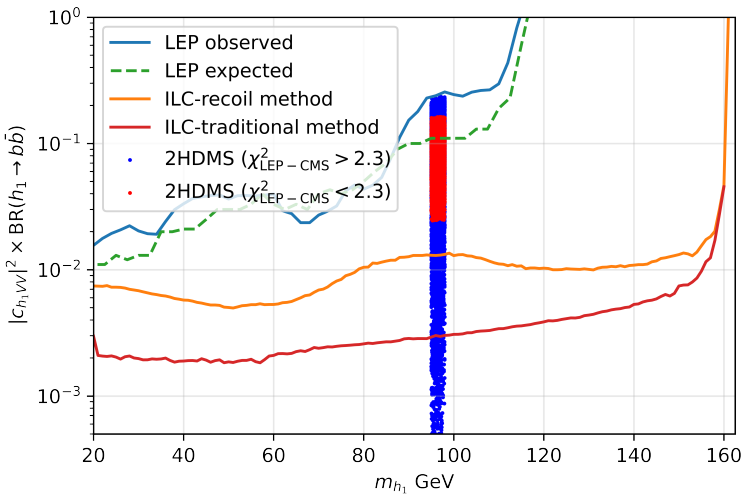
additional scalar, $\sin\theta$ rescaling wrt SM prediction, comparison of different detector models
recoil method

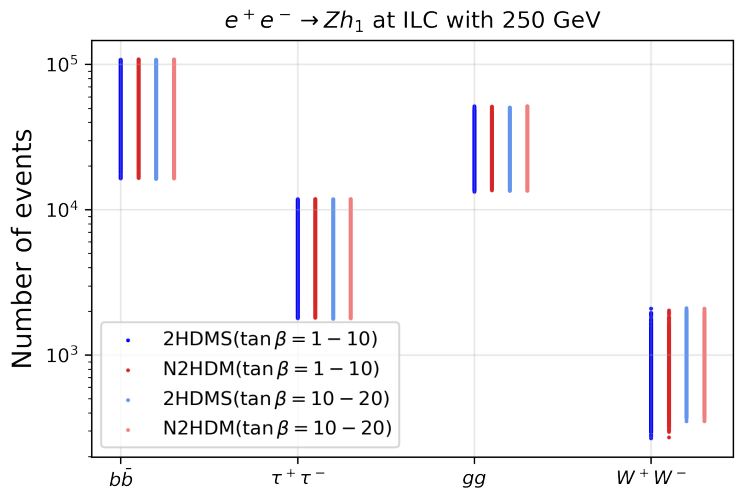
The 96 GeV LEP resonance

[S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, S. Paasch, Phys.Rev.D 106 (2022) 7, 075003]

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

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

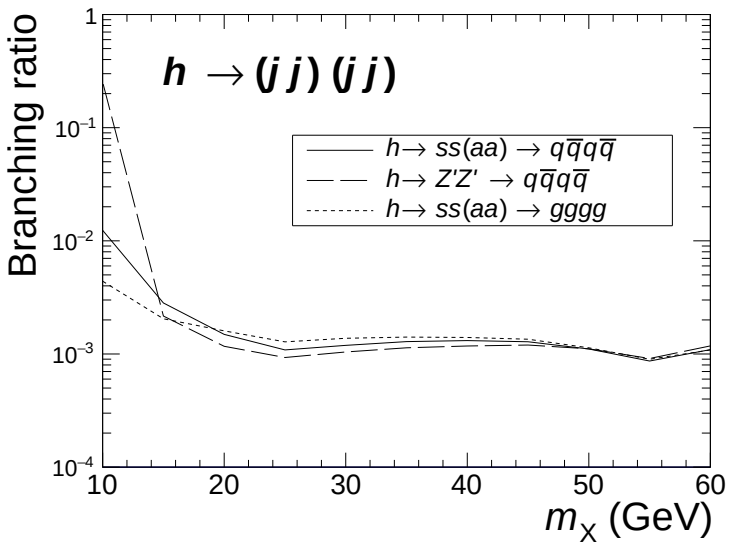


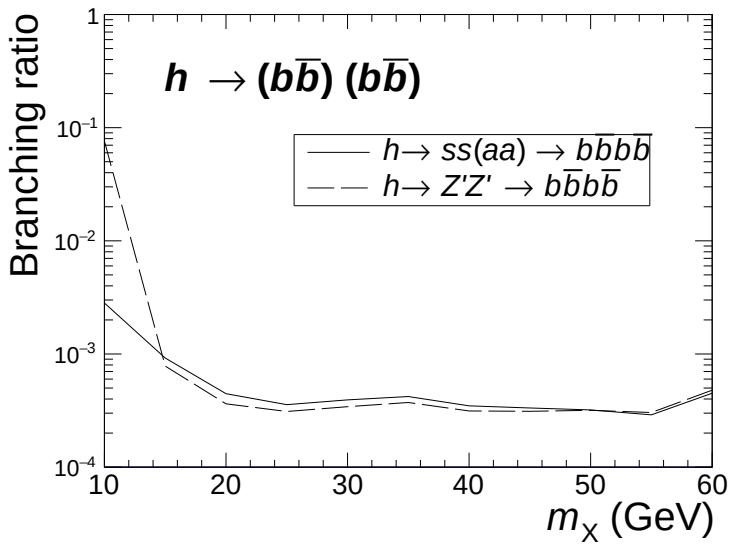


N2HDM/ 2HDMS: 2HDM extended by real (complex) singlet, various symmetries imposed, fit to LEP/ CMS data [within/ outside 1 σ]

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

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

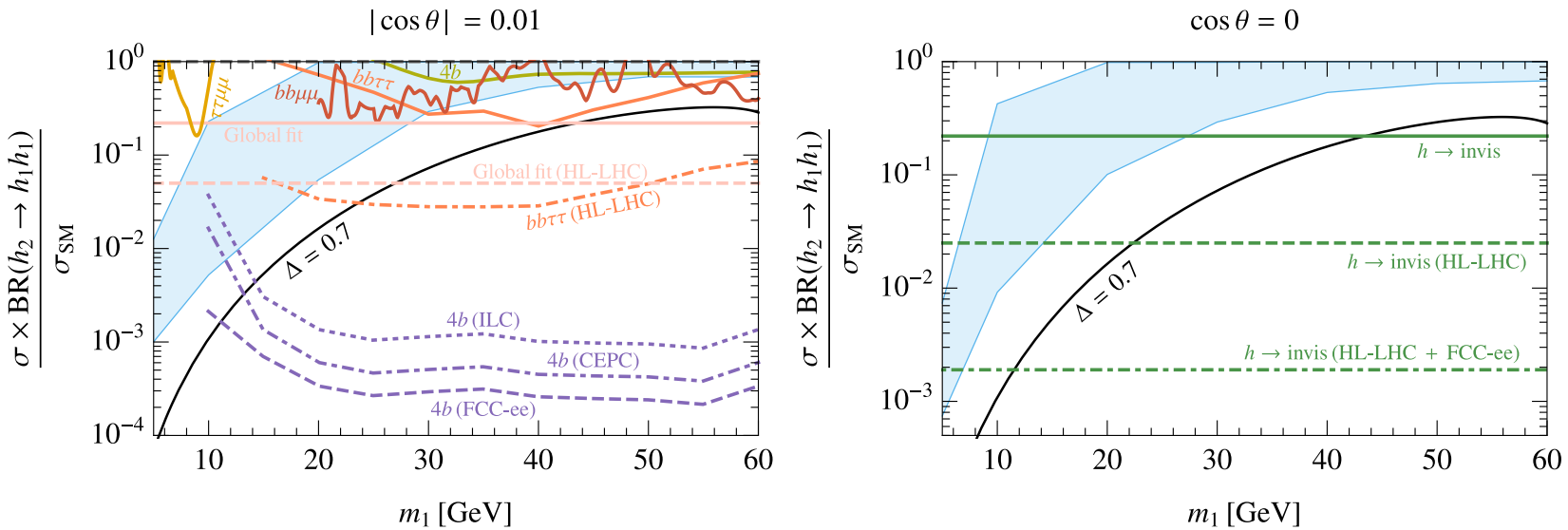




95% CL bounds, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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]



blue band = strong first-order electroweak phase transition

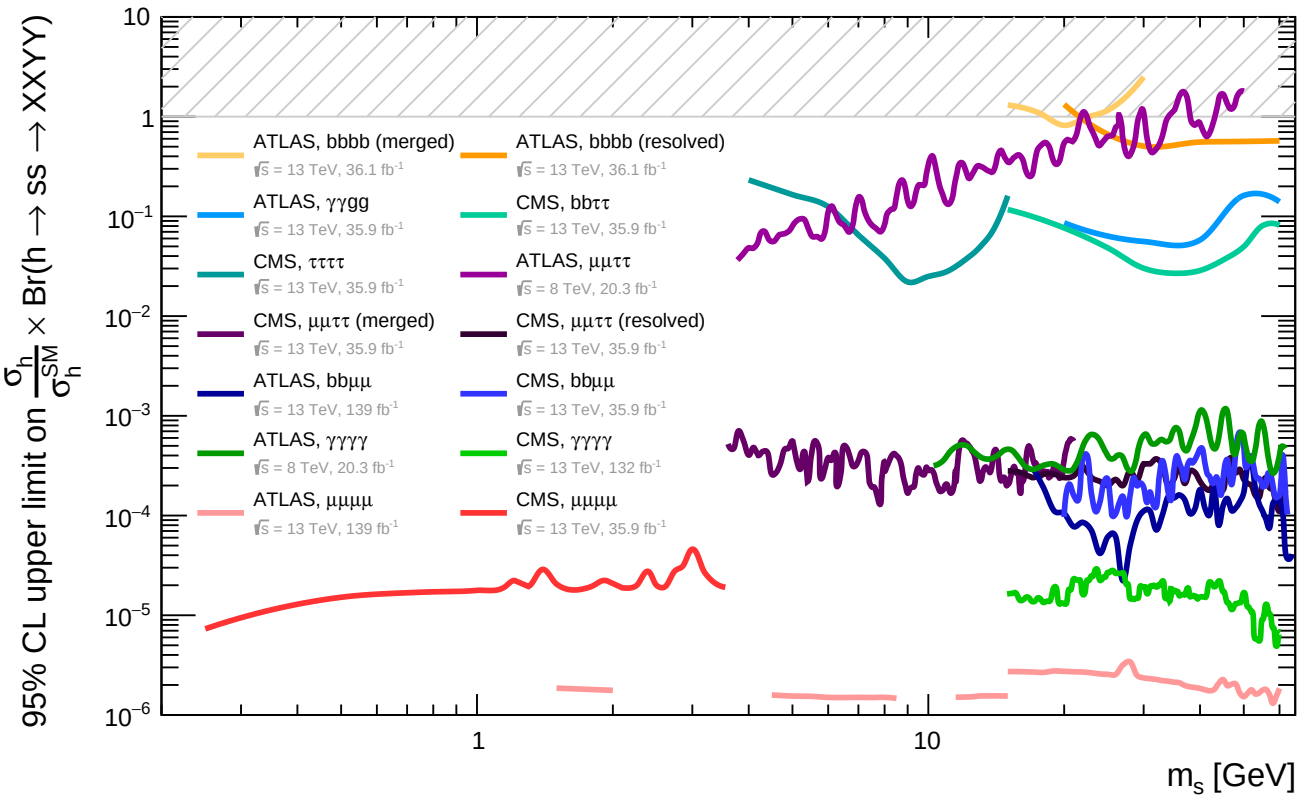
comment: **current constraints lead to prediction** $\lesssim 10^{-1}$

[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)]

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

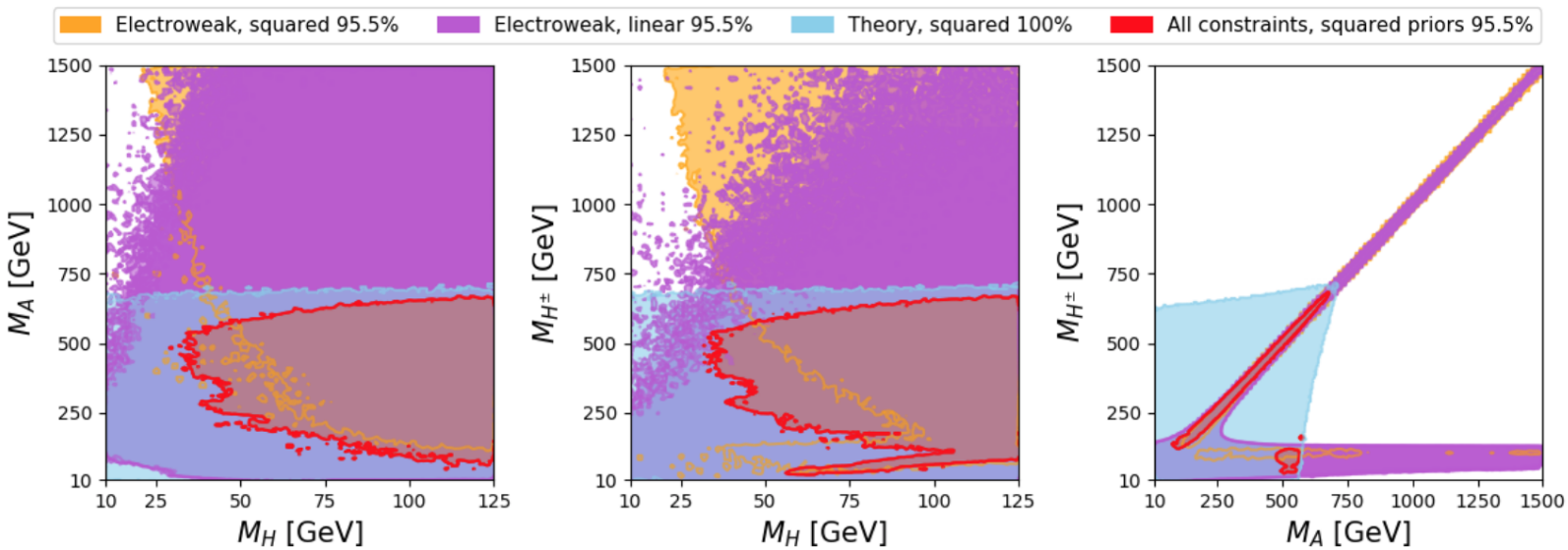
[M. Cepeda, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751]



bound on decays into lighter scalars from current searches

Aligned 2HDM

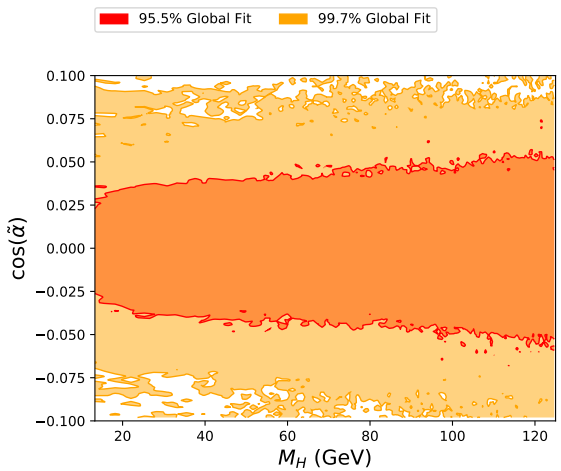
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]

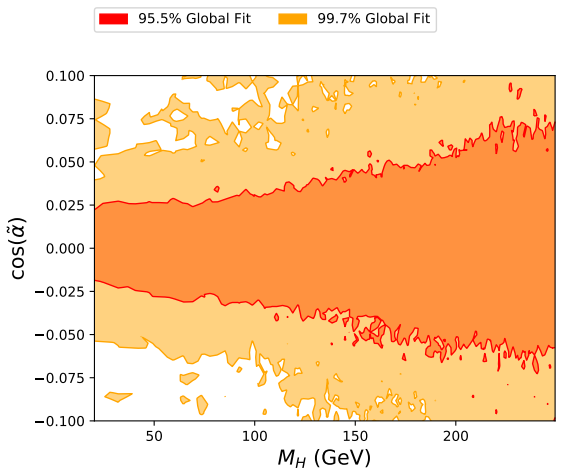


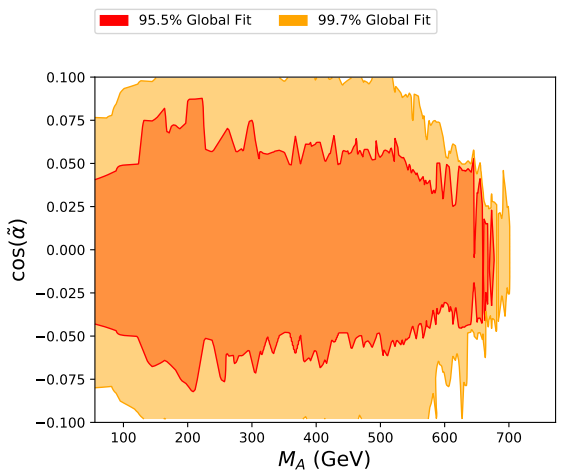
low mass region allowed; however, HZZ typically suppressed by $\cos(\beta-\alpha)$ [$\lesssim 0.25$]

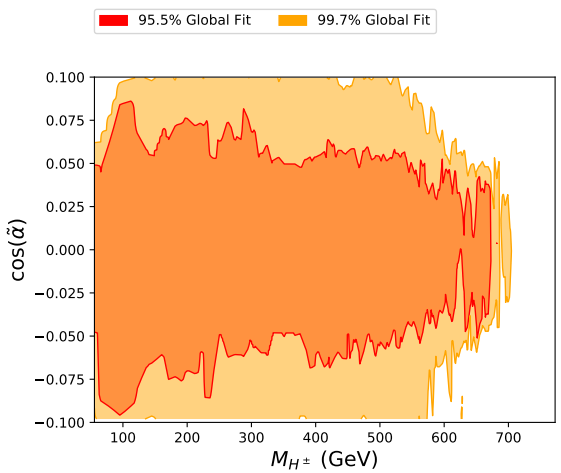
[aligned flavour structure: $Y_{d,\ell} = \varsigma_{d,\ell} M_{d,\ell}$, $Y_u = \varsigma_u^* M_u$]

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



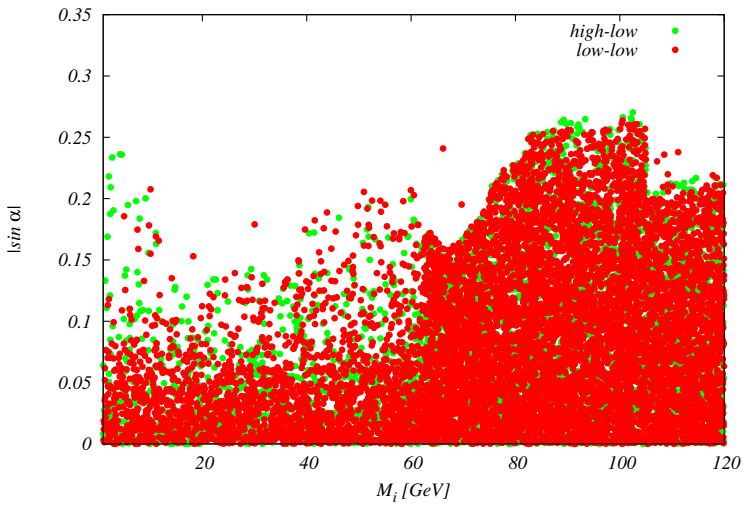




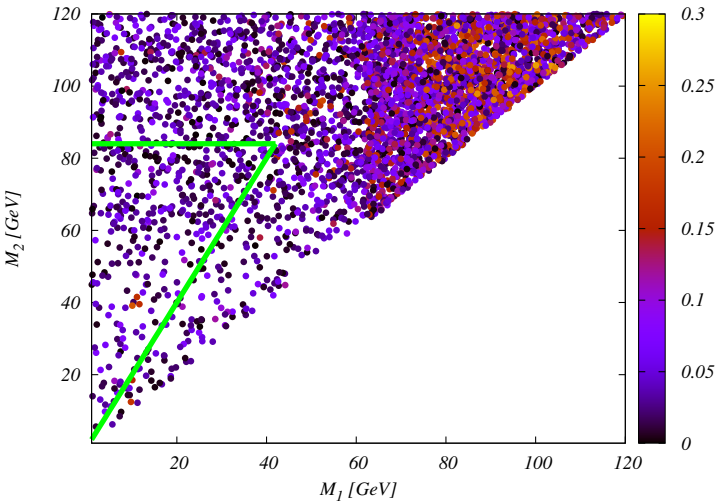


Singlet extensions [TR, arXiv:2203.08210 and Universe 8 (2022) 286]

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



mass and mixing angle



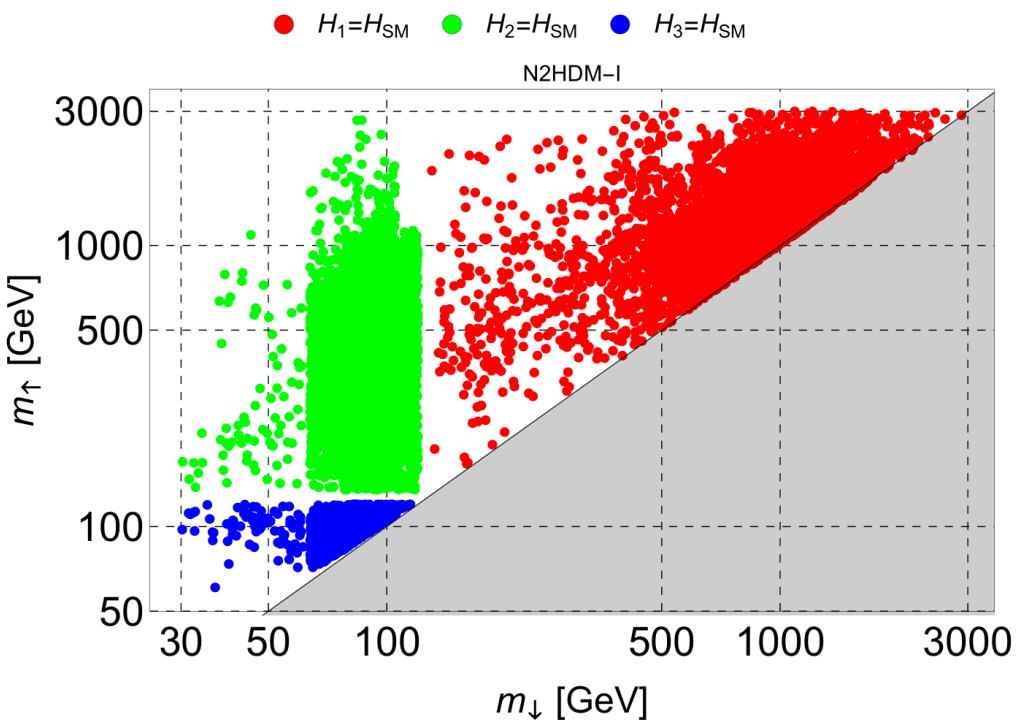
case with two light scalars;
color coding: h_1 rescaling

- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV

N2HDM example

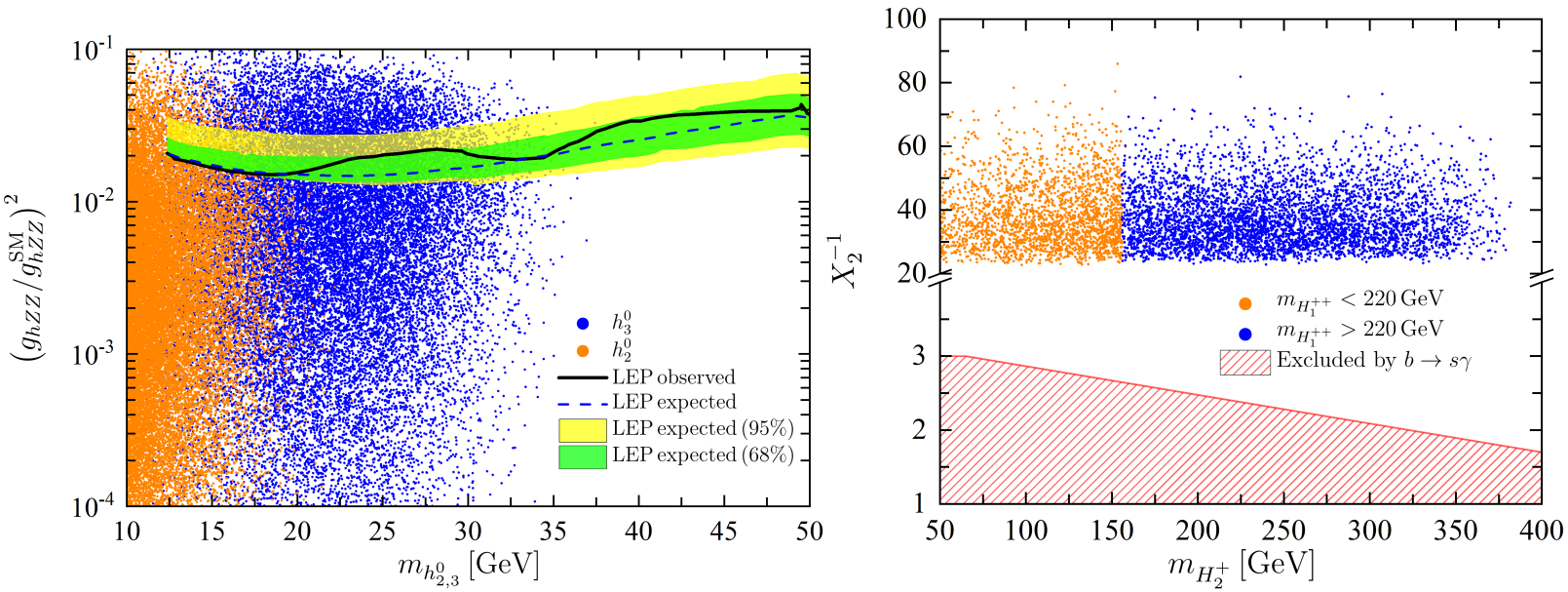
[H. Abouabid, A. Arhrib, D. Azevedo, J. El Falaki, P. M. Ferreira, M. Muehlleitner, R. Santos, JHEP 09 (2022) 011]

N2HDM: 2HDM+ real singlet



Scalar triplet model

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



5 neutral, 3 singly charged, 2 doubly charged scalars

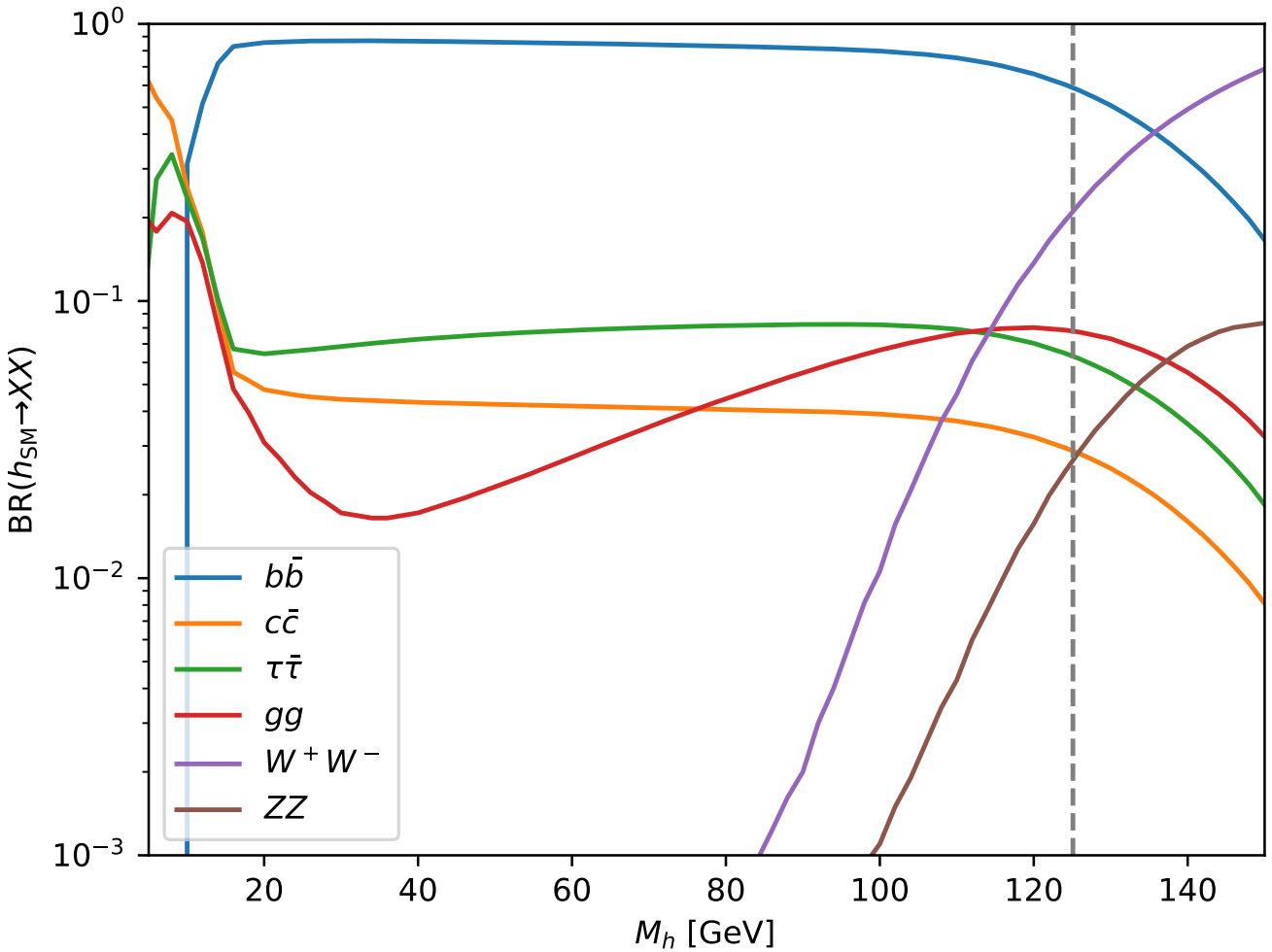
Conclusions

- **many new physics models predict one/ several scalars below 125 GeV**
- typical decays into $b\,\bar{b}$, $\tau^+\,\tau^-$
- cross sections could reach **up to** $50\,\mathrm{fb}$ **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

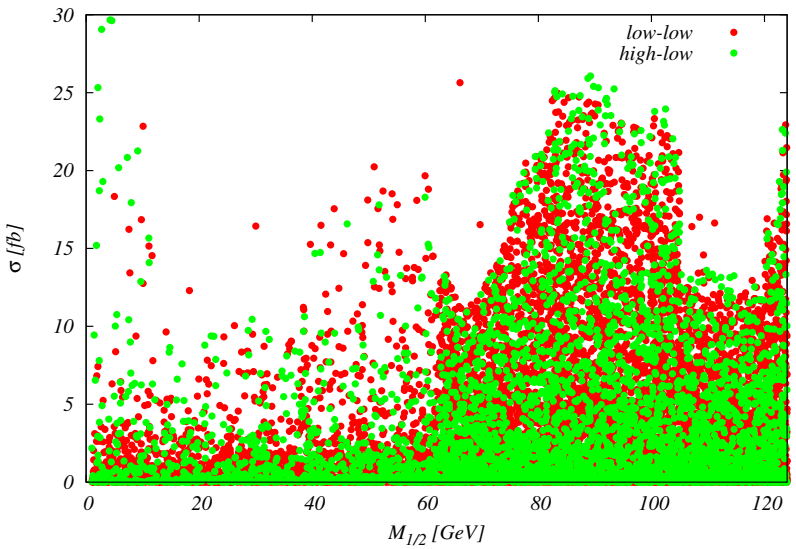
Decays of light SM-like scalars



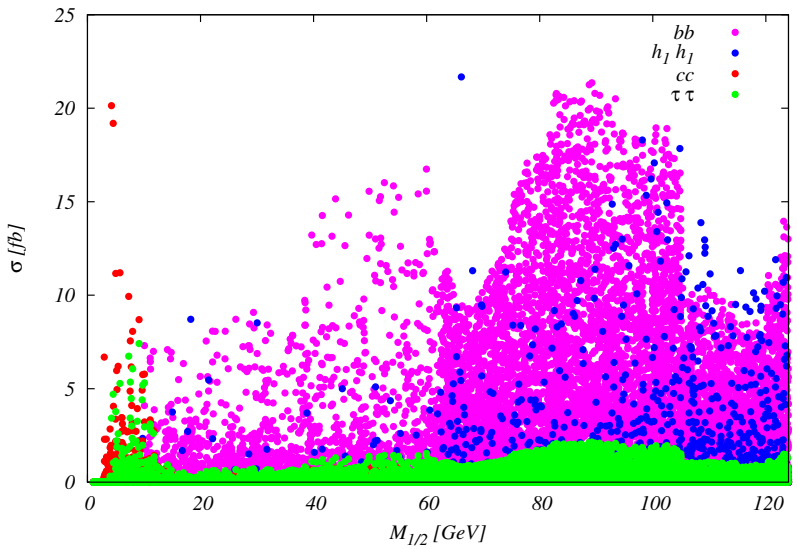
[from YREP 4/ HDecay]

Convoluted

with production cross sections



and decay rates

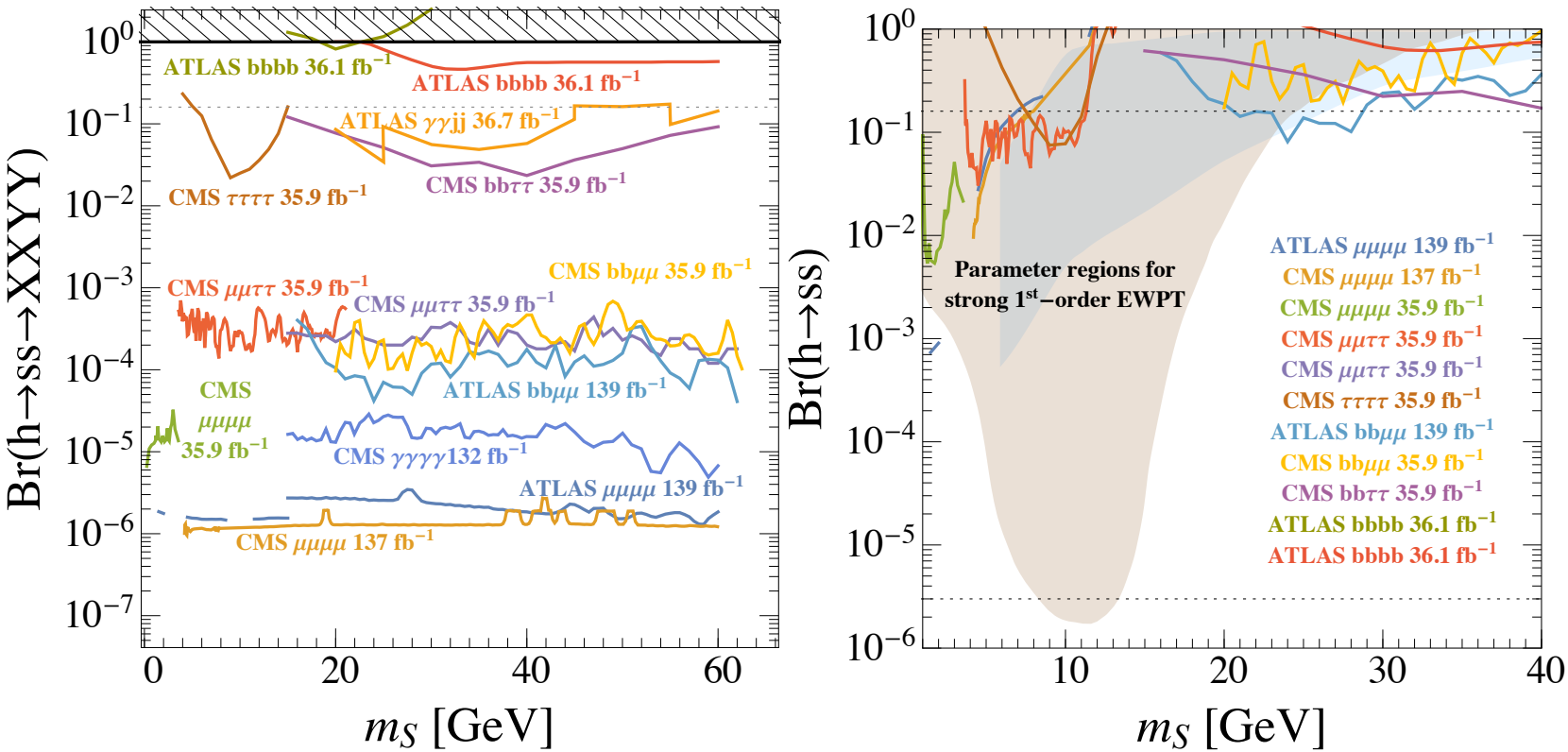


final states: $Z\,b\,\bar{b}$, $Z\,h_1\,h_1$, $Z\,c\,\bar{c}$, $Z\,\tau^+\,\tau^-$

numbers for $\sqrt{s} = 250\,\mathrm{GeV}$

Snowmass update

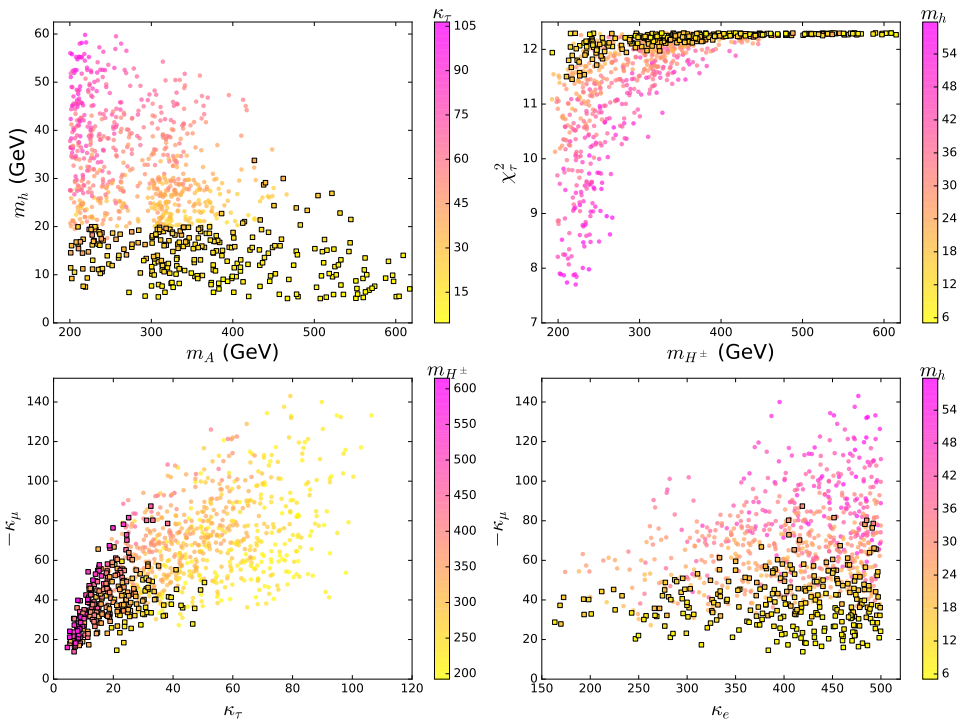
[M. Carena, J. Kozaczuk, Z. Liu, T. Ou, M. J. Ramsey-Musolf, J. Shelton, Y. Wang, K.-P. Xie, arXiv:2203.08206]



Lepton-specific IDM

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

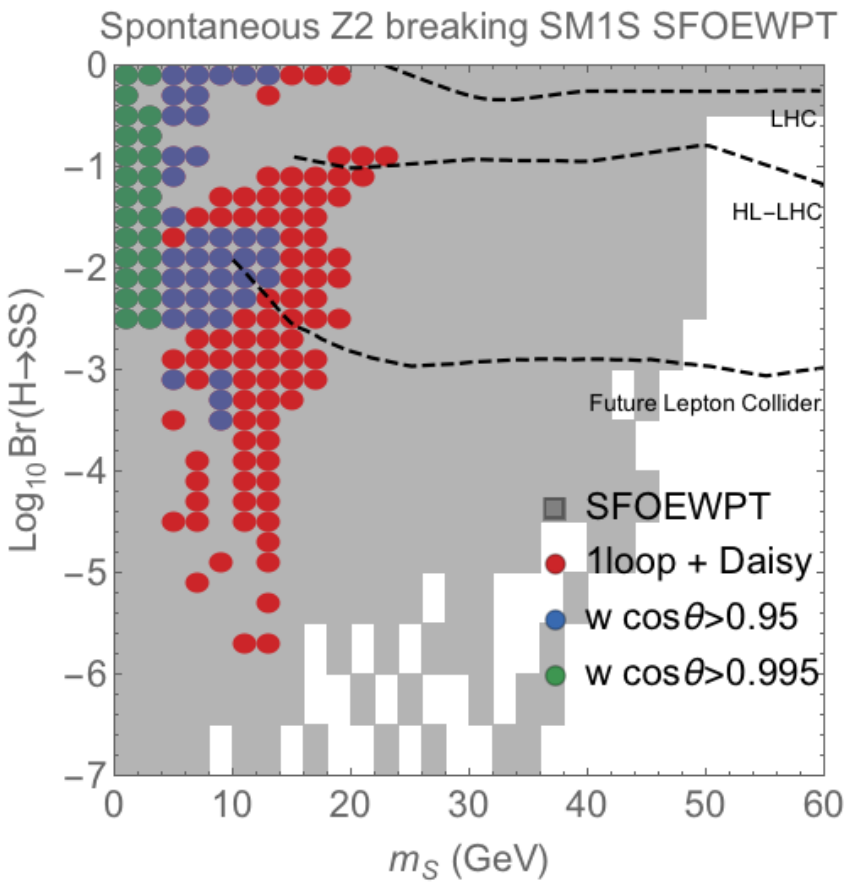
Inert Doublet Model, with $\mathbb{Z}_2$ breaking terms coupling to leptons



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

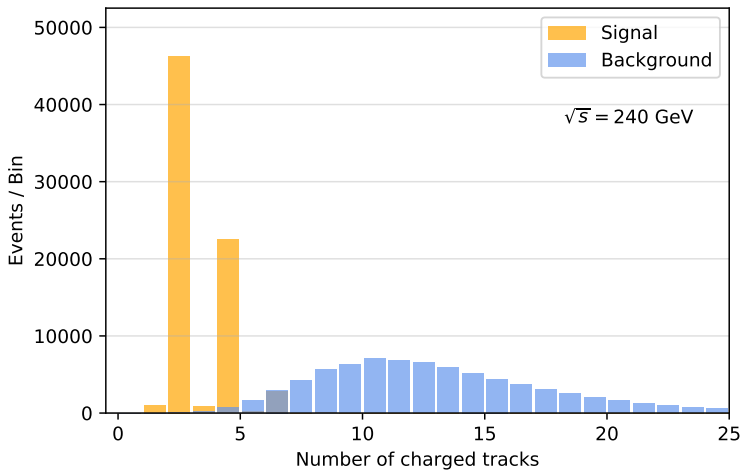
Singlet extension, spontaneous Z_2 breaking, with connection to strong first-order electroweak phase transition

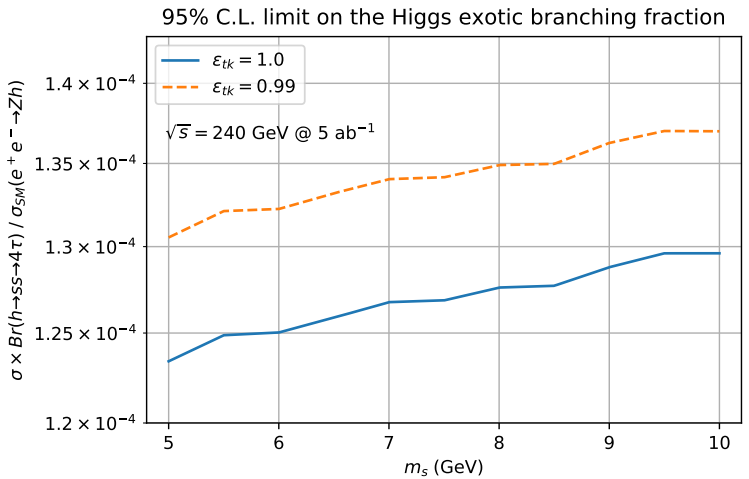
[M. Carena, Z. Liu, Y. Wang, JHEP 08 (2020) 107]



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]

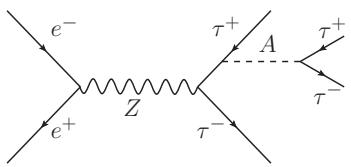
Type X 2HDM, 4τ final state via $\tau\tau A$ production

[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

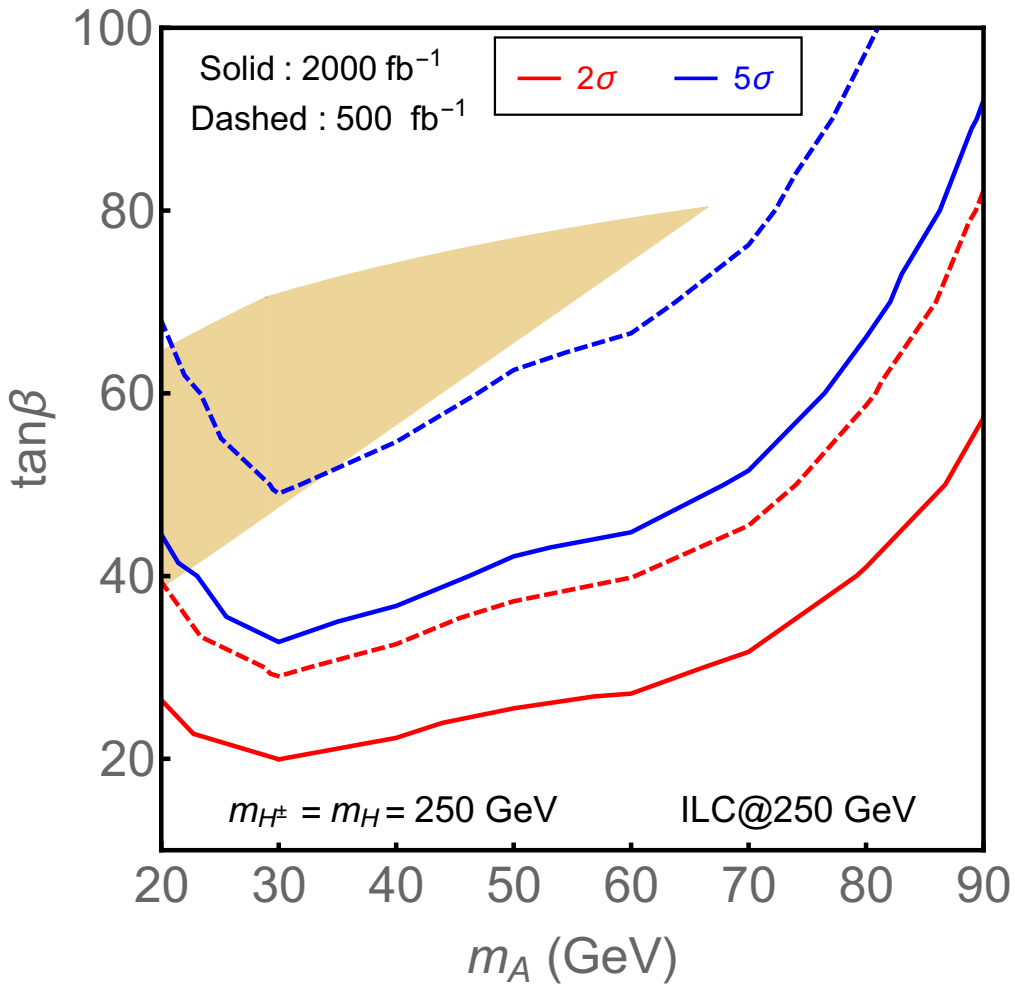
- The channel $Z \to h_{SM} A$ is not possible since the relevant coupling is proportional to $\cos(\beta - \alpha)$.
- At ILC250, $Z \to HA$ may not be feasible when H is heavier than 200 GeV.
- Possible option : $Z \to \tau\tau \to \tau\tau A \to 4\tau$. So called Yukawa production.



- 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

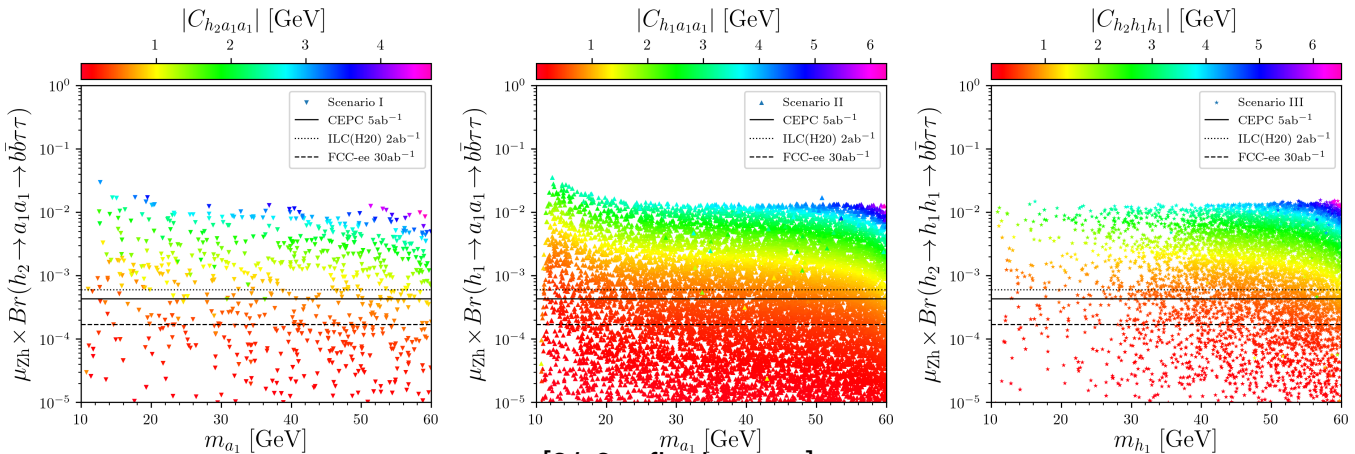
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]



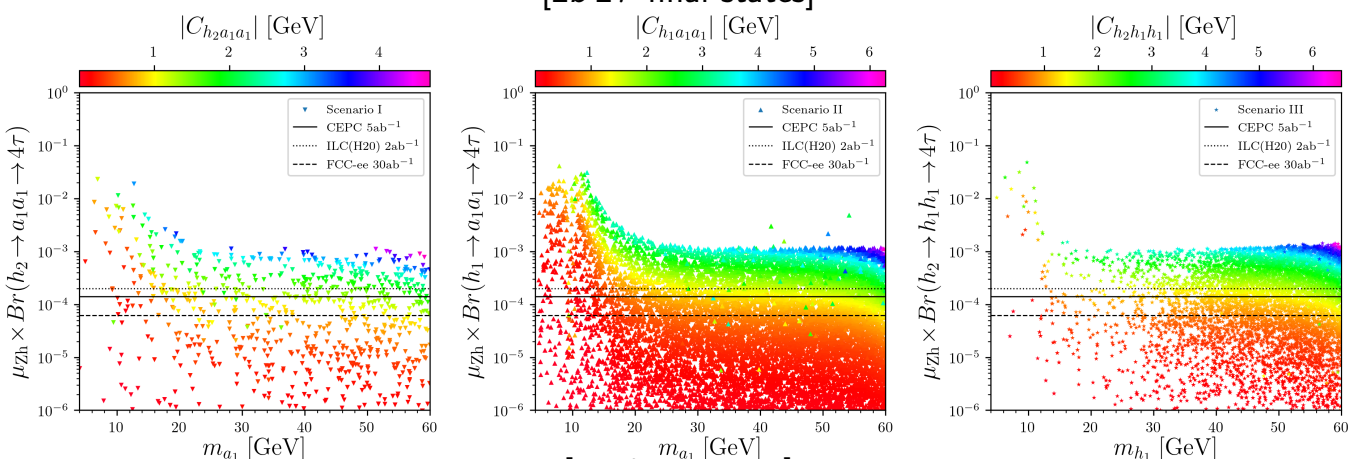
scNMSSM, $h \to s\,s \to$ various final states

[sc=semi-constrained, aka NUHM]

[S. Ma, K. Wang, J. Zhu, Chin.Phys.C 45 (2021) 2, 023113]



[$2b\,2\tau$ final states]

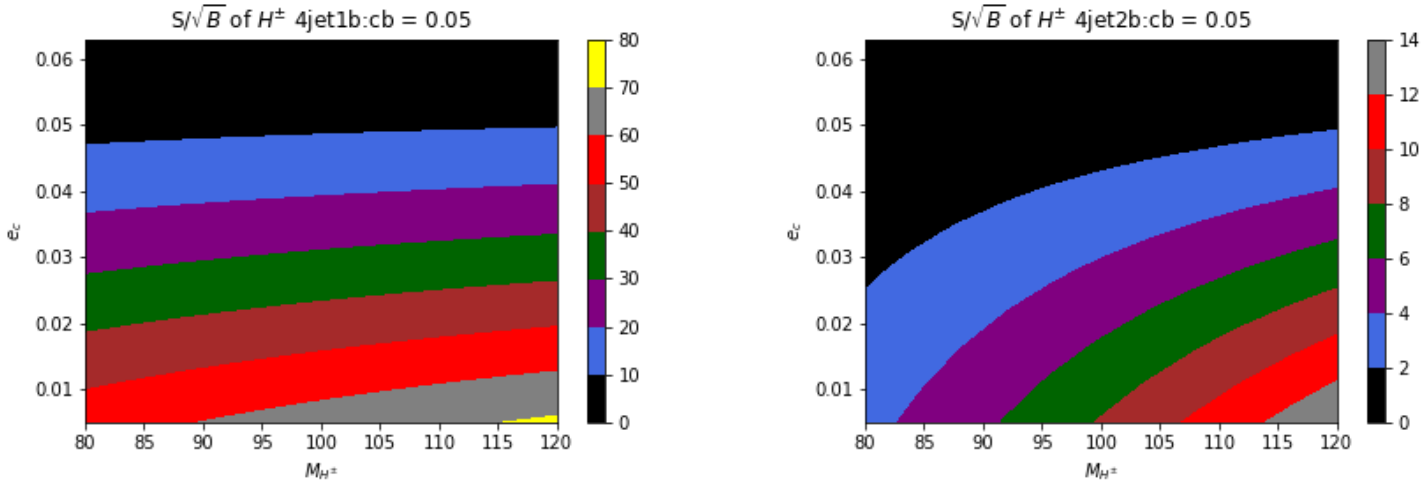


[4τ final states]

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

Light charged scalars, 3HDM, $H^+ \to c\bar{b}$ final state

[A.G.Akeroyd, S. Moretti, M. Song, Phys.Rev.D 101 (2020) 3, 035021]

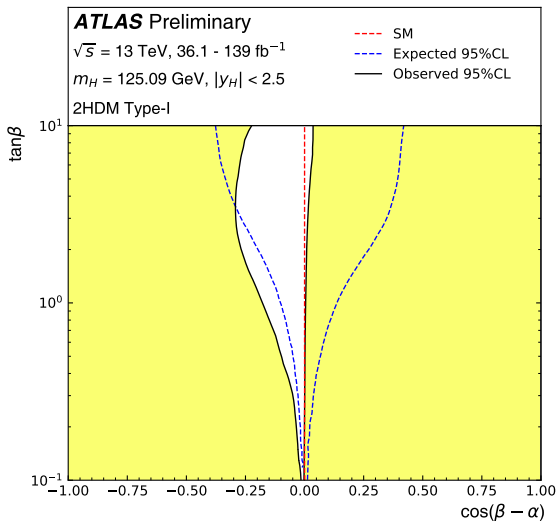


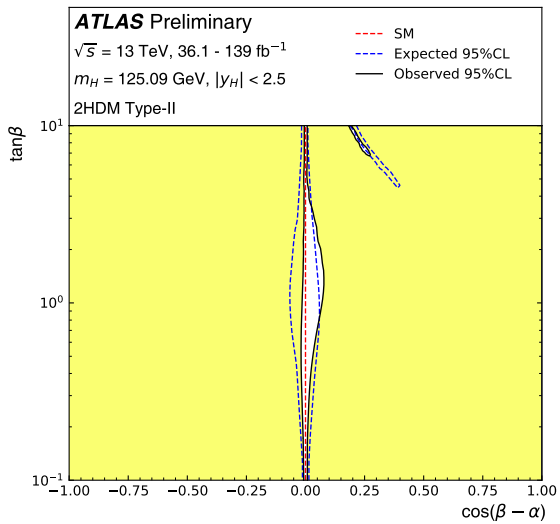
BR($H^+ \to c\,\bar{b} = 0.05$), e_c: charm tagging efficiency

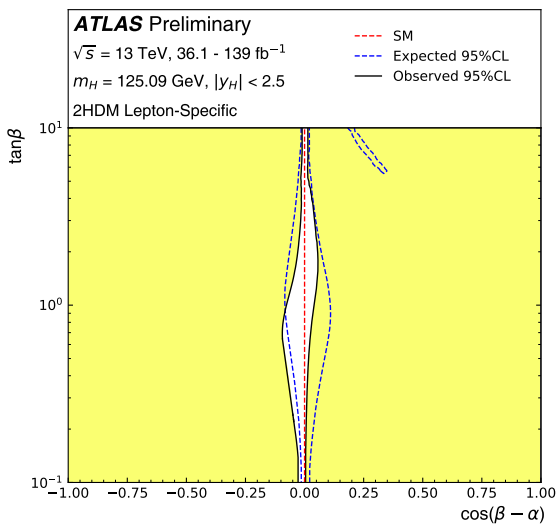
$$e^+\,e^- \to H^+\,H^-,\ \sqrt{s} = 240\,\mathrm{GeV}$$

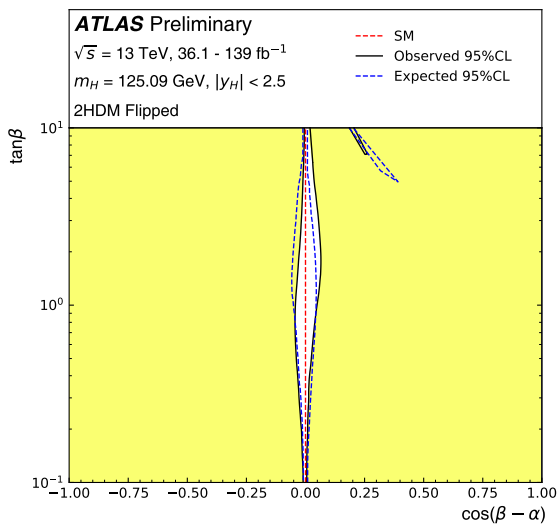
Current constraints on alignment in 2HDMs

[ATLAS-CONF-2021-053]



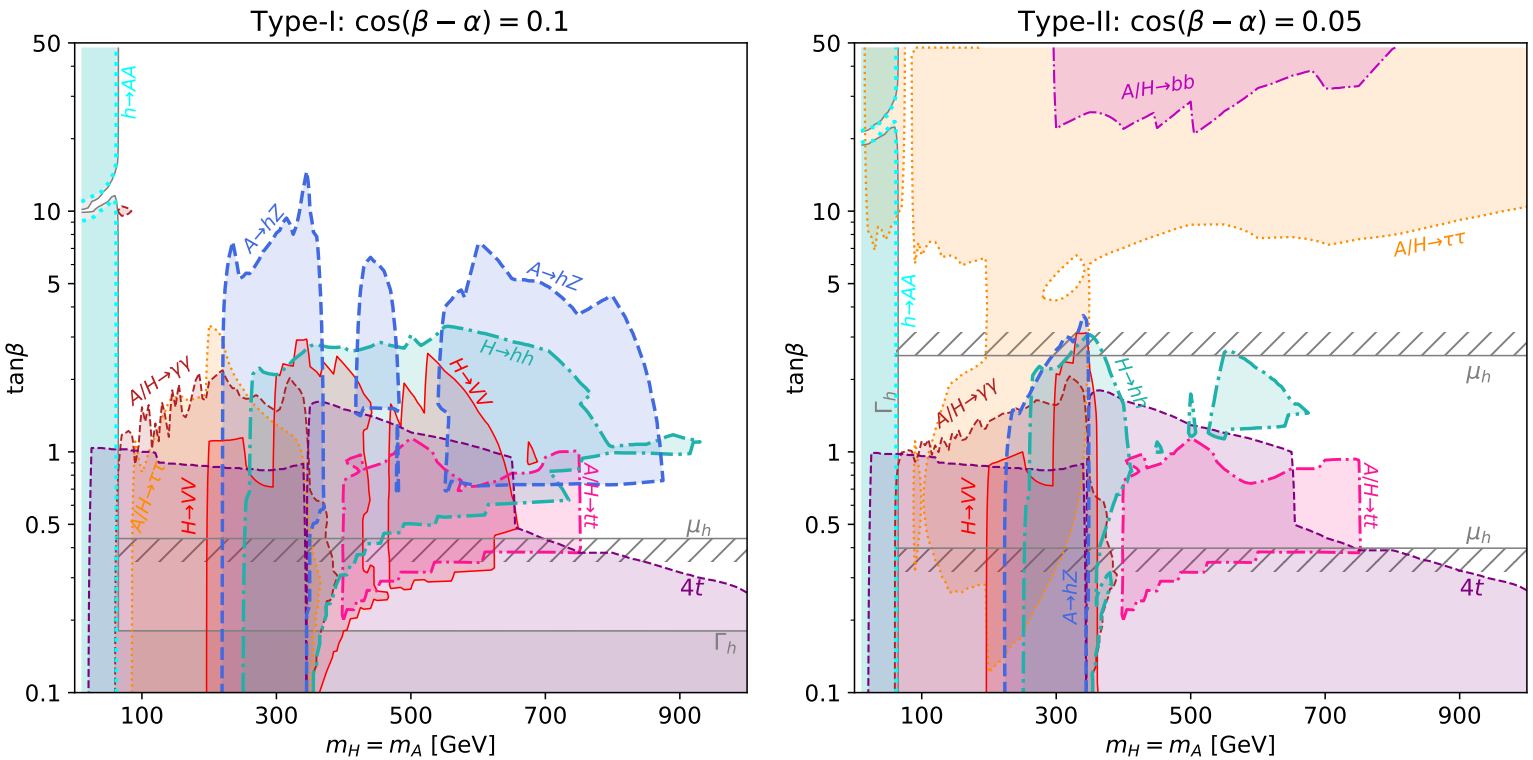






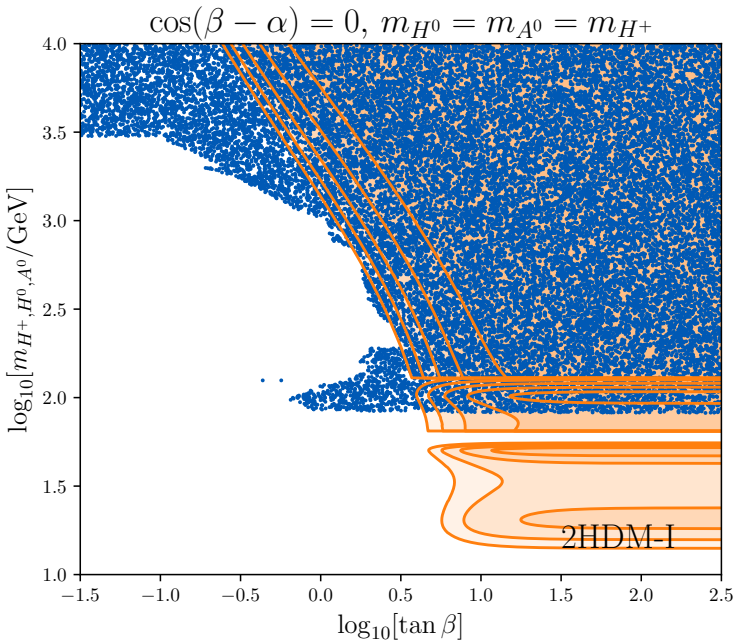
2HDM parameter space

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



Another recent 2HDM study

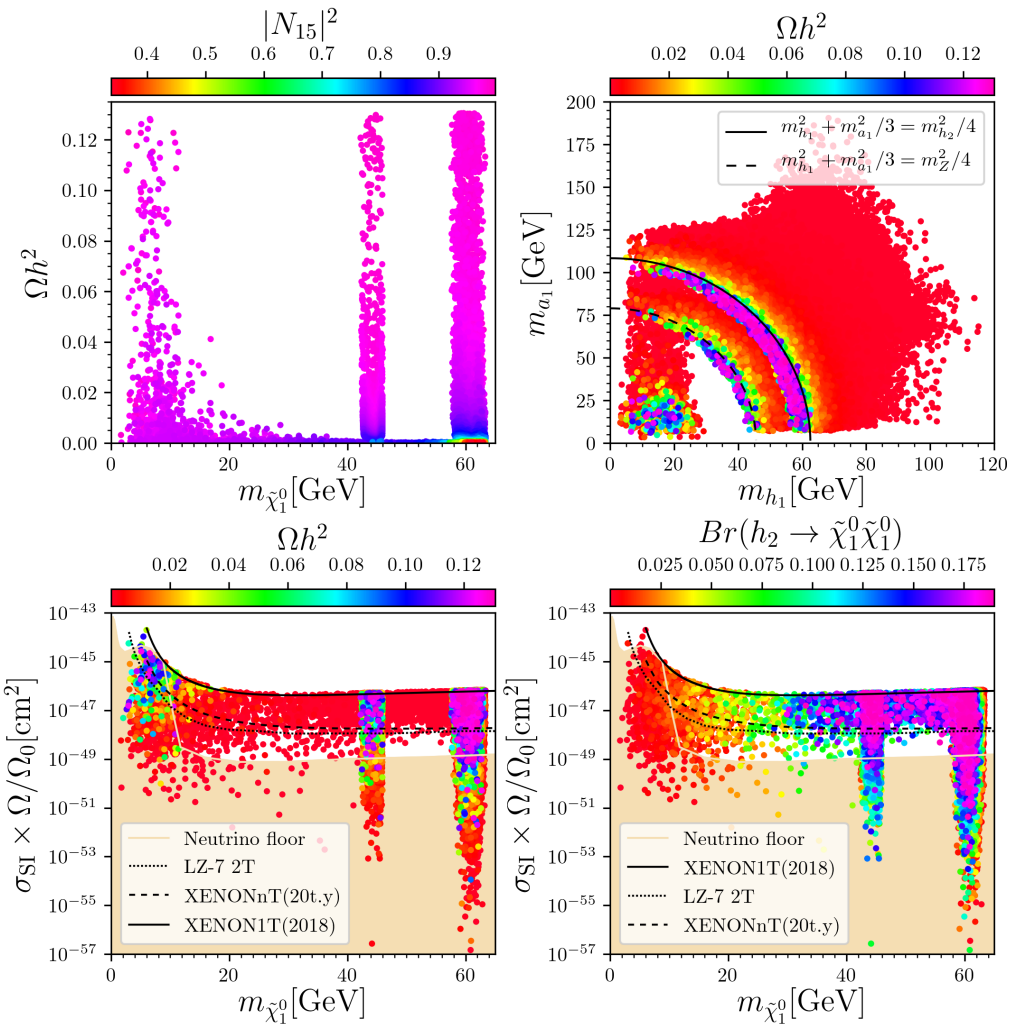
[O. Atkinson, M. Black, C. Englert, A. Lenz, A. Rusov, J. Wynne, arXiv:2202.08807]



2HDM Type I, direct searches, signal strength, and flavour constraints

scNMSSM parameter space

[K. Wang, J. Zhu, JHEP 06 (2020) 078]

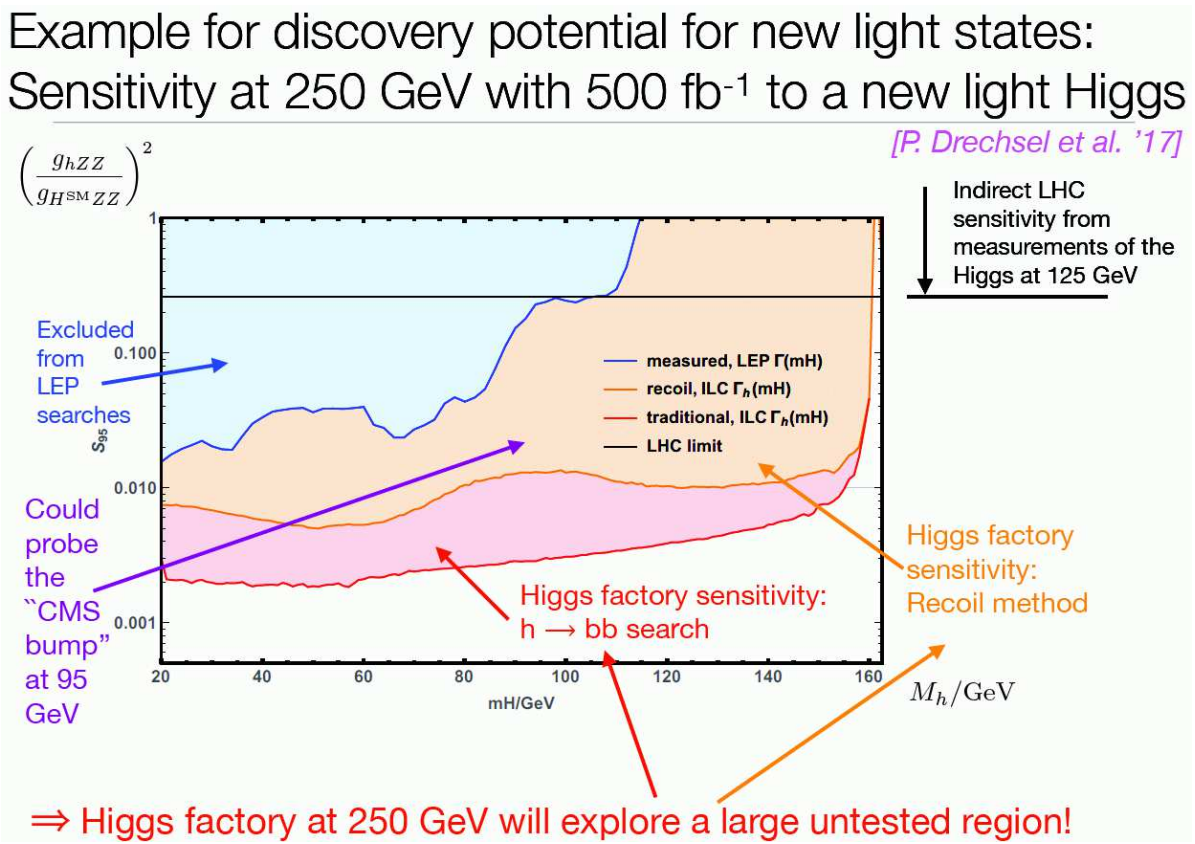


Parameter space for light scalar

[S. Heinemeyer, talk at ILCX 2021 workshop]

4. Direct detection of "light" BSM Higgs bosons

Example for discovery potential for new light states:
Sensitivity at 250 GeV with 500 fb^{-1} to a new light Higgs



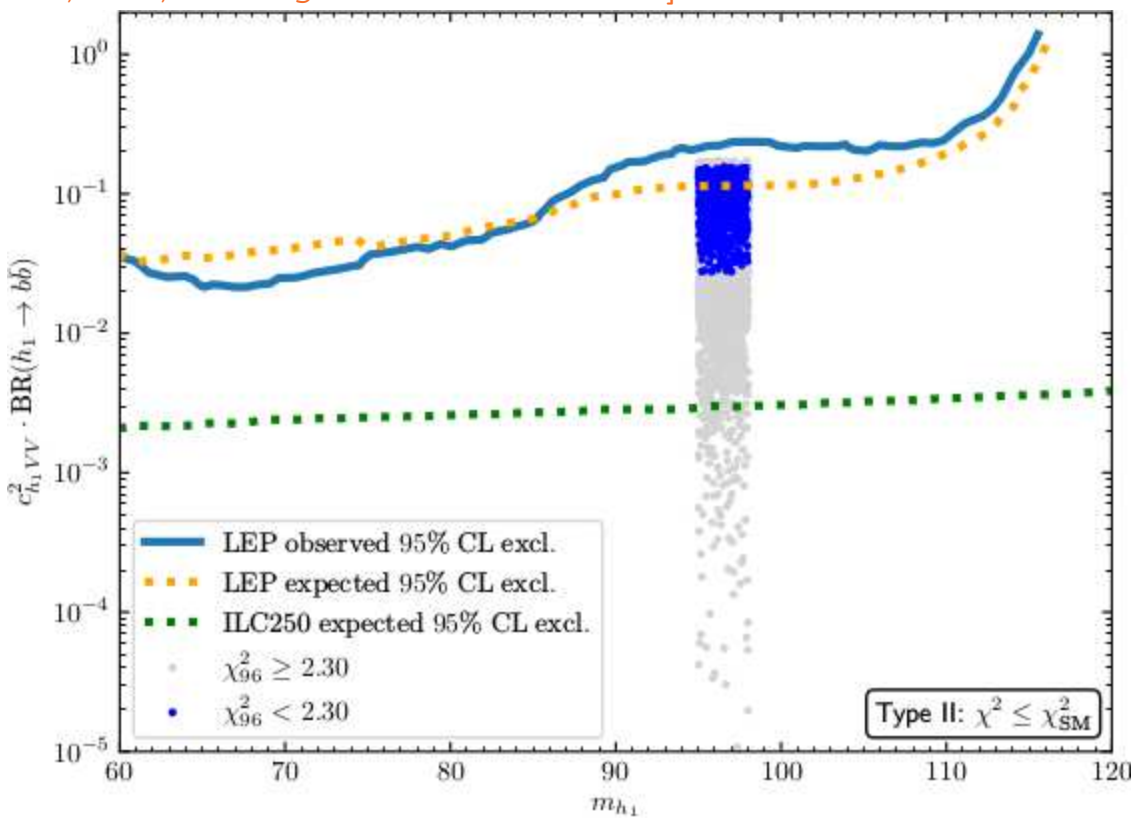
[*Taken from G. Weiglein '18*]

N2HDM (2HDM + singlet) type II, $h_1 \to b\bar{b}$

[S. Heinemeyer, talk at ILCX 2021 workshop]

ILC production of the light scalar in the N2HDM type II:

[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]

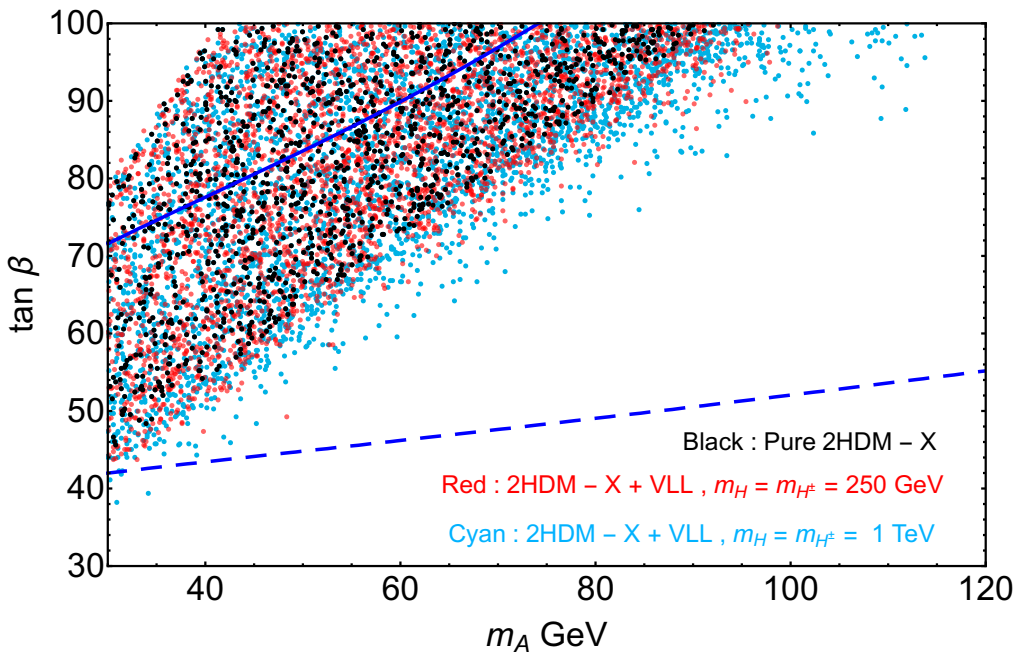


$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

Type X 2HDM with vector-like leptons

[E. J. Chun, T. Mondal, JHEP 11 (2020) 077]

... including connection to $g_\mu - 2$



Scalar triplet model

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

Mass spectrum		CP-Conserving	CP-Violating
Neutral	h_1^0	Massless - Goldstone boson	
	h_2^0	SM Higgs-like	Light
	h_3^0	Decoupled	
	h_4^0		SM Higgs-like
	h_5^0	Decoupled	Decoupled
	h_6^0		
Singly-charged	H_1^+	Massless - Goldstone boson	
	H_2^+	Decoupled	Electroweak
	H_3^+	Decoupled	Decoupled
Doubly-charged	H_1^{++}	Decoupled	Electroweak
	H_2^{++}	Decoupled	Decoupled