Low mass scalars at e^+e^- colliders

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mini-workshop on BSM at ILC
2. March '22

Models

- new low-mass 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**

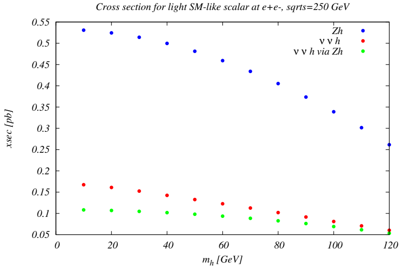
Models

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**
- ...

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]

- rule of thumb: **rescaling $\lesssim 0.1$**
- $\Rightarrow$ maximal production **cross sections around 50 fb**
- $\sim 10^5$ **events using full luminosity**

Possible searches

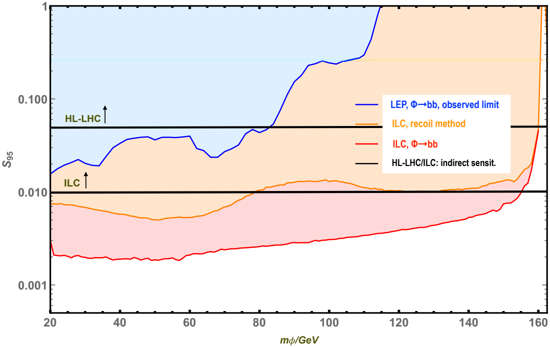
- one option: consider $h_{125} \rightarrow s\,s$
- also possible: **direct searches**
- for all of these: **dominant decays typically to $b\,\bar{b}$ or $\tau^+\tau^-$**

$\Rightarrow$ **mainly discussed here** $\Leftarrow$

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

Projections for additional scalar searches

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

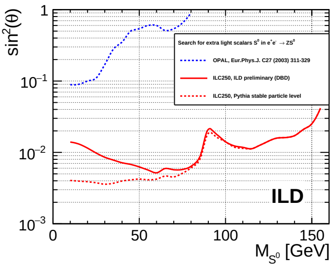


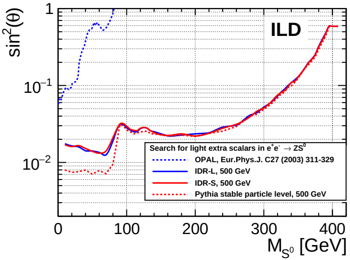
estimate of ILC sensitivity based on validation using LEP results

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]





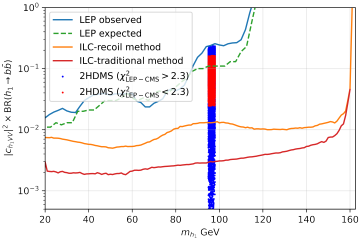
additional scalar, $\sin\theta$ rescaling wrt SM prediction, comparison of different detector models recoil method

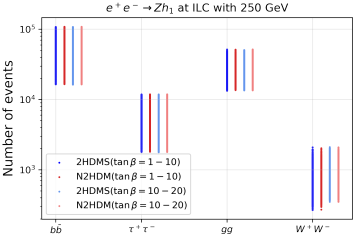
The 96 GeV LEP resonance

[S. Heinemeyer, C. Li, F. Lika, G. Moortgat-Pick, S. Paasch, 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

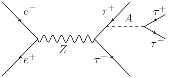
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]

one doublet couples to quarks, other to fermions; CP violation

Searches for light A in 2HDMX at ILC250

KIAS

- 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.

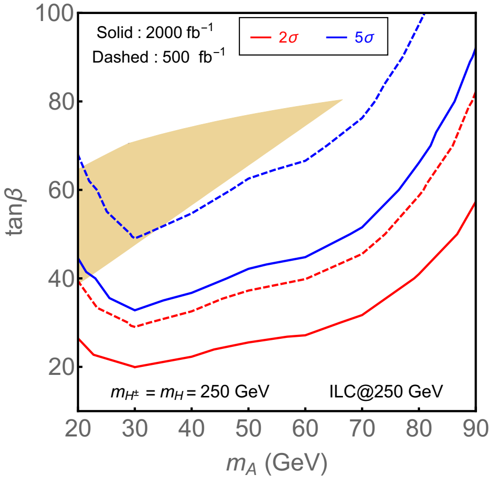


- This is the equivalent to ttH searches at LHC. Independent probe of Yukawa structure.
- At the ILC all the 4τ s can be reconstructed using collinear approximation.
- This enables to measure mass of the light particle.

Tanmoy Mondal, KIAS, Seoul ICHEP 2020, Prague Light (Pseudo)Scalar @ ILC

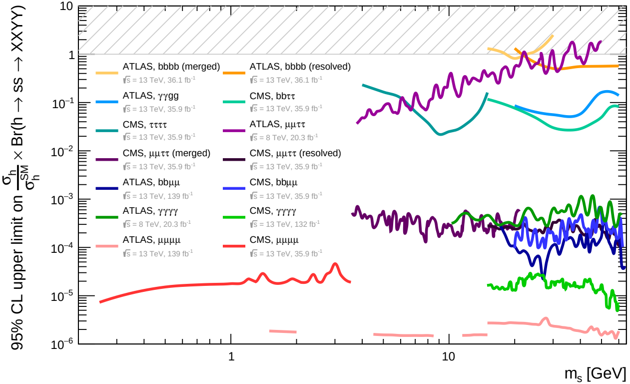
Type X 2HDM, 4 τ final state via $\tau\,\tau\,A$ production

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



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

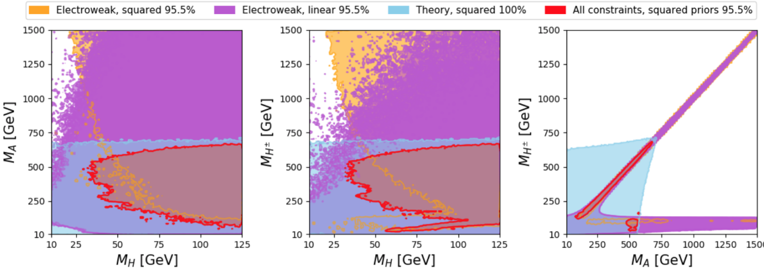
[M. Cepeda, S. Gori, V. Martinez Outschoorn, J. Shelton, arXiv:2111.12751]



bound on decays into lighter scalars from current searches

Aligned 2HDM

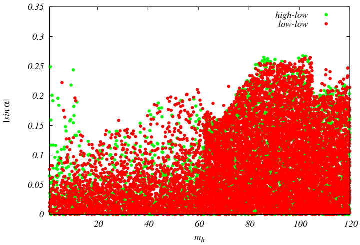
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]



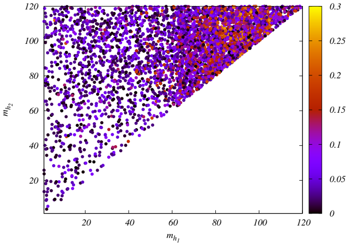
low mass region allowed; however, HZZ typically suppressed by $\cos(\beta - \alpha)$ [$\lesssim$ 0.25]

Singlet extensions [TR, preliminary]

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

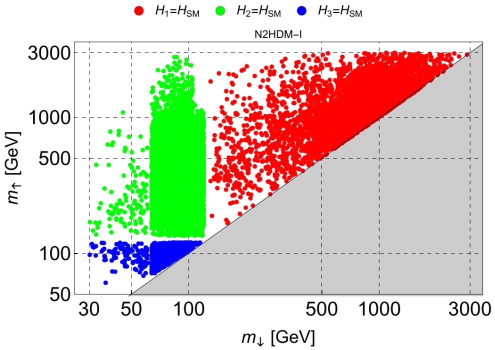
- **low-low:** both additional scalars below 125 GeV; **high-low:** one new scalar above 125 GeV

using ScannerS [M. Muehlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt, arXiv:2007.02985]

N2HDM example

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

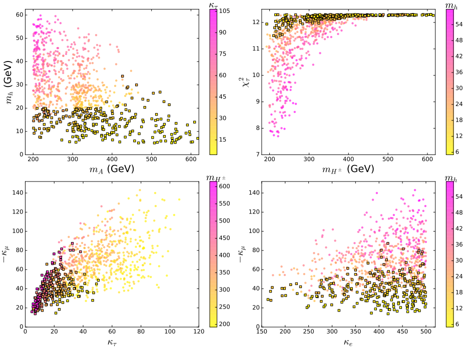
N2HDM: 2HDM+ real singlet



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

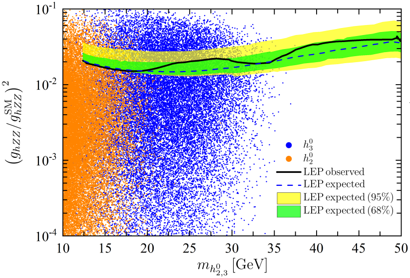


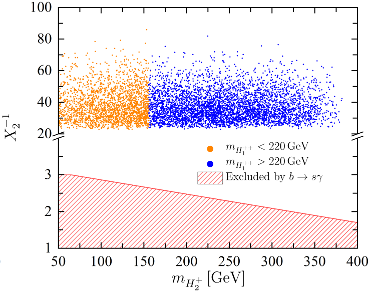
various constraints (including agreement with $g_\mu - 2$);

squares: allowed, bullets: forbidden

Scalar triplet model

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





5 neutral, 3 singly charged, 2 doubly charged scalars

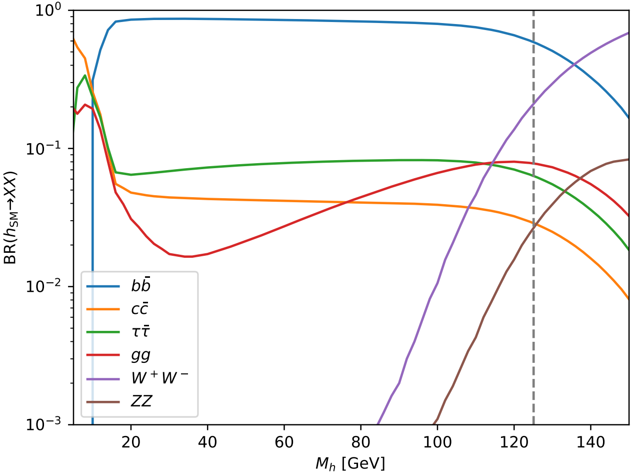
Conclusions

- **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 $h_{125} \rightarrow s\,s$ **also within reach**
- important connection to EWSB/ EW phase transitions

Still space for more studies !

Appendix

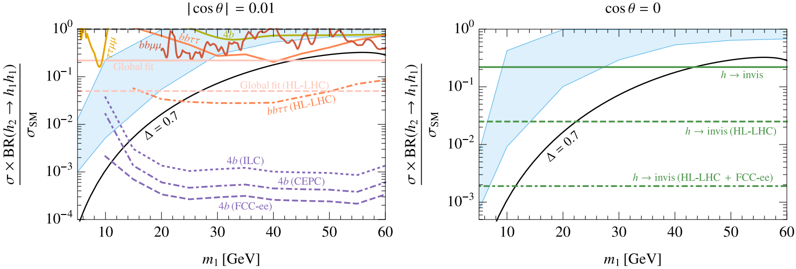
Decays of light SM-like scalars



[from YREP 4/ HDecay]

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

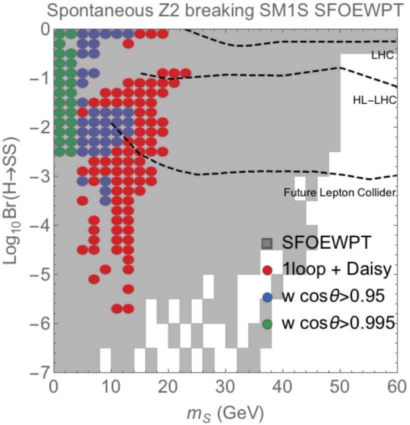
comment: **current constraints lead to prediction $\lesssim 10^{-1}$**

[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)]

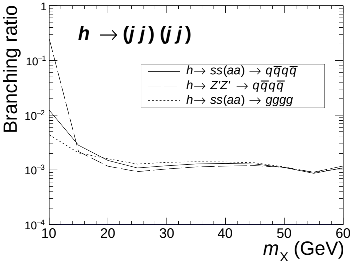
Singlet extension, spontaneous Z_2 breaking, with connection to strong first-order electroweak phase transition

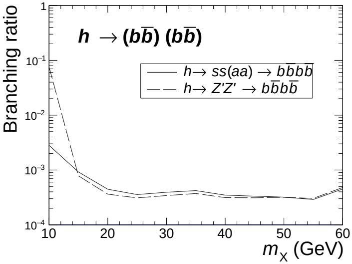
[M. Carena, Z. Liu, Y. Wang, JHEP 08 (2020) 107]



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

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

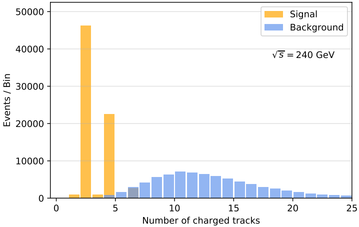


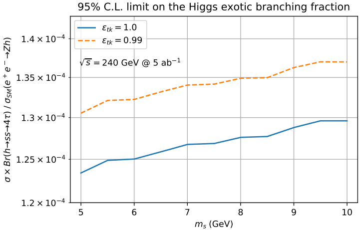


95% **CL bounds**, $\sqrt{s} = 240\,\text{GeV}$, $\int \mathcal{L} = 5\,\text{ab}^{-1}$

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 $h \to j\,j$]

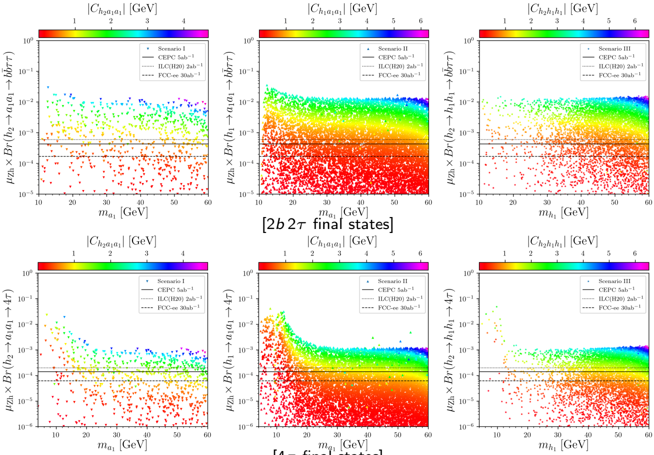
ε_{tk}: tracking efficiency

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

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

# scNMSSM, $h \rightarrow s\,s \rightarrow$ various final states
[sc=semi-constrained, aka NUHM]

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



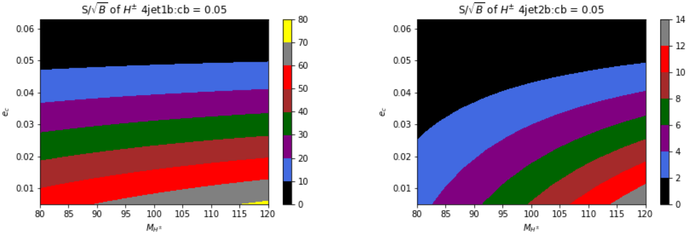
[$2b\,2\tau$ final states]

[4τ final states]

[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]
$m \leq 125\,\mathrm{GeV}$ @ e^+e^-

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

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

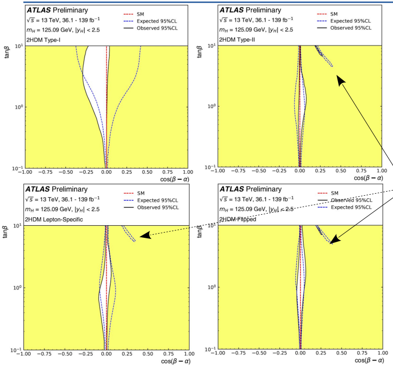
Current constraints on alignment in 2HDMs

[H. Arnold, talk at Higgs 2021]

2HDM interpretation: results

ATLAS-CONF-2021-053 Nikhef

New



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

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

$\rightarrow$ h indistinguishable from $H_{\rm SM}$

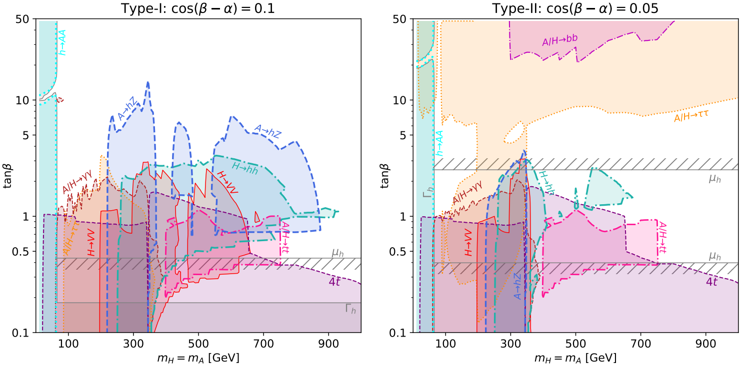
- The data is consistent with the ***alignment limit*** within 1 std. or better
- "petal" allowed regions: some fermion couplings have the same *magnitude* as in the SM, but the opposite *sign*

No surprises:
the observed Higgs boson is SM-like

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

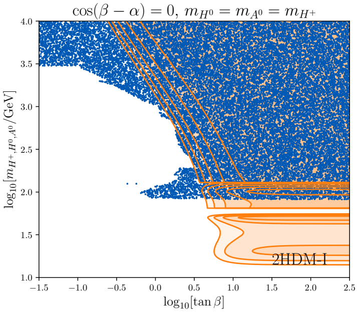
2HDM parameter space

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



Another recent 2HDM study

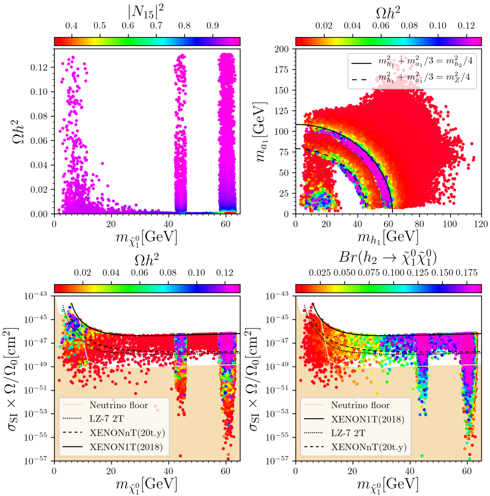
[O. Atkinson, M. Black, C. Englert, A. Lenz, A. Rusov, J. Wynne, arXiv:2202.08807]



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

scNMSSM parameter space

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

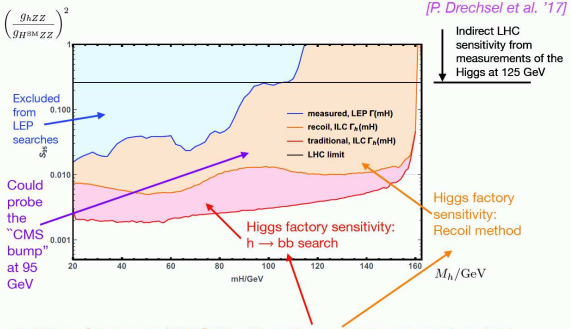


Parameter space for light scalar

[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



⇒ Higgs factory at 250 GeV will explore a large untested region!

[*Taken from G. Weiglein '18*]

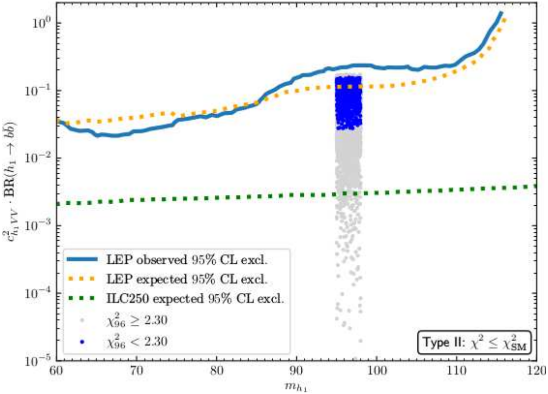
Sven Heinemeyer, ILCX workshop, 28.10.2021 28

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]

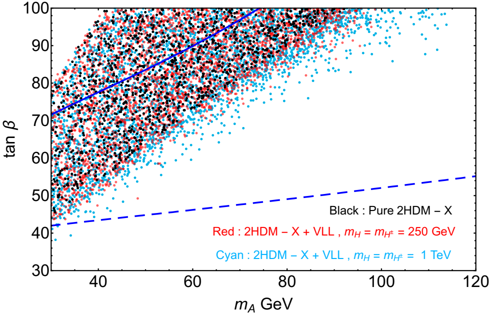


$\Rightarrow$ new state easily in the reach of the ILC $\Rightarrow$ coupling measurements

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