

Higgs bosons below 125 GeV at CEPC

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Models

- new low-mass scalars \Rightarrow **models with scalar extensions**
- many possibilities: 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:

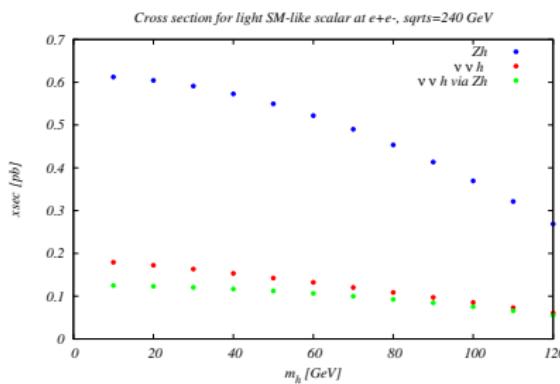
singlet extensions \Rightarrow additional CP-even/ odd
mass eigenstates

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

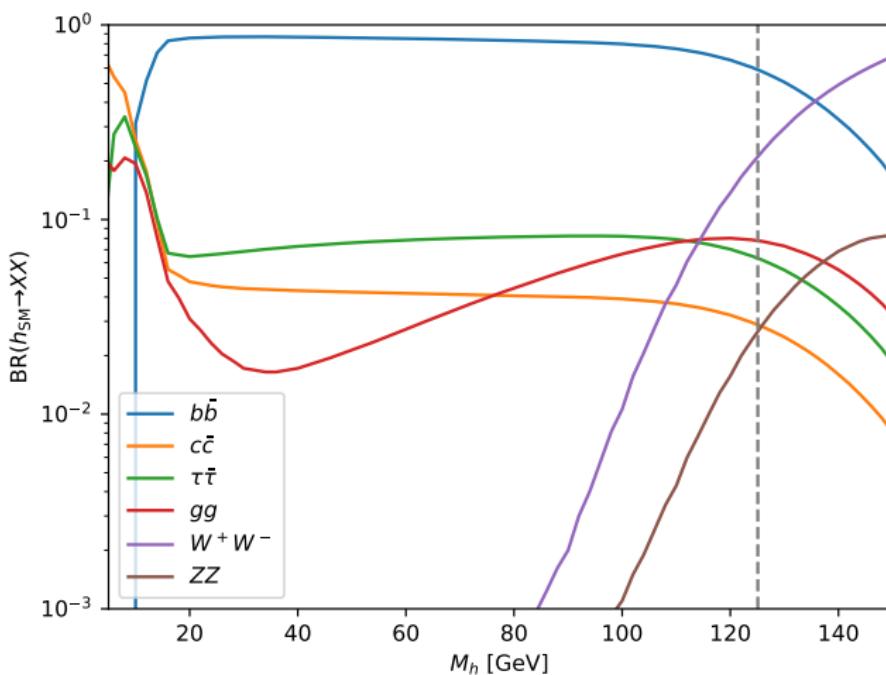
$e^+ e^- \rightarrow Z^* \rightarrow Zh, e^+ e^- \rightarrow \nu\bar{\nu}h$ (**VBF**)



[cross sections for $e^+ e^-$ at $\sqrt{s} = 240$ GeV using Madgraph5]

- rule of thumb: **rescaling $\lesssim 0.1$**
- \Rightarrow maximal production **cross sections around 60 fb**
- $\sim 10^5$ events using full luminosity**

Decays of light SM-like scalars



[from YREP 4/ HDecay]



Possible searches

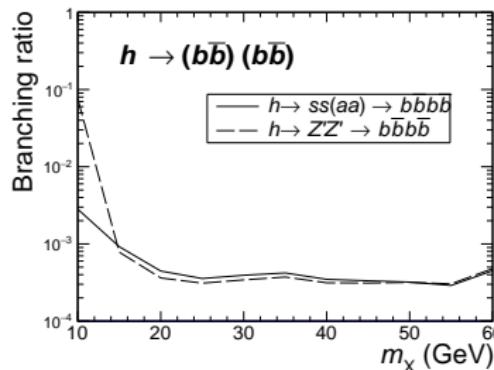
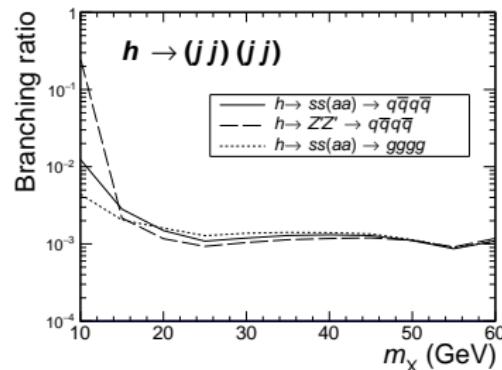
- one option: consider $h_{125} \rightarrow s s$

many searches focus on this

- 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 $\Gamma_{125} \leq 9 \text{ MeV}$, and $\text{BR}_{h \rightarrow \text{inv}} \leq 0.11$.

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

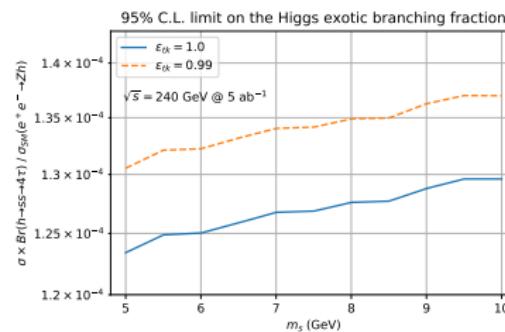
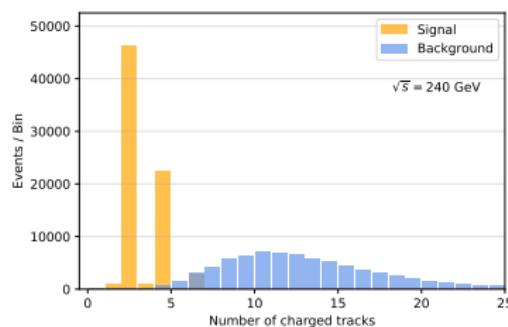
[Z. Liu, L.-T. Wang, H. Zhang, Chin.Phys.C 41 (2017) 6, 063102]



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

Exotic decays - $h \rightarrow ss \rightarrow 4\tau$

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



$[m_s = 7.5 \text{ GeV}; \text{background mainly from } h \rightarrow jj]$

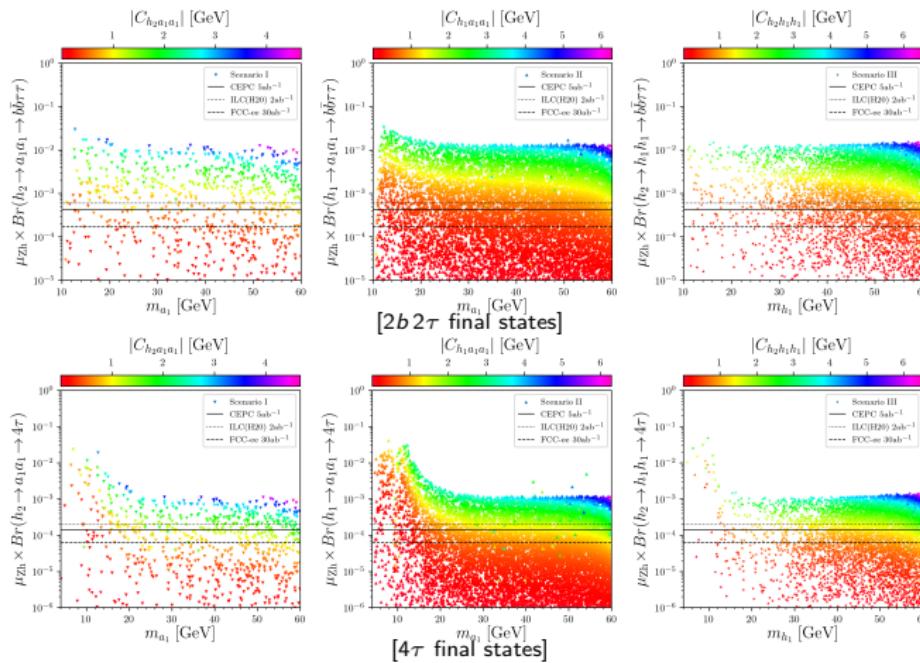
ε_{tk} : tracking efficiency

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

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

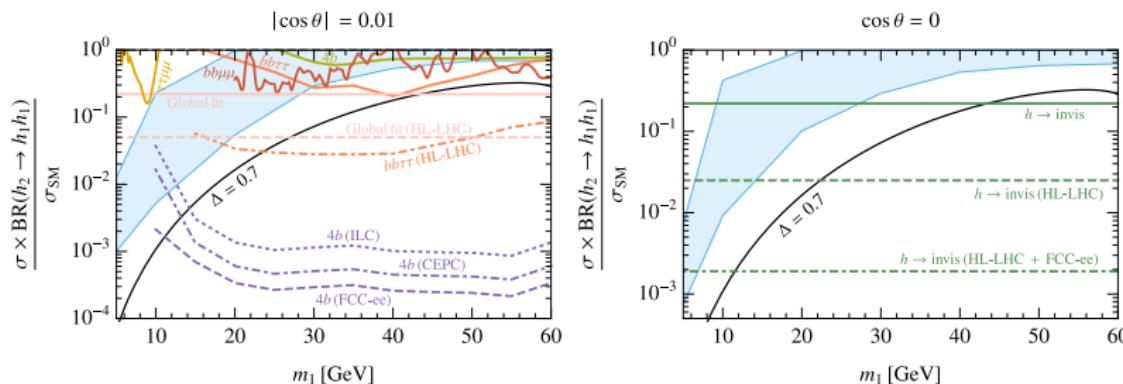
scNMSSM, $h \rightarrow s s \rightarrow$ various final states [sc=semi-constrained, aka NUHM]

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



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]

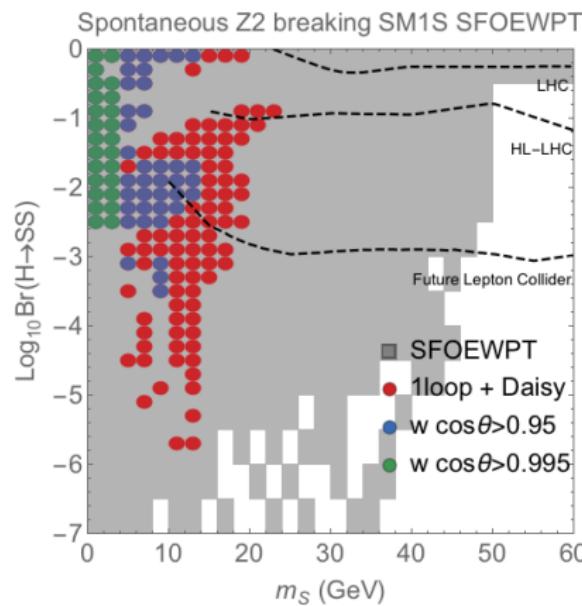
[projections taken from Z. Liu, L.-T. Wang, and H. Zhang, Chin. Phys. C 41, 063102 (2017)]
 Tania Robens

$m \leq 125$ GeV @ CEPC

CEPC workshop 2021, 8.11.'21

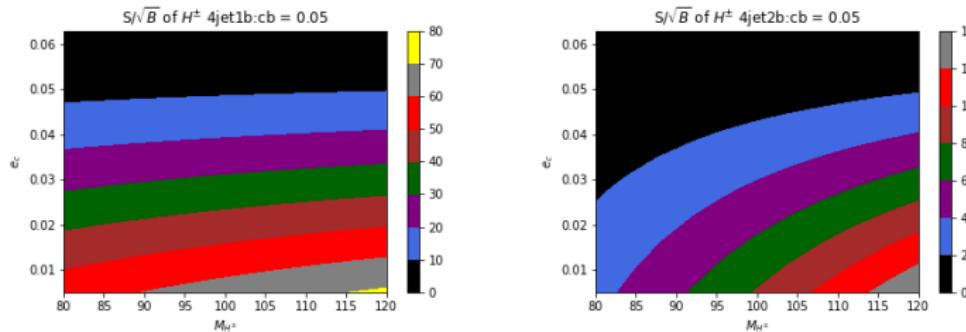
Singlet extension, spontaneous Z_2 breaking, with connection to strong first-order electroweak phase transition

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



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

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

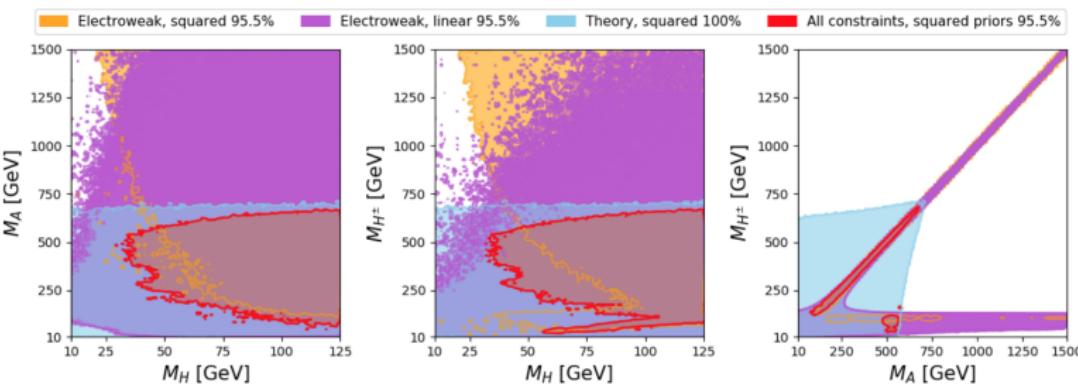


$\text{BR}(H^+ \rightarrow c\bar{b}) = 0.05$, e_c : charm tagging efficiency

$$e^+ e^- \rightarrow H^+ H^-, \sqrt{s} = 240 \text{ GeV}$$

Aligned 2HDM

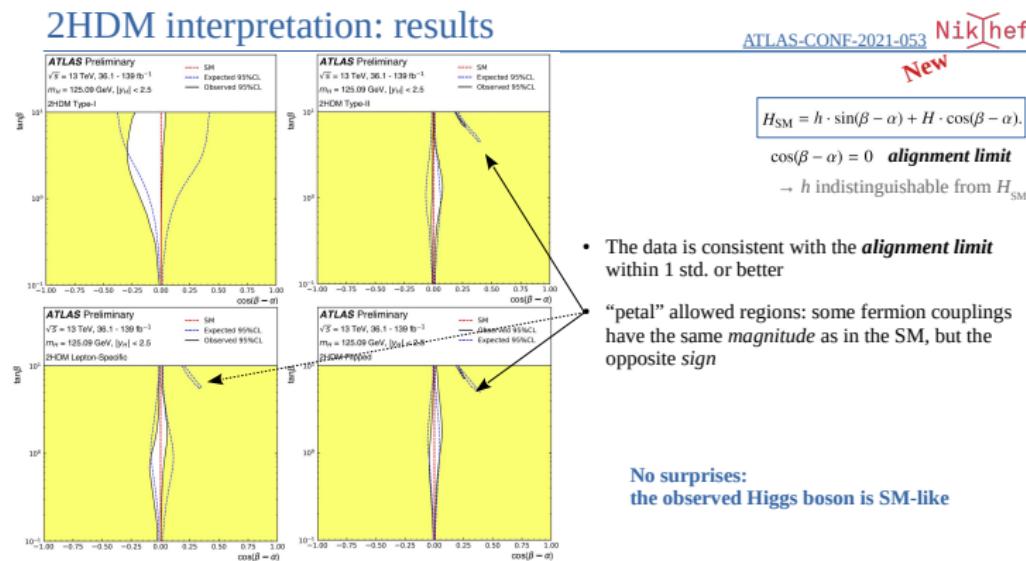
[O. Eberhardt, A. Penuelas Martinez, A. Pich, JHEP 05 (2021) 005]



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

Current constraints on alignment in 2HDMs

[H. Arnold, talk at Higgs 2021]



Hannah Arnold

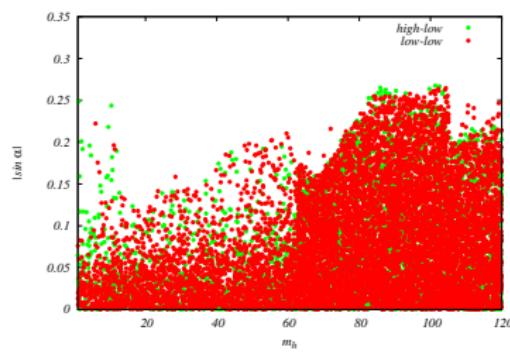
Higgs2021: Combined ATLAS Higgs measurements

21/10/21

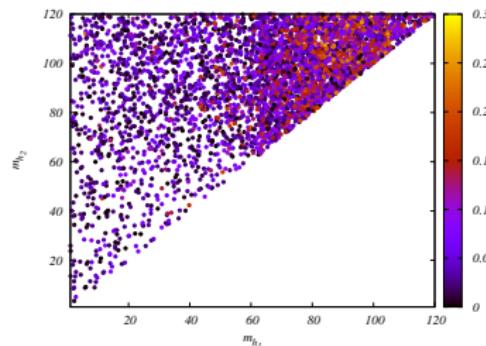
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Singlet extensions [TR, preliminary]

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

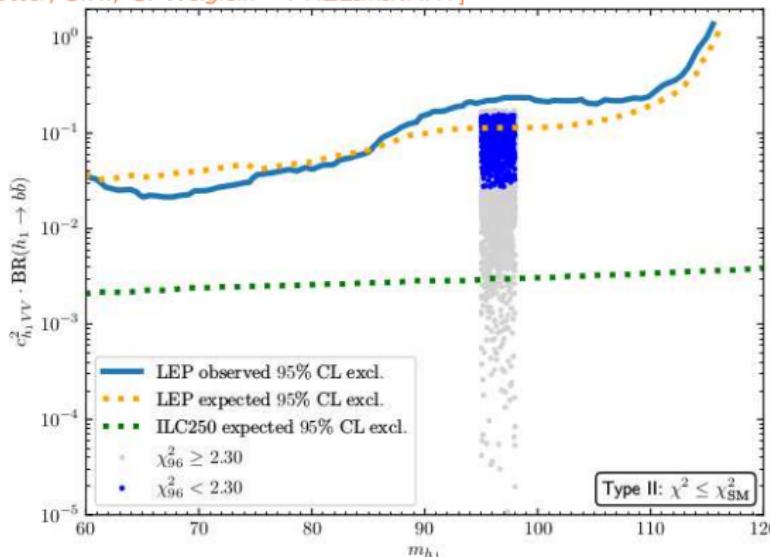
using ScannerS [M. Muehlleitner, M. O. P. Sampaio, R. Santos, J. Wittbrodt, arXiv:2007.02985]

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

[S. Heinemeyer, talk at ILCX 2021 workshop]

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

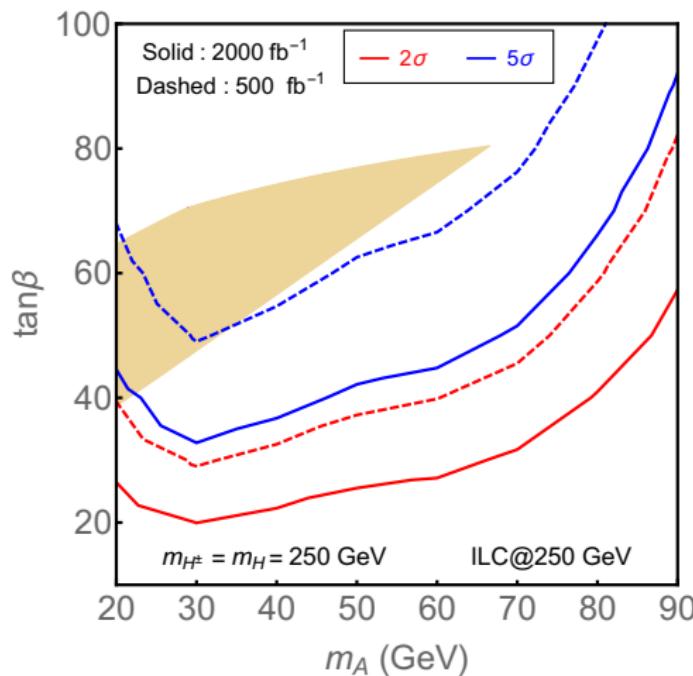
[T. Biekötter, S.H., G. Weiglein – PRELIMINARY]



⇒ new state easily in the reach of the ILC ⇒ coupling measurements

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

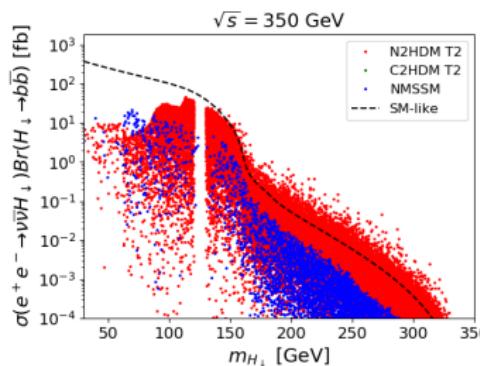
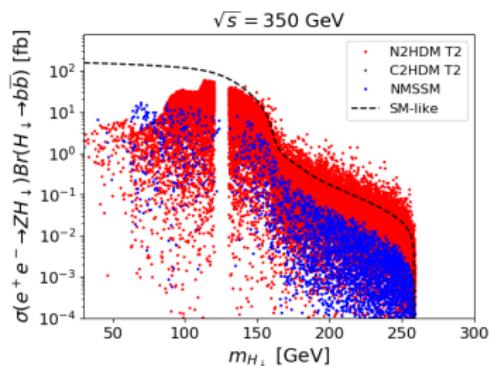
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]



N2HDM, C2HDM, NMSSM: $b\bar{b}$ final states @350 GeV

[D. Azevedo, P. Ferreira, M. Muehlleitner, R. Santos, J. Wittbrodt, Phys.Rev.D 99 (2019) 5, 055013]

variations/ extensions of 2HDMs



Conclusions

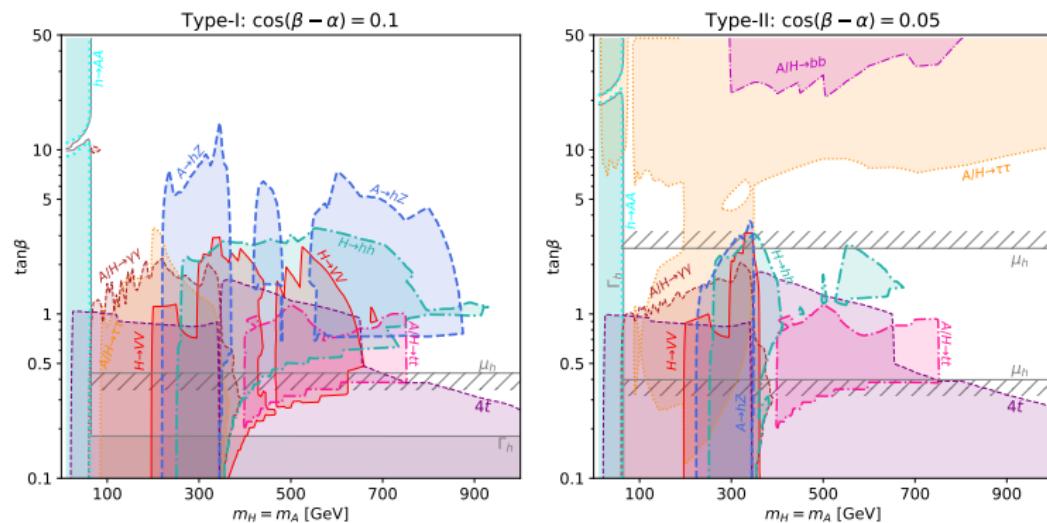
- many new physics models predict one/ several scalars below 125 GeV
- typical decays into $b\bar{b}$, $\tau^+ \tau^-$
- cross sections could reach up to 60 fb from Zh production
- decays of $h_{125} \rightarrow ss$ also within reach
- important connection to EWSB/ EW phase transitions

Still space for more studies !

Appendix

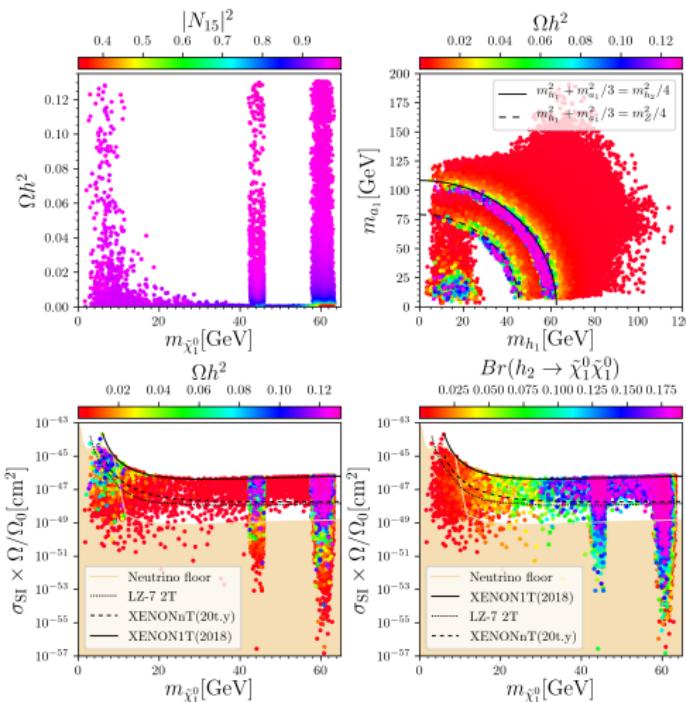
2HDM parameter space

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



scNMSSM parameter space

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

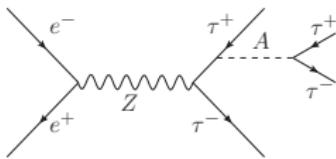


Searches for light A in 2HDMX at ILC250

imagine the impossible



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



- This is the equivalent to $t\bar{t}H$ 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.

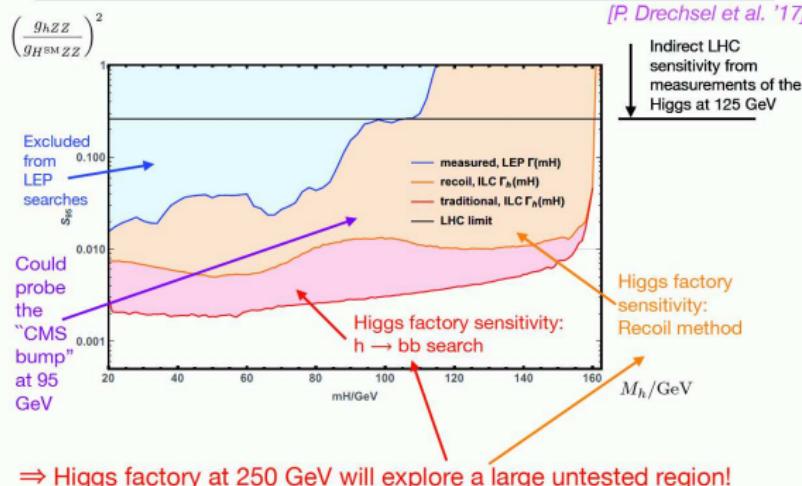
Parameter space for light scalar

[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]