Light BSM scalars at e^+e^- machines

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Future Circular Collider Physics Workshop
10. February '22

Models

- new low-mass 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**

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**
- ...

Center-of-mass energies [Eur.Phys.J.ST 228 (2019) 2, 261-623]

Current setup

- ***Z* peak:** $\sim 90\,\mathrm{GeV}$, $\int \mathcal{L} \sim 150\,\mathrm{ab}^{-1}$
- ***WW*:** $\sim 160\,\mathrm{GeV}$, $\int \mathcal{L} \sim 12\,\mathrm{ab}^{-1}$
- ***HZ*:** $\sim 240\,\mathrm{GeV}$, $\int \mathcal{L} \sim 4-5\,\mathrm{ab}^{-1}$
- ***t* $\bar{t}$:** $\sim 350-365\,\mathrm{GeV}$, $\mathcal{L} \sim 0.2\,\mathrm{ab}^{-1}$

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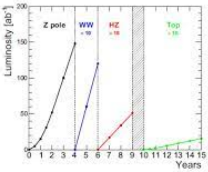


Fig. 1.2. Operation model for the FCC-ee, as a result of the five-year conceptual design study, showing the integrated luminosity at the Z pole (black), the WW threshold (blue), the Higgs factory (red), and the top-pair threshold (green) as a function of time. The hatched area indicates the shutdown time needed to prepare the collider for the highest energy runs.

first two: **already covered at LEP**

[Eur.Phys.J.C 47 (2006) 547-587/ Eur.Phys.J.C 27 (2003) 311-329]

1 slide on LEP results (for FCC-ee like $\sqrt{s}$)

[Eur.Phys.J.C 47 (2006) 547-587/ Eur.Phys.J.C 27 (2003) 311-329]

- center-of-mass energies: **91 GeV/ 161 GeV**
- channels: $H\,Z,\; H_1\,H_2,\; H_1\,H_1\,H_1$

⇒ including multitude of decay channels ⇐

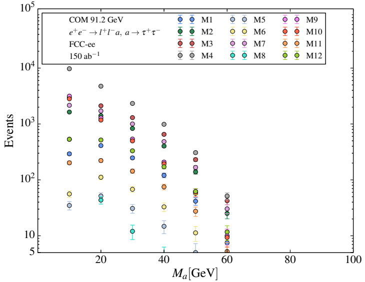
- searches from **Delphi/ OPAL**
- various integrated luminosities, **typically below** $80\,\mathrm{pb}^{-1}$
  [exception: model-independent search for HZ, OPAL, $\sim 120\,\mathrm{pb}^{-1}$]
- **varying mass ranges up to** $\sim 90\,\mathrm{GeV}^{(*)}$
- **FCC-ee: factor** $\gtrsim 10^6$ **difference in** $\int \mathcal{L}$

[$^{(*)}$ in combination with $\sqrt{s} = 170 - 172\,\mathrm{GeV}$]

Recent study at $\sqrt{s} \sim 91\,\mathrm{GeV}$

[A. S. Cornell, A. Deandrea, B. Fuks, L. Mason, Phys.Rev.D 102 (2020) 3, 035030]

- **composite models, additional pseudoscalar**
- channel considered: $e^+e^- \to \ell^+\ell^- a,\ a \to \tau^+\tau^-$



- using machine learning, **some benchmarks accessible in the low mass ($\sim 20\,\mathrm{GeV}$) region**

Higgs factories: Possible searches

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

many searches focus on this

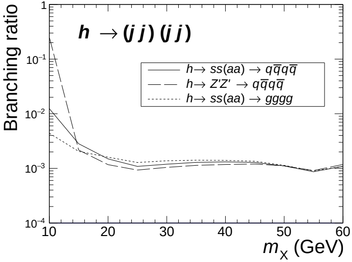
- also possible: **direct searches**
- for all of these: **dominant decays typically to $b\,\bar{b}$ or $\tau^+\,\tau^-$**

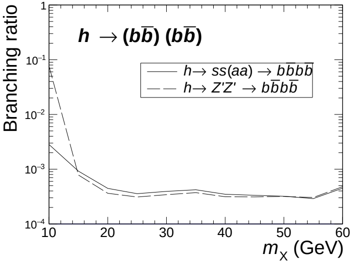
$\Rightarrow$ mainly discussed here $\Leftarrow$

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

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

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

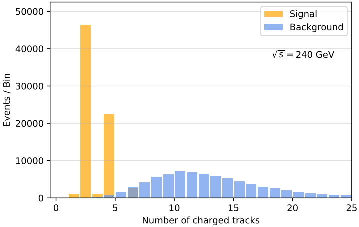


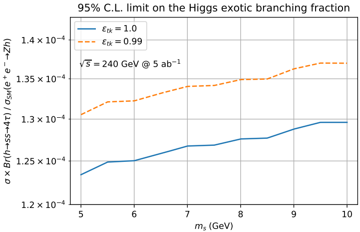


95% **CL bounds**, $\sqrt{s} = 240\,\mathrm{GeV}$, $\int \mathcal{L} = 5\,\mathrm{ab}^{-1}$

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 $h \to j\,j$]

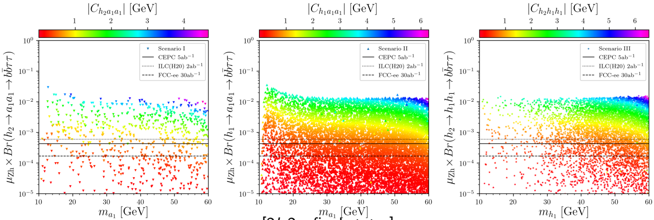
ε_{tk}: tracking efficiency

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

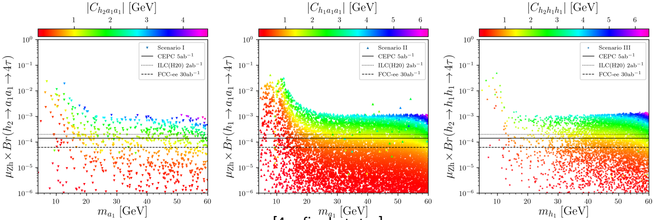
[invisible BR, signal strength, assumes SM-like decay to τs]

scNMSSM, $h \to s\,s \to$ 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]

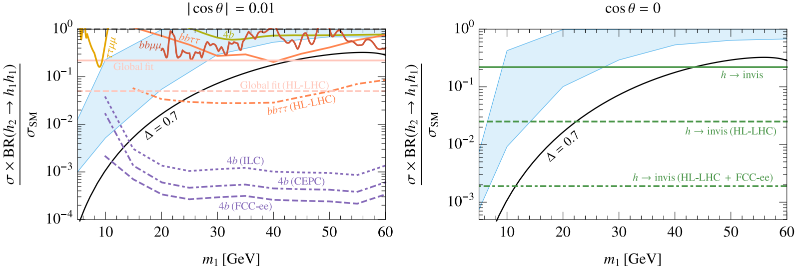


[4τ final states]

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

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 $\lesssim 10^{-1}$**

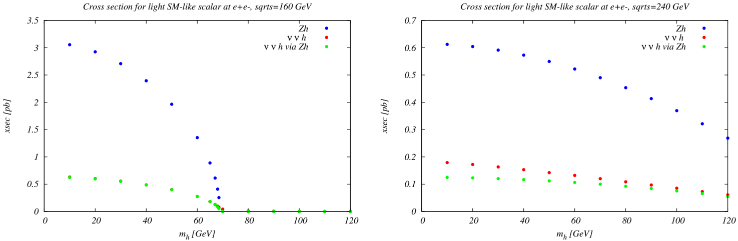
[invisible BR, signal strength, assumes SM-like decay to bs]

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

$m \leq 125\,\mathrm{GeV}$ @ e^+e^-

What about direct production ?

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

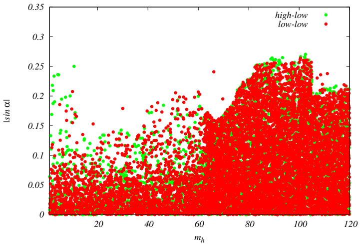


[on-shell production cross sections for $e^+ e^-$ at $\sqrt{s} = 160/\,240\,\mathrm{GeV}$ using Madgraph5]

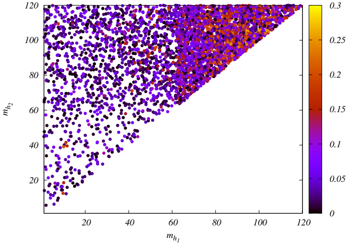
- rule of thumb: **rescaling** $\lesssim 0.1$
- $\Rightarrow$ maximal production **cross sections around 300/ 60 fb**
- $\sim 10^6/10^5$ **events using full luminosity**

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



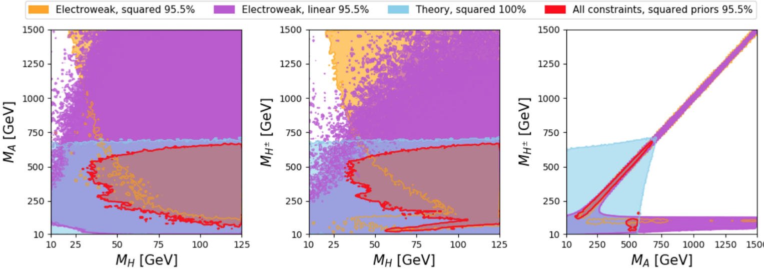
case with two light scalars;
color coding: h_1 rescaling

- **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]

Aligned 2HDM

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

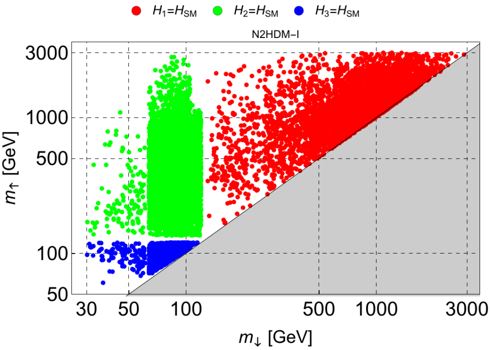


low mass region allowed; however, HZZ typically suppressed by $\cos(\beta - \alpha)$ [$\lesssim$ 0.25]

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



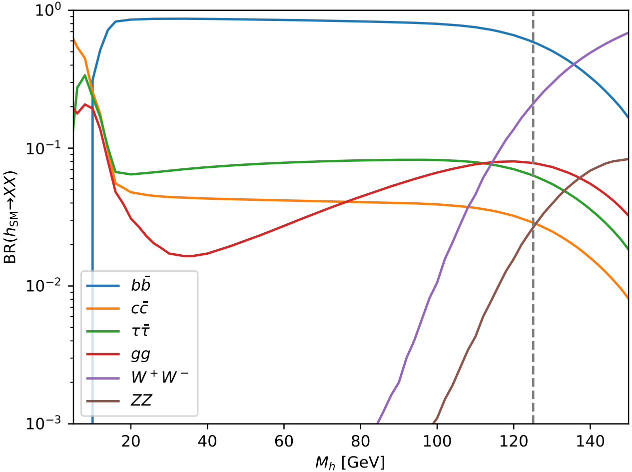
Conclusions

- **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** $300/\,60\,\mathrm{fb}$ **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 !

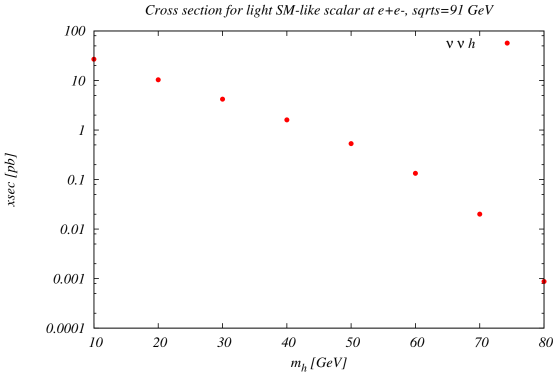
Appendix

Decays of light SM-like scalars



[from YREP 4/ HDecay]

Production cross sections for $e^+e^- \rightarrow h\,\nu_\ell\,\bar{\nu}_\ell,\ \sqrt{s} = 91\,\mathrm{GeV}$



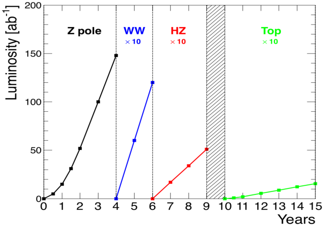
mainly via offshell Zh

Physics reach [slide from C. Grojean, this workshop]

FCC-ee Run Plan

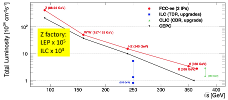
LEP data accumulated in first 3 mn. Then exciting & diverse programme with different priorities every few years.

(order of the different stages still subject to discussion/optimisation)



Phase	Run duration (years)	Center-of-mass Energies (GeV)	Integrated Luminosity (ab^{-1})
FCC-ee-Z	4	88-95	150
FCC-ee-W	2	158-162	12
FCC-ee-H	3	240	5
FCC-ee-tt	5	345-365	1.5

Superb statistics achieved in only 15 years



Event statistics (2IP)

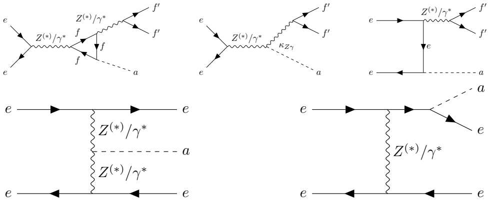
					E_{CM} errors:
Z peak	E_{cm} : 91 GeV	4yrs	5 10^{12} e+e- → Z	LEP x 10^5	<100 keV
WW threshold	$E_{cm} \geq$ 161 GeV	2yrs	>10^8 e+e- → WW	LEP x 2.10^3	<300 keV
ZH maximum	E_{cm} : 240 GeV	3yrs	> 10^6 e+e- → ZH	Never done	1 MeV
s-channel H	E_{cm} : m_H	*(3yrs?)*	*O(5000) e+e- → H*	*Never done*	<< 1 MeV
$\bar{t}t$	E_{cm} : ≥ 350 GeV	5yrs	10^6 e+e- → tt	Never done	2 MeV

6

Christophe Grojean FCC-ee Physics 4 FCC workshop, Feb. 2022

Recent study at $\sqrt{s} \sim 91\,\mathrm{GeV}$

[A. S. Cornell, A. Deandrea, B. Fuks, L. Mason, Phys.Rev.D 102 (2020) 3, 035030]



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

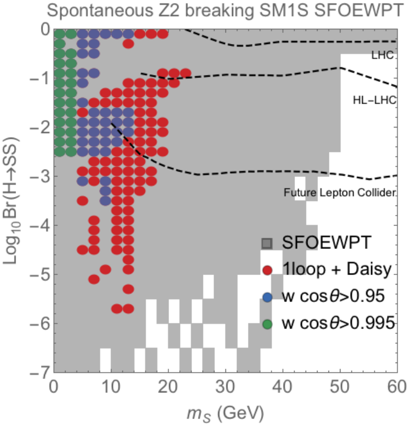
[S. Ma, K. Wang, J. Zhu, Chin.Phys.C 45 (2021) 2, 023113]

- Scenario I: $h_2 = h_{125}$, a_1 CP-odd
- Scenario II: $h_1 = h_{125}$, a_1 CP-odd
- Scenario III: $h_2 = h_{125}$, h_1 CP-even

particle content: $h_{1,2,3}$, $a_{1,2}$

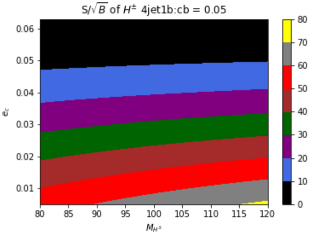
Singlet extension, spontaneous Z_2 breaking, with connection to strong first-order electroweak phase transition

[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]



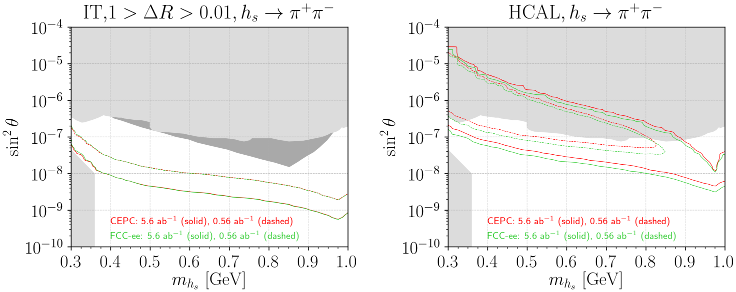
BR($H^+ \rightarrow c\,\bar{b} = 0.05$), e_c: charm tagging efficiency

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

Long-lived light scalars

[K. Cheung, Z. S. Wang, Phys.Rev.D 101 (2020) 3, 035003]

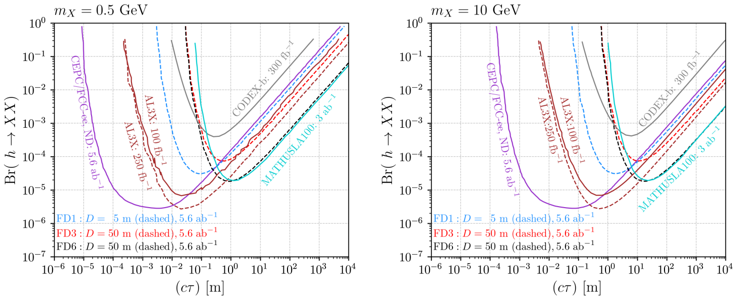
additional mixed-in light scalar, $h_{125} \rightarrow h_s\, h_s$



$$\sqrt{s} = 240\,\mathrm{GeV}$$

Long lived light scalars, comparison to other LLP experiments

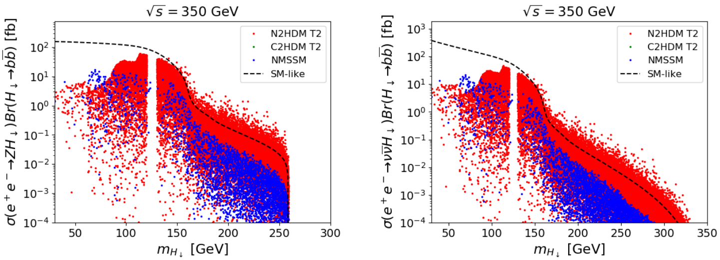
[Z. S. Wang, K. Wang, Phys.Rev.D 101 (2020) 7, 075046]



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

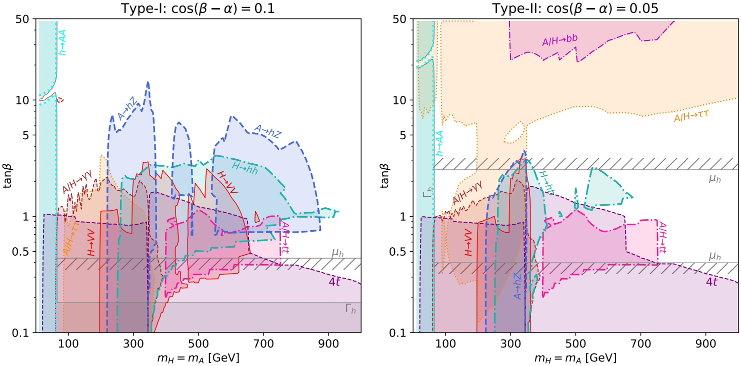
[D. Azevedo, P. Ferreira, M. Muehlleitner, R. Santos, J. Wittbrodt, Phys.Rev.D 99 (2019) 5, 055013]

variations/ extensions of 2HDMs



2HDM parameter space

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



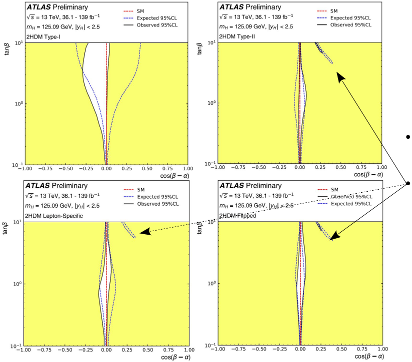
Current constraints on alignment in 2HDMs

[H. Arnold, talk at Higgs 2021]

2HDM interpretation: results

ATLAS-CONF-2021-053 Nikhef

New



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

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

→ h indistinguishable from H_{SM}

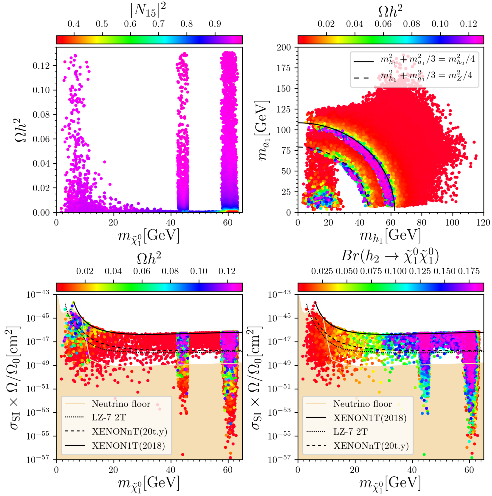
- The data is consistent with the ***alignment limit*** within 1 std. or better
- "petal" allowed regions: some fermion couplings have the same *magnitude* as in the SM, but the opposite *sign*

No surprises:
the observed Higgs boson is SM-like

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

scNMSSM parameter space

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

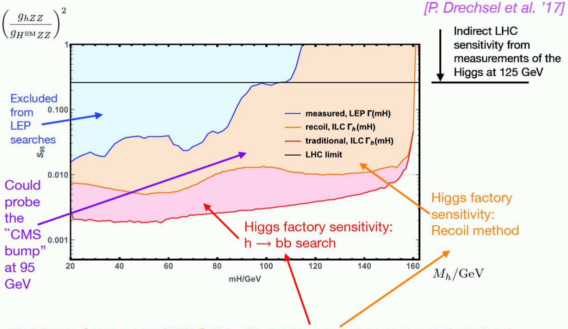


Parameter space for light scalar

[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*]

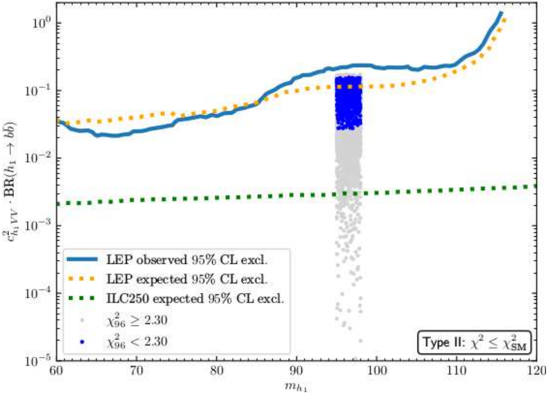
Sven Heinemeyer, ILCX workshop, 28.10.2021 28

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]

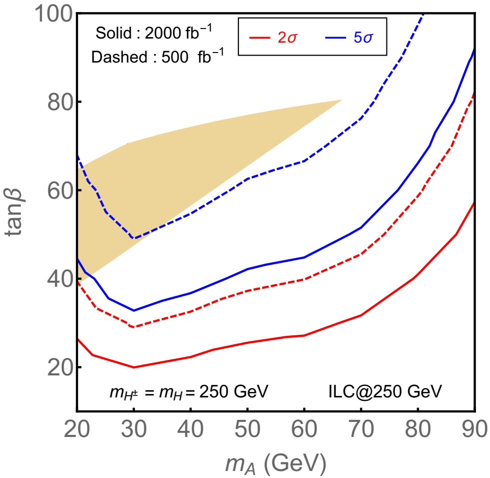


⇒ new state easily in the reach of the ILC ⇒ coupling measurements

Sven Heinemeyer, ILCX workshop, 28.10.2021 33

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

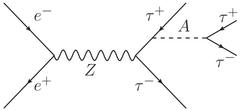
[E. J. Chun, T. Mondal, Phys.Lett.B 802 (2020) 135190]



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.

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