Prospects for light exotic scalar measurements at the e^+e^- Higgs factory

Aleksander Filip Żarnecki

Faculty of Physics, University of Warsaw

NATIONAL SCIENCE CENTRE
POLAND

Higgs 2023

Future colliders and experiments session

December 1, 2023

Outline:

1. Motivation
2. Analysis
3. Results
4. Conclusions

Work carried out in the framework of the ILD concept group
as a contribution to the ECFA e^+e^- Higgs/EW/Top factory study

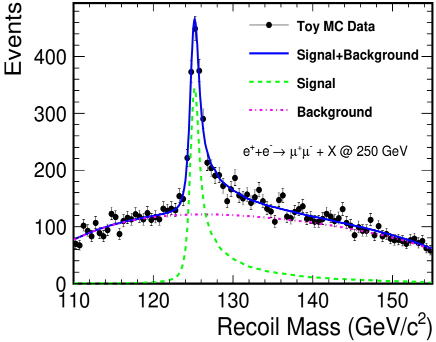
All presented results are preliminary

Motivation

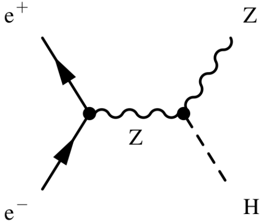
e^+e^- Higgs factory

Precision Higgs measurements are clearly the primary target for future Higgs factory.

See also dedicated talk by I.Bozovic on "Higgs Physics with ILC" in the morning session



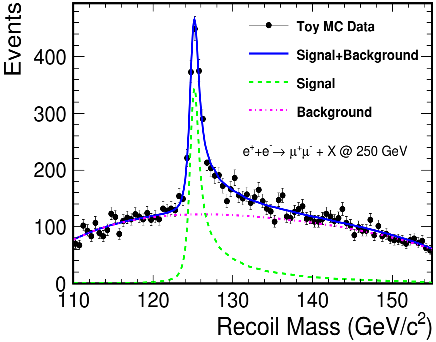
At 250 GeV we will focus on H_{125} production



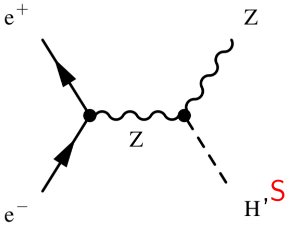
e^+e^- Higgs factory

Precision Higgs measurements are clearly the primary target for future Higgs factory.

See also dedicated talk by I.Bozovic on "Higgs Physics with ILC" in the morning session



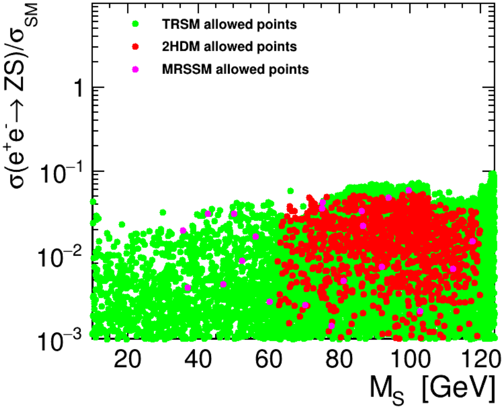
At 250 GeV we will focus on H_{125} production



But production of additional, light exotic scalar states is still not excluded by the existing data!

Possible scenarios

Benchmark points consistent with current experimental and theoretical bounds



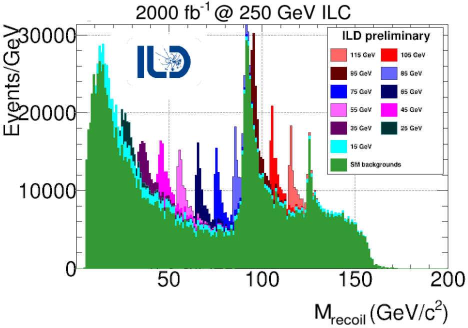
Two-Real-Singlet Model
thanks to Tania Robens
see arXiv:2209.10996 arXiv:2305.08595

Two Higgs-Doublet Model
thanks to Kateryna Radchenko
thdmTool package, see arXiv:2309.17431

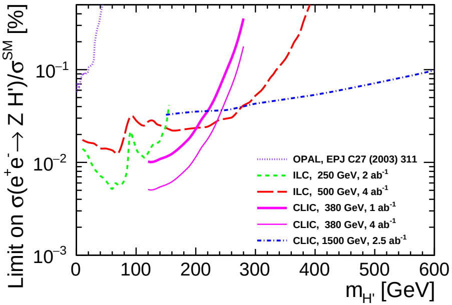
Minimal R-symmetric Supersymmetric SM
thanks to Wojciech Kotlarski arXiv:1511.09334

Previous studies General searches

ILD study arXiv:1903.01629 arXiv:2005.06265



Expected sensitivities of ILC and CLIC



Search independent on the scalar decay:

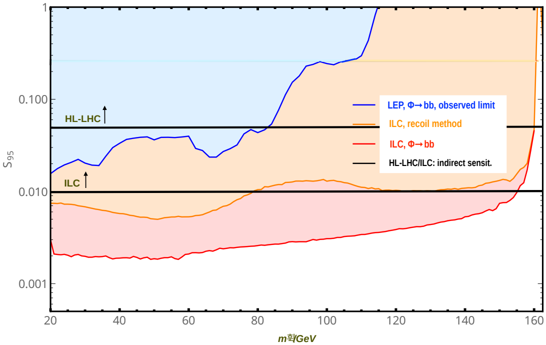
$$e^+e^- \to Z\,S^0 \to \mu^+\mu^- + X$$

CLIC search assuming invisible decays

arXiv:2002.06034 arXiv:2107.13903

Previous studies Searches in particular decay channels

Estimated prospects for new scalar discovery in $S \to b\bar{b}$ decay channel (LEP projection)



Expected 95% C.L. limits on the scalar production cross section σ/σ_{SM} assuming standard BRs

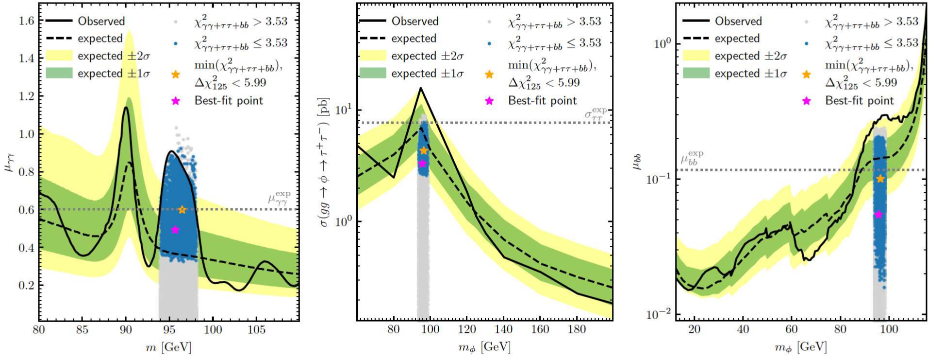
P. Drechsel, G. Moortgat-Pick, G. Weiglein, arXiv:1801.09662

Experimental hints...

T. Biekötter, S.Heinemeyer, G. Weiglein arXiv:2203.13180

Some discrepancies point to new scalar with mass of ∼95 GeV and dominant decay to $\tau\tau$...

$pp \to h_{95} \to \gamma\gamma$ $\qquad$ $gg \to h_{95} \to \tau^+\tau^-$ $\qquad$ $e^+e^- \to Zh_{95} \to Zb\bar{b}$



Sven Heinemeyer @ First ECFA WS on e^+e^- Higgs/EW/top factories, October 2022

Analysis

Signal scenarios

Consider production of light scalar in scalar-strahlung process:

$$e^+e^- \rightarrow Z\,S$$

with hadronic Z decays (for statistics) and scalar decays to tau lepton pairs:

$$Z \rightarrow q\,\bar{q} \qquad S \rightarrow \tau^+\tau^-$$

$\Rightarrow$ look for fully hadronic ($jjjj$), semi-leptonic (ℓjjj) or leptonic ($\ell\ell jj$) final state depending on the decays of two tau leptons

Considered mass range $M_S = 15 - 140$ GeV

Event samples

Signal and background samples generated with WHIZARD 3.1.2 using built-in SM_CKM model.

Signal samples generated by varying H mass in the model and forcing its decay to $\tau^+\tau^-$.

All relevant four-fermion final states considered as background.
SM-like Higgs boson contribution included in the background estimate.
Contribution from two-fermion and six-fermion processes found to be small.

ISR and luminosity spectra for ILC running at 250 GeV taken into account

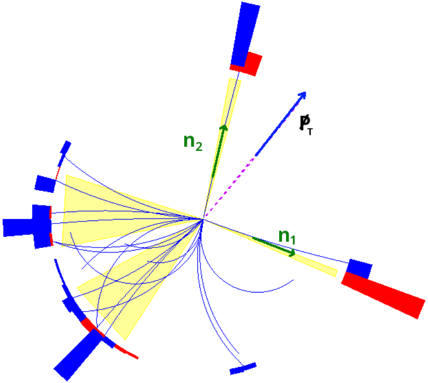
Total lumionsity of $2\,\mathrm{ab}^{-1}$, with $\pm 80\%/\pm 30\%$ polarisation for e^-/e^+ (H-20 scenario).

Fast detector simulation with Delphes ILCgen model.

Tau reconstruction

arXiv:1509.01885

Example signal event with hadronic tau decays



Tau leptons are very boosted ⇒ collinear approximation

Assume tau neutrinos are emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

$$\vec{p}_T \quad = \quad E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

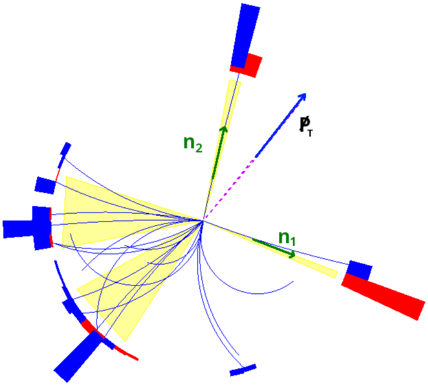
where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

Tau reconstruction

arXiv:1509.01885

Example signal event with hadronic tau decays



Tau leptons are very boosted ⇒ collinear approximation

Assume tau neutrinos are emitted in the tau jet direction.

Their energies can be found from transverse momentum balance:

$$\vec{\not p}_T \quad = \quad E_{\nu_1} \cdot \vec{n_1} + E_{\nu_2} \cdot \vec{n_2}$$

where $\vec{n_1}$ and $\vec{n_2}$ are directions of the two tau jets.

Unique solution !

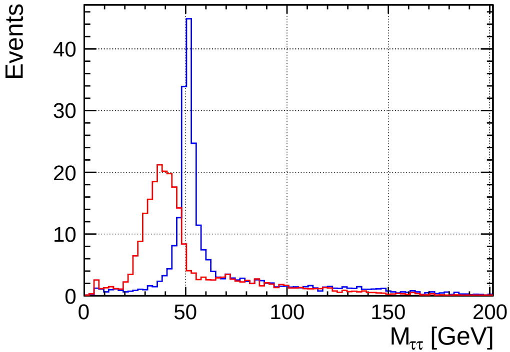
Works also for semi-leptonic and leptonic events!

Because of small tau mass ⇒ small invariant mass of neutrino pair

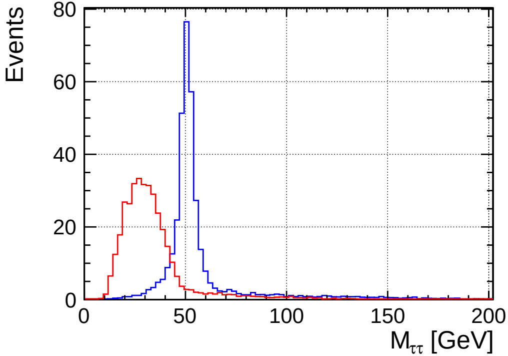
Tau reconstruction

Distribution of the raw and corrected mass of the tau candidate pair for $M_S = 50\,\mathrm{GeV}$

Hadronic events (two tagged jets)



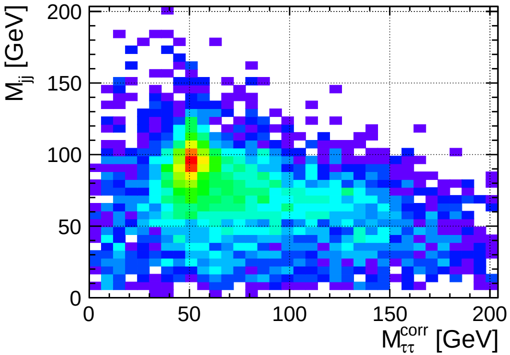
Semi-leptonic events (lepton and one tagged jet)



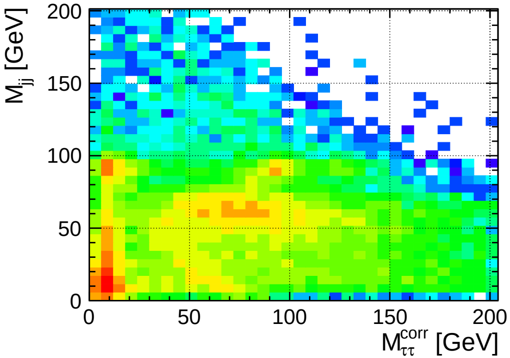
Kinematic distributions

Distribution of the reconstructed Z boson and scalar masses for $M_S = 50\,\mathrm{GeV}$

Hadronic signal events



Background events



Event pre-selection

Tight selection:

events with two tau candidates (leptons or jets with tau-tag) and two quark jets (no tau-tag)

Loose selection:

events with one or two tau candidates and two or three quark jets, respectively
(for one tau candidate, jet with the lowest invariant mass is taken as a second candidate!)

Analysis

Event pre-selection

Tight selection:

events with two tau candidates (leptons or jets with tau-tag) and two quark jets (no tau-tag)

Loose selection:

events with one or two tau candidates and two or three quark jets, respectively
(for one tau candidate, jet with the lowest invariant mass is taken as a second candidate!)

Final event selection

Based on the BDT classifier, trained separately for each scalar mass hypothesis.
Always trained for all data samples considered (beam polarisations, decay channels).

Cut on the BDT classifier response was optimized for signal significance assuming:

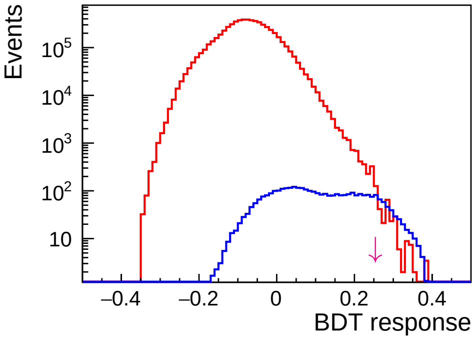
$$\sigma(e^+e^- \rightarrow Z\,S) \cdot BR(S \rightarrow \tau\tau)/\sigma_{SM}(M_S) \;=\; 1\%$$

Final event selection

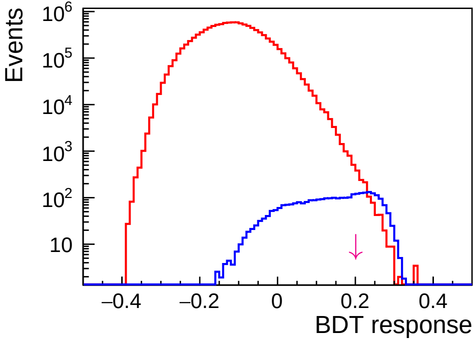
see backup slides for list of BDT input variables

Example of BDT response distribution for signal and background events, for $M_S = 50\,\text{GeV}$

Hadronic events



Semi-leptonic events



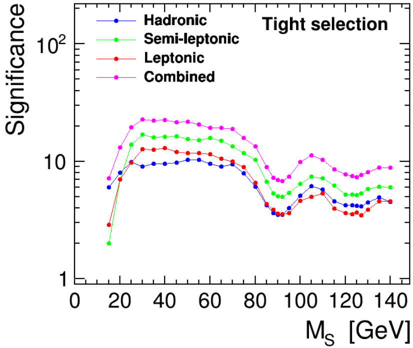
Loose pre-selection, signal normalized to $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)/\sigma_{SM} = 1\%$

Results

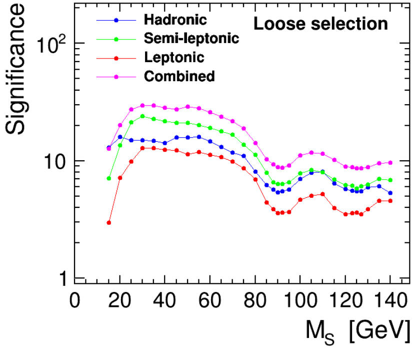
Significance Combined data, polarisation not taken into account!

Signal significance after optimized BDT response cut (assuming signal at 1% level)

Tight selection



Loose selection

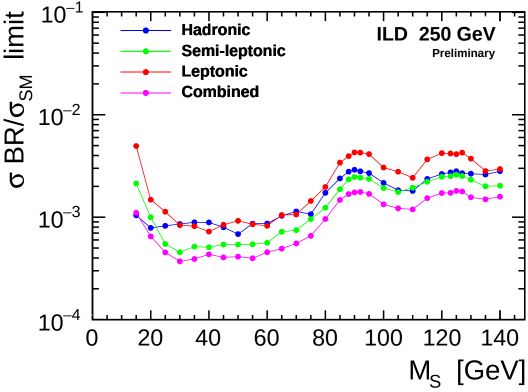


Loose selection results in higher significance ⇒ stronger limits

Cross section limits

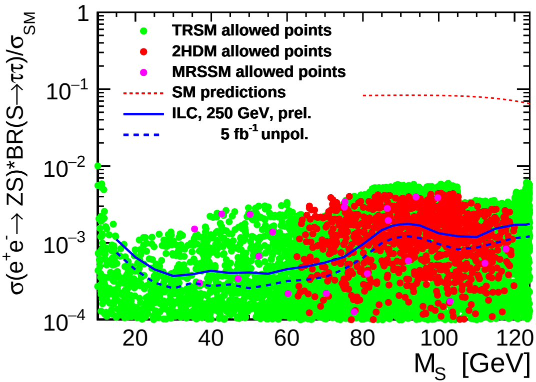
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$

BDT cut optimized for 1% signal level; combined data, polarisation not taken into account!



Cross section limits

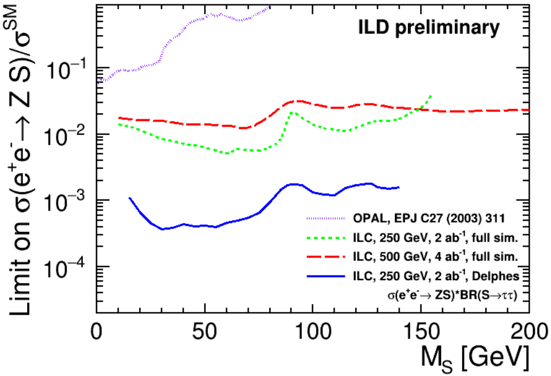
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with allowed scenarios in different models



See Motivation section for scan point references

Cross section limits

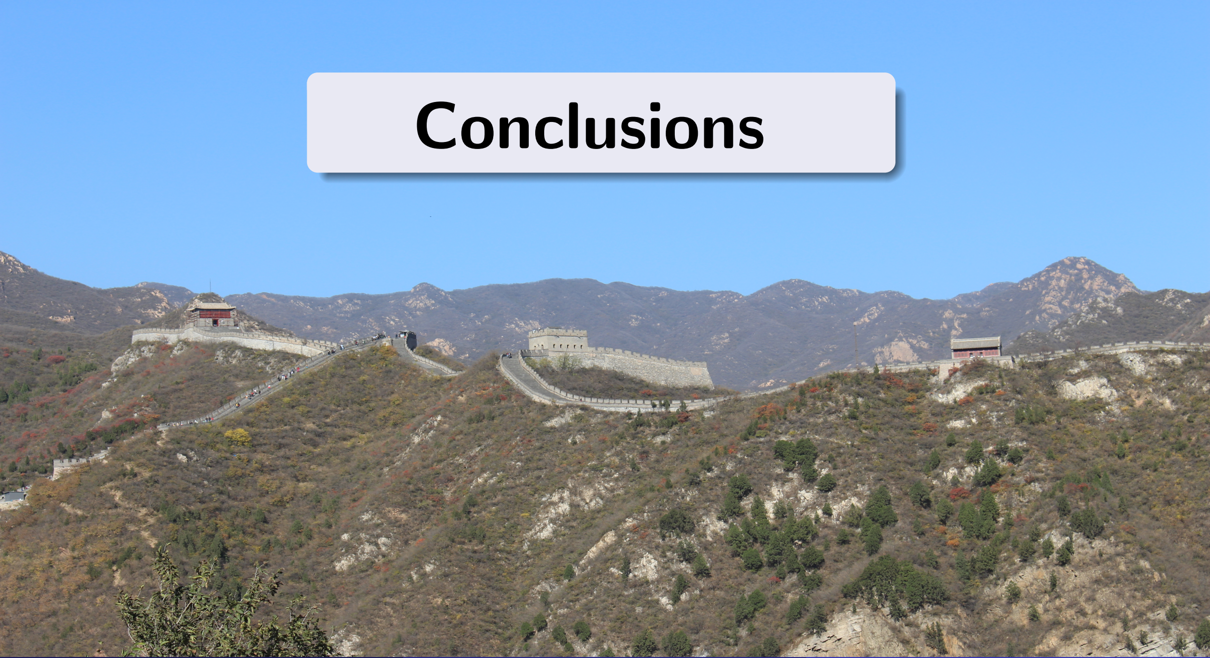
Cross section limits for $\sigma(e^+e^- \to Z\,S) \cdot BR(S \to \tau\tau)$
compared with decay independent limits on σ/σ_{SM} from earlier studies



Targeted analysis results in order of magnitude increase in sensitivity...

Possible gain in discovery reach depends on the BR!

Conclusions



Conclusions

BSM scenarios with light scalars still not excluded by existing data

Sizable production cross sections for new scalars can coincide with non-standard decay...

Light scalar decays to tau pairs seem a challenging scenario
and a good testing ground for different detector concepts and analysis methods

Conclusions

BSM scenarios with light scalars still not excluded by existing data
Sizable production cross sections for new scalars can coincide with non-standard decay...

Light scalar decays to tau pairs seem a challenging scenario
and a good testing ground for different detector concepts and analysis methods

Fast simulation study indicates high sensitivity to the considered signal

Order of magnitude limit improvement already with the very simple limit setting approach
Should improve further when properly combining results from different event samples
(beam polarisations and decay channels).

Conclusions

BSM scenarios with light scalars still not excluded by existing data
Sizable production cross sections for new scalars can coincide with non-standard decay...

Light scalar decays to tau pairs seem a challenging scenario
and a good testing ground for different detector concepts and analysis methods

Fast simulation study indicates high sensitivity to the considered signal

Order of magnitude limit improvement already with the very simple limit setting approach
Should improve further when properly combining results from different event samples
(beam polarisations and decay channels).

Detector response modeling in DELPHES is very simplified (eg. tau tagging)
Comparison with full simulation planned to confirm the results...

Conclusions

BSM scenarios with light scalars still not excluded by existing data
Sizable production cross sections for new scalars can coincide with non-standard decay...

Light scalar decays to tau pairs seem a challenging scenario
and a good testing ground for different detector concepts and analysis methods

Fast simulation study indicates high sensitivity to the considered signal

Order of magnitude limit improvement already with the very simple limit setting approach
Should improve further when properly combining results from different event samples
(beam polarisations and decay channels).

Detector response modeling in DELPHES is very simplified (eg. tau tagging)
Comparison with full simulation planned to confirm the results...

ECFA focus topic: other decay channels of the light scalar still to be explored !

Thank you!

ECFA study focus topic: EXscalar

Search for new exotic scalars was selected as one of the "focus topics" in the ongoing ECFA study on Higgs / Top / EW factories.

Target I:

Higgs factories are best suited to search for light exotic scalars in the process:

$$e^+e^- \rightarrow Z\ S$$

Production of new scalars can be tagged, independent of their decay, based on the recoil mass.

We should look for different scalar decay channels e.g. $b\bar{b}$, $W^{+(*)}W^{-(*)}$, $\tau^+\tau^-$ or invisible
Non-standard decays channels of the new scalar should also be looked for.

For maximum sensitivity, feasibility of including hadronic Z decays should be explored.

ECFA study focus topic: EXscalar

Search for new exotic scalars was selected as one of the "focus topics" in the ongoing ECFA study on Higgs / Top / EW factories.

Target II:

As as second benchmark scenario for the EXscalar focus topic, light scalar pair-production in 125 GeV Higgs boson decays is proposed:

$$e^+e^- \rightarrow Z\ H \rightarrow Z\ S\ S$$

Here again, different decay channels should be considered, both SM-like and exotic.

While new scalar states could in general be long-lived, only scenarios with prompt decays are included in the EXscalar focus topic (while a dedicated topic focuses on LLPs).

Motivation

N2HDM scenario arXiv:2203.13180

Parameters of the best-fit point (minimal value of χ^2)

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$		
95.68	125.09	713.24	811.20	677.38		
$\tan\beta$	α_1	α_2	α_3	m_{12}	v_S	
10.26	1.57	1.22	1.49	221.12	1333.47	
$\mathrm{BR}_{h_1}^{bb}$	$\mathrm{BR}_{h_1}^{gg}$	$\mathrm{BR}_{h_1}^{cc}$	$\mathrm{BR}_{h_1}^{\tau\tau}$	$\mathrm{BR}_{h_1}^{\gamma\gamma}$	$\mathrm{BR}_{h_1}^{WW}$	$\mathrm{BR}_{h_1}^{ZZ}$
$\Rightarrow$ 0.005	0.348	0.198	$\Rightarrow$ 0.412	$6.630 \cdot 10^{-3}$	0.025	$3.382 \cdot 10^{-3}$
$\mathrm{BR}_{h_2}^{bb}$	$\mathrm{BR}_{h_2}^{gg}$	$\mathrm{BR}_{h_2}^{cc}$	$\mathrm{BR}_{h_2}^{\tau\tau}$	$\mathrm{BR}_{h_2}^{\gamma\gamma}$	$\mathrm{BR}_{h_2}^{WW}$	$\mathrm{BR}_{h_2}^{ZZ}$
0.553	0.085	0.032	0.069	$2.537 \cdot 10^{-3}$	0.228	0.028
$\mathrm{BR}_{h_3}^{tt}$	$\mathrm{BR}_{h_3}^{bb}$	$\mathrm{BR}_{h_3}^{\tau\tau}$	$\mathrm{BR}_{h_3}^{h_1h_1}$	$\mathrm{BR}_{h_3}^{h_1h_2}$	$\mathrm{BR}_{h_3}^{h_2h_2}$	$\mathrm{BR}_{h_3}^{WW}$
0.123	0.739	0.000	0.002	0.072	0.030	0.022
BR_{A}^{tt}	BR_{A}^{bb}	$\mathrm{BR}_{A}^{\tau\tau}$	$\mathrm{BR}_{A}^{Zh_1}$	$\mathrm{BR}_{A}^{Zh_2}$	$\mathrm{BR}_{A}^{Zh_3}$	$\mathrm{BR}_{A}^{WH^\pm}$
0.053	0.173	0.000	0.024	0.001	0.015	0.734
$\mathrm{BR}_{H^\pm}^{tb}$	$\mathrm{BR}_{H^\pm}^{\tau\nu}$	$\mathrm{BR}_{H^\pm}^{Wh_1}$	$\mathrm{BR}_{H^\pm}^{Wh_2}$			
0.922	0.000	0.073	0.003			

Table 1: Parameters of the best-fit point for which the minimal value of χ^2 is found ($\chi^2 = 88.07$, $\chi^2_{125} = 86.24$) and branching ratios of the scalar particles in the type IV scenario. Dimensionful parameters are given in GeV, and the angles are given in radian.

Interesting pattern for light Higgs (h_1): no $b\bar{b}$ decays, $\tau^+\tau^-$ decays dominate...

ILC running scenario

The unique feature of the ILC is the possibility of having both electron and positron beams polarised! This is crucial for many precision measurements as well as BSM searches.

Four independent measurements instead of one:

- increase accuracy of precision measurements
- more input to global fits and analyses
- remove ambiguity in many BSM studies
- reduce sensitivity to systematic effects

Integrated luminosity planned with different polarisation settings [fb^{-1}]

H-20 $\sqrt{s}$	sgn($P(e^-), P(e^+)$) $(-,+)$	$(+,-)$	$(-,-)$	$(+,+)$	Total
250 GeV	900	900	100	100	2000
350 GeV	135	45	10	10	200
500 GeV	1600	1600	400	400	4000

arXiv:1903.01629

Signal event selection

Selection based on BDT classifier trained with following input variables:

- measured di-tau mass (before correction)
- corrected di-tau mass (scalar candidate mass)
- measured di-jet mass (Z boson mass)
- recoil mass calculated from Z boson four-momentum
- total event energy (after tau energy correction)
- jet clustering parameter y_{34}
- polar angle of the Z boson emission
- decay angles in the scalar rest frame
- azimuthal distance between two tau candidates

BDT selection

Selection results for **hadronic events** (loose selection), signal hypothesis with $M_S = 50\,\mathrm{GeV}$.
Combined $2\,\mathrm{ab}^{-1}$ of data, polarisation not taken into account.

Sample	N_{pres}	N_{BDT}	ε_{BDT} [%]
Signal	3404	823	24
$qq\tau\tau$	113990	725	0.64
$qqll$	263320	70.9	0.027
$qqqq$	1851500	1370	0.074
$qq\tau\nu$	2509100	52.7	0.0021
$qql\nu$	1381200	125	0.0091
Total	6119200	2347	**Sig = 14.6**

N_{pres} - events expected after pre-selection, N_{BDT} - after BDT response cut, BDT > 0.2.

BDT selection

Selection results for **semi-leptonic events** (loose selection), for signal with $M_S = 50\,\text{GeV}$.
Combined $2\,\text{ab}^{-1}$ of data, polarisation not taken into account.

Sample	N_{pres}	N_{BDT}	ε_{BDT} [%]
Signal	3079	999	32
$qq\tau\tau$	69160	860	1.2
$qqll$	359900	152	0.042
$qqqq$	2213	15.1	0.68
$qq\tau\nu$	1337700	79.1	0.0059
$ql\nu$	9366300	43.1	0.00046
Total	11135300	1149	**Sig = 21.6**

N_{pres} - events expected after pre-selection, N_{BDT} - after BDT response cut, BDT > 0.2.